

Influence of the Recovery Duration on the Cyclic Creep Response of Carbon Fibre Reinforced
Polymer Composites

By

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Abstract

Due to the viscoelastic nature of polymeric matrix, polymer composites exhibit time-dependent degradation in modulus and strength. The former is exhibited as time-dependent increase in strain under constant loading, known as creep. Upon unloading, this viscoelastic strain will recover completely if enough time is allowed. During cyclic loading the time for recovery may not be enough resulting in partial recovery. The effect of this partial recovery on subsequent creep and recovery has hardly been studied in the past and hence is the focus of this thesis. Numerous parameters are known to influence the creep response of viscoelastic materials, namely: the magnitude and rate of application of the load, temperature, creep duration. However, the influence of recovery duration, particularly in the case of cyclic creep loading, is more limited. Hence, the objective of this thesis was to investigate the effect that the recovery duration had on the cyclic creep response of a unidirectional carbon fibre reinforced polymer composite. Utilizing creep durations of 20s and 40s, and recovery durations varying from 1s to 80s, manufactured composite samples were subjected to cyclic creep loading conditions at two stress levels (8 / 0.1 MPa, 12.5 / 0.5 MPa) and four temperatures (room temperature, 80 °C, 120 °C, 180 °C). The maximum recorded strain during creep and recovery durations increased with the number of cycles for a given set of loading conditions and their magnitude decreased with increase in recovery duration for a given cycle. The unrecovered strain and the unrecovered stored energy at the end of each loading cycle increased with the number of cycles but decreased with recovery duration for a given cycle. The test temperature did not alter this effect of creep recovery duration; however, the magnitude of strains (creep, recovered, and unrecovered) increased with increase in test temperature. Similar effect was observed with applied peak load. Based on these results, it can be concluded that the recovery duration has significant effect on the creep and recovery response of carbon fibre reinforced epoxy composites during cycling loading.

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Nomenclature

FRP	Fibre Reinforced Polymers
PMC	Polymer Matrix Composite
CFRP	Carbon Fibre Reinforced Polymer
PTFE	Polytetrafluoroethylene
GFRP	Glass Fibre Reinforced Polymer
PEEK	Polyether Ether Ketone
DAQ	Data Acquisition, alternatively (Data Acquisition System).
COVID-19	Coronavirus Disease 2019
L	Length
d	Diameter
KP	Key Point
t	Time
t_c	Creep hold time
t_r	Recovery hold time
T	Temperature
ε	Strain
$\Delta\varepsilon_c$	Creep Strain
$\Delta\varepsilon_r$	Recovered Strain
ε_{ur}	Unrecovered Strain
$\Delta\varepsilon_{cr}$	Unrecovered Creep Strain
ε_{oc}	Unrecovered Instantaneous Strain (Loading)

ε_{or}	Unrecovered Instantaneous Strain (Unloading)
$\Delta\varepsilon_o$	Net Unrecovered Instantaneous Strain
σ	Stress
σ_c	Creep Stress
σ_r	Recovery Stress
E_l	Instantaneous Modulus (Loading)
E_u	Instantaneous Modulus (Unloading)
u	Strain Energy Density
u_T	Total Strain Energy Density
u_S	Stored Strain Energy Density
u_D	Dissipated Strain Energy Density
u_{ur}	Unrecovered Stored Strain Energy Density
NaN	Data set is unavailable

Chapter 1 Introduction

Composite materials, such as Fibre Reinforced Polymers (FRP), are an ever growing alternative to traditional engineering materials such as steel and aluminum. Owing to their high specific properties, enhanced corrosion resistance, and the ability to tailor their properties to a specific application, there has been a steady increase in their adoption in many engineering fields including the aerospace and automotive industries. These non-traditional engineering materials are composed of two constituents: a reinforcement and a matrix. The reinforcement shares the major portion of the load applied to the part, while the matrix's primary function is to bind the reinforcement, transfer the load to the reinforcement, and to protect the reinforcement.

1.1 Background

Composite materials can be divided into three main categories of composites identified based upon the type of matrix which is used: ceramic, metal, and polymer. Focusing on polymer matrix composites (PMC), the selection of an appropriate polymer matrix, along with the selection of an appropriate reinforcement geometry directly impacts the performance and attributes of the composite material. While numerous reinforcement geometries are available for use, the one which typically provides the best structural performance are continuous fibres. Continuous fibre reinforcements refer to reinforcements which have a length to diameter ratio greater than 1000 (Figure 1-1).

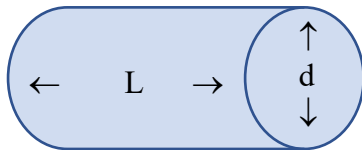


Figure 1-1: Image showing the measurements used in classification of fibre aspect ratio. L represents the length of the reinforcement, d the diameter.

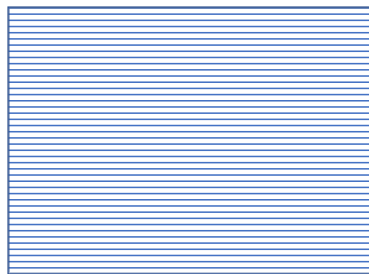


Figure 1-2: Unidirectional continuous fibre reinforcement architecture.



Figure 1-3: Woven continuous fibre reinforcement architecture.

Within the classification of continuous fibre reinforcements, there are two primary fibre architectures, unidirectional and woven (Figure 1-2 and Figure 1-3 respectively). Unidirectional continuous fibre composites feature fibres which run parallel to one another within a composite lamina (layer of the composite). With woven continuous fibre composites, the fibres within a lamina are interwoven with one another at two or more fibre orientations. When multiple lamina (whether unidirectional or woven) are stacked on top of each other and cured, this is referred to as a laminate (Figure 1-4). The number of lamina and the orientation of fibres within each lamina with respect to the loading axis are case specific and are dictated by the structural requirements of the finished part. While each type of architecture has numerous advantages and disadvantages, the focus of this thesis shall be on unidirectional continuous fibre polymer matrix composites.

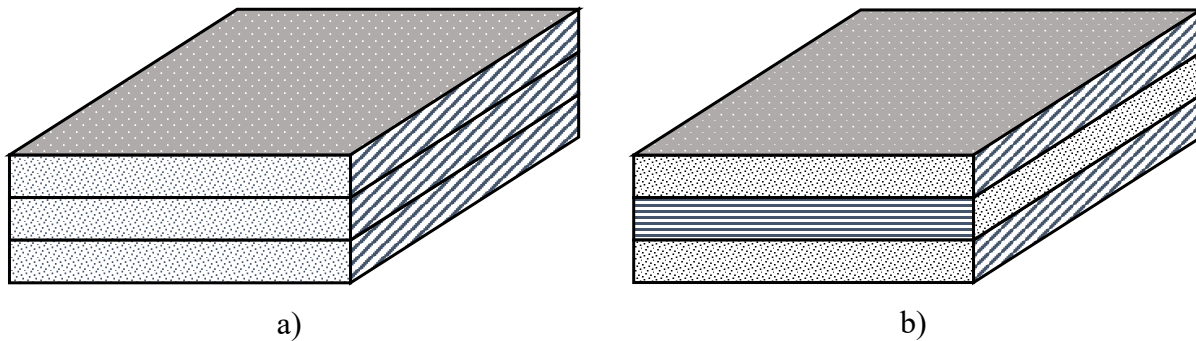


Figure 1-4: Showing stacking of numerous lamina to form a laminate: a) consists of four unidirectional fibre lamina's stacked on top of each other with lamina fibres oriented parallel to each other to form a unidirectional laminate. b) consists of four unidirectional fibre lamina stacked with varying fibre orientations to form a multidirectional laminate. Adapted from [1].

One of the most common methods to manufacture continuous fibre reinforced composites is autoclave manufacturing, which has been used in this research. This utilizes, a prepreg, which is a roll or sheet of parallelly aligned reinforcement fibres that have been pre-impregnated with an uncured resin. When manufacturing, the prepreg is cut to size to form the lamina, and then multiple lamina are laid on top of each other, with all lamina fibres orientated in the same direction in the case of a unidirectional laminate.

The strength and modulus of the composite part is primarily due to the reinforcement. Therefore, in the case of a unidirectional continuous fibre laminate, the composite is able to withstand the largest applied load parallel to the axis of the fibres (referred to as on-axis loading). This is a result of the fibres supporting the majority of the applied load in this orientation. Should the fibre orientation deviate from the loading axis (referred to as off-axis loading), the strength and

modulus of the composite decrease, until it reaches a minimum value when the fibres are oriented perpendicular to the axis of loading.

Due to the viscoelastic nature of the polymeric matrix, when PMC's are subjected to off-axis loading conditions with the matrix carrying an increasing proportion of the applied load, degradation in modulus and strength with time begin to become a concern. Specifically of interest to this research are two viscoelastic properties, creep and creep recovery. Creep is a process by which a viscoelastic material, when in the presence of an applied constant load, exhibits a time dependent increase in deformation. Figure 1-5 presents both a visual representation of the creep loading profile, along with a generalization of the corresponding creep and recovery strain response. Since this increase in deformation is a time dependent property, if the applied load is held longer, the creep strain experienced by the composite shall increase (at a decreasing rate) [2], or the sample fails due to a mechanism referred to as creep rupture [3]. Creep recovery, is the response of the material when the applied load is removed and the material is allowed to recover. During this unloading period, the composite shall recover some to all of the creep strain which occurred during the creep portion. As with the creep response, the recovery response is also time dependent [4].

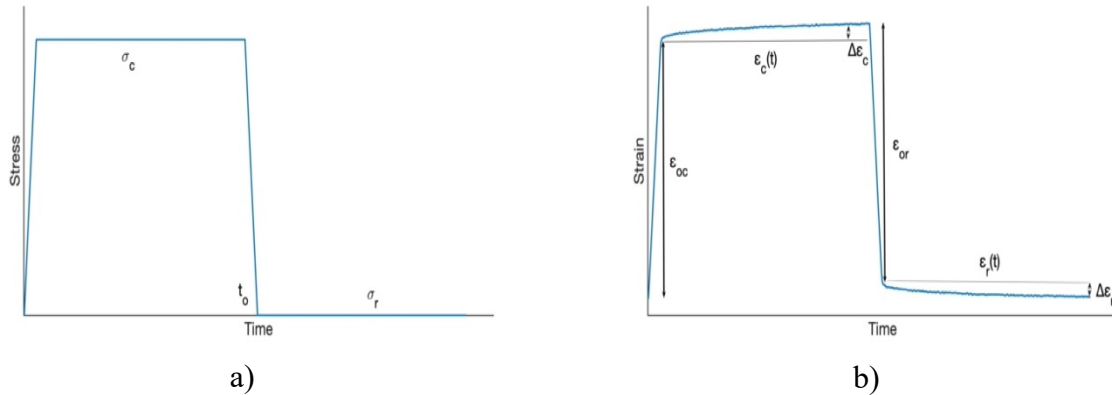


Figure 1-5: Symbolic representation of the creep loading. a) presents the symbolic representation of the applied load to the sample. b) presents the symbolic representation of the strain response of the material.

When evaluating the viscoelasticity of a PMC, it is necessary to also consider the service conditions which the PMC is subjected to. Operating temperature, magnitude and rate of application of the applied load, and duration of creep and creep recovery segments have all been observed to affect the viscoelastic response of the material [5]. As the viscoelasticity of the polymeric matrix of the composite is temperature-dependent, the creep strain is sensitive to

changes in the temperature and was observed to increase as the temperatures increases. Another factor which influences the viscoelastic response of the material is magnitude of the applied load. As the magnitude of the applied constant load increases, the creep strain increases. The rate at which a tensile load is applied to a sample shall affect the initial response of and thus total creep strain exhibited by the material. Lastly, the duration of the creep and creep recovery shall either increase or decrease the amount of creep and creep recovery strain which is accumulated or recovered.

When PMC's are subjected to cyclic loading, both creep and the creep recovery are encountered during the loading and unloading segments of the loading cycle. Depending on the frequency of the cyclic loading, the creep strain during the loading segment and recovery during the unloading segment will vary. Should the amount of time between loading cycles (i.e. recovery time) be insufficient there exists the possibility for the accumulated creep strain to have not fully recovered during the creep recovery portion, affecting the creep during subsequent load cycles. Therefore, accumulation of unrecovered strains during unloading cycles, and their effect on creep during subsequent loading cycles, is important in understanding the overall creep response of a part subjected to cyclic loading.

Previous work conducted on the subject matter of the viscoelasticity of PMC's has largely focused upon the creep portion of the creep/creep recovery cycle mostly during single loading cycles with the evaluation of the creep recovery portion being more limited. When evaluating the viscoelastic response of polymers and PMC's subjected to cyclic creep loading conditions, the majority of the research has involved testing the material operating in strain control conditions. The studies which were reviewed were found to typically focus on attempting to develop methodologies and models to predict the response of the material, and utilized variations in the previously discussed parameters.

However, with respect to the evolution of the strain response, in particular the accumulation of viscoelastic strains through subsequent cyclic loadings, the influence of the recovery duration has not been fully explored. Previous studies into the subject of the accumulation of strains during cyclic creep have largely focused on the accumulation of viscoplastic strains in thermoplastics, a phenomenon known as ratchetting. However, in contrast to thermoplastics,

thermosets such as CFRP's do not yield and as such there will not be any viscoplastic strains. When close to failure, it has been observed that CFRP's will experience strains due to damage, however before the material reaches that point the viscoelastic strains will be dominant in the response [6]. Therefore, a more comprehensive understanding of the influence that the recovery duration has on the cyclic response of the material will allow for better prediction of the evolution of the strain response, and in turn provide better understanding of the mechanisms responsible for failure of the material.

As such, to the best of the authors knowledge, an evaluation of the role that the recovery duration plays when a PMC is subjected to cyclic creep loading conditions has not been sufficiently evaluated. As well, the influence that the viscoelastic unrecovered creep recovery strains has on the cyclic response has been identified as needing further understanding.

1.2 Thesis Scope

Therefore, based upon the knowledge gap identified, the effect that the recovery duration (i.e. time elapsed between two loading cycles) has upon creep and creep recovery during subsequent cycles was studied experimentally. Using a manufactured unidirectional continuous fibre reinforced thermoset polymer composite, experimental creep and creep recovery strain was measured as a function of loading and unloading time, respectively, for 180 cycles for given load (stress cycle and test temperature). This experiment was repeated for various combinations of peak cyclic stress and test temperature as well as frequency of load cycling (i.e. varying recovery time). The data was analyzed to yield the evolution of the following as a function of number of cycles: Loading and unloading instantaneous modulus; unrecovered strain; total strain; total, stored, and dissipated strain energy density (i.e. hysteresis). The effect of recovery time, peak stress and test temperature on the above derived results was studied to understand the effect of recovery time on viscoelastic response of a unidirectional composite subjected to cyclic loading. While it is not pursued in this thesis, the evolution of stored strain energy density with cycles may be used to predict fracture of composites subjected to high cycle fatigue loading.

The research was limited to $[90^\circ]$ composite and tensile-tensile loading; the fibre orientation in the test coupons were oriented at 90° to the loading axis, since the viscoelastic response of the thermoset matrix, under tensile loading, would be maximum for this orientation.

1.3 Thesis Outline

Chapter 2 shall expand upon and further discuss current and previous works conducted into the subject matter to identify the knowledge gaps and provide a context for the objectives of this thesis. Chapter 3 shall present the processes used to manufacture the material for testing. This chapter shall also present the test equipment which was utilized to achieve the objectives of the thesis, the testing which was performed, and present formulations and the methodologies used in the evaluation. The results obtained via the experimental tests are presented and discussed in Chapter 4. Lastly, Chapter 5 shall summarize the results obtained and present the conclusions which have been drawn.

Chapter 2 Literature Review

This chapter shall present an overview of the published literature on the viscoelastic response of polymer and polymeric composites subjected to creep and cyclic creep loading conditions. First, presented will be background information pertaining to viscoelasticity, along with an overview of the parameters which influence the creep response of these materials. After which, the extension of these parameters to single cycle and cyclic creep loading, along with a discussion of the response of these materials to these conditions shall be discussed. Lastly the knowledge gaps identified in the field will be summarized and the objectives of the thesis will be presented.

2.1 Background Information

As previously identified polymeric composites such as fibre reinforced plastics (FRP's) are composed of two primary constituents; the matrix and the fibre. The literary review performed was primarily focused on the matrix of the composite as this is the portion which is mainly responsible for the viscoelastic properties. The amorphous polymer matrix (similar to the epoxy used in this thesis) is composed of many long and randomly oriented polymer chains [4]. When a state of stress is applied to the composite, these long polymers chains tend to reorient themselves in the direction of the applied load. This reorientation of the polymer chains cannot instantaneously; rather they occur with time. During this, the bonds between molecules in the chain rotate, chains unkink, and slide resulting in the macroscopically measured deformation / strain. These mechanisms as well as resulting magnitude of strain are time-dependent phenomena. Thus as the time that the load is applied increases, so too does the amount of reorientation which occurs within the polymer as well as the macroscopically measure strain. Also, the mobility of chain movement increases with increase in temperature and hence as the test temperature increases, the ability of the polymer chains to reorient and the resulting creep strain increase as well [7].

During creep, when a material is subjected to an applied load which is then held, the material experiences an initial deformation, after which the viscoelasticity begins to take effect. This results in the composite experiencing additional strain, with a decreasing strain rate. This additional strain is referred to as creep strain. Upon unloading of the material, the instantaneous strain recovers, followed by additional strain recovery of decreasing rate until an equilibrium is reached. During this recovery process, the polymer chains attempt to return to their initial orientation and length, resulting in the recovery of some, to all, of the accumulated strain.

Depending on the material, and the magnitude of the load which was applied during the loading portion, there exists the possibility for inelastic strains (viscoplastic) to develop within the material. Extended to cyclic loading conditions, when subjected to numerous creep loadings cycles within the plastic levels, the accumulation of these viscoplastic strains between cycles is a phenomenon referred to as ratchetting.

Beyond temperature, numerous other factors influence the creep and creep recovery response of a polymer or polymeric composite materials. These include but are not limited to the magnitude and rate of application of the loads, and the duration of the loading and unloading applied to the material [5]. Referring to Figure 1-5 a), σ_c corresponds to the creep (maximum) load applied to the material. This is the load which is applied to the material and maintained during the creep holding portion. Both the magnitude of this applied load, along with the duration that it is held (t_c) will influence the amount of creep strain which will be accumulated during the loading. Conversely, σ_r corresponds to the recovery (minimum) load applied to the material. This corresponds with the load at which the material is allowed to relax and recover any accumulated strains. Similar to the creep hold, both the magnitude of this recovery load, and the time which the material is allowed to recover for (t_r) both influence the amount strain which is able to be recovered. Of interest for this research was pure tensile-tensile creep loading of polymers and polymeric composites. This indicates a situation where the applied creep load is positive, and the recovery load is at minimum 0 MPa, with both loads being applied

When the loading profile presented in Figure 1-5 a), is applied to the material multiple times consecutively this is referred to as cyclic creep loading. The resultant stress-strain loading curve generated represents the strain energy density of the sample. During the loading and creep segments of curve, these combined are referred to as the total strain energy density. Upon the

release of the applied load, at the end of the creep segment, the resultant unloading and recovery curves correspond to the store strain energy density.

When the recovery time allowed between cycles is of sufficient duration, and the applied load be within the elastic limit, the hysteresis formed by the two curves shall form a closed loop. This closed loop is referred to as the dissipated strain energy density and corresponds to the energy lost via heat and other mechanisms. However, should the application of the load result in plastic deformation, or insufficient time allowed for the sample to recover, this results in the hysteresis forming an open loop and indicates the presence of unrecovered strain energy density.

2.2 Overview of Influence of Parameters

There has been considerable research already performed evaluating the role with which many of the previously identified parameters affect the monotonic creep response of polymers and polymeric composites. This section presents the effects that these parameters have on a single creep loading cycle. Discussed will be the effect of the magnitude of the creep and recovery load, temperature, and creep and recovery duration.

With respect to the influence of the applied load has on the viscoelastic response, the influence that the applied creep load has been documented extensively, [8], [9], [10], [11], [12]. Observed was that with an increase in the applied creep load on the sample, the creep strain experienced by the sample increased. Additionally, regardless of the applied creep load, the rate of accumulation of the creep strain decreased with increase in creep duration.

Zaoutsos and Papanicolaou, investigated the influence of preloading on carbon epoxy composites had on the response [13]. For the research performed, preloading of the samples involved applying a constant creep load for 168 hrs, followed by 168 hrs of recovery. After which, the primary testing was performed on the samples which consisted of cyclic sinusoidal loading conditions for 20 mins at a rate of 1 cycle per minute, followed by another static creep loading for the same creep and recovery duration as the preload. The samples were subjected to applied creep loads varying from 30 to 70% of the tensile failure stress.

By applying the varying loads upon the samples, demonstrated was that as the applied load on the sample was increased, the creep recovery strain response of the sample increased. Comparing

the creep strain of static tests with the preloaded-static tests, observed was the preloading of the samples this resulted in an increase in the creep strain. However, the authors did not study whether this increase was the result of any unrecovered strain, only identifying that the increase in the creep strain should be investigated further.

Zhu et al. presented similar results while developing a model to estimate the change in the viscoelastic and viscoplastic response of a polymer [14]. Studying polycarbonate subjected to stress controlled tensile-tensile creep tests, demonstrated by the authors was that with an increase in the applied stress level increased, the peak (maximum) and valley (minimum) strain recorded during cyclic loading both increased with increase in the applied stress. Performing the cyclic tests for a total of 200 cycles each, and both strains showed an increasing trend with number of cycles. However, the effect that the recovery duration had on the strain response was not investigated.

Similar to the influence of the applied load, the effect that changes in the temperature has on the response of the material have also been well documented [12], [15], [16], [17], [18]. Known is that with an increase in the temperature that the matrix of the materials softens and the stiffness decreases. This decrease in the stiffness correlates with a decrease in the modulus of the material with increase in the temperature. Due to the relationship between the temperature and the viscosity of the material, with an increase in the temperature this also corresponds with an increase in the creep strain and creep recovery strain.

Similarly, Jia et al. noted that for thermoplastics in general, that the creep and recovered strains decreased as the temperature decreased, and the creep strain rate increased with increase in temperature [19]. Of particular interest with this study was that at elevated temperatures, the authors observed that while the elastic strain recovered was larger, the unrecovered strain also increased. Similar results were also shown by Hao et al. [2].

Wang et al. performed experimentation evaluating the dependence of the creep and recovery of chemically reduced graphene oxide polymer composites [7]. The authors tested their composite materials in tensile creep at 5 MPa for a total creep duration of 900 s, at temperatures ranging from 25 to 70 °C. Demonstrated was as temperature increased the total, creep, and creep recovery strains increased.

With respect to the influence that the creep duration has, Zheng et al. performed compressive cyclic creep testing of PTFE gaskets to study creep ratcheting [20]. The authors performed experimentation varying the creep duration of the material and the temperature for 400 cycles of compressive creep testing. Consistent with other studies of polymers subjected to cyclic loading conditions, with an increase in the temperature there was an increase in the amount of creep strain (and accumulated ratchetting strain) experienced by the material. Similarly, the authors showed that as the creep hold time increased, there was an increase in the accumulation of creep ratchetting strains. However, no investigation was performed evaluating the effect that the recovery duration had on the accumulation of unrecovered strains.

Papanicolaou et al. performed tensile creep tests on a carbon epoxy composite with the purpose of fitting the acquired data to Schapery's non-linear viscoelastic model [21]. This non-linear viscoelastic model uses fitting of experimentally acquired data to obtain values for a number of parameters. Of particular interest in this study was that the authors noted that for all of their tests that "the instantaneous strain response of the material at the time of unloading was greater than the instantaneous strain response at the time of loading [21]."

2.3 Cyclic Creep Loading Conditions

In addition to the factors which were discussed in preceding section, when subjected to repeated cyclic creep loading conditions, changes in the material response become more prevalent.

Zaoutsos evaluated the effect that multiple loadings had upon the viscoelastic-viscoplastic response of a CFRP [22]. Using a set of published set of experimental cyclic data [23], the author evaluated the data using Schapery's equations. The data set was for $[\pm 45^\circ]$ laminate subjected to cyclic creep with approximately 480 hr of creep followed by 960 hr of creep recovery, for a total test duration of 10176 hrs (7 cycles). Observed from the data was that the strain increased during the holding period and at every successive loading step. Evaluating the unrecovered strain at the end of each cycle, the authors assumed them all to be viscoplastic strains and identified an increase trend with both applied load and cycle. However, the effect that changes in the recovery duration had were not evaluated.

Starkova et al. evaluated polypropylene / multiwalled carbon nanotube composites subjected to both creep and cyclic creep loading conditions [24]. Of particular interest in the study performed

was the effect that the viscoplastic strains, identified by the authors as residual strains, which the material experienced during cyclic loading, had on the response of the material. They identified these residual strains as those which remained after load removal for a duration greater than the time of active loading of the specimen. These included the viscoelastic, the viscoplastic, and damage strains (strains caused as by damage to the sample). This simplifies the evaluation making the source of the accumulating strains irrelevant, but in doing so does not allow for the evaluation of the role that recoverable viscoelastic strains have by themselves.

In the study the materials were subjected to various stresses, loading times, and number of cycles. Indicated by the authors' results, was that the creep response of the material increased with an increase in the applied load on the sample. Testing under cyclic creep conditions for 50 cycles, observed was the total creep and residual strains increasing with increase in loading time, applied load, and number of cycles. Of interest, the authors' observed that for cyclic creep at the same applied stresses, regardless of the creep and recovery durations, all tests followed the same creep strain response. However, all of the tests performed maintained the same ratio of creep to recovery duration of 1:3, thus changes in the strain response (in particular the unrecovered strain) arising from deviation from this ratio were not evaluated.

Adalja and Otaigbe studied the creep and recovery behavior of phosphate glass low-density polyethylene composite [25]. Studying the material response when subjected to varying temperatures, noted was a significant increase in the creep strain when the temperature increased. Performing cyclic creep tests on the novel material, they determined that the allowed recovery time was insufficient to allow for complete recovery, and they noted that as a result there were residual strains that influenced and are included in the future cyclic creep strain response. These residual strains resulted in an increase in the subsequent cycles creep strain, and were noted by the authors to possibly include plastic strain. Variation in the recovery duration and its influence on the accumulation was not investigated.

Li et al. performed creep and cyclic creep tests on a surface modified carbon fibre nano-composite [26]. Evaluating the composite the authors demonstrated that there was correlation between the creep strain response and the applied load, temperature. Noted was that above a certain stress threshold due to the applied stress field, that the samples experienced strain

hardening. The authors observed the creep modulus of the material decreased with increase in stress and temperature. When performing cyclic creep testing, the creep strain decreased with an increase in the number of cycles at a decreasing rate per cycle.

Movahedi-Rad et al. studied $\pm 45^\circ$ angle-ply GFRP's subjected to two loading situations [27]. The first loading parameter was an interrupted fatigue loading situation in which the GFRP sample was subjected to a fatigue loading pattern for a duration of approximately 20% of the sample fatigue life. After this the sample was unloaded and allowed to rest at zero-load for 2 hrs. This process of fatigue loading and then resting was performed repeatedly until sample failure occurred. During this rest interval, the recovery of the sample was evaluated. The remaining strain at the end of each recovery segment increased with the number of loadings.

The second loading pattern the authors evaluated was a sinusoidal fatigue loading. Performing this set of fatigue loading on their samples, the area of the hysteresis increased as the number of cycles increased. They attributed this increase in the area to both internal friction within the sample's damaged regions, self-generated heat, and the matrix viscoelasticity. Observed was a decreasing trend when analyzing the fatigue stiffness of the material.

Lemme and Smith studied the creep and cyclic stress response of a film adhesive [28]. The authors identified that given that the recovery of strain accumulated during creep can take a significant amount of time, they defined permanent strain to be any strain remaining after a time of nine times the creep duration. Based upon this definition, during cyclic testing that there was an accumulation of strain.

When subjected to cyclic creep loading conditions, as the number of cycles increased, as did the creep strain. Evaluating the recovery curves, the authors noted that the non-recoverable strain also increased with the number of cycles. However, as the authors note, that this unrecoverable strain may in fact be a result of the creep strain being given insufficient time to fully relax from the previous cycle.

Shen et al. studied the effect that uniaxial cyclic tests had on the deformation of an epoxy resin [29]. Subjecting the material to a cyclic tensile loading, the change in the hysteresis curve along

with the accumulation of ratcheting strains was evaluated. Observed was that the accumulation of ratcheting strain per cycle decreased as the number of cycles increased.

Kang et al. noted that while study of cyclic deformation of polymer matrix composites has been increasing, the research has primarily been conducted under strain control, with hardly any evaluation conducted under stress control [30]. The authors studied the ratchetting of polyester resin glass composites under stress control. Testing these materials under cyclic stress loading, with varying loading rates and peak hold times, observed was that with an increase in peak hold times, that the amount of accumulated strain increased (creep). Performing cyclic testing, noted was that the actual viscoplastic strain was relatively small, and that the accumulation of ratchetting strains in this scenario was rather mostly driven by the accumulation of viscoelastic strains. The authors summarized that this accumulation of ratchetting strains was a result of the viscous nature of the resin. It should be noted that while polyester is a thermoplastic, the ideas presented by the authors may have some cross-over which is also applicable to thermosets. Not discussed or evaluated by the authors was any discussion on what the effect that changes in the recovery hold time had on the response.

Liu et al. studied the response of a PEEK based composite reinforced with short carbon fibres subjected to uniaxial and cyclic compressive loading [31]. When evaluating the material subjected to cyclic loading, identified was that the unrecovered strain caused the hysteresis loop for the first cycle not forming a closed loop. This initial deviation was identified by the authors as the main cause of the accumulation of the ratcheting strain. Noted was that as the number of cycles increased, the shift in the hysteresis loop decreased indicating that the accumulation rate of the ratcheting strain decreased as the test progressed.

Jiang et al. performed cyclic creep tests operating in displacement control on polycarbonate to study the effect that stress level, rate, and hold duration had upon the ratcheting response of the material [32]. The authors attempted to use a valley time (recovery time) much larger than the hold time in an attempt to separate the viscoelastic and viscoplastic strains. Only two recovery durations, 0s and 300s, were evaluated. As expected, the accumulation of strain was smaller when the sample was allowed to recover to a longer duration, thus resulting in smaller residual (unrecovered) strains after completion of the testing.

Similar studies of the influence that the peak and valley times was performed by Chen et al [33]. However, the investigation of the effect of the peak and valley time was limited in variation and specifically related to its influence on ratchetting strains. Evaluation of the accumulation of unrecovered elastic strains were largely ignored.

Liu et al. evaluated the ratchetting strains of polymethyl methacrylate when subjected to cyclic creep [34]. While evaluating this, the authors presented a relationship between the shape and position of the hysteresis curve to the change in creep strain between cycles, along with the change in the plastic strain. Not considered was the influence that unrecovered elastic strains played on the change in the hysteresis.

Paimushin and Kholmogorov performed cyclic testing on a carbon fibre $[\pm 45^\circ]_{2s}$ tape composite [35]. What was noted was that with each successive cycle, the creep strain increased by an amount which decreases as the number of cycles increases. This decreasing change in the strain, was identified as being a result of hardening of the composite with each cycle, which they identified as the adaptability of the composite material.

2.4 Knowledge Gap

Based upon the literary sources presented, while there has been considerable research into the effects that temperature, the stress level, loading rate and the creep duration have on the response of a PMC when subjected to cyclic creep loading conditions, the influence of the recovery duration has not been fully evaluated. Discussions pertaining to the recovery of the sample while under cyclic conditions has typically been limited to analysis of viscoplastic strains, and the accumulation of these resulting in the phenomena called ratcheting. Most discussions pertaining to the effect that the unrecovered viscoelastic strains have with respect to the cyclic response of the material, has been to treat any unrecovered creep strains as viscoplastic strains, which would not typically be present if the applied load is of sufficiently low magnitude.

Largely, the effect that the unrecovered creep strains have on the viscoelastic response of the material during cyclic loading has not been studied, with most studies being performed on polymers, with studies on composites (and their fibre orientations) even more limited.

Thus, to the best of the author's knowledge, the influence of the recovery duration and the accumulation of unrecovered elastic strains during cyclic loading of a CFRP has not been thoroughly evaluated. Of particular interest in the study performed was the influence that these unrecovered viscoelastic strains have upon subsequent cycles, and changes in the material response as a result of them.

2.5 Thesis Objective

Hence, the overall goal of this thesis is to address some of the knowledge gaps identified above by focusing on the effect of recovery time on viscoelastic response (i.e. creep and creep recovery) of a polymer composite during cyclic loading. In order to realize this goal, the following objectives are proposed.

- Study the creep and creep recovery of polymer composite during cyclic loading with varying recovery time duration, for a given peak load and test temperature.
- Extend the above study to additional peak loads and test temperature to understand the interaction of these with the recovery time duration.
- Evaluate the effect of cyclic loading conditions on the evolution of unrecovered strain as a function of loading cycles and use it to understand the changes in; modulus; stored elastic energies, and dissipated strain energy density (hysteresis) during cycling loading.
- The research was limited to [90] carbon fibre reinforced composites and tensile loading; Fibre orientation in the test coupons were oriented at 90° to the loading axis, since the viscoelastic response of the thermoset matrix, under tensile loading, would be maximum for this orientation.

Chapter 3 Experimental Setup

Based upon the knowledge gaps identified in the preceding chapter, the following shall present the details of the experimentation performed to address these gaps. The material and manufacturing processes shall first be presented (Section 3.1), followed by details on the test coupon preparation (Section 3.2). Next details pertaining to the experimental parameters and procedures (Section 3.3) shall be presented. Lastly, the methodologies and procedures used to analyze the raw data shall be discussed (Section 0).

3.1 Material and Manufacturing Process

The composite material, which was supplied by Hexcel, and used for the experimentation conducted was composed of HexPly F263 epoxy resin, with Toho Tenax HTA40 fibre. This CFRP was shipped from the manufacturer as a rolled up continuous uncured prepreg tape with a width of 24". The prepreg was received and stored, vacuum sealed and maintained in a frozen state below 10 F when not in use. This section shall present the manufacturing processes and techniques, developed by Composite Materials and Structures Research Group at the University of Manitoba, used to manufacture this CFRP. Presented shall be the hand lay-up, cure cycle, and the post curing procedures used to manufacture the cured laminates.

3.1.1 Hand Lay-up

In order to properly manufacture a composite panel of the highest quality, numerous steps must be followed. The first step which is very crucial to the process is the cleaning of all surfaces with which the prepreg may come into contact with, so as to prevent any contamination. This is achieved through the use of alcohol based chemicals, typically methanol or acetone. In addition to sanitizing the workstation / surfaces, since the alcohol shall evaporate in short order, this also prevents moisture from coming into contact with the prepreg, thus reducing the possibility of defects caused by moisture present in other cleaners.

After the surfaces have been cleaned, as the prepreg is stored in a walk-in freezer at temperatures below zero Celsius, it must first be removed from the freezer and allowed to thaw to room temperature while contained within the storage bagging material. By allowing the prepreg to warm to room temperature, this will decrease the viscosity of the resin which will improve the flow during the curing process. Additionally, by keeping the prepreg contained within the vacuum seal during the thawing process, this prevents condensation from clinging to the material.

Upon reaching room temperature, the prepreg is removed from the vacuum seal, and using a cleaned 12" x 12" steel plate as a template, the prepreg is cut into square sheets. The template is aligned with great care to the virgin edges of the prepreg to ensure that all cut sheets have the same fibre orientation. Ensuring good fibre alignment is very important when manufacturing unidirectional CFRP. Should the alignment of the fibres stray from the desired final angle this can result in suboptimal properties for the cured laminate, and possibly result in warping of the final product.

With the prepreg material now cut to size, a steel caul plate which is used to provide shape to the laminate during the curing process is positioned on the work surface. It is then covered with a spray-on releasing agent (Frekote) and to allow for easy removal of the composite part from the plate after the curing has been completed. Next a non-perforated release film (Wrightlon 4600) and a perforated release film (Wrightlon 5200) are placed. In addition to the release spray, these release films also assist in the ease of removal of the cured composite from the layup assembly, while the perforated release film allows for excess resin to bleed from the laminate during the cure. After the release films, the next component used is a layer of peel ply (RELEASE EASE 234TFP 38"). The peel ply allows for ease of removal of the rest of the layup materials from the cured composite, while allowing the excess resin to bleed. Additionally, the peel ply provides texture to the cured composite part.

With the preceding layers all stacked and aligned upon one another, the next step is to lay-up the cut carbon fibre prepreg. Removing the protective silicon and wax paper coatings from the cut prepreg sheets, each lamina of the laminate are then stacked one upon another, one at a time. Using the utmost care, the virgin uncut edges of the prepreg are aligned with one another to ensure that the fibres of each lamina are oriented in the same direction. As with the cutting

process, should the fibre orientations vary from lamina to lamina, this would result in imperfection in the properties of the cured composite.

With all layers of the prepreg now lain and aligned, another layer of peel play is placed, followed by another layer of the perforated release film. After these two layers, a cotton bleeder/breather is placed on top. The breather allows for gases to escape from the laminate during the curing process, along with absorbs the excess resin which bleeds out during the curing process. On top of the bleeder/breather another layer of non-perforated release film is placed, followed by the other release film covered caul plate. A visualization of this stacking sequence is visible in Figure 3-1.

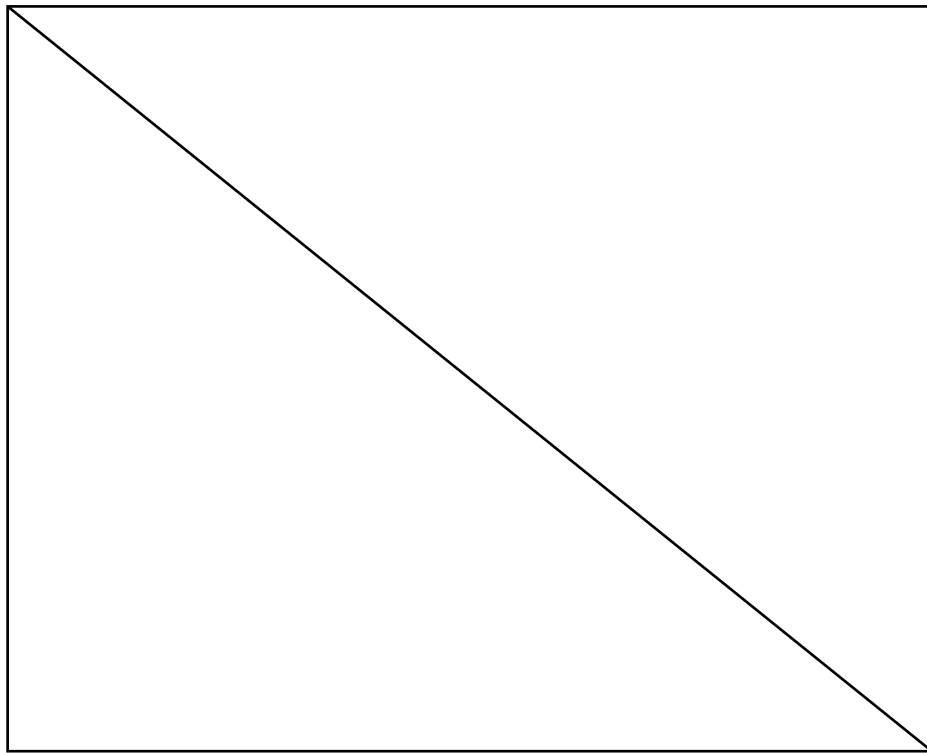


Figure 3-1: Visualization of Lay-Up Stacking Sequence and mold. Adapted from [36]. Image removed due to copyright.

3.1.2 Cure Cycle

With the completion of the hand lay-up process, the next set is to begin the curing of the composite laminate. To achieve this, elected for this research was the use of autoclave curing. However, due to the extensive costs associated with procurement and operation of a full-sized autoclave this is not feasible, thus instead simulated autoclave conditions have been used to

manufacture the composite part. This was performed using a Carver hydraulic press (WABASH-440H-42) equipped with platen temperature controls Figure 3-2.



Figure 3-2: Carver Hydraulic Press.

Using a 2-piece steel mold, with the bottom half equipped with a vacuum port, and the upper half partially hollowed out and equipped with a fitting to permit the flow of nitrogen into the mold, this allowed for the control of the pressure applied to the composite part during curing. A visual representation of the two halves of the mold can be seen in Figure 3-1. Placing the lay-up on the lower half of the mold, a silicon pad (AIRTECH-1024-.60-48") is placed on top to prevent the flow of the nitrogen from evacuating through the vacuum line. As a result, during the manufacturing process the lower portion of the mold is under a negative pressure due to the applied vacuum, while the upper portion is under a positive pressure applied by the nitrogen. Additionally, a piece of glass fibre was placed and secured above the edge of the bleeder leading to the vacuum line hole, allowing for gas within the composite to be drawn out, as well as preventing the silicon pad from blocking the vacuum line hole.

Placing the steel mold within the hydraulic press and attaching the vacuum and nitrogen line, the laminate is ready to be manufactured. The hydraulic press is then set to close with a force of 23 tons, the heat and vacuum line are then turned on. Upon reaching a temperature of 80 °C, the

vacuum is then shut off and line valve closed, after which the nitrogen valve is opened and a pressure of approximately 85 psi is allowed to enter the upper cavity of the mold. Due to the increase in the temperature, as per ideal gas law, the pressure within the upper portion of the mold is susceptible to increase. Should the pressure increase above the acceptable tolerance, a nitrogen bleed off line is opened to decrease the pressure within. The temperature then continues to increase until it reaches a final cure temperature of 180 °C, and is held at this temperature for 2 hours. After the 2 hour hold, the heat to the platens is shut-off, and the mold is allowed to cool via convection with the ambient room temperature. Upon the platens reaching a temperature of 60 °C, the nitrogen valve is closed, and the force applied to the mold removed, thus releasing the pressure within the mold. This described cure cycle can be seen visually in Figure 3-3.

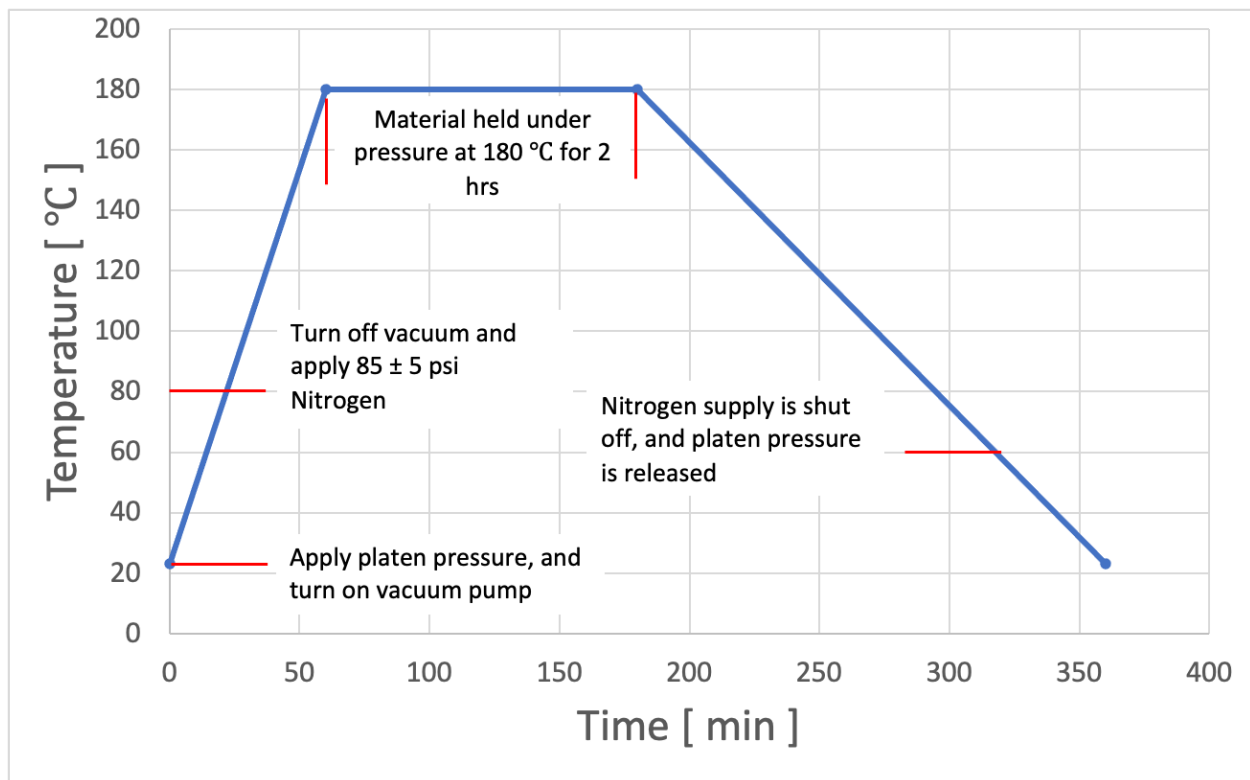


Figure 3-3: Cure Cycle used to manufacture composite laminate. Adapted from [1].

3.1.3 Post Curing

After allowing sufficient time for the hydraulic press platens to cool to temperatures safe to handle, the mold can then be removed from the press. The laminate is then be removed from the mold, with the expendable materials discarded. Care is made to keep track during the process of

the aligned virgin edge. While the utmost care is made to ensure alignment of the lamina, the cut edges are susceptible to variations and thus cannot be considered as reliable references for future measurements when cutting.

While the cure cycle used in manufacturing the composite part will result in the majority of the resin becoming cured, there is the possibility for small portions to be incompletely cured. As such, a post cure is required to ensure complete cure and crosslinking of the polymer. The cured laminate is then placed within a high temperature oven, and heated to a temperature of 220 °C and held at this temperature for a total of 4 hours.

3.2 Test Coupon Preparation

The following sections shall outline the methodology used in preparation of the test coupons for use in cyclic tensile creep testing. Section 3.2.1 presents information with respect to the preparation of the samples to meet their desired dimensions including discussion of bonding of tabbing material. While section 3.2.2 provides information with respect to the processes used to bond the strain gages along with the gage specifications.

3.2.1 Sample preparation

Taking the cured continuous unidirectional carbon fibre panel manufactured using the methods outlined in Section 3.1, test coupons are then prepared for testing. Due to size restrictions based upon the stroke length of the test equipment, samples must be cut to a size suitable to fit within the chamber and test fixture.

Using the virgin edge of the laminate plate as a reference, the laminate plate is measured and marked to produce cut panels with an initial width and length of 12 and five inches respectively, with a fibre orientation of 90° with respect to cut plate length. This width of 5 inches shall provide the final length of the samples after further preparation has been performed. This is achieved using Micro-Matic Precision Wafering Machine (Figure 3-4) equipped with a diamond saw blade.



Figure 3-4: Micro-Matic Precision Wafering Machine.

Before further preparations of the samples is possible, the tabbing needs to be bonded to these cut plates. Tabbing is used to protect the sample while gripped within the load frame, and to concentrate the load within the gage length of the coupon. The tabbing used consists of 4 plies of M42 50% G939 (manufactured by Hexcel), which is a woven continuous carbon fibre and was provided by UMSAE formula team. Following the same procedure outlined in Section 3.1, a 12" and 12" plate of woven composite is manufactured. After successful completion of both the curing and the post curing process, the cured woven laminate is then cut using the diamond saw into four pieces with dimensions 1.25" by 12". These four cut woven pieces are then to be bonded onto the cut unidirectional composite plate. This bonding is achieved via a high temperature adhesive (Hysol EA 9673). Cutting the adhesive into strips slightly undersized in comparison to the cut pieces of the woven composite. The adhesive is placed between the tabbing and the laminate it is then held in place using a high temperature tape (FLASHBREAKER-1-1").

Placing the prepared assembly between two steel plates, with a layer of non-perforated release film above and below, the assembly is loaded into the hydraulic press. Lastly, above the top of the steel plates, a silicon pad is placed above to assist in even distribution of the applied load during the bonding process. When curing the bonding adhesive, a two-step process is used as per the manufacturer [37]. The hydraulic press is set to apply a compressive load between 5 and 15 psi at a temperature of 120 °C for a duration of 1 hour. After the completion of the hour, the

compressive load is increased to between 25 and 50 psi, and the temperature is increased to 180 °C and is held for an additional hour. By utilizing a two-step process, this decreases the amount of resin which flows away from the area's being bonded, thus resulting in a cleaner surface finish after the completion of the process.

With the tabbing now bonded onto the laminate, the laminate is then cut, again making use of the reference edge to ensure the fibre orientation matches the desired 90°, using the diamond saw to produce coupons with an approximate width of 15 mm. When the samples are cut by the diamond saw, sharp edges may be left on the edges of the sample, which left unaccounted are locations where stress concentrations may occur. Therefore, to reduce the possibility of premature failure as a result of these edge stress effects, to bring the coupon to the desired final with, the samples are then polished using water equipped polishing station (Figure 3-5). Using carbide polishing grit tapes fixed to this station, the sample is evenly polished on all sides starting at a grit of 120, progressively increasing to final grit of 600. The sample is polished until an acceptable edge smoothness is achieved, with a final approximate sample dimensions of 127 mm x 13 mm. The final sample dimensions were selected based upon sample dimensions used by a previous student in our research group (Asadi, [38]). Figure 3-6 presents a schematic view of the approximate final test coupon dimensions.

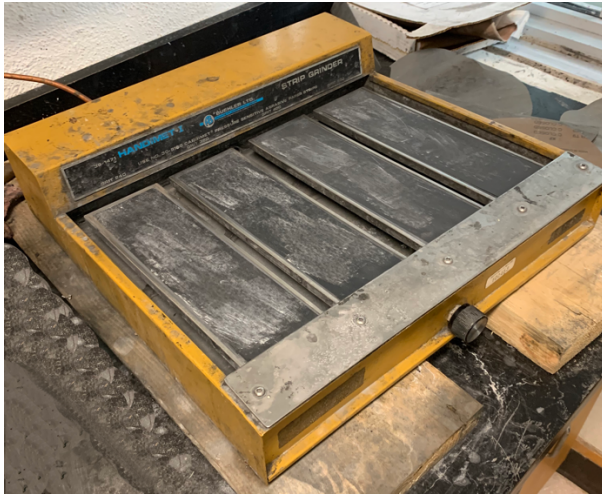


Figure 3-5: Polishing Station

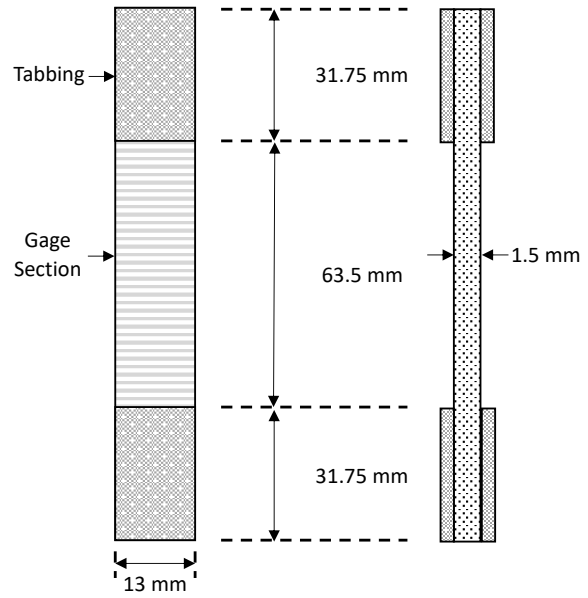


Figure 3-6: Schematic of sample dimensions. Adapted from [38].

3.2.2 Strain Gage

With the test coupons prepared, the next step is to bond on appropriate strain gages. Selected for this research were Micro-Measurements WK-06-250BG-350, which is a 350 Ω strain gage which is capable of operating within the temperature range of -269°C to 290°C [39]. To bond the gages to the surface of the samples, m-bond 610 was chosen as a suitable adhesive as it is capable of performing within the service temperature, as well is suitable for dynamic (cyclic) loading conditions [40].

Starting with a prepared tensile coupon, the dimensions of the specimen are first measured and recorded before any impediments are caused by the bonded gage, as well as eliminating the possibility of damaging the bonded gage. With the specimen properly measured, both the workstation and sample are thoroughly cleaned using the previously mentioned ethanol solution. M-prep conditioner A is then applied to the area of the specimen which is to have the gage bonded to it, and starting with a 320 grit carbide paper, the surface is the carefully polished. The conditioner is wiped clean from the surface using gauze pads, and the process is then repeated using a 400 grit carbide paper. After wiping clean the conditioner from the surface, using a lead pencil, alignment marks are placed on the surface. The conditioner is then repeatedly applied, and scrubbed with cotton swabs. Upon no longer collecting sediments from the surface, the

sample is wiped clean using the gauze, and the m-prep neutralizer 5A is applied to the surface. Similarly, the neutralizer laden sample is rubbed using the cotton swabs, and lastly using a slow singular wiping motion, the solution is removed from the surface of the sample [41].

With the sample surface now prepared, a WK gage and 2 terminal section are placed upon a clean glass surface with approximately 1 cm separating the strain gage and terminals. Using MJG-2 mylar tape, the 2 terminal piece is covered with a strip of tape, the lead wires from the WK gage are placed on top of this section of tape, and a second strip of mylar tape is placed over the WK gage only covering the terminal section of the gage. Slowly peeling back both pieces of mylar tape and low angle, the gage is removed from the glass surface and is transferred to the test coupon. The gage is then aligned using the previously made alignment mark and notches on the gage.

After careful alignment of the strain gage, the gage is then partially removed from the surface of the sample. With a slow single stroke, the bottom surfaces of the gage and terminal pad have the m-bond 610 adhesive applied, as well the prepared surface of the specimen has a layer applied to it. After allowing all surfaces which have had the m-bond 610 applied to them to sit exposed to the ambient air for a duration of at least 5 minutes, the gage is then reapplied to the surface of the specimen, realigning as needed. A strip of Teflon tape is then placed on top of the gage area, followed by a silicon pad, and lastly a metal backing. This setup is then secured using spring loaded clamps and placed within the oven. The oven is then ramped to a temperature of 180 °C and held at this temperature for a duration of 1 hour. Upon conclusion of this hour, the samples are then removed from the oven and allowed to cool to room temperature. Figure 3-7 shows images of seven prepared test coupons with strain gages bonded to the surface.



Figure 3-7: Seven prepared samples after polishing of the edges and bonding of the strain gage.

3.3 Test Equipment, Parameters, and Procedure

The following section shall describe the testing equipment utilized to conduct the experimentation for the research, along with the parameters and procedures used. This includes descriptions of the Instron 8562 and the Micro-Measurements Strain Smart 8000 (DAQ) and the settings utilized by the various equipment in sections 3.3.1 and 3.3.2 After which, the test parameters and procedure shall be presented (Section 3.3.3 and 3.3.4).

3.3.1 Instron 8562

Tensile and cyclic creep testing were performed using an Instron 8562 servo-electric load frame (Figure 3-8). The load frame was equipped with a $\pm 25\text{kN}$ load cell, the smallest available dynamic load cell which the laboratory had, and wedge grips to clamp the samples during testing. In order to test the specimens at elevated temperatures, a high temperature oven capable of achieving temperatures up to $350\text{ }^{\circ}\text{C}$ was attached to the load frame. When performing tests at elevated temperature, in order to prevent the heat within the chamber from interfering with the load cell, the shaft between the load cell and the grip was connected to a water line which allowed for cold water to flow through and cool the shaft.

The load frame was connected to an Instron 8800 mini tower control system (Figure 3-9) which can control the load frame via either the attached handset or through connection to a PC. Utilizing the PC connection, the load frame and cell were controlled via the included software WaveMatrix. This software allows for the generation of pre-set commands which the load frame would follow. Using the built in trapezoidal function, the software was set to operate in load control mode, with the desired stress, ramp rates, creep and recovery durations inputted based upon the test being conducted. The parameters used shall be discussed in section 3.3.3.

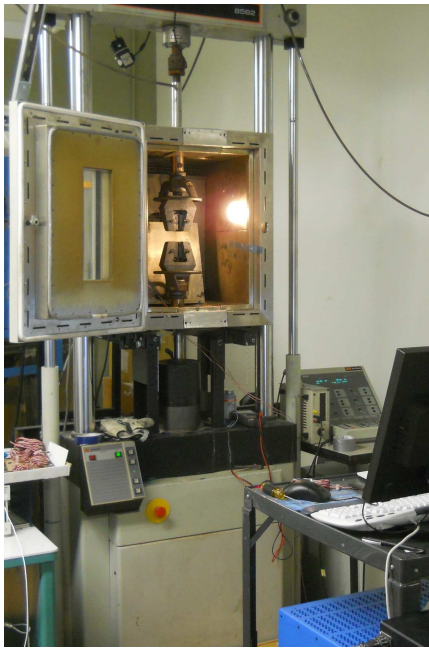


Figure 3-8: Instron 8562 with high temperature oven visible.



Figure 3-9: Instron 8800 mini tower control system.

3.3.2 DAQ

In order to accurately collect the strain data generated during tested by the bonded strain gages, a MicroMeasurement Strain Smart 8000 Data Acquisition System (Figure 3-10) was used. This DAQ is equipped with 8 ethernet input channels, and is capable of collecting data at up to 1000 Hz per channel. Using the included input ethernet connections, the wires soldered onto the strain gages were connected to the cables and inserted into the DAQ system. For the testing performed, two input channels were used, each collecting the data from two separate strain gages (sample and dummy), configured in quarter bridge configuration.



Figure 3-10: MicroMeasurements Strain Smart 8000 Data Acquisition System

3.3.3 Test Parameters

In order to evaluate the effect the recovery duration has upon the creep response of the material during cyclic creep loading conditions several parameters were chosen for evaluation. These include the effect of temperature, stress level, loading rate, and variations in the creep and recovery duration. Four temperatures were selected to evaluate the effect which change in temperature has upon the creep and creep recovery response, these being room temperature, 80, 120 and 180C.

Performing preliminary tensile tests on the manufactured composite, the average ultimate tensile strength (UTS) of the material was approximately 25 MPa. Using this measured value, an initial creep stress of 50% of the UTS (12.5 MPa) was selected. Based upon fluctuations in the load cell while operating under load control, the recovery stress value was chosen to be a non-zero value so as to not induce any compressive states into the sample. Thus, two sets of creep and recovery stress values were selected, 12.5 and 0.5 MPa, and 8 MPa and 0.1 MPa.

Two loading rates were selected to be evaluated, 1 and 10 MPa/s. Lastly numerous creep and recovery durations were chosen for evaluation. The shortest recovery duration being evaluated was a 1s time frame, while the largest was 80s, A summary of the variations used can be found in Table 3-I.

Table 3-I: Summary Of Performed Cyclic Tests

Temperature [°C]	Stress (Creep/Recovery) [MPa]	Stress Rate [MPa/s]	Hold Durations (Creep / Recovery) [s]
RT 80 120 180	12.5 / 0.5	10	20 / 1
			20 / 10
			20 / 20
			20 / 40
	8 / 0.1	10	20 / 80
			40 / 20
			1 / 1
			1 / 1
RT 80 120 180	12.5 / 0.5	1	20 / 40
			1 / 1
			1 / 1
			1 / 1
	8 / 0.1	10	20 / 1
			20 / 10
			20 / 20
			20 / 40
RT 80 120 180	12.5 / 0.5	10	20 / 80
			40 / 20
			1 / 1
			1 / 1
	8 / 0.1	10	20 / 1
			20 / 10
			20 / 20
			20 / 40
RT 80 120 180	12.5 / 0.5	1	20 / 80
			40 / 20
			1 / 1
			1 / 1
	8 / 0.1	10	20 / 1
			20 / 10
			20 / 20
			20 / 40
RT 80 120 180	12.5 / 0.5	1	20 / 80
			40 / 20
			1 / 1
			1 / 1
	8 / 0.1	10	20 / 1
			20 / 10
			20 / 20
			20 / 40

In addition to the tests outlined in Table 3-I, 1hr creep followed by 1 hr of recovery tests were performed for a single cycle. Based upon this 1 hour of creep time for the single cycle tests, each test was performed for a total of 180 cycles, such that those tests with a creep duration of 20s, were subjected to a total of 1hr of creep time to match the single cycle tests. In order to accurately capture the often subtle changes in the response of the material, both the Instron and the DAQ were set to acquire the data at a rate of 20 Hz. This corresponds to the shortest time frame necessary to capture changes in the response of the 12.5 / 0.5 MPa tests with a loading rate of 10 MPa/s.

While all the testing parameters identified in Table 3-I were performed, for the purpose of this thesis, the results obtained for the 1 MPa/s tests, along with the 1s creep / 1s recovery test at 10 MPa/s were not included in the analysis and were saved for future research. Owing to human error, the non-continuous test performed at 12.5 / 0.5 MPa, at room temperature, with a creep duration of 20 s, and recovery duration of 40s, was mistakenly acquired at 10 Hz. Additionally, owing to premature sample fracture, test results were not obtained for non-continuous testing at

12.5 / 0.5 MPa and 120 °C with recovery durations of 1 s, 10 s, and the 40 s creep and 20 s recovery test.

3.3.4 Test Procedure

Before commencing testing the samples were first subjected to an erasing procedure, to erase any physical aging which may have transpired in the time before the test was commenced [42]. This was achieved by placing the sample within a high temperature oven and heated to a temperature of 270 °C. The sample was allowed to soak at this temperature for a duration of 15 mins, after which it was removed and allowed to cool to room temperature. After completion of this cooling, the high temperature wire (326-FTE) were then bonded to the strain gages and loaded into the test chamber.

When loading the test coupon into the test chamber, initially it was fixed only to the upper grip. The lower wedge grip was then moved into position using the handset, and using a set of calipers, the test coupon was aligned as close as possible to the center of the grip, along with as close as possible to parallel to the shafts. This was done so as to ensure, to the best of the researchers ability, the loading was applied completely through the centre of the sample, and the angle being studied matched the desired 90°. Additionally, should there be any curvature to the samples, shims were placed between the edges of the tabbing and the grip face so as to minimize any induced stresses caused by said curvature.

With the test coupon aligned, the dummy gage was then securely fastened to the face of the upper grip using high temperature tape (Figure 3-11). The Instron 8562 set to position control to maintain the current position of the lower grip. The lower grip was then opened and ensured that no contact was being made with the test coupon. This initial lack of contact with the sample was done to allow for the chamber and the sample to equilibrate within the testing chamber unimpeded. Discovered was that even though water was supplied to the shaft to keep limit the effects of temperature on the load cell, fluctuations in the load cell were still present during the heating process. Therefore, until a near equilibrium state was reached within the chamber the sample was held suspended. The temperature chamber door was then closed and using the PC connected to the Instron, the load cell was then electronically zeroed out to read approximately a 0N load.

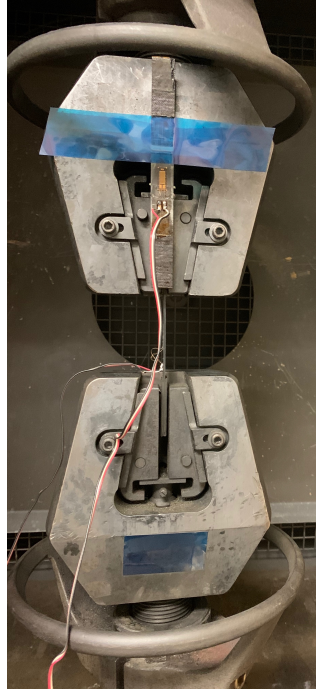


Figure 3-11: Test Coupon and Dummy Gage Mounted Within Load Frame

With the load frame now in a fixed position and the sample aligned, the strain gages were zeroed out using the StrainSmart software and the data acquisition began using the DAQ at a frequency of 20Hz. Depending on the test being conducted, if being performed at temperatures above room temperature, the oven was then turned on and set to the desired temperature and fan turned on to circulate the heat. The chamber was then allowed to ramp to the desired temperature and held in this position until the strain readings on the DAQ achieved a near equilibrium state.

Upon the strain gages reaching this equilibrium, the Instron was then transitioned into high power mode, and the load cell was then zeroed again. The chamber door was then opened, the shims inserted where required, and the lower grip fixture was carefully clamped closed. The chamber door was then closed, and using the Instron PC interface the load frame was transitioned to load control and set to maintain a load of 0N. Again, monitoring the readings generated using the DAQ, the system was then allowed time to reach an equilibrium state.

Allowing sufficient time for the system to reach this equilibrium, the DAQ recordings were then stopped. Due to fluctuations in the load cell as a result of operating near the noise floor, the readings on the load cell were then monitored until they were near a zero reading. Upon achieving this 0 N value, the strain gages were then zeroed out again. Then in as close to unison

as possible, the pre-set WaveMatrix program and the DAQ were both started and allowed to run continuously and uninterrupted until completion of the test being conducted.

3.3.5 Methodology changes due to COVID-19

Before COVID-19, the previously outlined methodologies were used to conduct the majority of 12.5 / 0.5 MPa cyclic creep testing on an individual basis. However, as a result of COVID-19 access restrictions enacted at the University of Manitoba, this methodology for testing the samples was no longer feasible due to the time required to perform each test. As a result, changes to the methodology were needed to be made that would allow for the tests to be conducted within the time constraints imposed.

A solution to get around this time restriction was to perform all of the tests for a single temperature and stress level consecutively without unloading of the sample, allowing for all tests to be run within the time restrictions placed. This change would also allow for better comparison in contrast to the previous methodology of individual tests as it would result in all loadings being performed on the same sample. Additionally, by not removing the sample from the grips, this would also eliminate any possible effect of change in test coupon alignment between the tests.

Before moving forward with this change in methodology, evaluations were performed to determine if there would be any change in the response of the material by switching to this consecutive testing method. This involved performing sample consecutive tests with prolonged periods of rest before commencing the next test. It was determined that the amount of rest necessary would need to be long enough for all unrecovered strain from the previous test to be completely recovered, while not being so long that the effects of aging begin to affect the response of the material. Another factor influencing the duration of the rest was the acquisition of the strain data by the DAQ. Due to limitations in the methods which the DAQ could collect the data (to the authors best knowledge), it either needed to all be collected as one file, or be split into evenly sized files. Due to computational limitations with the PC which was connected to the DAQ and the frequency with which the data was collected, it was observed that the larger the extracted segment was, the more prone the software was to crashing while performing the data extraction. As the longest test to be performed was just over 5 hrs, the smallest size chosen for the testing was selected to be 6 hr segments.

Based upon this 6 hr time segment, preliminary testing was performed to determine whether just adding on at the end of each test a rest period such that each test equaled 6 hrs was sufficient rest, or if to add on an additional 6 hr segment to each. Following a similar procedure as that outline in section 3.3.4, a test coupon (and dummy) had their previous physical aging erased and then were loaded into a test chamber. Using the WaveMatrix software, a test sequence was created as shown in Figure 3-12.

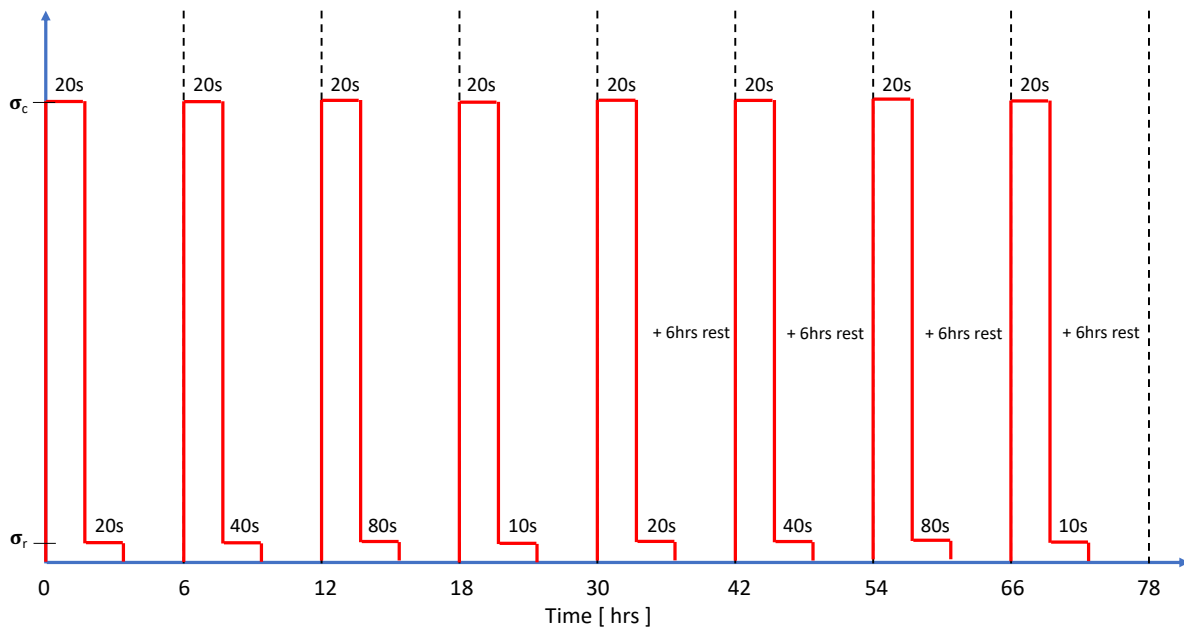


Figure 3-12: Overview of Preliminary testing to determine if consecutive testing was a viable option

Each test consisted of the base cyclic creep test, followed by a slow ramp down from the final end stress to a value of approximately 0 N, this no load condition was then held such that the total time for this segment was equivalent to 6 hrs or 12 hrs. Additionally, due to the time required by the automated DAQ software to automatically save the file and begin a new test, a buffer rest period of 3 mins was also added to each segment so that no experimental test data points would be missed by the DAQ. A schematic of one 12 hr segment is visible in Figure 3-13.

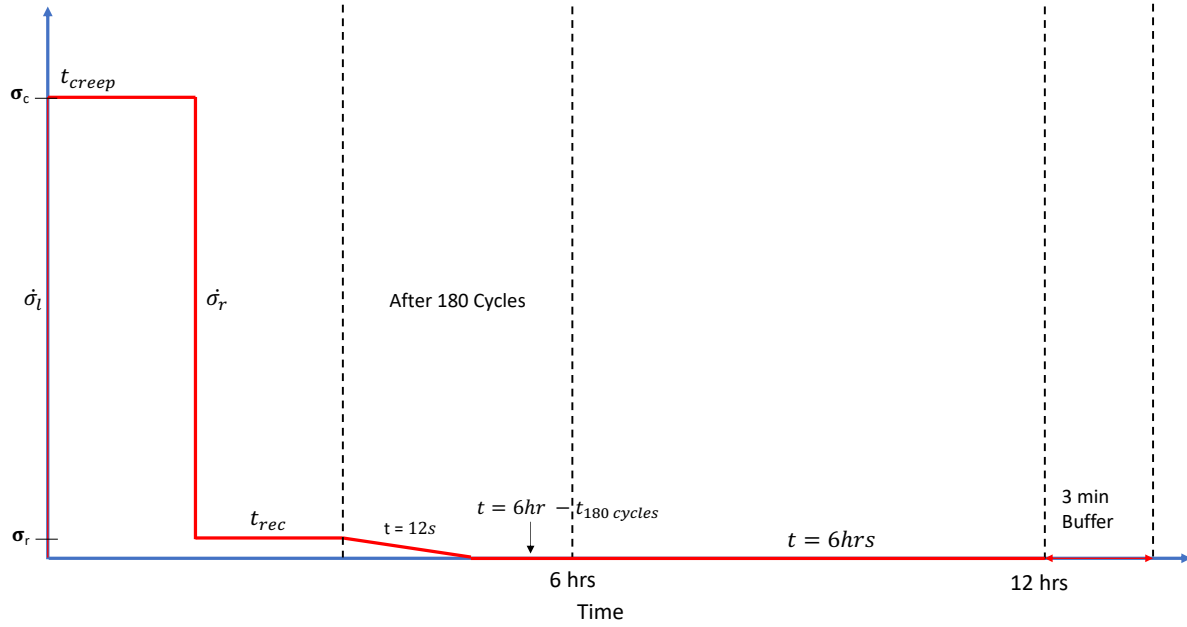


Figure 3-13: Stress Schematic of a single 12 hour segment

Figure 3-14 presents the results obtained when the sequence shown in Figure 3-13 was run. While some the tests without the extra period of rest (first four segments) approach the initial strain value of $0 \mu\epsilon$, this was not the case for all tests. While the tests with the additional period for rest provided the sample further time to rest and recover any additional unrecovered creep strain. Therefore, based upon the results obtained, this previously described method was determined to be sufficient to satisfy the needs relating to performing the consecutive testing.

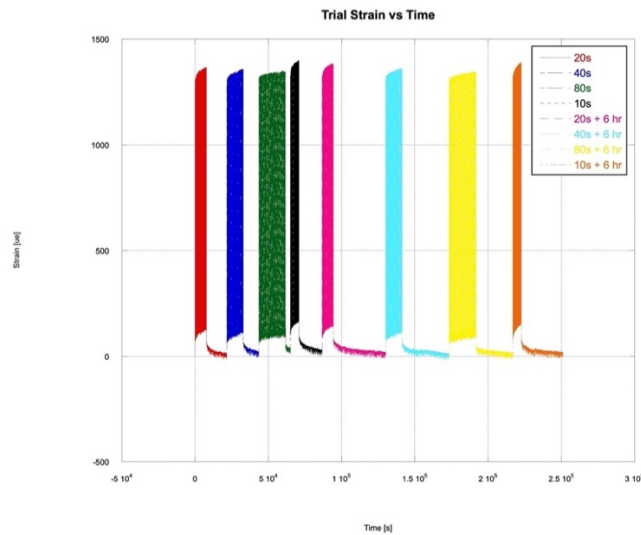


Figure 3-14: Trial Consecutive Testing Strain vs Time

Using this methodology of performing all tests for a given temperature and stress level consecutively, the following sequence was chosen. The first tests which were conducted were those which had previously been performed already, the 20s, 40s, 80s, 40s at 1 MPa/s and the 1s/1s at 1 MPa/s tests. After which, tests which were added in to be evaluated as well 10s, 40s/20s were to be conducted. Lastly in the sequence were the two tests which were deemed to be the most aggressive were conducted 1s, and 1s/1s at 10 MPa/s. Additionally, it was chosen that to see if there was any changes in the response over the course of the sequence, a 1hr/1hr single cycle to test was to be conducted at the start and at the end of the sequence. The performed testing sequence can be seen in Figure 3-15.

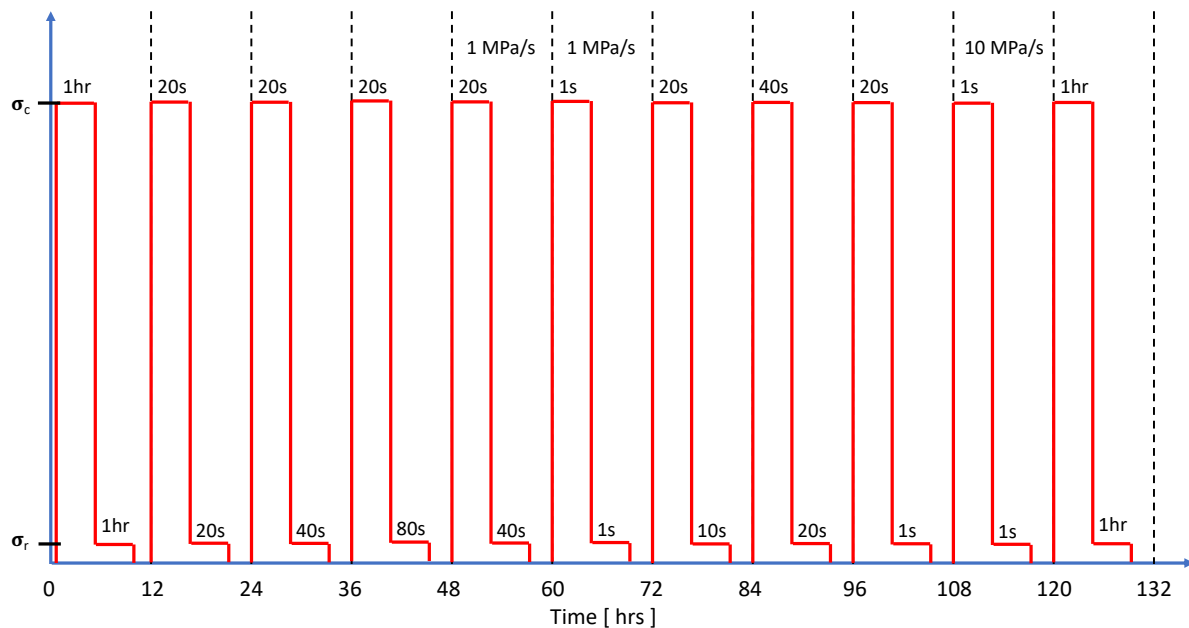


Figure 3-15: Overview of Order of Creep Testing

To differentiate the data acquired via individual testing prior to COVID-19 and that acquired using the sequential testing after COVID-19, the data generated prior shall be referred to as non-continuous and the sequential shall be referred to as continuous.

3.4 Analysis Procedure

To analyze and interpret the data obtain from the experimentation outline in the proceeding sections, the raw data must first be processed. The following shall present the methodologies and equations used to analyze and interpret this raw data.

3.4.1 Initial Data Processing

After the completion of the testing, the raw data is extracted from the two computer systems and transferred to a personal computer for processing. As discussed in the previous chapter, due to the limitations of the computer connected to the DAQ system, the DAQ data was collected in batches of 6 hr segments, while the data from the Instron was collected in a single csv file. As such, the two data sets need to be preprocessed and then married to one another before analysis.

As the amount of data collected via the Instron in the csv file exceeded the limitations of a single excel file, using MATLAB, this set of data was first partitioned into numerous smaller files. Using these smaller files, the data sets from the Instron and the DAQ were then merged together according to the test segment, and aligned together. Owing to the delay in the automated DAQ system when a scan session ended and a new one started, this alignment was needed to be performed for every test conducted. These alignments were done as carefully as possible to ensure, to the best of the authors abilities, that there was good agreement between the two sets of the data.

After combining and aligning the two data sets, the next step involved compensating for the thermal strain experienced by the test coupon using the dummy gage. This is accomplished using equation 1 and 2, where ε_1 is the strain measured by the test coupon, ε_2 is the strain measured by the dummy gage which was subjected to no load, and the T subscript signifies thermal strain.

$$\varepsilon_2(t) = \varepsilon_T(t) \quad (1)$$

$$\Delta\varepsilon(t) = \varepsilon_1(t) - \varepsilon_{2,t}(t) \quad (2)$$

The formula presented in equation 2 was applied to all time stamps, for every test performed. As discussed in the previous chapter the dummy gage was mounted on the face of the upper grip to be as close to the test coupon as possible. As this sample was only fixed on one end to allow the sample to expand and contract unimpeded, this left it susceptible to minor vibrations when operating at elevated temperatures as a result of the chamber fan circulating air within the chamber.

After compensating for the thermal strain, since the data is collected continuously across all segments, each data set is manually zeroed out using the first data point for each test segment, with all other data points adjusted accordingly. With the strain data compensated for the thermal effects and manually zeroed, the data was then fed into a MATLAB code, and using the index values which were generated via the Instron, the start of each cycle portion (loading, creep, unloading, recovery) was collected for all cycles in a testing segment, Figure 3-16. These values were collected to be used in the proceeding calculations to accurately measure the changes in the material response.

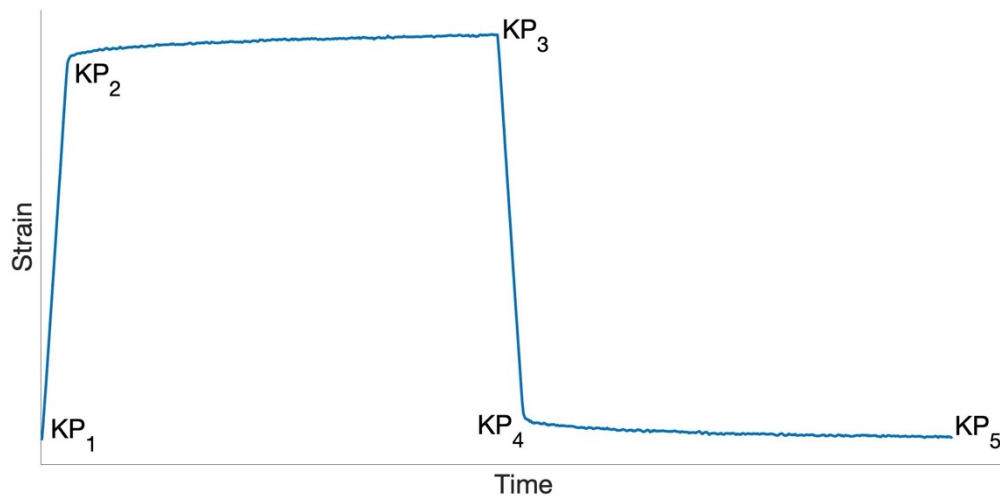


Figure 3-16: Image of the indexing used. 1: represents the start of a new cycle and is the start of loading of the sample; 2: is the end of the ramping portion and signifies the start of the creep segment; 3: is the end of the creep and the beginning of the unloading of the sample; 4: identifies the end of unloading and the start of creep recovery; 5: identifies the end of the creep recovery and signifies the end of the cycle.

3.4.2 Instantaneous Modulus Calculations

With the raw data now prepared and indexed it is then ready to begin the calculations to determine the changes over the duration of each test. The first calculation which is performed on the data was to calculate the instantaneous modulus of each cycle during the loading and unloading portions. As these moduli are based upon the relation between stress and strain (equation 3), using the previously mentioned index values, the modulus was calculated during both the loading and unloading portion. These calculations were performed by taking the data for the stress and strain and finding the line of best fit using MATLAB (Figure 3-17).

$$\sigma = E_o \varepsilon \quad (3)$$

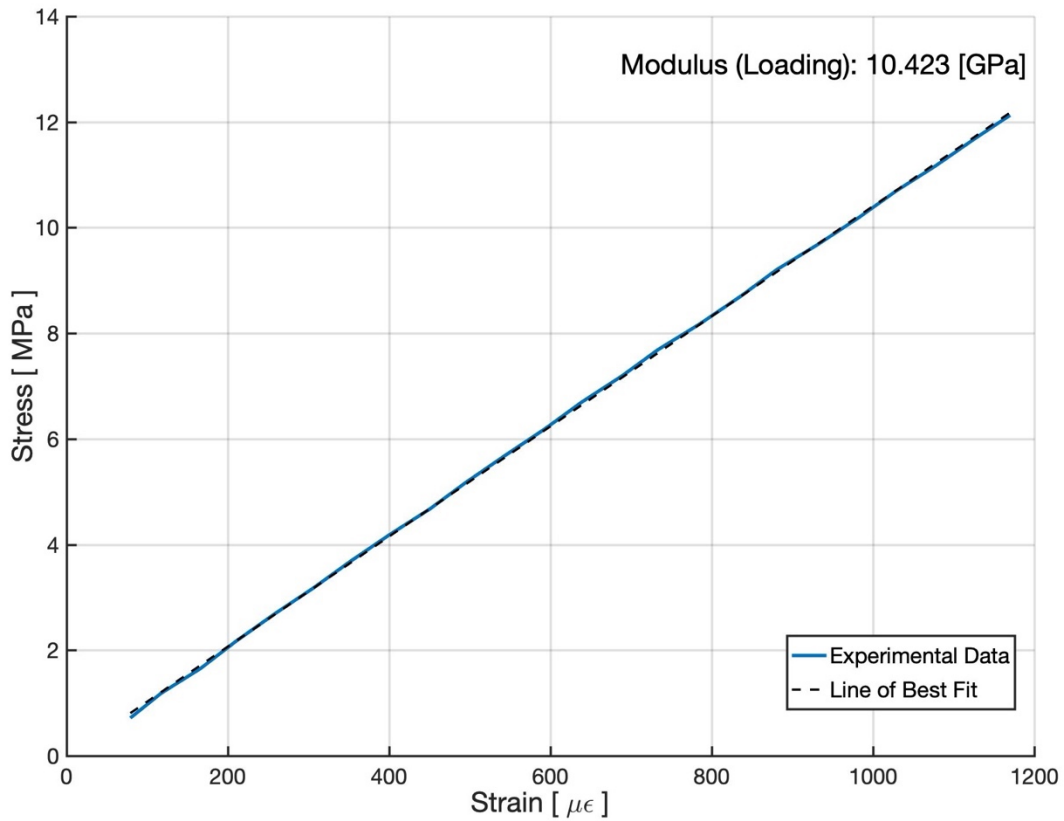


Figure 3-17: Example of the calculations performed to calculate the instantaneous modulus of the sample during the loading. Identified in the top right corner of the image is the calculated modulus. Similar procedure was followed for the unloading segment.

This methodology for the selection of the calculated modulus was chosen after considering several alternatives. One of the issues observed in the analysis of the modulus was inertial effects which occurs during the load ramping portions due to accelerations in the equipment. While it was considered to use a more central measurement for the modulus calculations rather than the indexed values, this was decided against as it would not be possible to select new values without introducing experimenter bias. Thus, the methodology mentioned above was chosen using the indexed values.

These instantaneous modulus values were collected for all cycles for both the loading and the unloading portions of each cycle of each test.

3.4.3 Cycle Energy Calculations

After the calculations for the modulus have been performed, the next aspect which was evaluated was the change in the energy during each of the cycles, with the intent to measure the dissipated energy during each cycle. This was performed using the stress and strain values as well. Figure 3-18 shows a schematic of a typical hysteresis, while Figure 3-19 shows an example using the experimental data with the upper curve shown as blue representing the loading path, and the lower curve shown as orange representing the unloading path.

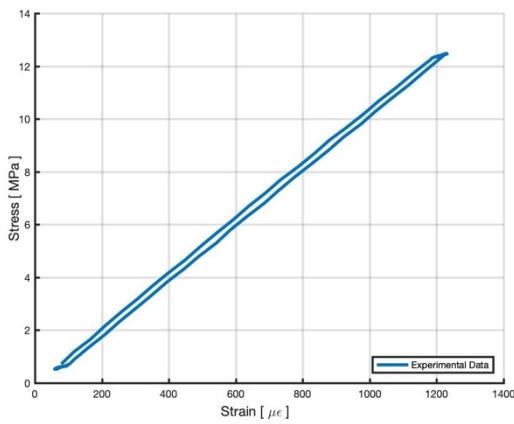


Figure 3-18: Sample hysteresis curve identifying the crucial elements of the curve.

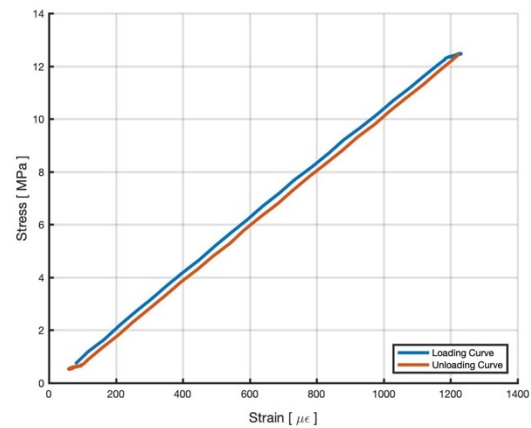


Figure 3-19: Example of experimentally obtained hysteresis curve, showing how the cycle data was separated into to parts. The loading path (upper curve) is colored blue, and the unloading path (lower curve) is colored orange.

To calculate the energy values, the total energy and the stored energy (area under the loading and unloading curves respectively) first needs to be calculated. This was accomplished by breaking up the curve into numerous trapezoidal segments using the numerous time stamps in the experimental data and calculating the area of each of the trapezoid. A visual representation of this segmentation can be seen in Figure 3-20, with equation 4 representing the generic equation used to calculate the area of an individual trapezoidal element.

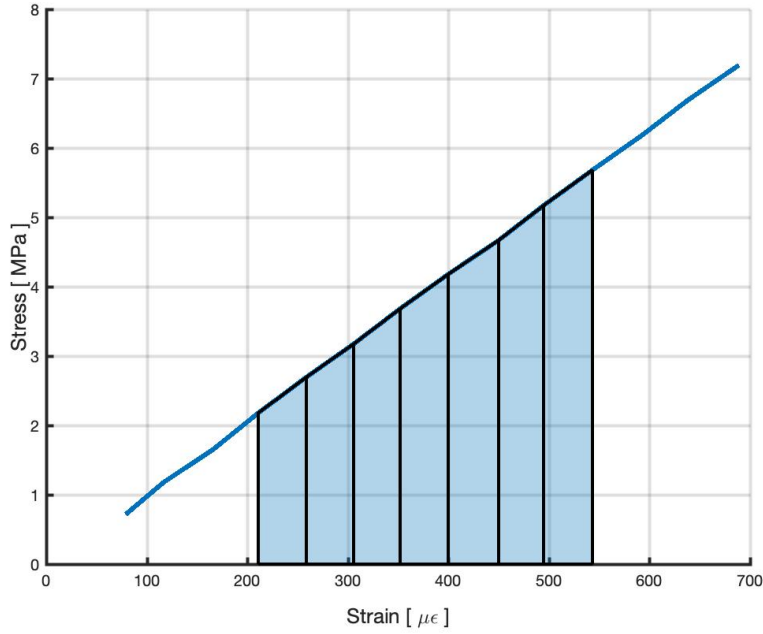


Figure 3-20: Example of the segmentation of the area under a loading path into trapezoidal elements based upon the time stamps used to calculate the area under a curve.

$$A = \frac{a + b}{2} * h \quad (4)$$

Substituting in the experimental parameters into equation 4, A represents the energy, u, of a trapezoidal element, a and b represent the stress at time intervals i and i+1, and h represents difference in the strains at those corresponding times. As such, equation 4 can be rewritten as the equation 5.

$$u(t) = \frac{\sigma_i + \sigma_{i+1}}{2} * (\epsilon_{i+1} - \epsilon_1) \quad (5)$$

As this equation represents only a single element, the summation of all elements is used to calculate the total energy E_T and stored energy E_S for each cycle. Therefore, these energy values can be calculated using equation 6 and 7, with 1, 3, and 5 representing the respective index values for each cycle identified in Figure 3-16. Figure 3-21 and Figure 3-22 present visual representations of the entire area calculated when calculating total and stored energy respectively.

$$u_T = \sum_1^3 \frac{\sigma_i + \sigma_{i+1}}{2} * (\varepsilon_{i+1} - \varepsilon_1) \quad (6)$$

$$u_S = \sum_3^5 \frac{\sigma_i + \sigma_{i+1}}{2} * (\varepsilon_{i+1} - \varepsilon_1) \quad (7)$$

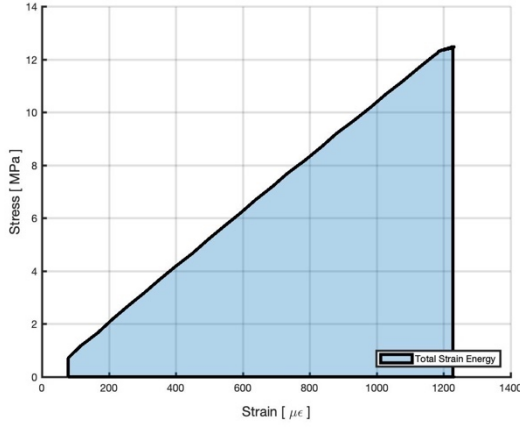


Figure 3-21: Visual representation of the total area under the loading curve, corresponding to the total energy of the sample.

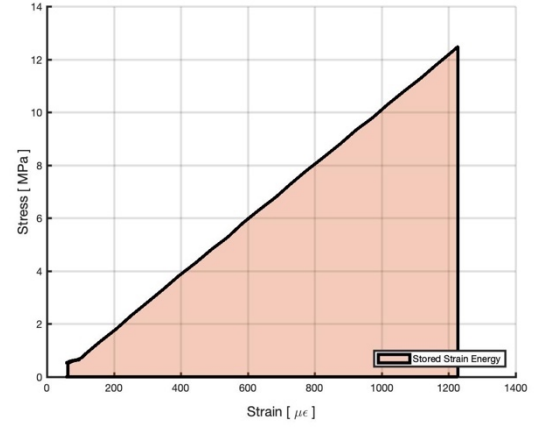


Figure 3-22: Visual representation of the total area under the unloading curve, corresponding to the stored energy of the sample.

After calculating the total and stored energy for a cycle, the final aspect which is then calculated is the dissipated energy. This dissipated energy (E_D) can be calculated by taking the area under the upper curve (total energy) and subtracting the area under the lower curve (stored energy), equation 8. The resulting cycle dissipated energy calculated using this equation can be seen in Figure 3-23.

$$u_D = u_T - u_S \quad (8)$$

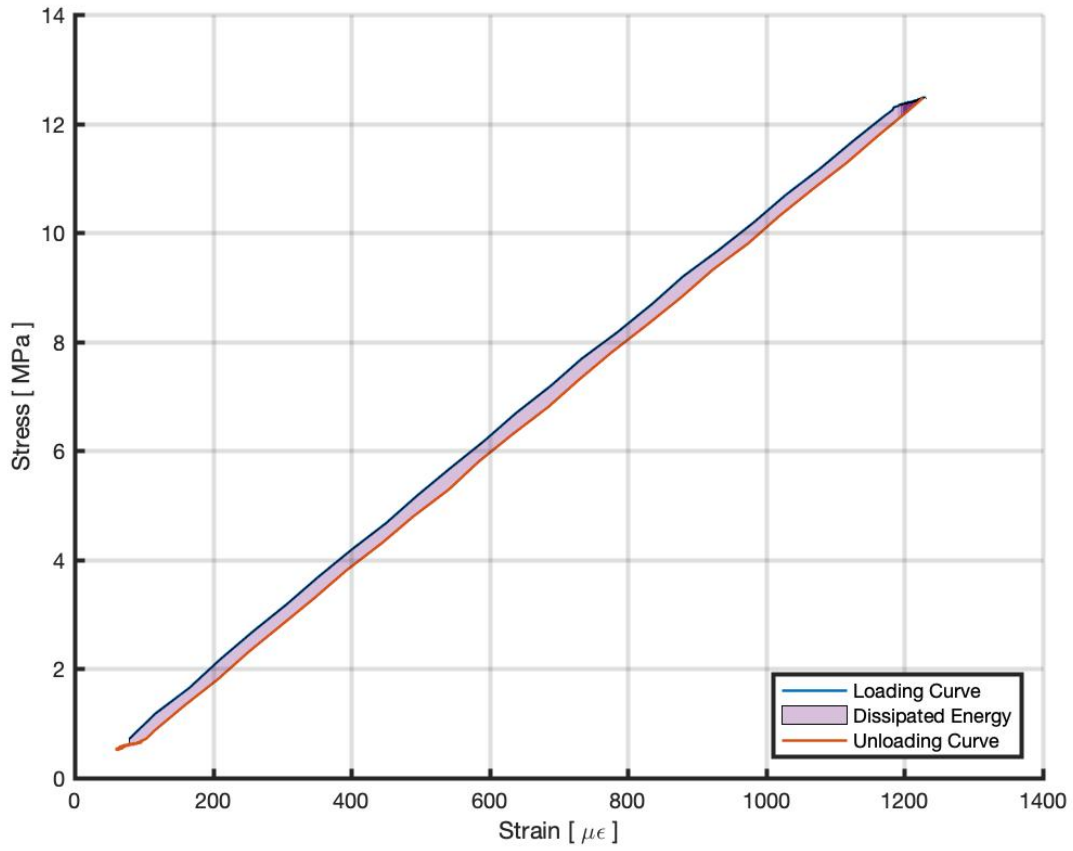


Figure 3-23: Visual representation of the dissipated energy of the sample over a single creep cycle. The area between the two curves colored purple represents this energy. Note the data used in this image was modified to be able to visually present the dissipated energy.

3.4.4 Strain Values

After analysis of the factors which are related to the recorded stress values, next analyzed are the changes in the strain response of the material. Referencing Figure 3-16, and using the previously discussed indexed values, the values for the strains identified in this image can be obtained using equations 9 through 12.

$$\varepsilon_{o,l} = \varepsilon_2 - \varepsilon_1 \quad (9)$$

$$\Delta\varepsilon_c = \varepsilon_3 - \varepsilon_2 \quad (10)$$

$$\varepsilon_{o,u} = \varepsilon_3 - \varepsilon_4 \quad (11)$$

$$\Delta\varepsilon_r = \varepsilon_4 - \varepsilon_5 \quad (12)$$

Performing the calculations as presented in the above equations using the indexed values will provide the respective strain values based upon the raw data. However, upon further evaluation of the results, when evaluating the creep and recovery, it was discovered that the applied load to the test coupon does not fully reach the desired creep and recovery loads at the starting index values (Figure 3-24). Rather the Instron identified a region where the load had reached a value close to the desired applied load and then proceeded to gradually increase the load until reaching the desired amount. Therefore, it was determined that to more accurately evaluate the changes in the strain values during these portions, the influence of this additional change in stress was needed to be taken into account.

Similarly, to the modulus calculations, initial deliberation on this issue lead to thoughts of changing the location of the indices which identified the start of the creep and creep recovery portions. However, as with the modulus calculations this methodology was abandoned after determining that it would not be possible to adjust these index values without introducing bias into the analysis.

Thus, to eliminate the effect of the gradual change stress, the instantaneous strain was removed from the sample using the experimental stress and the calculated instantaneous modulus. Using the experimental stress recorded for each time stamp, and the calculated instantaneous modulus, equation 13 was used to convert this stress to an instantaneous strain value. An example of this conversion of the stress to corresponding modified strain values visible in Figure 3-25.

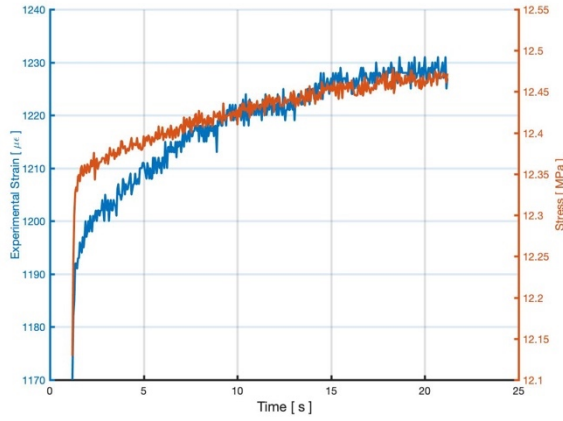


Figure 3-24: Stress and strain values during the creep portion using the indices identified by the Instron software. Visible in the image for the orange stress curve is a gradual increase in the applied stress over the duration of the creep hold for this cycle.

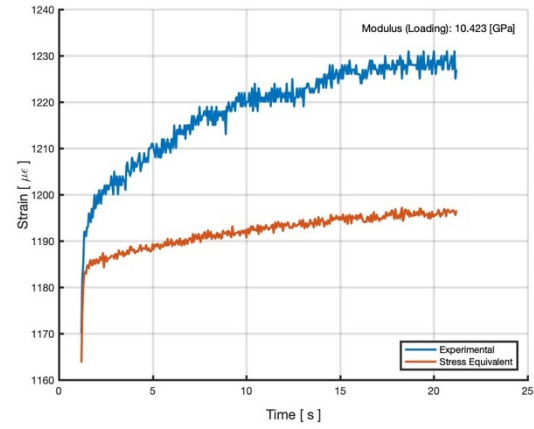


Figure 3-25: Conversion of the experimental stress to a corresponding instantaneous strain value, using the calculated instantaneous modulus indicated in the upper right hand corner.

$$\varepsilon_o(t) = \frac{\sigma(t)}{E_o} \quad (13)$$

Next, after converting the instantaneous stress to a strain value, these values are then subtracted from the experimental total strain during the creep (and creep recovery) portions (equation 14). After performing this subtraction what is left is only the creep (creep recovery) strain which is experienced by the test coupon. Figure 3-26 presents an example of the creep strain remaining.

$$\Delta\varepsilon_c(t) = \varepsilon(t) - \varepsilon_o(t) \quad (14)$$

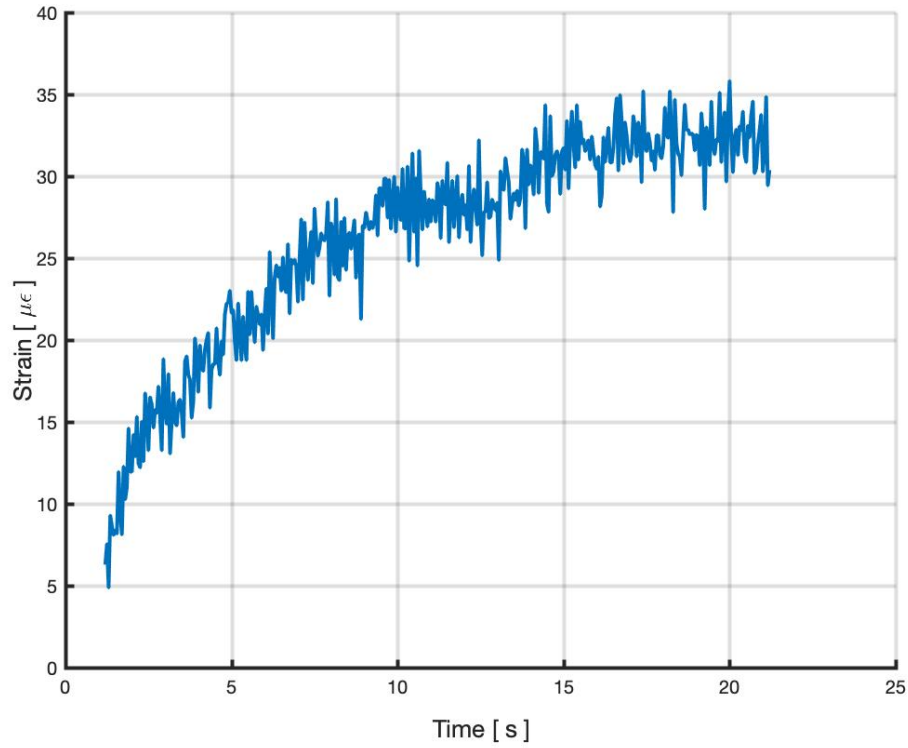


Figure 3-26: Creep strain remaining after subtracting the calculated instantaneous strain from the total strain during the creep portion identified via the indexed values.

Upon initial evaluation of the unrecovered strain with the unrecovered creep strain, it was determined that the accumulation of the unrecovered strains could not be quantified solely by the difference between the creep and recovered strain. Owing to the change in the instantaneous modulus, determined was that the change in the strain response during the loading and unloading segments must be considered. Equation 15 presents the calculation used to determine the unrecovered instantaneous strain.

$$\varepsilon_{UR,i+1} = \varepsilon_{UR,i} + \Delta\varepsilon_{cr} + \Delta\varepsilon_o \quad (15)$$

Where,

$$\Delta\varepsilon_{cr} = \Delta\varepsilon_c - \Delta\varepsilon_r \quad (16)$$

$$\Delta\varepsilon_o = \varepsilon_{o,l} - \varepsilon_{o,u} \quad (17)$$

Chapter 4 Results and Discussion

This chapter presents and discusses the results obtained through the cyclic creep testing discussed in the previous chapter. An overview of the data collected shall first be presented. After which, using the calculations previously outlined, the resultant calculated results shall be then presented and discussed.

As discussed in section 3.3, due to sample failure, data could not be collected for the non-continuous 12.5 / 0.5 MPa tests at 80 °C with recovery durations of 1s and 10s, along with the test of 40s creep and 20s recovery. Therefore, throughout this chapter any relevant tables which would include these results, NaN will be listed to indicate that the results were not available for analysis.

4.1 Cyclic Creep Test Results

As indicated, presented first shall be the test results and evaluations performed on an individual cyclic creep test. For simplification and demonstrative purposes, all results and figures presented in this section were from the testing performed at 12.5 MPa creep stress and 0.5 MPa recovery stress at a temperature of 120 °C, and with both a creep and creep recovery duration of 20s, collected using the continuous testing procedure.

The most basic analysis performed on the data was a comparison of change in the stress and strain over the entirety of the experiment. Figure 4-1 shows the typical shape of the stress and strain vs time plot acquired via the cyclic creep testing. The blue line (corresponding to the blue left y-axis) represents the total strain of the sample over the entirety of the test. The orange curve (which corresponds to the orange right y-axis) represents the recorded stress over the entirety of the testing using these parameters. The path showing for both curves is typical of the results obtained via the other testing conditions.

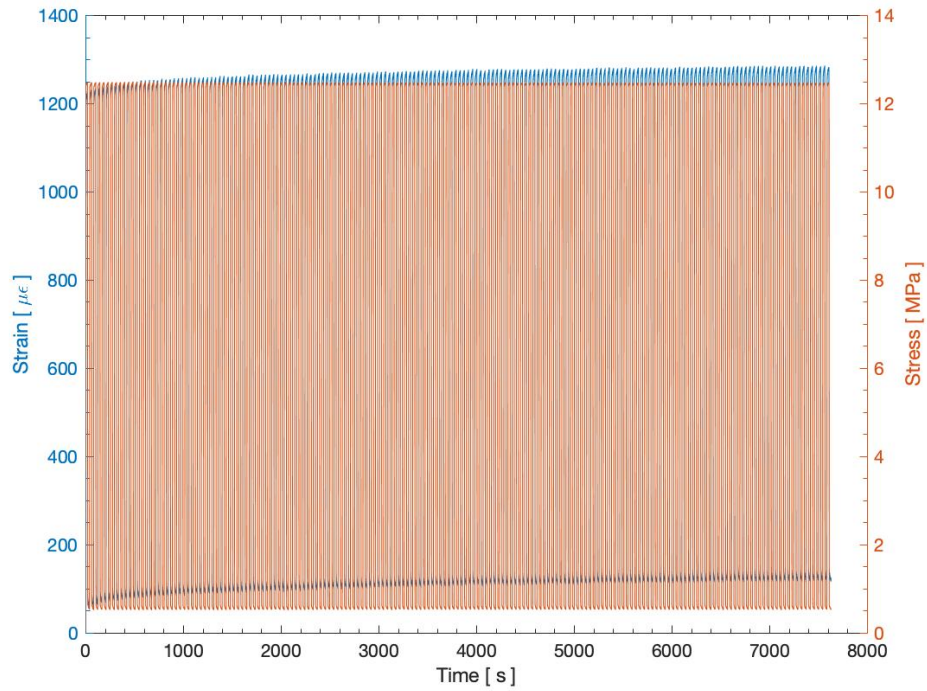


Figure 4-1: Stress and strain vs time plot for cyclic creep testing at 12.5 / 0.5 MPa loading level at 120 °C, creep and creep recovery duration of 20s using the continuous testing methodology.

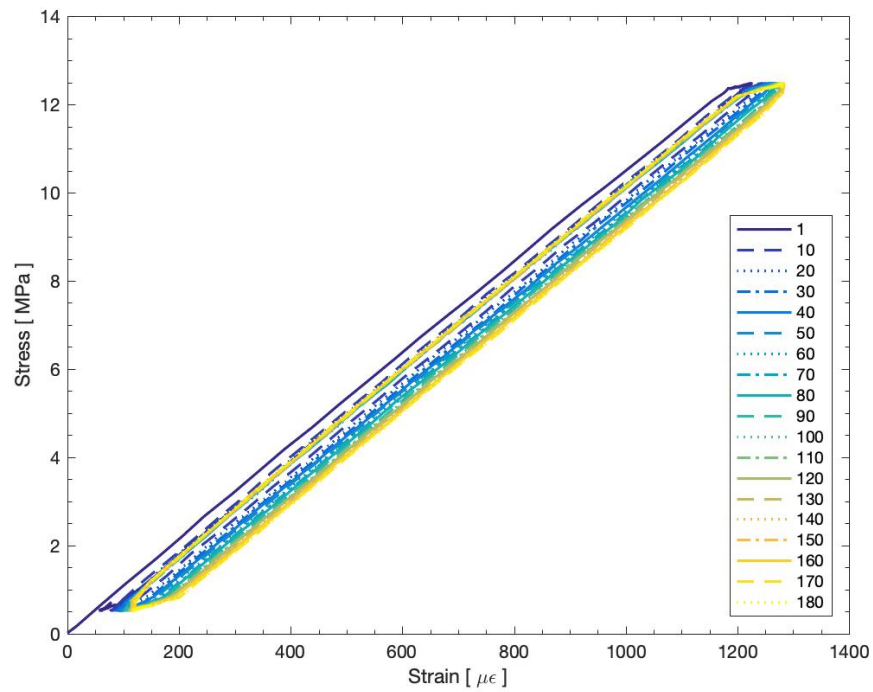


Figure 4-2: Cyclic stress-strain plot for every 10th cycle at 12.5 MPa continuous testing, with a creep and creep recovery duration of 20s and at a test temperature of 120 °C.

The next evaluation performed on the data was to compare the cyclic stress – strain response over the totality of an experiment. For the same data set, Figure 4-2 presents the stress vs strain plot, and shows the hysteresis formed over the course of the testing (i.e. the loading and unloading curves do not superpose). To provide easier visualization of the change in the hysteresis over time, the plot features only every 10th cycle, plotted in progressively changing colours and line styles.

From this figure, due to changes in the response of the material, the hysteresis can be seen to shift to the right and slightly expand as the test progressed. Comparing the plot shown with other stress – strain hysteresis curves generated via the other testing parameters, a general trend was present, showing the dissipated strain energy density (the area bound within the hysteresis) increasing as the recovery duration increased. This shall be further discussed and evaluated in section 4.2.3.

Using the stress vs strain curves, and following the methodology outlined in section 3.4.3, the total, stored and dissipated strain energy density were calculated accordingly for every cycle. An example of the change in these energy values over the course of an experiment can be visually seen in Figure 4-3. The trends apparent in this image are typical of the trends observed in the other data sets. Over the course of a testing segment, the total strain energy density (corresponding to the area under the loading curve) increased, the stored strain energy density (area under the unloading curve) decreased, and as a result, the dissipated strain energy density (area bound by the two curves) increased overall. The results observed via this analysis shall be presented and discussed in section 4.2.3, 4.3.3, 4.4.3, and 4.5.3. Generally, the Total Strain Energy Density during the initial cycles was larger than that of the stored strain energy density as is expected. However, owing to the couple outliers previously discussed, in a few circumstances this was not the case.

Using the acquired stress and strain data, the changes in the instantaneous modulus over the course of each test segment were calculated. Again, using the methodology identified in section 3.4.2 the modulus was calculated for both the loading and unloading segments for every cycle. Figure 4-4 presents the corresponding calculated moduli for the same sample test conditions. In

this plot, the blue curve represents the calculated modulus during the loading segment, and the orange curve represents the calculate modulus during the unloading.

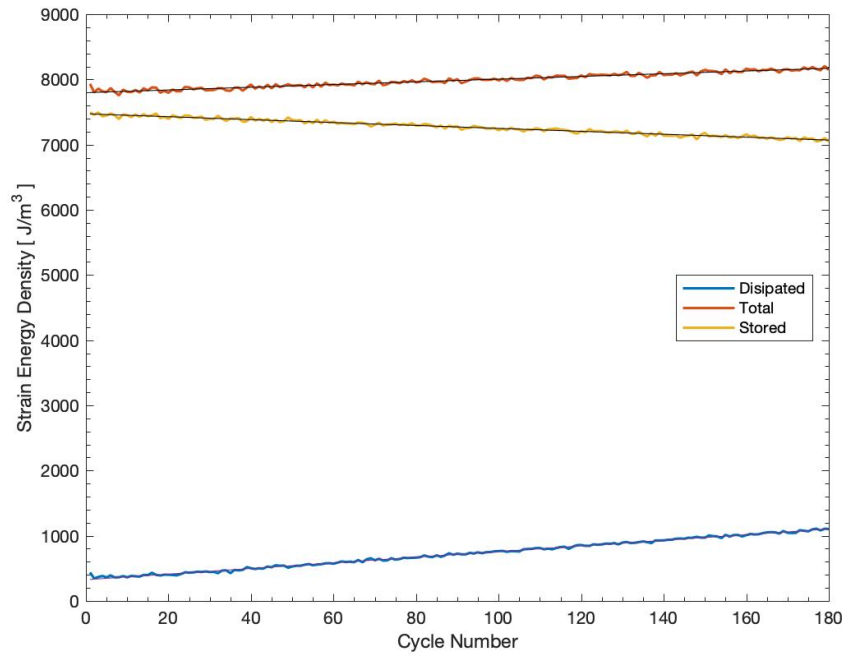


Figure 4-3: Total (loading), stored (unloading), and dissipated energy at 12.5 MPa / 0.5 MPa continuous loading at 120 °C and creep and creep recovery duration of 20s.

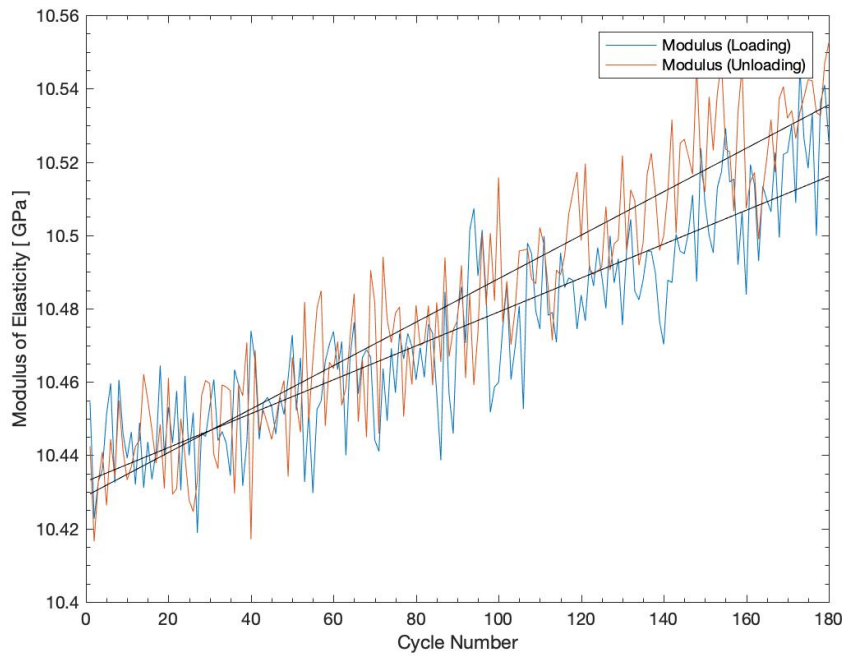


Figure 4-4: Modulus of elasticity calculated for 12.5 / 0.5 MPa Continuous loading at 120 °C and creep and creep recovery duration of 20s.

Similar to the data shown in Figure 4-4, general trends in the modulus data, visually, were consistent for the majority of the tests performed. In the general case, it was found that both the loading and unloading instantaneous modulus showed an increasing trend as the number of cycles increased. Another common trend among the calculated modulus values was for unloading modulus to be larger than the loading modulus. This was believed to be a result of accumulated unrecovered strain, however further discussion pertaining to the changes in the modulus with variation as a result of changes in the recovery duration and temperature are presented in sections 4.2.2, 4.3.2, 4.4.2, and 4.5.2.

After evaluating the change in the modulus, the next aspect evaluated was the change in the strain response of the material. Of particular interest was the change in the creep and creep recovery strains, as well as the changes in the unrecovered strain. As previously discussed in section 3.4.4, after reviewing the acquired data, it was found that the applied load had not yet fully reached the desired magnitude at the segment indicators generated by the Instron. Rather, over the course of the hold portions, the applied load slowly increased (decreased) until the desired value had been reached. As such, to compensate for the effect that the change in the applied load had on the strain response of the material, using the recorded experimental stress value and the calculated instantaneous loading (unloading) modulus for that cycle, the strain corresponding to this slow increase in applied load to the desired value was subtracted from the recorded strain values. Resultant to leave only the creep (creep recovery) strain without any contribution from the instantaneous strain.

Figure 4-5 and Figure 4-7 present the creep and recovered strain vs time curves for every 30th cycle after this load correction was applied to the same data set. The creep and recovered curves presented in this plot were shifted to have a corresponding minimum strain value for each curve of 0 $\mu\epsilon$. Visible from these plots is that each of the curves for each of the cycles follow quite similar curves, albeit with a vertical shift in the final value. These corresponding final strain values can be seen in Figure 4-6 and Figure 4-8. Both the cycle creep and recovered strain show an increasing trend as the number of cycles increases. For the particular set of test conditions from which this data set was gathered, the trend in the creep and recovered strain both present a near linear increasing trend.

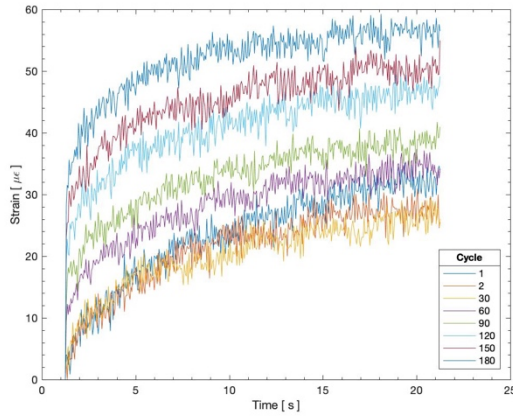


Figure 4-5: Creep Strain for every 30th cycle for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery duration of 20s.

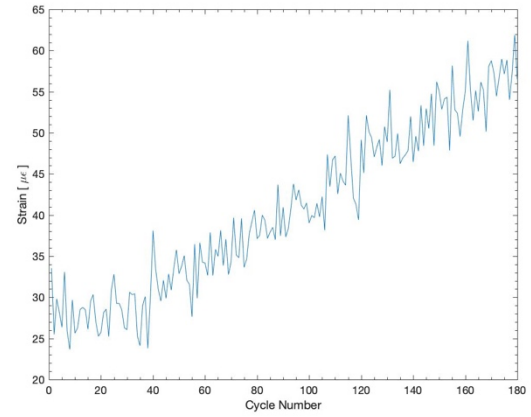


Figure 4-6: Cycle creep strain over duration of testing for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery of 20s.

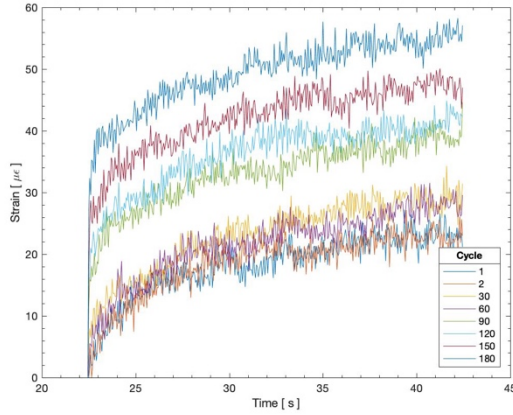


Figure 4-7: Recovered Strain for every 30th cycle for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery duration of 20s.

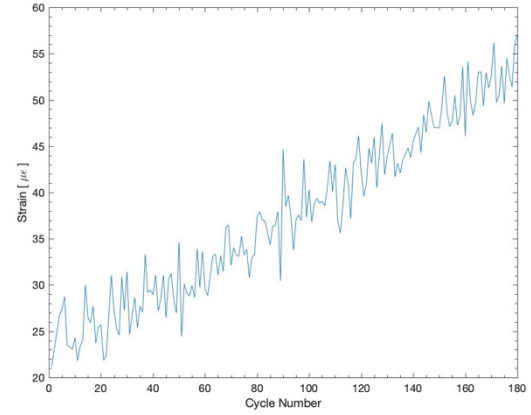


Figure 4-8: Cycle recovered strain over duration of testing for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery of 20s.

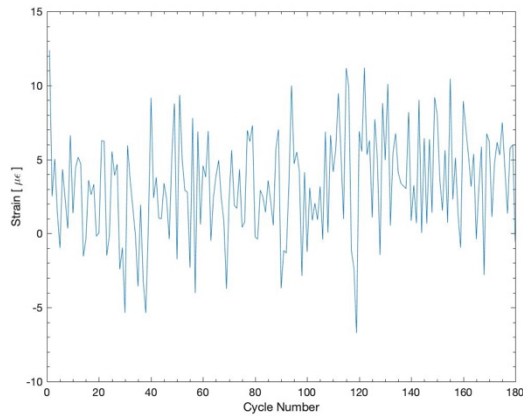


Figure 4-9: Unrecovered creep strain vs cycle for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery of 20s.

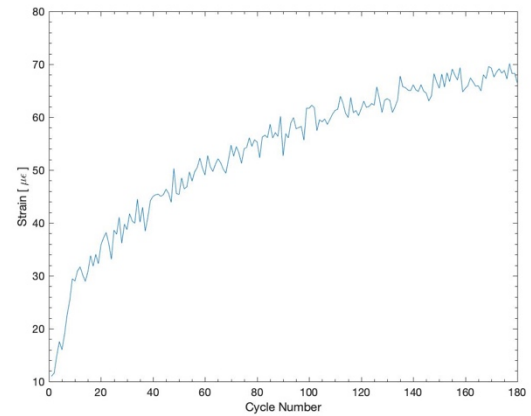


Figure 4-10: Total unrecovered strain at the end of each cycle for the 12.5 / 0.5 MPa Continuous loading at 120 °C with creep and creep recovery of 20s.

Taking the difference between the cycle creep and recovered strain values shown in Figure 4-6 and Figure 4-8, what is left is the unrecovered creep strain for each cycle (Figure 4-9). This represents the creep strain which has not been recovered during the recovery hold. Visible in the plot is that fluctuations between cycles are relatively large in comparison to the strain magnitudes, indicating that the amount unrecovered for this particular case is not entirely predictable. As well, the curve can also be seen to dip below 0, which indicates that for these cycles, that the amount of strain recovered is larger than that accumulated during the creep hold.

Lastly, taking the final calculated load adjusted strain value for each cycle to be the total unrecovered strain. The accumulation / change in the unrecovered strains over the duration of the experiment is presented in Figure 4-10. Viewing the curve presented in this image, a logarithmically decaying increase in the rate of accumulation in the unrecovered strain can be seen.

4.2 Effect of Recovery Duration

With examples of the acquired data presented, the first variable which was evaluated was the effect that changes in the recovery duration had on the cyclic response. The following section shall first present the effect that changes in the recovery duration had on the strain response of the material. After which, trends in the changes in the modulus shall be evaluated. Lastly, the effect that the recovery duration has on the strain energy density shall be presented.

Numerical values and figures shall be included for all loading parameter tests. Owing to the 1st cycle for all of the data sets begins from a value of approximately 0 N, rather than the recovery loads of 0.1 and 0.5 MPa, analysis conducted with respect to the evolution of the material properties (Instantaneous Modulus and Strain Energy Density) were numerically evaluated between the 2nd and final cycles (180th) to eliminate any inconsistencies which may be present during the first cycle. However, when evaluating the strain response, since this starting point of 0 N does not influence the creep and creep recovery strain response, these comparisons shall be between the 1st and final cycle.

For demonstrative purposes, only a limited selection of the generated figures were included in this section. Selected for inclusion in this section were the figures generated utilizing the data

acquired at 120 °C, showing only every 10th cycle after the initial two cycles. For additional plots containing all cycles, refer to Appendix A.

4.2.1 Strain Response

As indicated, the first analysis which shall be presented is the effect that the recovery duration had on the strain response. Presented first will be the figures and measurements calculated for the creep, recovered, the unrecovered creep strain (difference between the two), and the summation of the unrecovered creep strain over the totality of each testing. After, the total unrecovered strain, the unrecovered creep strain, and the resultant calculated unrecovered instantaneous strain shall be presented.

4.2.1.1 *Creep / Recovered Strain*

As previously discussed, as a result of the applied load not reaching the desired levels at the start of the holding portions, the calculated values for the creep and creep recovery strains initially contained additional strain which is not a result of the viscoelastic nature of the material. Using the recorded applied load and the calculated modulus, the corresponding instantaneous strain at each time stamp was removed from the total strain to leave only the resultant creep and creep recovery strains. The calculated strain values are shown visually in Figure 4-11 through Figure 4-22 and the first, final, and the difference between the two cycles are presented in Table 4-I through Table 4-XII.

Evaluating first the calculated creep strain, as discussed previously, observed was over the duration of the cyclic testing, there was a general increase in the amount of creep strain. This is supported by the positive values in the difference column presented in the tables. Evaluating the data further, for the first cycle, there is no apparent trend in the data with change in the recovery duration. This lack of clear trend in the data is expected given that the strain recorded for the first cycle occurs before the recovery segment, thus changes with respect to recovery duration should not factor into this measurement. While there are slightly increasing trends for a couple of the test conditions with increase in the recovery duration, this is most likely coincidental, and was not present in the majority of tests. In comparison, both the final cycle and the difference between the initial and final cycles show a strongly increasing trend as the recovery duration increases.

With respect to the recovered strain, similar to the change in the creep strain, over the course of the cyclic testing, observed was a general increasing trend as the number of cycles increased. Evaluating the recovered strain for trends, excluding a couple outlier sets in the data, the first, final and difference between the two cycles show an increasing trend as the recovery strain increases. An example of a one of these outliers is the 12.5 MPa Continuous room temperature test with a recovery duration of 10s. When this data set is excluded, the increasing trend becomes much stronger for that combination of load and temperature. This increasing trend in the recovered strain increasing as the recovery duration increases is expected as the sample is allowed to recover for long thus providing the sample with longer to recover. Using the line of best fit data for the first cycle, the calculated coefficient of correlation indicate a very weak trend. However for the final cycle along with the difference between the final and initial cycle, the calculated correlation coefficient and coefficient of determination indicate a much strong strength.

Evaluating the unrecovered creep strain, the difference between the creep and recovered strains within a cycle, there was large variation in the data from cycle to cycle regardless of the conditions. This large variation is partially masked by the reduction applied to the figures included but can be seen clearer in the figures included in Appendix A. Looking at the data contained in the tables, there is a weakly decreasing trend in the unrecovered creep strains for the first cycle as the recovery duration increases. With respect to the final cycle, and the difference between the initial and final cycles, there does not appear to be any trend in the data, with the difference in particular showing both increasing and decreasing trends in various test conditions. Lastly, evaluating the accumulation of the unrecovered creep strain over the entirety of the testing, there is a generally weakly decreasing trend as the recovery duration increases. However, as half of the data sets show an overall increase, and half showing a decrease, no conclusion can be drawn.

Table 4-XIII presents the calculated values for the slope, intercept, and correlations for the lines of best fit. Figure 4-23 through Figure 4-28 present a visualization of the creep strain as a function of recovery duration for the final cycle and the change in the creep strain over the duration of testing. A visualization for the recovered strain as a function of recovery duration for the same sets of data can be seen in Figure 4-29 through Figure 4-34.

Excluding the 12.5 MPa individual tests, the best fit lines for the two continuous testing show fairly good agreement between temperatures. While there are some outliers within the data, the general overlap for the two sequences would suggest that the change in the measured creep and creep recovery strain over the duration of the cyclic loading is influenced more by the recovery duration than the change in the temperature. It should be noted, that this line of best fit is from simply a linear fit of the data calculated for only the 1st and final data points along with the difference between the two. To obtain a more accurate reflection of the change in these strain values, the rate of change over the entirety of the experiment should be considered.

This indicates that when subjected to longer recovery durations that the material tends to experience more creep and creep recovery, and that these strains tend to increase more over the duration of the testing.

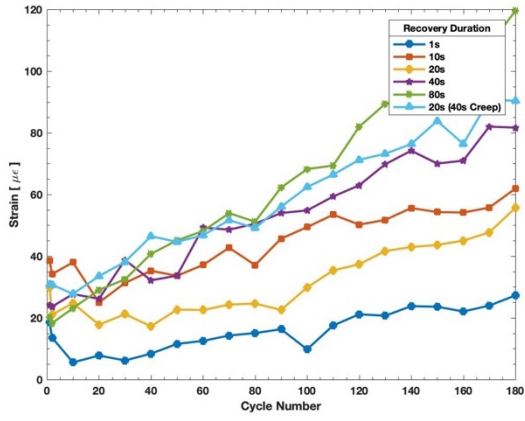


Figure 4-11: 8 MPa – 120 °C – Creep Strain

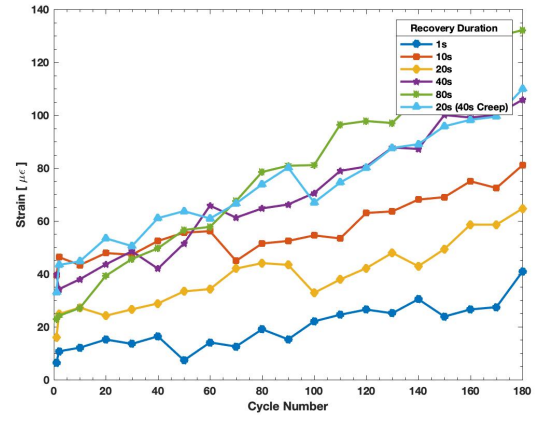


Figure 4-12: 8 MPa – 120 °C - Recovered Strain

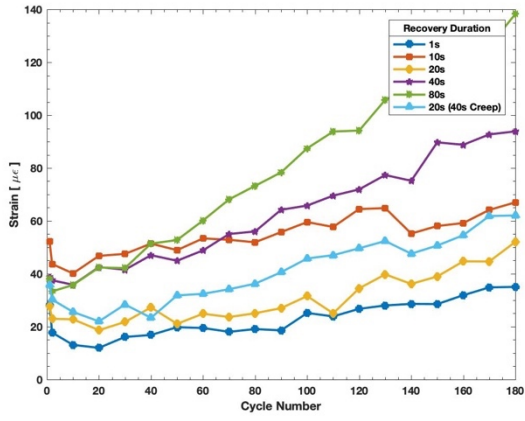


Figure 4-13: 12.5 MPa – 120 °C - Creep Strain

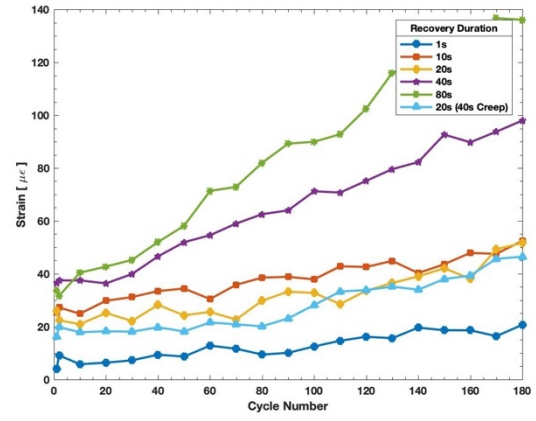


Figure 4-14: 12.5 MPa – 120 °C - Recovered Strain

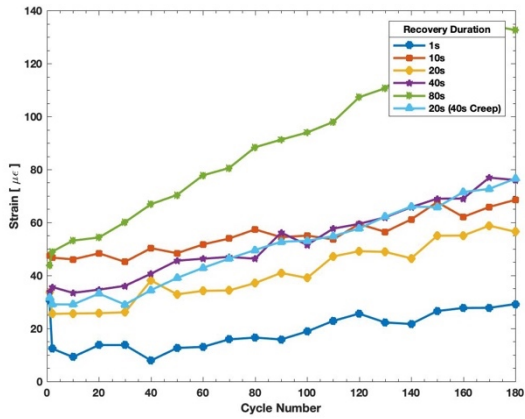


Figure 4-15: 12.5 MPa Continuous – 120 °C - Creep Strain

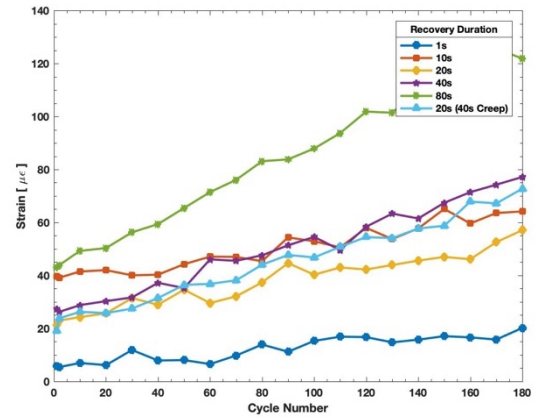


Figure 4-16: 12.5 MPa Continuous – 120 °C - Recovered Strain

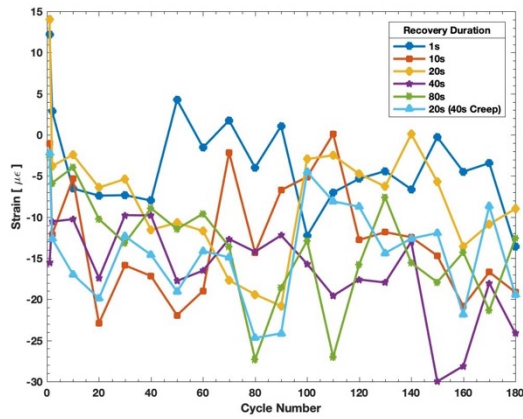


Figure 4-17: 8 MPa – 120 °C – Unrecovered Creep Strain

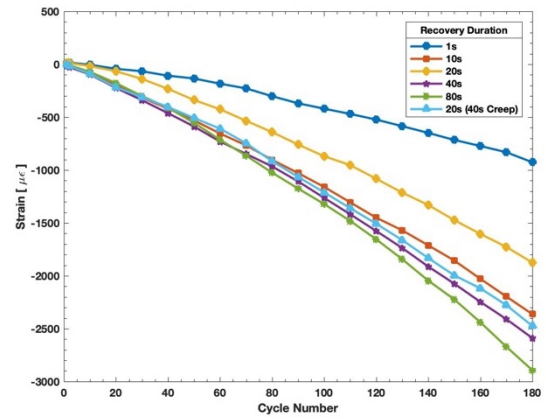


Figure 4-18: 8 MPa – 120 °C – Accumulated Unrecovered Creep Strain

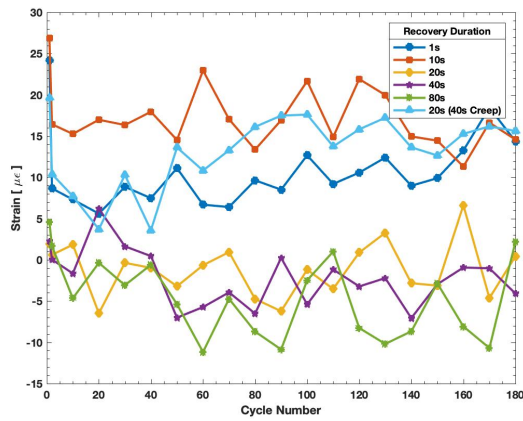


Figure 4-19: 12.5 MPa – 120 °C – Unrecovered Creep Strain

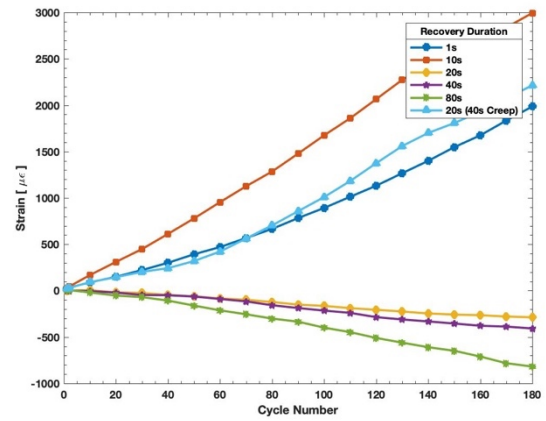


Figure 4-20: 12.5 MPa – 120 °C – Accumulated Unrecovered Creep Strain

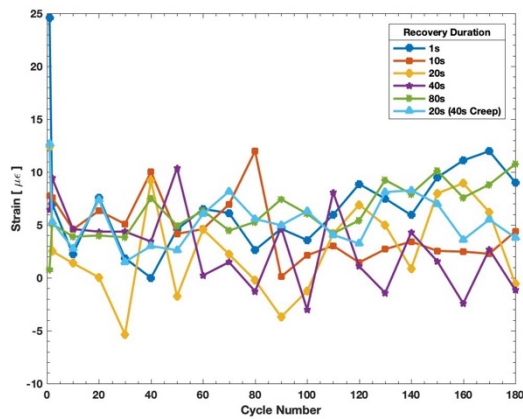


Figure 4-21: 12.5 MPa Continuous – 120 °C – Unrecovered Creep Strain

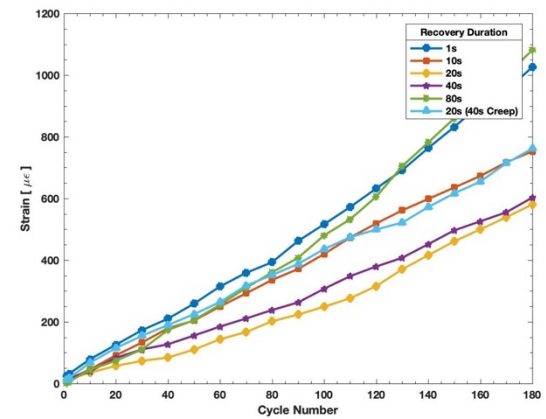


Figure 4-22: 12.5 MPa Continuous – 120 °C – Accumulated Unrecovered Creep Strain

Table 4-I: Recovery Duration - 8 MPa - Room Temperature - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
20	1	RT	9	6	-2	4	11	7	5	-5	-9	-208
20	10	RT	14	42	28	21	58	37	-7	-16	-9	-2015
20	20	RT	12	33	21	13	57	44	-1	-23	-23	-1771
20	40	RT	19	75	56	33	103	70	-15	-28	-14	-2995
20	80	RT	26	122	95	41	160	119	-14	-39	-24	-3823
40	20	RT	25	80	54	36	109	73	-10	-30	-19	-2978

Table 4-II: Recovery Duration - 8 MPa – 80 $^{\circ}\text{C}$ - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
20	1	80	15	16	1	7	14	7	7	2	-5	-570
20	10	80	40	67	27	54	77	23	-15	-10	4	-2198
20	20	80	30	60	30	39	83	44	-9	-23	-14	-2377
20	40	80	22	76	54	31	104	74	-9	-28	-19	-2792
20	80	80	45	142	97	49	157	108	-4	-15	-11	-3409
40	20	80	16	60	44	16	88	72	0	-28	-28	-2193

Table 4-III: Recovery Duration - 8 MPa – 120 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
20	1	120	18	27	9	6	41	35	12	-14	-26	-926
20	10	120	38	62	23	40	81	42	-1	-19	-18	-2363
20	20	120	30	56	26	16	65	49	14	-9	-23	-1875
20	40	120	24	82	58	40	106	66	-16	-24	-9	-2589
20	80	120	20	120	99	23	132	109	-2	-13	-10	-2893
40	20	120	31	90	60	33	110	77	-2	-19	-17	-2474

Table 4-IV: Recovery Duration - 8 MPa – 180 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
20	1	180	43	42	-1	30	52	22	13	-10	-23	-540
20	10	180	44	70	26	47	76	29	-3	-6	-3	-1205
20	20	180	54	85	31	57	95	39	-3	-11	-8	-1572
20	40	180	40	95	55	35	105	70	5	-10	-15	-1858
20	80	180	51	148	97	52	164	113	0	-16	-16	-1947
40	20	180	29	47	17	27	59	32	3	-12	-15	-894

Table 4-V: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	16	10	-6	2	3	1	13	6	-7	660
20	1	RT										
20	10	RT	24	39	15	11	28	17	13	12	-1	2750
20	20	RT	9	51	42	7	47	40	2	4	2	371
20	40	RT	6	45	39	13	21	7	-8	24	32	1550
20	80	RT	8	74	65	8	77	69	0	-3	-3	-226
40	20	RT	41	85	44	20	60	40	21	25	5	3418

Table 4-VI: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]										
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce		
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	27	71	44	19	64	45	8	7	-1	295	
20	40	80	28	103	75	27	106	79	1	-3	-4	-639	
20	80	80	23	125	101	20	126	105	3	-1	-4	-710	
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-VII: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{1}^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	28	35	7	4	21	17	24	14	-10	1986
20	1	120										
20	10	120	52	67	15	25	52	27	27	15	-12	2994
20	20	120	28	52	24	26	52	26	2	0	-1	-288
20	40	120	39	94	55	37	98	61	2	-4	-6	-408
20	80	120	38	138	100	34	136	102	5	2	-2	-818
40	20	120	36	62	26	16	46	30	20	16	-4	2215

Table 4-VIII: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]										
20	1	180	42	45	4	10	38	28	32	7	-25	1234
20	10	180	42	58	15	26	59	33	16	-1	-17	587
20	20	180	76	81	5	47	81	33	29	0	-29	583
20	40	180	48	87	39	40	81	41	8	6	-2	375
20	80	180	41	128	87	36	122	85	5	6	1	496
40	20	180	53	108	56	35	101	66	18	7	-11	748

Table 4-IX: Recovery Duration - 12.5 MPa Continuous – Room Temperature - Creep / Recovered Strain

			Strain [$\mu\epsilon$]										
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$	
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	13	26	12	5	22	17	9	4	-5	529	
20	1	RT	36	59	22	27	55	28	10	4	-6	493	
20	10	RT		15	45	30	10	43	34	5	1	-4	384
20	20	RT		15	62	47	11	60	49	4	2	-2	333
20	40	RT		20	101	81	17	97	80	4	5	1	385
20	80	RT		40	85	45	29	81	52	11	4	-7	684
40	20	RT											

Table 4-X: Recovery Duration - 12.5 MPa Continuous - 80 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	36	47	11	22	41	20	15	6	-9	451
20	1	80										
20	10	80	36	55	19	19	53	34	17	2	-15	236
20	20	80	22	45	24	13	43	31	9	2	-7	173
20	40	80	34	90	56	36	89	52	-2	2	4	160
20	80	80	41	128	87	35	123	88	6	5	-2	232
40	20	80	30	73	43	14	74	60	15	-2	-17	100

Table 4-XI: Recovery Duration - 12.5 MPa Continuous - 120 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	1 st Cycle	Final Cycle	Differen ce	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	30	29	-1	6	20	14	25	9	-16	1026
20	1	120										
20	10	120	47	69	21	40	64	24	8	4	-3	753
20	20	120	34	56	23	21	57	36	12	-1	-13	581
20	40	120	34	76	42	27	77	50	6	-1	-8	603
20	80	120	44	133	89	43	122	79	1	11	10	1081
40	20	120	32	77	45	19	73	54	13	4	-9	761

Table 4-XII: Recovery Duration - 12.5 MPa Continuous - 180 °C - Creep / Recovered Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			1 st Cycle	Final Cycle	Difference	1 st Cycle	Final Cycle	Difference	1 st Cycle	Final Cycle	Difference	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]										
20	1	180	41	18	-23	6	9	3	35	8	-26	1381
20	10	180	51	61	10	24	51	27	27	10	-18	1198
20	20	180	55	76	21	40	67	26	14	10	-5	1299
20	40	180	47	89	42	35	79	44	12	10	-2	1367
20	80	180	65	144	79	52	136	85	13	7	-6	1464
40	20	180	66	99	33	35	87	52	31	12	-18	1752

Table 4-XIII: Tabulation of line of best fit parameters for change in creep and creep recovery strain over duration of testing with respect to recovery duration

Applied Loads [MPa]	Temperature [°C]	$\Delta\epsilon_{c(180-1)}$				$\Delta\epsilon_{r(180-1)}$			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²
8 / 0.1	RT	1.161	4.432	0.975	0.951	1.326	15.367	0.988	0.976
	80	1.134	7.764	0.988	0.977	1.269	12.749	0.982	0.964
	120	1.146	8.336	0.995	0.989	0.951	31.351	0.997	0.994
	180	1.152	6.779	0.987	0.974	1.186	18.578	0.996	0.993
12.5 / 0.5	RT	0.780	7.619	0.897	0.805	0.687	5.912	0.782	0.611
	80	0.914	30.758	0.971	0.943	0.953	32.215	0.964	0.929
	120	1.212	3.627	0.998	0.995	1.117	12.923	0.988	0.976
	180	1.076	-2.572	0.969	0.939	0.715	22.571	0.956	0.914
12.5 / 0.5 Continuous	RT	0.859	12.437	0.999	0.999	0.778	18.028	0.998	0.997
	80	1.000	9.024	0.989	0.979	0.847	19.402	0.988	0.976
	120	1.068	2.476	0.990	0.979	0.794	16.657	0.995	0.990
	180	1.165	-9.352	0.966	0.934	0.946	8.496	0.981	0.963
Averages	8 / 0.1 MPa	1.148	6.828	0.986	0.973	1.183	19.511	0.991	0.982
	12.5 / 0.5 MPa	0.995	9.858	0.959	0.921	0.868	18.405	0.922	0.858
	12.5 / 0.5 MPa Continuous	1.023	3.646	0.986	0.973	0.841	15.646	0.991	0.981

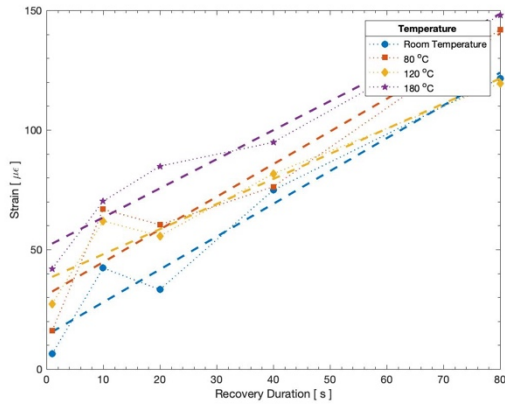


Figure 4-23: Final cycle creep strain as a function of recovery duration for the tests performed at 8 MPa.

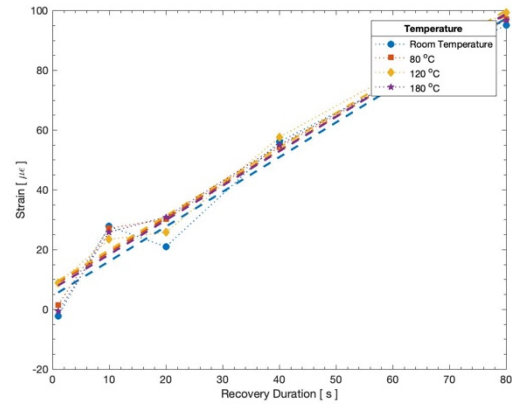


Figure 4-24: Change in the creep strain from initial cycle to the final cycle as a function of recovery duration for the tests performed at 8 MPa.

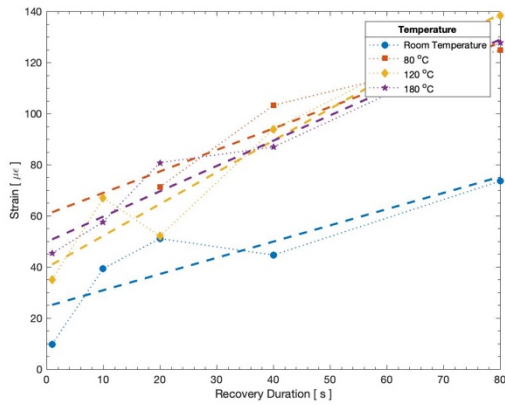


Figure 4-25: Final cycle creep strain as a function of recovery duration for the tests performed at 12.5 MPa Non-Continuous testing conditions.

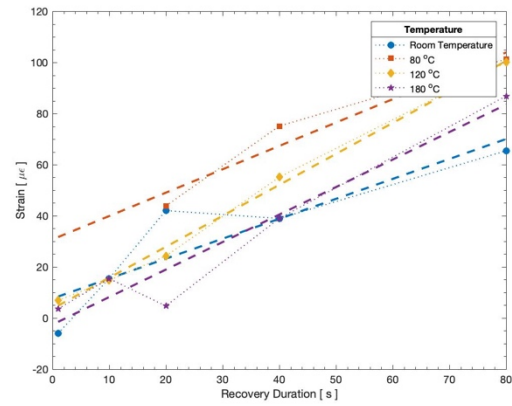


Figure 4-26: Change in the creep strain from initial cycle to the final cycle as a function of recovery duration for the tests performed using 12.5 MPa Non-Continuous testing conditions.

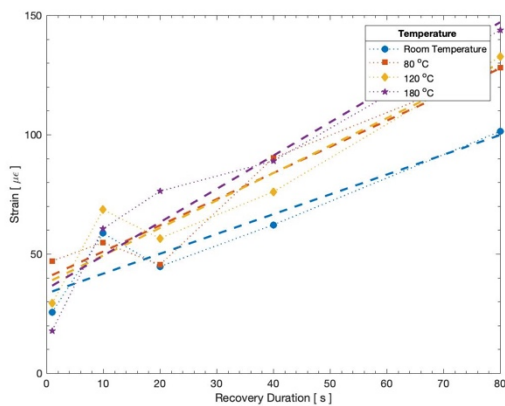


Figure 4-27: Final cycle creep strain as a function of recovery duration for the tests performed at 12.5 MPa Continuous testing conditions.

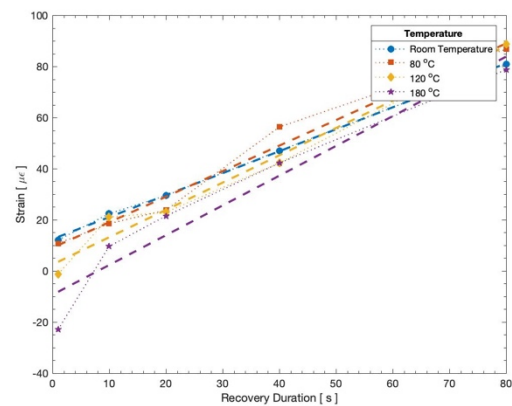


Figure 4-28: Change in the creep strain from initial cycle to the final cycle as a function of recovery duration for the tests performed using 12.5 MPa Continuous testing conditions.

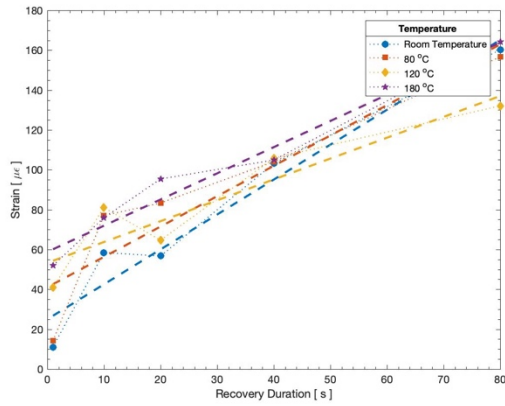


Figure 4-29: Final cycle recovered strain as a function of recovery duration performed at 8 MPa.

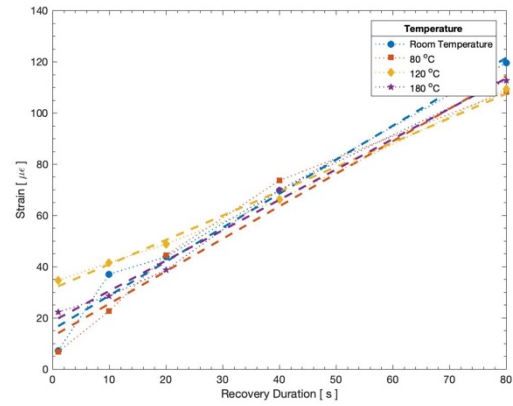


Figure 4-30: Change in recovered strain over all cycles as a function of recovery duration performed at 8 MPa.

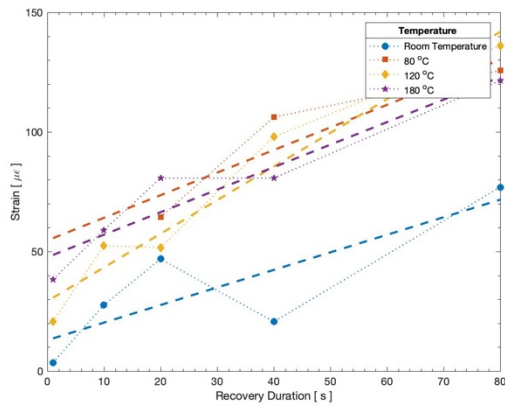


Figure 4-31: Final cycle recovered strain as a function of recovery duration performed using 12.5 MPa Non-Continuous testing conditions.

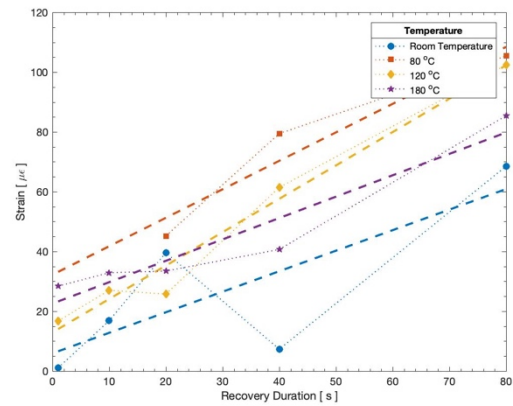


Figure 4-32: Change in recovered strain over all cycles as a function of recovery duration performed using 12.5 MPa Non-Continuous testing conditions.

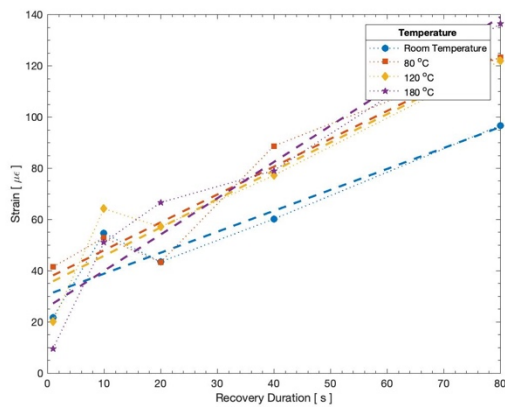


Figure 4-33: Final cycle recovered strain as a function of recovery duration performed using 12.5 MPa Continuous testing conditions.

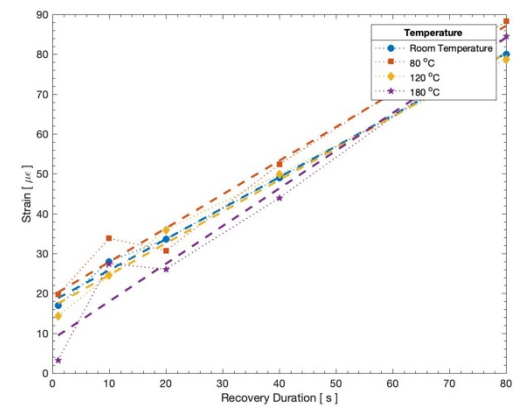


Figure 4-34: Change in recovered strain over all cycles as a function of recovery duration performed using 12.5 MPa Continuous testing conditions.

4.2.1.2 Unrecovered Strain

With the creep, recovered and unrecovered creep strains evaluated, the unrecovered strain was next to be evaluated. Comparing the total and cycle unrecovered strain with the unrecovered creep strain, and using the formulation presented in section 3.4.4 the unrecovered instantaneous stress was then calculated. Table 4-XIV through Table 4-XXV present the tabulations of the total unrecovered, unrecovered creep and unrecovered instantaneous strains, with Figure 4-35 through Figure 4-40 sample comparison plots for the parameters.

Evaluating the total unrecovered strain, over the course of the testing, there is a logarithmic decaying increase as the cycle number increases. This visual trend is supported by the majority of the values presented in the difference column for the unrecovered strain being positive. Evaluating the unrecovered strain for trends based on the recovery duration; for the initial, final, and difference between the two cycles there is a general decreasing trend as the recovery duration increases. While this trend is present for the majority of the load-temperature combinations, there are outliers for each of the evaluated cycles. For this first cycle, the correlation is generally a weak relationship, which is slightly stronger for the two continuous loading conditions. The final cycle shows a borderline weak to strong relationship between the unrecovered strain and the recovery duration, confirmed via the correlation coefficient. For the change in the unrecovered strain over the course of the cyclic loading, the decreasing trend present shows a relatively strong correlation with the line of best fit.

Evaluating the calculated unrecovered instantaneous strain, similar to the unrecovered creep strain, there is no clear trends in any of the cycles, or via the change over the duration of the experiment. Based on the formulations used to calculate the unrecovered instantaneous strain, and when viewing the individual plots of the unrecovered creep strain and overall unrecovered strain, observed were large fluctuations in the strain response, and as such if there were any trends in the data for an individual cycle, they would most likely have occurred by coincidence.

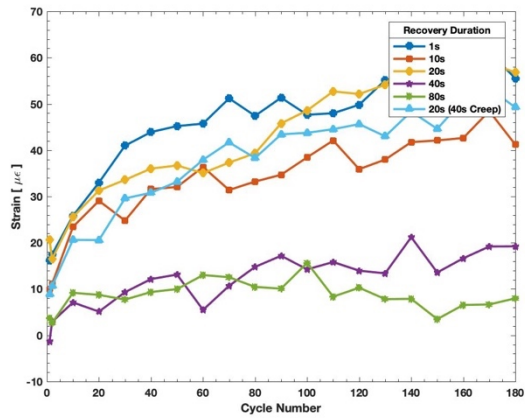


Figure 4-35: 8 MPa – 120 °C – Total Unrecovered Strain

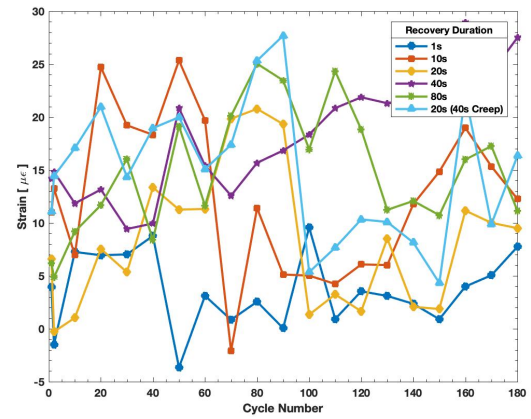


Figure 4-36: 8 MPa – 120 °C – Unrecovered Instantaneous Strain

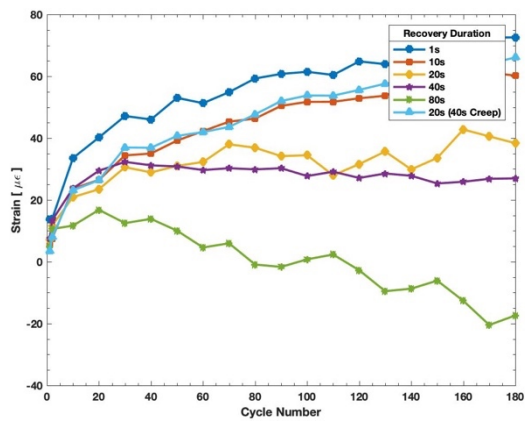


Figure 4-37: 12.5 MPa – 120 °C – Total Unrecovered Strain

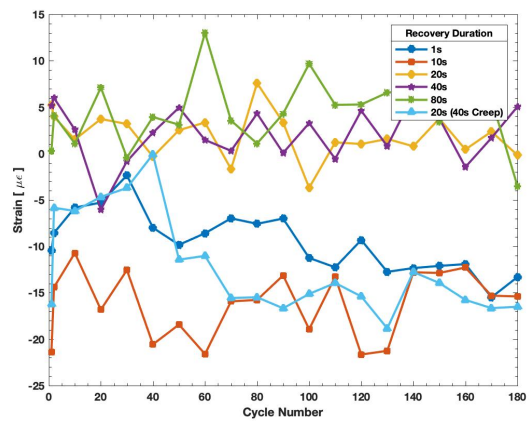


Figure 4-38: 12.5 MPa – 120 °C – Unrecovered Instantaneous Strain

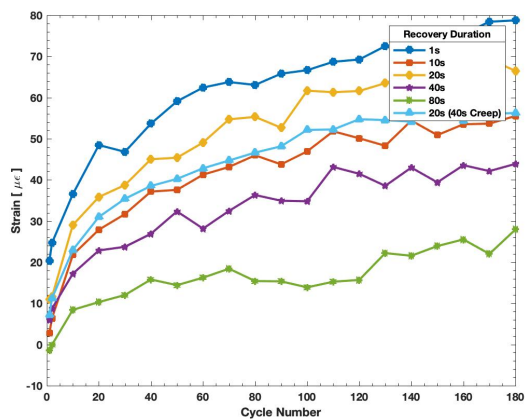


Figure 4-39: 12.5 MPa Continuous – 120 °C – Total Unrecovered Strain

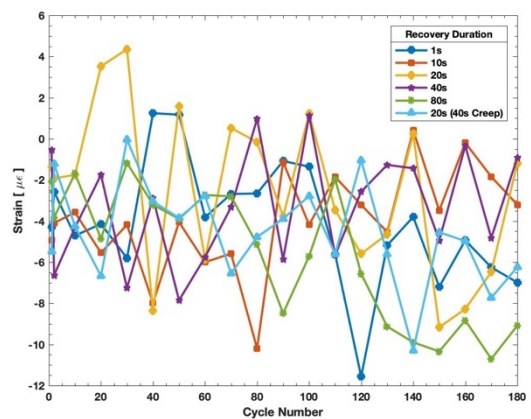


Figure 4-40: 12.5 MPa Continuous – 120 °C – Unrecovered Instantaneous Strain

Table 4-XIV: Recovery Duration - 8 MPa - Room Temperature - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	11	33	22	5	-5	-9	6	6	0
20	10	RT	5	20	15	-7	-16	-9	12	16	4
20	20	RT	4	19	15	-1	-23	-23	5	24	19
20	40	RT	5	18	14	-15	-28	-14	19	29	10
20	80	RT	2	16	13	-14	-39	-24	17	39	22
40	20	RT	6	22	16	-10	-30	-19	16	29	12

Table 4-XV: Recovery Duration - 8 MPa - 80 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	80	11	44	33	7	2	-5	4	-1	-5
20	10	80	3	27	23	-15	-10	4	18	12	-6
20	20	80	15	38	23	-9	-23	-14	24	17	-6
20	40	80	7	31	24	-9	-28	-19	15	31	15
20	80	80	7	21	14	-4	-15	-11	10	13	2
40	20	80	10	50	41	0	-28	-28	10	27	17

Table 4-XVI: Recovery Duration - 8 MPa - 120 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	120	16	56	39	12	-14	-26	4	8	4
20	10	120	10	41	31	-1	-19	-18	11	12	1
20	20	120	21	57	36	14	-9	-23	7	10	3
20	40	120	-1	19	21	-16	-24	-9	14	28	13
20	80	120	4	8	4	-2	-13	-10	6	11	5
40	20	120	9	49	40	-2	-19	-17	11	16	5

Table 4-XVII: Recovery Duration - 8 MPa - 180 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	180	24	96	73	13	-10	-23	11	10	-1
20	10	180	5	79	73	-3	-6	-3	8	6	-3
20	20	180	11	90	79	-3	-11	-8	14	13	-1
20	40	180	9	59	50	5	-10	-15	4	13	9
20	80	180	5	26	21	0	-16	-16	5	19	14
40	20	180	9	86	77	3	-12	-15	7	10	4

Table 4-XVIII: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	-1	23	24	13	6	-7	-14	-5	9
20	10	RT	-5	17	22	13	12	-1	-18	-11	7
20	20	RT	2	6	4	2	4	2	0	-4	-4
20	40	RT	-3	6	10	-8	24	32	4	-24	-28
20	80	RT	5	6	2	0	-3	-3	5	1	-4
40	20	RT	-2	25	27	21	25	5	-23	-25	-2

Table 4-XIX: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	7	8	1	8	7	-1	-1	-5	-3
20	40	80	10	37	27	1	-3	-4	9	9	0
20	80	80	3	21	18	3	-1	-4	0	2	2
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-XX: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	120	14	73	59	24	14	-10	-10	-13	-3
20	10	120	5	60	55	27	15	-12	-21	-15	6
20	20	120	7	38	31	2	0	-1	5	0	-5
20	40	120	7	27	20	2	-4	-6	5	5	0
20	80	120	5	-17	-22	5	2	-2	0	-4	-4
40	20	120	3	66	63	20	16	-4	-16	-17	0

Table 4-XXI: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	180	27	128	101	32	7	-25	-5	-6	-1
20	10	180	10	106	96	16	-1	-17	-6	-1	5
20	20	180	25	239	214	29	0	-29	-4	1	4
20	40	180	8	87	78	8	6	-2	1	-5	-6
20	80	180	5	61	57	5	6	1	0	-9	-9
40	20	180	15	114	99	18	7	-11	-3	-3	0

Table 4-XXII: Recovery Duration - 12.5 MPa Continuous - Room Temperature - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	9	37	28	9	4	-5	0	-3	-3
20	10	RT	5	28	23	10	4	-6	-5	-3	2
20	20	RT	3	21	18	5	1	-4	-2	-2	0
20	40	RT	1	20	19	4	2	-2	-3	-2	1
20	80	RT	1	17	16	4	5	1	-2	-3	-1
40	20	RT	3	30	27	11	4	-7	-8	-4	4

Table 4-XXIII: Recovery Duration - 12.5 MPa Continuous - 80 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	80	14	57	43	15	6	-9	0	-3	-3
20	10	80	14	48	34	17	2	-15	-3	-1	2
20	20	80	10	45	35	9	2	-7	1	0	-1
20	40	80	11	35	23	-2	2	4	14	0	-13
20	80	80	4	19	15	6	5	-2	-3	-5	-2
40	20	80	9	49	41	15	-2	-17	-6	1	7

Table 4-XXIV: Recovery Duration - 12.5 MPa Continuous - 120 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	120	20	79	58	25	9	-16	-4	-7	-3
20	10	120	3	56	53	8	4	-3	-5	-3	2
20	20	120	11	67	56	12	-1	-13	-1	-1	0
20	40	120	6	44	38	6	-1	-8	-1	-1	0
20	80	120	-1	28	29	1	11	10	-2	-9	-7
40	20	120	7	56	49	13	4	-9	-5	-6	-1

Table 4-XXV: Recovery Duration - 12.5 MPa Continuous - 180 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	180	31	150	119	35	8	-26	-3	-8	-5
20	10	180	14	118	104	27	10	-18	-14	-10	4
20	20	180	19	167	148	14	10	-5	5	-10	-14
20	40	180	7	105	97	12	10	-2	-5	-12	-8
20	80	180	1	70	68	13	7	-6	-12	-8	4
40	20	180	19	144	125	31	12	-18	-12	-11	1

Table 4-XXVI: Tabulation of line of best fit parameters for total unrecovered strain with respect to recovery duration

Applied Load [MPa]	Temperature [°C]	$\varepsilon_{UR,180}$				$\Delta\varepsilon_{UR,180-1}$			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R^2	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R^2
8 / 0.1	RT	-0.146	25.504	-0.698	0.487	-0.071	17.843	-0.644	0.415
	80	-0.224	38.820	-0.760	0.577	-0.186	29.103	-0.874	0.763
	120	-0.621	54.924	-0.892	0.796	-0.440	39.659	-0.970	0.942
	180	-0.875	96.433	-0.966	0.933	-0.728	81.250	-0.949	0.900
12.5 / 0.5	RT	-0.181	17.216	-0.702	0.493	-0.259	20.039	-0.781	0.610
	80	0.137	15.652	0.287	0.082	0.219	5.007	0.506	0.257
	120	-1.098	69.329	-0.989	0.978	-1.030	59.541	-0.989	0.979
	180	-1.117	157.853	-0.511	0.261	-0.881	135.657	-0.454	0.206
12.5 / 0.5 Continuous	RT	-0.201	30.522	-0.788	0.620	-0.122	24.305	-0.787	0.619
	80	-0.461	54.658	-0.989	0.978	-0.335	40.161	-0.962	0.926
	120	-0.578	71.987	-0.921	0.849	-0.383	58.337	-0.956	0.913
	180	-1.010	152.462	-0.828	0.686	-0.694	128.468	-0.746	0.556
Averages	8 / 0.1 MPa	-0.467	53.920	-0.829	0.699	-0.356	41.964	-0.859	0.755
	12.5 / 0.5 MPa	-0.565	65.013	-0.479	0.454	-0.488	55.061	-0.429	0.513
	12.5 / 0.5 MPa Continuous	-0.563	77.407	-0.882	0.783	-0.383	62.818	-0.863	0.754

Table 4-XXVI presents the slope, intercept, correlation coefficient, and coefficient of determination for the final cycle and the change in the total unrecovered strain. Comparing first the parameters for the lines of best fit, ignoring the 80 °C non-continuous 12.5 MPa testing conditions, there is a decreasing trend in the slope and increasing trend in the intercept as the temperature increases. This indicates that there is also a relationship between the unrecovered strain and the temperature. This relationship shall be further explored in section 4.3.1.2.

Overall, considering these general trends in the creep, recovered, and unrecovered data; When the sample is allowed to recover for a longer duration it is able to recover more creep strain, thus less unrecovered strains are able to transfer into the next cycle and accumulate less. Where as for the testing with shorter recovery durations, as less strain is able to be recovered during the recovery segment, this unrecovered strain is accumulated further and is carried over to subsequent cycles via the instantaneous strains. As the creep strain is not fully recovered, the sample is only able to creep by a reduced amount in subsequent cycles during the creep portion. Therefore, indicating that the recovery duration influences the accumulation of unrecovered strain.

4.2.2 Modulus

The next material property evaluated with respect to the effect that changes in the recovery duration had on the response was the instantaneous modulus. Presented in Table 4-XXVII through Table 4-XXXVIII are the calculated values for the moduli for all loadings and temperatures following the same order as the previous section, sorted based on the recovery duration. Included are the instantaneous modulus values for both the loading, unloading segments and the difference between the two moduli. Sample plots showing the evolution of the moduli with increase in cycle number are presented in Figure 4-41 through Figure 4-49.

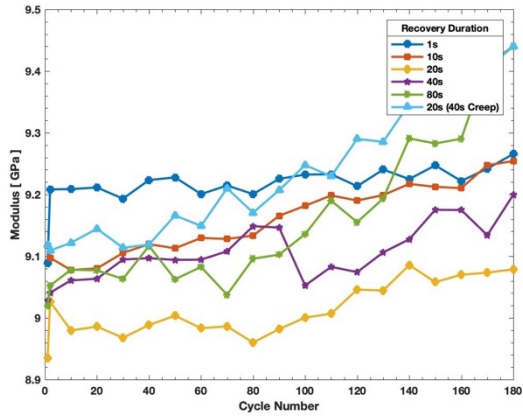


Figure 4-41: 8 MPa – 120 °C - Instantaneous Modulus (Loading)

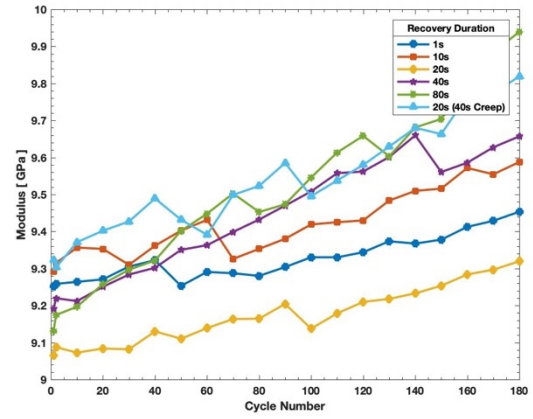


Figure 4-42: 8 MPa – 120 °C - Instantaneous Modulus (Unloading)

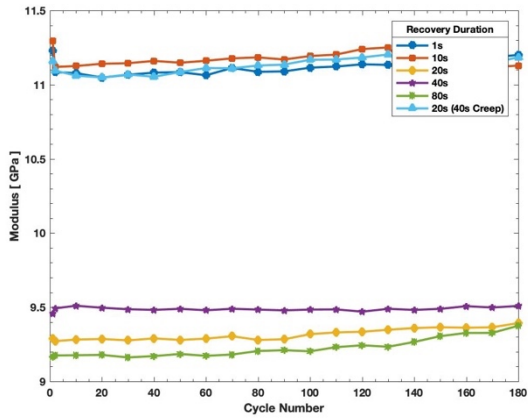


Figure 4-43: 12.5 MPa – 120 °C - Instantaneous Modulus (Loading)

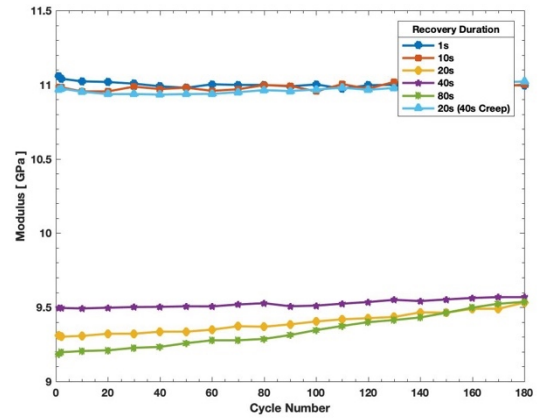


Figure 4-44: 12.5 MPa – 120 °C - Instantaneous Modulus (Unloading)

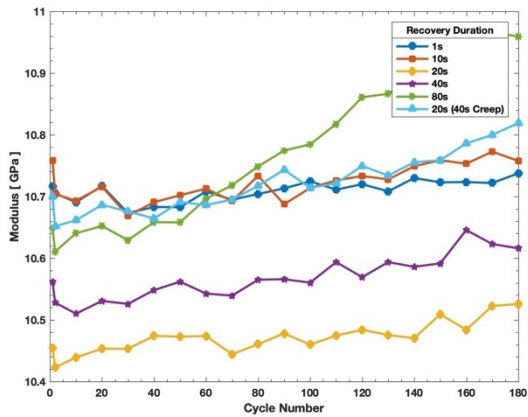


Figure 4-45: 12.5 MPa Continuous – 120 °C - Instantaneous Modulus (Loading)

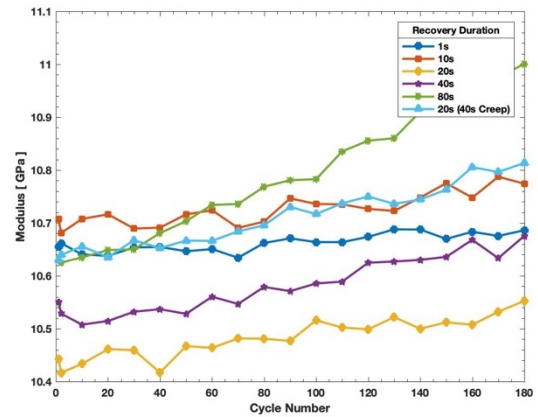


Figure 4-46: 12.5 MPa Continuous – 120 °C - Instantaneous Modulus (Unloading)

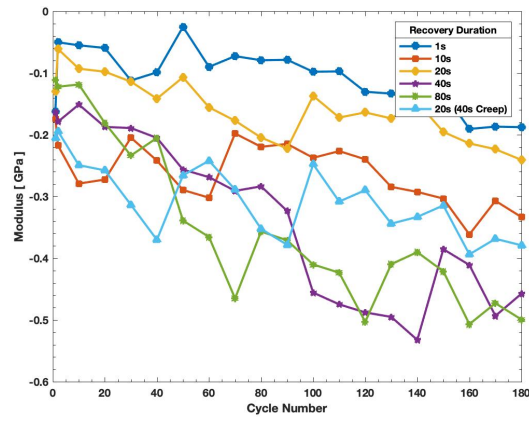


Figure 4-47: 8 MPa – 120 °C - Instantaneous Modulus (Difference)

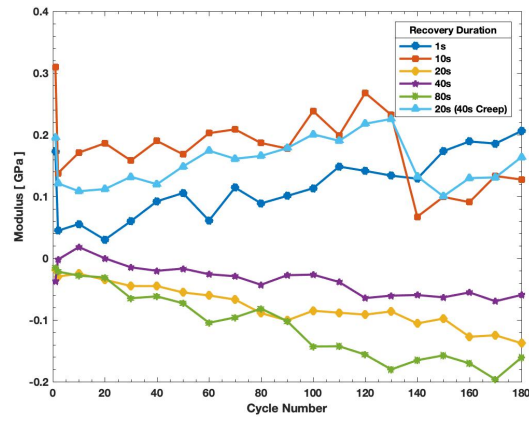


Figure 4-48: 12.5 MPa – 120 °C - Instantaneous Modulus (Difference)

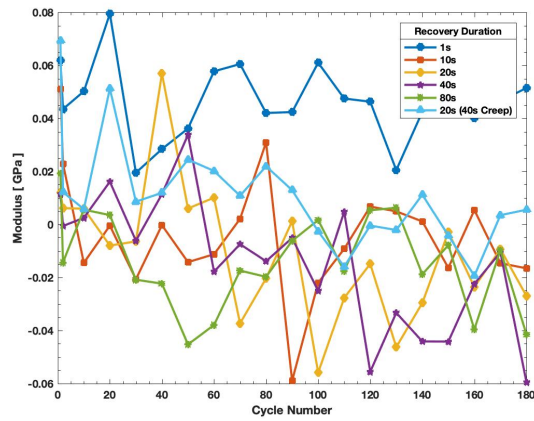


Figure 4-49: 12.5 MPa Continuous – 120 °C - Instantaneous Modulus (Difference)

Table 4-XXVII: Recovery Duration - 8 MPa - Room Temperature – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	9.12	9.11	-0.02	9.08	9.22	0.13	0.04	-0.11	-0.15
20	10	RT	9.10	9.21	0.11	9.19	9.51	0.32	-0.09	-0.30	-0.21
20	20	RT	8.99	9.04	0.04	9.08	9.34	0.26	-0.09	-0.31	-0.22
20	40	RT	8.99	9.07	0.08	9.16	9.60	0.44	-0.17	-0.53	-0.36
20	80	RT	9.03	9.35	0.32	9.24	10.10	0.87	-0.21	-0.76	-0.55
40	20	RT	9.07	9.15	0.08	9.21	9.85	0.64	-0.14	-0.70	-0.56

Table 4-XXVIII: Recovery Duration - 8 MPa - 80 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	9.17	9.23	0.06	9.17	9.29	0.12	0.00	-0.06	-0.06
20	10	80	9.24	9.32	0.07	9.49	9.64	0.15	-0.25	-0.32	-0.08
20	20	80	9.04	9.13	0.09	9.16	9.60	0.43	-0.12	-0.47	-0.35
20	40	80	9.07	9.24	0.18	9.29	9.76	0.47	-0.22	-0.51	-0.29
20	80	80	9.12	9.83	0.70	9.39	10.36	0.96	-0.27	-0.53	-0.26
40	20	80	9.06	9.24	0.17	9.16	9.64	0.48	-0.09	-0.40	-0.31

Table 4-XXIX: Recovery Duration - 8 MPa - 120 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	9.21	9.27	0.06	9.26	9.45	0.19	-0.05	-0.19	-0.14
20	10	120	9.10	9.25	0.16	9.31	9.59	0.27	-0.22	-0.33	-0.12
20	20	120	9.03	9.08	0.05	9.09	9.32	0.23	-0.06	-0.24	-0.18
20	40	120	9.04	9.20	0.16	9.22	9.66	0.44	-0.18	-0.46	-0.28
20	80	120	9.05	9.44	0.39	9.17	9.94	0.76	-0.12	-0.50	-0.38
40	20	120	9.11	9.44	0.33	9.30	9.82	0.52	-0.19	-0.38	-0.18

Table 4-XXX: Recovery Duration - 8 MPa - 180 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	9.12	9.16	0.04	9.17	9.35	0.17	-0.05	-0.18	-0.13
20	10	180	9.05	9.18	0.13	9.17	9.49	0.32	-0.12	-0.31	-0.19
20	20	180	8.83	8.97	0.15	8.94	9.33	0.38	-0.11	-0.35	-0.24
20	40	180	8.84	9.04	0.20	8.94	9.42	0.48	-0.10	-0.37	-0.27
20	80	180	8.96	9.43	0.47	9.08	9.82	0.74	-0.12	-0.39	-0.27
40	20	180	8.98	9.09	0.11	9.02	9.25	0.23	-0.04	-0.16	-0.12

Table 4-XXXI: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	12.31	12.28	-0.02	12.12	12.15	0.02	0.18	0.13	-0.05
20	10	RT	12.28	12.42	0.14	12.17	12.20	0.03	0.11	0.22	0.11
20	20	RT	11.45	11.55	0.10	11.44	11.56	0.12	0.01	-0.01	-0.02
20	40	RT	10.78	10.70	-0.08	10.77	10.70	-0.07	0.01	0.00	-0.01
20	80	RT	11.49	11.52	0.03	11.42	11.68	0.26	0.07	-0.16	-0.23
40	20	RT	12.45	12.66	0.21	12.19	12.38	0.19	0.26	0.28	0.02

Table 4-XXXII: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	9.54	9.71	0.17	9.54	9.73	0.19	-0.01	-0.02	-0.02
20	40	80	9.54	9.76	0.21	9.58	9.93	0.35	-0.04	-0.18	-0.14
20	80	80	9.92	10.10	0.18	9.95	10.31	0.35	-0.03	-0.21	-0.17
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-XXXIII: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	11.08	11.20	0.12	11.04	10.99	-0.05	0.04	0.21	0.16
20	10	120	11.12	11.13	0.01	10.98	11.00	0.02	0.14	0.13	-0.01
20	20	120	9.27	9.39	0.12	9.30	9.53	0.23	-0.03	-0.14	-0.11
20	40	120	9.49	9.51	0.02	9.49	9.57	0.07	0.00	-0.06	-0.06
20	80	120	9.17	9.38	0.20	9.20	9.54	0.34	-0.02	-0.16	-0.14
40	20	120	11.09	11.18	0.09	10.97	11.02	0.05	0.12	0.16	0.04

Table 4-XXXIV: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	9.93	10.00	0.07	9.90	9.99	0.09	0.03	0.01	-0.02
20	10	180	9.88	9.97	0.08	9.89	9.99	0.10	0.00	-0.02	-0.02
20	20	180	9.36	9.50	0.14	9.32	9.49	0.18	0.05	0.01	-0.04
20	40	180	9.76	9.87	0.12	9.75	9.88	0.12	0.00	0.00	-0.01
20	80	180	9.82	10.09	0.27	9.83	10.14	0.31	-0.01	-0.05	-0.04
40	20	180	9.90	10.10	0.20	9.90	10.16	0.26	0.00	-0.06	-0.06

Table 4-XXXV: Recovery Duration - 12.5 MPa Continuous - Room Temperature - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	11.07	11.09	0.02	11.06	11.11	0.05	0.01	-0.01	-0.03
20	10	RT	11.13	11.23	0.09	11.14	11.26	0.11	-0.01	-0.03	-0.02
20	20	RT	11.02	11.12	0.10	11.02	11.12	0.10	0.00	0.00	0.00
20	40	RT	11.03	11.17	0.14	11.02	11.20	0.18	0.01	-0.03	-0.04
20	80	RT	11.05	11.33	0.29	11.04	11.39	0.35	0.01	-0.06	-0.06
40	20	RT	11.15	11.37	0.22	11.15	11.40	0.26	0.00	-0.04	-0.04

Table 4-XXXVI: Recovery Duration - 12.5 MPa Continuous - 80 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	10.54	10.57	0.03	10.55	10.62	0.07	-0.01	-0.05	-0.04
20	10	80	10.52	10.62	0.10	10.55	10.66	0.11	-0.03	-0.04	-0.01
20	20	80	10.35	10.46	0.11	10.35	10.48	0.13	0.00	-0.02	-0.02
20	40	80	10.47	10.63	0.16	10.49	10.74	0.25	-0.02	-0.11	-0.08
20	80	80	10.48	10.81	0.33	10.51	10.91	0.40	-0.04	-0.10	-0.06
40	20	80	10.52	10.66	0.14	10.52	10.74	0.22	-0.01	-0.08	-0.07

Table 4-XXXVII: Recovery Duration - 12.5 MPa Continuous - 120 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	10.71	10.74	0.03	10.66	10.69	0.02	0.04	0.05	0.01
20	10	120	10.70	10.76	0.05	10.68	10.77	0.09	0.02	-0.02	-0.04
20	20	120	10.42	10.53	0.10	10.42	10.55	0.14	0.01	-0.03	-0.03
20	40	120	10.53	10.62	0.09	10.53	10.68	0.15	0.00	-0.06	-0.06
20	80	120	10.61	10.96	0.35	10.63	11.00	0.38	-0.01	-0.04	-0.03
40	20	120	10.65	10.82	0.17	10.64	10.81	0.17	0.01	0.01	-0.01

Table 4-XXXVIII: Recovery Duration - 12.5 MPa Continuous - 180 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	10.29	10.24	-0.05	10.18	10.17	-0.02	0.11	0.08	-0.03
20	10	180	10.27	10.27	-0.01	10.23	10.24	0.01	0.04	0.03	-0.01
20	20	180	9.95	10.07	0.11	9.91	9.99	0.08	0.05	0.08	0.03
20	40	180	10.07	10.25	0.18	10.01	10.16	0.16	0.07	0.08	0.02
20	80	180	10.15	10.47	0.32	10.15	10.44	0.29	0.00	0.03	0.03
40	20	180	10.32	10.41	0.10	10.24	10.37	0.13	0.08	0.04	-0.04

Reviewing the modulus data several trends are present. With respect to the 2nd cycle data for the both the loading and unloading modulus, when evaluated based upon the recovery duration, there is no trend present in the data. However, for the two continuous testing conditions (8 MPa / 0.1 MPa and 12.5 MPa / 0.5 MPa), there is a marginal increasing trend in the moduli with respect to the order in which the tests were performed. This order, as presented in section 3.3.5 (ignoring tests performed but not included in this thesis), was 20s, 40s, 80s, 10s, 1s. For both continuous loading scenarios and all temperatures, this trend is present. Since the rest time between tests was found to be sufficient to allow for complete recovery of any accumulated unrecovered strains, this is believed to be due to physical aging of the specimen during the rest period before the start of the next test segment. However, as both modulus values are quite similar to one another, this suggests that any effects of physical aging are not significant.

Evaluating the final cycle for both instantaneous moduli, there is a general slight increasing trend as the recovery duration increases. For the loading modulus this is a rather weakly correlated trend, which is non-existent to reverse for the non-continuous loading condition. For the unloading modulus, the correlation is stronger than that of the loading modulus, however similar to the loading modulus shows weaker to non-existent trends for the non-continuous. Unlike the values for the 2nd cycle, there is no trend in the moduli values for the final cycle with respect to the order in which the samples were tested.

Evaluating the difference between the 2nd and the final cycles, for both the loading and the unloading modulus, there is a strong increasing trend with number of cycles. For a given recovery duration, the loading and unloading moduli increased with number of cycles. Moreover, the unloading modulus is marginally higher than the loading modulus. This correlates well with the observed increase in the size of the hysteresis loop. The difference between the 2nd and final cycles increase with the recovery duration time, which also correlates with the increase in dissipated energy with recovery duration, to be discussed in the next section. This trend is strongest for the two continuous data sets, but is also present in the individual testing results, indicating that it is a consistent result.

4.2.3 Strain Energy Density

The last parameter which was evaluated with respect to the effect of the recovery duration was the changes in the strain energy density. Presented first will be the calculations for the overall strain energy densities. After which, the total and stored strain energy densities decomposed to compose of the loading (unloading) and creep (recovery) segments for both the total and stored strain energy densities.

4.2.3.1 Overall Strain Energy Density

As indicated first presented will be the changes in the overall strain energy densities. Similar to the preceding sections, Figure 4-50 through Figure 4-61 present sample plots for the cyclic strain energy density responses. Table 4-XXXIX through Table 4-L present the calculated total, stored, dissipated and unrecovered strain energy densities in the same order as presented in the preceding sections.

Evaluating first the cyclic response of the total strain energy density, there is a general increase with increase in the number of cycles. Comparing the total strain energy density for trends in the second cycle, for the majority of the load-temperature combinations there is a slight increasing trend with increase in recovery duration. However, in a quarter of the combinations this trend is not present, and when evaluating the correlation of data to the trend line, the correlation is rather weak indicating a generally poor relationship. This is not totally unsurprising as during these initial cycles, any changes in the material response would not be too significant. However, when evaluating the final cycle, and the change over the course of testing, there is a strong increasing trend for all data sets. Evaluating the trend lines, and their corresponding correlation coefficients (Figure 4-62 and Table 4-LI), further confirms that there is a very strong increasing linear relationship between the total strain energy density and the recovery duration. This relationship is strongest for the two continuous loading scenarios, and while both the final cycle and the change over all cycles show very strong correlation, is slightly stronger for the overall change.

The stored strain energy density was observed to decrease with increase in number of cycles. Evaluating the calculated values for the second cycle, there was no clear trend in the data with half showing an increasing trend and half showing a decreasing trend. While both the final cycle, and the difference between the 2nd and final cycle, both showed a strongly decreasing trend as

the recovery duration increased. Similar to the total strain energy density, this decreasing trend was correlated strongest for the two continuous testing scenarios, and showed weakest correlation for the non-continuous testing. Similarly, the change in the stored strain energy density over the course of testing showed a very strong linear correlation with the recovery duration (Figure 4-62 and Table 4-LI).

Evaluating the change in the dissipated energy over the course of the cyclic loading, observed was an increase with increase in the number of cycles. Evaluating next, the calculated values for the 2nd cycle, consistent with the other energies, there was no apparent trend in the data. However, for the final cycle and the change in the energy, the test samples exhibited an increasing trend with exceptionally strong correlation.

The difference in energies (corresponding to the change between the last and 2nd cycles) are plotted in Figure 4-62 as a function of recovery duration to understand the effect of the recovery duration and test temperature. Included in the figures is a line of best fit for each temperature, along with the slope of these lines identified. These best fit line parameters are collocated in Table 4-LI.

Viewing the data contained in the figures and table, the close proximity of the generated lines of best fit, and relatively high correlation coefficients for the two continuous loading scenarios indicate that the service temperature does not have as much effect on the strain energy density as the effect of creep recovery duration during cyclic loading. However, the data for discontinuous testing at 12.5 MPa exhibits a larger scatter that is difficult to interpret the trend in the effect of test temperature. This scatter is likely due to sample-to-sample variation since primarily different samples were used for each test, in contrast to the continuous tests which utilized the same sample for a given loading level at all test temperatures.

Lastly, the unrecovered strain energy density for all cycles showed a strong decreasing trend with increase in the recovery duration. This matches what would be expected since with the increase in the recovery duration, this allows for more creep strain to recover between cycles.

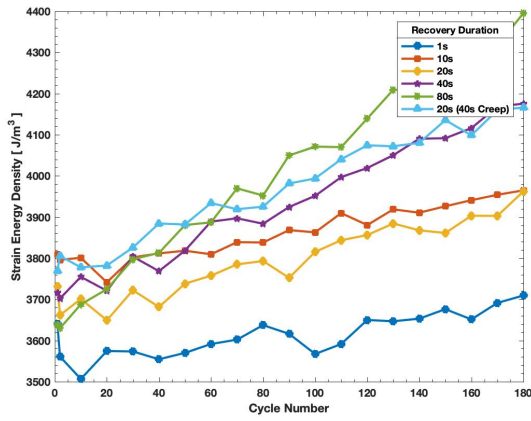


Figure 4-50: 8 MPa – 120 °C – Total Strain Energy Density

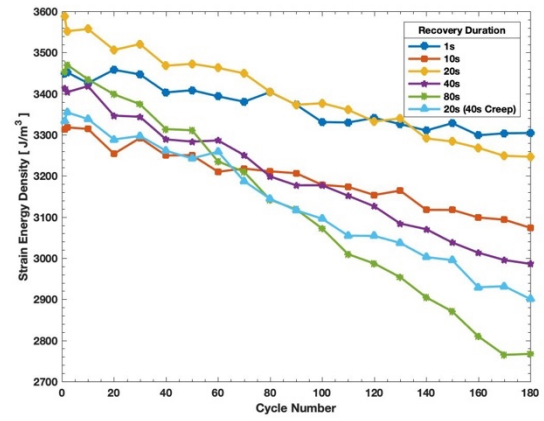


Figure 4-51: 8 MPa – 120 °C – Stored Strain Energy Density

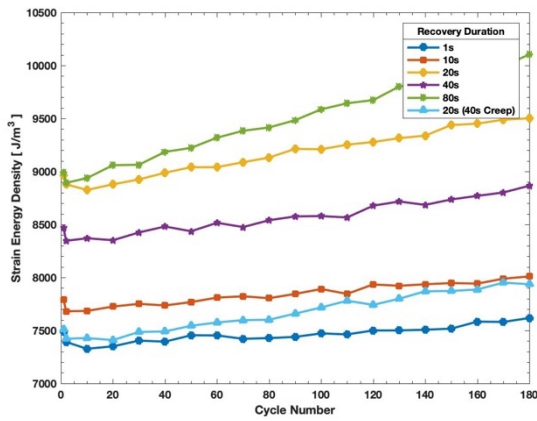


Figure 4-52: 12.5 MPa – 120 °C – Total Strain Energy Density

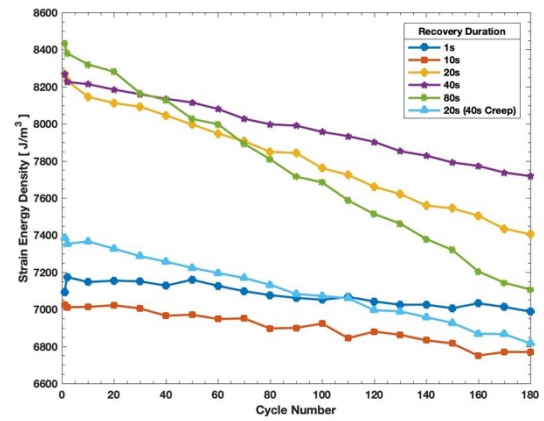


Figure 4-53: 12.5 MPa – 120 °C – Stored Strain Energy Density

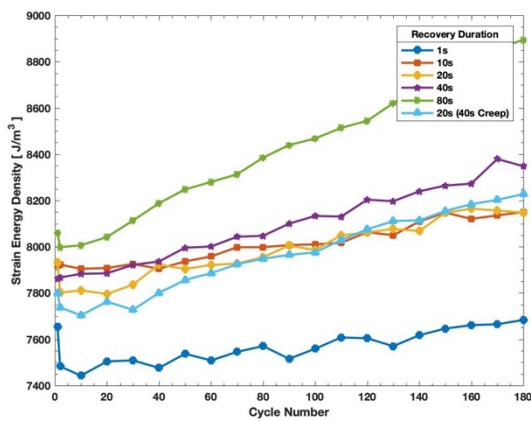


Figure 4-54: 12.5 MPa Continuous – 120 °C – Total Strain Energy Density

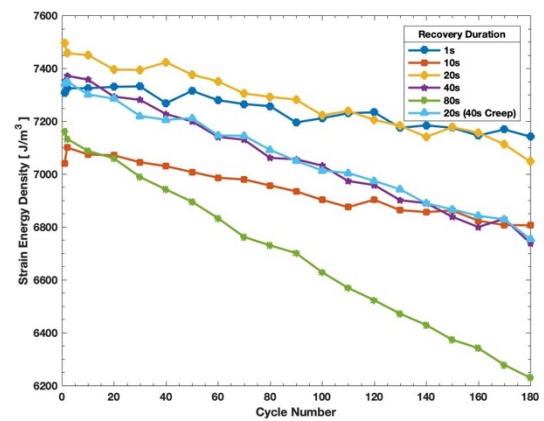


Figure 4-55: 12.5 MPa Continuous – 120 °C – Stored Strain Energy Density

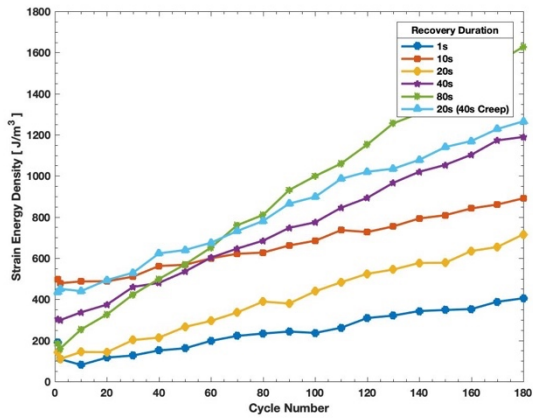


Figure 4-56: 8 MPa - 120 °C - Dissipated Strain Energy Density

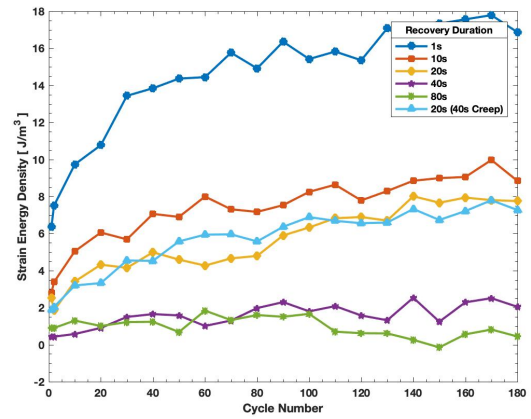


Figure 4-57: 8 MPa - 120 °C - Unrecovered Strain Energy Density

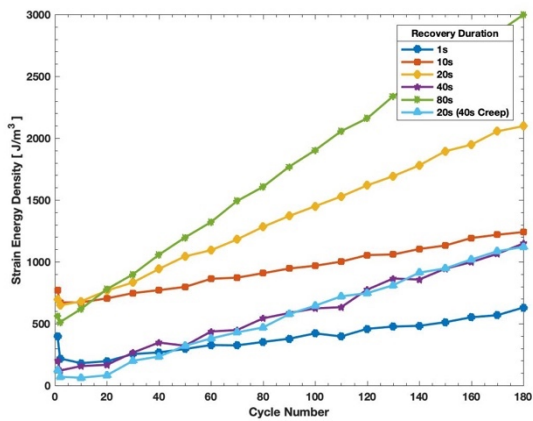


Figure 4-58: 12.5 MPa - 120 °C - Dissipated Strain Energy Density

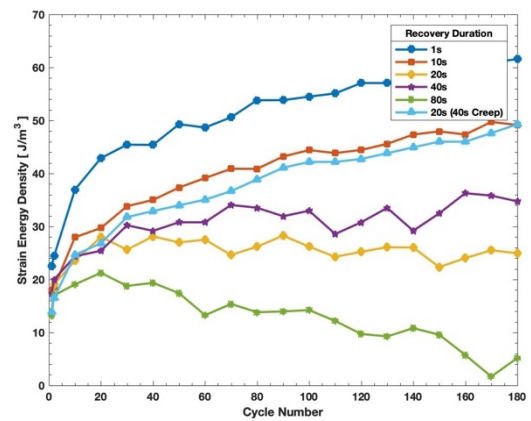


Figure 4-59: 12.5 MPa - 120 °C - Unrecovered Strain Energy Density

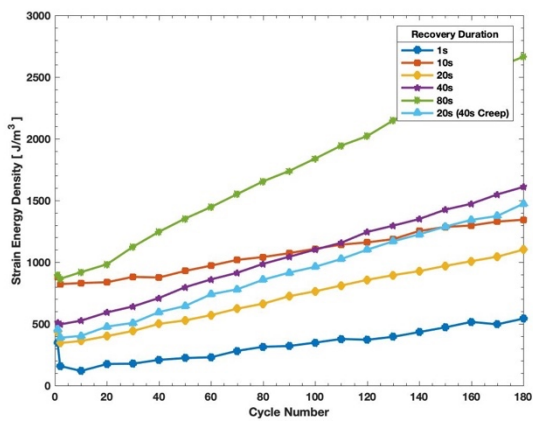


Figure 4-60: 12.5 MPa Continuous- 120 °C - Dissipated Strain Energy Density

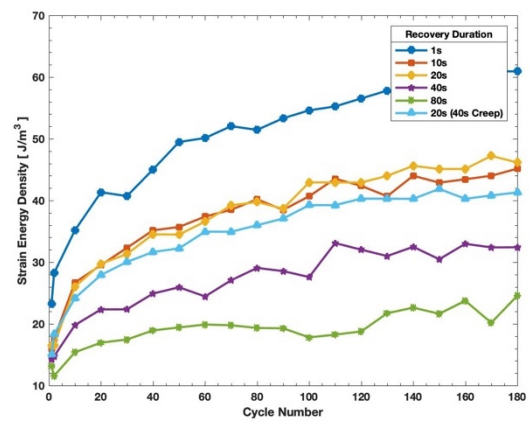


Figure 4-61: 12.5 MPa Continuous - 120 °C - Unrecovered Strain Energy Density

Table 4-XXXIX: Recovery Duration - 8 MPa - Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3412.23	3558.58	146.36	3592.34	3420.74	-171.60	-180.11	137.85	317.96	6.48	10.82	4.34
20	10	RT	3600.69	3820.50	219.81	3398.32	3163.53	-234.80	202.37	656.97	454.60	2.48	4.76	2.28
20	20	RT	3508.84	3811.03	302.19	3555.59	3232.51	-323.09	-46.75	578.53	625.28	1.57	3.08	1.50
20	40	RT	3680.85	4130.53	449.68	3394.49	2930.00	-464.49	286.36	1200.53	914.17	0.71	2.00	1.29
20	80	RT	3764.38	4488.15	723.77	3317.17	2588.69	-728.48	447.21	1899.46	1452.25	0.64	1.86	1.22
40	20	RT	3727.26	4160.48	433.22	3354.75	2902.05	-452.70	372.51	1258.44	885.92	1.69	3.58	1.89

Table 4-XL: Recovery Duration - 8 MPa - 80 °C – Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	3482.62	3607.13	124.51	3515.17	3333.89	-181.28	-32.56	273.24	305.80	5.68	13.86	8.18
20	10	80	3810.99	4015.21	204.22	3183.64	2966.42	-217.22	627.35	1048.79	421.44	3.53	6.40	2.87
20	20	80	3690.81	3973.22	282.41	3353.20	3065.28	-287.92	337.61	907.94	570.33	2.93	4.91	1.98
20	40	80	3685.65	4128.62	442.97	3350.13	2907.40	-442.73	335.53	1221.23	885.70	0.42	3.93	3.51
20	80	80	3830.03	4520.55	690.52	3230.82	2532.73	-698.09	599.21	1987.82	1388.61	1.37	2.27	0.90
40	20	80	3567.67	4003.31	435.64	3490.84	3049.60	-441.23	76.83	953.70	876.88	2.24	6.94	4.70

Table 4-XLI: Recovery Duration - 8 MPa - 120 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	3560.88	3709.30	148.42	3451.89	3304.45	-147.44	108.99	404.85	295.86	7.50	16.87	9.36
20	10	120	3796.04	3964.85	168.82	3317.85	3073.84	-244.01	478.19	891.02	412.83	3.38	8.84	5.46
20	20	120	3661.65	3962.43	300.78	3551.87	3246.62	-305.25	109.78	715.81	606.03	1.84	7.75	5.91
20	40	120	3702.21	4175.57	473.36	3403.70	2986.08	-417.62	298.51	1189.49	890.98	0.43	2.04	1.61
20	80	120	3629.97	4395.62	765.65	3470.11	2767.19	-702.91	159.86	1628.42	1468.56	0.90	0.44	-0.46
40	20	120	3805.40	4166.17	360.78	3354.54	2900.58	-453.95	450.86	1265.59	814.73	2.03	7.27	5.24

Table 4-XLII: Recovery Duration - 8 MPa - 180 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	3762.94	3899.04	136.10	3395.67	3236.65	-159.02	367.27	662.39	295.12	8.84	25.33	16.48
20	10	180	3888.92	4058.44	169.52	3384.85	3165.05	-219.80	504.07	893.39	389.32	4.54	15.67	11.13
20	20	180	3972.01	4257.01	285.00	3489.62	3213.81	-275.81	482.39	1043.20	560.81	2.48	12.40	9.92
20	40	180	3873.95	4297.10	423.15	3583.57	3118.43	-465.13	290.38	1178.66	888.28	0.60	6.72	6.12
20	80	180	3937.11	4674.07	736.96	3424.13	2717.61	-706.52	512.99	1956.46	1443.48	0.07	3.11	3.04
40	20	180	3583.52	3968.47	384.96	3742.32	3333.06	-409.27	-158.81	635.42	794.22	3.01	12.25	9.24

Table 4-XLIII: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6455.13	6643.92	188.79	6647.17	6489.31	-157.86	-192.03	154.61	346.65	19.25	34.55	15.30
20	10	RT	6768.96	7031.28	262.32	6394.60	6155.65	-238.96	374.36	875.63	501.27	14.87	24.66	9.79
20	20	RT	6939.68	7412.49	472.81	6801.57	6397.56	-404.01	138.11	1014.93	876.81	12.14	14.21	2.07
20	40	RT	6898.69	8023.71	1125.02	7038.12	6837.22	-200.91	-139.43	1186.49	1325.92	11.21	16.36	5.15
20	80	RT	6615.24	7724.04	1108.80	6981.58	5979.21	-1002.37	-366.34	1744.84	2111.17	12.37	12.80	0.43
40	20	RT	6914.40	7399.60	485.20	6312.11	5826.82	-485.29	602.30	1572.78	970.48	12.48	25.40	12.92

Table 4-XLIV: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	8187.41	8649.31	461.90	7787.16	7240.52	-546.64	400.25	1408.79	1008.54	16.82	16.37	-0.45
20	40	80	8497.21	9206.49	709.28	7898.98	7123.33	-775.66	598.23	2083.16	1484.93	15.38	29.86	14.48
20	80	80	8157.81	9329.63	1171.81	7661.45	6501.36	-1160.09	496.36	2828.27	2331.91	12.64	23.30	10.65
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-XLV: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	7390.82	7617.15	226.33	7173.48	6987.42	-186.06	217.33	629.72	412.39	24.43	61.59	37.16
20	10	120	7680.90	8009.65	328.75	7010.62	6769.47	-241.15	670.27	1240.18	569.90	18.55	49.15	30.60
20	20	120	8878.24	9501.31	623.08	8230.57	7404.07	-826.51	647.66	2097.24	1449.58	19.09	24.92	5.83
20	40	120	8345.78	8865.33	519.55	8225.53	7717.93	-507.60	120.24	1147.40	1027.16	19.99	34.73	14.74
20	80	120	8892.66	10103.93	1211.27	8380.39	7106.48	-1273.91	512.27	2997.45	2485.18	16.99	5.17	-11.82
40	20	120	7421.62	7936.09	514.48	7351.95	6815.61	-536.33	69.67	1120.48	1050.81	16.54	49.28	32.74

Table 4-XLVI: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	8239.99	8430.66	190.67	7768.45	7539.90	-228.55	471.54	890.76	419.22	36.99	91.25	54.27
20	10	180	8392.26	8583.23	190.97	7853.41	7490.94	-362.47	538.85	1092.30	553.45	21.11	71.26	50.15
20	20	180	9010.15	9266.94	256.79	8527.52	8000.56	-526.95	482.63	1266.37	783.74	30.05	135.98	105.93
20	40	180	8344.95	8994.34	649.39	8134.59	7517.94	-616.64	210.36	1476.40	1266.04	18.26	53.49	35.23
20	80	180	8321.51	9383.18	1061.66	8019.51	6976.49	-1043.01	302.01	2406.68	2104.68	14.58	41.26	26.68
40	20	180	8562.13	9168.30	606.18	7736.73	7111.81	-624.92	825.40	2056.50	1231.09	22.13	69.41	47.29

Table 4-XLVII: Recovery Duration - 12.5 MPa Continuous - Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	7171.66	7358.13	186.47	7027.03	6828.67	-198.36	144.63	529.46	384.83	22.71	39.37	16.67
20	10	RT	7447.53	7707.84	260.31	6792.81	6493.60	-299.20	654.73	1214.24	559.51	16.47	28.44	11.97
20	20	RT	7238.67	7590.90	352.22	7071.40	6692.53	-378.87	167.27	898.36	731.09	15.14	23.75	8.61
20	40	RT	7235.12	7759.42	524.29	7090.46	6514.82	-575.64	144.66	1244.60	1099.93	11.95	21.51	9.56
20	80	RT	7306.07	8189.33	883.25	6966.72	6073.47	-893.25	339.35	2115.85	1776.50	12.30	18.89	6.58
40	20	RT	7500.75	8008.95	508.21	6824.44	6272.88	-551.56	676.30	1736.07	1059.77	16.24	28.09	11.85

Table 4-XLVIII: Recovery Duration - 12.5 MPa Continuous - 80 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	7803.16	7994.26	191.09	7130.82	6931.00	-199.82	672.35	1063.26	390.91	26.01	49.89	23.88
20	10	80	7753.66	8054.65	300.98	7241.62	6958.80	-282.81	512.05	1095.84	583.79	19.22	38.51	19.29
20	20	80	7631.54	8006.39	374.84	7570.80	7169.59	-401.20	60.75	836.79	776.04	16.12	34.14	18.03
20	40	80	7941.23	8489.34	548.11	7214.14	6628.51	-585.63	727.09	1860.83	1133.74	14.72	25.72	11.00
20	80	80	7927.09	8843.66	916.57	7182.48	6238.33	-944.15	744.61	2605.33	1860.72	13.06	19.07	6.01
40	20	80	7710.67	8284.52	573.85	7374.72	6813.56	-561.17	335.94	1470.96	1135.02	16.71	37.60	20.89

Table 4-XLIX: Recovery Duration - 12.5 MPa Continuous - 120 °C - Overall Strain Energy Density

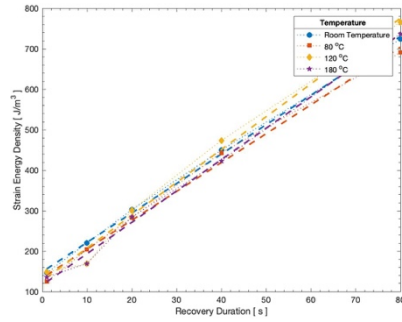
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	7482.75	7683.35	200.61	7324.41	7141.30	-183.10	158.34	542.05	383.71	28.24	60.94	32.69
20	10	120	7922.58	8150.50	227.92	7100.30	6806.32	-293.97	822.29	1344.18	521.89	17.64	45.16	27.53
20	20	120	7801.42	8147.93	346.50	7457.05	7047.18	-409.87	344.38	1100.75	756.37	16.51	46.16	29.65
20	40	120	7867.07	8348.00	480.93	7371.43	6738.62	-632.81	495.65	1609.38	1113.74	14.75	32.41	17.66
20	80	120	7997.92	8894.44	896.53	7133.18	6229.43	-903.75	864.73	2665.01	1800.28	11.57	24.56	12.99
40	20	120	7737.64	8227.55	489.91	7350.50	6754.17	-596.32	387.14	1473.38	1086.23	18.34	41.30	22.96

Table 4-L: Recovery Duration - 12.5 MPa Continuous - 180 °C - Overall Strain Energy Density

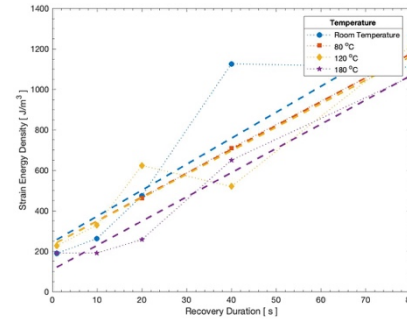
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	7674.69	7908.24	233.54	7879.09	7698.31	-180.78	-204.40	209.92	414.32	32.39	109.15	76.76
20	10	180	8071.17	8398.82	327.65	7647.73	7406.19	-241.54	423.44	992.63	569.19	23.64	80.48	56.83
20	20	180	8421.42	8727.73	306.31	8007.13	7621.51	-385.63	414.29	1106.23	691.94	25.63	96.43	70.80
20	40	180	8227.62	8786.33	558.70	7960.34	7357.00	-603.34	267.29	1429.33	1162.04	15.76	62.95	47.19
20	80	180	8425.40	9360.25	934.86	7546.20	6636.11	-910.09	879.20	2724.15	1844.95	14.86	45.51	30.65
40	20	180	8267.60	8811.59	543.99	7616.62	7083.52	-533.10	650.98	1728.07	1077.09	22.36	86.58	64.22

Table 4-LI: Tabulation of parameters for the relationship between the change in the overall strain energy densities as a function of recovery duration

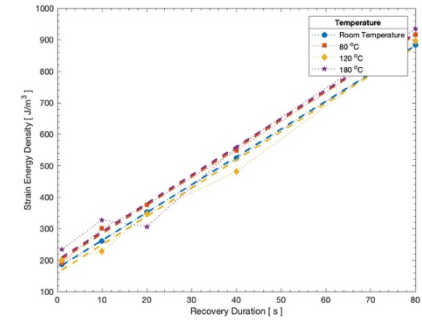
Applied Load [MPa]	Temperature [°C]	Total				Stored				Dissipated			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²
8 / 0.1	RT	7.271	148.770	0.999	0.999	-7.050	-171.592	-0.999	0.998	14.321	320.361	0.999	0.998
	80	7.127	133.682	0.997	0.995	-6.721	-162.477	-0.999	0.997	13.848	296.159	0.999	0.998
	120	8.109	126.511	0.995	0.991	-6.788	-158.450	-0.998	0.995	14.897	284.961	0.999	0.999
	180	7.750	116.088	0.998	0.996	-7.066	-151.861	-0.997	0.993	14.816	267.949	0.999	0.998
12.5 / 0.5	RT	12.842	243.706	0.886	0.784	-9.726	-107.083	-0.875	0.765	22.569	350.789	0.995	0.991
	80	11.794	230.629	1.000	1.000	-10.137	-354.421	-0.999	0.998	21.930	585.050	1.000	0.999
	120	11.624	230.748	0.948	0.899	-12.607	-226.323	-0.877	0.770	24.231	457.072	0.916	0.838
	180	11.975	108.257	0.984	0.968	-9.799	-259.606	-0.990	0.979	21.774	367.862	0.999	0.998
12.5 / 0.5 Continuous	RT	8.838	174.405	1.000	1.000	-8.735	-205.253	-0.999	0.997	17.573	379.658	1.000	1.000
	80	9.017	194.010	0.999	0.999	-9.419	-198.273	-0.999	0.998	18.436	392.283	1.000	0.999
	120	8.974	159.487	0.995	0.990	-9.070	-210.790	-0.990	0.981	18.044	370.277	0.999	0.998
	180	9.000	200.401	0.988	0.977	-9.425	-179.624	-0.994	0.988	18.426	380.025	0.998	0.996
Averages	8 / 0.1 MPa	7.564	131.263	0.997	0.995	-6.906	-161.095	-0.998	0.996	14.471	292.358	0.999	0.998
	12.5 / 0.5 MPa	12.059	203.335	0.954	0.913	-10.567	-236.858	-0.935	0.878	22.626	440.193	0.977	0.957
	12.5 / 0.5 MPa Continuous	8.957	182.076	0.996	0.991	-9.162	-198.485	-0.996	0.991	18.120	380.561	0.999	0.998



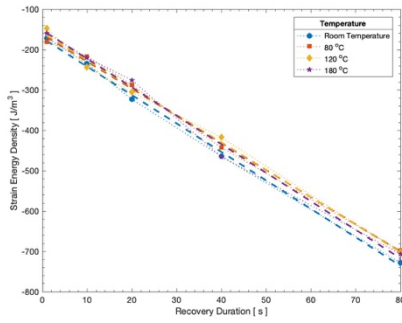
a)



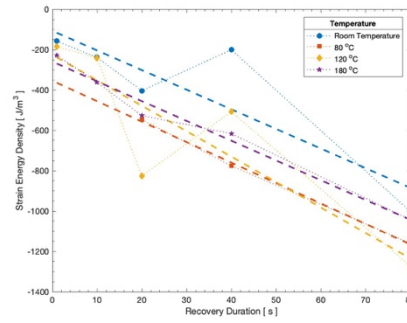
b)



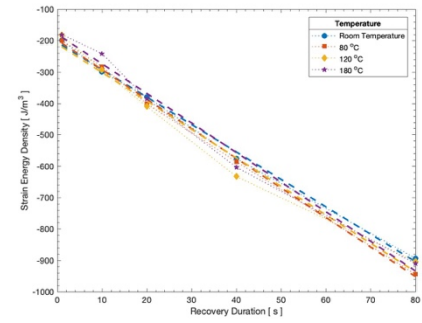
c)



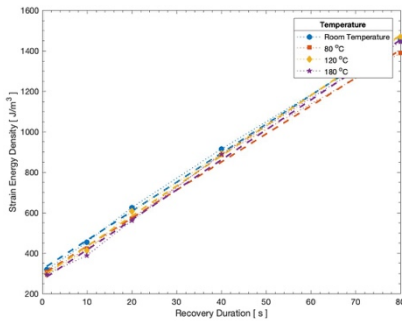
d)



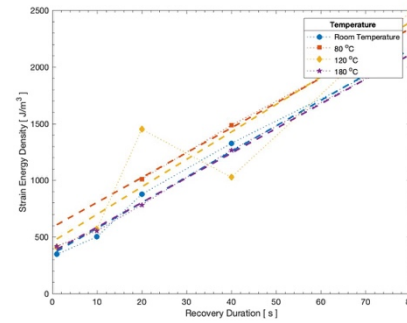
e)



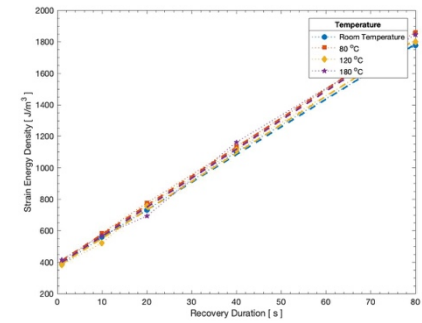
f)



g)



h)



i)

Figure 4-62: Change in Strain Energy Density over all cycles plotted as a function of Recovery Duration. a) through c) show the Total Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. d) through f) show the Stored Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. g) through i) show the Dissipated Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively.

4.2.3.2 Total Strain Energy Density

To better understand the driving mechanism behind the increasing trend in the total strain energy density as a function of the recovery duration, the energy was partitioned into the two segments with which it was compromised of: loading, and creep hold. Table 4-LII through Table 4-LXIII present the total strain energy density segmented for further analysis, and Figure 4-63 through Figure 4-68 present sample plots of the cyclic responses.

When evaluating the energy accumulated during the instantaneous loading segment, there does not appear be any correlation between the strain energy density for this segment and the recovery duration. The magnitudes of the energy for the two continuous loadings are all in fact relatively close together. This observation was also true for the non-continuous testing which were conducted using the same sample.

For the total strain energy density accumulated during the creep hold, during the final cycle along with the change over the cyclic test, both show an increasing trend as the recovery duration increases. This combined with the lack of changes in the energy accumulated during the loading segment indicates that the creeping portion is largely responsible for any changes in the total strain energy density.

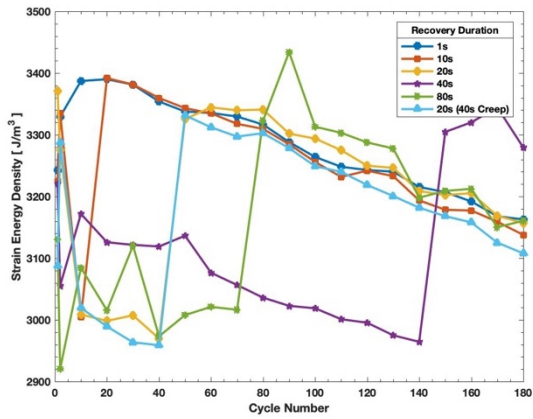


Figure 4-63: 8 MPa - 120 °C - Total Stored Energy Density (Loading)

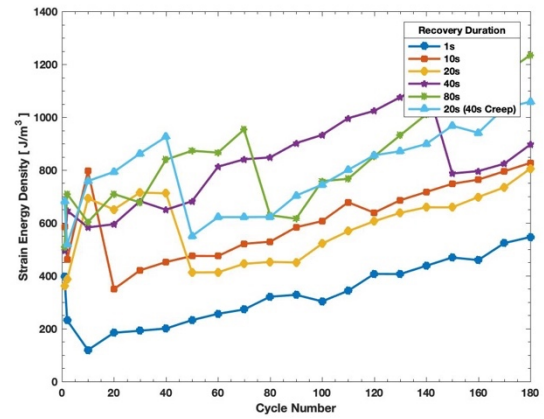


Figure 4-64: 8 MPa - 120 °C - Total Stored Energy Density (Creep)

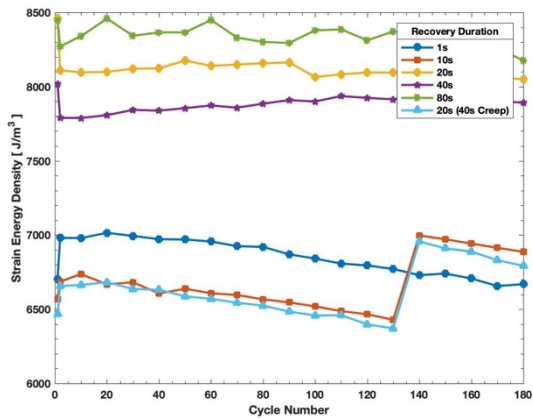


Figure 4-65: 12.5 MPa - 120 °C - Total Stored Energy Density (Loading)

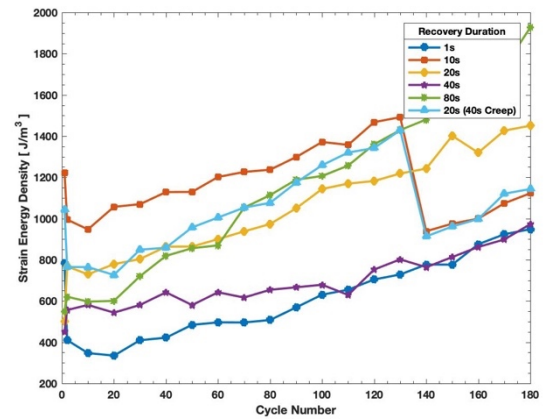


Figure 4-66: 12.5 MPa - 120 °C - Total Stored Energy Density (Creep)

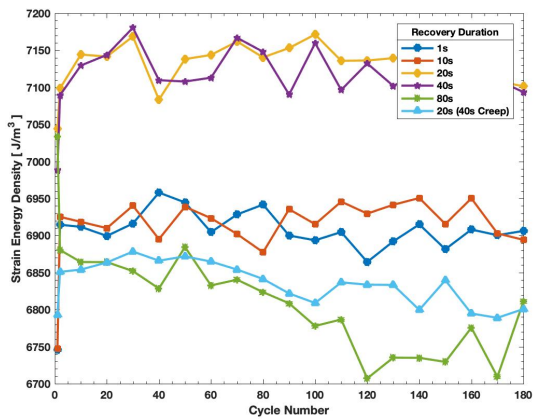


Figure 4-67: 12.5 MPa Continuous - 120 °C - Total Stored Energy Density (Loading)

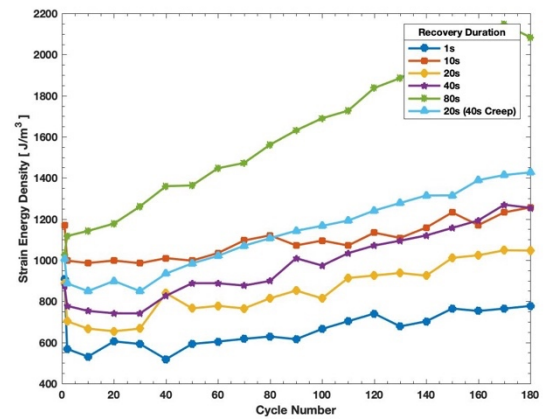


Figure 4-68: 12.5 MPa Continuous - 120 °C - Total Stored Energy Density (Creep)

Table 4-LII: Recovery Duration - 8 MPa - Room Temperature - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3082.55	3280.20	197.65	329.68	278.39	-51.29	3412.23	3558.58	146.36
20	10	RT	3314.81	3112.68	-202.13	285.88	707.82	421.94	3600.69	3820.50	219.81
20	20	RT	3154.30	3375.20	220.91	354.55	435.83	81.28	3508.84	3811.03	302.19
20	40	RT	3178.40	3365.36	186.96	502.45	765.17	262.72	3680.85	4130.53	449.68
20	80	RT	3191.18	3342.98	151.80	573.20	1145.17	571.97	3764.38	4488.15	723.77
40	20	RT	3261.14	3046.42	-214.72	466.13	1114.06	647.94	3727.26	4160.48	433.22

Table 4-LIII: Recovery Duration - 8 MPa - 80 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	3181.06	3334.76	153.70	301.55	272.37	-29.18	3482.62	3607.13	124.51
20	10	80	3103.77	3286.79	183.02	707.23	728.43	21.20	3810.99	4015.21	204.22
20	20	80	3226.41	3013.11	-213.30	464.40	960.12	495.71	3690.81	3973.22	282.41
20	40	80	3085.04	3302.40	217.35	600.61	826.23	225.62	3685.65	4128.62	442.97
20	80	80	3307.60	3067.42	-240.17	522.43	1453.12	930.69	3830.03	4520.55	690.52
40	20	80	3109.87	3308.12	198.25	457.80	695.18	237.39	3567.67	4003.31	435.64

Table 4-LIV: Recovery Duration - 8 MPa - 120 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	3329.32	3162.79	-166.53	231.56	546.50	314.95	3560.88	3709.30	148.42
20	10	120	3334.94	3137.72	-197.22	461.10	827.13	366.03	3796.04	3964.85	168.82
20	20	120	3275.19	3157.05	-118.13	386.46	805.38	418.92	3661.65	3962.43	300.78
20	40	120	3055.33	3279.35	224.02	646.88	896.22	249.34	3702.21	4175.57	473.36
20	80	120	2920.22	3160.60	240.38	709.75	1235.01	525.26	3629.97	4395.62	765.65
40	20	120	3287.78	3107.77	-180.00	517.62	1058.40	540.78	3805.40	4166.17	360.78

Table 4-LV: Recovery Duration - 8 MPa - 180 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	3178.62	3419.93	241.31	584.32	479.11	-105.22	3762.94	3899.04	136.10
20	10	180	3165.20	2952.56	-212.64	723.73	1105.88	382.16	3888.92	4058.44	169.52
20	20	180	3107.54	2976.65	-130.90	864.47	1280.37	415.90	3972.01	4257.01	285.00
20	40	180	3146.12	2955.58	-190.54	727.83	1341.52	613.69	3873.95	4297.10	423.15
20	80	180	3117.82	3234.53	116.71	819.29	1439.54	620.25	3937.11	4674.07	736.96
40	20	180	3076.92	3327.81	250.89	506.59	640.66	134.07	3583.52	3968.47	384.96

Table 4-LVI: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6073.14	6248.14	175.00	381.99	395.78	13.79	6455.13	6643.92	188.79
20	10	RT	6250.40	6375.86	125.46	518.56	655.42	136.86	6768.96	7031.28	262.32
20	20	RT	6617.27	6306.34	-310.93	322.41	1106.15	783.74	6939.68	7412.49	472.81
20	40	RT	7108.01	7633.93	525.91	-209.33	389.78	599.10	6898.69	8023.71	1125.02
20	80	RT	6355.36	6659.85	304.48	259.88	1064.20	804.32	6615.24	7724.04	1108.80
40	20	RT	5911.00	5972.67	61.67	1003.40	1426.93	423.52	6914.40	7399.60	485.20

Table 4-LVII: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	7652.36	7189.38	-462.98	535.05	1459.93	924.88	8187.41	8649.31	461.90
20	40	80	7875.23	7349.32	-525.91	621.98	1857.17	1235.19	8497.21	9206.49	709.28
20	80	80	7647.61	7596.21	-51.40	510.21	1733.42	1223.21	8157.81	9329.63	1171.81
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-LVIII: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	6980.91	6668.69	-312.22	409.91	948.46	538.55	7390.82	7617.15	226.33
20	10	120	6686.00	6886.81	200.81	994.90	1122.84	127.94	7680.90	8009.65	328.75
20	20	120	8110.61	8050.57	-60.04	767.62	1450.74	683.12	8878.24	9501.31	623.08
20	40	120	7789.59	7892.64	103.05	556.18	972.68	416.50	8345.78	8865.33	519.55
20	80	120	8272.04	8176.70	-95.34	620.62	1927.23	1306.62	8892.66	10103.93	1211.27
40	20	120	6656.55	6792.69	136.14	765.06	1143.40	378.34	7421.62	7936.09	514.48

Table 4-LIX: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	7791.70	7380.66	-411.04	448.29	1050.00	601.70	8239.99	8430.66	190.67
20	10	180	7722.19	7317.39	-404.80	670.07	1265.85	595.78	8392.26	8583.23	190.97
20	20	180	7872.81	7596.89	-275.91	1137.34	1670.04	532.70	9010.15	9266.94	256.79
20	40	180	7590.35	7336.49	-253.86	754.60	1657.86	903.26	8344.95	8994.34	649.39
20	80	180	7651.02	7208.34	-442.68	670.49	2174.84	1504.34	8321.51	9383.18	1061.66
40	20	180	7670.12	7224.58	-445.54	892.01	1943.72	1051.71	8562.13	9168.30	606.18

Table 4-LX: Recovery Duration - 12.5 MPa Continuous - Room Temperature - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6812.00	6837.20	25.20	359.66	520.93	161.27	7171.66	7358.13	186.47
20	10	RT	6551.02	6491.72	-59.30	896.51	1216.12	319.61	7447.53	7707.84	260.31
20	20	RT	6660.67	6669.07	8.40	578.00	921.83	343.83	7238.67	7590.90	352.22
20	40	RT	6644.32	6571.22	-73.10	590.80	1188.19	597.39	7235.12	7759.42	524.29
20	80	RT	6690.78	6581.29	-109.49	615.29	1608.04	992.75	7306.07	8189.33	883.25
40	20	RT	6400.36	6318.36	-82.00	1100.39	1690.59	590.20	7500.75	8008.95	508.21

Table 4-LXI: Recovery Duration - 12.5 MPa Continuous - 80 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	7243.92	7212.93	-30.99	559.25	781.33	222.08	7803.16	7994.26	191.09
20	10	80	6714.54	6694.34	-20.20	1039.12	1360.31	321.19	7753.66	8054.65	300.98
20	20	80	6763.68	6759.45	-4.22	867.87	1246.93	379.07	7631.54	8006.39	374.84
20	40	80	6863.96	6856.28	-7.68	1077.27	1633.06	555.79	7941.23	8489.34	548.11
20	80	80	6980.37	6795.19	-185.18	946.71	2048.46	1101.75	7927.09	8843.66	916.57
40	20	80	6791.55	6786.91	-4.64	919.12	1497.61	578.49	7710.67	8284.52	573.85

Table 4-LXII: Recovery Duration - 12.5 MPa Continuous - 120 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	6914.58	6906.19	-8.39	568.17	777.17	209.00	7482.75	7683.35	200.61
20	10	120	6925.19	6894.15	-31.03	997.40	1256.35	258.95	7922.58	8150.50	227.92
20	20	120	7098.61	7101.35	2.73	702.81	1046.58	343.77	7801.42	8147.93	346.50
20	40	120	7089.37	7093.54	4.17	777.70	1254.46	476.76	7867.07	8348.00	480.93
20	80	120	6880.41	6810.93	-69.48	1117.50	2083.51	966.01	7997.92	8894.44	896.53
40	20	120	6850.87	6800.76	-50.11	886.77	1426.79	540.02	7737.64	8227.55	489.91

Table 4-LXIII: Recovery Duration - 12.5 MPa Continuous - 180 °C - Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	7142.93	7156.33	13.40	531.77	751.91	220.14	7674.69	7908.24	233.54
20	10	180	7123.37	7168.63	45.26	947.80	1230.19	282.39	8071.17	8398.82	327.65
20	20	180	6917.72	6934.25	16.53	1503.71	1793.49	289.78	8421.42	8727.73	306.31
20	40	180	6941.21	6814.09	-127.12	1286.42	1972.23	685.82	8227.62	8786.33	558.70
20	80	180	7353.32	7167.55	-185.77	1072.08	2192.70	1120.63	8425.40	9360.25	934.86
40	20	180	6966.81	6935.04	-31.77	1300.79	1876.55	575.76	8267.60	8811.59	543.99

4.2.3.3 Stored Strain Energy Density

Following a similar method as that used for the total strain energy density, the stored strain energy density was also decomposed into the two segments (unloading, recovery) for further evaluation. Table 4-LXIV through Table 4-LXXV present the calculated values for this decomposition, and Figure 4-69 through Figure 4-74 provide visual examples of the changes as a result of the cyclic loading.

Unlike the total strain energy density, for the unloading segment the stored strain energy density exhibited a decreasing trend for both the final cycle and the change over all of the cycles. This decreasing trend showed a very strong correlation for both of the continuous conditions. For the non-continuous loading conditions, the correlations were weaker for the final cycle data, but improved in strength considerably to show a quite strong correlation in the difference between the final and 2nd cycle. This decreasing trend in the stored strain energy over the course of the testing can be seen in the included plots.

For the stored energy accumulated during the recovery portion, there was an increasing trend for each experiment as the recovery duration increased. However, this increasing trend was relatively weak. Additionally, the magnitude of the energy accumulated during this segment is several orders smaller in comparison with the other segments. Thus, while there may be a slight increase in this segment as a result of the increase in the recovery duration, overall in comparison with the other segments it is not the driving force of the change in the dissipated energy.

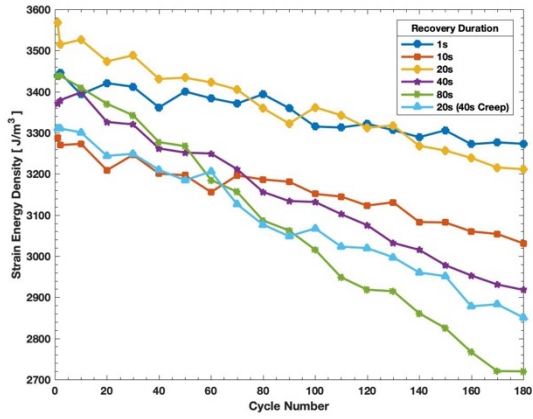


Figure 4-69: 8 MPa - 120 °C - Stored Strain Energy Density (Unloading)

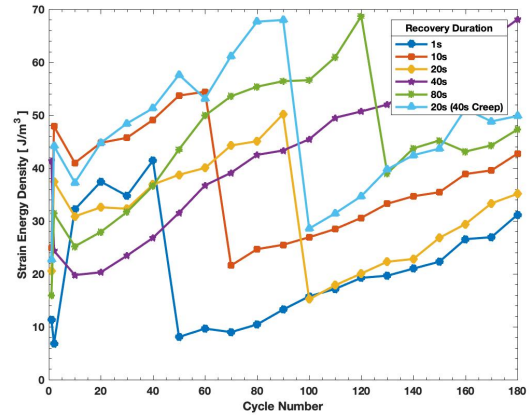


Figure 4-70: 8 MPa - 120 °C - Stored Strain Energy Density (Recovery)

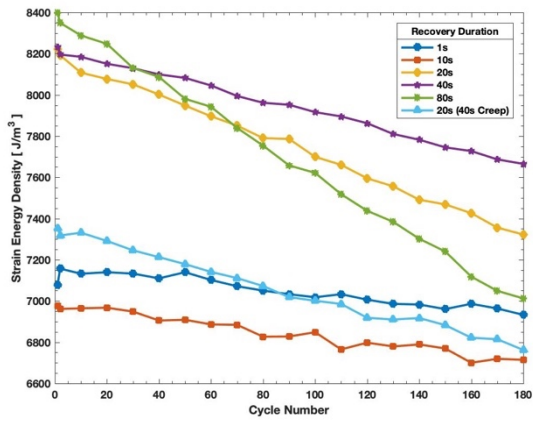


Figure 4-71: 12.5 MPa - 120 °C - Stored Strain Energy Density (Unloading)

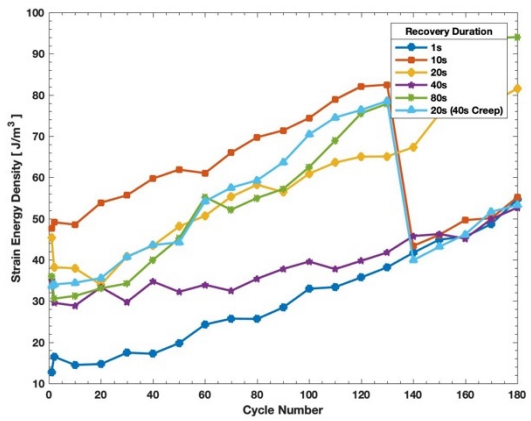


Figure 4-72: 12.5 MPa - 120 °C - Stored Strain Energy Density (Recovery)

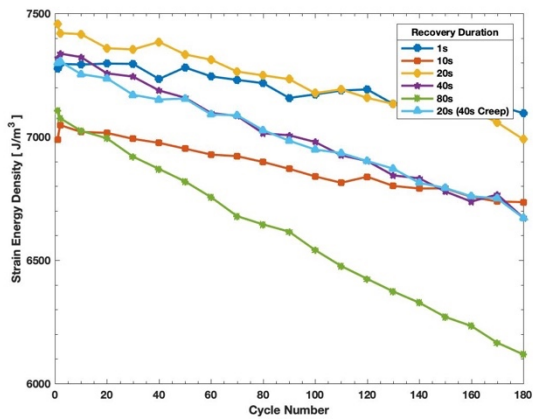


Figure 4-73: 12.5 MPa Continuous - 120 °C - Stored Strain Energy Density (Unloading)

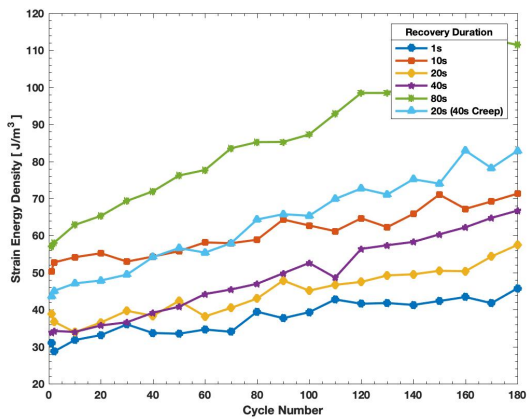


Figure 4-74: 12.5 MPa Continuous - 120 °C - Stored Strain Energy Density (Recovery)

Table 4-LXIV: Recovery Duration - 8 MPa - Room Temperature - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3577.69	3410.58	-167.11	14.65	10.15	-4.50	3592.34	3420.74	-171.60
20	10	RT	3390.12	3129.58	-260.54	8.20	33.95	25.74	3398.32	3163.53	-234.80
20	20	RT	3545.68	3188.17	-357.51	9.91	44.34	34.43	3555.59	3232.51	-323.09
20	40	RT	3376.58	2872.79	-503.79	17.91	57.21	39.30	3394.49	2930.00	-464.49
20	80	RT	3296.04	2515.51	-780.53	21.14	73.18	52.04	3317.17	2588.69	-728.48
40	20	RT	3338.22	2845.23	-492.99	16.53	56.81	40.28	3354.75	2902.05	-452.70

Table 4-LXV: Recovery Duration - 8 MPa - 80 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	3505.31	3324.94	-180.37	9.86	8.95	-0.91	3515.17	3333.89	-181.28
20	10	80	3153.67	2937.00	-216.68	29.97	29.43	-0.54	3183.64	2966.42	-217.22
20	20	80	3339.41	3017.88	-321.53	13.78	47.40	33.61	3353.20	3065.28	-287.92
20	40	80	3326.31	2845.01	-481.30	23.81	62.39	38.57	3350.13	2907.40	-442.73
20	80	80	3185.74	2473.56	-712.18	45.08	59.17	14.09	3230.82	2532.73	-698.09
40	20	80	3475.49	2989.64	-485.84	15.35	59.96	44.61	3490.84	3049.60	-441.23

Table 4-LXVI: Recovery Duration - 8 MPa - 120 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	3445.10	3273.29	-171.82	6.79	31.17	24.38	3451.89	3304.45	-147.44
20	10	120	3269.99	3031.13	-238.86	47.86	42.71	-5.16	3317.85	3073.84	-244.01
20	20	120	3514.46	3211.51	-302.95	37.41	35.12	-2.30	3551.87	3246.62	-305.25
20	40	120	3379.36	2917.99	-461.37	24.34	68.09	43.76	3403.70	2986.08	-417.62
20	80	120	3438.72	2719.92	-718.80	31.39	47.27	15.89	3470.11	2767.19	-702.91
40	20	120	3310.41	2850.75	-459.66	44.13	49.83	5.70	3354.54	2900.58	-453.95

Table 4-LXVII: Recovery Duration - 8 MPa - 180 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	3369.67	3180.73	-188.94	26.01	55.92	29.91	3395.67	3236.65	-159.02
20	10	180	3353.44	3102.66	-250.78	31.41	62.39	30.98	3384.85	3165.05	-219.80
20	20	180	3448.00	3139.26	-308.74	41.62	74.55	32.93	3489.62	3213.81	-275.81
20	40	180	3555.57	3043.01	-512.56	28.00	75.43	47.43	3583.57	3118.43	-465.13
20	80	180	3386.23	2616.04	-770.19	37.89	101.56	63.67	3424.13	2717.61	-706.52
40	20	180	3722.88	3273.34	-449.54	19.44	59.72	40.27	3742.32	3333.06	-409.27

Table 4-LXVIII: Recovery Duration - 12.5 MPa Non-Continuous - Room Temperature - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6629.45	6469.29	-160.16	17.71	20.01	2.30	6647.17	6489.31	-157.86
20	10	RT	6368.59	6125.22	-243.37	26.02	30.43	4.41	6394.60	6155.65	-238.96
20	20	RT	6787.87	6337.17	-450.70	13.70	60.39	46.69	6801.57	6397.56	-404.01
20	40	RT	7020.26	6814.74	-205.52	17.86	22.47	4.61	7038.12	6837.22	-200.91
20	80	RT	6969.81	5923.12	-1046.69	11.76	56.09	44.33	6981.58	5979.21	-1002.37
40	20	RT	6257.15	5753.35	-503.80	54.96	73.47	18.51	6312.11	5826.82	-485.29

Table 4-LXIX: Recovery Duration - 12.5 MPa Non-Continuous - 80 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	20	80	7765.86	7161.89	-603.97	21.30	78.64	57.33	7787.16	7240.52	-546.64
20	40	80	7873.83	7007.00	-866.83	25.16	116.33	91.17	7898.98	7123.33	-775.66
20	80	80	7652.01	6414.56	-1237.44	9.44	86.80	77.35	7661.45	6501.36	-1160.09
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-LXX: Recovery Duration - 12.5 MPa Non-Continuous - 120 °C - Stores Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	7157.02	6932.78	-224.24	16.46	54.65	38.18	7173.48	6987.42	-186.06
20	10	120	6961.51	6714.30	-247.21	49.11	55.17	6.05	7010.62	6769.47	-241.15
20	20	120	8192.38	7322.51	-869.87	38.19	81.56	43.37	8230.57	7404.07	-826.51
20	40	120	8195.99	7665.26	-530.73	29.54	52.67	23.13	8225.53	7717.93	-507.60
20	80	120	8349.82	7012.45	-1337.37	30.57	94.03	63.46	8380.39	7106.48	-1273.91
40	20	120	7317.93	6762.38	-555.55	34.01	53.24	19.22	7351.95	6815.61	-536.33

Table 4-LXXI: Recovery Duration - 12.5 MPa Non-Continuous - 180 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	7751.35	7478.61	-272.74	17.10	61.29	44.19	7768.45	7539.90	-228.55
20	10	180	7820.30	7414.74	-405.56	33.11	76.20	43.09	7853.41	7490.94	-362.47
20	20	180	8479.60	7901.57	-578.02	47.92	98.99	51.07	8527.52	8000.56	-526.95
20	40	180	8096.87	7422.15	-674.73	37.71	95.79	58.08	8134.59	7517.94	-616.64
20	80	180	7982.88	6855.01	-1127.88	36.63	121.49	84.86	8019.51	6976.49	-1043.01
40	20	180	7695.78	7004.28	-691.49	40.95	107.52	66.57	7736.73	7111.81	-624.92

Table 4-LXXII: Recovery Duration - 12.5 MPa Continuous - Room Temperature - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	7012.63	6801.91	-210.73	14.40	26.77	12.37	7027.03	6828.67	-198.36
20	10	RT	6741.82	6422.23	-319.59	50.99	71.37	20.38	6792.81	6493.60	-299.20
20	20	RT	7043.85	6641.49	-402.36	27.55	51.04	23.49	7071.40	6692.53	-378.87
20	40	RT	7060.77	6450.56	-610.21	29.69	64.26	34.58	7090.46	6514.82	-575.64
20	80	RT	6937.14	5988.54	-948.59	29.58	84.93	55.35	6966.72	6073.47	-893.25
40	20	RT	6759.81	6170.80	-589.02	64.63	102.08	37.45	6824.44	6272.88	-551.56

Table 4-LXXIII: Recovery Duration - 12.5 MPa Continuous - 80 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	7104.54	6893.50	-211.04	26.27	37.50	11.22	7130.82	6931.00	-199.82
20	10	80	7177.32	6875.33	-301.99	64.29	83.47	19.18	7241.62	6958.80	-282.81
20	20	80	7516.25	7092.79	-423.46	54.55	76.80	22.26	7570.80	7169.59	-401.20
20	40	80	7149.42	6534.05	-615.37	64.72	94.46	29.74	7214.14	6628.51	-585.63
20	80	80	7128.56	6129.77	-998.79	53.92	108.56	54.64	7182.48	6238.33	-944.15
40	20	80	7322.35	6722.74	-599.60	52.38	90.81	38.44	7374.72	6813.56	-561.17

Table 4-LXXIV: Recovery Duration - 12.5 MPa Continuous - 120 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	7295.73	7095.57	-200.16	28.68	45.74	17.06	7324.41	7141.30	-183.10
20	10	120	7047.57	6735.03	-312.53	52.73	71.29	18.56	7100.30	6806.32	-293.97
20	20	120	7420.30	6989.72	-430.58	36.75	57.46	20.71	7457.05	7047.18	-409.87
20	40	120	7337.21	6671.90	-665.31	34.22	66.72	32.50	7371.43	6738.62	-632.81
20	80	120	7075.14	6117.95	-957.19	58.04	111.48	53.44	7133.18	6229.43	-903.75
40	20	120	7305.44	6671.30	-634.14	45.05	82.88	37.82	7350.50	6754.17	-596.32

Table 4-LXXV: Recovery Duration - 12.5 MPa Continuous - 180 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	7851.57	7655.44	-196.14	27.51	42.87	15.36	7879.09	7698.31	-180.78
20	10	180	7599.48	7335.89	-263.59	48.25	70.30	22.05	7647.73	7406.19	-241.54
20	20	180	7923.81	7505.05	-418.76	83.32	116.46	33.13	8007.13	7621.51	-385.63
20	40	180	7881.02	7234.19	-646.83	79.32	122.81	43.49	7960.34	7357.00	-603.34
20	80	180	7488.67	6518.85	-969.81	57.53	117.25	59.72	7546.20	6636.11	-910.09
40	20	180	7544.92	6973.56	-571.36	71.70	109.96	38.26	7616.62	7083.52	-533.10

4.3 Effect of Temperature

The next parameter evaluated was the effect that the service temperature had on the response of the material when subjected to cyclic creep loading. Similar to the previous section, presented first will be the changes in the strain response, followed by the changes in the instantaneous moduli. Lastly, the effect that the temperature has on the strain energy density will be presented.

The data presented is the same as the previous section, however it has been sorted based on the service temperature at a given recovery duration for an individual loading condition. As with the preceding section, sample plots have been included for demonstrative purposes. The plots included in this section are of the variation in the 12.5 MPa continuous loading with change in temperature. For additional plots pertaining to the other loading conditions variation with temperature, see Appendix B.

4.3.1 Strain Response

4.3.1.1 *Creep / Recovered Strain*

As with the previous section, presented first is the variation in the creep and recovered strain response of the material with changes in the service temperature. Presented first will be the results for the 8 / 0.1 MPa cyclic loadings, followed by the discontinuous 12.5 / 0.5 MPa loading, and lastly the 12.5 / 0.5 MPa continuous loading. For each applied load, the data is sorted based on increasing recovery duration and concludes with the 40s creep / 20s recovery test. Table 4-LXXVI through Table 4-XCIII present the variation of the creep and recovered strain response for a given recovery duration and applied load, and Figure 4-75 through Figure 4-98 provide a demonstrative visual representation of the data.

Evaluating the change in the creep strain with changes in temperature, for the initial and the final cycles there is an increase in the strain response as the temperature increases. Evaluating the correlation coefficient, the initial cycle showed fairly strong correlation, however, for the final cycle the calculated values indicates a relatively weak trend. An increasing trend for the creep strain with increase in the temperature is an expected result. As previously identified, as creep is a viscoelastic property, as the temperature increases the creep strain will increase. However, when evaluating the difference between the final cycle and the initial cycle, a slight majority of the data sets present a decreasing trend. This decreasing trend would indicate that as the

temperature increases, the change in the creep strain over the course of cyclic loading is smaller than tests performed at lower temperatures. This decreasing trend is only present in 2/3rds of the data sets, and as such, no trends can be concluded based on testing performed. The slope of the trendlines for the difference between the cycles are all fairly similar and close to a value of 0, indicating little change with respect to change in temperature.

Evaluating next the effect of temperature on the amount of strain recovered during the recovery hold, for both the initial and final cycle there is a general increasing trend with increase in temperature. This trend shows the strongest correlation for the discontinuous loading, and is weaker for the two continuous loading scenarios. As with the creep strain, when evaluating the difference between the final and the initial cycle, there is no clear trend with change in the temperature. Similarly, the slope of the line of best fit for the change in the recovered strain is generally relatively close to 0 as well, indicating little variation with change in the temperature.

As with the change in the creep and creep recovered strains, when evaluating the change in the unrecovered creep strain there is an increasing trend with increase in temperature. This trend is stronger for the initial cycle and less prevalent for the final cycle data. For the initial cycle, the data shows generally a strong correlation with the best fit line, with the 8 / 0.1 MPa loading showing weaker trends than the two 12.5 / 0.5 MPa loadings. The final cycle shows generally weaker correlation with the best fit trend line, with the discontinuous loading showing weak to reverse trends. As well, the difference between the final and initial cycle, show no clear trend with respect to change in temperature. Similar to the previously discussed strains, the best fit lines have a slope close to 0 and generally a low correlation coefficient.

Lastly, evaluating the accumulated unrecovered creep strain by the end of testing, there is an increasing trend present in the majority of the data sets. This trend is fairly strong for the two continuous loading scenarios, and weak to reverse for the discontinuous. However, as previously discussed in the discussion of the effect of the recovery duration, half of the data sets indicate positive accumulation of unrecovered creep strain, the other half negative.

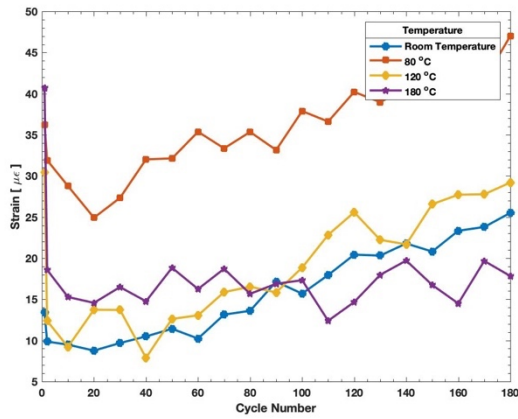


Figure 4-75: 12.5 MPa Continuous - 1s - Creep Strain

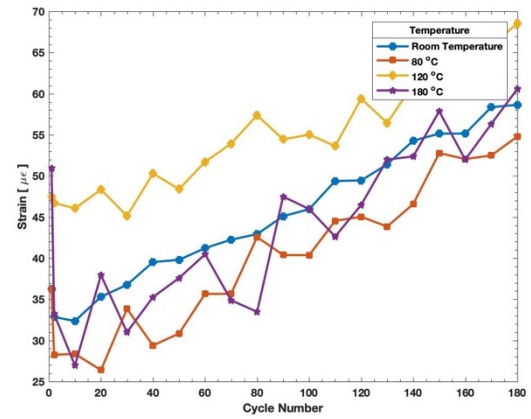


Figure 4-76: 12.5 MPa Continuous - 10s - Creep Strain

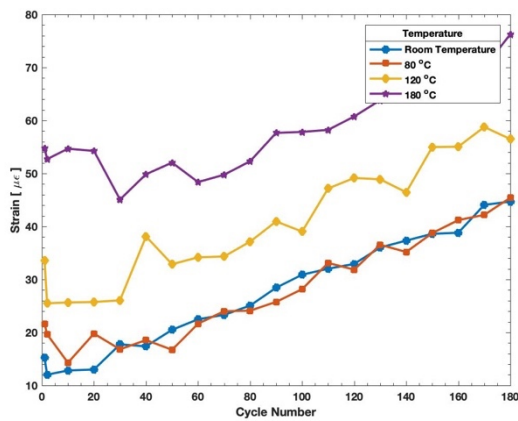


Figure 4-77: 12.5 MPa Continuous - 20s - Creep Strain

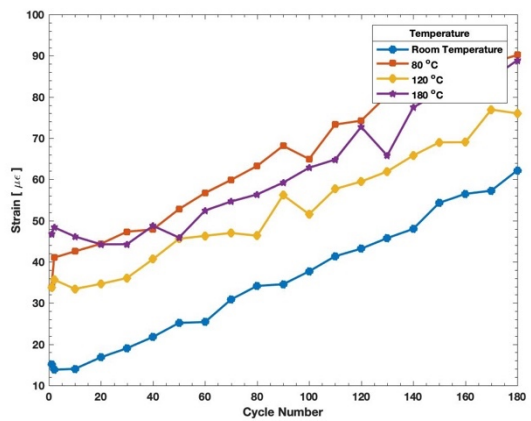


Figure 4-78: 12.5 MPa Continuous - 40s - Creep Strain

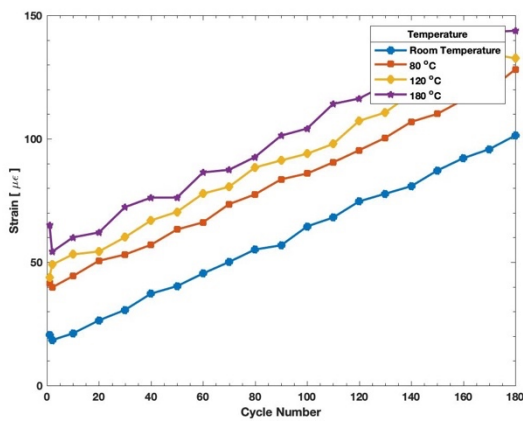


Figure 4-79: 12.5 MPa Continuous - 80s - Creep Strain

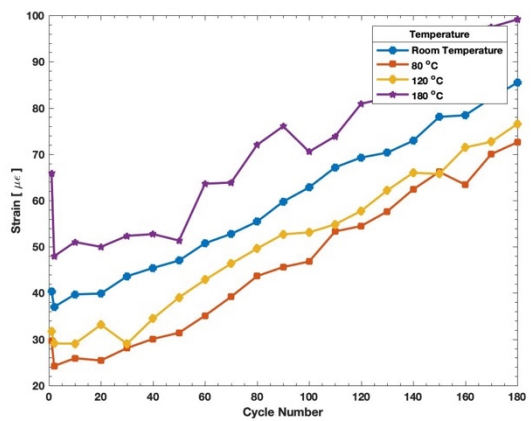


Figure 4-80: 12.5 MPa Continuous - 20s (40s Creep) - Creep Strain

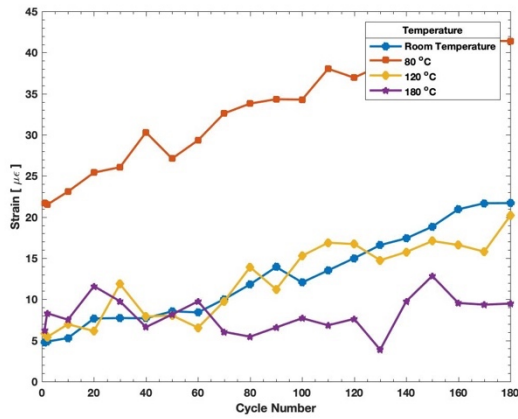


Figure 4-81: 12.5 MPa Continuous - 1s - Recovered Strain

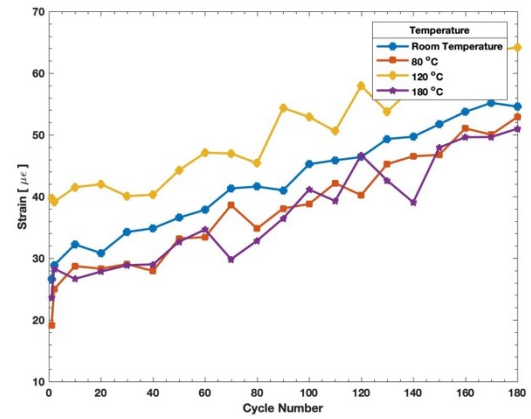


Figure 4-82: 12.5 MPa Continuous - 10s - Recovered Strain

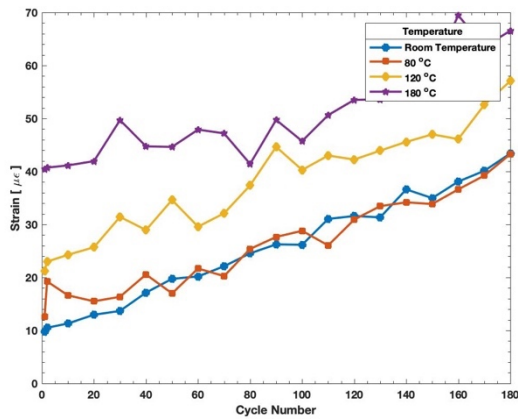


Figure 4-83: 12.5 MPa Continuous - 20s - Recovered Strain

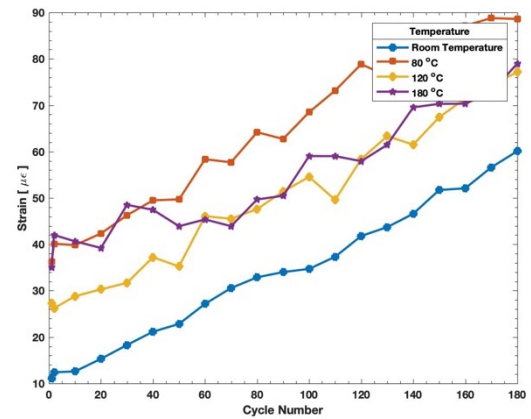


Figure 4-84: 12.5 MPa Continuous - 40s - Recovered Strain

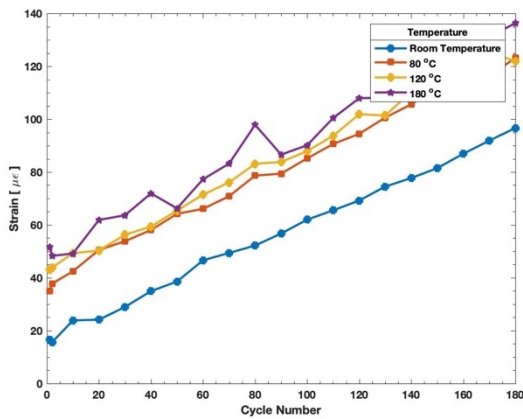


Figure 4-85: 12.5 MPa Continuous - 80s - Recovered Strain

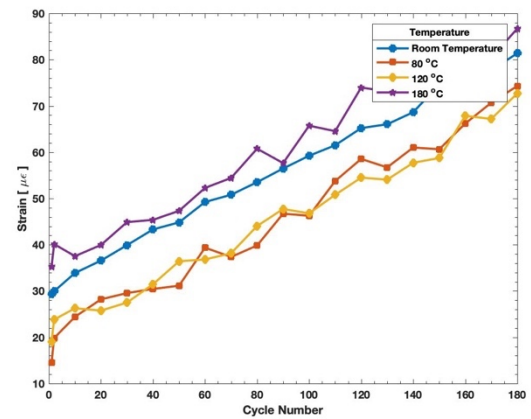


Figure 4-86: 12.5 MPa Continuous - 20s (40s Creep) - Recovered Strain

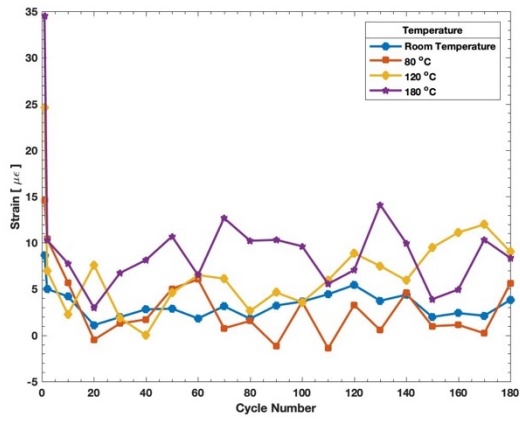


Figure 4-87: 12.5 MPa Continuous - 1s - Unrecovered Creep Strain

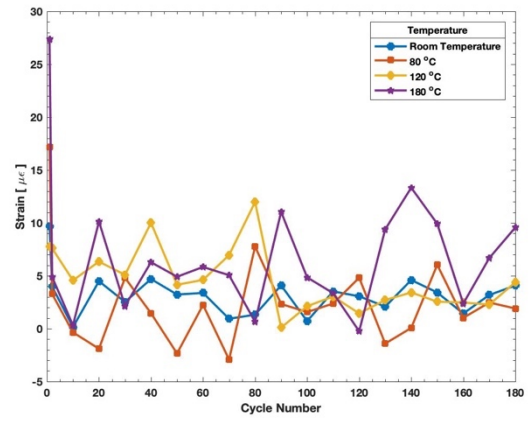


Figure 4-88: 12.5 MPa Continuous - 10s - Unrecovered Creep Strain

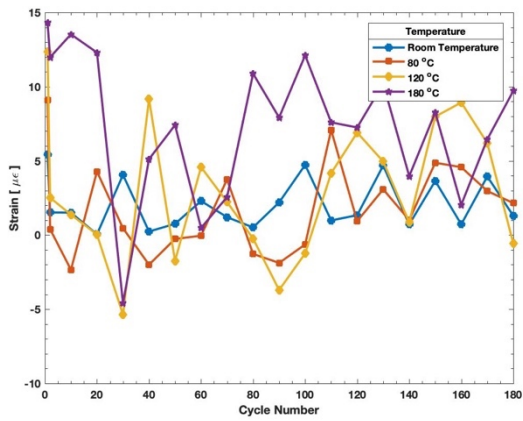


Figure 4-89: 12.5 MPa Continuous - 20s - Unrecovered Creep Strain

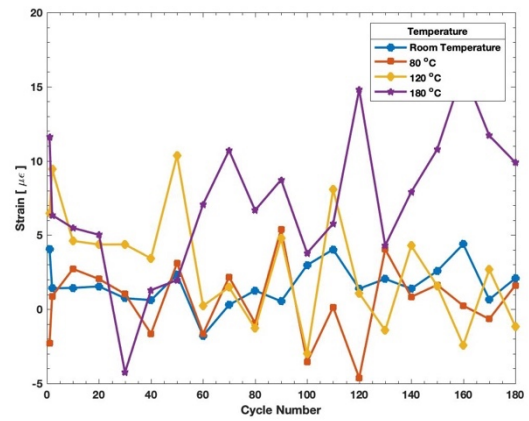


Figure 4-90: 12.5 MPa Continuous - 40s - Unrecovered Creep Strain

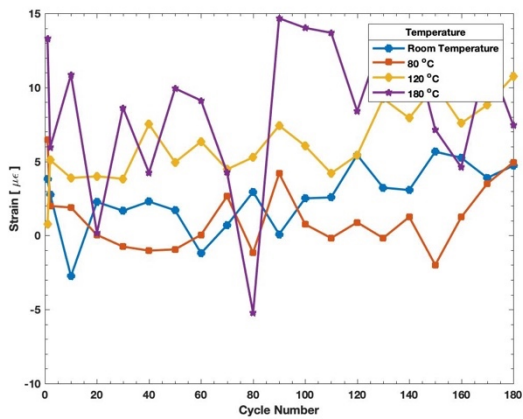


Figure 4-91: 12.5 MPa Continuous - 80s - Unrecovered Creep Strain

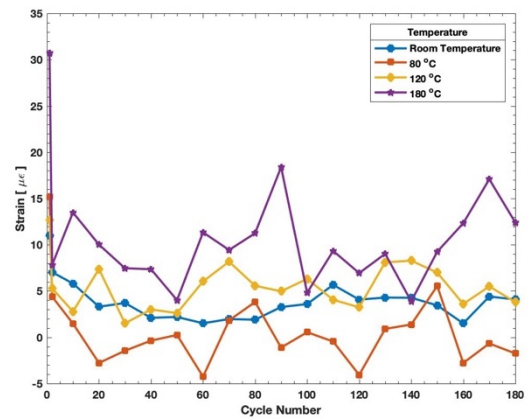


Figure 4-92: 12.5 MPa Continuous - 20s (40s Creep) - Unrecovered Creep Strain

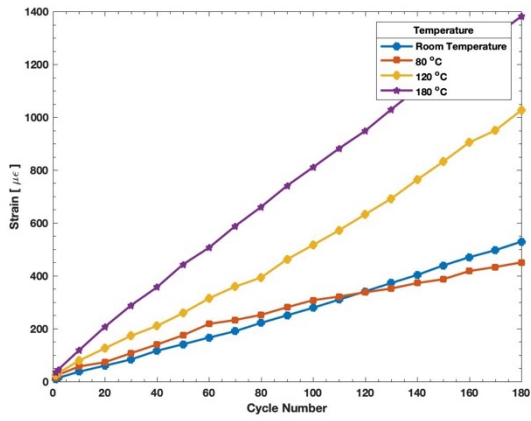


Figure 4-93: 12.5 MPa Continuous - 1s - Accumulated Unrecovered Creep Strain

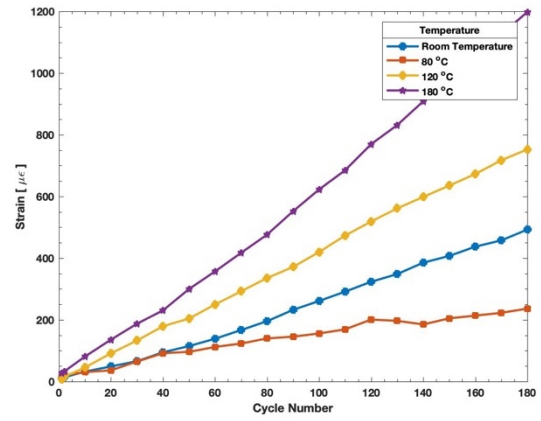


Figure 4-94: 12.5 MPa Continuous - 10s - Accumulated Unrecovered Creep Strain

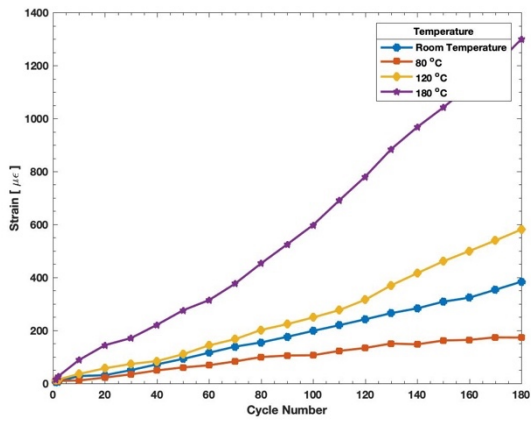


Figure 4-95: 12.5 MPa Continuous - 20s - Accumulated Unrecovered Creep Strain

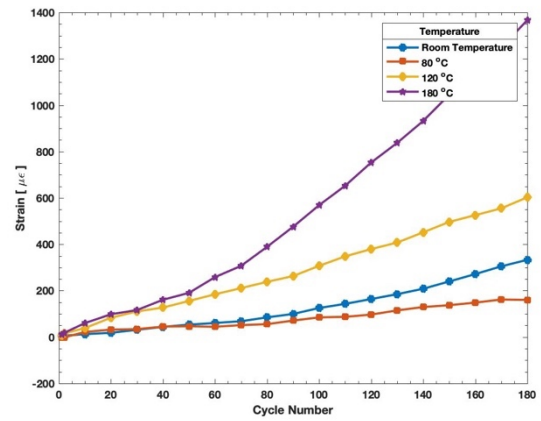


Figure 4-96: 12.5 MPa Continuous - 40s - Accumulated Unrecovered Creep Strain

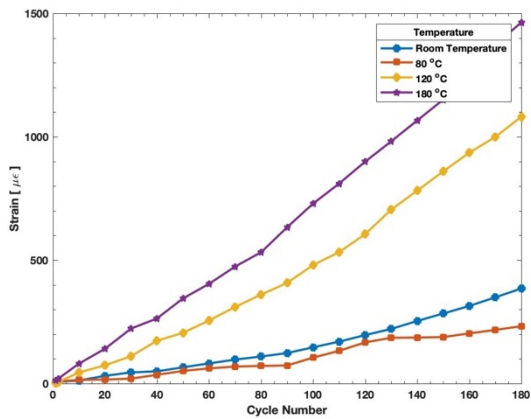


Figure 4-97: 12.5 MPa Continuous - 80s - Accumulated Unrecovered Creep Strain

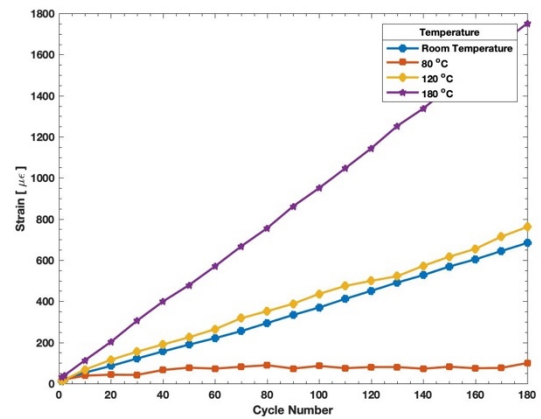


Figure 4-98: 12.5 MPa Continuous - 20s (40s Creep) - Accumulated Unrecovered Creep Strain

Table 4-LXXVI: Temperature - 8 MPa - 1s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	RT	9	6	-2	4	11	7	5	-5	-9	-208
20	1	80	15	16	1	7	14	7	7	2	-5	-570
20	1	120	18	27	9	6	41	35	12	-14	-26	-926
20	1	180	43	42	-1	30	52	22	13	-10	-23	-540

Table 4-LXXVII: Temperature - 8 MPa - 10s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	10	RT	14	42	28	21	58	37	-7	-16	-9	-2015
20	10	80	40	67	27	54	77	23	-15	-10	4	-2198
20	10	120	38	62	23	40	81	42	-1	-19	-18	-2363
20	10	180	44	70	26	47	76	29	-3	-6	-3	-1205

Table 4-LXXVIII: Temperature - 8 MPa - 20s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]										
20	20	RT	12	33	21	13	57	44	-1	-23	-23	-1771
20	20	80	30	60	30	39	83	44	-9	-23	-14	-2377
20	20	120	30	56	26	16	65	49	14	-9	-23	-1875
20	20	180	54	85	31	57	95	39	-3	-11	-8	-1572

Table 4-LXXIX: Temperature - 8 MPa - 40s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	40	RT	19	75	56	33	103	70	-15	-28	-14	-2995
20	40	80	22	76	54	31	104	74	-9	-28	-19	-2792
20	40	120	24	82	58	40	106	66	-16	-24	-9	-2589
20	40	180	40	95	55	35	105	70	5	-10	-15	-1858

Table 4-LXXX: Temperature - 8 MPa - 80s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	RT	26	122	95	41	160	119	-14	-39	-24	-3823
20	80	80	45	142	97	49	157	108	-4	-15	-11	-3409
20	80	120	20	120	99	23	132	109	-2	-13	-10	-2893
20	80	180	51	148	97	52	164	113	0	-16	-16	-1947

Table 4-LXXXI: Temperature - 8 MPa - 40s Creep (20s Recovery) - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
40	20	RT	25	80	54	36	109	73	-10	-30	-19	-2978
40	20	80	16	60	44	16	88	72	0	-28	-28	-2193
40	20	120	31	90	60	33	110	77	-2	-19	-17	-2474
40	20	180	29	47	17	27	59	32	3	-12	-15	-894

Table 4-LXXXII: Temperature - 12.5 MPa Non-Continuous - 1s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	RT	16	10	-6	2	3	1	13	6	-7	660
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	28	35	7	4	21	17	24	14	-10	1986
20	1	180	42	45	4	10	38	28	32	7	-25	1234

Table 4-LXXXIII: Temperature - 12.5 MPa Non-Continuous - 10s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	24	39	15	11	28	17	13	12	-1	2750
20	10	RT	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	52	67	15	25	52	27	27	15	-12	2994
20	10	120	42	58	15	26	59	33	16	-1	-17	587
20	10	180										

Table 4-LXXXIV: Temperature - 12.5 MPa Non-Continuous - 20s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	9	51	42	7	47	40	2	4	2	371
20	20	RT	27	71	44	19	64	45	8	7	-1	295
20	20	80	28	52	24	26	52	26	2	0	-1	-288
20	20	120	76	81	5	47	81	33	29	0	-29	583
20	20	180										

Table 4-LXXXV: Temperature - 12.5 MPa Non-Continuous - 40s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]										
20	40	RT	6	45	39	13	21	7	-8	24	32	1550
20	40	80	28	103	75	27	106	79	1	-3	-4	-639
20	40	120	39	94	55	37	98	61	2	-4	-6	-408
20	40	180	48	87	39	40	81	41	8	6	-2	375

Table 4-LXXXVI: Temperature - 12.5 MPa Non-Continuous - 80s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	8	74	65	8	77	69	0	-3	-3	-226
20	80	RT										
20	80	80	23	125	101	20	126	105	3	-1	-4	-710
20	80	120	38	138	100	34	136	102	5	2	-2	-818
20	80	180	41	128	87	36	122	85	5	6	1	496

Table 4-LXXXVII: Temperature - 12.5 MPa Non-Continuous - 40s Creep (20s Recovery) - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	41	85	44	20	60	40	21	25	5	3418
40	20	RT	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	36	62	26	16	46	30	20	16	-4	2215
40	20	120	53	108	56	35	101	66	18	7	-11	748
40	20	180										

Table 4-LXXXVIII: Temperature - 12.5 MPa Continuous - 1s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	RT	13	26	12	5	22	17	9	4	-5	529
20	1	80	36	47	11	22	41	20	15	6	-9	451
20	1	120	30	29	-1	6	20	14	25	9	-16	1026
20	1	180	41	18	-23	6	9	3	35	8	-26	1381

Table 4-LXXXIX: Temperature - 12.5 MPa Continuous - 10s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	10	RT	36	59	22	27	55	28	10	4	-6	493
20	10	80	36	55	19	19	53	34	17	2	-15	236
20	10	120	47	69	21	40	64	24	8	4	-3	753
20	10	180	51	61	10	24	51	27	27	10	-18	1198

Table 4-XC: Temperature - 12.5 MPa Continuous - 20s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	20	RT	15	45	30	10	43	34	5	1	-4	384
20	20	80	22	45	24	13	43	31	9	2	-7	173
20	20	120	34	56	23	21	57	36	12	-1	-13	581
20	20	180	55	76	21	40	67	26	14	10	-5	1299

Table 4-XCI: Temperature - 12.5 MPa Continuous - 40s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]									
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	15	62	47	11	60	49	4	2	-2	333
20	40	80	34	90	56	36	89	52	-2	2	4	160
20	40	120	34	76	42	27	77	50	6	-1	-8	603
20	40	180	47	89	42	35	79	44	12	10	-2	1367

Table 4-XCII: Temperature - 12.5 MPa Continuous - 80s - Creep / Recovery Strain

			Strain [$\mu\epsilon$]												
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$			
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1				
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	20	80	RT	20	101	81	17	97	80	4	5	1	385
20	80	80	41	128	87	35	123	88	6	5	-2	232			
20	80	120	44	133	89	43	122	79	1	11	10	1081			
20	80	180	65	144	79	52	136	85	13	7	-6	1464			

Table 4-XCIII: Temperature - 12.5 MPa Continuous - 40s Creep (20s Recovery) - Creep / Recovery Strain

			Strain [$\mu\epsilon$]												
			$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$			
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1				
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	40	20	RT	40	85	45	29	81	52	11	4	-7	684
40	20	80	30	73	43	14	74	60	15	-2	-17	100			
40	20	120	32	77	45	19	73	54	13	4	-9	761			
40	20	180	66	99	33	35	87	52	31	12	-18	1752			

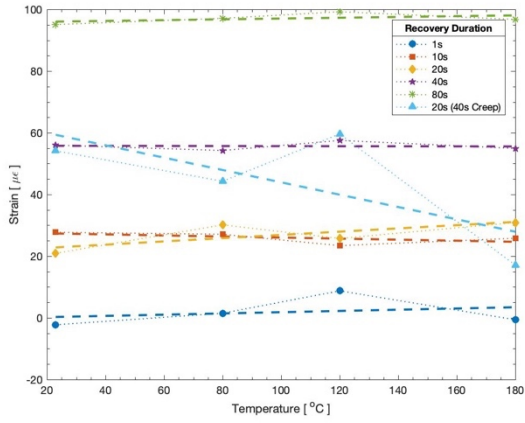


Figure 4-99: Change in Creep Strain from cyclic loading at 8 / 0.1 MPa loading as a function of temperature.

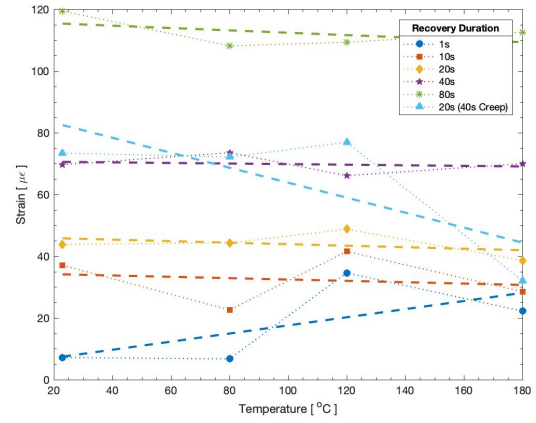


Figure 4-100: Change in Recovered Strain from cyclic loading at 8 / 0.1 MPa loading as a function of temperature.

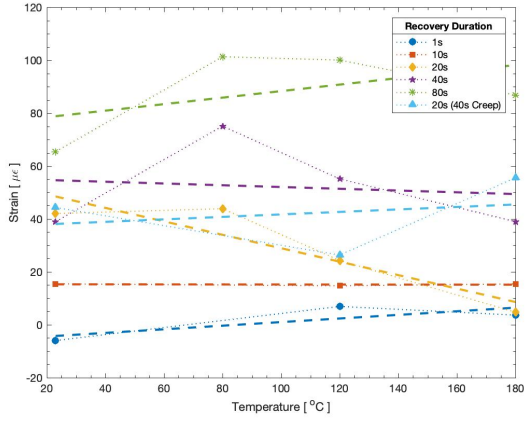


Figure 4-101: Change in Creep Strain from cyclic loading at 12.5 / 0.5 MPa non-continuous loading as a function of temperature.

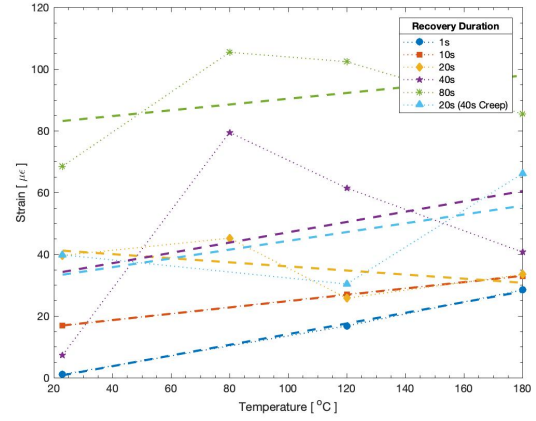


Figure 4-102: Change in Recovered Strain from cyclic loading at 12.5 / 0.5 MPa non-continuous loading as a function of temperature.

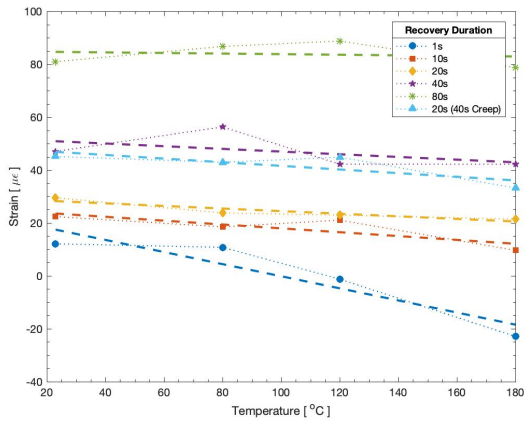


Figure 4-103: Change in Creep Strain from cyclic loading at 12.5 / 0.5 MPa continuous loading as a function of temperature.

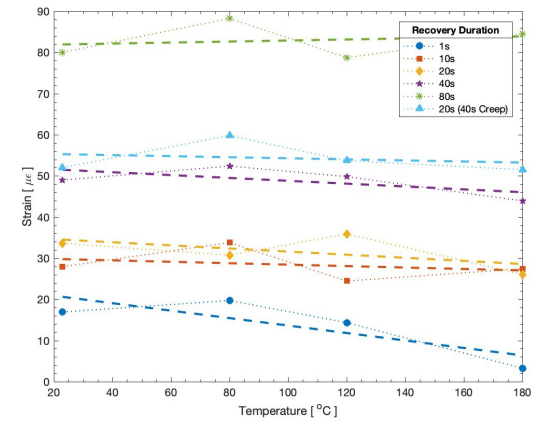


Figure 4-104: Change in Recovered Strain from cyclic loading at 12.5 / 0.5 MPa continuous loading as a function of temperature.

Table 4-XCIV: Tabulation of trendline data for change over cyclic testing in Creep and Recoverd Strain with respect to temperature

Applied Load [MPa]	Recovery Duration [s]	Creep				Recovered			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²
8 / 0.1	1	0.020	-0.182	0.274	0.075	0.132	4.419	0.651	0.423
	10	-0.017	27.735	-0.590	0.348	-0.022	34.626	-0.171	0.029
	20	0.053	21.618	0.758	0.575	-0.025	46.349	-0.392	0.154
	40	-0.001	55.814	-0.062	0.004	-0.009	70.775	-0.205	0.042
	80	0.013	95.758	0.500	0.250	-0.038	116.224	-0.499	0.249
	20 (40s Creep)	-0.200	63.943	-0.700	0.490	-0.243	88.069	-0.759	0.577
12.5 / 0.5	1	0.068	-5.811	0.805	0.648	0.173	-3.207	0.999	0.997
	10	-0.001	15.302	-0.176	0.031	0.102	14.551	1.000	1.000
	20	-0.254	54.329	-0.920	0.846	-0.066	42.669	-0.525	0.275
	40	-0.033	55.384	-0.128	0.016	0.167	30.409	0.357	0.127
	80	0.123	75.991	0.490	0.240	0.094	81.003	0.363	0.132
	20 (40s Creep)	0.047	37.017	0.252	0.064	0.142	30.086	0.608	0.370
12.5 / 0.5 Continuous	1	-0.229	22.726	-0.934	0.872	-0.091	22.695	-0.832	0.692
	10	-0.073	25.227	-0.839	0.704	-0.017	30.176	-0.296	0.088
	20	-0.049	29.365	-0.922	0.850	-0.038	35.383	-0.589	0.347
	40	-0.051	52.049	-0.506	0.256	-0.035	52.279	-0.649	0.421
	80	-0.011	84.908	-0.156	0.024	0.012	81.651	0.189	0.036
	20 (40s Creep)	-0.069	48.450	-0.809	0.654	-0.013	55.571	-0.224	0.050
Averages	8 / 0.1 MPa	-0.022	44.114	0.030	0.290	-0.034	60.077	-0.229	0.246
	12.5 / 0.5 MPa	-0.008	38.702	0.054	0.307	0.102	32.585	0.467	0.484
	12.5 / 0.5 MPa Continuous	-0.080	43.788	-0.694	0.560	-0.030	46.293	-0.400	0.272

4.3.1.2 Unrecovered Strain

Evaluating the unrecovered strain, Table 4-XCV through Table 4-CXII contain the data sorted based on increase in temperature. Figure 4-105 through Figure 4-116 provide visualization of the relationship for the table elements with temperature for the same test conditions as the previous section.

Evaluating the total unrecovered strain with respect to temperature, observed was that as the temperature increased the amount of unrecovered strain experienced by the sample increased. This increase is consistent for the initial and final cycle, along with the difference between the two cycles. Evaluating the correlation between the data and the best fit trendline, the correlation between unrecovered strain and the temperature was weakest for the initial cycle. For the final and the difference between the final and initial, there was a generally very strong correlation between the data and the trendline. This strong correlation indicates that there is indeed a relationship between the total unrecovered strain and temperature. Upon viewing the plotted data for the relationship between unrecovered strain and temperature, it appears that this relationship may in fact be exponential, however fitting of this data to precisely determine the relationship is beyond the scope of the research performed.

When evaluating the calculated unrecovered instantaneous strain, no clear trends were apparent for any of the data sets evaluated. While somewhat unexpected, this matches what was seen visually when the unrecovered instantaneous strains were plotted as a function of cycles. These plots showed large fluctuations in the calculated values cycle to cycle, which would lend credence to the lack of trend in the data sets.

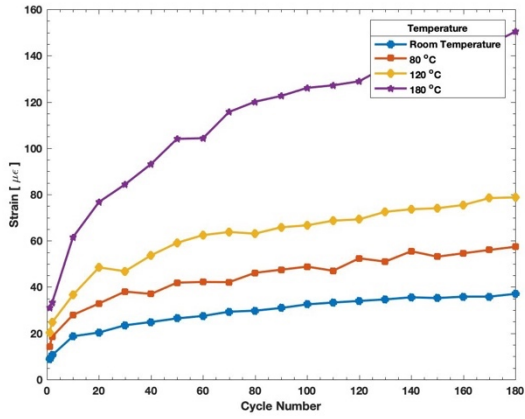


Figure 4-105: 12.5 MPa Continuous - 1s - Total Unrecovered Strain

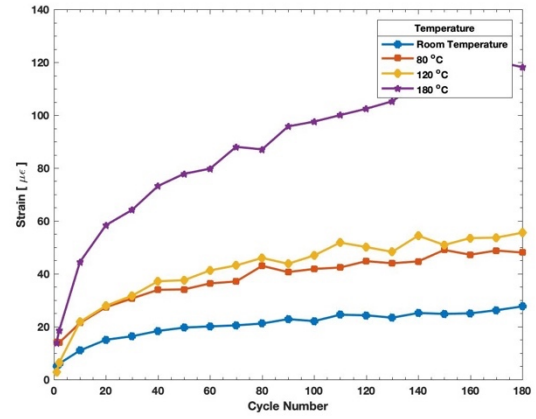


Figure 4-106: 12.5 MPa Continuous - 10s - Total Unrecovered Strain

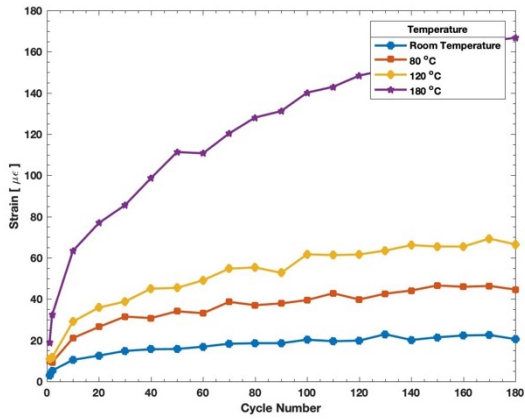


Figure 4-107: 12.5 MPa Continuous - 20s - Total Unrecovered Strain

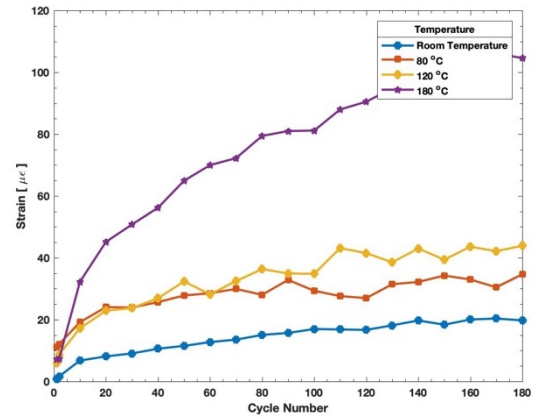


Figure 4-108: 12.5 MPa Continuous - 40s - Total Unrecovered Strain

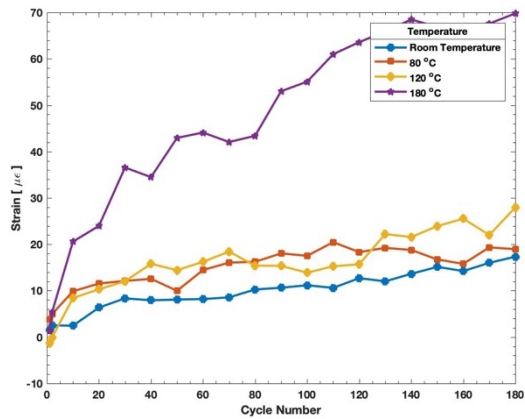


Figure 4-109: 12.5 MPa Continuous - 80s - Total Unrecovered Strain

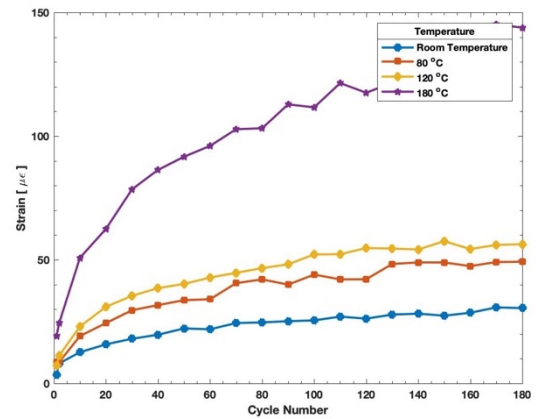


Figure 4-110: 12.5 MPa Continuous - 20s (40s Creep) - Total Unrecovered Strain

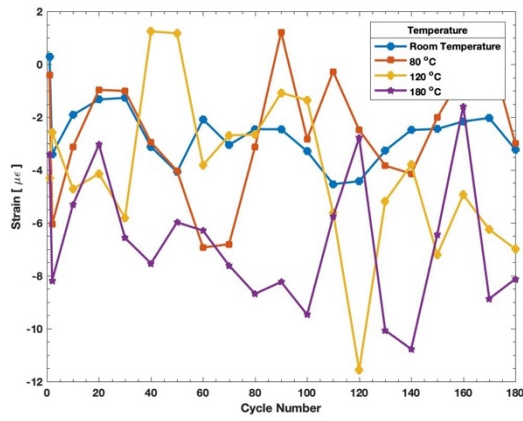


Figure 4-111: 12.5 MPa Continuous - 1s - Cycle Unrecovered Instantaneous

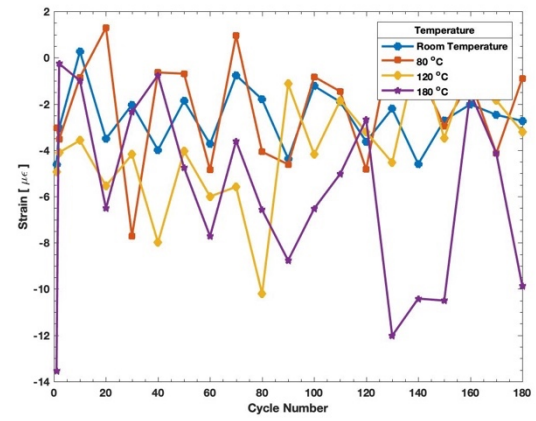


Figure 4-112: 12.5 MPa Continuous - 10s - Cycle Unrecovered Instantaneous

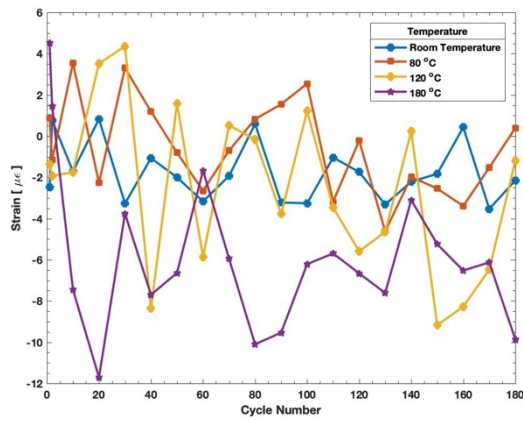


Figure 4-113: 12.5 MPa Continuous - 20s - Cycle Unrecovered Instantaneous

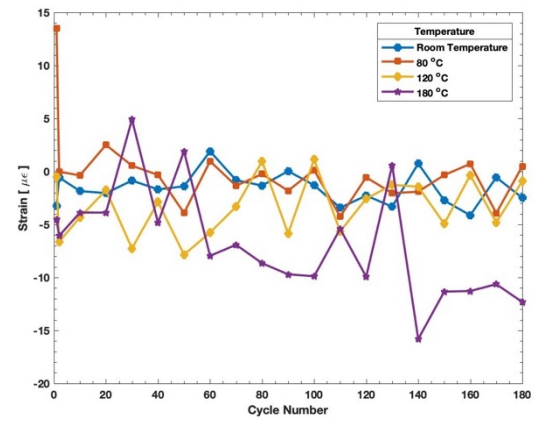


Figure 4-114: 12.5 MPa Continuous - 40s - Cycle Unrecovered Instantaneous

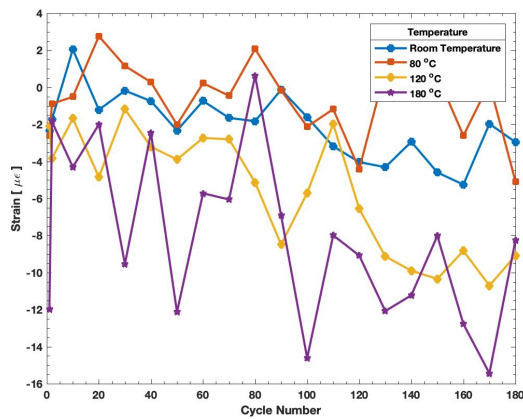


Figure 4-115: 12.5 MPa Continuous - 80s - Cycle Unrecovered Instantaneous

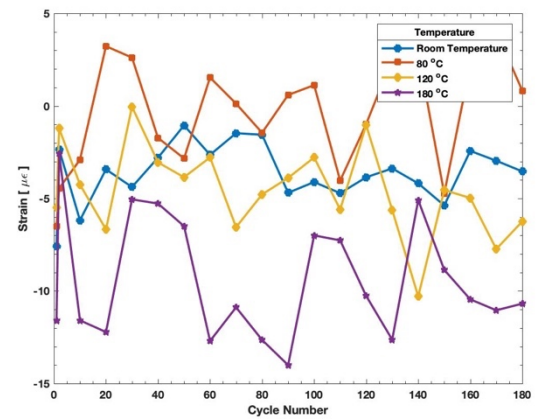


Figure 4-116: 12.5 MPa Continuous - 20s (40s Creep) - Cycle Unrecovered Instantaneous

Table 4-XCV: Temperature - 8 MPa - 1s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	11	33	22	5	-5	-9	6	6	0
20	1	80	11	44	33	7	2	-5	4	-1	-5
20	1	120	16	56	39	12	-14	-26	4	8	4
20	1	180	24	96	73	13	-10	-23	11	10	-1

Table 4-XCVI: Temperature - 8 MPa - 10s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	10	RT	5	20	15	-7	-16	-9	12	16	4
20	10	80	3	27	23	-15	-10	4	18	12	-6
20	10	120	10	41	31	-1	-19	-18	11	12	1
20	10	180	5	79	73	-3	-6	-3	8	6	-3

Table 4-XCVII: Temperature - 8 MPa - 20s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	20	RT	4	19	15	-1	-23	-23	5	24	19
20	20	80	15	38	23	-9	-23	-14	24	17	-6
20	20	120	21	57	36	14	-9	-23	7	10	3
20	20	180	11	90	79	-3	-11	-8	14	13	-1

Table 4-XCVIII: Temperature - 8 MPa - 40s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	40	RT	5	18	14	-15	-28	-14	19	29	10
20	40	80	7	31	24	-9	-28	-19	15	31	15
20	40	120	-1	19	21	-16	-24	-9	14	28	13
20	40	180	9	59	50	5	-10	-15	4	13	9

Table 4-XCIX: Temperature - 8 MPa - 80s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	2	16	13	-14	-39	-24	17	39	22
20	80	80	7	21	14	-4	-15	-11	10	13	2
20	80	120	4	8	4	-2	-13	-10	6	11	5
20	80	180	5	26	21	0	-16	-16	5	19	14

Table 4-C: Temperature - 8 MPa - 40s Creep (20s Recovery) - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
40	20	RT	6	22	16	-10	-30	-19	16	29	12
40	20	80	10	50	41	0	-28	-28	10	27	17
40	20	120	9	49	40	-2	-19	-17	11	16	5
40	20	180	9	86	77	3	-12	-15	7	10	4

Table 4-CI: Temperature - 12.5 Non-Continuous - 1s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	-1	23	24	13	6	-7	-14	-5	9
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	14	73	59	24	14	-10	-10	-13	-3
20	1	180	27	128	101	32	7	-25	-5	-6	-1

Table 4-CII: Temperature - 12.5 Non-Continuous - 10s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	10	RT	-5	17	22	13	12	-1	-18	-11	7
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	120	5	60	55	27	15	-12	-21	-15	6
20	10	180	10	106	96	16	-1	-17	-6	-1	5

Table 4-CIII: Temperature - 12.5 Non-Continuous - 20s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	20	RT	2	6	4	2	4	2	0	-4	-4
20	20	80	7	8	1	8	7	-1	-1	-5	-3
20	20	120	7	38	31	2	0	-1	5	0	-5
20	20	180	25	239	214	29	0	-29	-4	1	4

Table 4-CIV: Temperature - 12.5 Non-Continuous - 40s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	40	RT	-3	6	10	-8	24	32	4	-24	-28
20	40	80	10	37	27	1	-3	-4	9	9	0
20	40	120	7	27	20	2	-4	-6	5	5	0
20	40	180	8	87	78	8	6	-2	1	-5	-6

Table 4-CV: Temperature - 12.5 Non-Continuous - 80s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	5	6	2	0	-3	-3	5	1	-4
20	80	80	3	21	18	3	-1	-4	0	2	2
20	80	120	5	-17	-22	5	2	-2	0	-4	-4
20	80	180	5	61	57	5	6	1	0	-9	-9

Table 4-CVI: Temperature - 12.5 Non-Continuous - 40s Creep (20s Recovery) - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
40	20	RT	-2	25	27	21	25	5	-23	-25	-2
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	120	3	66	63	20	16	-4	-16	-17	0
40	20	180	15	114	99	18	7	-11	-3	-3	0

Table 4-CVII: Temperature - 12.5 Continuous - 1s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	9	37	28	9	4	-5	0	-3	-3
20	1	80	14	57	43	15	6	-9	0	-3	-3
20	1	120	20	79	58	25	9	-16	-4	-7	-3
20	1	180	31	150	119	35	8	-26	-3	-8	-5

Table 4-CVIII: Temperature - 12.5 Continuous - 10s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	10	RT	5	28	23	10	4	-6	-5	-3	2
20	10	80	14	48	34	17	2	-15	-3	-1	2
20	10	120	3	56	53	8	4	-3	-5	-3	2
20	10	180	14	118	104	27	10	-18	-14	-10	4

Table 4-CIX: Temperature - 12.5 Continuous - 20s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	20	RT	3	21	18	5	1	-4	-2	-2	0
20	20	80	10	45	35	9	2	-7	1	0	-1
20	20	120	11	67	56	12	-1	-13	-1	-1	0
20	20	180	19	167	148	14	10	-5	5	-10	-14

Table 4-CX: Temperature - 12.5 Continuous - 40s - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	40	RT	1	20	19	4	2	-2	-3	-2	1
20	40	80	11	35	23	-2	2	4	14	0	-13
20	40	120	6	44	38	6	-1	-8	-1	-1	0
20	40	180	7	105	97	12	10	-2	-5	-12	-8

Table 4-CXI: Temperature - 12.5 Continuous - 80s - Unrecovered Strain

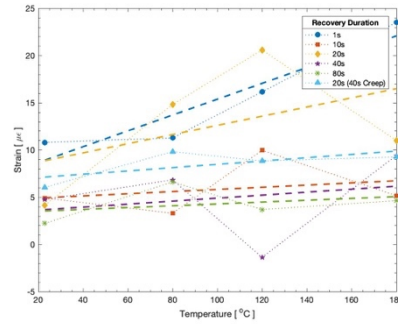
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	1	17	16	4	5	1	-2	-3	-1
20	80	80	4	19	15	6	5	-2	-3	-5	-2
20	80	120	-1	28	29	1	11	10	-2	-9	-7
20	80	180	1	70	68	13	7	-6	-12	-8	4

Table 4-CXII: Temperature - 12.5 Continuous – 40s Creep (20s Recovery) - Unrecovered Strain

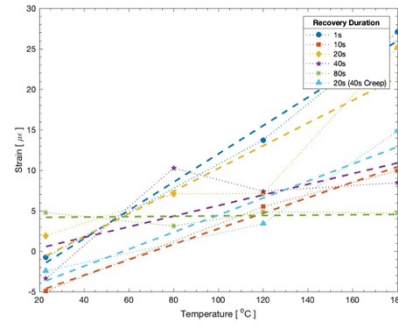
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain [$\mu\epsilon$]								
			ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
			Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
40	20	RT	3	30	27	11	4	-7	-8	-4	4
40	20	80	9	49	41	15	-2	-17	-6	1	7
40	20	120	7	56	49	13	4	-9	-5	-6	-1
40	20	180	19	144	125	31	12	-18	-12	-11	1

Table 4-CXIII: Tabulation of trendline data for Unrecovered Strain with respect to temperature

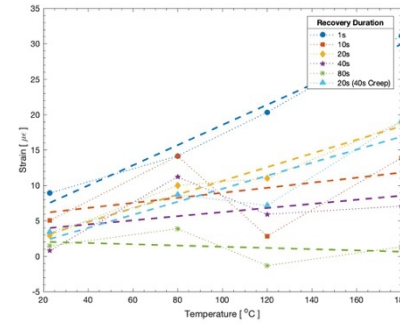
Applied Load [MPa]	Recovery Duration [s]	Cycle 1				Cycle 180				Cycle 180 - 1			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²
8 / 0.1	1	0.084	6.985	0.940	0.883	0.398	16.978	0.955	0.912	0.315	9.993	0.954	0.909
	10	0.011	4.674	0.263	0.069	0.377	3.477	0.948	0.898	0.366	-1.198	0.927	0.860
	20	0.049	7.746	0.466	0.217	0.455	5.220	0.992	0.984	0.406	-2.525	0.939	0.882
	40	0.016	3.312	0.228	0.052	0.229	8.851	0.792	0.627	0.213	5.539	0.889	0.790
	80	0.010	3.314	0.349	0.122	0.041	13.406	0.360	0.129	0.032	10.092	0.302	0.091
	20 (40s Creep)	0.018	6.724	0.690	0.477	0.383	13.441	0.961	0.924	0.366	6.717	0.961	0.923
12.5 / 0.5	1	0.174	-5.438	0.994	0.988	0.650	4.593	0.986	0.972	0.476	10.031	0.982	0.965
	10	0.096	-6.815	0.996	0.991	0.553	1.520	0.988	0.977	0.458	8.335	0.980	0.959
	20	0.140	-3.794	0.908	0.824	1.452	-73.614	0.859	0.739	1.312	-69.820	0.853	0.727
	40	0.066	-0.940	0.706	0.498	0.468	-7.962	0.906	0.821	0.402	-7.023	0.869	0.755
	80	0.002	4.114	0.183	0.033	0.274	-9.717	0.548	0.301	0.272	-13.831	0.542	0.293
	20 (40s Creep)	0.105	-6.085	0.949	0.901	0.555	8.464	0.985	0.970	0.449	14.549	0.990	0.981
12.5 C / 0.5	1	0.143	4.267	0.988	0.975	0.714	9.003	0.956	0.914	0.571	4.736	0.945	0.893
	10	0.036	5.384	0.400	0.160	0.555	6.406	0.941	0.885	0.520	1.022	0.951	0.904
	20	0.097	0.954	0.982	0.965	0.913	-17.337	0.939	0.882	0.816	-18.291	0.928	0.862
	40	0.029	3.318	0.447	0.199	0.524	-2.080	0.930	0.866	0.495	-5.398	0.903	0.815
	80	-0.009	2.211	-0.271	0.074	0.330	0.282	0.885	0.784	0.339	-1.929	0.893	0.798
	20 (40s Creep)	0.092	0.317	0.905	0.820	0.693	0.133	0.908	0.825	0.601	-0.184	0.906	0.821
Averages	8 / 0.1 MPa	0.031	5.459	0.489	0.303	0.314	10.229	0.835	0.746	0.283	4.770	0.829	0.743
	12.5 / 0.5 MPa	0.097	-3.159	0.789	0.706	0.659	-12.786	0.879	0.797	0.561	-9.627	0.869	0.780
	12.5 / 0.5 MPa Continuous	0.065	2.742	0.575	0.532	0.621	-0.599	0.927	0.859	0.557	-3.341	0.921	0.849



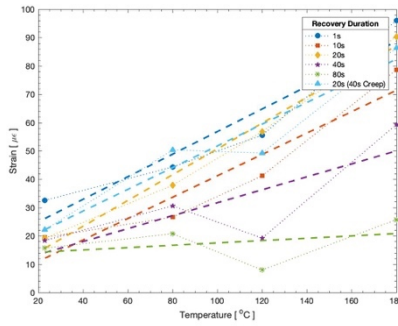
a)



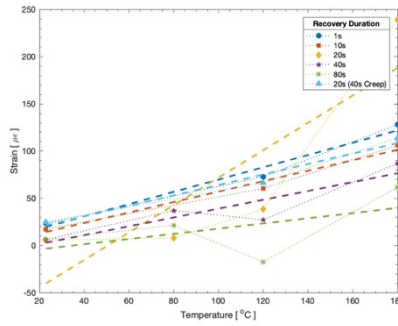
b)



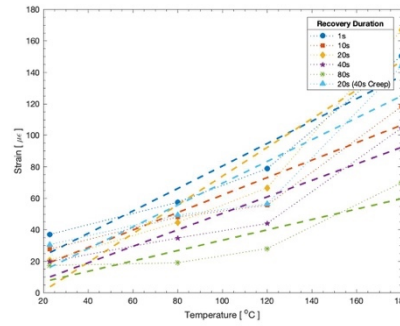
c)



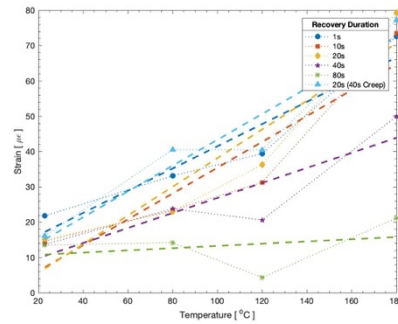
d)



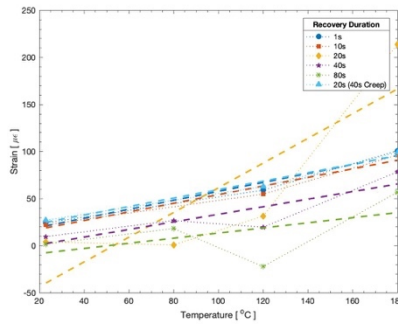
e)



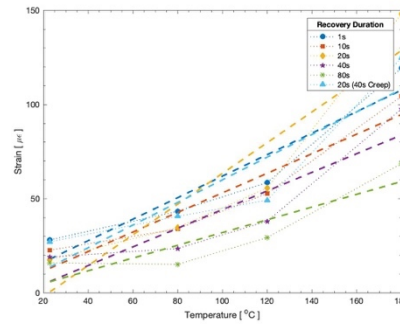
f)



g)



h)



i)

Figure 4-117: Unrecovered Strain plotted as a function of temperature; a) through c) show the Unrecovered Strain for the 1st cycle at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. d) through f) show the final cycle strain for 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. g) through i) show cyclic change at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively

4.3.2 Modulus

Sorting the collected modulus data based upon the loading and hold duration in a similar manner as the preceding sections, Table 4-CXIV through Table 4-CXXXI present the variation in the calculated moduli with change in temperature. Figure 4-118 through Figure 4-135 present modulus versus cycle number data for the previously identified data set.

First evaluating the instantaneous modulus calculated using the loading segment, observed for the initial and final cycles there was a decreasing trend as the temperature increased. This decreasing trend is strongest for the two 12.5 / 0.5 MPa loading conditions, and weakest for the 8 / 0.1 MPa. No trend was observed for the instantaneous modulus for the difference between the final and initial cycle.

Similar trends were observed for the unloading modulus as the loading modulus. For the 2nd and 180th cycle, there is a decreasing trend as the temperature increases. As with the loading modulus, this trend shows strongest correlation to the best fit line for the two 12.5 / 0.5 MPa tests, and weak correlation for the 8 / 0.1 MPa testing. Similarly, there is no clear trend in the difference between the final and initial cycles.

This decreasing trend in the calculated modulus for both the loading and unloading segments with increase in temperature is consistent with what has been noted in literature. It has been well documented that as the service temperature increases the instantaneous modulus decreases. However, with respect to the lack of trend in the difference between the final and initial cycles, this indicates that the change in the moduli over the course of the cyclic testing was not influenced by the temperature.

Evaluating the difference between the loading and unloading modulus, there is a slight increasing trend as the temperature increases. This relationship is present for the majority of the tests, however is most prevalent for the two continuous testing conditions. When evaluating the strength of the correlation, the coefficient of determination and correlation coefficient indicate a weak relationship.

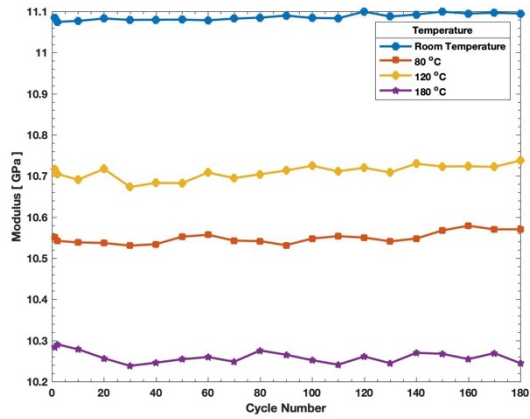


Figure 4-118: 12.5 MPa Continuous - 1s - Instantaneous Modulus (Loading)

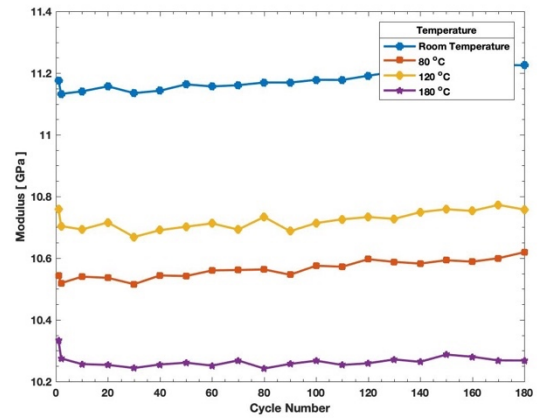


Figure 4-119: 12.5 MPa Continuous - 10s - Instantaneous Modulus (Loading)

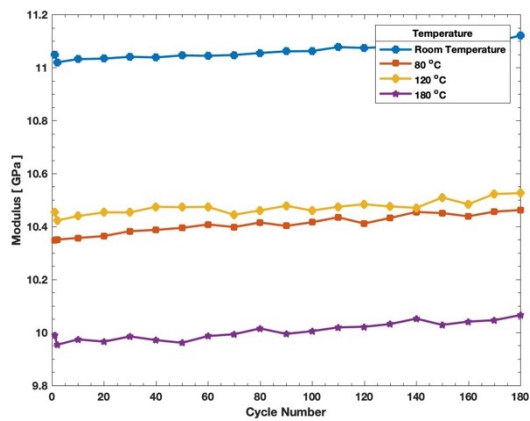


Figure 4-120: 12.5 MPa Continuous - 20s - Instantaneous Modulus (Loading)

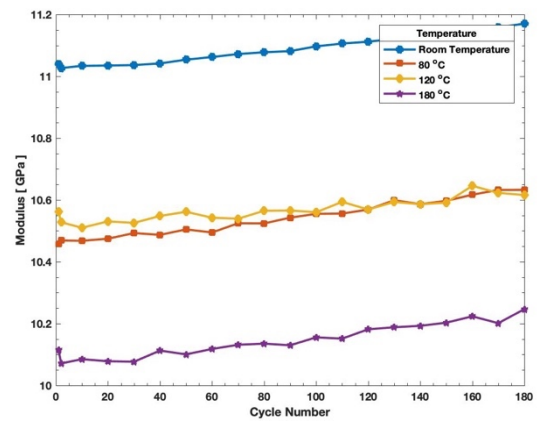


Figure 4-121: 12.5 MPa Continuous - 40s - Instantaneous Modulus (Loading)

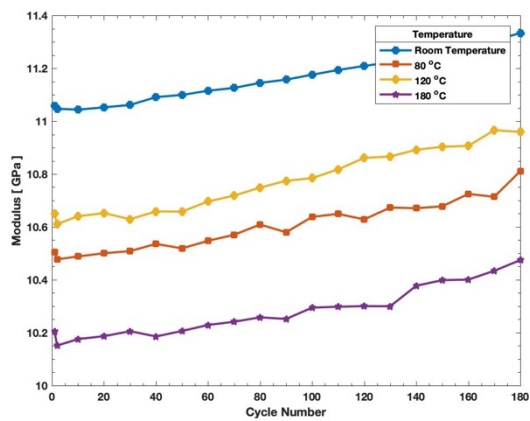


Figure 4-122: 12.5 MPa Continuous - 80s - Instantaneous Modulus (Loading)

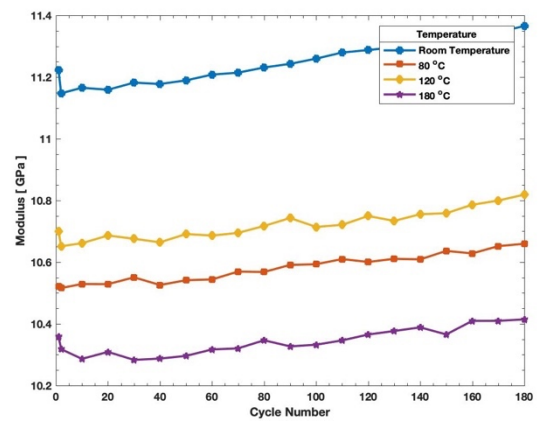


Figure 4-123: 12.5 MPa Continuous - 20s (40s Creep) - Instantaneous Modulus (Loading)

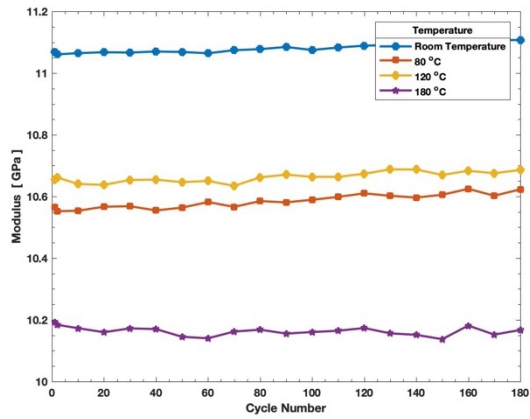


Figure 4-124: 12.5 MPa Continuous - 1s - Instantaneous Modulus (Unloading)

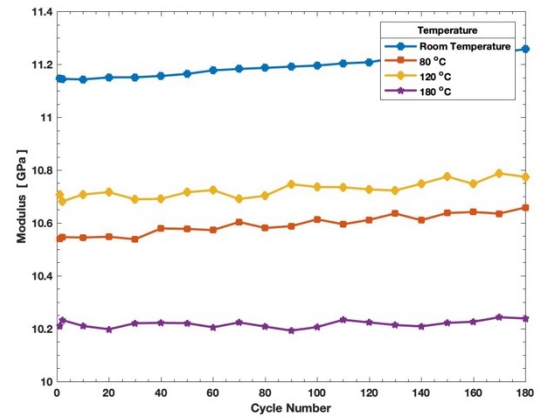


Figure 4-125: 12.5 MPa Continuous - 10s - Instantaneous Modulus (Unloading)

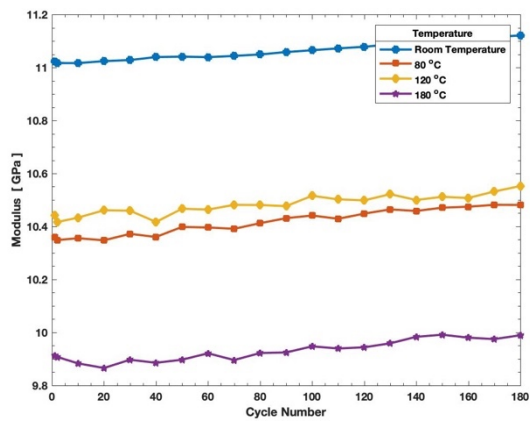


Figure 4-126: 12.5 MPa Continuous - 20s - Instantaneous Modulus (Unloading)

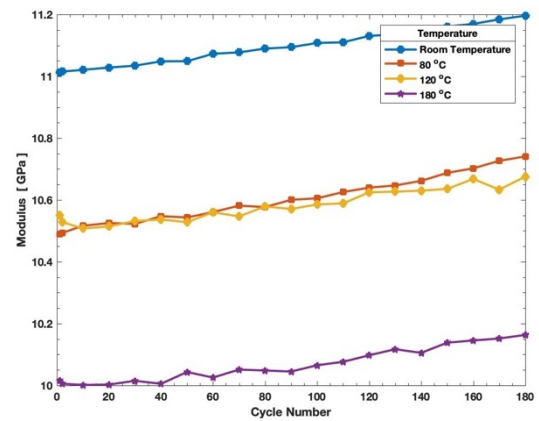


Figure 4-127: 12.5 MPa Continuous - 40s - Instantaneous Modulus (Unloading)

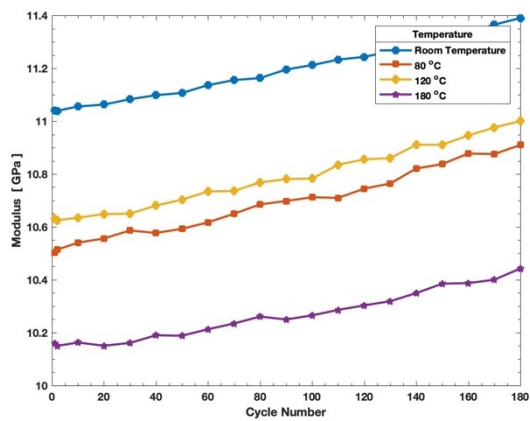


Figure 4-128: 12.5 MPa Continuous - 80s - Instantaneous Modulus (Unloading)

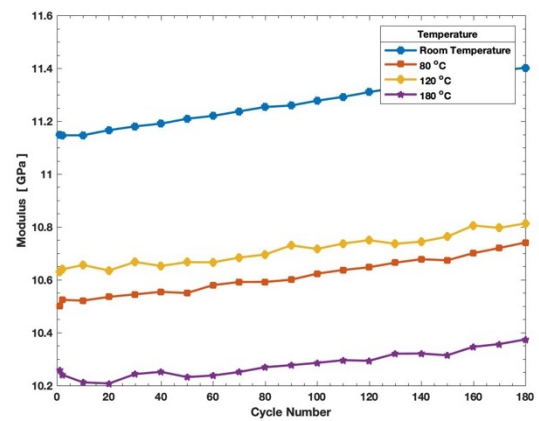


Figure 4-129: 12.5 MPa Continuous - 20s (40s Creep) - Instantaneous Modulus (Unloading)

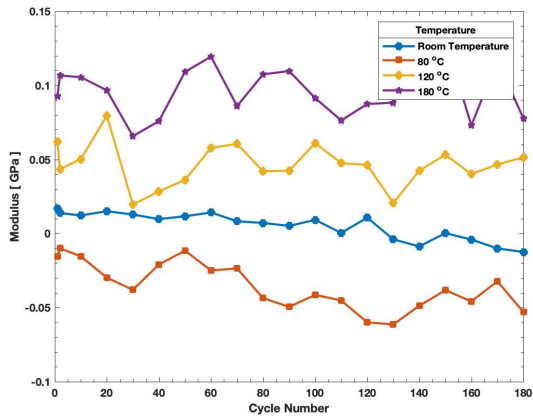


Figure 4-130: 12.5 MPa Continuous - 1s - Instantaneous Modulus (Difference)

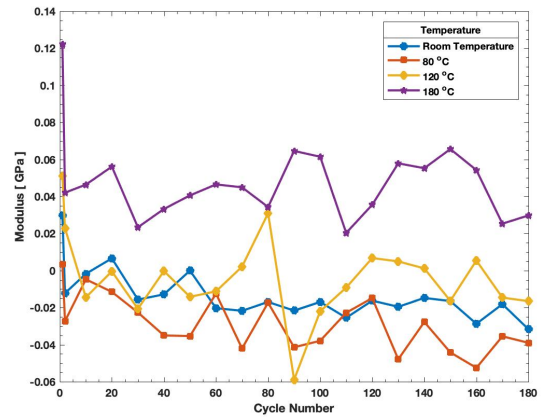


Figure 4-131: 12.5 MPa Continuous - 10s - Instantaneous Modulus (Difference)

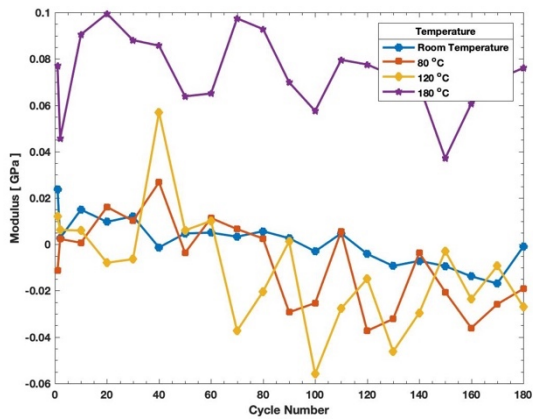


Figure 4-132: 12.5 MPa Continuous - 20s - Instantaneous Modulus (Difference)

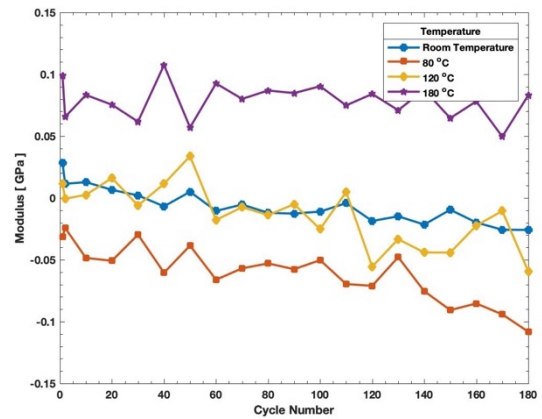


Figure 4-133: 12.5 MPa Continuous - 40s - Instantaneous Modulus (Difference)

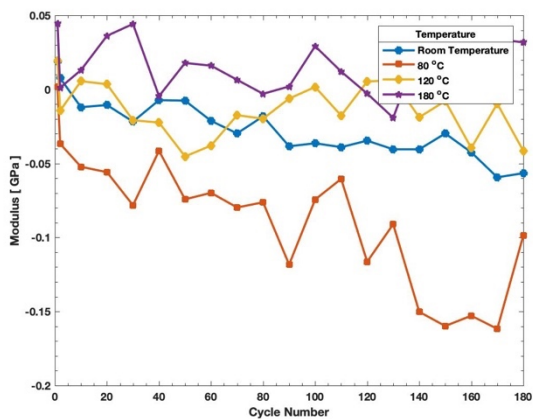


Figure 4-134: 12.5 MPa Continuous - 80s - Instantaneous Modulus (Difference)

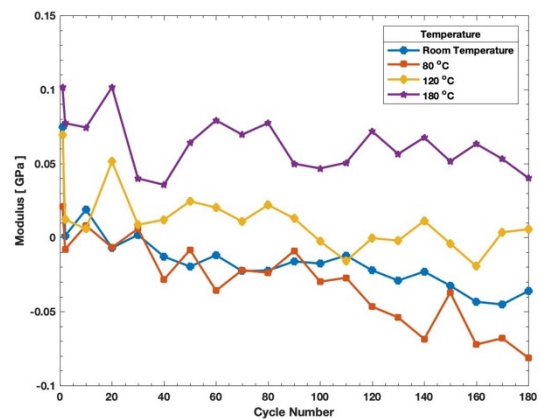


Figure 4-135: 12.5 MPa Continuous - 20s (40s Creep) - Instantaneous Modulus (Difference)

Table 4-CXIV: Temperature - 8 MPa - 1s – Instantaneous Modulus

			Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	9.12	9.11	-0.02	9.08	9.22	0.13	0.04	-0.11	-0.15
20	1	80	9.17	9.23	0.06	9.17	9.29	0.12	0.00	-0.06	-0.06
20	1	120	9.21	9.27	0.06	9.26	9.45	0.19	-0.05	-0.19	-0.14
20	1	180	9.12	9.16	0.04	9.17	9.35	0.17	-0.05	-0.18	-0.13

Table 4-CXV: Temperature - 8 MPa - 10s – Instantaneous Modulus

			Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	9.10	9.21	0.11	9.19	9.51	0.32	-0.09	-0.30	-0.21
20	10	80	9.24	9.32	0.07	9.49	9.64	0.15	-0.25	-0.32	-0.08
20	10	120	9.10	9.25	0.16	9.31	9.59	0.27	-0.22	-0.33	-0.12
20	10	180	9.05	9.18	0.13	9.17	9.49	0.32	-0.12	-0.31	-0.19

Table 4-CXVI: Temperature - 8 MPa - 20s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	8.99	9.04	0.04	9.08	9.34	0.26	-0.09	-0.31	-0.22
20	20	80	9.04	9.13	0.09	9.16	9.60	0.43	-0.12	-0.47	-0.35
20	20	120	9.03	9.08	0.05	9.09	9.32	0.23	-0.06	-0.24	-0.18
20	20	180	8.83	8.97	0.15	8.94	9.33	0.38	-0.11	-0.35	-0.24

Table 4-CXVII: Temperature - 8 MPa – 40s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	8.99	9.07	0.08	9.16	9.60	0.44	-0.17	-0.53	-0.36
20	40	80	9.07	9.24	0.18	9.29	9.76	0.47	-0.22	-0.51	-0.29
20	40	120	9.04	9.20	0.16	9.22	9.66	0.44	-0.18	-0.46	-0.28
20	40	180	8.84	9.04	0.20	8.94	9.42	0.48	-0.10	-0.37	-0.27

Table 4-CXVIII: Temperature - 8 MPa – 80s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	9.03	9.35	0.32	9.24	10.10	0.87	-0.21	-0.76	-0.55
20	80	80	9.12	9.83	0.70	9.39	10.36	0.96	-0.27	-0.53	-0.26
20	80	120	9.05	9.44	0.39	9.17	9.94	0.76	-0.12	-0.50	-0.38
20	80	180	8.96	9.43	0.47	9.08	9.82	0.74	-0.12	-0.39	-0.27

Table 4-CXIX: Temperature - 8 MPa – 40s Creep (20s Recovery) – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	9.07	9.15	0.08	9.21	9.85	0.64	-0.14	-0.70	-0.56
40	20	80	9.06	9.24	0.17	9.16	9.64	0.48	-0.09	-0.40	-0.31
40	20	120	9.11	9.44	0.33	9.30	9.82	0.52	-0.19	-0.38	-0.18
40	20	180	8.98	9.09	0.11	9.02	9.25	0.23	-0.04	-0.16	-0.12

Table 4-CXX: Temperature - 12.5 MPa Non-Continuous – 1s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	12.31	12.28	-0.02	12.12	12.15	0.02	0.18	0.13	-0.05
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	11.08	11.20	0.12	11.04	10.99	-0.05	0.04	0.21	0.16
20	1	180	9.93	10.00	0.07	9.90	9.99	0.09	0.03	0.01	-0.02

Table 4-CXXI: Temperature - 12.5 MPa Non-Continuous – 10s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	12.28	12.42	0.14	12.17	12.20	0.03	0.11	0.22	0.11
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	120	11.12	11.13	0.01	10.98	11.00	0.02	0.14	0.13	-0.01
20	10	180	9.88	9.97	0.08	9.89	9.99	0.10	0.00	-0.02	-0.02

Table 4-CXXII: Temperature - 12.5 MPa Non-Continuous – 20s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	11.45	11.55	0.10	11.44	11.56	0.12	0.01	-0.01	-0.02
20	20	80	9.54	9.71	0.17	9.54	9.73	0.19	-0.01	-0.02	-0.02
20	20	120	9.27	9.39	0.12	9.30	9.53	0.23	-0.03	-0.14	-0.11
20	20	180	9.36	9.50	0.14	9.32	9.49	0.18	0.05	0.01	-0.04

Table 4-CXXIII: Temperature - 12.5 MPa Non-Continuous – 40s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	10.78	10.70	-0.08	10.77	10.70	-0.07	0.01	0.00	-0.01
20	40	80	9.54	9.76	0.21	9.58	9.93	0.35	-0.04	-0.18	-0.14
20	40	120	9.49	9.51	0.02	9.49	9.57	0.07	0.00	-0.06	-0.06
20	40	180	9.76	9.87	0.12	9.75	9.88	0.12	0.00	0.00	-0.01

Table 4-CXXIV: Temperature - 12.5 MPa Non-Continuous – 80s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	11.49	11.52	0.03	11.42	11.68	0.26	0.07	-0.16	-0.23
20	80	80	9.92	10.10	0.18	9.95	10.31	0.35	-0.03	-0.21	-0.17
20	80	120	9.17	9.38	0.20	9.20	9.54	0.34	-0.02	-0.16	-0.14
20	80	180	9.82	10.09	0.27	9.83	10.14	0.31	-0.01	-0.05	-0.04

Table 4-CXXV: Temperature - 12.5 MPa Non-Continuous – 40s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	12.45	12.66	0.21	12.19	12.38	0.19	0.26	0.28	0.02
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	120	11.09	11.18	0.09	10.97	11.02	0.05	0.12	0.16	0.04
40	20	180	9.90	10.10	0.20	9.90	10.16	0.26	0.00	-0.06	-0.06

Table 4-CXXVI: Temperature - 12.5 MPa Continuous - 1s - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	11.07	11.09	0.02	11.06	11.11	0.05	0.01	-0.01	-0.03
20	1	80	10.54	10.57	0.03	10.55	10.62	0.07	-0.01	-0.05	-0.04
20	1	120	10.71	10.74	0.03	10.66	10.69	0.02	0.04	0.05	0.01
20	1	180	10.29	10.24	-0.05	10.18	10.17	-0.02	0.11	0.08	-0.03

Table 4-CXXVII: Temperature - 12.5 MPa Continuous - 10s - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	11.13	11.23	0.09	11.14	11.26	0.11	-0.01	-0.03	-0.02
20	10	80	10.52	10.62	0.10	10.55	10.66	0.11	-0.03	-0.04	-0.01
20	10	120	10.70	10.76	0.05	10.68	10.77	0.09	0.02	-0.02	-0.04
20	10	180	10.27	10.27	-0.01	10.23	10.24	0.01	0.04	0.03	-0.01

Table 4-CXXVIII: Temperature - 12.5 MPa Continuous – 20s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	11.02	11.12	0.10	11.02	11.12	0.10	0.00	0.00	0.00
20	20	80	10.35	10.46	0.11	10.35	10.48	0.13	0.00	-0.02	-0.02
20	20	120	10.42	10.53	0.10	10.42	10.55	0.14	0.01	-0.03	-0.03
20	20	180	9.95	10.07	0.11	9.91	9.99	0.08	0.05	0.08	0.03

Table 4-CXXIX: Temperature - 12.5 MPa Continuous – 40s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	11.03	11.17	0.14	11.02	11.20	0.18	0.01	-0.03	-0.04
20	40	80	10.47	10.63	0.16	10.49	10.74	0.25	-0.02	-0.11	-0.08
20	40	120	10.53	10.62	0.09	10.53	10.68	0.15	0.00	-0.06	-0.06
20	40	180	10.07	10.25	0.18	10.01	10.16	0.16	0.07	0.08	0.02

Table 4-CXXX: Temperature - 12.5 MPa Continuous – 80s – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	11.05	11.33	0.29	11.04	11.39	0.35	0.01	-0.06	-0.06
20	80	80	10.48	10.81	0.33	10.51	10.91	0.40	-0.04	-0.10	-0.06
20	80	120	10.61	10.96	0.35	10.63	11.00	0.38	-0.01	-0.04	-0.03
20	80	180	10.15	10.47	0.32	10.15	10.44	0.29	0.00	0.03	0.03

Table 4-CXXXI: Temperature - 12.5 MPa Continuous – 40s Creep (20s Recovery) – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Instantaneous Modulus [GPa]								
			E_l			E_u			$E_l - E_u$		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	11.15	11.37	0.22	11.15	11.40	0.26	0.00	-0.04	-0.04
40	20	80	10.52	10.66	0.14	10.52	10.74	0.22	-0.01	-0.08	-0.07
40	20	120	10.65	10.82	0.17	10.64	10.81	0.17	0.01	0.01	-0.01
40	20	180	10.32	10.41	0.10	10.24	10.37	0.13	0.08	0.04	-0.04

4.3.3 Strain Energy Density

4.3.3.1 Overall Strain Energy Density

Table 4-CXXXII through Table 4-CXLIX contain the calculated overall strain energy density values sorted similar to the previous sections. Figure 4-136 through Figure 4-159 provide plots for the same set of data, for the parameters presented in the tables.

Comparing the total strain energy density for variation with change in temperature, there was an increasing trend in the calculated energy density as the temperature increased. This trend was consistent for the majority of the test conditions with the only outlier in the data sets which did not follow this trend being the 40s creep / 20s recovery tested at 8 / 0.1 MPa. For the data sets which did follow this trend, the trend present showed generally a very strong correlation with the line of best fit. Comparing the change in the total strain energy density between the final and initial cycle, no trend was apparent in the data. However, evaluating the magnitude of the difference in energy, especially for the two continuous tests, the values were quite similar regardless of the service temperature.

This indicates that the total strain energy density of the material increases as the service temperature increases, however the change in this strain energy density over the duration of the cyclic testing is unaffected by the service temperature. The variation in the calculated differences in total strain energy density for the individual tests can be partially explained by the use of different specimens, which in turn have different cross-sectional areas (i.e. volumes).

Similar to the total strain energy density, the stored strain energy density showed an increasing trend as the temperature increased for the cyclic data. This trend was present in the majority of the data sets, with the two 12.5 / 0.5 MPa loading conditions showed very strong correlation between the trend line and the data. Of the tests performed at 8 / 0.1 MPa; three had fairly strong correlation with the increasing trend line, one showed quite weak correlation, and this trend was not present for the 1s and 20s recovery duration tests. Lastly, evaluating the difference between the final and initial cycles, no trends were present in the data. However as with the total strain energy density, the magnitudes for this difference are generally of similar magnitude, with the continuous loading data sets showing this trend more so than the discontinuous loading. This provides further confirmation that changes in the strain energy density as a result of cyclic

loading may be unaffected by changes in the service temperature, as previously identified in analysis of the effect of the recovery duration.

With respect to the dissipated energy, for the initial and final cycles, both showed a slight increasing trend with increase in temperature. However, this increasing trend is not present in one third of the data sets, with the two continuous loadings only showing this trend in half of the sets. The correlation of the data to these trend lines ranged from extremely poor to strong. As such, no conclusions can be definitively drawn with respect to the relationship between the temperature and the cycle dissipated strain energy density. Lastly, the difference between the two cycles showed no trend with respect to temperature, but as with the total and stored, the magnitudes quite were similar particularly for the continuous loadings, indicating that change in the energy as a result of the cyclic loading was independent of the temperature.

Since neither the total, stored, or dissipated strain energy density showed any trend between the temperature and the difference between the final and initial cycles, this would indicate that there does not appear to be any correlation between the temperature and the change in the energy over the course of the cyclic loading. This is further supported by the fact that the magnitude of the difference values are all quite similar. Therefore, this would indicate that the evolution of the strain energy density of the material when subjected to cyclic loading is independent of the service temperature.

Lastly, evaluating the unrecovered strain energy density, the initial, final, and difference between the two cycles all show an increasing trend as the temperature increases. Comparing the data, with the trend lines, the calculated correlation coefficient's indicate a strong correlation between the unrecovered strain energy density and the change in temperature.

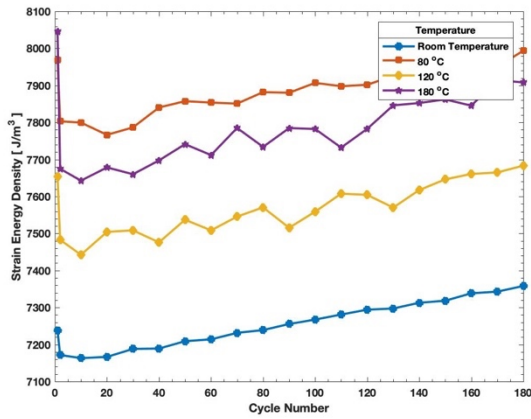


Figure 4-136: 12.5 MPa Continuous – 1s – Total Strain Energy Density

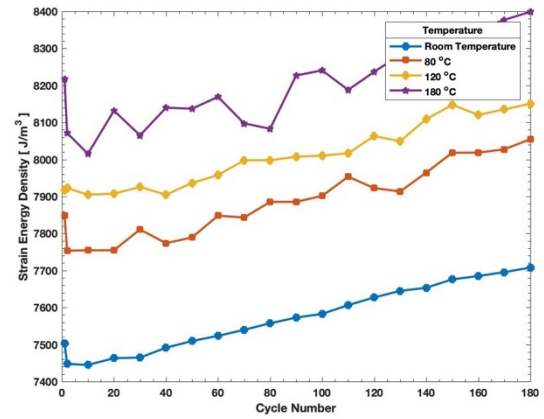


Figure 4-137: 12.5 MPa Continuous – 10s – Total Strain Energy Density

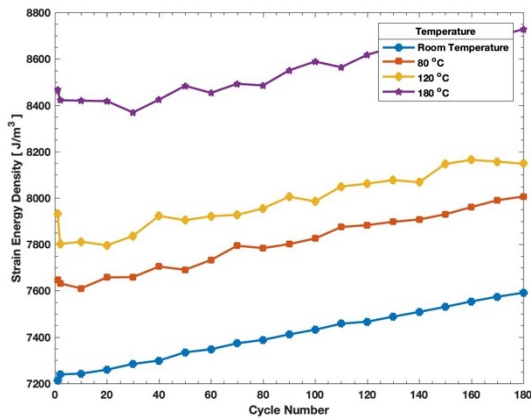


Figure 4-138: 12.5 MPa Continuous – 20s – Total Strain Energy Density

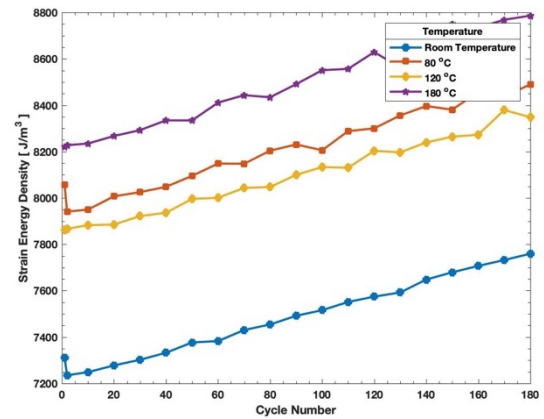


Figure 4-139: 12.5 MPa Continuous – 40s – Total Strain Energy Density

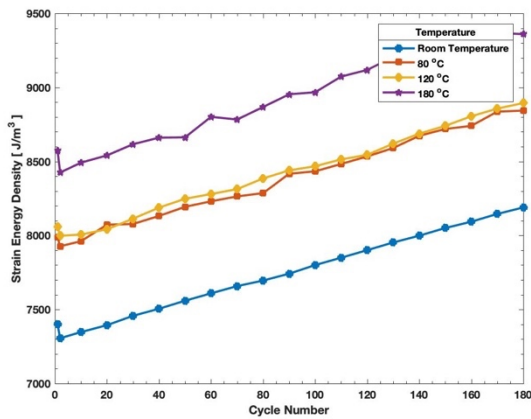


Figure 4-140: 12.5 MPa Continuous – 80s – Total Strain Energy Density

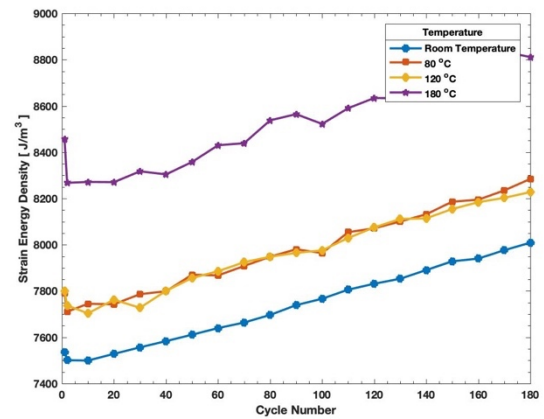


Figure 4-141: 12.5 MPa Continuous – 20s (40s Creep) – Total Strain Energy Density

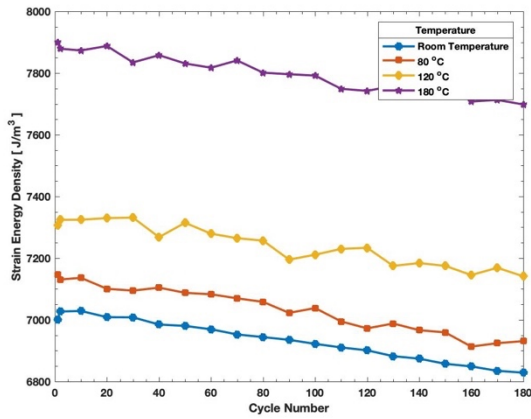


Figure 4-142: 12.5 MPa Continuous – 1s – Stored Strain Energy Density

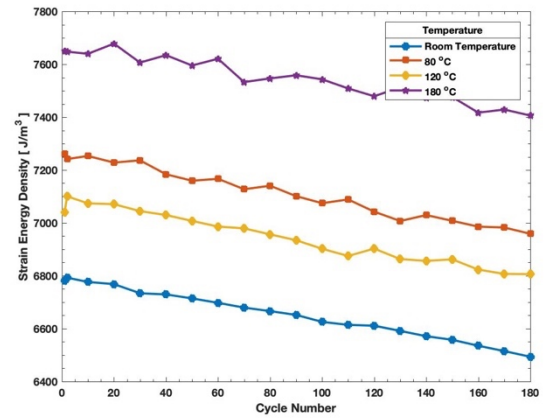


Figure 4-143: 12.5 MPa Continuous – 10s – Stored Strain Energy Density

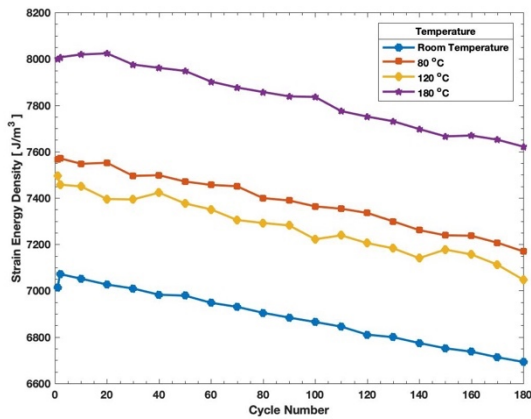


Figure 4-144: 12.5 MPa Continuous – 20s – Stored Strain Energy Density

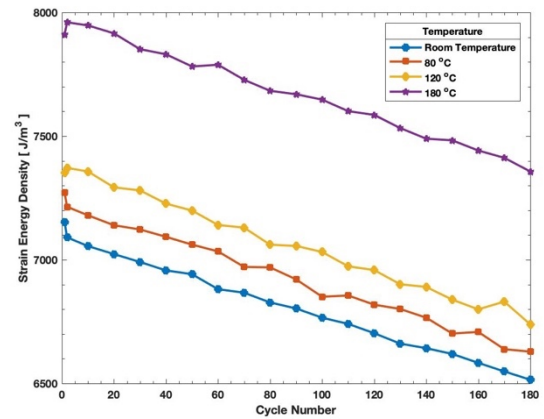


Figure 4-145: 12.5 MPa Continuous – 40s – Stored Strain Energy Density

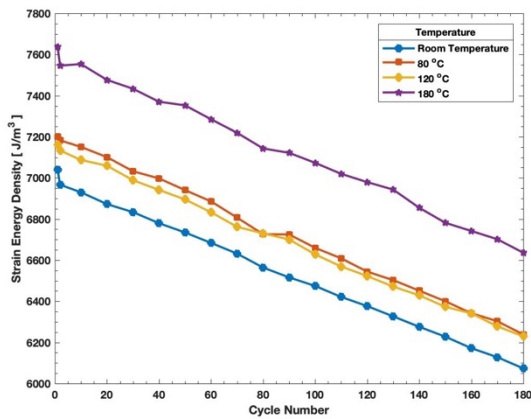


Figure 4-146: 12.5 MPa Continuous – 80s – Stored Strain Energy Density

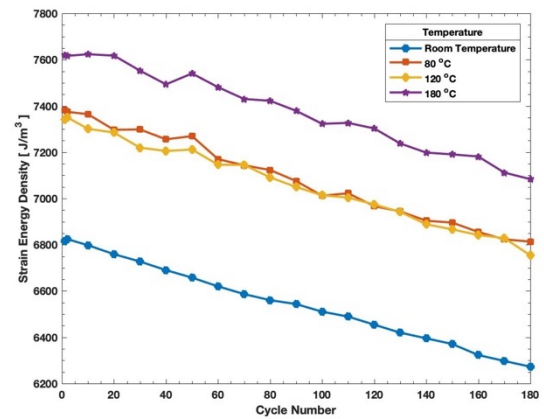


Figure 4-147: 12.5 MPa Continuous – 20s (40s Creep) – Stored Strain Energy Density

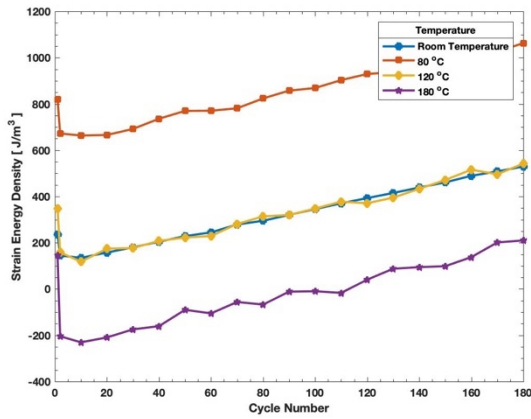


Figure 4-148: 12.5 MPa Continuous – 1s – Dissipated Strain Energy Density

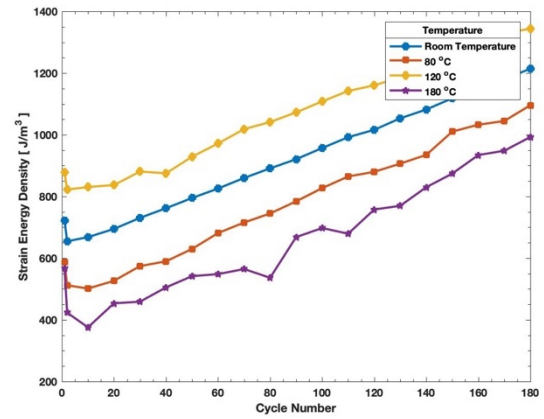


Figure 4-149: 12.5 MPa Continuous – 10s – Dissipated Strain Energy Density

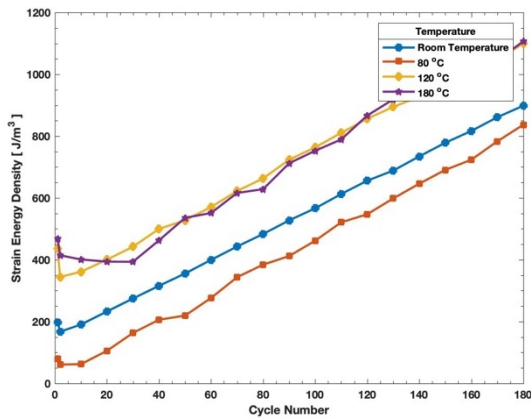


Figure 4-150: 12.5 MPa Continuous – 20s – Dissipated Strain Energy Density

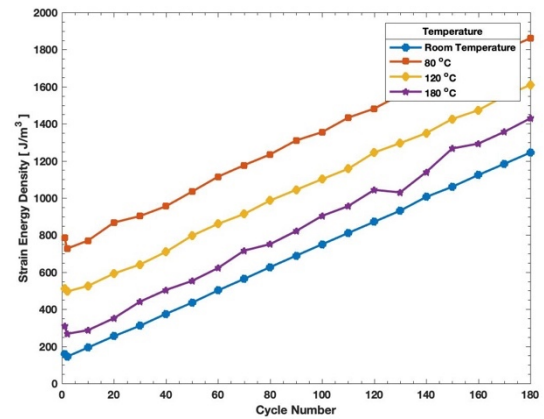


Figure 4-151: 12.5 MPa Continuous – 40s – Dissipated Strain Energy Density

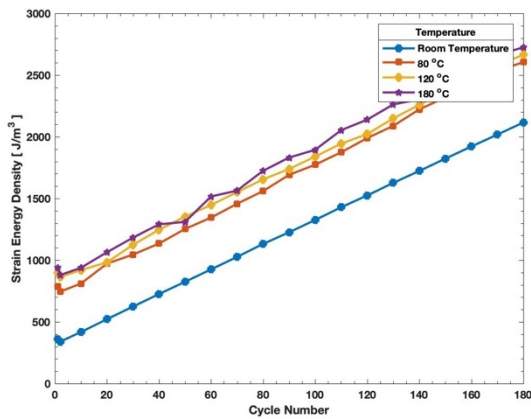


Figure 4-152: 12.5 MPa Continuous – 80s – Dissipated Strain Energy Density

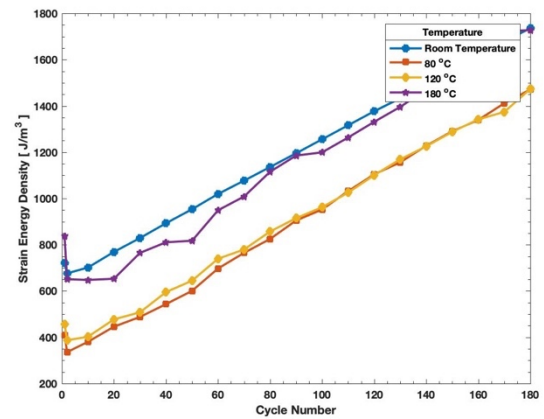


Figure 4-153: 12.5 MPa Continuous – 20s (40s Creep) – Dissipated Strain Energy Density

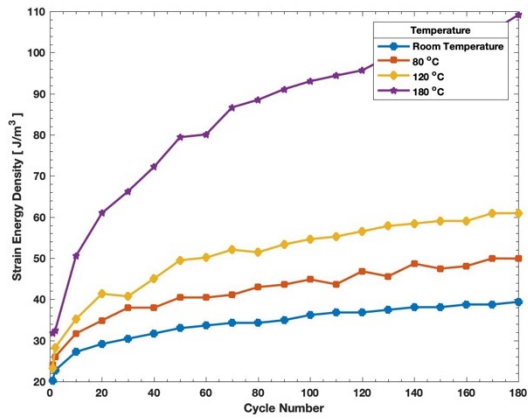


Figure 4-154: 12.5 MPa Continuous – 1s – Unrecovered Strain Energy Density

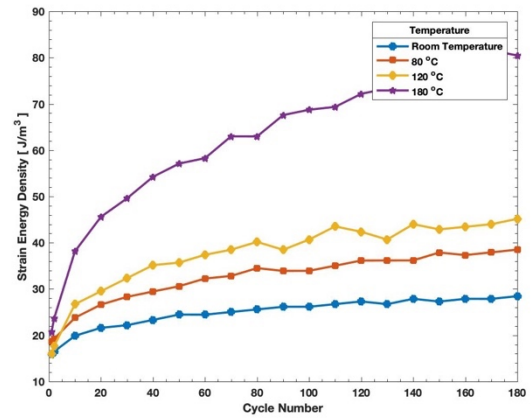


Figure 4-155: 12.5 MPa Continuous – 10s – Unrecovered Strain Energy Density

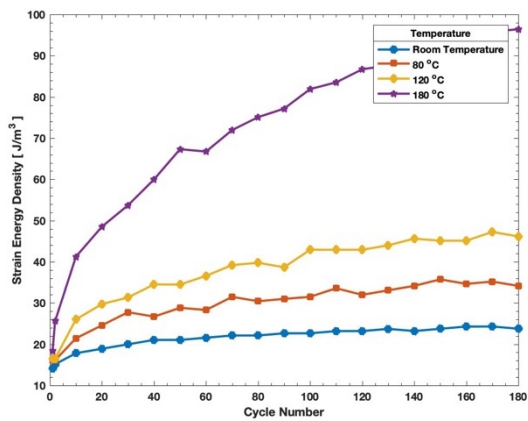


Figure 4-156: 12.5 MPa Continuous – 20s – Unrecovered Strain Energy Density

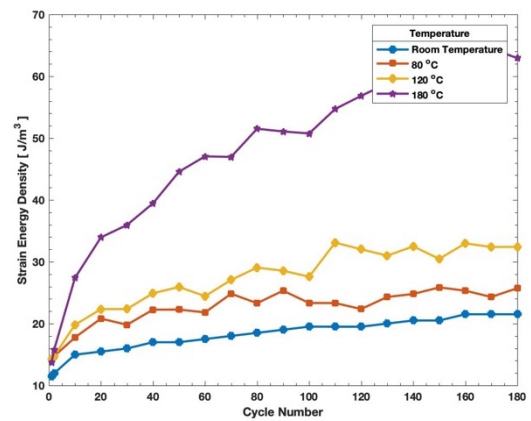


Figure 4-157: 12.5 MPa Continuous – 40s – Unrecovered Strain Energy Density

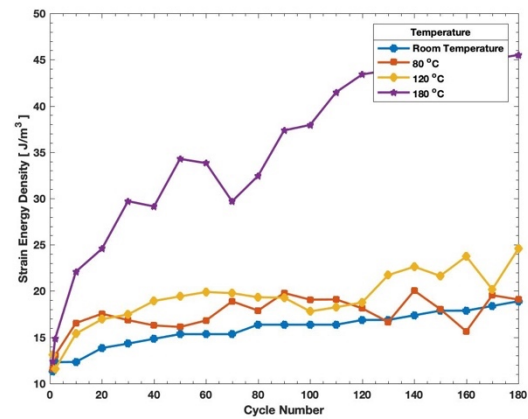


Figure 4-158: 12.5 MPa Continuous – 80s – Unrecovered Strain Energy Density

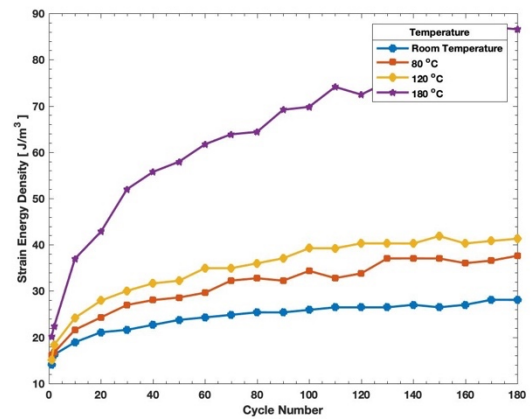


Figure 4-159: 12.5 MPa Continuous – 20s (40s Creep) – Unrecovered Strain Energy Density

Table 4-CXXXII: Temperature - 8 MPa - 1s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3412.23	3558.58	146.36	3592.34	3420.74	-171.60	-180.11	137.85	317.96	6.48	10.82	4.34
20	1	80	3482.62	3607.13	124.51	3515.17	3333.89	-181.28	-32.56	273.24	305.80	5.68	13.86	8.18
20	1	120	3560.88	3709.30	148.42	3451.89	3304.45	-147.44	108.99	404.85	295.86	7.50	16.87	9.36
20	1	180	3762.94	3899.04	136.10	3395.67	3236.65	-159.02	367.27	662.39	295.12	8.84	25.33	16.48

Table 4-CXXXIII: Temperature - 8 MPa - 10s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	3600.69	3820.50	219.81	3398.32	3163.53	-234.80	202.37	656.97	454.60	2.48	4.76	2.28
20	10	80	3810.99	4015.21	204.22	3183.64	2966.42	-217.22	627.35	1048.79	421.44	3.53	6.40	2.87
20	10	120	3796.04	3964.85	168.82	3317.85	3073.84	-244.01	478.19	891.02	412.83	3.38	8.84	5.46
20	10	180	3888.92	4058.44	169.52	3384.85	3165.05	-219.80	504.07	893.39	389.32	4.54	15.67	11.13

Table 4-CXXXIV: Temperature - 8 MPa - 20s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	3508.84	3811.03	302.19	3555.59	3232.51	-323.09	-46.75	578.53	625.28	1.57	3.08	1.50
20	20	80	3690.81	3973.22	282.41	3353.20	3065.28	-287.92	337.61	907.94	570.33	2.93	4.91	1.98
20	20	120	3661.65	3962.43	300.78	3551.87	3246.62	-305.25	109.78	715.81	606.03	1.84	7.75	5.91
20	20	180	3972.01	4257.01	285.00	3489.62	3213.81	-275.81	482.39	1043.20	560.81	2.48	12.40	9.92

Table 4-CXXXV: Temperature - 8 MPa – 40s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	3680.85	4130.53	449.68	3394.49	2930.00	-464.49	286.36	1200.53	914.17	0.71	2.00	1.29
20	40	80	3685.65	4128.62	442.97	3350.13	2907.40	-442.73	335.53	1221.23	885.70	0.42	3.93	3.51
20	40	120	3702.21	4175.57	473.36	3403.70	2986.08	-417.62	298.51	1189.49	890.98	0.43	2.04	1.61
20	40	180	3873.95	4297.10	423.15	3583.57	3118.43	-465.13	290.38	1178.66	888.28	0.60	6.72	6.12

Table 4-CXXXVI: Temperature - 8 MPa - 80s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	3764.38	4488.15	723.77	3317.17	2588.69	-728.48	447.21	1899.46	1452.25	0.64	1.86	1.22
20	80	80	3830.03	4520.55	690.52	3230.82	2532.73	-698.09	599.21	1987.82	1388.61	1.37	2.27	0.90
20	80	120	3629.97	4395.62	765.65	3470.11	2767.19	-702.91	159.86	1628.42	1468.56	0.90	0.44	-0.46
20	80	180	3937.11	4674.07	736.96	3424.13	2717.61	-706.52	512.99	1956.46	1443.48	0.07	3.11	3.04

Table 4-CXXXVII: Temperature - 8 MPa - 40s Creep (20s Recovery) - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	3727.26	4160.48	433.22	3354.75	2902.05	-452.70	372.51	1258.44	885.92	1.69	3.58	1.89
40	20	80	3567.67	4003.31	435.64	3490.84	3049.60	-441.23	76.83	953.70	876.88	2.24	6.94	4.70
40	20	120	3805.40	4166.17	360.78	3354.54	2900.58	-453.95	450.86	1265.59	814.73	2.03	7.27	5.24
40	20	180	3583.52	3968.47	384.96	3742.32	3333.06	-409.27	-158.81	635.42	794.22	3.01	12.25	9.24

Table 4-CXXXVIII: Temperature - 12.5 MPa Non-Continuous - 1s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6455.13	6643.92	188.79	6647.17	6489.31	-157.86	-192.03	154.61	346.65	19.25	34.55	15.30
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	7390.82	7617.15	226.33	7173.48	6987.42	-186.06	217.33	629.72	412.39	24.43	61.59	37.16
20	1	180	8239.99	8430.66	190.67	7768.45	7539.90	-228.55	471.54	890.76	419.22	36.99	91.25	54.27

Table 4-CXXXIX: Temperature - 12.5 MPa Non-Continuous - 10s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	6768.96	7031.28	262.32	6394.60	6155.65	-238.96	374.36	875.63	501.27	14.87	24.66	9.79
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	120	7680.90	8009.65	328.75	7010.62	6769.47	-241.15	670.27	1240.18	569.90	18.55	49.15	30.60
20	10	180	8392.26	8583.23	190.97	7853.41	7490.94	-362.47	538.85	1092.30	553.45	21.11	71.26	50.15

Table 4-CXL: Temperature - 12.5 MPa Non-Continuous - 20s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	6939.68	7412.49	472.81	6801.57	6397.56	-404.01	138.11	1014.93	876.81	12.14	14.21	2.07
20	20	80	8187.41	8649.31	461.90	7787.16	7240.52	-546.64	400.25	1408.79	1008.54	16.82	16.37	-0.45
20	20	120	8878.24	9501.31	623.08	8230.57	7404.07	-826.51	647.66	2097.24	1449.58	19.09	24.92	5.83
20	20	180	9010.15	9266.94	256.79	8527.52	8000.56	-526.95	482.63	1266.37	783.74	30.05	135.98	105.93

Table 4-CXLI: Temperature - 12.5 MPa Non-Continuous - 40s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	6898.69	8023.71	1125.02	7038.12	6837.22	-200.91	-139.43	1186.49	1325.92	11.21	16.36	5.15
20	40	80	8497.21	9206.49	709.28	7898.98	7123.33	-775.66	598.23	2083.16	1484.93	15.38	29.86	14.48
20	40	120	8345.78	8865.33	519.55	8225.53	7717.93	-507.60	120.24	1147.40	1027.16	19.99	34.73	14.74
20	40	180	8344.95	8994.34	649.39	8134.59	7517.94	-616.64	210.36	1476.40	1266.04	18.26	53.49	35.23

Table 4-CXLII: Temperature - 12.5 MPa Non-Continuous - 80s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	6615.24	7724.04	1108.80	6981.58	5979.21	-1002.37	-366.34	1744.84	2111.17	12.37	12.80	0.43
20	80	80	8157.81	9329.63	1171.81	7661.45	6501.36	-1160.09	496.36	2828.27	2331.91	12.64	23.30	10.65
20	80	120	8892.66	10103.93	1211.27	8380.39	7106.48	-1273.91	512.27	2997.45	2485.18	16.99	5.17	-11.82
20	80	180	8321.51	9383.18	1061.66	8019.51	6976.49	-1043.01	302.01	2406.68	2104.68	14.58	41.26	26.68

Table 4-CXLIII: Temperature - 12.5 MPa Non-Continuous - 40s Creep (20s Recovery) - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	6914.40	7399.60	485.20	6312.11	5826.82	-485.29	602.30	1572.78	970.48	12.48	25.40	12.92
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	120	7421.62	7936.09	514.48	7351.95	6815.61	-536.33	69.67	1120.48	1050.81	16.54	49.28	32.74
40	20	180	8562.13	9168.30	606.18	7736.73	7111.81	-624.92	825.40	2056.50	1231.09	22.13	69.41	47.29

Table 4-CXLIV: Temperature - 12.5 MPa Continuous - 1s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	7171.66	7358.13	186.47	7027.03	6828.67	-198.36	144.63	529.46	384.83	22.71	39.37	16.67
20	1	80	7803.16	7994.26	191.09	7130.82	6931.00	-199.82	672.35	1063.26	390.91	26.01	49.89	23.88
20	1	120	7482.75	7683.35	200.61	7324.41	7141.30	-183.10	158.34	542.05	383.71	28.24	60.94	32.69
20	1	180	7674.69	7908.24	233.54	7879.09	7698.31	-180.78	-204.40	209.92	414.32	32.39	109.15	76.76

Table 4-CXLV: Temperature - 12.5 MPa Continuous - 10s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	7447.53	7707.84	260.31	6792.81	6493.60	-299.20	654.73	1214.24	559.51	16.47	28.44	11.97
20	10	80	7753.66	8054.65	300.98	7241.62	6958.80	-282.81	512.05	1095.84	583.79	19.22	38.51	19.29
20	10	120	7922.58	8150.50	227.92	7100.30	6806.32	-293.97	822.29	1344.18	521.89	17.64	45.16	27.53
20	10	180	8071.17	8398.82	327.65	7647.73	7406.19	-241.54	423.44	992.63	569.19	23.64	80.48	56.83

Table 4-CXLVI: Temperature - 12.5 MPa Continuous - 20s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	7238.67	7590.90	352.22	7071.40	6692.53	-378.87	167.27	898.36	731.09	15.14	23.75	8.61
20	20	80	7631.54	8006.39	374.84	7570.80	7169.59	-401.20	60.75	836.79	776.04	16.12	34.14	18.03
20	20	120	7801.42	8147.93	346.50	7457.05	7047.18	-409.87	344.38	1100.75	756.37	16.51	46.16	29.65
20	20	180	8421.42	8727.73	306.31	8007.13	7621.51	-385.63	414.29	1106.23	691.94	25.63	96.43	70.80

Table 4-CXLVII: Temperature - 12.5 MPa Continuous - 40s - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	7235.12	7759.42	524.29	7090.46	6514.82	-575.64	144.66	1244.60	1099.93	11.95	21.51	9.56
20	40	80	7941.23	8489.34	548.11	7214.14	6628.51	-585.63	727.09	1860.83	1133.74	14.72	25.72	11.00
20	40	120	7867.07	8348.00	480.93	7371.43	6738.62	-632.81	495.65	1609.38	1113.74	14.75	32.41	17.66
20	40	180	8227.62	8786.33	558.70	7960.34	7357.00	-603.34	267.29	1429.33	1162.04	15.76	62.95	47.19

Table 4-CXLVIII: Temperature - 12.5 MPa Continuous - 80s - Overall Strain Energy Density

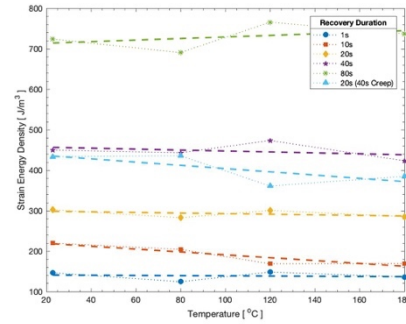
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	7306.07	8189.33	883.25	6966.72	6073.47	-893.25	339.35	2115.85	1776.50	12.30	18.89	6.58
20	80	80	7927.09	8843.66	916.57	7182.48	6238.33	-944.15	744.61	2605.33	1860.72	13.06	19.07	6.01
20	80	120	7997.92	8894.44	896.53	7133.18	6229.43	-903.75	864.73	2665.01	1800.28	11.57	24.56	12.99
20	80	180	8425.40	9360.25	934.86	7546.20	6636.11	-910.09	879.20	2724.15	1844.95	14.86	45.51	30.65

Table 4-CXLIX: Temperature - 12.5 MPa Continuous - 40s Creep (20s Recovery) - Overall Strain Energy Density

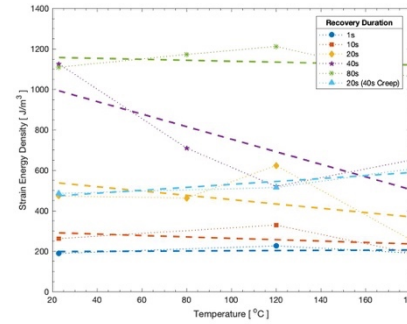
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	7500.75	8008.95	508.21	6824.44	6272.88	-551.56	676.30	1736.07	1059.77	16.24	28.09	11.85
40	20	80	7710.67	8284.52	573.85	7374.72	6813.56	-561.17	335.94	1470.96	1135.02	16.71	37.60	20.89
40	20	120	7737.64	8227.55	489.91	7350.50	6754.17	-596.32	387.14	1473.38	1086.23	18.34	41.30	22.96
40	20	180	8267.60	8811.59	543.99	7616.62	7083.52	-533.10	650.98	1728.07	1077.09	22.36	86.58	64.22

Table 4-CL: Tabulation of parameters for the relationship between the change in the Strain Energy Densities as a function of temperature

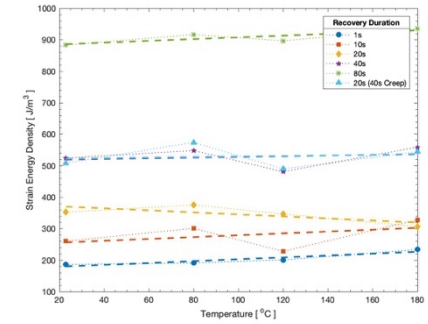
Applied Load [MPa]	Recovery Duration [s]	Total				Stored				Dissipated			
		Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²	Slope	Intercept	Correlation Coefficient, R	Coefficient of Determination, R ²
8 / 0.1	1	-0.024	141.305	-0.147	0.0216	0.127	-177.599	0.568	0.3227	-0.151	318.904	-0.935	0.8738
	10	-0.354	226.233	-0.916	0.8391	0.049	-233.916	0.257	0.0659	-0.403	460.149	-0.986	0.9727
	20	-0.075	300.108	-0.477	0.2276	0.256	-323.808	0.821	0.6742	-0.331	623.915	-0.724	0.5237
	40	-0.115	458.859	-0.367	0.1345	0.030	-450.560	0.090	0.0080	-0.145	909.419	-0.733	0.5379
	80	0.194	709.718	0.411	0.1688	0.122	-721.298	0.601	0.3609	0.072	1431.017	0.137	0.0186
	20 (40s Creep)	-0.401	444.095	-0.720	0.5178	0.242	-463.697	0.770	0.5926	-0.644	907.792	-0.939	0.8818
12.5 / 0.5	1	0.048	196.792	0.179	0.0319	-0.435	-143.980	-0.969	0.9381	0.483	340.772	0.954	0.9109
	10	-0.346	297.917	-0.398	0.1581	-0.714	-203.996	-0.800	0.6402	0.368	501.913	0.814	0.6623
	20	-1.067	561.097	-0.469	0.2199	-1.136	-461.538	-0.421	0.1773	0.070	1022.635	0.016	0.0002
	40	-3.102	1063.358	-0.784	0.6147	-2.051	-318.548	-0.559	0.3128	-1.051	1381.905	-0.366	0.1341
	80	-0.234	1161.958	-0.233	0.0545	-0.394	-1080.123	-0.213	0.0453	0.160	2242.081	0.057	0.0033
	20 (40s Creep)	0.726	457.127	0.911	0.8302	-0.855	-456.815	-0.958	0.9187	1.581	913.942	0.938	0.8804
12.5 C / 0.5	1	0.298	172.944	0.927	0.8590	0.131	-203.693	0.868	0.7541	0.167	376.636	0.773	0.5976
	10	0.295	249.516	0.443	0.1964	0.330	-312.620	0.835	0.6970	-0.035	562.136	-0.088	0.0077
	20	-0.321	377.342	-0.745	0.5550	-0.051	-388.758	-0.238	0.0565	-0.270	766.100	-0.493	0.2428
	40	0.106	517.277	0.204	0.0416	-0.235	-575.650	-0.621	0.3853	0.342	1092.928	0.838	0.7029
	80	0.278	879.760	0.813	0.6610	-0.037	-909.118	-0.110	0.0121	0.315	1788.877	0.534	0.2856
	20 (40s Creep)	0.085	520.383	0.151	0.0228	0.061	-566.685	0.152	0.0231	0.024	1087.067	0.050	0.0025
Averages	8 / 0.1 MPa	-0.129	380.053	-0.369	0.318	0.138	-395.146	0.518	0.337	-0.267	775.199	-0.697	0.635
	12.5 / 0.5 MPa	-0.662	623.041	-0.132	0.318	-0.931	-444.167	-0.653	0.505	0.268	1067.208	0.402	0.432
	12.5 / 0.5 MPa Continuous	0.124	452.870	0.299	0.389	0.033	-492.754	0.148	0.321	0.090	945.624	0.269	0.307



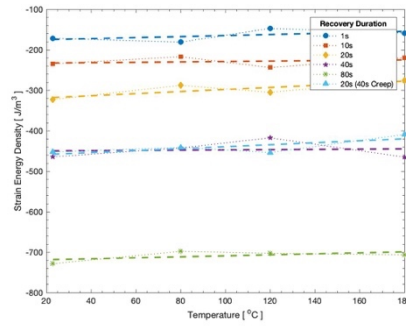
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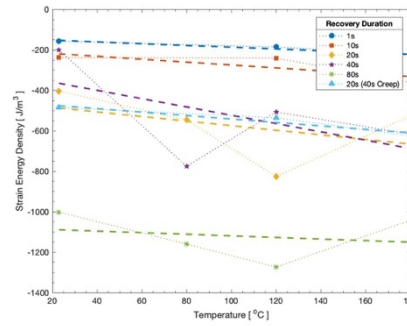
b)



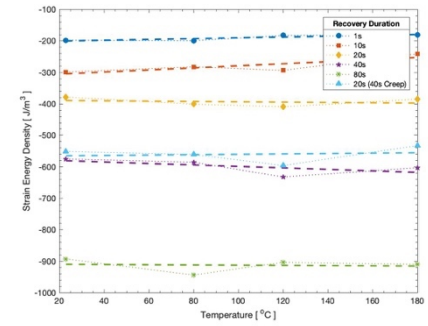
c)



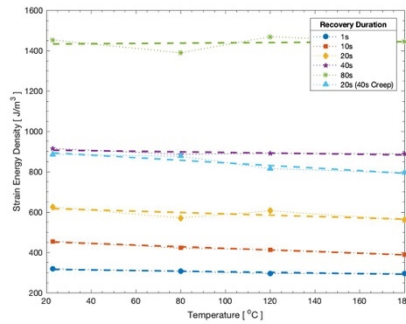
d)



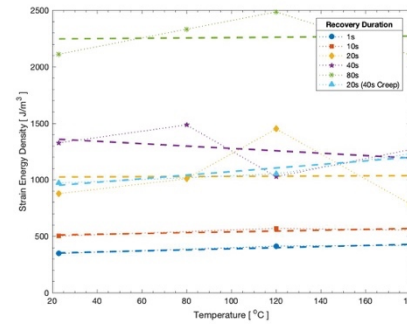
e)



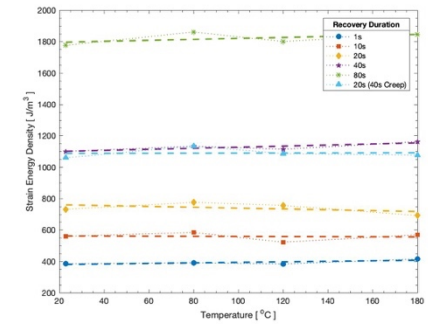
f)



g)



h)



i)

Figure 4-160: Change in Strain Energy Density over all cycles plotted as a function of Temperature; a) through c) show the Total Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. d) through f) show the Stored Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively. g) through i) show the Dissipated Strain Energy Density at 8MPa, 12.5 MPa, and 12.5 MPa Continuous respectively.

4.3.3.2 Total Strain Energy Density

As previously performed in section 4.2.3.2, the total strain energy density was separated into the two segments during which it accumulates during a cycle, however now sorted based change in temperature. Table 4-CLI through Table 4-CLXVIII contain these segmented total strain energy density values sorted by temperature, and Figure 4-161 through Figure 4-172 present plots demonstrating the changes in the strain energy density elements.

Evaluating first the total strain energy density accumulated during the loading segment, there is a slight increasing trend in the response for the initial and final cycles as the temperature increases. However, this trend is only present in around two thirds of the data sets, with the two 12.5 / 0.5 MPa loading scenarios compromising the majority of these with the 8 / 0.1 MPa loading not entirely following this trend. Of those in the two 12.5 / 0.5 MPa tests which follow an increasing trend, the correlation to the best fit trendline is rather strong. However, upon examining the magnitude of these cycles, they are somewhat close regardless of the temperature. This similarity in the magnitudes is closest for the 8 / 0.1 MPa testing scenario. Based upon these variations no conclusions can be drawn at this moment, and further examination may be required. With respect to the difference between the final and initial cycles, a slight decreasing trend was present in two thirds of the data sets. However, this combined with an analysis of the data to the best fit line and the correlation coefficient being quite weak, this would indicate that there is no trend with respect to change in temperature.

Evaluating the total strain energy density accumulated during the creep hold, for the 2nd and final cycle, there is an increasing trend with increase in temperature. This trend is fairly consistent among all data sets, and when compared with the trendlines both show a moderately strong correlation. This correlation is generally stronger for the final cycle than it is for the 2nd cycle. This indicates that as the temperature increases, the more strain energy density that accumulates during the creep hold. For the change in the strain energy density between the 2nd cycle and the final cycle, there is an increasing trend in a slight majority of the data sets. However upon evaluating the correlation coefficient, these trends are generally rather weak and as such no clear trend in the data can be surmised for the change over the cyclic loading.

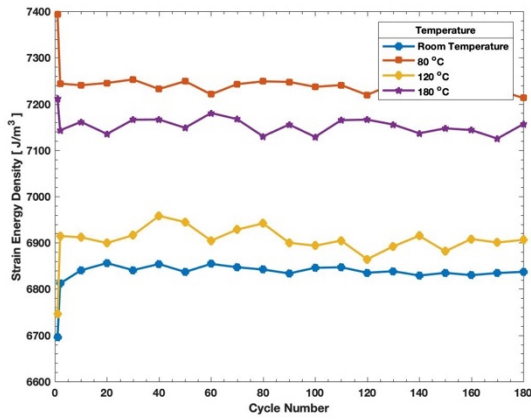


Figure 4-161: 12.5 MPa Continuous - 1s - Total Strain Energy Density (Loading)

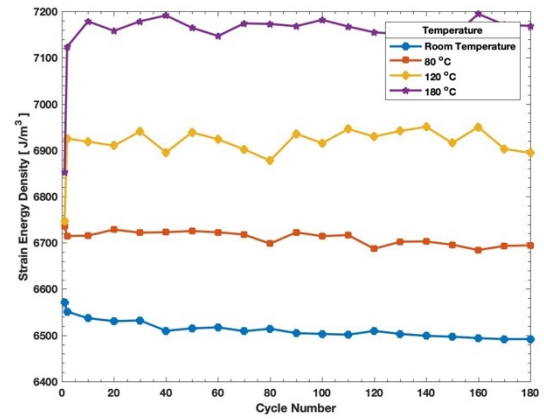


Figure 4-162: 12.5 MPa Continuous - 10s - Total Strain Energy Density (Loading)

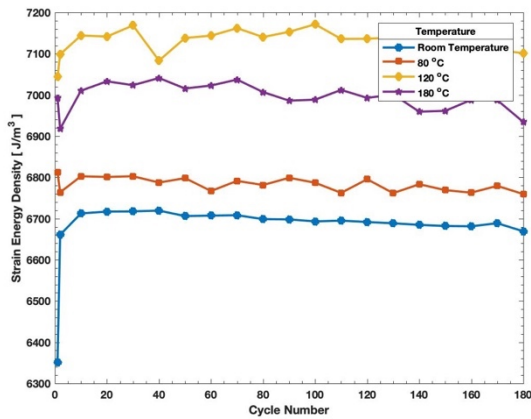


Figure 4-163: 12.5 MPa Continuous - 20s - Total Strain Energy Density (Loading)

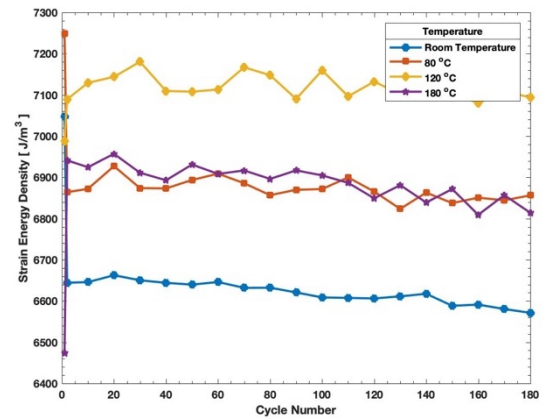


Figure 4-164: 12.5 MPa Continuous - 40s - Total Strain Energy Density (Loading)

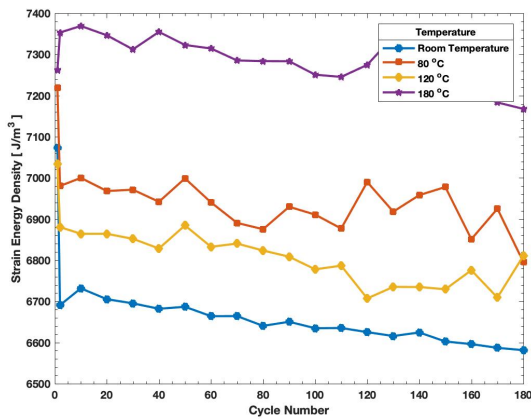


Figure 4-165: 12.5 MPa Continuous - 80s - Total Strain Energy Density (Loading)

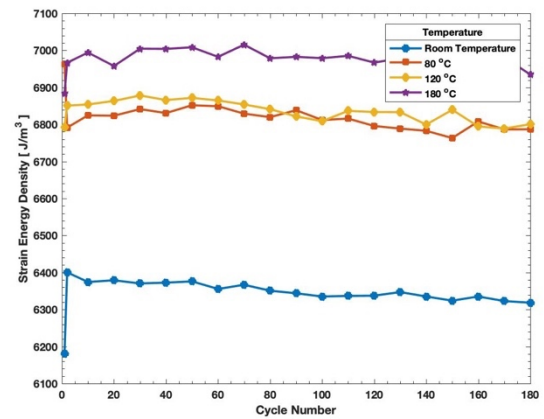


Figure 4-166: 12.5 MPa Continuous - 20s (40s Creep) - Total Strain Energy Density (Loading)

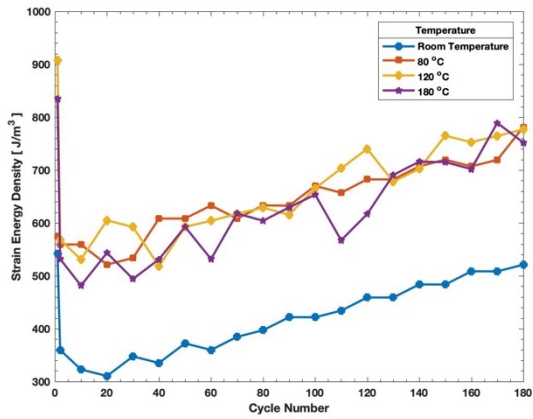


Figure 4-167: 12.5 MPa Continuous - 1s - Total Strain Energy Density (Creep)

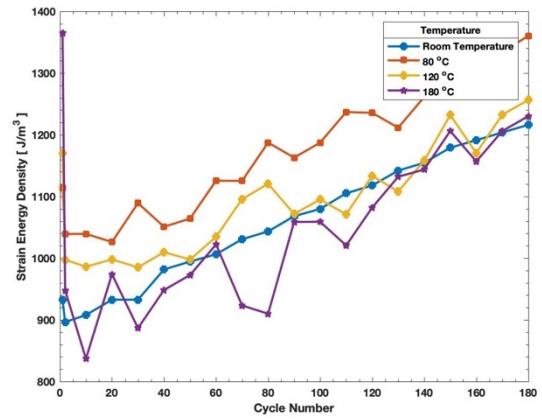


Figure 4-168: 12.5 MPa Continuous - 10s - Total Strain Energy Density (Creep)

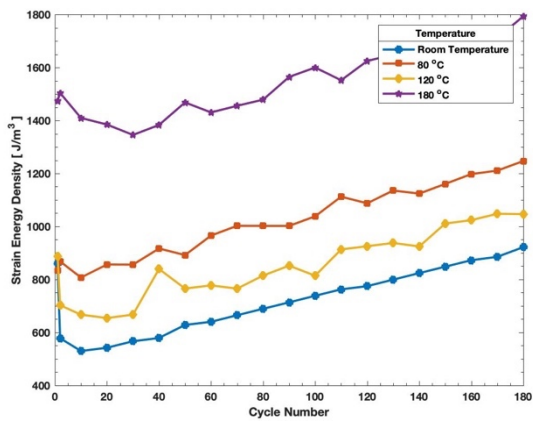


Figure 4-169: 12.5 MPa Continuous - 20s - Total Strain Energy Density (Creep)

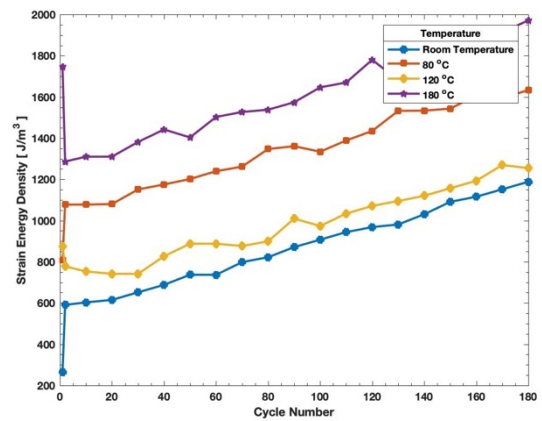


Figure 4-170: 12.5 MPa Continuous - 40s - Total Strain Energy Density (Creep)

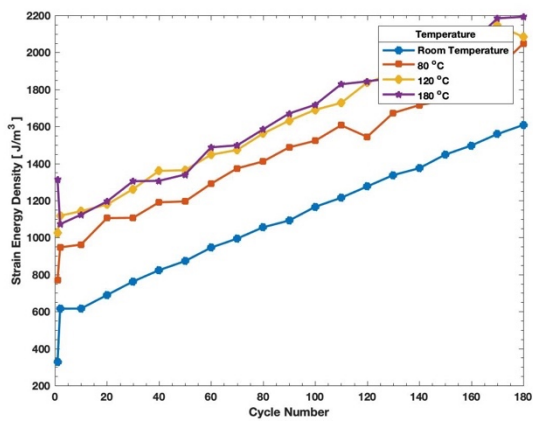


Figure 4-171: 12.5 MPa Continuous - 80s - Total Strain Energy Density (Creep)

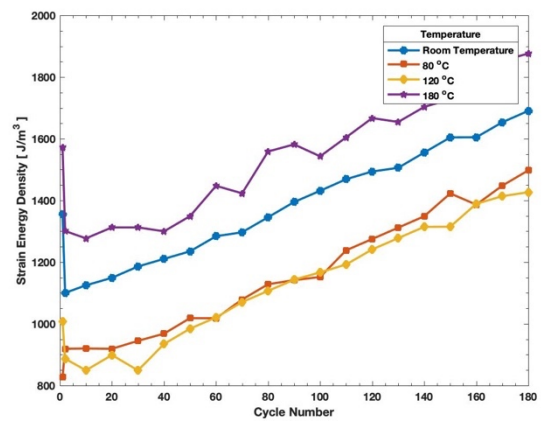


Figure 4-172: 12.5 MPa Continuous - 20s (40s Creep) - Total Strain Energy Density (Creep)

Table 4-CLI: Temperature - 8 MPa – 1s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3082.55	3280.20	197.65	329.68	278.39	-51.29	3412.23	3558.58	146.36
20	1	80	3181.06	3334.76	153.70	301.55	272.37	-29.18	3482.62	3607.13	124.51
20	1	120	3329.32	3162.79	-166.53	231.56	546.50	314.95	3560.88	3709.30	148.42
20	1	180	3178.62	3419.93	241.31	584.32	479.11	-105.22	3762.94	3899.04	136.10

Table 4-CLII: Temperature - 8 MPa – 10s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	3314.81	3112.68	-202.13	285.88	707.82	421.94	3600.69	3820.50	219.81
20	10	80	3103.77	3286.79	183.02	707.23	728.43	21.20	3810.99	4015.21	204.22
20	10	120	3334.94	3137.72	-197.22	461.10	827.13	366.03	3796.04	3964.85	168.82
20	10	180	3165.20	2952.56	-212.64	723.73	1105.88	382.16	3888.92	4058.44	169.52

Table 4-CLIII: Temperature - 8 MPa – 20s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	3154.30	3375.20	220.91	354.55	435.83	81.28	3508.84	3811.03	302.19
20	20	80	3226.41	3013.11	-213.30	464.40	960.12	495.71	3690.81	3973.22	282.41
20	20	120	3275.19	3157.05	-118.13	386.46	805.38	418.92	3661.65	3962.43	300.78
20	20	180	3107.54	2976.65	-130.90	864.47	1280.37	415.90	3972.01	4257.01	285.00

Table 4-CLIV: Temperature - 8 MPa – 40s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	3178.40	3365.36	186.96	502.45	765.17	262.72	3680.85	4130.53	449.68
20	40	80	3085.04	3302.40	217.35	600.61	826.23	225.62	3685.65	4128.62	442.97
20	40	120	3055.33	3279.35	224.02	646.88	896.22	249.34	3702.21	4175.57	473.36
20	40	180	3146.12	2955.58	-190.54	727.83	1341.52	613.69	3873.95	4297.10	423.15

Table 4-CLV: Temperature - 8 MPa – 80s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	3191.18	3342.98	151.80	573.20	1145.17	571.97	3764.38	4488.15	723.77
20	80	80	3307.60	3067.42	-240.17	522.43	1453.12	930.69	3830.03	4520.55	690.52
20	80	120	2920.22	3160.60	240.38	709.75	1235.01	525.26	3629.97	4395.62	765.65
20	80	180	3117.82	3234.53	116.71	819.29	1439.54	620.25	3937.11	4674.07	736.96

Table 4-CLVI: Temperature - 8 MPa – 40s Creep (20s Recovery) – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	3261.14	3046.42	-214.72	466.13	1114.06	647.94	3727.26	4160.48	433.22
40	20	80	3109.87	3308.12	198.25	457.80	695.18	237.39	3567.67	4003.31	435.64
40	20	120	3287.78	3107.77	-180.00	517.62	1058.40	540.78	3805.40	4166.17	360.78
40	20	180	3076.92	3327.81	250.89	506.59	640.66	134.07	3583.52	3968.47	384.96

Table 4-CLVII: Temperature - 12.5 MPa Non-Continuous – 1s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6073.14	6248.14	175.00	381.99	395.78	13.79	6455.13	6643.92	188.79
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	6980.91	6668.69	-312.22	409.91	948.46	538.55	7390.82	7617.15	226.33
20	1	180	7791.70	7380.66	-411.04	448.29	1050.00	601.70	8239.99	8430.66	190.67

Table 4-CLVIII: Temperature - 12.5 MPa Non-Continuous – 10s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	6250.40	6375.86	125.46	518.56	655.42	136.86	6768.96	7031.28	262.32
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	120	6686.00	6886.81	200.81	994.90	1122.84	127.94	7680.90	8009.65	328.75
20	10	180	7722.19	7317.39	-404.80	670.07	1265.85	595.78	8392.26	8583.23	190.97

Table 4-CLIX: Temperature - 12.5 MPa Non-Continuous – 20s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	6617.27	6306.34	-310.93	322.41	1106.15	783.74	6939.68	7412.49	472.81
20	20	80	7652.36	7189.38	-462.98	535.05	1459.93	924.88	8187.41	8649.31	461.90
20	20	120	8110.61	8050.57	-60.04	767.62	1450.74	683.12	8878.24	9501.31	623.08
20	20	180	7872.81	7596.89	-275.91	1137.34	1670.04	532.70	9010.15	9266.94	256.79

Table 4-CLX: Temperature - 12.5 MPa Non-Continuous – 40s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	7108.01	7633.93	525.91	-209.33	389.78	599.10	6898.69	8023.71	1125.02
20	40	80	7875.23	7349.32	-525.91	621.98	1857.17	1235.19	8497.21	9206.49	709.28
20	40	120	7789.59	7892.64	103.05	556.18	972.68	416.50	8345.78	8865.33	519.55
20	40	180	7590.35	7336.49	-253.86	754.60	1657.86	903.26	8344.95	8994.34	649.39

Table 4-CLXI: Temperature - 12.5 MPa Non-Continuous – 80s – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	6355.36	6659.85	304.48	259.88	1064.20	804.32	6615.24	7724.04	1108.80
20	80	80	7647.61	7596.21	-51.40	510.21	1733.42	1223.21	8157.81	9329.63	1171.81
20	80	120	8272.04	8176.70	-95.34	620.62	1927.23	1306.62	8892.66	10103.93	1211.27
20	80	180	7651.02	7208.34	-442.68	670.49	2174.84	1504.34	8321.51	9383.18	1061.66

Table 4-CLXII: Temperature - 12.5 MPa Non-Continuous – 40s Creep (20s Recovery) – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	5911.00	5972.67	61.67	1003.40	1426.93	423.52	6914.40	7399.60	485.20
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	120	6656.55	6792.69	136.14	765.06	1143.40	378.34	7421.62	7936.09	514.48
40	20	180	7670.12	7224.58	-445.54	892.01	1943.72	1051.71	8562.13	9168.30	606.18

Table 4-CLXIII: Temperature - 12.5 MPa Continuous – 1s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6812.00	6837.20	25.20	359.66	520.93	161.27	7171.66	7358.13	186.47
20	1	80	7243.92	7212.93	-30.99	559.25	781.33	222.08	7803.16	7994.26	191.09
20	1	120	6914.58	6906.19	-8.39	568.17	777.17	209.00	7482.75	7683.35	200.61
20	1	180	7142.93	7156.33	13.40	531.77	751.91	220.14	7674.69	7908.24	233.54

Table 4-CLXIV: Temperature - 12.5 MPa Continuous – 10s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	6551.02	6491.72	-59.30	896.51	1216.12	319.61	7447.53	7707.84	260.31
20	10	80	6714.54	6694.34	-20.20	1039.12	1360.31	321.19	7753.66	8054.65	300.98
20	10	120	6925.19	6894.15	-31.03	997.40	1256.35	258.95	7922.58	8150.50	227.92
20	10	180	7123.37	7168.63	45.26	947.80	1230.19	282.39	8071.17	8398.82	327.65

Table 4-CLXV: Temperature - 12.5 MPa Continuous – 20s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	6660.67	6669.07	8.40	578.00	921.83	343.83	7238.67	7590.90	352.22
20	20	80	6763.68	6759.45	-4.22	867.87	1246.93	379.07	7631.54	8006.39	374.84
20	20	120	7098.61	7101.35	2.73	702.81	1046.58	343.77	7801.42	8147.93	346.50
20	20	180	6917.72	6934.25	16.53	1503.71	1793.49	289.78	8421.42	8727.73	306.31

Table 4-CLXVI: Temperature - 12.5 MPa Continuous – 40s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	6644.32	6571.22	-73.10	590.80	1188.19	597.39	7235.12	7759.42	524.29
20	40	80	6863.96	6856.28	-7.68	1077.27	1633.06	555.79	7941.23	8489.34	548.11
20	40	120	7089.37	7093.54	4.17	777.70	1254.46	476.76	7867.07	8348.00	480.93
20	40	180	6941.21	6814.09	-127.12	1286.42	1972.23	685.82	8227.62	8786.33	558.70

Table 4-CLXVII: Temperature - 12.5 MPa Continuous – 80s – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	6690.78	6581.29	-109.49	615.29	1608.04	992.75	7306.07	8189.33	883.25
20	80	80	6980.37	6795.19	-185.18	946.71	2048.46	1101.75	7927.09	8843.66	916.57
20	80	120	6880.41	6810.93	-69.48	1117.50	2083.51	966.01	7997.92	8894.44	896.53
20	80	180	7353.32	7167.55	-185.77	1072.08	2192.70	1120.63	8425.40	9360.25	934.86

Table 4-CLXVIII: Temperature - 12.5 MPa Continuous – 40s Creep (20s Recovery) – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	6400.36	6318.36	-82.00	1100.39	1690.59	590.20	7500.75	8008.95	508.21
40	20	80	6791.55	6786.91	-4.64	919.12	1497.61	578.49	7710.67	8284.52	573.85
40	20	120	6850.87	6800.76	-50.11	886.77	1426.79	540.02	7737.64	8227.55	489.91
40	20	180	6966.81	6935.04	-31.77	1300.79	1876.55	575.76	8267.60	8811.59	543.99

4.3.3.3 Stored Strain Energy Density

Lastly, the variation in the segments of the stored energy density with temperature are presented in Table 4-CLXIX through Table 4-CLXXXVI, and Figure 4-173 through Figure 4-184 provide plots showing the cyclic change of the table elements. Evaluating the stored strain energy density accumulated during the unloading segment, present in the majority of the data sets was an increasing trend for the 2nd and final cycles. This trend is strongest for the two 12.5 / 0.5 MPa loading, and weaker or nonexistent for the 8 / 0.1 MPa. However for the 8 / 0.1 MPa loading, the magnitudes of the values they are quite similar regardless of the temperature. With respect to the difference between the final and the initial cycles, there is no clear trend with respect to the temperature. However, for the two continuous loading cases (and some of the non-continuous), the magnitudes are very similar to each other, indicating that the change in the stored energy during the unloading segment is not reliant on the temperature. This matches what was previously discussed when evaluating the effect of the recovery duration.

The stored strain energy density accumulated during the recovery hold, presented a general increasing trend with increase in temperature for all scenarios. This increasing trend was present for the majority of the data sets, with an increasing proportion of the data sets following this trend from 2nd cycle, final cycle, and difference. This increasing trend showed weak to strong correlation for the 2nd cycle and change data compared with the trendline, and generally strong for the final cycle.

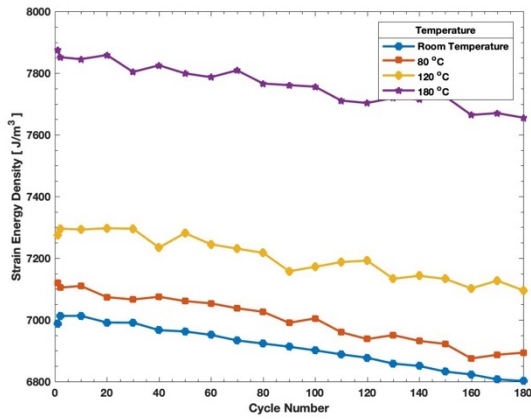


Figure 4-173: 12.5 MPa Continuous - 1s - Stored Strain Energy Density (Unloading)

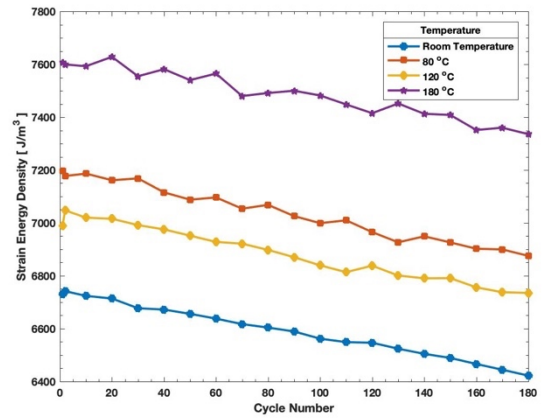


Figure 4-174: 12.5 MPa Continuous - 10s - Stored Strain Energy Density (Unloading)

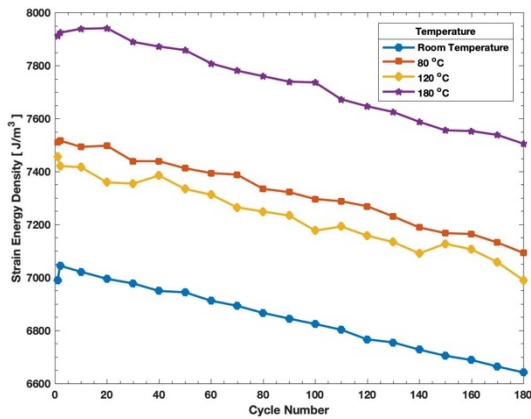


Figure 4-175: 12.5 MPa Continuous - 20s - Stored Strain Energy Density (Unloading)

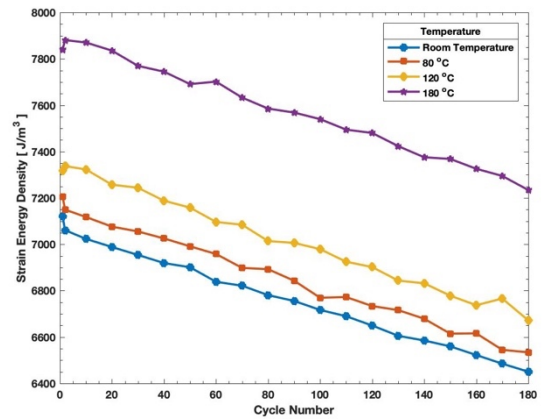


Figure 4-176: 12.5 MPa Continuous - 40s - Stored Strain Energy Density (Unloading)

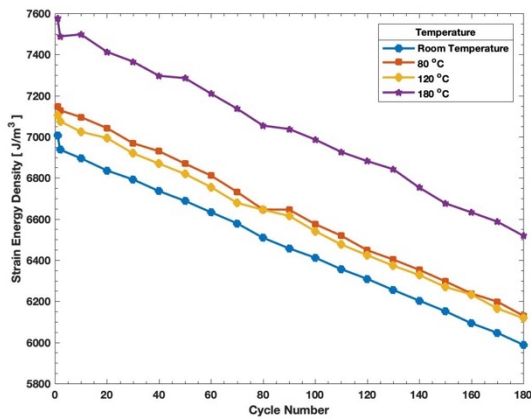


Figure 4-177: 12.5 MPa Continuous - 80s - Stored Strain Energy Density (Unloading)

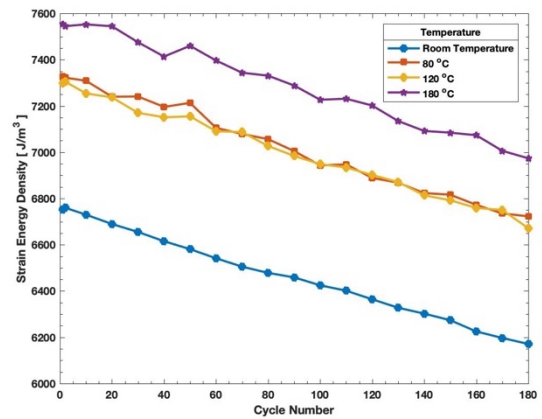


Figure 4-178: 12.5 MPa Continuous - 20s (40s Creep) - Stored Strain Energy Density (Unloading)

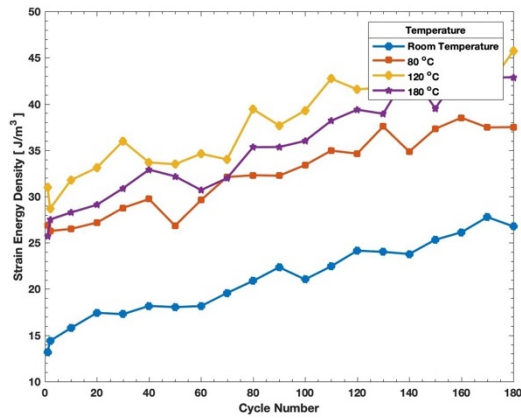


Figure 4-179: 12.5 MPa Continuous - 1s - Stored Strain Energy Density (Recovery)

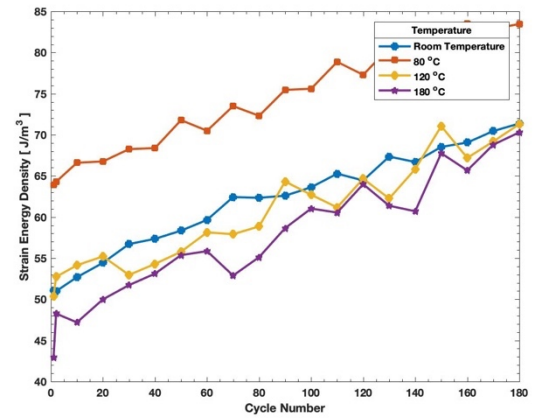


Figure 4-180: 12.5 MPa Continuous - 10s - Stored Strain Energy Density (Recovery)

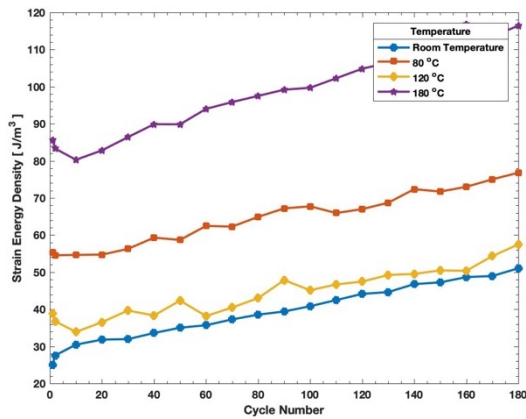


Figure 4-181: 12.5 MPa Continuous - 20s - Stored Strain Energy Density (Recovery)

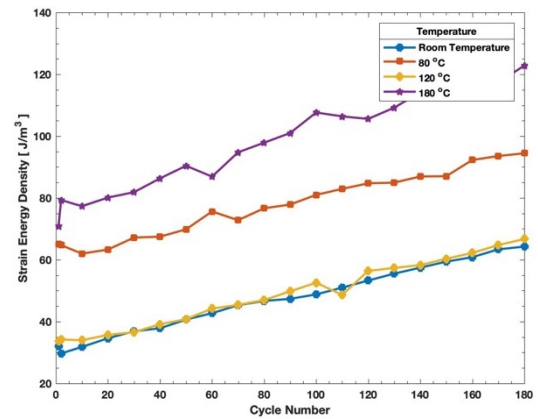


Figure 4-182: 12.5 MPa Continuous - 40s - Stored Strain Energy Density (Recovery)

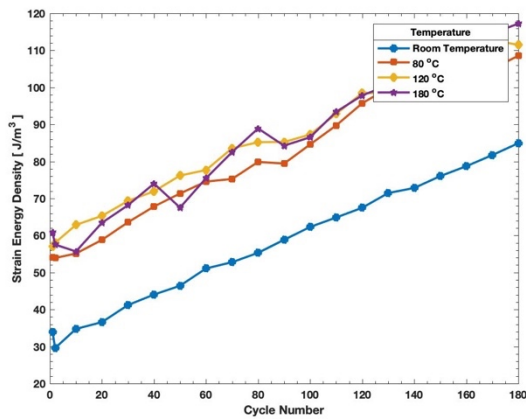


Figure 4-183: 12.5 MPa Continuous - 80s - Stored Strain Energy Density (Recovery)

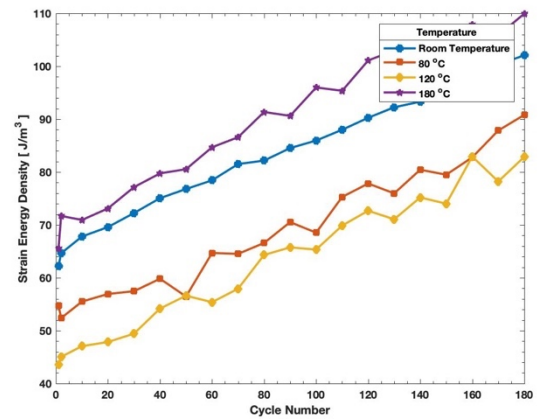


Figure 4-184: 12.5 MPa Continuous - 20s (40s Creep) - Stored Strain Energy Density (Recovery)

Table 4-CLXIX: Temperature - 8 MPa – 1s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	3577.69	3410.58	-167.11	14.65	10.15	-4.50	3592.34	3420.74	-171.60
20	1	80	3505.31	3324.94	-180.37	9.86	8.95	-0.91	3515.17	3333.89	-181.28
20	1	120	3445.10	3273.29	-171.82	6.79	31.17	24.38	3451.89	3304.45	-147.44
20	1	180	3369.67	3180.73	-188.94	26.01	55.92	29.91	3395.67	3236.65	-159.02

Table 4-CLXX: Temperature - 8 MPa – 10s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	3390.12	3129.58	-260.54	8.20	33.95	25.74	3398.32	3163.53	-234.80
20	10	80	3153.67	2937.00	-216.68	29.97	29.43	-0.54	3183.64	2966.42	-217.22
20	10	120	3269.99	3031.13	-238.86	47.86	42.71	-5.16	3317.85	3073.84	-244.01
20	10	180	3353.44	3102.66	-250.78	31.41	62.39	30.98	3384.85	3165.05	-219.80

Table 4-CLXXI: Temperature - 8 MPa – 20s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	3545.68	3188.17	-357.51	9.91	44.34	34.43	3555.59	3232.51	-323.09
20	20	80	3339.41	3017.88	-321.53	13.78	47.40	33.61	3353.20	3065.28	-287.92
20	20	120	3514.46	3211.51	-302.95	37.41	35.12	-2.30	3551.87	3246.62	-305.25
20	20	180	3448.00	3139.26	-308.74	41.62	74.55	32.93	3489.62	3213.81	-275.81

Table 4-CLXXII: Temperature - 8 MPa – 40s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	3376.58	2872.79	-503.79	17.91	57.21	39.30	3394.49	2930.00	-464.49
20	40	80	3326.31	2845.01	-481.30	23.81	62.39	38.57	3350.13	2907.40	-442.73
20	40	120	3379.36	2917.99	-461.37	24.34	68.09	43.76	3403.70	2986.08	-417.62
20	40	180	3555.57	3043.01	-512.56	28.00	75.43	47.43	3583.57	3118.43	-465.13

Table 4-CLXXIII: Temperature - 8 MPa – 80s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	3296.04	2515.51	-780.53	21.14	73.18	52.04	3317.17	2588.69	-728.48
20	80	80	3185.74	2473.56	-712.18	45.08	59.17	14.09	3230.82	2532.73	-698.09
20	80	120	3438.72	2719.92	-718.80	31.39	47.27	15.89	3470.11	2767.19	-702.91
20	80	180	3386.23	2616.04	-770.19	37.89	101.56	63.67	3424.13	2717.61	-706.52

Table 4-CLXXIV: Temperature - 8 MPa – 40s Creep (20s Recovery) – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	3338.22	2845.23	-492.99	16.53	56.81	40.28	3354.75	2902.05	-452.70
40	20	80	3475.49	2989.64	-485.84	15.35	59.96	44.61	3490.84	3049.60	-441.23
40	20	120	3310.41	2850.75	-459.66	44.13	49.83	5.70	3354.54	2900.58	-453.95
40	20	180	3722.88	3273.34	-449.54	19.44	59.72	40.27	3742.32	3333.06	-409.27

Table 4-CLXXV: Temperature - 12.5 MPa Non-Continuous – 1s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	6629.45	6469.29	-160.16	17.71	20.01	2.30	6647.17	6489.31	-157.86
20	1	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	120	7157.02	6932.78	-224.24	16.46	54.65	38.18	7173.48	6987.42	-186.06
20	1	180	7751.35	7478.61	-272.74	17.10	61.29	44.19	7768.45	7539.90	-228.55

Table 4-CLXXVI: Temperature - 12.5 MPa Non-Continuous – 10s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	6368.59	6125.22	-243.37	26.02	30.43	4.41	6394.60	6155.65	-238.96
20	10	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	120	6961.51	6714.30	-247.21	49.11	55.17	6.05	7010.62	6769.47	-241.15
20	10	180	7820.30	7414.74	-405.56	33.11	76.20	43.09	7853.41	7490.94	-362.47

Table 4-CLXXVII: Temperature - 12.5 MPa Non-Continuous – 20s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	6787.87	6337.17	-450.70	13.70	60.39	46.69	6801.57	6397.56	-404.01
20	20	80	7765.86	7161.89	-603.97	21.30	78.64	57.33	7787.16	7240.52	-546.64
20	20	120	8192.38	7322.51	-869.87	38.19	81.56	43.37	8230.57	7404.07	-826.51
20	20	180	8479.60	7901.57	-578.02	47.92	98.99	51.07	8527.52	8000.56	-526.95

Table 4-CLXXVIII: Temperature - 12.5 MPa Non-Continuous – 40s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	7020.26	6814.74	-205.52	17.86	22.47	4.61	7038.12	6837.22	-200.91
20	40	80	7873.83	7007.00	-866.83	25.16	116.33	91.17	7898.98	7123.33	-775.66
20	40	120	8195.99	7665.26	-530.73	29.54	52.67	23.13	8225.53	7717.93	-507.60
20	40	180	8096.87	7422.15	-674.73	37.71	95.79	58.08	8134.59	7517.94	-616.64

Table 4-CLXXIX: Temperature - 12.5 MPa Non-Continuous – 80s – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	6969.81	5923.12	-1046.69	11.76	56.09	44.33	6981.58	5979.21	-1002.37
20	80	80	7652.01	6414.56	-1237.44	9.44	86.80	77.35	7661.45	6501.36	-1160.09
20	80	120	8349.82	7012.45	-1337.37	30.57	94.03	63.46	8380.39	7106.48	-1273.91
20	80	180	7982.88	6855.01	-1127.88	36.63	121.49	84.86	8019.51	6976.49	-1043.01

Table 4-CLXXX: Temperature - 12.5 MPa Non-Continuous – 40s Creep (20s Recovery) – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	6257.15	5753.35	-503.80	54.96	73.47	18.51	6312.11	5826.82	-485.29
40	20	80	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	120	7317.93	6762.38	-555.55	34.01	53.24	19.22	7351.95	6815.61	-536.33
40	20	180	7695.78	7004.28	-691.49	40.95	107.52	66.57	7736.73	7111.81	-624.92

Table 4-CLXXXI: Temperature - 12.5 MPa Continuous – 1s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	7012.63	6801.91	-210.73	14.40	26.77	12.37	7027.03	6828.67	-198.36
20	1	80	7104.54	6893.50	-211.04	26.27	37.50	11.22	7130.82	6931.00	-199.82
20	1	120	7295.73	7095.57	-200.16	28.68	45.74	17.06	7324.41	7141.30	-183.10
20	1	180	7851.57	7655.44	-196.14	27.51	42.87	15.36	7879.09	7698.31	-180.78

Table 4-CLXXXII: Temperature - 12.5 MPa Continuous – 10s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	10	RT	6741.82	6422.23	-319.59	50.99	71.37	20.38	6792.81	6493.60	-299.20
20	10	80	7177.32	6875.33	-301.99	64.29	83.47	19.18	7241.62	6958.80	-282.81
20	10	120	7047.57	6735.03	-312.53	52.73	71.29	18.56	7100.30	6806.32	-293.97
20	10	180	7599.48	7335.89	-263.59	48.25	70.30	22.05	7647.73	7406.19	-241.54

Table 4-CLXXXIII: Temperature - 12.5 MPa Continuous – 20s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	20	RT	7043.85	6641.49	-402.36	27.55	51.04	23.49	7071.40	6692.53	-378.87
20	20	80	7516.25	7092.79	-423.46	54.55	76.80	22.26	7570.80	7169.59	-401.20
20	20	120	7420.30	6989.72	-430.58	36.75	57.46	20.71	7457.05	7047.18	-409.87
20	20	180	7923.81	7505.05	-418.76	83.32	116.46	33.13	8007.13	7621.51	-385.63

Table 4-CLXXXIV: Temperature - 12.5 MPa Continuous – 40s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	40	RT	7060.77	6450.56	-610.21	29.69	64.26	34.58	7090.46	6514.82	-575.64
20	40	80	7149.42	6534.05	-615.37	64.72	94.46	29.74	7214.14	6628.51	-585.63
20	40	120	7337.21	6671.90	-665.31	34.22	66.72	32.50	7371.43	6738.62	-632.81
20	40	180	7881.02	7234.19	-646.83	79.32	122.81	43.49	7960.34	7357.00	-603.34

Table 4-CLXXXV: Temperature - 12.5 MPa Continuous – 80s – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	6937.14	5988.54	-948.59	29.58	84.93	55.35	6966.72	6073.47	-893.25
20	80	80	7128.56	6129.77	-998.79	53.92	108.56	54.64	7182.48	6238.33	-944.15
20	80	120	7075.14	6117.95	-957.19	58.04	111.48	53.44	7133.18	6229.43	-903.75
20	80	180	7488.67	6518.85	-969.81	57.53	117.25	59.72	7546.20	6636.11	-910.09

Table 4-CLXXXVI: Temperature - 12.5 MPa Continuous – 40s Creep (20s Recovery) – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
40	20	RT	6759.81	6170.80	-589.02	64.63	102.08	37.45	6824.44	6272.88	-551.56
40	20	80	7322.35	6722.74	-599.60	52.38	90.81	38.44	7374.72	6813.56	-561.17
40	20	120	7305.44	6671.30	-634.14	45.05	82.88	37.82	7350.50	6754.17	-596.32
40	20	180	7544.92	6973.56	-571.36	71.70	109.96	38.26	7616.62	7083.52	-533.10

4.4 Effect of Creep Duration

This section evaluates the effects that the creep duration has on the response of the material. As the majority of the testing conditions were performed with a creep duration of 20s, with only one having a creep duration of 40s, in order to better evaluate the influence of the creep duration the ratio of the creep to recovery duration is used.

In this section, when evaluating the relationship between the parameters as a function of the creep to recovery ratio, the 20s creep / 1s recovery was not always included when calculating the trend line or fitting the data. Since this testing scenario results in a ratio of 20 which is significantly larger than the other ratios, including this data set could significantly skew the trend line, and special consideration was required to ensure it did not skew any relationships.

As the data compared in this section is the same as that presented when evaluating the influence of the recovery duration, figures showing the cycle response of the data shall not be presented, and the reader referred to figures presented in the section 4.2 and the Appendix A.

4.4.1 Strain

4.4.1.1 *Creep / Recovered Strain*

As with the previous sections, Table 4-CLXXXVII through Table 4-CXCVIII contain the creep and recovered strain data sorted based on the ratio of the creep to the recovery duration. The data is sorted similar to the tables in section 4.2.1, with each of the test temperatures for a single loading condition presented together.

First evaluating the cycle creep strain, the data shows a general decreasing trend as the creep ratio increases. However, this trend is shows fairly weak correlation with the best fit line. There is a slight improvement in the correlation for the difference between the final and initial cycles, however it is still fairly weak. Comparing the 40s creep / 20s recovery test with the 20s creep / 20s recovery, the creep strain is generally larger for the 40s testing scenario. This result is somewhat expected as the sample is allowed to creep for longer durations, allowing more time for the samples to creep. Comparing the 40s creep / 20s recovery scenario with the other test with a creep to recovery ratio of 2 (20s creep / 10s recovery), particularly for the final cycle and the overall change in the creep strain, the 40s creep test is generally larger in magnitude.

Similar to the creep strain, the recovered strain shows a decreasing trend with increase in the ratio. As with the creep strain, this trend has a weak correlation between the data and the trend line. The recovered strain shows an improvement in the correlation coefficient for the final cycle and the difference between the cycles, but is still relatively weak. Comparing the 40s / 20s test with the 20s / 20s, the first cycle does not show any clear trend with respect to the recovered strain. However, the majority of the data sets for the final cycle and the difference between the final and initial are larger for the 40s / 20s recovered strains. Similarly, comparing the two data sets with a ratio of 2, while no clear trend is present for the initial cycles, for the final cycle and difference in cycles, the 40s / 20s are larger.

Evaluating the unrecovered creep strain with respect to an increase in the creep to recovery ratio, there is a slight increasing trend as the ratio increases for the first and final cycles. However, this trend is generally a weak correlation for the data sets. For the difference between the final and initial cycles, present in the majority of the data sets there is decreasing trend, however this trend shows quite weak correlation. Excluding the 20s creep / 1s recovery data set is not included when evaluating the trendline, the correlation improves particularly for the 12.5 / 0.5 MPa continuous loading, however is generally quite weak for the other loading scenarios.

Lastly, comparing the accumulated unrecovered creep strain by the final cycle, there is an increasing trend present in the majority of the data sets. This increasing relationship shows generally weak correlation with the trend line, with the strongest correlations present for the 8 / 0.1 MPa loading. Comparing the 40s / 20s with the 20s / 20s test, the amount of accumulated unrecovered strain is generally larger for the 40s / 20s tests. Comparing the 40s / 20s with the 20s / 10s, there is no clear difference with half of the data sets showing larger values for the 40s / 20s, and the other half larger for the other.

Table 4-CLXXXVII: Creep Ratio - 8 MPa - Room Temperature - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	RT	0.25	26	122	95	41	160	119	-14	-39	-24	-3823
20	40	RT	0.5	19	75	56	33	103	70	-15	-28	-14	-2995
20	20	RT	1	12	33	21	13	57	44	-1	-23	-23	-1771
20	10	RT	2	14	42	28	21	58	37	-7	-16	-9	-2015
40	20	RT	2	25	80	54	36	109	73	-10	-30	-19	-2978
20	1	RT	20	9	6	-2	4	11	7	5	-5	-9	-208

Table 4-CLXXXVIII: Creep Ratio - 8 MPa - 80 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{-1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	80	0.25	45	142	97	49	157	108	-4	-15	-11	-3409
20	40	80	0.5	22	76	54	31	104	74	-9	-28	-19	-2792
20	20	80	1	30	60	30	39	83	44	-9	-23	-14	-2377
20	10	80	2	40	67	27	54	77	23	-15	-10	4	-2198
40	20	80	2	16	60	44	16	88	72	0	-28	-28	-2193
20	1	80	20	15	16	1	7	14	7	7	2	-5	-570

Table 4-CLXXXIX: Creep Ratio - 8 MPa - 120 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	120	0.25	20	120	99	23	132	109	-2	-13	-10	-2893
20	40	120	0.5	24	82	58	40	106	66	-16	-24	-9	-2589
20	20	120	1	30	56	26	16	65	49	14	-9	-23	-1875
20	10	120	2	38	62	23	40	81	42	-1	-19	-18	-2363
40	20	120	2	31	90	60	33	110	77	-2	-19	-17	-2474
20	1	120	20	18	27	9	6	41	35	12	-14	-26	-926

Table 4-CXC: Creep Ratio - 8 MPa - 180 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	180	0.25	51	148	97	52	164	113	0	-16	-16	-1947
20	40	180	0.5	40	95	55	35	105	70	5	-10	-15	-1858
20	20	180	1	54	85	31	57	95	39	-3	-11	-8	-1572
20	10	180	2	44	70	26	47	76	29	-3	-6	-3	-1205
40	20	180	2	29	47	17	27	59	32	3	-12	-15	-894
20	1	180	20	43	42	-1	30	52	22	13	-10	-23	-540

Table 4-CXCI: Creep Ratio - 12.5 MPa Non-Continuous - Room Temperature - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	RT	0.25	8	74	65	8	77	69	0	-3	-3	-226
20	40	RT	0.5	6	45	39	13	21	7	-8	24	32	1550
20	20	RT	1	9	51	42	7	47	40	2	4	2	371
20	10	RT	2	24	39	15	11	28	17	13	12	-1	2750
40	20	RT	2	41	85	44	20	60	40	21	25	5	3418
20	1	RT	20	16	10	-6	2	3	1	13	6	-7	660

Table 4-CXCII: Creep Ratio - 12.5 MPa Non-Continuous - 80 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	80	0.25	23	125	101	20	126	105	3	-1	-4	-710
20	40	80	0.5	28	103	75	27	106	79	1	-3	-4	-639
20	20	80	1	27	71	44	19	64	45	8	7	-1	295
20	10	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CXCIII: Creep Ratio - 12.5 MPa Non-Continuous - 120 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{-1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	120	0.25	38	138	100	34	136	102	5	2	-2	-818
20	40	120	0.5	39	94	55	37	98	61	2	-4	-6	-408
20	20	120	1	28	52	24	26	52	26	2	0	-1	-288
20	10	120	2	52	67	15	25	52	27	27	15	-12	2994
40	20	120	2	36	62	26	16	46	30	20	16	-4	2215
20	1	120	20	28	35	7	4	21	17	24	14	-10	1986

Table 4-CXCIV: Creep Ratio - 12.5 MPa Non-Continuous - 180 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Creep : Recovery Ratio										
20	80	180	0.25	41	128	87	36	122	85	5	6	1	496
20	40	180	0.5	48	87	39	40	81	41	8	6	-2	375
20	20	180	1	76	81	5	47	81	33	29	0	-29	583
20	10	180	2	42	58	15	26	59	33	16	-1	-17	587
40	20	180	2	53	108	56	35	101	66	18	7	-11	748
20	1	180	20	42	45	4	10	38	28	32	7	-25	1234

Table 4-CXCV: Creep Ratio - 12.5 MPa Continuous - Room Temperature - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [$^{\circ}\text{C}$]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	RT	0.25	20	101	81	17	97	80	4	5	1	385
20	40	RT	0.5	15	62	47	11	60	49	4	2	-2	333
20	20	RT	1	15	45	30	10	43	34	5	1	-4	384
20	10	RT	2	36	59	22	27	55	28	10	4	-6	493
40	20	RT	2	40	85	45	29	81	52	11	4	-7	684
20	1	RT	20	13	26	12	5	22	17	9	4	-5	529

Table 4-CXCVI: Creep Ratio - 12.5 MPa Continuous - 80 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{j=1}^{180} (\epsilon_c - \epsilon_r)$
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	80	80	0.25	41	128	87	35	123	88	6	5	-2	232
20	40	80	0.5	34	90	56	36	89	52	-2	2	4	160
20	20	80	1	22	45	24	13	43	31	9	2	-7	173
20	10	80	2	36	55	19	19	53	34	17	2	-15	236
40	20	80	2	30	73	43	14	74	60	15	-2	-17	100
20	1	80	20	36	47	11	22	41	20	15	6	-9	451

Table 4-CXCVII: Creep Ratio - 12.5 MPa Continuous - 120 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio										
20	80	120	0.25	44	133	89	43	122	79	1	11	10	1081
20	40	120	0.5	34	76	42	27	77	50	6	-1	-8	603
20	20	120	1	34	56	23	21	57	36	12	-1	-13	581
20	10	120	2	47	69	21	40	64	24	8	4	-3	753
40	20	120	2	32	77	45	19	73	54	13	4	-9	761
20	1	120	20	30	29	-1	6	20	14	25	9	-16	1026

Table 4-CXCVIII: Creep Ratio - 12.5 MPa Continuous - 180 °C - Creep / Recovery Strain

				Strain [$\mu\epsilon$]									$\sum_1^{180} (\epsilon_c - \epsilon_r)$
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio										
20	80	180	0.25	65	144	79	52	136	85	13	7	-6	1464
20	40	180	0.5	47	89	42	35	79	44	12	10	-2	1367
20	20	180	1	55	76	21	40	67	26	14	10	-5	1299
20	10	180	2	51	61	10	24	51	27	27	10	-18	1198
40	20	180	2	66	99	33	35	87	52	31	12	-18	1752
20	1	180	20	41	18	-23	6	9	3	35	8	-26	1381

4.4.1.2 Unrecovered Strain

Evaluating next the unrecovered strain, Table 4-CXCIX through Table 4-CCX contain the unrecovered strain data sorted based on increasing creep to recovery duration ratio. Comparing the change in the unrecovered strain with change in the creep ratio, as the ratio increased there was an increase in the unrecovered strain. Generally, the correlation is somewhat weak, however when the ratio value of 20 was excluded from the trend data, the final and difference correlation improved and became stronger. Comparing the 40s / 20s with the 20s / 20s data sets, there is no clear difference between the two sets. However, when comparing the two ratios of 2, the 40s / 20s showed consistently larger values for the unrecovered strain for the final cycle and the difference between the cycles than the 20s / 10s.

Comparing the calculated unrecovered instantaneous strain with the creep ratio, there is a general decreasing trend in the calculated unrecovered instantaneous strain as the ratio increases for the 1st and 180th cycles. However, this decreasing trend shows generally weak correlation with the best fit trendline, regardless if the 20 ratio is included or not. With respect to the difference between the final and initial cycle, there is no clear trend in the data. Comparing the 40s / 20s with the 20s / 20s and 20s / 10s tests, there is no clear difference between either of these data sets. As previously discussed, this lack of trends or correlations between the creep ratio and the unrecovered instantaneous is not entirely surprising when compared with the plotted values for the unrecovered instantaneous strain which shows large fluctuations cycle to cycle.

Table 4-CXCIX: Creep Ratio - 8 MPa – Room Temperature – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	0.25	2	16	13	-14	-39	-24	17	39	22
20	40	RT	0.5	5	18	14	-15	-28	-14	19	29	10
20	20	RT	1	4	19	15	-1	-23	-23	5	24	19
20	10	RT	2	5	20	15	-7	-16	-9	12	16	4
40	20	RT	2	6	22	16	-10	-30	-19	16	29	12
20	1	RT	20	11	33	22	5	-5	-9	6	6	0

Table 4-CC: Creep Ratio - 8 MPa – 80 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	80	0.25	7	21	14	-4	-15	-11	10	13	2
20	40	80	0.5	7	31	24	-9	-28	-19	15	31	15
20	20	80	1	15	38	23	-9	-23	-14	24	17	-6
20	10	80	2	3	27	23	-15	-10	4	18	12	-6
40	20	80	2	10	50	41	0	-28	-28	10	27	17
20	1	80	20	11	44	33	7	2	-5	4	-1	-5

Table 4-CCI: Creep Ratio - 8 MPa – 120 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	120	0.25	4	8	4	-2	-13	-10	6	11	5
20	40	120	0.5	-1	19	21	-16	-24	-9	14	28	13
20	20	120	1	21	57	36	14	-9	-23	7	10	3
20	10	120	2	10	41	31	-1	-19	-18	11	12	1
40	20	120	2	9	49	40	-2	-19	-17	11	16	5
20	1	120	20	16	56	39	12	-14	-26	4	8	4

Table 4-CCII: Creep Ratio - 8 MPa – 180 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	180	0.25	5	26	21	0	-16	-16	5	19	14
20	40	180	0.5	9	59	50	5	-10	-15	4	13	9
20	20	180	1	11	90	79	-3	-11	-8	14	13	-1
20	10	180	2	5	79	73	-3	-6	-3	8	6	-3
40	20	180	2	9	86	77	3	-12	-15	7	10	4
20	1	180	20	24	96	73	13	-10	-23	11	10	-1

Table 4-CCIII: Creep Ratio - 12.5 MPa Non-Continuous - Room Temperature - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	0.25	5	6	2	0	-3	-3	5	1	-4
20	40	RT	0.5	-3	6	10	-8	24	32	4	-24	-28
20	20	RT	1	2	6	4	2	4	2	0	-4	-4
20	10	RT	2	-5	17	22	13	12	-1	-18	-11	7
40	20	RT	2	-2	25	27	21	25	5	-23	-25	-2
20	1	RT	20	-1	23	24	13	6	-7	-14	-5	9

Table 4-CCIV: Creep Ratio - 12.5 MPa Non-Continuous– 80 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	80	0.25	3	21	18	3	-1	-4	0	2	2
20	40	80	0.5	10	37	27	1	-3	-4	9	9	0
20	20	80	1	7	8	1	8	7	-1	-1	-5	-3
20	10	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CCV: Creep Ratio - 12.5 MPa Non-Continuous– 120 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	120	0.25	5	-17	-22	5	2	-2	0	-4	-4
20	40	120	0.5	7	27	20	2	-4	-6	5	5	0
20	20	120	1	7	38	31	2	0	-1	5	0	-5
20	10	120	2	5	60	55	27	15	-12	-21	-15	6
40	20	120	2	3	66	63	20	16	-4	-16	-17	0
20	1	120	20	14	73	59	24	14	-10	-10	-13	-3

Table 4-CCVI: Creep Ratio - 12.5 MPa Non-Continuous– 180 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	180	0.25	5	61	57	5	6	1	0	-9	-9
20	40	180	0.5	8	87	78	8	6	-2	1	-5	-6
20	20	180	1	25	239	214	29	0	-29	-4	1	4
20	10	180	2	10	106	96	16	-1	-17	-6	-1	5
40	20	180	2	15	114	99	18	7	-11	-3	-3	0
20	1	180	20	27	128	101	32	7	-25	-5	-6	-1

Table 4-CCVII: Creep Ratio - 12.5 MPa Continuous– Room Temperature – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	RT	0.25	1	17	16	4	5	1	-2	-3	-1
20	40	RT	0.5	1	20	19	4	2	-2	-3	-2	1
20	20	RT	1	3	21	18	5	1	-4	-2	-2	0
20	10	RT	2	5	28	23	10	4	-6	-5	-3	2
40	20	RT	2	3	30	27	11	4	-7	-8	-4	4
20	1	RT	20	9	37	28	9	4	-5	0	-3	-3

Table 4-CCVIII: Creep Ratio - 12.5 MPa Continuous– 80 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	80	0.25	4	19	15	6	5	-2	-3	-5	-2
20	40	80	0.5	11	35	23	-2	2	4	14	0	-13
20	20	80	1	10	45	35	9	2	-7	1	0	-1
20	10	80	2	14	48	34	17	2	-15	-3	-1	2
40	20	80	2	9	49	41	15	-2	-17	-6	1	7
20	1	80	20	14	57	43	15	6	-9	0	-3	-3

Table 4-CCIX: Creep Ratio - 12.5 MPa Continuous– 120 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	120	0.25	-1	28	29	1	11	10	-2	-9	-7
20	40	120	0.5	6	44	38	6	-1	-8	-1	-1	0
20	20	120	1	11	67	56	12	-1	-13	-1	-1	0
20	10	120	2	3	56	53	8	4	-3	-5	-3	2
40	20	120	2	7	56	49	13	4	-9	-5	-6	-1
20	1	120	20	20	79	58	25	9	-16	-4	-7	-3

Table 4-CCX: Creep Ratio - 12.5 MPa Continuous– 180 °C – Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	80	180	0.25	1	70	68	13	7	-6	-12	-8	4
20	40	180	0.5	7	105	97	12	10	-2	-5	-12	-8
20	20	180	1	19	167	148	14	10	-5	5	-10	-14
20	10	180	2	14	118	104	27	10	-18	-14	-10	4
40	20	180	2	19	144	125	31	12	-18	-12	-11	1
20	1	180	20	31	150	119	35	8	-26	-3	-8	-5

4.4.2 Modulus

Table 4-CCXI through Table 4-CCXXII contain the calculated values for the instantaneous modulus sorted based on increasing ratio of the creep to recovery duration.

Evaluating first the instantaneous modulus calculated using the loading curve, for the 2nd cycle there is an increasing trend in the instantaneous modulus as the creep ratio increases. For the difference between the final cycle and the 2nd cycle, there is a decreasing trend. However, both these trends show generally weak correlation between the trendline and the data. For the majority of the testing conditions the instantaneous modulus calculated was higher for the 40s / 20s test than the 20s / 20s. Comparing the two 2 ratios, for the final cycle and the difference between the cycles, the instantaneous modulus is larger for the 40s / 20s in approximately 2/3rds of the data sets.

As with the instantaneous modulus for the loading curve, comparing the modulus calculated from the unloading curve, for the 2nd cycle there is a general increasing trend in the modulus with increase in ratio. Evaluating the final cycle, for the two continuous loading conditions there is a decreasing trend in the modulus data with increase in the ratio. However, this trend is not present for the non-continuous loading scenario. Lastly, comparing the difference between the cycles, there is a decreasing trend in the modulus with increase in the ratio. When evaluating the correlation coefficient between the trends and the data sets, there is a general weak correlation, with the difference between the cycles showing the strongest correlation. Comparing the 40s / 20s with the 20s / 20s, as with the instantaneous loading modulus the 40s / 20s is larger for the majority of data sets. When comparing the two 2 ratio's, while no clear difference for the 2nd cycle, the final cycle and difference are larger for the 40s / 20s test.

With respect to the difference between the two modulus values, as the creep ratio increases the difference between them increased as well. This trend was fairly consistent for all analysis, however when evaluating the correlation coefficient, the relationship is weakly correlated. The exception to this being the 12.5 / 0.5 MPa non-continuous loading which showed very strong correlation for three temperatures (the exception being the 180 °C).

Table 4-CCXI: Creep Ratio - 8 MPa – Room Temperature – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	0.25	9.03	9.35	0.32	9.24	10.10	0.87	-0.21	-0.76	-0.55
20	40	RT	0.5	8.99	9.07	0.08	9.16	9.60	0.44	-0.17	-0.53	-0.36
20	20	RT	1	8.99	9.04	0.04	9.08	9.34	0.26	-0.09	-0.31	-0.22
20	10	RT	2	9.10	9.21	0.11	9.19	9.51	0.32	-0.09	-0.30	-0.21
40	20	RT	2	9.07	9.15	0.08	9.21	9.85	0.64	-0.14	-0.70	-0.56
20	1	RT	20	9.12	9.11	-0.02	9.08	9.22	0.13	0.04	-0.11	-0.15

Table 4-CCXII: Creep Ratio - 8 MPa – 80 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	80	0.25	9.12	9.83	0.70	9.39	10.36	0.96	-0.27	-0.53	-0.26
20	40	80	0.5	9.07	9.24	0.18	9.29	9.76	0.47	-0.22	-0.51	-0.29
20	20	80	1	9.04	9.13	0.09	9.16	9.60	0.43	-0.12	-0.47	-0.35
20	10	80	2	9.24	9.32	0.07	9.49	9.64	0.15	-0.25	-0.32	-0.08
40	20	80	2	9.06	9.24	0.17	9.16	9.64	0.48	-0.09	-0.40	-0.31
20	1	80	20	9.17	9.23	0.06	9.17	9.29	0.12	0.00	-0.06	-0.06

Table 4-CCXIII: Creep Ratio - 8 MPa – 120 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	120	0.25	9.05	9.44	0.39	9.17	9.94	0.76	-0.12	-0.50	-0.38
20	40	120	0.5	9.04	9.20	0.16	9.22	9.66	0.44	-0.18	-0.46	-0.28
20	20	120	1	9.03	9.08	0.05	9.09	9.32	0.23	-0.06	-0.24	-0.18
20	10	120	2	9.10	9.25	0.16	9.31	9.59	0.27	-0.22	-0.33	-0.12
40	20	120	2	9.11	9.44	0.33	9.30	9.82	0.52	-0.19	-0.38	-0.18
20	1	120	20	9.21	9.27	0.06	9.26	9.45	0.19	-0.05	-0.19	-0.14

Table 4-CCXIV: Creep Ratio - 8 MPa – 180 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	180	0.25	8.96	9.43	0.47	9.08	9.82	0.74	-0.12	-0.39	-0.27
20	40	180	0.5	8.84	9.04	0.20	8.94	9.42	0.48	-0.10	-0.37	-0.27
20	20	180	1	8.83	8.97	0.15	8.94	9.33	0.38	-0.11	-0.35	-0.24
20	10	180	2	9.05	9.18	0.13	9.17	9.49	0.32	-0.12	-0.31	-0.19
40	20	180	2	8.98	9.09	0.11	9.02	9.25	0.23	-0.04	-0.16	-0.12
20	1	180	20	9.12	9.16	0.04	9.17	9.35	0.17	-0.05	-0.18	-0.13

Table 4-CCXV: Creep Ratio - 12.5 MPa Non-Continuous – Room Temperature – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	0.25	11.49	11.52	0.03	11.42	11.68	0.26	0.07	-0.16	-0.23
20	40	RT	0.5	10.78	10.70	-0.08	10.77	10.70	-0.07	0.01	0.00	-0.01
20	20	RT	1	11.45	11.55	0.10	11.44	11.56	0.12	0.01	-0.01	-0.02
20	10	RT	2	12.28	12.42	0.14	12.17	12.20	0.03	0.11	0.22	0.11
40	20	RT	2	12.45	12.66	0.21	12.19	12.38	0.19	0.26	0.28	0.02
20	1	RT	20	12.31	12.28	-0.02	12.12	12.15	0.02	0.18	0.13	-0.05

Table 4-CCXVI: Creep Ratio - 12.5 MPa Non-Continuous – 80 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	80	0.25	9.92	10.10	0.18	9.95	10.31	0.35	-0.03	-0.21	-0.17
20	40	80	0.5	9.54	9.76	0.21	9.58	9.93	0.35	-0.04	-0.18	-0.14
20	20	80	1	9.54	9.71	0.17	9.54	9.73	0.19	-0.01	-0.02	-0.02
20	10	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CCXVII: Creep Ratio - 12.5 MPa Non-Continuous – 120 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_t			E_u			$E_t - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	120	0.25	9.17	9.38	0.20	9.20	9.54	0.34	-0.02	-0.16	-0.14
20	40	120	0.5	9.49	9.51	0.02	9.49	9.57	0.07	0.00	-0.06	-0.06
20	20	120	1	9.27	9.39	0.12	9.30	9.53	0.23	-0.03	-0.14	-0.11
20	10	120	2	11.12	11.13	0.01	10.98	11.00	0.02	0.14	0.13	-0.01
40	20	120	2	11.09	11.18	0.09	10.97	11.02	0.05	0.12	0.16	0.04
20	1	120	20	11.08	11.20	0.12	11.04	10.99	-0.05	0.04	0.21	0.16

Table 4-CCXVIII: Creep Ratio - 12.5 MPa Non-Continuous – 180 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_t			E_u			$E_t - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	180	0.25	9.82	10.09	0.27	9.83	10.14	0.31	-0.01	-0.05	-0.04
20	40	180	0.5	9.76	9.87	0.12	9.75	9.88	0.12	0.00	0.00	-0.01
20	20	180	1	9.36	9.50	0.14	9.32	9.49	0.18	0.05	0.01	-0.04
20	10	180	2	9.88	9.97	0.08	9.89	9.99	0.10	0.00	-0.02	-0.02
40	20	180	2	9.90	10.10	0.20	9.90	10.16	0.26	0.00	-0.06	-0.06
20	1	180	20	9.93	10.00	0.07	9.90	9.99	0.09	0.03	0.01	-0.02

Table 4-CCXIX: Creep Ratio - 12.5 MPa Continuous – Room Temperature – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	RT	0.25	11.05	11.33	0.29	11.04	11.39	0.35	0.01	-0.06	-0.06
20	40	RT	0.5	11.03	11.17	0.14	11.02	11.20	0.18	0.01	-0.03	-0.04
20	20	RT	1	11.02	11.12	0.10	11.02	11.12	0.10	0.00	0.00	0.00
20	10	RT	2	11.13	11.23	0.09	11.14	11.26	0.11	-0.01	-0.03	-0.02
40	20	RT	2	11.15	11.37	0.22	11.15	11.40	0.26	0.00	-0.04	-0.04
20	1	RT	20	11.07	11.09	0.02	11.06	11.11	0.05	0.01	-0.01	-0.03

Table 4-CCXX: Creep Ratio - 12.5 MPa Continuous – 80 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	80	0.25	10.48	10.81	0.33	10.51	10.91	0.40	-0.04	-0.10	-0.06
20	40	80	0.5	10.47	10.63	0.16	10.49	10.74	0.25	-0.02	-0.11	-0.08
20	20	80	1	10.35	10.46	0.11	10.35	10.48	0.13	0.00	-0.02	-0.02
20	10	80	2	10.52	10.62	0.10	10.55	10.66	0.11	-0.03	-0.04	-0.01
40	20	80	2	10.52	10.66	0.14	10.52	10.74	0.22	-0.01	-0.08	-0.07
20	1	80	20	10.54	10.57	0.03	10.55	10.62	0.07	-0.01	-0.05	-0.04

Table 4-CCXXI: Creep Ratio - 12.5 MPa Continuous – 120 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	120	0.25	10.61	10.96	0.35	10.63	11.00	0.38	-0.01	-0.04	-0.03
20	40	120	0.5	10.53	10.62	0.09	10.53	10.68	0.15	0.00	-0.06	-0.06
20	20	120	1	10.42	10.53	0.10	10.42	10.55	0.14	0.01	-0.03	-0.03
20	10	120	2	10.70	10.76	0.05	10.68	10.77	0.09	0.02	-0.02	-0.04
40	20	120	2	10.65	10.82	0.17	10.64	10.81	0.17	0.01	0.01	-0.01
20	1	120	20	10.71	10.74	0.03	10.66	10.69	0.02	0.04	0.05	0.01

Table 4-CCXXII: Creep Ratio - 12.5 MPa Continuous – 180 °C – Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Creep : Recovery Ratio	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	180	0.25	10.15	10.47	0.32	10.15	10.44	0.29	0.00	0.03	0.03
20	40	180	0.5	10.07	10.25	0.18	10.01	10.16	0.16	0.07	0.08	0.02
20	20	180	1	9.95	10.07	0.11	9.91	9.99	0.08	0.05	0.08	0.03
20	10	180	2	10.27	10.27	-0.01	10.23	10.24	0.01	0.04	0.03	-0.01
40	20	180	2	10.32	10.41	0.10	10.24	10.37	0.13	0.08	0.04	-0.04
20	1	180	20	10.29	10.24	-0.05	10.18	10.17	-0.02	0.11	0.08	-0.03

4.4.3 Strain Energy Density

4.4.3.1 Overall Strain Energy Density

Table 4-CCXXIII through Table 4-CCXXXIV present the overall strain energy densities sorted based on increasing creep ratio. Comparing the overall total strain energy density, there is a decreasing trend in the data as the creep to recovery ratio increases. This trend is present for the 2nd, 180th cycles and the difference between the two cycles. When comparing the trend line with the data sets, there is a moderate correlation for the 2nd cycle and the difference between the cycles, and a slightly stronger correlation for the 180th cycle.

Evaluating the overall stored strain energy density, no clear trend is present for the data for the 2nd cycle. Both the final cycle and the difference between the cycles show an increasing trend with increase in the ratio. These trends when compared with the line of best fit show a moderate correlation.

The dissipated strain energy density shows a decreasing trend with increase in the ratio, with a moderate to strong correlation with the line of best fit. Lastly, the unrecovered strain energy density shows an increasing trend, with generally weak to moderate correlation for the 2nd cycle and strong correlation for the final cycle and change.

Comparing the data for the 40s / 20s and 20s / 20s tests, the overall total strain energy does not show any clear distinction for the 2nd or final cycle. However for the difference between the two cycles, the 40s / 20s has a value larger than that of the other test. With respect to the overall strain energy density, the 40s / 20s is consistently smaller than the values calculated for the 20s / 20s. The dissipated strain energy density values were larger for the 40s / 20s test, and no trend was present for the unrecovered strain energy density.

Comparing the two 2 ratios, the 40s / 20s and the 20s / 10s, both the total and dissipated strain energy are larger for the 40s / 20s while the stored and unrecovered are smaller. These relationships are particularly noticeable for the final cycle and the difference between the cycles.

Table 4-CCXXIII: Creep Ratio - 8 MPa – Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3764.38	4488.15	723.77	3317.17	2588.69	-728.48	447.21	1899.46	1452.25	0.64	1.86	1.22
20	40	0.5	3680.85	4130.53	449.68	3394.49	2930.00	-464.49	286.36	1200.53	914.17	0.71	2.00	1.29
20	20	1	3508.84	3811.03	302.19	3555.59	3232.51	-323.09	-46.75	578.53	625.28	1.57	3.08	1.50
20	10	2	3600.69	3820.50	219.81	3398.32	3163.53	-234.80	202.37	656.97	454.60	2.48	4.76	2.28
40	20	2	3727.26	4160.48	433.22	3354.75	2902.05	-452.70	372.51	1258.44	885.92	1.69	3.58	1.89
20	1	20	3412.23	3558.58	146.36	3592.34	3420.74	-171.60	-180.11	137.85	317.96	6.48	10.82	4.34

Table 4-CCXXIV: Creep Ratio - 8 MPa – 80 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3830.03	4520.55	690.52	3230.82	2532.73	-698.09	599.21	1987.82	1388.61	1.37	2.27	0.90
20	40	0.5	3685.65	4128.62	442.97	3350.13	2907.40	-442.73	335.53	1221.23	885.70	0.42	3.93	3.51
20	20	1	3690.81	3973.22	282.41	3353.20	3065.28	-287.92	337.61	907.94	570.33	2.93	4.91	1.98
20	10	2	3810.99	4015.21	204.22	3183.64	2966.42	-217.22	627.35	1048.79	421.44	3.53	6.40	2.87
40	20	2	3567.67	4003.31	435.64	3490.84	3049.60	-441.23	76.83	953.70	876.88	2.24	6.94	4.70
20	1	20	3482.62	3607.13	124.51	3515.17	3333.89	-181.28	-32.56	273.24	305.80	5.68	13.86	8.18

Table 4-CCXXV: Creep Ratio - 8 MPa – 120 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3629.97	4395.62	765.65	3470.11	2767.19	-702.91	159.86	1628.42	1468.56	0.90	0.44	-0.46
20	40	0.5	3702.21	4175.57	473.36	3403.70	2986.08	-417.62	298.51	1189.49	890.98	0.43	2.04	1.61
20	20	1	3661.65	3962.43	300.78	3551.87	3246.62	-305.25	109.78	715.81	606.03	1.84	7.75	5.91
20	10	2	3796.04	3964.85	168.82	3317.85	3073.84	-244.01	478.19	891.02	412.83	3.38	8.84	5.46
40	20	2	3805.40	4166.17	360.78	3354.54	2900.58	-453.95	450.86	1265.59	814.73	2.03	7.27	5.24
20	1	20	3560.88	3709.30	148.42	3451.89	3304.45	-147.44	108.99	404.85	295.86	7.50	16.87	9.36

Table 4-CCXXVI: Creep Ratio - 8 MPa – 180 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3937.11	4674.07	736.96	3424.13	2717.61	-706.52	512.99	1956.46	1443.48	0.07	3.11	3.04
20	40	0.5	3873.95	4297.10	423.15	3583.57	3118.43	-465.13	290.38	1178.66	888.28	0.60	6.72	6.12
20	20	1	3972.01	4257.01	285.00	3489.62	3213.81	-275.81	482.39	1043.20	560.81	2.48	12.40	9.92
20	10	2	3888.92	4058.44	169.52	3384.85	3165.05	-219.80	504.07	893.39	389.32	4.54	15.67	11.13
40	20	2	3583.52	3968.47	384.96	3742.32	3333.06	-409.27	-158.81	635.42	794.22	3.01	12.25	9.24
20	1	20	3762.94	3899.04	136.10	3395.67	3236.65	-159.02	367.27	662.39	295.12	8.84	25.33	16.48

Table 4-CCXXVII: Creep Ratio - 12.5 MPa Non-Continuous – Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6615.24	7724.04	1108.80	6981.58	5979.21	-	-366.34	1744.84	2111.17	12.37	12.80	0.43
20	40	0.5	6898.69	8023.71	1125.02	7038.12	6837.22	-200.91	-139.43	1186.49	1325.92	11.21	16.36	5.15
20	20	1	6939.68	7412.49	472.81	6801.57	6397.56	-404.01	138.11	1014.93	876.81	12.14	14.21	2.07
20	10	2	6768.96	7031.28	262.32	6394.60	6155.65	-238.96	374.36	875.63	501.27	14.87	24.66	9.79
40	20	2	6914.40	7399.60	485.20	6312.11	5826.82	-485.29	602.30	1572.78	970.48	12.48	25.40	12.92
20	1	20	6455.13	6643.92	188.79	6647.17	6489.31	-157.86	-192.03	154.61	346.65	19.25	34.55	15.30

Table 4-CCXXVIII: Creep Ratio - 12.5 MPa Non-Continuous – 80 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8157.81	9329.63	1171.81	7661.45	6501.36	-	496.36	2828.27	2331.91	12.64	23.30	10.65
20	40	0.5	8497.21	9206.49	709.28	7898.98	7123.33	-775.66	598.23	2083.16	1484.93	15.38	29.86	14.48
20	20	1	8187.41	8649.31	461.90	7787.16	7240.52	-546.64	400.25	1408.79	1008.54	16.82	16.37	-0.45
20	10	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CCXXIX: Creep Ratio - 12.5 MPa Non-Continuous – 120 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8892.66	10103.93	1211.27	8380.39	7106.48	-1273.91	512.27	2997.45	2485.18	16.99	5.17	-11.82
20	40	0.5	8345.78	8865.33	519.55	8225.53	7717.93	-507.60	120.24	1147.40	1027.16	19.99	34.73	14.74
20	20	1	8878.24	9501.31	623.08	8230.57	7404.07	-826.51	647.66	2097.24	1449.58	19.09	24.92	5.83
20	10	2	7680.90	8009.65	328.75	7010.62	6769.47	-241.15	670.27	1240.18	569.90	18.55	49.15	30.60
40	20	2	7421.62	7936.09	514.48	7351.95	6815.61	-536.33	69.67	1120.48	1050.81	16.54	49.28	32.74
20	1	20	7390.82	7617.15	226.33	7173.48	6987.42	-186.06	217.33	629.72	412.39	24.43	61.59	37.16

Table 4-CCXXX: Creep Ratio - 12.5 MPa Non-Continuous – 180 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8321.51	9383.18	1061.66	8019.51	6976.49	-1043.01	302.01	2406.68	2104.68	14.58	41.26	26.68
20	40	0.5	8344.95	8994.34	649.39	8134.59	7517.94	-616.64	210.36	1476.40	1266.04	18.26	53.49	35.23
20	20	1	9010.15	9266.94	256.79	8527.52	8000.56	-526.95	482.63	1266.37	783.74	30.05	135.98	105.93
20	10	2	8392.26	8583.23	190.97	7853.41	7490.94	-362.47	538.85	1092.30	553.45	21.11	71.26	50.15
40	20	2	8562.13	9168.30	606.18	7736.73	7111.81	-624.92	825.40	2056.50	1231.09	22.13	69.41	47.29
20	1	20	8239.99	8430.66	190.67	7768.45	7539.90	-228.55	471.54	890.76	419.22	36.99	91.25	54.27

Table 4-CCXXXI: Creep Ratio - 12.5 MPa Non-Continuous – Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7306.07	8189.33	883.25	6966.72	6073.47	-893.25	339.35	2115.85	1776.50	12.30	18.89	6.58
20	40	0.5	7235.12	7759.42	524.29	7090.46	6514.82	-575.64	144.66	1244.60	1099.93	11.95	21.51	9.56
20	20	1	7238.67	7590.90	352.22	7071.40	6692.53	-378.87	167.27	898.36	731.09	15.14	23.75	8.61
20	10	2	7447.53	7707.84	260.31	6792.81	6493.60	-299.20	654.73	1214.24	559.51	16.47	28.44	11.97
40	20	2	7500.75	8008.95	508.21	6824.44	6272.88	-551.56	676.30	1736.07	1059.77	16.24	28.09	11.85
20	1	20	7171.66	7358.13	186.47	7027.03	6828.67	-198.36	144.63	529.46	384.83	22.71	39.37	16.67

Table 4-CCXXXII: Creep Ratio - 12.5 MPa Continuous – 80 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7927.09	8843.66	916.57	7182.48	6238.33	-944.15	744.61	2605.33	1860.72	13.06	19.07	6.01
20	40	0.5	7941.23	8489.34	548.11	7214.14	6628.51	-585.63	727.09	1860.83	1133.74	14.72	25.72	11.00
20	20	1	7631.54	8006.39	374.84	7570.80	7169.59	-401.20	60.75	836.79	776.04	16.12	34.14	18.03
20	10	2	7753.66	8054.65	300.98	7241.62	6958.80	-282.81	512.05	1095.84	583.79	19.22	38.51	19.29
40	20	2	7710.67	8284.52	573.85	7374.72	6813.56	-561.17	335.94	1470.96	1135.02	16.71	37.60	20.89
20	1	20	7803.16	7994.26	191.09	7130.82	6931.00	-199.82	672.35	1063.26	390.91	26.01	49.89	23.88

Table 4-CCXXXIII: Creep Ratio - 12.5 MPa Continuous – 120 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7997.92	8894.44	896.53	7133.18	6229.43	-903.75	864.73	2665.01	1800.28	11.57	24.56	12.99
20	40	0.5	7867.07	8348.00	480.93	7371.43	6738.62	-632.81	495.65	1609.38	1113.74	14.75	32.41	17.66
20	20	1	7801.42	8147.93	346.50	7457.05	7047.18	-409.87	344.38	1100.75	756.37	16.51	46.16	29.65
20	10	2	7922.58	8150.50	227.92	7100.30	6806.32	-293.97	822.29	1344.18	521.89	17.64	45.16	27.53
40	20	2	7737.64	8227.55	489.91	7350.50	6754.17	-596.32	387.14	1473.38	1086.23	18.34	41.30	22.96
20	1	20	7482.75	7683.35	200.61	7324.41	7141.30	-183.10	158.34	542.05	383.71	28.24	60.94	32.69

Table 4-CCXXXIV: Creep Ratio - 12.5 MPa Continuous – 180 °C - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]											
			Total			Stored			Dissipated			Unrecovered		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8425.40	9360.25	934.86	7546.20	6636.11	-910.09	879.20	2724.15	1844.95	14.86	45.51	30.65
20	40	0.5	8227.62	8786.33	558.70	7960.34	7357.00	-603.34	267.29	1429.33	1162.04	15.76	62.95	47.19
20	20	1	8421.42	8727.73	306.31	8007.13	7621.51	-385.63	414.29	1106.23	691.94	25.63	96.43	70.80
20	10	2	8071.17	8398.82	327.65	7647.73	7406.19	-241.54	423.44	992.63	569.19	23.64	80.48	56.83
40	20	2	8267.60	8811.59	543.99	7616.62	7083.52	-533.10	650.98	1728.07	1077.09	22.36	86.58	64.22
20	1	20	7674.69	7908.24	233.54	7879.09	7698.31	-180.78	-204.40	209.92	414.32	32.39	109.15	76.76

4.4.3.2 Total Strain Energy Density

Table 4-CCXXXV through Table 4-CCXLVI present the segmented total strain energy density values. With respect to the accumulated strain energy during the loading section, there is no clear trend with respect to change in the creep to recovery ratio. However as previously identified in section 4.2.3.2, particularly for the two continuous loading scenarios, the magnitude of the values for the 2nd (and 180th cycle) are all similar to each other regardless of the ratio. The total strain energy density accumulated during the creep portion for the 180th and the difference between the cycles shows a decreasing trend with increase in the ratio.

When comparing the 40s / 20s test with the 20s / 20s test, with the increase in the creep hold duration this results in smaller total stored strain energy density during the loading segment and larger during the creep. This trend is most prevalent for the two 12.5 / 0.5 MPa loading scenarios. When comparing the 2 ratios, similar trends are observed with the 40s / 20s values being larger particularly for the two 12.5 / 0.5 MPa tests.

Table 4-CCXXXV: Creep Ratio - 8 MPa – Room Temperature – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3191.18	3342.98	151.80	573.20	1145.17	571.97	3764.38	4488.15	723.77
20	40	0.5	3178.40	3365.36	186.96	502.45	765.17	262.72	3680.85	4130.53	449.68
20	20	1	3154.30	3375.20	220.91	354.55	435.83	81.28	3508.84	3811.03	302.19
20	10	2	3314.81	3112.68	-202.13	285.88	707.82	421.94	3600.69	3820.50	219.81
40	20	2	3261.14	3046.42	-214.72	466.13	1114.06	647.94	3727.26	4160.48	433.22
20	1	20	3082.55	3280.20	197.65	329.68	278.39	-51.29	3412.23	3558.58	146.36

Table 4-CCXXXVI: Creep Ratio - 8 MPa – 80 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3307.60	3067.42	-240.17	522.43	1453.12	930.69	3830.03	4520.55	690.52
20	40	0.5	3085.04	3302.40	217.35	600.61	826.23	225.62	3685.65	4128.62	442.97
20	20	1	3226.41	3013.11	-213.30	464.40	960.12	495.71	3690.81	3973.22	282.41
20	10	2	3103.77	3286.79	183.02	707.23	728.43	21.20	3810.99	4015.21	204.22
40	20	2	3109.87	3308.12	198.25	457.80	695.18	237.39	3567.67	4003.31	435.64
20	1	20	3181.06	3334.76	153.70	301.55	272.37	-29.18	3482.62	3607.13	124.51

Table 4-CCXXXVII: Creep Ratio - 8 MPa – 120 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	2920.22	3160.60	240.38	709.75	1235.01	525.26	3629.97	4395.62	765.65
20	40	0.5	3055.33	3279.35	224.02	646.88	896.22	249.34	3702.21	4175.57	473.36
20	20	1	3275.19	3157.05	-118.13	386.46	805.38	418.92	3661.65	3962.43	300.78
20	10	2	3334.94	3137.72	-197.22	461.10	827.13	366.03	3796.04	3964.85	168.82
40	20	2	3287.78	3107.77	-180.00	517.62	1058.40	540.78	3805.40	4166.17	360.78
20	1	20	3329.32	3162.79	-166.53	231.56	546.50	314.95	3560.88	3709.30	148.42

Table 4-CCXXXVIII: Creep Ratio - 8 MPa – 180 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3117.82	3234.53	116.71	819.29	1439.54	620.25	3937.11	4674.07	736.96
20	40	0.5	3146.12	2955.58	-190.54	727.83	1341.52	613.69	3873.95	4297.10	423.15
20	20	1	3107.54	2976.65	-130.90	864.47	1280.37	415.90	3972.01	4257.01	285.00
20	10	2	3165.20	2952.56	-212.64	723.73	1105.88	382.16	3888.92	4058.44	169.52
40	20	2	3076.92	3327.81	250.89	506.59	640.66	134.07	3583.52	3968.47	384.96
20	1	20	3178.62	3419.93	241.31	584.32	479.11	-105.22	3762.94	3899.04	136.10

Table 4-CCXXXIX: Creep Ratio - 12.5 MPa Non-Continuous – Room Temperature – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6355.36	6659.85	304.48	259.88	1064.20	804.32	6615.24	7724.04	1108.80
20	40	0.5	7108.01	7633.93	525.91	-209.33	389.78	599.10	6898.69	8023.71	1125.02
20	20	1	6617.27	6306.34	-310.93	322.41	1106.15	783.74	6939.68	7412.49	472.81
20	10	2	6250.40	6375.86	125.46	518.56	655.42	136.86	6768.96	7031.28	262.32
40	20	2	5911.00	5972.67	61.67	1003.40	1426.93	423.52	6914.40	7399.60	485.20
20	1	20	6073.14	6248.14	175.00	381.99	395.78	13.79	6455.13	6643.92	188.79

Table 4-CCXL: Creep Ratio - 12.5 MPa Non-Continuous – 80 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7647.61	7596.21	-51.40	510.21	1733.42	1223.21	8157.81	9329.63	1171.81
20	40	0.5	7875.23	7349.32	-525.91	621.98	1857.17	1235.19	8497.21	9206.49	709.28
20	20	1	7652.36	7189.38	-462.98	535.05	1459.93	924.88	8187.41	8649.31	461.90
20	10	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CCXLI: Creep Ratio - 12.5 MPa Non-Continuous – 120 °C – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8272.04	8176.70	-95.34	620.62	1927.23	1306.62	8892.66	10103.93	1211.27
20	40	0.5	7789.59	7892.64	103.05	556.18	972.68	416.50	8345.78	8865.33	519.55
20	20	1	8110.61	8050.57	-60.04	767.62	1450.74	683.12	8878.24	9501.31	623.08
20	10	2	6686.00	6886.81	200.81	994.90	1122.84	127.94	7680.90	8009.65	328.75
40	20	2	6656.55	6792.69	136.14	765.06	1143.40	378.34	7421.62	7936.09	514.48
20	1	20	6980.91	6668.69	-312.22	409.91	948.46	538.55	7390.82	7617.15	226.33

Table 4-CCXLII: Creep Ratio - 12.5 MPa Non-Continuous – 180 °C – Total Strain Energy Density

			Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7651.02	7208.34	-442.68	670.49	2174.84	1504.34	8321.51	9383.18	1061.66
20	40	0.5	7590.35	7336.49	-253.86	754.60	1657.86	903.26	8344.95	8994.34	649.39
20	20	1	7872.81	7596.89	-275.91	1137.34	1670.04	532.70	9010.15	9266.94	256.79
20	10	2	7722.19	7317.39	-404.80	670.07	1265.85	595.78	8392.26	8583.23	190.97
40	20	2	7670.12	7224.58	-445.54	892.01	1943.72	1051.71	8562.13	9168.30	606.18
20	1	20	7791.70	7380.66	-411.04	448.29	1050.00	601.70	8239.99	8430.66	190.67

Table 4-CCXLIII: Creep Ratio - 12.5 MPa Continuous – Room Temperature – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6690.78	6581.29	-109.49	615.29	1608.04	992.75	7306.07	8189.33	883.25
20	40	0.5	6644.32	6571.22	-73.10	590.80	1188.19	597.39	7235.12	7759.42	524.29
20	20	1	6660.67	6669.07	8.40	578.00	921.83	343.83	7238.67	7590.90	352.22
20	10	2	6551.02	6491.72	-59.30	896.51	1216.12	319.61	7447.53	7707.84	260.31
40	20	2	6400.36	6318.36	-82.00	1100.39	1690.59	590.20	7500.75	8008.95	508.21
20	1	20	6812.00	6837.20	25.20	359.66	520.93	161.27	7171.66	7358.13	186.47

Table 4-CCXLIV: Creep Ratio - 12.5 MPa Continuous – 80 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6980.37	6795.19	-185.18	946.71	2048.46	1101.75	7927.09	8843.66	916.57
20	40	0.5	6863.96	6856.28	-7.68	1077.27	1633.06	555.79	7941.23	8489.34	548.11
20	20	1	6763.68	6759.45	-4.22	867.87	1246.93	379.07	7631.54	8006.39	374.84
20	10	2	6714.54	6694.34	-20.20	1039.12	1360.31	321.19	7753.66	8054.65	300.98
40	20	2	6791.55	6786.91	-4.64	919.12	1497.61	578.49	7710.67	8284.52	573.85
20	1	20	7243.92	7212.93	-30.99	559.25	781.33	222.08	7803.16	7994.26	191.09

Table 4-CCXLV: Creep Ratio - 12.5 MPa Continuous – 120 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6880.41	6810.93	-69.48	1117.50	2083.51	966.01	7997.92	8894.44	896.53
20	40	0.5	7089.37	7093.54	4.17	777.70	1254.46	476.76	7867.07	8348.00	480.93
20	20	1	7098.61	7101.35	2.73	702.81	1046.58	343.77	7801.42	8147.93	346.50
20	10	2	6925.19	6894.15	-31.03	997.40	1256.35	258.95	7922.58	8150.50	227.92
40	20	2	6850.87	6800.76	-50.11	886.77	1426.79	540.02	7737.64	8227.55	489.91
20	1	20	6914.58	6906.19	-8.39	568.17	777.17	209.00	7482.75	7683.35	200.61

Table 4-CCXLVI: Creep Ratio - 12.5 MPa Continuous – 180 °C – Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Total - Loading			Total - Creep			Total – Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7353.32	7167.55	-185.77	1072.08	2192.70	1120.63	8425.40	9360.25	934.86
20	40	0.5	6941.21	6814.09	-127.12	1286.42	1972.23	685.82	8227.62	8786.33	558.70
20	20	1	6917.72	6934.25	16.53	1503.71	1793.49	289.78	8421.42	8727.73	306.31
20	10	2	7123.37	7168.63	45.26	947.80	1230.19	282.39	8071.17	8398.82	327.65
40	20	2	6966.81	6935.04	-31.77	1300.79	1876.55	575.76	8267.60	8811.59	543.99
20	1	20	7142.93	7156.33	13.40	531.77	751.91	220.14	7674.69	7908.24	233.54

4.4.3.3 *Stored Strain Energy Density*

Table 4-CCXLVII through Table 4-CCLVIII present the segmented stored strain energy density values. Evaluating the accumulated stored strain energy density during the unloading segment, no trend is present for the 2nd cycle, however the final and the difference between the cycles show an increasing trend as the ratio increases. When compared to the best fit trendline, there is a moderate correlation with the data sets, which is strongest for the difference data set.

Next comparing the stored energy response during the recovery hold, there is a decreasing trend with increase in the creep to recovery ratio. Evaluating the correlation coefficient of the data with the line of best fit, the two continuous test conditions showed fairly strong correlation for the final cycle, with the rest of the data sets showing moderate to weak correlation.

Comparing the 40s / 20s test with the 20s / 20s, the stored strain energy during the unloading segment was smaller in magnitude for the 40s / 20s. The stored strain energy during the recovery hold was generally larger for the 40s / 20s compared to the 20s / 20s. When comparing the 40s / 20s with the 20s / 10s, for the final cycle and the difference between the two cycles, the 40s / 20s is smaller in magnitude during the unloading segment. In contrast, the 40s / 20s stored energy was larger in magnitude during the recovery holding segment.

Table 4-CCXLVII: Creep Ratio - 8 MPa – Room Temperature – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3296.04	2515.51	-780.53	21.14	73.18	52.04	3317.17	2588.69	-728.48
20	40	0.5	3376.58	2872.79	-503.79	17.91	57.21	39.30	3394.49	2930.00	-464.49
20	20	1	3545.68	3188.17	-357.51	9.91	44.34	34.43	3555.59	3232.51	-323.09
20	10	2	3390.12	3129.58	-260.54	8.20	33.95	25.74	3398.32	3163.53	-234.80
40	20	2	3338.22	2845.23	-492.99	16.53	56.81	40.28	3354.75	2902.05	-452.70
20	1	20	3577.69	3410.58	-167.11	14.65	10.15	-4.50	3592.34	3420.74	-171.60

Table 4-CCXLVIII: Creep Ratio - 8 MPa – 80 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3185.74	2473.56	-712.18	45.08	59.17	14.09	3230.82	2532.73	-698.09
20	40	0.5	3326.31	2845.01	-481.30	23.81	62.39	38.57	3350.13	2907.40	-442.73
20	20	1	3339.41	3017.88	-321.53	13.78	47.40	33.61	3353.20	3065.28	-287.92
20	10	2	3153.67	2937.00	-216.68	29.97	29.43	-0.54	3183.64	2966.42	-217.22
40	20	2	3475.49	2989.64	-485.84	15.35	59.96	44.61	3490.84	3049.60	-441.23
20	1	20	3505.31	3324.94	-180.37	9.86	8.95	-0.91	3515.17	3333.89	-181.28

Table 4-CCXLIX: Creep Ratio - 8 MPa – 120 °C – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3438.72	2719.92	-718.80	31.39	47.27	15.89	3470.11	2767.19	-702.91
20	40	0.5	3379.36	2917.99	-461.37	24.34	68.09	43.76	3403.70	2986.08	-417.62
20	20	1	3514.46	3211.51	-302.95	37.41	35.12	-2.30	3551.87	3246.62	-305.25
20	10	2	3269.99	3031.13	-238.86	47.86	42.71	-5.16	3317.85	3073.84	-244.01
40	20	2	3310.41	2850.75	-459.66	44.13	49.83	5.70	3354.54	2900.58	-453.95
20	1	20	3445.10	3273.29	-171.82	6.79	31.17	24.38	3451.89	3304.45	-147.44

Table 4-CCL: Creep Ratio - 8 MPa – 180 °C – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	3386.23	2616.04	-770.19	37.89	101.56	63.67	3424.13	2717.61	-706.52
20	40	0.5	3555.57	3043.01	-512.56	28.00	75.43	47.43	3583.57	3118.43	-465.13
20	20	1	3448.00	3139.26	-308.74	41.62	74.55	32.93	3489.62	3213.81	-275.81
20	10	2	3353.44	3102.66	-250.78	31.41	62.39	30.98	3384.85	3165.05	-219.80
40	20	2	3722.88	3273.34	-449.54	19.44	59.72	40.27	3742.32	3333.06	-409.27
20	1	20	3369.67	3180.73	-188.94	26.01	55.92	29.91	3395.67	3236.65	-159.02

Table 4-CCLI: Creep Ratio - 12.5 MPa Non-Continuous– Room Temperature – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6969.81	5923.12	-1046.69	11.76	56.09	44.33	6981.58	5979.21	-1002.37
20	40	0.5	7020.26	6814.74	-205.52	17.86	22.47	4.61	7038.12	6837.22	-200.91
20	20	1	6787.87	6337.17	-450.70	13.70	60.39	46.69	6801.57	6397.56	-404.01
20	10	2	6368.59	6125.22	-243.37	26.02	30.43	4.41	6394.60	6155.65	-238.96
40	20	2	6257.15	5753.35	-503.80	54.96	73.47	18.51	6312.11	5826.82	-485.29
20	1	20	6629.45	6469.29	-160.16	17.71	20.01	2.30	6647.17	6489.31	-157.86

Table 4-CCLII: Creep Ratio - 12.5 MPa Non-Continuous– 80 °C – Stored Strain Energy Density

			Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7652.01	6414.56	-1237.44	9.44	86.80	77.35	7661.45	6501.36	-1160.09
20	40	0.5	7873.83	7007.00	-866.83	25.16	116.33	91.17	7898.98	7123.33	-775.66
20	20	1	7765.86	7161.89	-603.97	21.30	78.64	57.33	7787.16	7240.52	-546.64
20	10	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table 4-CCLIII: Creep Ratio - 12.5 MPa Non-Continuous– 120 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	8349.82	7012.45	-1337.37	30.57	94.03	63.46	8380.39	7106.48	-1273.91
20	40	0.5	8195.99	7665.26	-530.73	29.54	52.67	23.13	8225.53	7717.93	-507.60
20	20	1	8192.38	7322.51	-869.87	38.19	81.56	43.37	8230.57	7404.07	-826.51
20	10	2	6961.51	6714.30	-247.21	49.11	55.17	6.05	7010.62	6769.47	-241.15
40	20	2	7317.93	6762.38	-555.55	34.01	53.24	19.22	7351.95	6815.61	-536.33
20	1	20	7157.02	6932.78	-224.24	16.46	54.65	38.18	7173.48	6987.42	-186.06

Table 4-CCLIV: Creep Ratio - 12.5 MPa Non-Continuous– 180 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7982.88	6855.01	-1127.88	36.63	121.49	84.86	8019.51	6976.49	-1043.01
20	40	0.5	8096.87	7422.15	-674.73	37.71	95.79	58.08	8134.59	7517.94	-616.64
20	20	1	8479.60	7901.57	-578.02	47.92	98.99	51.07	8527.52	8000.56	-526.95
20	10	2	7820.30	7414.74	-405.56	33.11	76.20	43.09	7853.41	7490.94	-362.47
40	20	2	7695.78	7004.28	-691.49	40.95	107.52	66.57	7736.73	7111.81	-624.92
20	1	20	7751.35	7478.61	-272.74	17.10	61.29	44.19	7768.45	7539.90	-228.55

Table 4-CCLV: Creep Ratio - 12.5 MPa Continuous– Room Temperature – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	6937.14	5988.54	-948.59	29.58	84.93	55.35	6966.72	6073.47	-893.25
20	40	0.5	7060.77	6450.56	-610.21	29.69	64.26	34.58	7090.46	6514.82	-575.64
20	20	1	7043.85	6641.49	-402.36	27.55	51.04	23.49	7071.40	6692.53	-378.87
20	10	2	6741.82	6422.23	-319.59	50.99	71.37	20.38	6792.81	6493.60	-299.20
40	20	2	6759.81	6170.80	-589.02	64.63	102.08	37.45	6824.44	6272.88	-551.56
20	1	20	7012.63	6801.91	-210.73	14.40	26.77	12.37	7027.03	6828.67	-198.36

Table 4-CCLVI: Creep Ratio - 12.5 MPa Continuous– 80 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7128.56	6129.77	-998.79	53.92	108.56	54.64	7182.48	6238.33	-944.15
20	40	0.5	7149.42	6534.05	-615.37	64.72	94.46	29.74	7214.14	6628.51	-585.63
20	20	1	7516.25	7092.79	-423.46	54.55	76.80	22.26	7570.80	7169.59	-401.20
20	10	2	7177.32	6875.33	-301.99	64.29	83.47	19.18	7241.62	6958.80	-282.81
40	20	2	7322.35	6722.74	-599.60	52.38	90.81	38.44	7374.72	6813.56	-561.17
20	1	20	7104.54	6893.50	-211.04	26.27	37.50	11.22	7130.82	6931.00	-199.82

Table 4-CCLVII: Creep Ratio - 12.5 MPa Continuous– 120 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7075.14	6117.95	-957.19	58.04	111.48	53.44	7133.18	6229.43	-903.75
20	40	0.5	7337.21	6671.90	-665.31	34.22	66.72	32.50	7371.43	6738.62	-632.81
20	20	1	7420.30	6989.72	-430.58	36.75	57.46	20.71	7457.05	7047.18	-409.87
20	10	2	7047.57	6735.03	-312.53	52.73	71.29	18.56	7100.30	6806.32	-293.97
40	20	2	7305.44	6671.30	-634.14	45.05	82.88	37.82	7350.50	6754.17	-596.32
20	1	20	7295.73	7095.57	-200.16	28.68	45.74	17.06	7324.41	7141.30	-183.10

Table 4-CCLVIII: Creep Ratio - 12.5 MPa Continuous– 180 °C – Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Creep : Recovery Ratio	Strain Energy Density [J/m ³]								
			Stored - Unloading			Stored - Recovery			Stored - Overall		
			Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	80	0.25	7488.67	6518.85	-969.81	57.53	117.25	59.72	7546.20	6636.11	-910.09
20	40	0.5	7881.02	7234.19	-646.83	79.32	122.81	43.49	7960.34	7357.00	-603.34
20	20	1	7923.81	7505.05	-418.76	83.32	116.46	33.13	8007.13	7621.51	-385.63
20	10	2	7599.48	7335.89	-263.59	48.25	70.30	22.05	7647.73	7406.19	-241.54
40	20	2	7544.92	6973.56	-571.36	71.70	109.96	38.26	7616.62	7083.52	-533.10
20	1	20	7851.57	7655.44	-196.14	27.51	42.87	15.36	7879.09	7698.31	-180.78

4.5 Effect of Applied Load Levels

The last parameter which was evaluated with respect to its effect on the material response was the effect of the applied load. Analysis performed was a comparison of the effect of the magnitude of the applied load during the creep and recovery hold portions, along with a comparison between the two loading methods; continuous and discontinuous.

Similar to the preceding sections in this chapter, to assist in the visualization of variation as a result of changing loading conditions, figures included in this section are for all recovery durations performed at 120 °C. Additional plots for the other temperatures and recovery durations are included in Appendix C.

4.5.1 Strain

4.5.1.1 Creep / Recovered Strain

Table 4-CCLIX through Table 4-CCLXII contain the creep and recovered strain data sorted and arranged by changing applied load, and Figure 4-185 through Figure 4-208 provide visual representation of the cycle data contained within the tables.

Evaluating the change in the creep strain response with changes in applied load during the creep hold, for the 1st cycle, the majority of data sets showed larger creep strain values for the 12.5 MPa. For the final cycle, there was an almost even split between which loading resulted in larger creep strain values. However, for the difference between the final and initial cycles, the 8 MPa scenario was larger for the majority of the sets. Comparing the two 12.5 MPa creep loading scenarios, the continuous loading scenario was larger for the majority of the data sets for the 1st and 180th cycle, and the non-continuous loading was larger for the majority for the differences between the cycles.

Next, evaluating the recovered strain, the 0.1 MPa recovery load experienced larger recovered strain values for the 1st, final and difference between the two cycles when compared to the 0.5 MPa recovery load. This is expected as the recovery load in this situation is lower and since closer to a no load condition will theoretically allow faster recovery. Comparing the two 0.5 MPa recovered strains, the continuous loading scenario was larger for the 1st cycle, while the non-continuous loading was larger for the final cycle and difference between the cycles. However,

these results for the two 0.5 MPa recovery loads were only present in a slim majority of the tests. The lack of clear distinction between the two loading methodology lends further justification to the viability of the switch to the continuous loading scenario.

Evaluating the unrecovered creep strain, both of the 12.5 / 0.5 MPa loading conditions present larger strain values for all cycles evaluated compared to the 8 / 0.1 MPa tests. When comparing the two 12.5 / 0.5 MPa loadings, the continuous loading scenario experienced more unrecovered creep strain for a slim majority of the conditions. Where as the difference between the two cycles was larger for the non-continuous loading scenario. Lastly, comparing the accumulated unrecovered creep strain by the final cycle, the 12.5 / 0.5 MPa loadings are larger in magnitude than the 8 / 0.1 MPa, and the continuous 12.5 / 0.5 MPa is larger than the discontinuous.

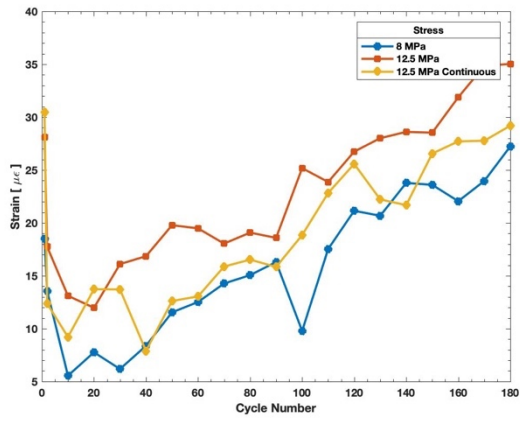


Figure 4-185: 120 °C - 1s - Creep Strain

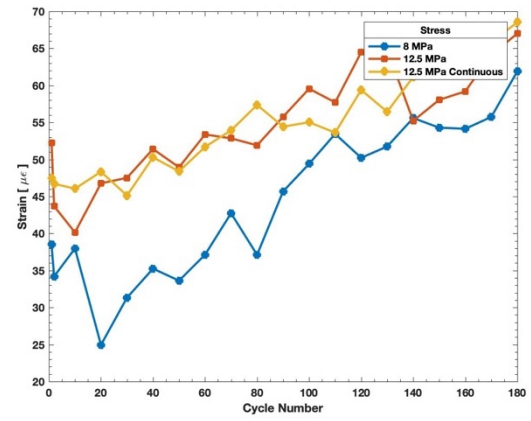


Figure 4-186: 120 °C - 10s - Creep Strain

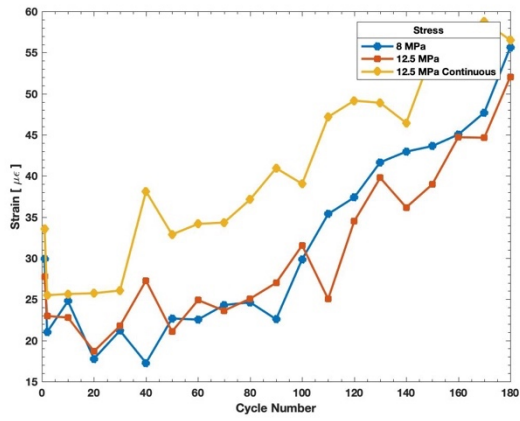


Figure 4-187: 120 °C - 20s - Creep Strain

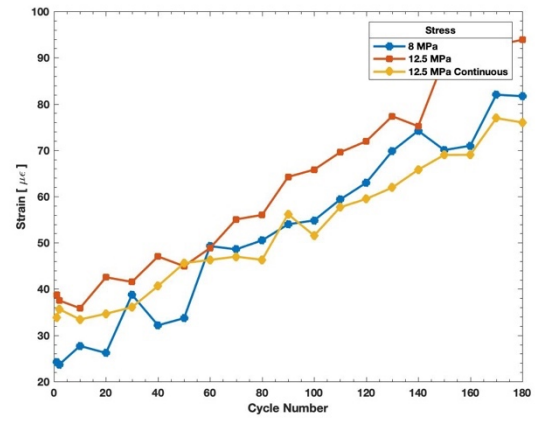


Figure 4-188: 120 °C - 40s - Creep Strain

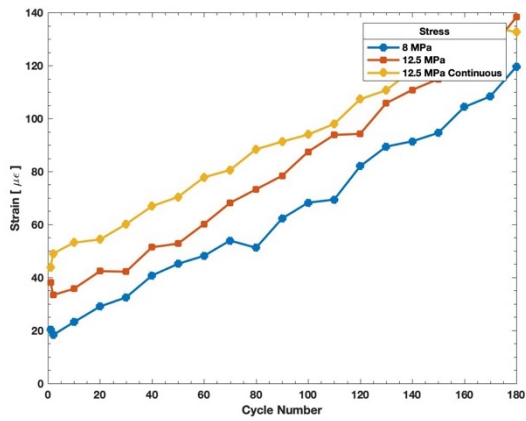


Figure 4-189: 120 °C - 80s - Creep Strain

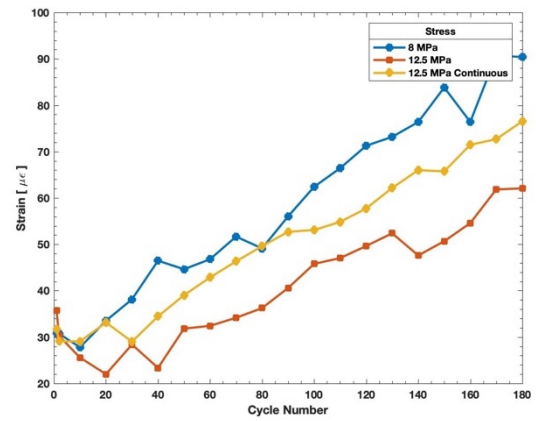


Figure 4-190: 120 °C - 20s (40s Creep) - Creep Strain

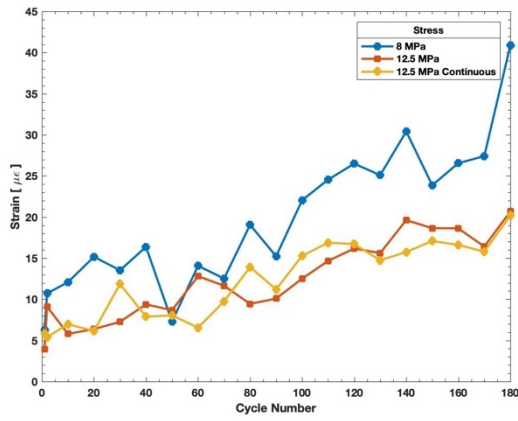


Figure 4-191: 120 °C - 1s - Recovered Strain

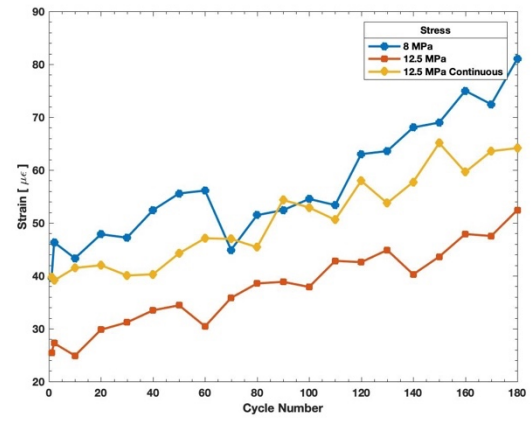


Figure 4-192: 120 °C - 10s - Recovered Strain

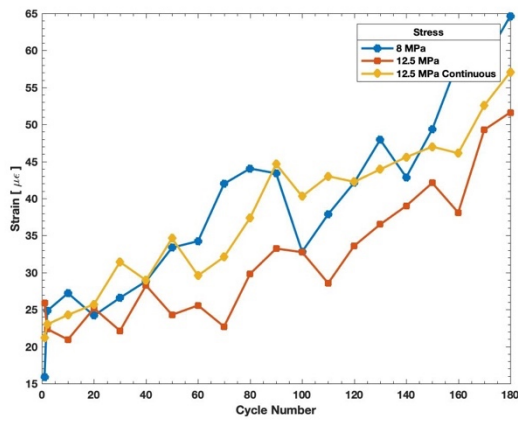


Figure 4-193: 120 °C - 20s - Recovered Strain

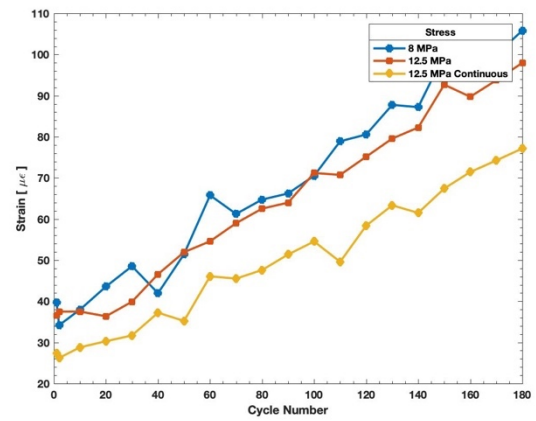


Figure 4-194: 120 °C - 40s - Recovered Strain

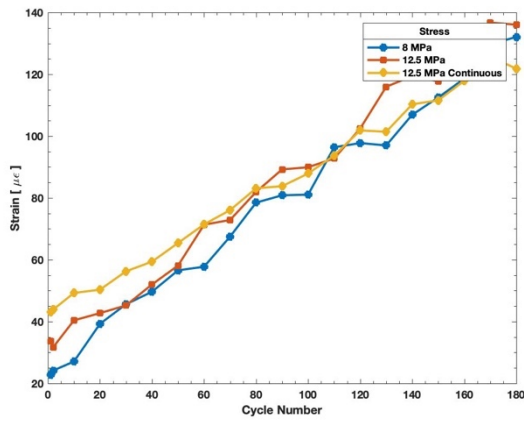


Figure 4-195: 120 °C - 80s - Recovered Strain

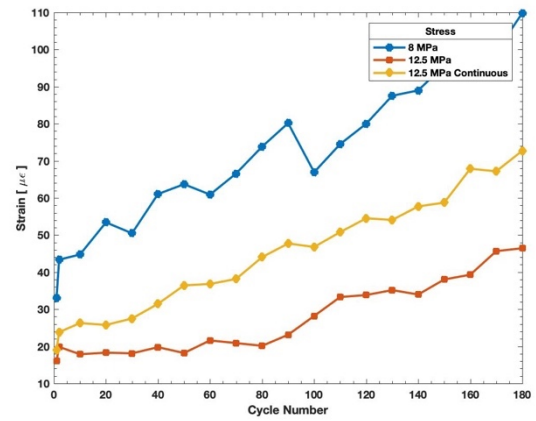


Figure 4-196: 120 °C - 20s (40s Creep) - Recovered Strain

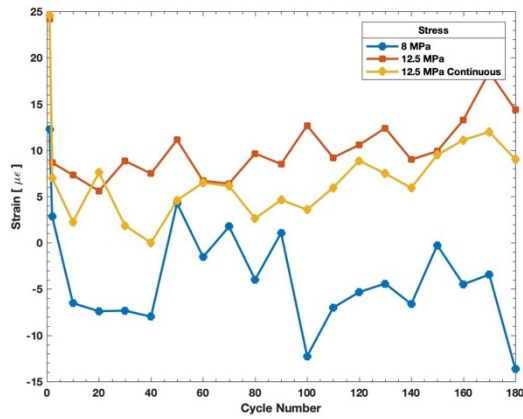


Figure 4-197: 120 °C - 1s – Cycle Unrecovered Creep Strain

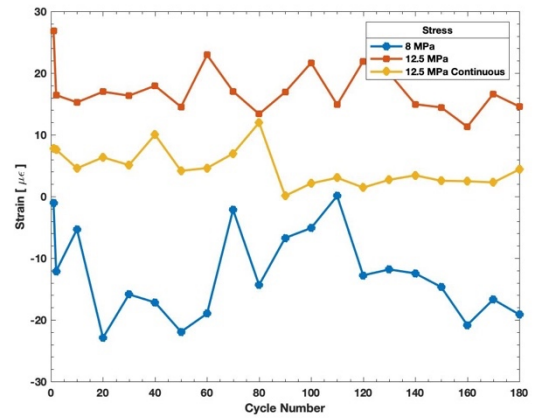


Figure 4-198: 120 °C - 10s – Cycle Unrecovered Creep Strain

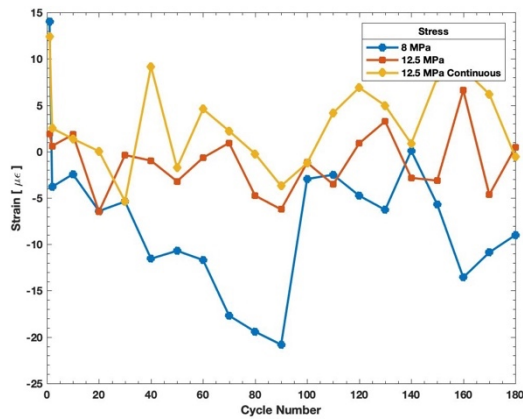


Figure 4-199: 120 °C - 20s – Cycle Unrecovered Creep Strain

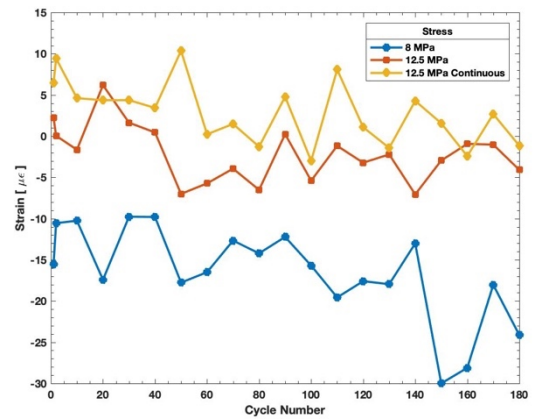


Figure 4-200: 120 °C - 40s – Cycle Unrecovered Creep Strain

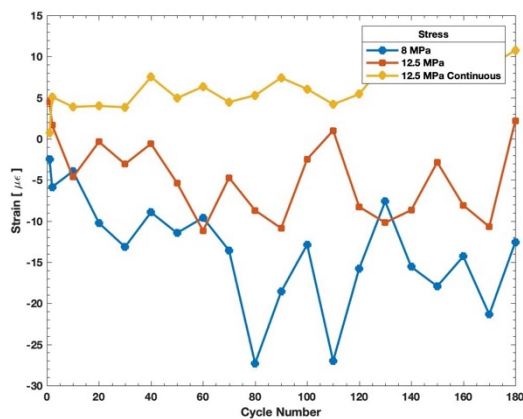


Figure 4-201: 120 °C - 80s – Cycle Unrecovered Creep Strain

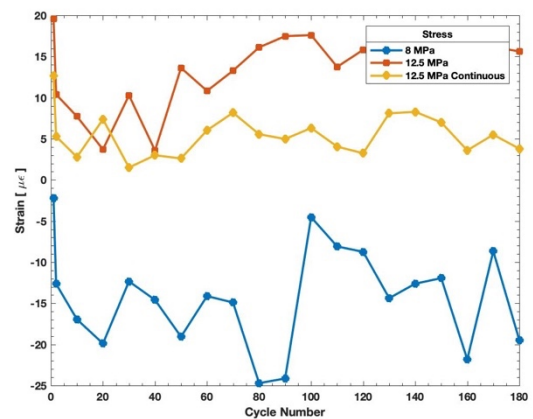


Figure 4-202: 120 °C - 20s (40s Creep) – Cycle Unrecovered Creep Strain

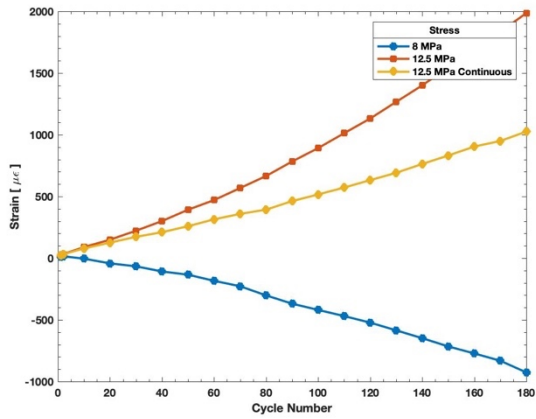


Figure 4-203: 120 °C - 1s – Accumulated Unrecovered Creep Strain

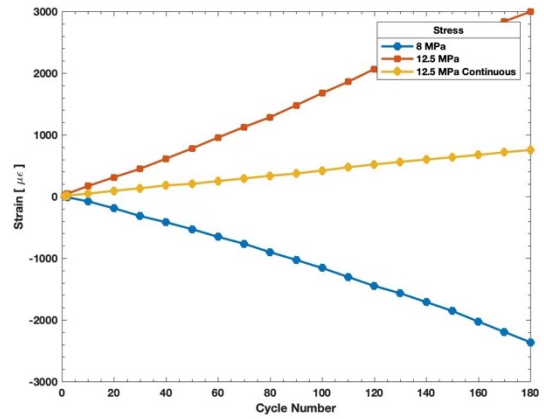


Figure 4-204: 120 °C - 10s – Accumulated Unrecovered Creep Strain

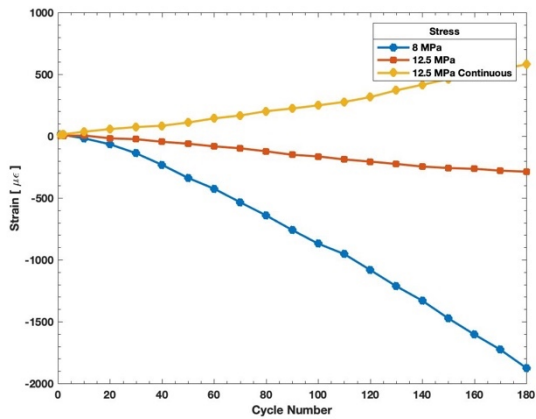


Figure 4-205: 120 °C - 20s – Accumulated Unrecovered Creep Strain

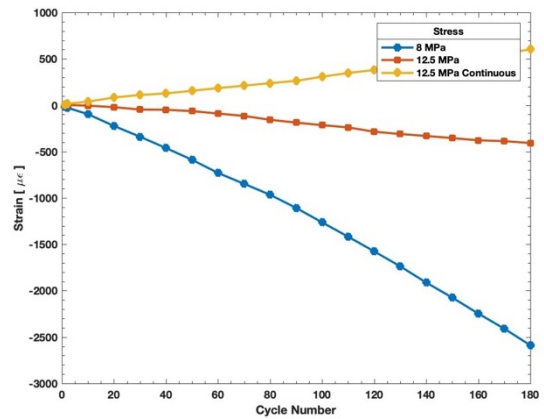


Figure 4-206: 120 °C - 40s – Accumulated Unrecovered Creep Strain

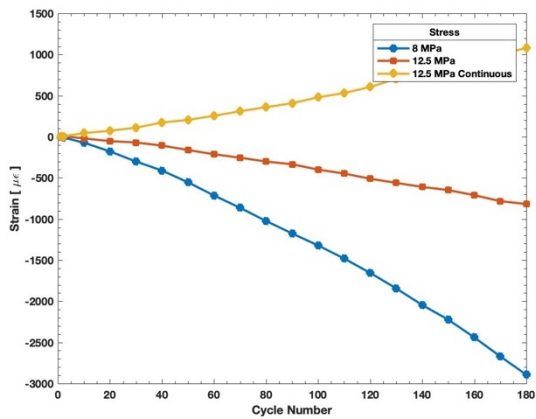


Figure 4-207: 120 °C - 80s – Accumulated Unrecovered Creep Strain

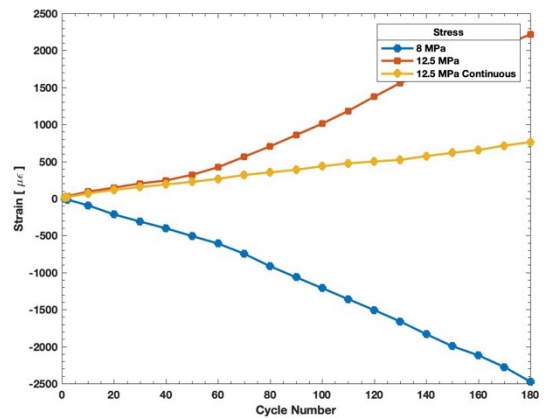


Figure 4-208: 120 °C - 20s (40s Creep) – Accumulated Unrecovered Creep Strain

Table 4-CCLIX: Applied Load - Room Temperature – Creep / Recovery Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_{i=1}^{180} (\epsilon_c - \epsilon_r)$
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	RT	8 / 0.1	9	6	-2	4	11	7	5	-5	-9	-208
20	1	RT	12.5 / 0.5	16	10	-6	2	3	1	13	6	-7	660
20	1	RT	12.5 / 0.5 C	13	26	12	5	22	17	9	4	-5	529
20	10	RT	8 / 0.1	14	42	28	21	58	37	-7	-16	-9	-2015
20	10	RT	12.5 / 0.5	24	39	15	11	28	17	13	12	-1	2750
20	10	RT	12.5 / 0.5 C	36	59	22	27	55	28	10	4	-6	493
20	20	RT	8 / 0.1	12	33	21	13	57	44	-1	-23	-23	-1771
20	20	RT	12.5 / 0.5	9	51	42	7	47	40	2	4	2	371
20	20	RT	12.5 / 0.5 C	15	45	30	10	43	34	5	1	-4	384
20	40	RT	8 / 0.1	19	75	56	33	103	70	-15	-28	-14	-2995
20	40	RT	12.5 / 0.5	6	45	39	13	21	7	-8	24	32	1550
20	40	RT	12.5 / 0.5 C	15	62	47	11	60	49	4	2	-2	333
20	80	RT	8 / 0.1	26	122	95	41	160	119	-14	-39	-24	-3823
20	80	RT	12.5 / 0.5	8	74	65	8	77	69	0	-3	-3	-226
20	80	RT	12.5 / 0.5 C	20	101	81	17	97	80	4	5	1	385
40	20	RT	8 / 0.1	25	80	54	36	109	73	-10	-30	-19	-2978
40	20	RT	12.5 / 0.5	41	85	44	20	60	40	21	25	5	3418
40	20	RT	12.5 / 0.5 C	40	85	45	29	81	52	11	4	-7	684

Table 4-CCLX: Applied Load - 80 °C – Creep / Recovery Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	80	8 / 0.1	15	16	1	7	14	7	7	2	-5	-570
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	36	47	11	22	41	20	15	6	-9	451
20	10	80	8 / 0.1	40	67	27	54	77	23	-15	-10	4	-2198
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	36	55	19	19	53	34	17	2	-15	236
20	20	80	8 / 0.1	30	60	30	39	83	44	-9	-23	-14	-2377
20	20	80	12.5 / 0.5	27	71	44	19	64	45	8	7	-1	295
20	20	80	12.5 / 0.5 C	22	45	24	13	43	31	9	2	-7	173
20	40	80	8 / 0.1	22	76	54	31	104	74	-9	-28	-19	-2792
20	40	80	12.5 / 0.5	28	103	75	27	106	79	1	-3	-4	-639
20	40	80	12.5 / 0.5 C	34	90	56	36	89	52	-2	2	4	160
20	80	80	8 / 0.1	45	142	97	49	157	108	-4	-15	-11	-3409
20	80	80	12.5 / 0.5	23	125	101	20	126	105	3	-1	-4	-710
20	80	80	12.5 / 0.5 C	41	128	87	35	123	88	6	5	-2	232
40	20	80	8 / 0.1	16	60	44	16	88	72	0	-28	-28	-2193
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	30	73	43	14	74	60	15	-2	-17	100

Table 4-CCLXI: Applied Load - 120 °C – Creep / Recovery Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	120	8 / 0.1	18	27	9	6	41	35	12	-14	-26	-926
20	1	120	12.5 / 0.5	28	35	7	4	21	17	24	14	-10	1986
20	1	120	12.5 / 0.5 C	30	29	-1	6	20	14	25	9	-16	1026
20	10	120	8 / 0.1	38	62	23	40	81	42	-1	-19	-18	-2363
20	10	120	12.5 / 0.5	52	67	15	25	52	27	27	15	-12	2994
20	10	120	12.5 / 0.5 C	47	69	21	40	64	24	8	4	-3	753
20	20	120	8 / 0.1	30	56	26	16	65	49	14	-9	-23	-1875
20	20	120	12.5 / 0.5	28	52	24	26	52	26	2	0	-1	-288
20	20	120	12.5 / 0.5 C	34	56	23	21	57	36	12	-1	-13	581
20	40	120	8 / 0.1	24	82	58	40	106	66	-16	-24	-9	-2589
20	40	120	12.5 / 0.5	39	94	55	37	98	61	2	-4	-6	-408
20	40	120	12.5 / 0.5 C	34	76	42	27	77	50	6	-1	-8	603
20	80	120	8 / 0.1	20	120	99	23	132	109	-2	-13	-10	-2893
20	80	120	12.5 / 0.5	38	138	100	34	136	102	5	2	-2	-818
20	80	120	12.5 / 0.5 C	44	133	89	43	122	79	1	11	10	1081
40	20	120	8 / 0.1	31	90	60	33	110	77	-2	-19	-17	-2474
40	20	120	12.5 / 0.5	36	62	26	16	46	30	20	16	-4	2215
40	20	120	12.5 / 0.5 C	32	77	45	19	73	54	13	4	-9	761

Table 4-CCLXII: Applied Load - 180 °C – Creep / Recovery Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]									
				$\Delta\epsilon_c$			$\Delta\epsilon_r$			$\Delta\epsilon_c - \Delta\epsilon_r$			$\sum_1^{180} (\epsilon_c - \epsilon_r)$
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	
20	1	180	8 / 0.1	43	42	-1	30	52	22	13	-10	-23	-540
20	1	180	12.5 / 0.5	42	45	4	10	38	28	32	7	-25	1234
20	1	180	12.5 / 0.5 C	41	18	-23	6	9	3	35	8	-26	1381
20	10	180	8 / 0.1	44	70	26	47	76	29	-3	-6	-3	-1205
20	10	180	12.5 / 0.5	42	58	15	26	59	33	16	-1	-17	587
20	10	180	12.5 / 0.5 C	51	61	10	24	51	27	27	10	-18	1198
20	20	180	8 / 0.1	54	85	31	57	95	39	-3	-11	-8	-1572
20	20	180	12.5 / 0.5	76	81	5	47	81	33	29	0	-29	583
20	20	180	12.5 / 0.5 C	55	76	21	40	67	26	14	10	-5	1299
20	40	180	8 / 0.1	40	95	55	35	105	70	5	-10	-15	-1858
20	40	180	12.5 / 0.5	48	87	39	40	81	41	8	6	-2	375
20	40	180	12.5 / 0.5 C	47	89	42	35	79	44	12	10	-2	1367
20	80	180	8 / 0.1	51	148	97	52	164	113	0	-16	-16	-1947
20	80	180	12.5 / 0.5	41	128	87	36	122	85	5	6	1	496
20	80	180	12.5 / 0.5 C	65	144	79	52	136	85	13	7	-6	1464
40	20	180	8 / 0.1	29	47	17	27	59	32	3	-12	-15	-894
40	20	180	12.5 / 0.5	53	108	56	35	101	66	18	7	-11	748
40	20	180	12.5 / 0.5 C	66	99	33	35	87	52	31	12	-18	1752

4.5.1.2 *Unrecovered Strain*

Table 4-CCLXIII through Table 4-CCLXVI contain the unrecovered strain organized based on variation in the loading conditions. Figure 4-209 through Figure 4-220 present plots showing the difference between loadings for the relevant parameters in the tables.

Comparing the unrecovered strain measured during the 1st cycle, the 8 / 0.1 MPa loading condition is larger for the majority of the data sets. For the 180th cycle and the difference between the cycles, both of the 12.5 / 0.5 MPa loading scenarios were larger in magnitude. When comparing the two 12.5 / 0.5 MPa loadings, the continuous loading scenario was larger than the non-continuous.

Comparing the calculated unrecovered instantaneous strains, the 8 MPa / 0.1 MPa loading values are larger than both of the 12.5 / 0.5 MPa tests. When comparing the two 12.5 / 0.5 MPa conditions, the non-continuous are larger for a slim majority of the data sets, however this majority is quite small and as such no clear conclusions should be drawn.

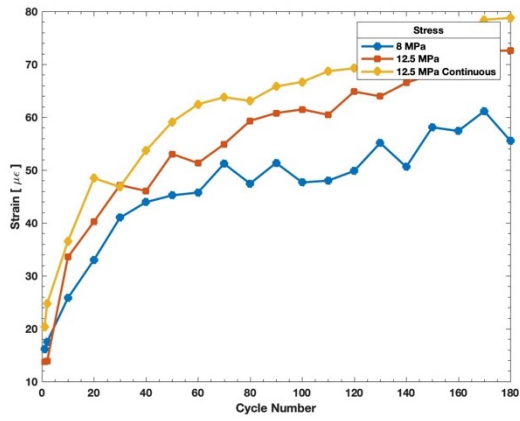


Figure 4-209: 120 °C - 1s – Total Unrecovered Strain

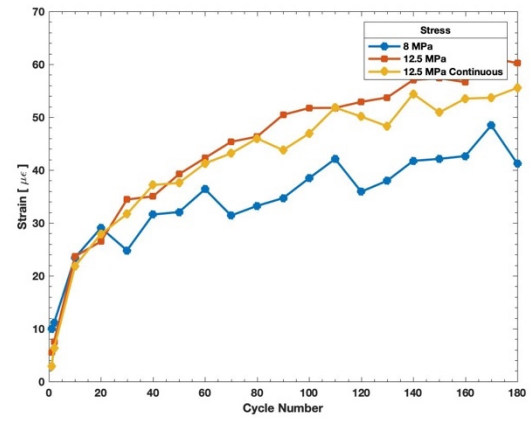


Figure 4-210: 120 °C - 10s – Total Unrecovered Strain

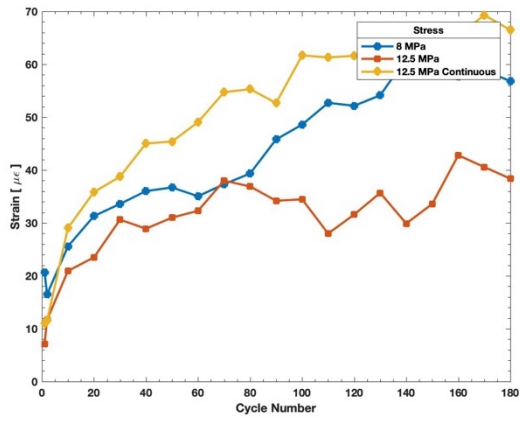


Figure 4-211: 120 °C - 20s – Total Unrecovered Strain

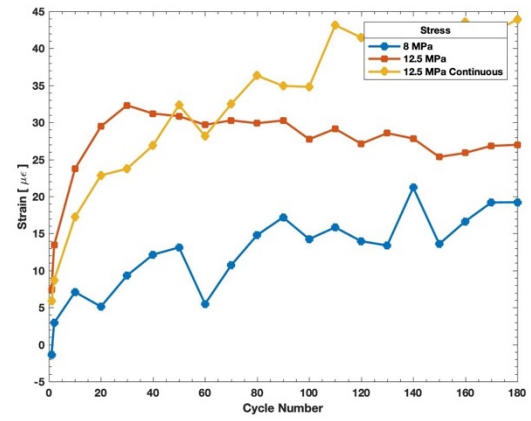


Figure 4-212: 120 °C - 40s – Total Unrecovered Strain

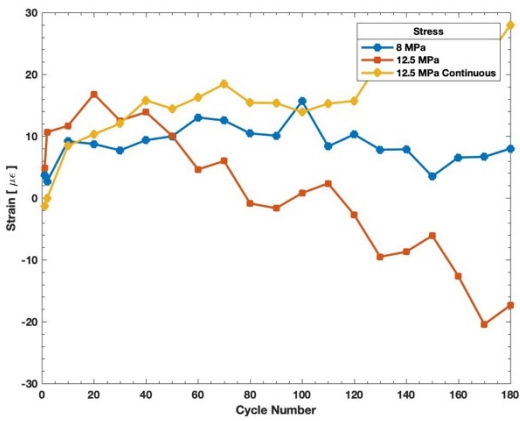


Figure 4-213: 120 °C - 80s – Total Unrecovered Strain

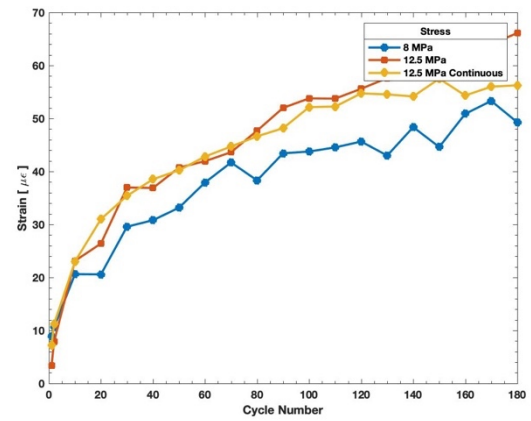


Figure 4-214: 120 °C - 20s (40s Creep) – Total Unrecovered Strain

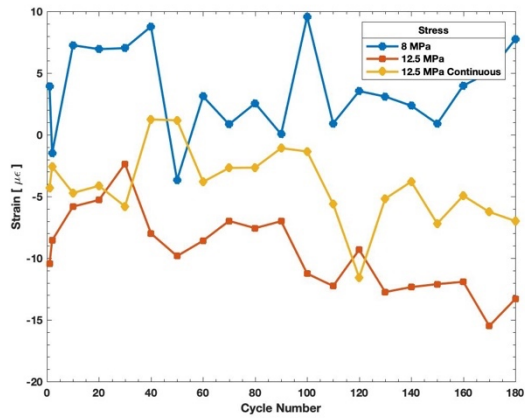


Figure 4-215: 120 °C - 1s – Cycle Unrecovered Instantaneous Strain

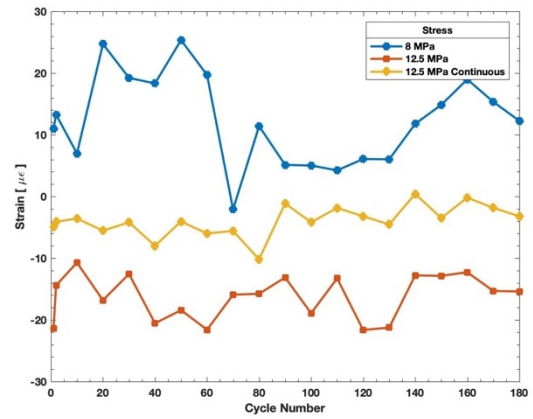


Figure 4-216: 120 °C - 10s – Cycle Unrecovered Instantaneous Strain

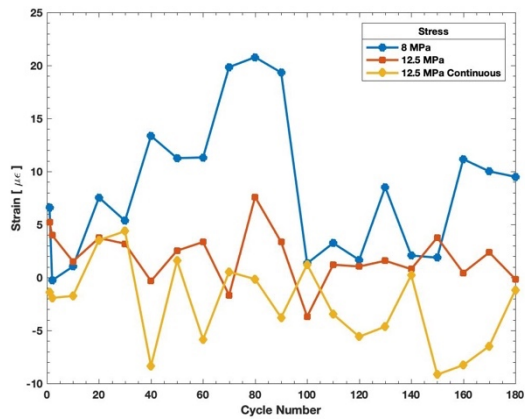


Figure 4-217: 120 °C - 20s – Cycle Unrecovered Instantaneous Strain

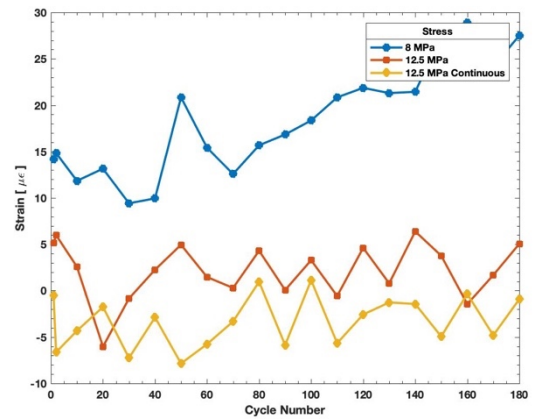


Figure 4-218: 120 °C - 40s – Cycle Unrecovered Instantaneous Strain

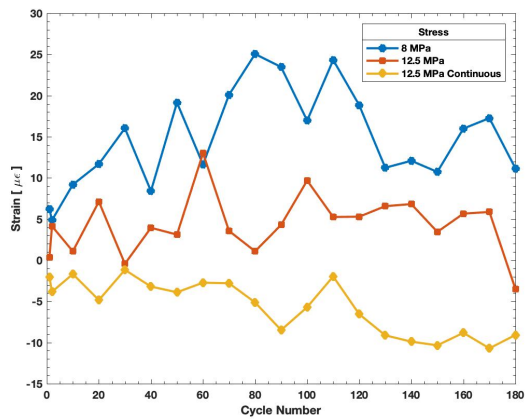


Figure 4-219: 120 °C - 80s – Cycle Unrecovered Instantaneous Strain

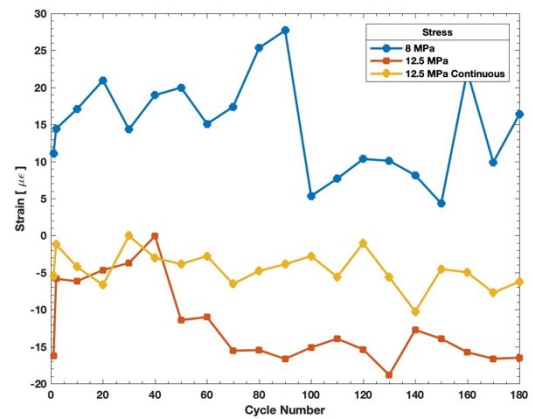


Figure 4-220: 120 °C - 20s (40s Creep) – Cycle Unrecovered Instantaneous Strain

Table 4-CCLXIII: Applied Load - Room Temperature - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	RT	8 / 0.1	11	33	22	5	-5	-9	6	6	0
20	1	RT	12.5 / 0.5	-1	23	24	13	6	-7	-14	-5	9
20	1	RT	12.5 / 0.5 C	9	37	28	9	4	-5	0	-3	-3
20	10	RT	8 / 0.1	5	20	15	-7	-16	-9	12	16	4
20	10	RT	12.5 / 0.5	-5	17	22	13	12	-1	-18	-11	7
20	10	RT	12.5 / 0.5 C	5	28	23	10	4	-6	-5	-3	2
20	20	RT	8 / 0.1	4	19	15	-1	-23	-23	5	24	19
20	20	RT	12.5 / 0.5	2	6	4	2	4	2	0	-4	-4
20	20	RT	12.5 / 0.5 C	3	21	18	5	1	-4	-2	-2	0
20	40	RT	8 / 0.1	5	18	14	-15	-28	-14	19	29	10
20	40	RT	12.5 / 0.5	-3	6	10	-8	24	32	4	-24	-28
20	40	RT	12.5 / 0.5 C	1	20	19	4	2	-2	-3	-2	1
20	80	RT	8 / 0.1	2	16	13	-14	-39	-24	17	39	22
20	80	RT	12.5 / 0.5	5	6	2	0	-3	-3	5	1	-4
20	80	RT	12.5 / 0.5 C	1	17	16	4	5	1	-2	-3	-1
40	20	RT	8 / 0.1	6	22	16	-10	-30	-19	16	29	12
40	20	RT	12.5 / 0.5	-2	25	27	21	25	5	-23	-25	-2
40	20	RT	12.5 / 0.5 C	3	30	27	11	4	-7	-8	-4	4

Table 4-CCLXIV: Applied Load - 80 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	80	8 / 0.1	11	44	33	7	2	-5	4	-1	-5
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	14	57	43	15	6	-9	0	-3	-3
20	10	80	8 / 0.1	3	27	23	-15	-10	4	18	12	-6
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	14	48	34	17	2	-15	-3	-1	2
20	20	80	8 / 0.1	15	38	23	-9	-23	-14	24	17	-6
20	20	80	12.5 / 0.5	7	8	1	8	7	-1	-1	-5	-3
20	20	80	12.5 / 0.5 C	10	45	35	9	2	-7	1	0	-1
20	40	80	8 / 0.1	7	31	24	-9	-28	-19	15	31	15
20	40	80	12.5 / 0.5	10	37	27	1	-3	-4	9	9	0
20	40	80	12.5 / 0.5 C	11	35	23	-2	2	4	14	0	-13
20	80	80	8 / 0.1	7	21	14	-4	-15	-11	10	13	2
20	80	80	12.5 / 0.5	3	21	18	3	-1	-4	0	2	2
20	80	80	12.5 / 0.5 C	4	19	15	6	5	-2	-3	-5	-2
40	20	80	8 / 0.1	10	50	41	0	-28	-28	10	27	17
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	9	49	41	15	-2	-17	-6	1	7

Table 4-CCLXV: Applied Load - 120 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	120	8 / 0.1	16	56	39	12	-14	-26	4	8	4
20	1	120	12.5 / 0.5	14	73	59	24	14	-10	-10	-13	-3
20	1	120	12.5 / 0.5 C	20	79	58	25	9	-16	-4	-7	-3
20	10	120	8 / 0.1	10	41	31	-1	-19	-18	11	12	1
20	10	120	12.5 / 0.5	5	60	55	27	15	-12	-21	-15	6
20	10	120	12.5 / 0.5 C	3	56	53	8	4	-3	-5	-3	2
20	20	120	8 / 0.1	21	57	36	14	-9	-23	7	10	3
20	20	120	12.5 / 0.5	7	38	31	2	0	-1	5	0	-5
20	20	120	12.5 / 0.5 C	11	67	56	12	-1	-13	-1	-1	0
20	40	120	8 / 0.1	-1	19	21	-16	-24	-9	14	28	13
20	40	120	12.5 / 0.5	7	27	20	2	-4	-6	5	5	0
20	40	120	12.5 / 0.5 C	6	44	38	6	-1	-8	-1	-1	0
20	80	120	8 / 0.1	4	8	4	-2	-13	-10	6	11	5
20	80	120	12.5 / 0.5	5	-17	-22	5	2	-2	0	-4	-4
20	80	120	12.5 / 0.5 C	-1	28	29	1	11	10	-2	-9	-7
40	20	120	8 / 0.1	9	49	40	-2	-19	-17	11	16	5
40	20	120	12.5 / 0.5	3	66	63	20	16	-4	-16	-17	0
40	20	120	12.5 / 0.5 C	7	56	49	13	4	-9	-5	-6	-1

Table 4-CCLXVI: Applied Load - 180 °C - Unrecovered Strain

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain [$\mu\epsilon$]								
				ϵ_{UR}			$\Delta\epsilon_c - \Delta\epsilon_r$			$\Delta\epsilon_{o,l} - \Delta\epsilon_{o,u}$		
				Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1	Cycle 1	Cycle 180	Cycle 180 - 1
20	1	180	8 / 0.1	24	96	73	13	-10	-23	11	10	-1
20	1	180	12.5 / 0.5	27	128	101	32	7	-25	-5	-6	-1
20	1	180	12.5 / 0.5 C	31	150	119	35	8	-26	-3	-8	-5
20	10	180	8 / 0.1	5	79	73	-3	-6	-3	8	6	-3
20	10	180	12.5 / 0.5	10	106	96	16	-1	-17	-6	-1	5
20	10	180	12.5 / 0.5 C	14	118	104	27	10	-18	-14	-10	4
20	20	180	8 / 0.1	11	90	79	-3	-11	-8	14	13	-1
20	20	180	12.5 / 0.5	25	239	214	29	0	-29	-4	1	4
20	20	180	12.5 / 0.5 C	19	167	148	14	10	-5	5	-10	-14
20	40	180	8 / 0.1	9	59	50	5	-10	-15	4	13	9
20	40	180	12.5 / 0.5	8	87	78	8	6	-2	1	-5	-6
20	40	180	12.5 / 0.5 C	7	105	97	12	10	-2	-5	-12	-8
20	80	180	8 / 0.1	5	26	21	0	-16	-16	5	19	14
20	80	180	12.5 / 0.5	5	61	57	5	6	1	0	-9	-9
20	80	180	12.5 / 0.5 C	1	70	68	13	7	-6	-12	-8	4
40	20	180	8 / 0.1	9	86	77	3	-12	-15	7	10	4
40	20	180	12.5 / 0.5	15	114	99	18	7	-11	-3	-3	0
40	20	180	12.5 / 0.5 C	19	144	125	31	12	-18	-12	-11	1

4.5.2 Modulus

Table 4-CCLXVII through Table 4-CCLXX contain the instantaneous modulus data arranged and sorted to analyze the changes with respect to the loading, and Figure 4-221 through Figure 4-238 present plots containing the variation in the modulus over the cyclic testing.

Comparing the instantaneous moduli calculated for both the loading and unloading segments, both of the 12.5 / 0.5 MPa scenarios were larger than those for the 8 / 0.1 MPa for the 2nd and the final cycle. However, the difference between these two cycles were larger for the 8 / 0.1 MPa. Comparing the two 12.5 / 0.5 MPa tests, the continuous loading conditions were larger than the non-continuous for the majority of the data sets. This indicates that while the modulus values were generally larger for the two 12.5 / 0.5 MPa tests, the overall change as a result of the cyclic loadings was larger for the 8 / 0.1 MPa.

Lastly, the difference between the two instantaneous modulus values was larger for the two 12.5 / 0.5 MPa conditions for all cycles and the difference between the cycles. This difference was larger for the continuous loading scenario.

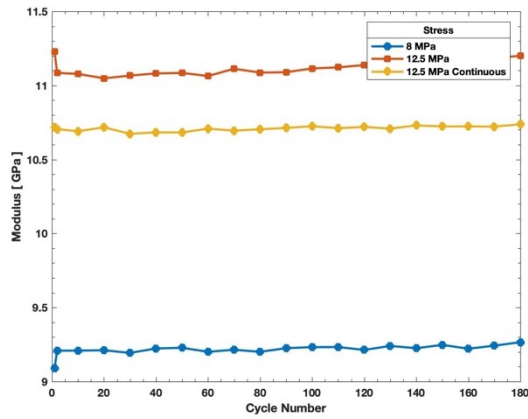


Figure 4-221: 120 °C - 1s - Instantaneous Modulus (Loading)

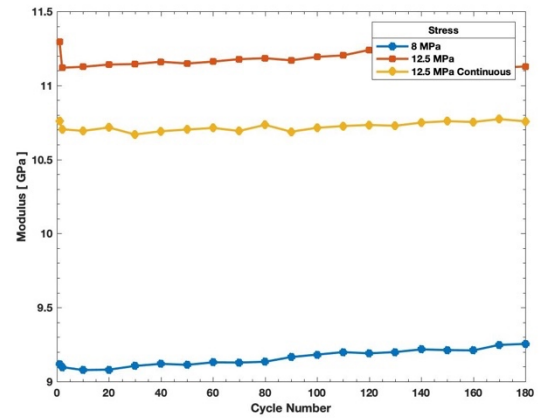


Figure 4-222: 120 °C - 10s - Instantaneous Modulus (Loading)

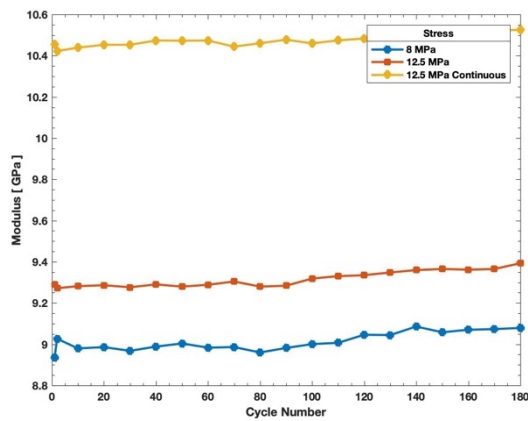


Figure 4-223: 120 °C - 20s - Instantaneous Modulus (Loading)

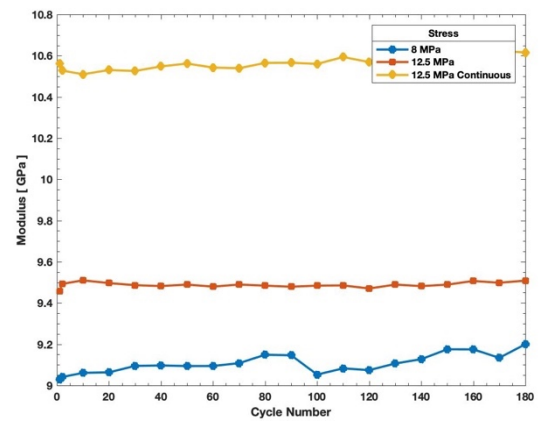


Figure 4-224: 120 °C - 40s - Instantaneous Modulus (Loading)

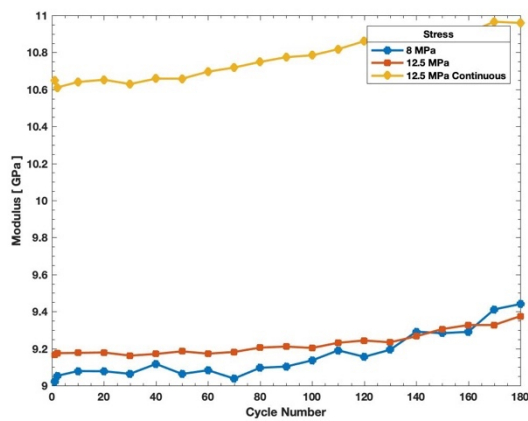


Figure 4-225: 120 °C - 80s - Instantaneous Modulus (Loading)

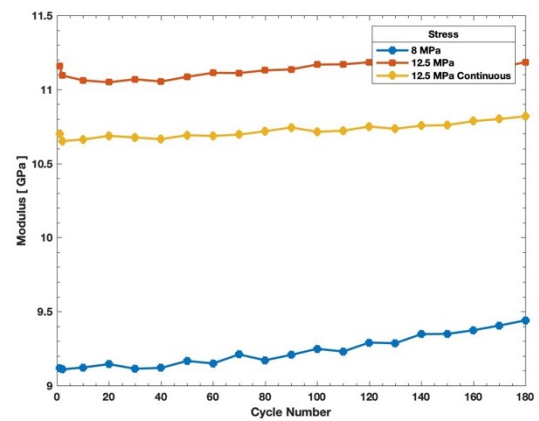


Figure 4-226: 120 °C - 20s (40s Creep) - Instantaneous Modulus (Loading)

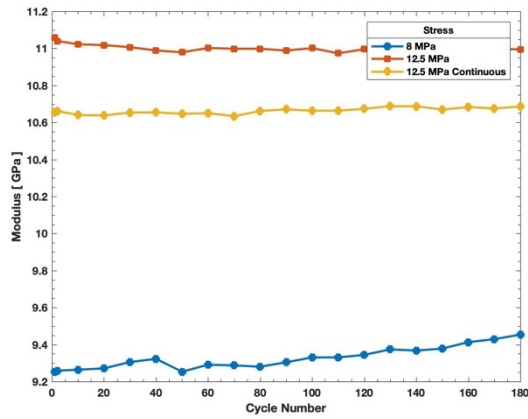


Figure 4-227: 120 °C - 1s - Instantaneous Modulus (Unloading)

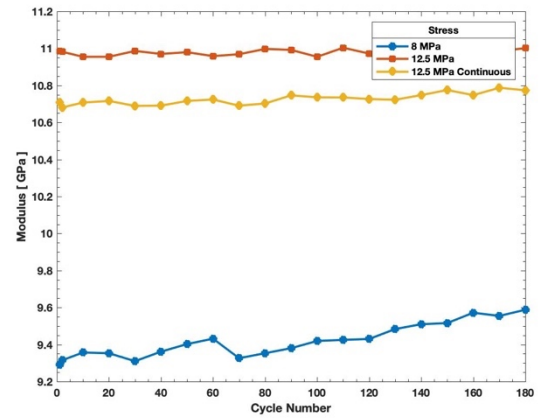


Figure 4-228: 120 °C - 10s - Instantaneous Modulus (Unloading)

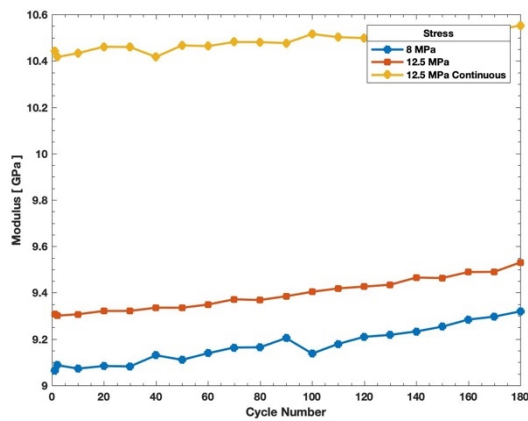


Figure 4-229: 120 °C - 20s - Instantaneous Modulus (Unloading)

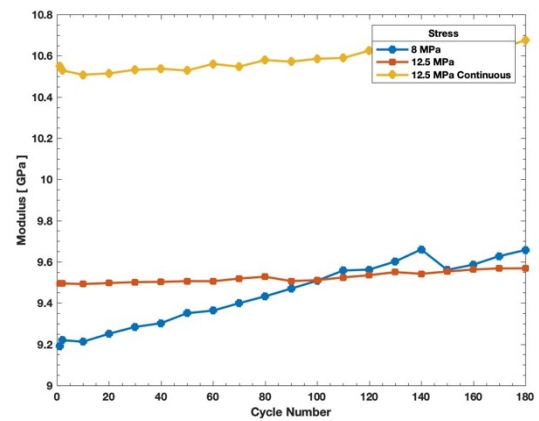


Figure 4-230: 120 °C - 40s - Instantaneous Modulus (Unloading)

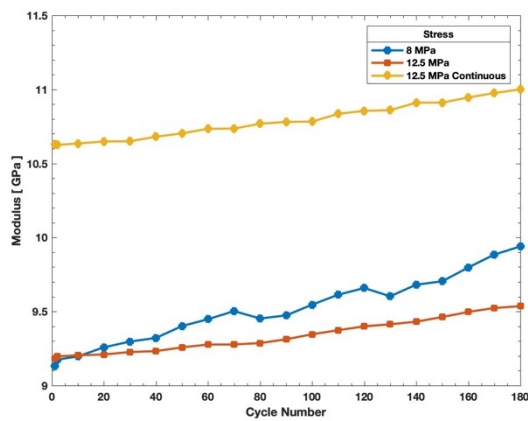


Figure 4-231: 120 °C - 80s - Instantaneous Modulus (Unloading)

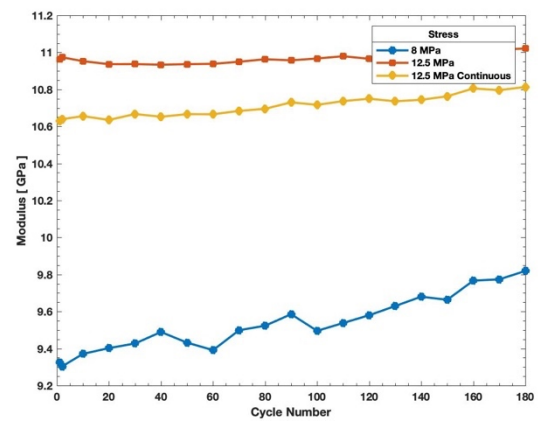


Figure 4-232: 120 °C - 20s (40s Creep) - Instantaneous Modulus (Unloading)

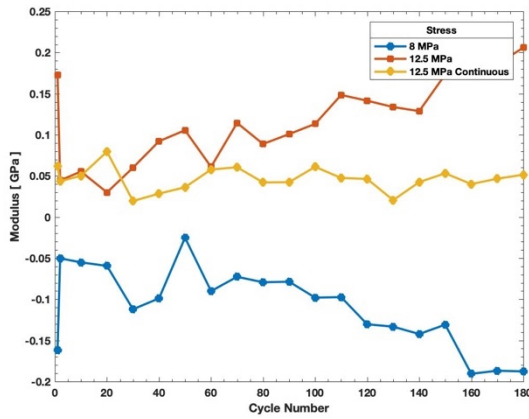


Figure 4-233: 120 °C - 1s - Instantaneous Modulus (Difference)

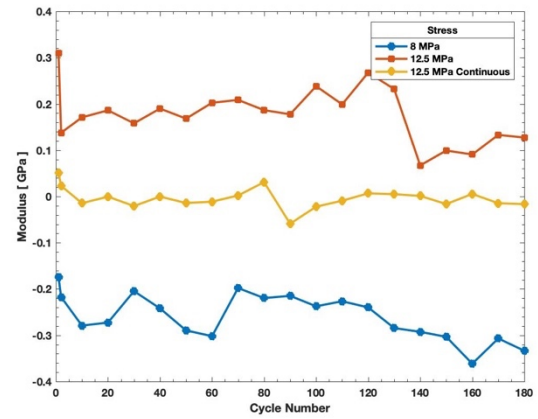


Figure 4-234: 120 °C - 10s - Instantaneous Modulus (Difference)

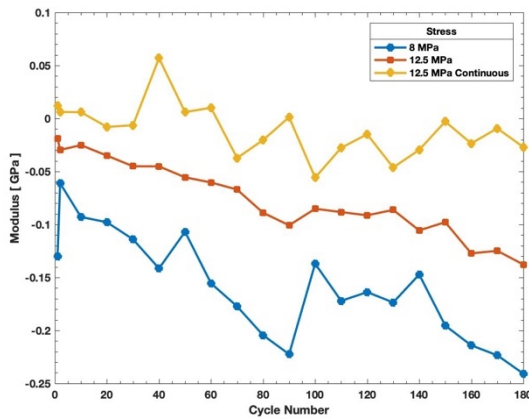


Figure 4-235: 120 °C - 20s - Instantaneous Modulus (Difference)

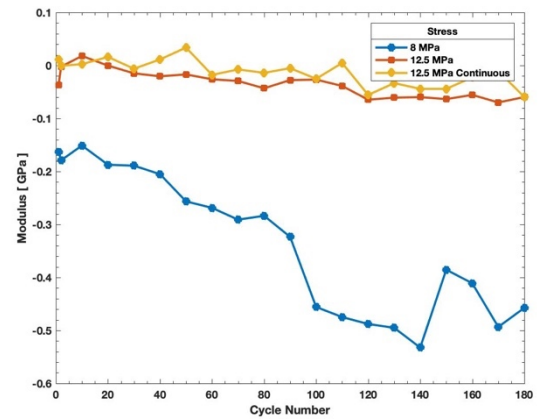


Figure 4-236: 120 °C - 40s - Instantaneous Modulus (Difference)

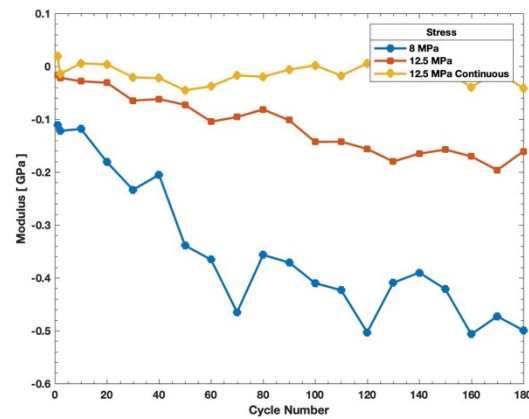


Figure 4-237: 120 °C - 80s - Instantaneous Modulus (Difference)

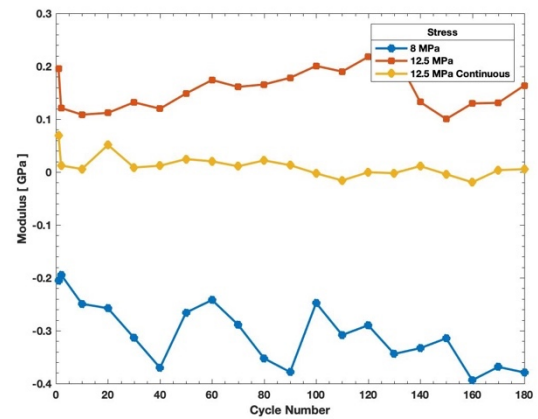


Figure 4-238: 120 °C - 20s (40s Creep) - Instantaneous Modulus (Difference)

Table 4-CCLXVII: Applied Load - Room Temperature - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Instantaneous Modulus [GPa]								
				E_t			E_u			$E_t - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	8 / 0.1	9.12	9.11	-0.02	9.08	9.22	0.13	0.04	-0.11	-0.15
20	1	RT	12.5 / 0.5	12.31	12.28	-0.02	12.12	12.15	0.02	0.18	0.13	-0.05
20	1	RT	12.5 / 0.5 C	11.07	11.09	0.02	11.06	11.11	0.05	0.01	-0.01	-0.03
20	10	RT	8 / 0.1	9.10	9.21	0.11	9.19	9.51	0.32	-0.09	-0.30	-0.21
20	10	RT	12.5 / 0.5	12.28	12.42	0.14	12.17	12.20	0.03	0.11	0.22	0.11
20	10	RT	12.5 / 0.5 C	11.13	11.23	0.09	11.14	11.26	0.11	-0.01	-0.03	-0.02
20	20	RT	8 / 0.1	8.99	9.04	0.04	9.08	9.34	0.26	-0.09	-0.31	-0.22
20	20	RT	12.5 / 0.5	11.45	11.55	0.10	11.44	11.56	0.12	0.01	-0.01	-0.02
20	20	RT	12.5 / 0.5 C	11.02	11.12	0.10	11.02	11.12	0.10	0.00	0.00	0.00
20	40	RT	8 / 0.1	8.99	9.07	0.08	9.16	9.60	0.44	-0.17	-0.53	-0.36
20	40	RT	12.5 / 0.5	10.78	10.70	-0.08	10.77	10.70	-0.07	0.01	0.00	-0.01
20	40	RT	12.5 / 0.5 C	11.03	11.17	0.14	11.02	11.20	0.18	0.01	-0.03	-0.04
20	80	RT	8 / 0.1	9.03	9.35	0.32	9.24	10.10	0.87	-0.21	-0.76	-0.55
20	80	RT	12.5 / 0.5	11.49	11.52	0.03	11.42	11.68	0.26	0.07	-0.16	-0.23
20	80	RT	12.5 / 0.5 C	11.05	11.33	0.29	11.04	11.39	0.35	0.01	-0.06	-0.06
40	20	RT	8 / 0.1	9.07	9.15	0.08	9.21	9.85	0.64	-0.14	-0.70	-0.56
40	20	RT	12.5 / 0.5	12.45	12.66	0.21	12.19	12.38	0.19	0.26	0.28	0.02
40	20	RT	12.5 / 0.5 C	11.15	11.37	0.22	11.15	11.40	0.26	0.00	-0.04	-0.04

Table 4-CCLXVIII: Applied Load - 80 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	8 / 0.1	9.17	9.23	0.06	9.17	9.29	0.12	0.00	-0.06	-0.06
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	10.54	10.57	0.03	10.55	10.62	0.07	-0.01	-0.05	-0.04
20	10	80	8 / 0.1	9.24	9.32	0.07	9.49	9.64	0.15	-0.25	-0.32	-0.08
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	10.52	10.62	0.10	10.55	10.66	0.11	-0.03	-0.04	-0.01
20	20	80	8 / 0.1	9.04	9.13	0.09	9.16	9.60	0.43	-0.12	-0.47	-0.35
20	20	80	12.5 / 0.5	9.54	9.71	0.17	9.54	9.73	0.19	-0.01	-0.02	-0.02
20	20	80	12.5 / 0.5 C	10.35	10.46	0.11	10.35	10.48	0.13	0.00	-0.02	-0.02
20	40	80	8 / 0.1	9.07	9.24	0.18	9.29	9.76	0.47	-0.22	-0.51	-0.29
20	40	80	12.5 / 0.5	9.54	9.76	0.21	9.58	9.93	0.35	-0.04	-0.18	-0.14
20	40	80	12.5 / 0.5 C	10.47	10.63	0.16	10.49	10.74	0.25	-0.02	-0.11	-0.08
20	80	80	8 / 0.1	9.12	9.83	0.70	9.39	10.36	0.96	-0.27	-0.53	-0.26
20	80	80	12.5 / 0.5	9.92	10.10	0.18	9.95	10.31	0.35	-0.03	-0.21	-0.17
20	80	80	12.5 / 0.5 C	10.48	10.81	0.33	10.51	10.91	0.40	-0.04	-0.10	-0.06
40	20	80	8 / 0.1	9.06	9.24	0.17	9.16	9.64	0.48	-0.09	-0.40	-0.31
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	10.52	10.66	0.14	10.52	10.74	0.22	-0.01	-0.08	-0.07

Table 4-CCLXIX: Applied Load - 120 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	8 / 0.1	9.21	9.27	0.06	9.26	9.45	0.19	-0.05	-0.19	-0.14
20	1	120	12.5 / 0.5	11.08	11.20	0.12	11.04	10.99	-0.05	0.04	0.21	0.16
20	1	120	12.5 / 0.5 C	10.71	10.74	0.03	10.66	10.69	0.02	0.04	0.05	0.01
20	10	120	8 / 0.1	9.10	9.25	0.16	9.31	9.59	0.27	-0.22	-0.33	-0.12
20	10	120	12.5 / 0.5	11.12	11.13	0.01	10.98	11.00	0.02	0.14	0.13	-0.01
20	10	120	12.5 / 0.5 C	10.70	10.76	0.05	10.68	10.77	0.09	0.02	-0.02	-0.04
20	20	120	8 / 0.1	9.03	9.08	0.05	9.09	9.32	0.23	-0.06	-0.24	-0.18
20	20	120	12.5 / 0.5	9.27	9.39	0.12	9.30	9.53	0.23	-0.03	-0.14	-0.11
20	20	120	12.5 / 0.5 C	10.42	10.53	0.10	10.42	10.55	0.14	0.01	-0.03	-0.03
20	40	120	8 / 0.1	9.04	9.20	0.16	9.22	9.66	0.44	-0.18	-0.46	-0.28
20	40	120	12.5 / 0.5	9.49	9.51	0.02	9.49	9.57	0.07	0.00	-0.06	-0.06
20	40	120	12.5 / 0.5 C	10.53	10.62	0.09	10.53	10.68	0.15	0.00	-0.06	-0.06
20	80	120	8 / 0.1	9.05	9.44	0.39	9.17	9.94	0.76	-0.12	-0.50	-0.38
20	80	120	12.5 / 0.5	9.17	9.38	0.20	9.20	9.54	0.34	-0.02	-0.16	-0.14
20	80	120	12.5 / 0.5 C	10.61	10.96	0.35	10.63	11.00	0.38	-0.01	-0.04	-0.03
40	20	120	8 / 0.1	9.11	9.44	0.33	9.30	9.82	0.52	-0.19	-0.38	-0.18
40	20	120	12.5 / 0.5	11.09	11.18	0.09	10.97	11.02	0.05	0.12	0.16	0.04
40	20	120	12.5 / 0.5 C	10.65	10.82	0.17	10.64	10.81	0.17	0.01	0.01	-0.01

Table 4-CCLXX: Applied Load - 180 °C - Instantaneous Modulus

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Instantaneous Modulus [GPa]								
				E_l			E_u			$E_l - E_u$		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	8 / 0.1	9.12	9.16	0.04	9.17	9.35	0.17	-0.05	-0.18	-0.13
20	1	180	12.5 / 0.5	9.93	10.00	0.07	9.90	9.99	0.09	0.03	0.01	-0.02
20	1	180	12.5 / 0.5 C	10.29	10.24	-0.05	10.18	10.17	-0.02	0.11	0.08	-0.03
20	10	180	8 / 0.1	9.05	9.18	0.13	9.17	9.49	0.32	-0.12	-0.31	-0.19
20	10	180	12.5 / 0.5	9.88	9.97	0.08	9.89	9.99	0.10	0.00	-0.02	-0.02
20	10	180	12.5 / 0.5 C	10.27	10.27	-0.01	10.23	10.24	0.01	0.04	0.03	-0.01
20	20	180	8 / 0.1	8.83	8.97	0.15	8.94	9.33	0.38	-0.11	-0.35	-0.24
20	20	180	12.5 / 0.5	9.36	9.50	0.14	9.32	9.49	0.18	0.05	0.01	-0.04
20	20	180	12.5 / 0.5 C	9.95	10.07	0.11	9.91	9.99	0.08	0.05	0.08	0.03
20	40	180	8 / 0.1	8.84	9.04	0.20	8.94	9.42	0.48	-0.10	-0.37	-0.27
20	40	180	12.5 / 0.5	9.76	9.87	0.12	9.75	9.88	0.12	0.00	0.00	-0.01
20	40	180	12.5 / 0.5 C	10.07	10.25	0.18	10.01	10.16	0.16	0.07	0.08	0.02
20	80	180	8 / 0.1	8.96	9.43	0.47	9.08	9.82	0.74	-0.12	-0.39	-0.27
20	80	180	12.5 / 0.5	9.82	10.09	0.27	9.83	10.14	0.31	-0.01	-0.05	-0.04
20	80	180	12.5 / 0.5 C	10.15	10.47	0.32	10.15	10.44	0.29	0.00	0.03	0.03
40	20	180	8 / 0.1	8.98	9.09	0.11	9.02	9.25	0.23	-0.04	-0.16	-0.12
40	20	180	12.5 / 0.5	9.90	10.10	0.20	9.90	10.16	0.26	0.00	-0.06	-0.06
40	20	180	12.5 / 0.5 C	10.32	10.41	0.10	10.24	10.37	0.13	0.08	0.04	-0.04

4.5.3 Strain Energy Density

4.5.3.1 Overall Strain Energy Density

Table 4-CCLXXI through Table 4-CCLXXIV contain the overall strain energy density values sorted based on the changes in the loading conditions. Figure 4-239 through Figure 4-262 provide plots showing the variation in the strain energy density values based on the loading condition.

Comparing the total strain energy density values, the two 12.5 / 0.5 MPa conditions were larger than the 8 / 0.1 MPa loading. This was valid for all the cycles evaluated along with the difference between the cycles. When comparing the two 12.5 / 0.5 MPa conditions, the non-continuous was larger for a slim majority of tests.

Comparing the stored strain energy density, similar to the total strain energy density, the stored was larger for the two 12.5 MPa testing scenarios for the 2nd and 180th cycle. However, unlike the total strain energy density, the difference between the two cycles was larger for the 8 / 0.1 MPa loading condition. When comparing the two 12.5 / 0.5 MPa conditions, the non-continuous was larger for the 2nd and 180th cycle, but the difference between the two cycles was larger for the continuous loading scenario.

The dissipated strain energy density was larger for the two 12.5 / 0.5 MPa loadings for the two cycles and the difference between the cycles. Comparing the two 12.5 / 0.5 MPa loading conditions, the continuous scenario was larger for the 2nd cycle, while the non-continuous was larger for the final cycle and the difference between the two cycles.

Lastly, the unrecovered strain energy density was larger for the two 12.5 / 0.5 MPa conditions for all cycles and the difference. The continuous loading conditions unrecovered strain energy density was larger in magnitude than the non-continuous.

Therefore, it can be summarized that as the stress is increased from 8 to 12.5 MPa in the continuous tests, the magnitude of total, stored, and dissipated energies increased as expected. The higher slope for the 12.5 MPa conditions in Table 4-LI suggests that the effect of creep recovery duration on changes in energies increases with stress.

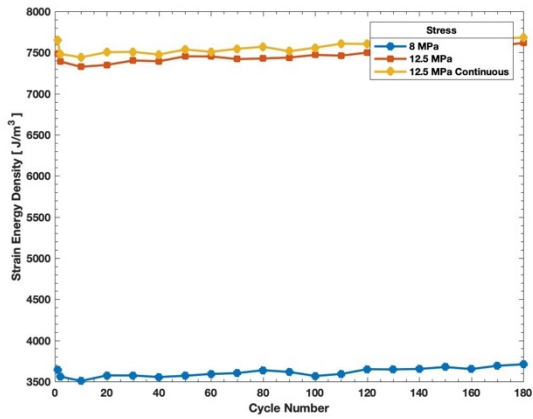


Figure 4-239: 120 °C - 1s - Total Strain Energy Density

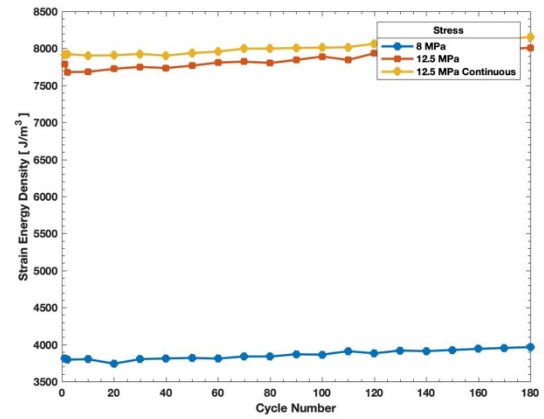


Figure 4-240: 120 °C - 10s - Total Strain Energy Density

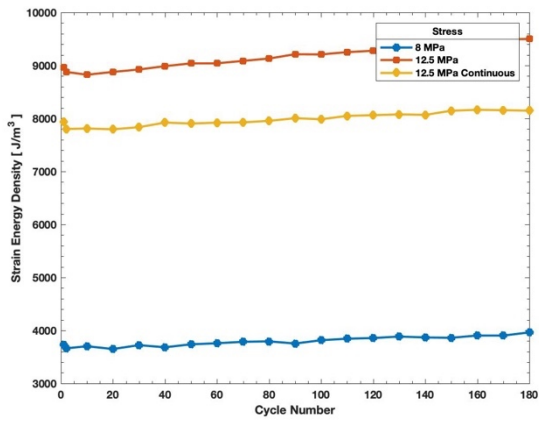


Figure 4-241: 120 °C - 20s - Total Strain Energy Density

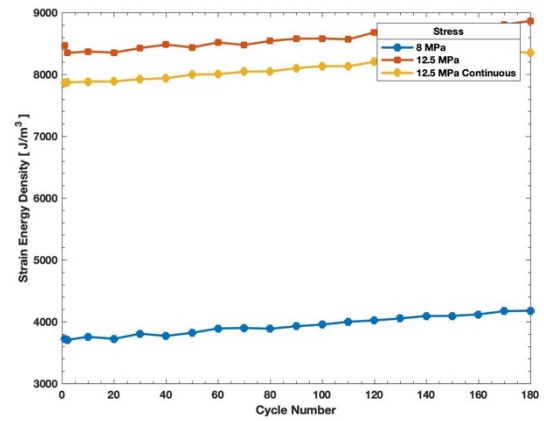


Figure 4-242: 120 °C - 40s - Total Strain Energy Density

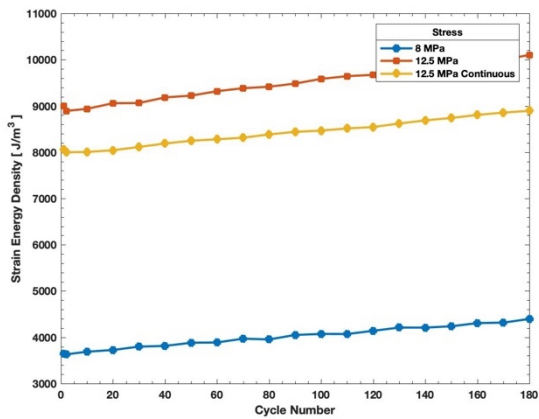


Figure 4-243: 120 °C - 80s - Total Strain Energy Density

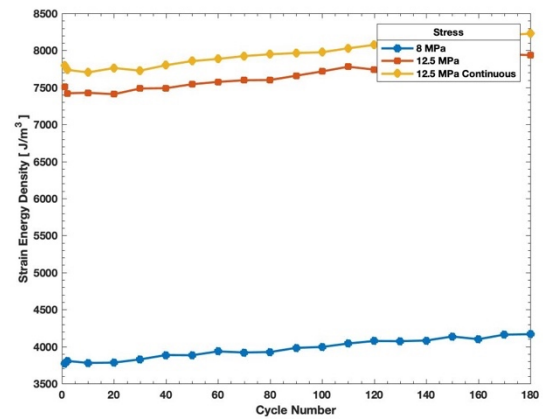


Figure 4-244: 120 °C - 20s (40s Creep) - Total Strain Energy Density

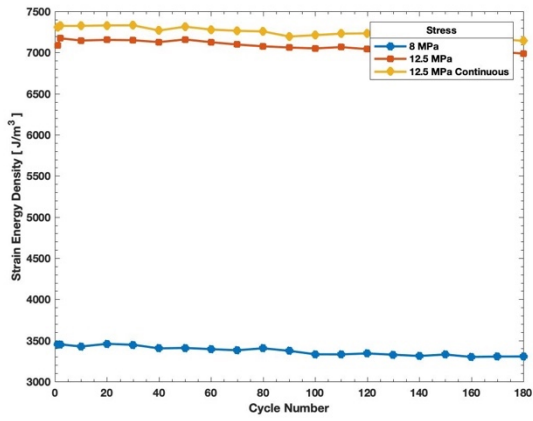


Figure 4-245: 120 °C - 1s - Stored Strain Energy Density

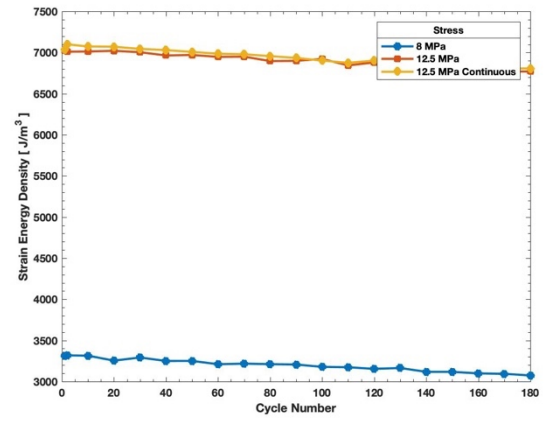


Figure 4-246: 120 °C - 10s - Stored Strain Energy Density

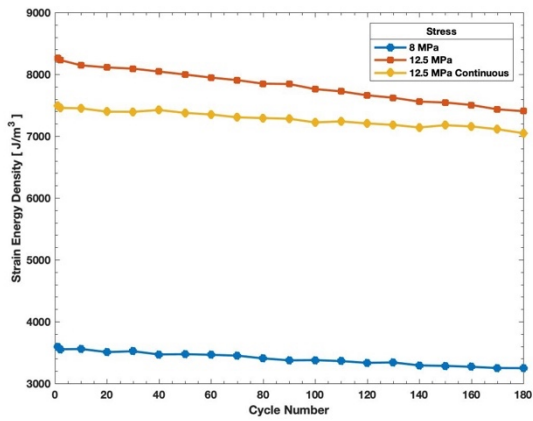


Figure 4-247: 120 °C - 20s - Stored Strain Energy Density

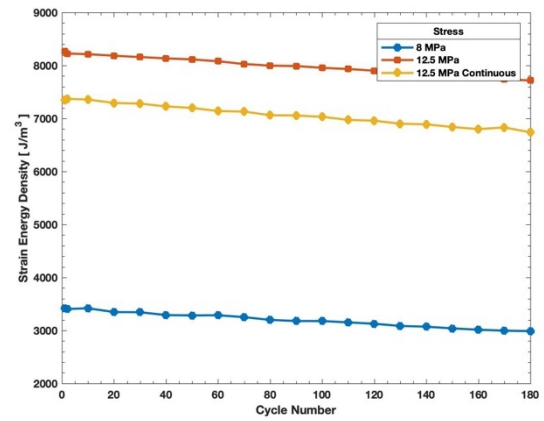


Figure 4-248: 120 °C - 40s - Stored Strain Energy Density

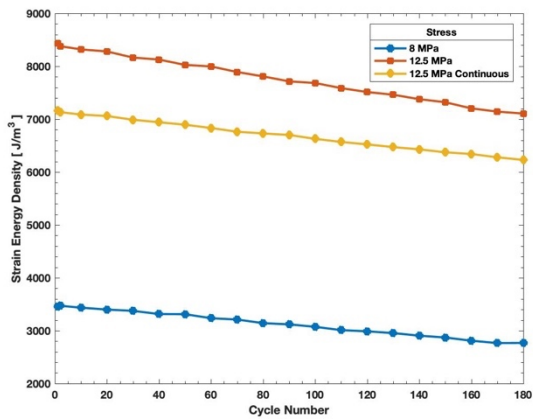


Figure 4-249: 120 °C - 80s - Stored Strain Energy Density

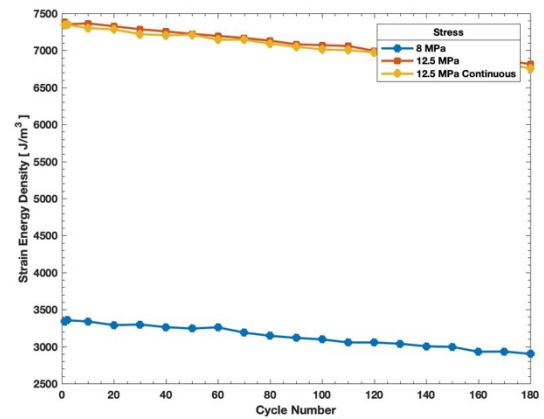


Figure 4-250: 120 °C - 20s (40s Creep) - Stored Strain Energy Density

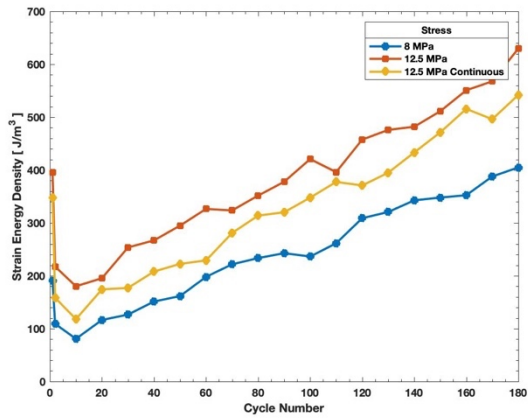


Figure 4-251: 120 °C - 1s - Dissipated Strain Energy Density

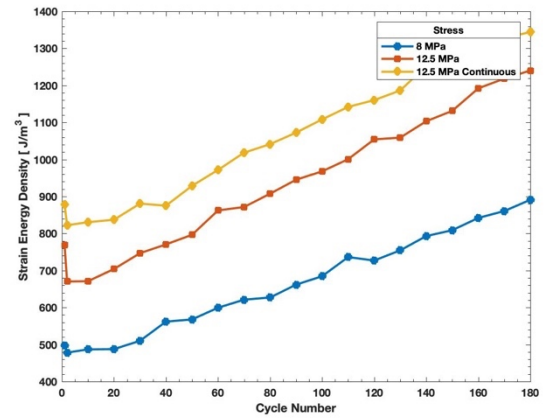


Figure 4-252: 120 °C - 10s - Dissipated Strain Energy Density

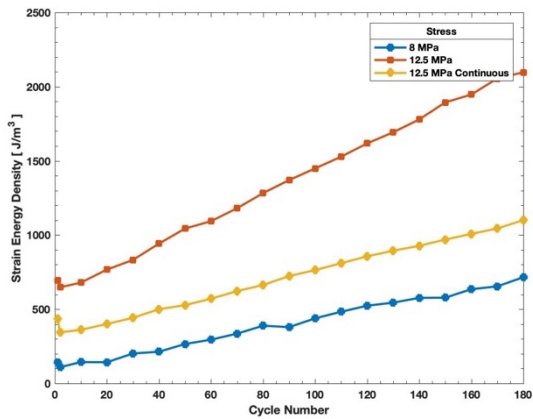


Figure 4-253: 120 °C - 20s - Dissipated Strain Energy Density

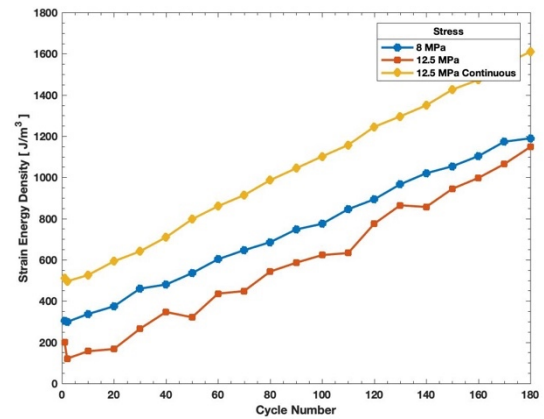


Figure 4-254: 120 °C - 40s - Dissipated Strain Energy Density

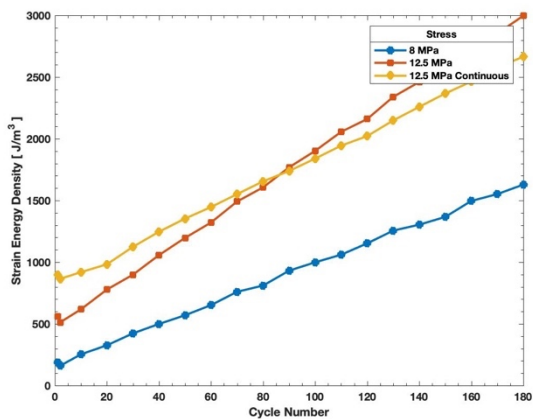


Figure 4-255: 120 °C - 80s - Dissipated Strain Energy Density

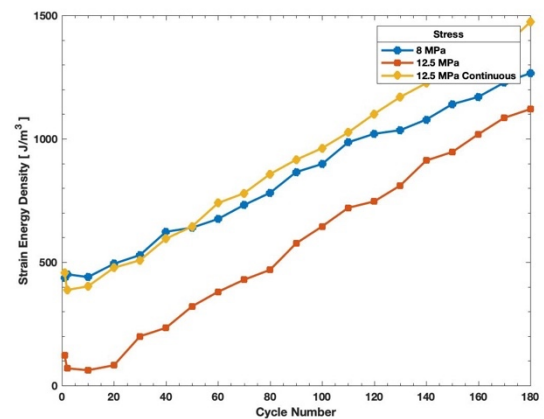


Figure 4-256: 120 °C - 20s (40s Creep) - Dissipated Strain Energy Density

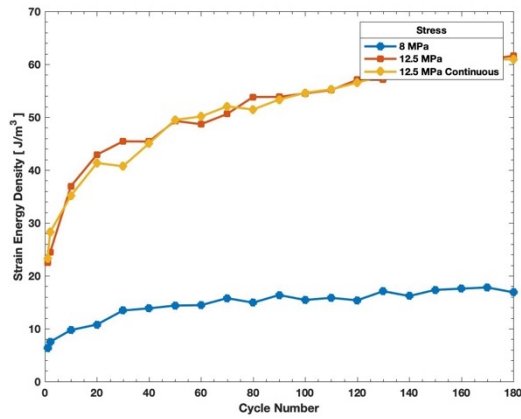


Figure 4-257: 120 °C - 1s - Unrecovered Strain Energy Density

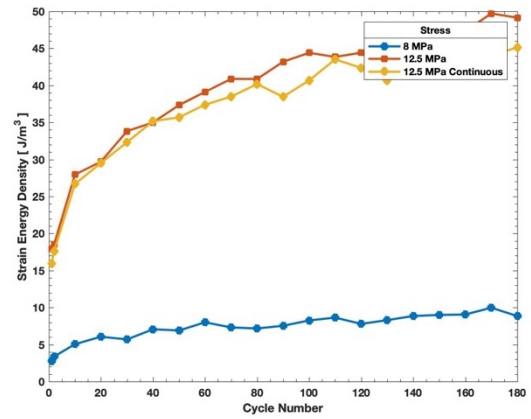


Figure 4-258: 120 °C - 10s - Unrecovered Strain Energy Density

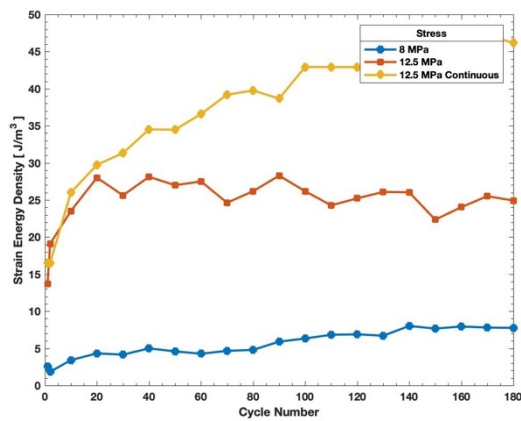


Figure 4-259: 120 °C - 20s - Unrecovered Strain Energy Density

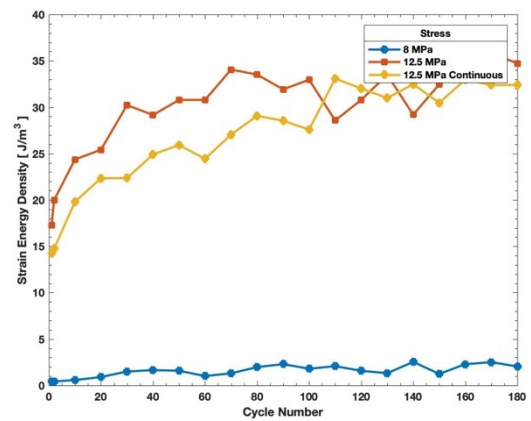


Figure 4-260: 120 °C - 40s - Unrecovered Strain Energy Density

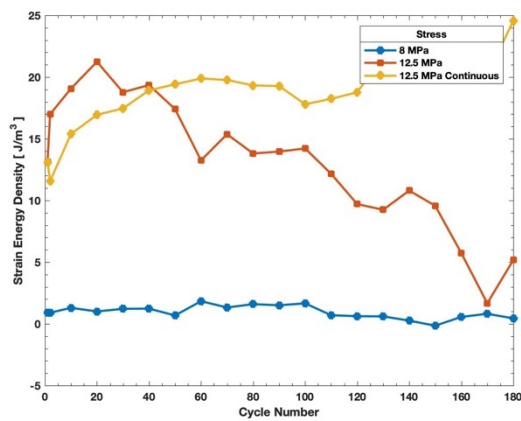


Figure 4-261: 120 °C - 80s - Unrecovered Strain Energy Density

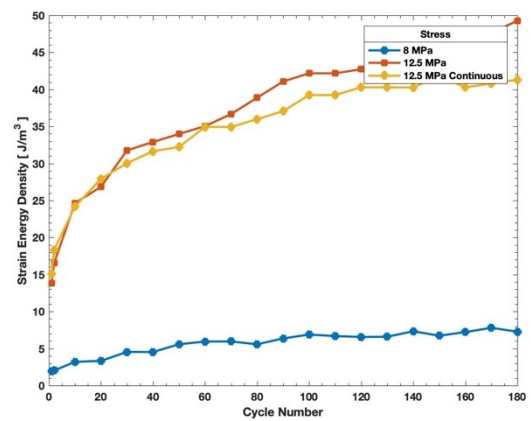


Figure 4-262: 120 °C - 20s (40s Creep) - Unrecovered Strain Energy Density

Table 4-CCLXXI: Applied Load - Room Temperature - Overall Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]											
				Total			Stored			Dissipated			Unrecovered		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	8 / 0.1	3412.23	3558.58	146.36	3592.34	3420.74	-171.60	-180.11	137.85	317.96	6.48	10.82	4.34
20	1	RT	12.5 / 0.5	6455.13	6643.92	188.79	6647.17	6489.31	-157.86	-192.03	154.61	346.65	19.25	34.55	15.30
20	1	RT	12.5 / 0.5 C	7171.66	7358.13	186.47	7027.03	6828.67	-198.36	144.63	529.46	384.83	22.71	39.37	16.67
20	10	RT	8 / 0.1	3600.69	3820.50	219.81	3398.32	3163.53	-234.80	202.37	656.97	454.60	2.48	4.76	2.28
20	10	RT	12.5 / 0.5	6768.96	7031.28	262.32	6394.60	6155.65	-238.96	374.36	875.63	501.27	14.87	24.66	9.79
20	10	RT	12.5 / 0.5 C	7447.53	7707.84	260.31	6792.81	6493.60	-299.20	654.73	1214.24	559.51	16.47	28.44	11.97
20	20	RT	8 / 0.1	3508.84	3811.03	302.19	3555.59	3232.51	-323.09	-46.75	578.53	625.28	1.57	3.08	1.50
20	20	RT	12.5 / 0.5	6939.68	7412.49	472.81	6801.57	6397.56	-404.01	138.11	1014.93	876.81	12.14	14.21	2.07
20	20	RT	12.5 / 0.5 C	7238.67	7590.90	352.22	7071.40	6692.53	-378.87	167.27	898.36	731.09	15.14	23.75	8.61
20	40	RT	8 / 0.1	3680.85	4130.53	449.68	3394.49	2930.00	-464.49	286.36	1200.53	914.17	0.71	2.00	1.29
20	40	RT	12.5 / 0.5	6898.69	8023.71	1125.02	7038.12	6837.22	-200.91	-139.43	1186.49	1325.92	11.21	16.36	5.15
20	40	RT	12.5 / 0.5 C	7235.12	7759.42	524.29	7090.46	6514.82	-575.64	144.66	1244.60	1099.93	11.95	21.51	9.56
20	80	RT	8 / 0.1	3764.38	4488.15	723.77	3317.17	2588.69	-728.48	447.21	1899.46	1452.25	0.64	1.86	1.22
20	80	RT	12.5 / 0.5	6615.24	7724.04	1108.80	6981.58	5979.21	-1002.37	-366.34	1744.84	2111.17	12.37	12.80	0.43
20	80	RT	12.5 / 0.5 C	7306.07	8189.33	883.25	6966.72	6073.47	-893.25	339.35	2115.85	1776.50	12.30	18.89	6.58
40	20	RT	8 / 0.1	3727.26	4160.48	433.22	3354.75	2902.05	-452.70	372.51	1258.44	885.92	1.69	3.58	1.89
40	20	RT	12.5 / 0.5	6914.40	7399.60	485.20	6312.11	5826.82	-485.29	602.30	1572.78	970.48	12.48	25.40	12.92
40	20	RT	12.5 / 0.5 C	7500.75	8008.95	508.21	6824.44	6272.88	-551.56	676.30	1736.07	1059.77	16.24	28.09	11.85

Table 4-CCLXXII: Applied Load - 80 °C - Overall Strain Energy Density

				Strain Energy Density [J/m ³]											
				Total			Stored			Dissipated			Unrecovered		
Creep Duration [s]	Recovery Duration [s]	Temperat ure [°C]	Stress [MPa]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	8 / 0.1	3482.62	3607.13	124.51	3515.17	3333.89	-181.28	-32.56	273.24	305.80	5.68	13.86	8.18
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	7803.16	7994.26	191.09	7130.82	6931.00	-199.82	672.35	1063.26	390.91	26.01	49.89	23.88
20	10	80	8 / 0.1	3810.99	4015.21	204.22	3183.64	2966.42	-217.22	627.35	1048.79	421.44	3.53	6.40	2.87
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	7753.66	8054.65	300.98	7241.62	6958.80	-282.81	512.05	1095.84	583.79	19.22	38.51	19.29
20	20	80	8 / 0.1	3690.81	3973.22	282.41	3353.20	3065.28	-287.92	337.61	907.94	570.33	2.93	4.91	1.98
20	20	80	12.5 / 0.5	8187.41	8649.31	461.90	7787.16	7240.52	-546.64	400.25	1408.79	1008.54	16.82	16.37	-0.45
20	20	80	12.5 / 0.5 C	7631.54	8006.39	374.84	7570.80	7169.59	-401.20	60.75	836.79	776.04	16.12	34.14	18.03
20	40	80	8 / 0.1	3685.65	4128.62	442.97	3350.13	2907.40	-442.73	335.53	1221.23	885.70	0.42	3.93	3.51
20	40	80	12.5 / 0.5	8497.21	9206.49	709.28	7898.98	7123.33	-775.66	598.23	2083.16	1484.93	15.38	29.86	14.48
20	40	80	12.5 / 0.5 C	7941.23	8489.34	548.11	7214.14	6628.51	-585.63	727.09	1860.83	1133.74	14.72	25.72	11.00
20	80	80	8 / 0.1	3830.03	4520.55	690.52	3230.82	2532.73	-698.09	599.21	1987.82	1388.61	1.37	2.27	0.90
20	80	80	12.5 / 0.5	8157.81	9329.63	1171.81	7661.45	6501.36	-1160.09	496.36	2828.27	2331.91	12.64	23.30	10.65
20	80	80	12.5 / 0.5 C	7927.09	8843.66	916.57	7182.48	6238.33	-944.15	744.61	2605.33	1860.72	13.06	19.07	6.01
40	20	80	8 / 0.1	3567.67	4003.31	435.64	3490.84	3049.60	-441.23	76.83	953.70	876.88	2.24	6.94	4.70
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	7710.67	8284.52	573.85	7374.72	6813.56	-561.17	335.94	1470.96	1135.02	16.71	37.60	20.89

Table 4-CCLXXIII: Applied Load - 120 °C - Overall Strain Energy Density

				Strain Energy Density [J/m ³]											
				Total			Stored			Dissipated			Unrecovered		
Creep Duration [s]	Recovery Duration [s]	Temperat ure [°C]	Stress [MPa]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	8 / 0.1	3560.88	3709.30	148.42	3451.89	3304.45	-147.44	108.99	404.85	295.86	7.50	16.87	9.36
20	1	120	12.5 / 0.5	7390.82	7617.15	226.33	7173.48	6987.42	-186.06	217.33	629.72	412.39	24.43	61.59	37.16
20	1	120	12.5 / 0.5 C	7482.75	7683.35	200.61	7324.41	7141.30	-183.10	158.34	542.05	383.71	28.24	60.94	32.69
20	10	120	8 / 0.1	3796.04	3964.85	168.82	3317.85	3073.84	-244.01	478.19	891.02	412.83	3.38	8.84	5.46
20	10	120	12.5 / 0.5	7680.90	8009.65	328.75	7010.62	6769.47	-241.15	670.27	1240.18	569.90	18.55	49.15	30.60
20	10	120	12.5 / 0.5 C	7922.58	8150.50	227.92	7100.30	6806.32	-293.97	822.29	1344.18	521.89	17.64	45.16	27.53
20	20	120	8 / 0.1	3661.65	3962.43	300.78	3551.87	3246.62	-305.25	109.78	715.81	606.03	1.84	7.75	5.91
20	20	120	12.5 / 0.5	8878.24	9501.31	623.08	8230.57	7404.07	-826.51	647.66	2097.24	1449.58	19.09	24.92	5.83
20	20	120	12.5 / 0.5 C	7801.42	8147.93	346.50	7457.05	7047.18	-409.87	344.38	1100.75	756.37	16.51	46.16	29.65
20	40	120	8 / 0.1	3702.21	4175.57	473.36	3403.70	2986.08	-417.62	298.51	1189.49	890.98	0.43	2.04	1.61
20	40	120	12.5 / 0.5	8345.78	8865.33	519.55	8225.53	7717.93	-507.60	120.24	1147.40	1027.16	19.99	34.73	14.74
20	40	120	12.5 / 0.5 C	7867.07	8348.00	480.93	7371.43	6738.62	-632.81	495.65	1609.38	1113.74	14.75	32.41	17.66
20	80	120	8 / 0.1	3629.97	4395.62	765.65	3470.11	2767.19	-702.91	159.86	1628.42	1468.56	0.90	0.44	-0.46
20	80	120	12.5 / 0.5	8892.66	10103.93	1211.27	8380.39	7106.48	-1273.91	512.27	2997.45	2485.18	16.99	5.17	-11.82
20	80	120	12.5 / 0.5 C	7997.92	8894.44	896.53	7133.18	6229.43	-903.75	864.73	2665.01	1800.28	11.57	24.56	12.99
40	20	120	8 / 0.1	3805.40	4166.17	360.78	3354.54	2900.58	-453.95	450.86	1265.59	814.73	2.03	7.27	5.24
40	20	120	12.5 / 0.5	7421.62	7936.09	514.48	7351.95	6815.61	-536.33	69.67	1120.48	1050.81	16.54	49.28	32.74
40	20	120	12.5 / 0.5 C	7737.64	8227.55	489.91	7350.50	6754.17	-596.32	387.14	1473.38	1086.23	18.34	41.30	22.96

Table 4-CCLXXIV: Applied Load - 180 °C - Overall Strain Energy Density

				Strain Energy Density [J/m ³]											
				Total			Stored			Dissipated			Unrecovered		
Creep Duration [s]	Recovery Duration [s]	Temperat ure [°C]	Stress [MPa]	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	8 / 0.1	3762.94	3899.04	136.10	3395.67	3236.65	-159.02	367.27	662.39	295.12	8.84	25.33	16.48
20	1	180	12.5 / 0.5	8239.99	8430.66	190.67	7768.45	7539.90	-228.55	471.54	890.76	419.22	36.99	91.25	54.27
20	1	180	12.5 / 0.5 C	7674.69	7908.24	233.54	7879.09	7698.31	-180.78	-204.40	209.92	414.32	32.39	109.15	76.76
20	10	180	8 / 0.1	3888.92	4058.44	169.52	3384.85	3165.05	-219.80	504.07	893.39	389.32	4.54	15.67	11.13
20	10	180	12.5 / 0.5	8392.26	8583.23	190.97	7853.41	7490.94	-362.47	538.85	1092.30	553.45	21.11	71.26	50.15
20	10	180	12.5 / 0.5 C	8071.17	8398.82	327.65	7647.73	7406.19	-241.54	423.44	992.63	569.19	23.64	80.48	56.83
20	20	180	8 / 0.1	3972.01	4257.01	285.00	3489.62	3213.81	-275.81	482.39	1043.20	560.81	2.48	12.40	9.92
20	20	180	12.5 / 0.5	9010.15	9266.94	256.79	8527.52	8000.56	-526.95	482.63	1266.37	783.74	30.05	135.98	105.93
20	20	180	12.5 / 0.5 C	8421.42	8727.73	306.31	8007.13	7621.51	-385.63	414.29	1106.23	691.94	25.63	96.43	70.80
20	40	180	8 / 0.1	3873.95	4297.10	423.15	3583.57	3118.43	-465.13	290.38	1178.66	888.28	0.60	6.72	6.12
20	40	180	12.5 / 0.5	8344.95	8994.34	649.39	8134.59	7517.94	-616.64	210.36	1476.40	1266.04	18.26	53.49	35.23
20	40	180	12.5 / 0.5 C	8227.62	8786.33	558.70	7960.34	7357.00	-603.34	267.29	1429.33	1162.04	15.76	62.95	47.19
20	80	180	8 / 0.1	3937.11	4674.07	736.96	3424.13	2717.61	-706.52	512.99	1956.46	1443.48	0.07	3.11	3.04
20	80	180	12.5 / 0.5	8321.51	9383.18	1061.66	8019.51	6976.49	-1043.01	302.01	2406.68	2104.68	14.58	41.26	26.68
20	80	180	12.5 / 0.5 C	8425.40	9360.25	934.86	7546.20	6636.11	-910.09	879.20	2724.15	1844.95	14.86	45.51	30.65
40	20	180	8 / 0.1	3583.52	3968.47	384.96	3742.32	3333.06	-409.27	-158.81	635.42	794.22	3.01	12.25	9.24
40	20	180	12.5 / 0.5	8562.13	9168.30	606.18	7736.73	7111.81	-624.92	825.40	2056.50	1231.09	22.13	69.41	47.29
40	20	180	12.5 / 0.5 C	8267.60	8811.59	543.99	7616.62	7083.52	-533.10	650.98	1728.07	1077.09	22.36	86.58	64.22

4.5.3.2 Total Strain Energy Density

Figure 4-263 through Figure 4-274 provide plots of the segments of the total strain energy density comparing the loading parameters, and Table 4-CCLXXV through Table 4-CCLXXVIII contain the segmented total strain energy density arranged to compare the loading scenarios.

Evaluating first the accumulated strain energy during the loading segment, the 12.5 MPa testing conditions were larger than the 8 MPa for the 2nd and 180th cycle. However, the difference between the two cycles was observed to be larger for the 8 MPa conditions. Comparing the two 12.5 MPa loading conditions, the non-continuous was larger than the continuous for the 2nd and final cycle, and larger for the continuous when evaluating the difference between the cycles.

Comparing the accumulated strain energy density during the creep hold, for both cycles and the difference between the cycles, the 12.5 MPa was larger than the 8 MPa condition. Between the two 12.5 MPa loading scenarios, the continuous was observed to be larger for the 2nd and final cycle, while the non-continuous was larger for the difference between the two cycles.

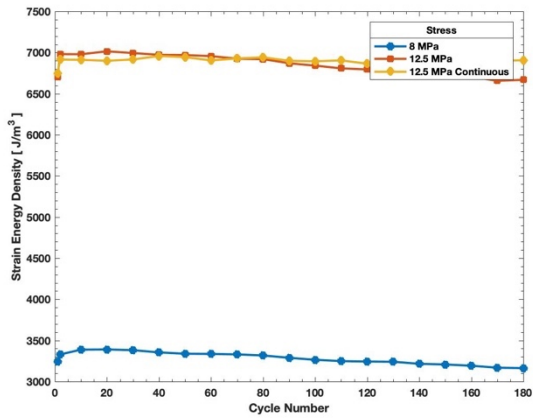


Figure 4-263: 120 °C - 1s - Total Strain Energy Density (Loading)

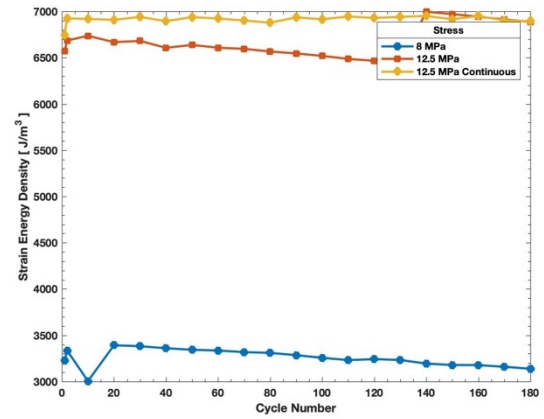


Figure 4-264: 120 °C - 10s - Total Strain Energy Density (Loading)

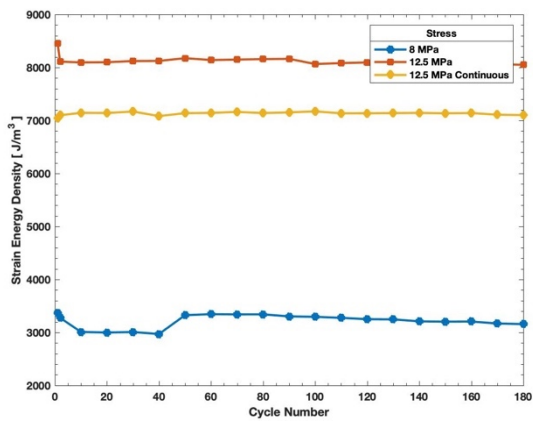


Figure 4-265: 120 °C - 20s - Total Strain Energy Density (Loading)

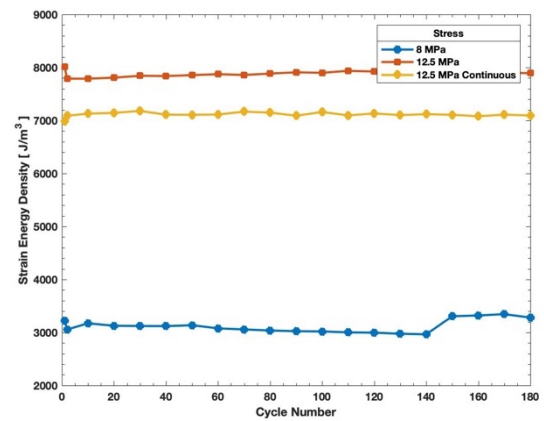


Figure 4-266: 120 °C - 40s - Total Strain Energy Density (Loading)

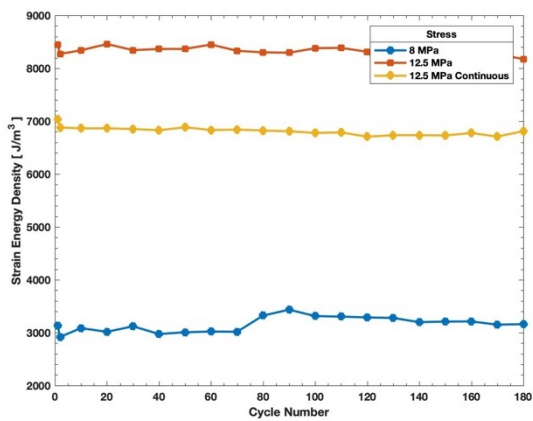


Figure 4-267: 120 °C - 80s - Total Strain Energy Density (Loading)

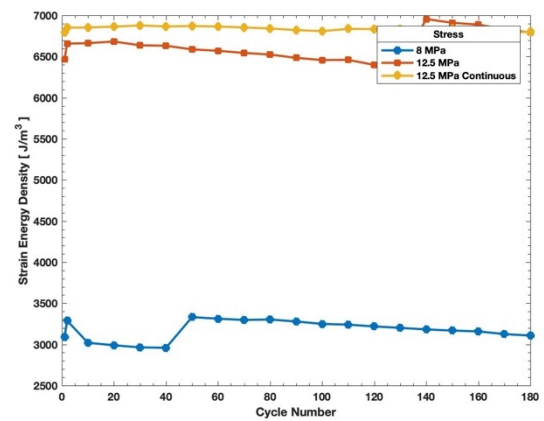


Figure 4-268: 120 °C - 20s (40s Creep) - Total Strain Energy Density (Loading)

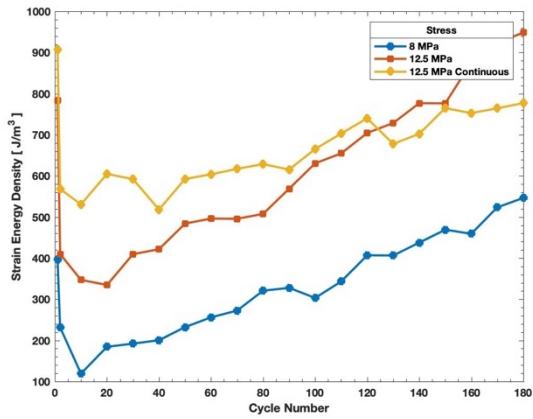


Figure 4-269: 120 °C - 1s - Total Strain Energy Density (Creep)

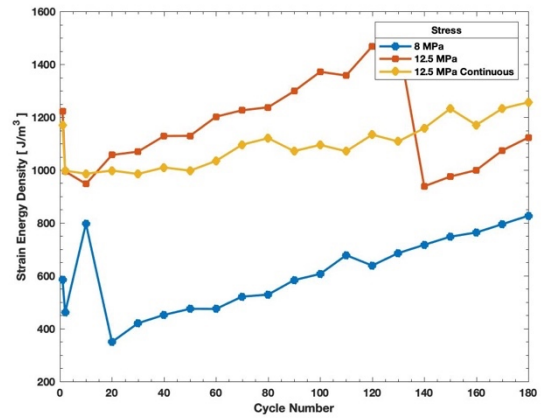


Figure 4-270: 120 °C - 10s - Total Strain Energy Density (Creep)

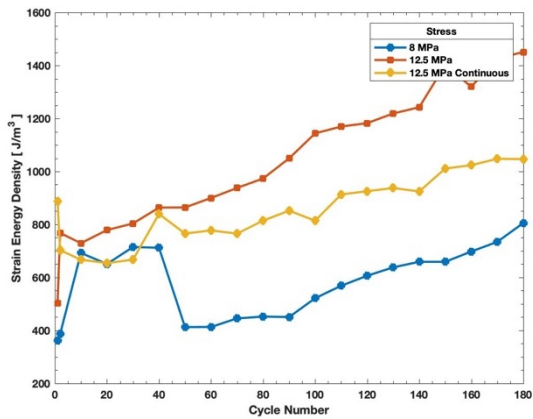


Figure 4-271: 120 °C - 20s - Total Strain Energy Density (Creep)

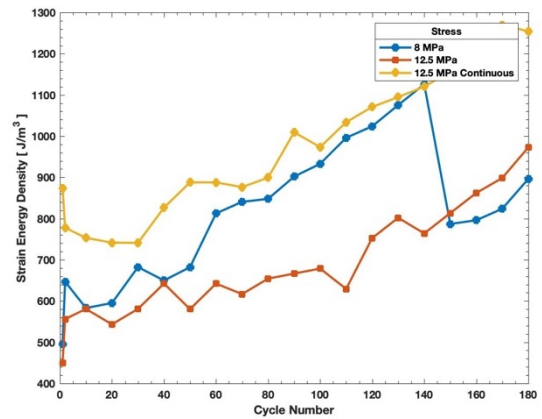


Figure 4-272: 120 °C - 40s - Total Strain Energy Density (Creep)

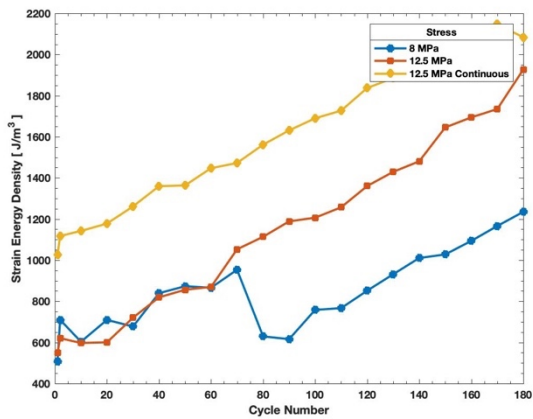


Figure 4-273: 120 °C - 80s - Total Strain Energy Density (Creep)

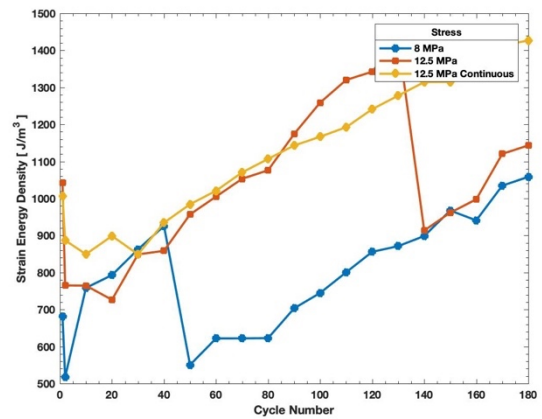


Figure 4-274: 120 °C - 20s (40s Creep) - Total Strain Energy Density (Creep)

Table 4-CCLXXV: Applied Load - Room Temperature - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Total - Loading			Total - Creep			Total – Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	8 / 0.1	3082.55	3280.20	197.65	329.68	278.39	-51.29	3412.23	3558.58	146.36
20	1	RT	12.5 / 0.5	6073.14	6248.14	175.00	381.99	395.78	13.79	6455.13	6643.92	188.79
20	1	RT	12.5 / 0.5 C	6812.00	6837.20	25.20	359.66	520.93	161.27	7171.66	7358.13	186.47
20	10	RT	8 / 0.1	3314.81	3112.68	-202.13	285.88	707.82	421.94	3600.69	3820.50	219.81
20	10	RT	12.5 / 0.5	6250.40	6375.86	125.46	518.56	655.42	136.86	6768.96	7031.28	262.32
20	10	RT	12.5 / 0.5 C	6551.02	6491.72	-59.30	896.51	1216.12	319.61	7447.53	7707.84	260.31
20	20	RT	8 / 0.1	3154.30	3375.20	220.91	354.55	435.83	81.28	3508.84	3811.03	302.19
20	20	RT	12.5 / 0.5	6617.27	6306.34	-310.93	322.41	1106.15	783.74	6939.68	7412.49	472.81
20	20	RT	12.5 / 0.5 C	6660.67	6669.07	8.40	578.00	921.83	343.83	7238.67	7590.90	352.22
20	40	RT	8 / 0.1	3178.40	3365.36	186.96	502.45	765.17	262.72	3680.85	4130.53	449.68
20	40	RT	12.5 / 0.5	7108.01	7633.93	525.91	-209.33	389.78	599.10	6898.69	8023.71	1125.02
20	40	RT	12.5 / 0.5 C	6644.32	6571.22	-73.10	590.80	1188.19	597.39	7235.12	7759.42	524.29
20	80	RT	8 / 0.1	3191.18	3342.98	151.80	573.20	1145.17	571.97	3764.38	4488.15	723.77
20	80	RT	12.5 / 0.5	6355.36	6659.85	304.48	259.88	1064.20	804.32	6615.24	7724.04	1108.80
20	80	RT	12.5 / 0.5 C	6690.78	6581.29	-109.49	615.29	1608.04	992.75	7306.07	8189.33	883.25
40	20	RT	8 / 0.1	3261.14	3046.42	-214.72	466.13	1114.06	647.94	3727.26	4160.48	433.22
40	20	RT	12.5 / 0.5	5911.00	5972.67	61.67	1003.40	1426.93	423.52	6914.40	7399.60	485.20
40	20	RT	12.5 / 0.5 C	6400.36	6318.36	-82.00	1100.39	1690.59	590.20	7500.75	8008.95	508.21

Table 4-CCLXXVI: Applied Load - 80 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Total - Loading			Total - Creep			Total – Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	8 / 0.1	3181.06	3334.76	153.70	301.55	272.37	-29.18	3482.62	3607.13	124.51
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	7243.92	7212.93	-30.99	559.25	781.33	222.08	7803.16	7994.26	191.09
20	10	80	8 / 0.1	3103.77	3286.79	183.02	707.23	728.43	21.20	3810.99	4015.21	204.22
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	6714.54	6694.34	-20.20	1039.12	1360.31	321.19	7753.66	8054.65	300.98
20	20	80	8 / 0.1	3226.41	3013.11	-213.30	464.40	960.12	495.71	3690.81	3973.22	282.41
20	20	80	12.5 / 0.5	7652.36	7189.38	-462.98	535.05	1459.93	924.88	8187.41	8649.31	461.90
20	20	80	12.5 / 0.5 C	6763.68	6759.45	-4.22	867.87	1246.93	379.07	7631.54	8006.39	374.84
20	40	80	8 / 0.1	3085.04	3302.40	217.35	600.61	826.23	225.62	3685.65	4128.62	442.97
20	40	80	12.5 / 0.5	7875.23	7349.32	-525.91	621.98	1857.17	1235.19	8497.21	9206.49	709.28
20	40	80	12.5 / 0.5 C	6863.96	6856.28	-7.68	1077.27	1633.06	555.79	7941.23	8489.34	548.11
20	80	80	8 / 0.1	3307.60	3067.42	-240.17	522.43	1453.12	930.69	3830.03	4520.55	690.52
20	80	80	12.5 / 0.5	7647.61	7596.21	-51.40	510.21	1733.42	1223.21	8157.81	9329.63	1171.81
20	80	80	12.5 / 0.5 C	6980.37	6795.19	-185.18	946.71	2048.46	1101.75	7927.09	8843.66	916.57
40	20	80	8 / 0.1	3109.87	3308.12	198.25	457.80	695.18	237.39	3567.67	4003.31	435.64
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	6791.55	6786.91	-4.64	919.12	1497.61	578.49	7710.67	8284.52	573.85

Table 4-CCLXXVII: Applied Load - 120 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Total - Loading			Total - Creep			Total – Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	8 / 0.1	3329.32	3162.79	-166.53	231.56	546.50	314.95	3560.88	3709.30	148.42
20	1	120	12.5 / 0.5	6980.91	6668.69	-312.22	409.91	948.46	538.55	7390.82	7617.15	226.33
20	1	120	12.5 / 0.5 C	6914.58	6906.19	-8.39	568.17	777.17	209.00	7482.75	7683.35	200.61
20	10	120	8 / 0.1	3334.94	3137.72	-197.22	461.10	827.13	366.03	3796.04	3964.85	168.82
20	10	120	12.5 / 0.5	6686.00	6886.81	200.81	994.90	1122.84	127.94	7680.90	8009.65	328.75
20	10	120	12.5 / 0.5 C	6925.19	6894.15	-31.03	997.40	1256.35	258.95	7922.58	8150.50	227.92
20	20	120	8 / 0.1	3275.19	3157.05	-118.13	386.46	805.38	418.92	3661.65	3962.43	300.78
20	20	120	12.5 / 0.5	8110.61	8050.57	-60.04	767.62	1450.74	683.12	8878.24	9501.31	623.08
20	20	120	12.5 / 0.5 C	7098.61	7101.35	2.73	702.81	1046.58	343.77	7801.42	8147.93	346.50
20	40	120	8 / 0.1	3055.33	3279.35	224.02	646.88	896.22	249.34	3702.21	4175.57	473.36
20	40	120	12.5 / 0.5	7789.59	7892.64	103.05	556.18	972.68	416.50	8345.78	8865.33	519.55
20	40	120	12.5 / 0.5 C	7089.37	7093.54	4.17	777.70	1254.46	476.76	7867.07	8348.00	480.93
20	80	120	8 / 0.1	2920.22	3160.60	240.38	709.75	1235.01	525.26	3629.97	4395.62	765.65
20	80	120	12.5 / 0.5	8272.04	8176.70	-95.34	620.62	1927.23	1306.62	8892.66	10103.93	1211.27
20	80	120	12.5 / 0.5 C	6880.41	6810.93	-69.48	1117.50	2083.51	966.01	7997.92	8894.44	896.53
40	20	120	8 / 0.1	3287.78	3107.77	-180.00	517.62	1058.40	540.78	3805.40	4166.17	360.78
40	20	120	12.5 / 0.5	6656.55	6792.69	136.14	765.06	1143.40	378.34	7421.62	7936.09	514.48
40	20	120	12.5 / 0.5 C	6850.87	6800.76	-50.11	886.77	1426.79	540.02	7737.64	8227.55	489.91

Table 4-CCLXXVIII: Applied Load - 180 °C - Total Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Total - Loading			Total - Creep			Total – Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	8 / 0.1	3178.62	3419.93	241.31	584.32	479.11	-105.22	3762.94	3899.04	136.10
20	1	180	12.5 / 0.5	7791.70	7380.66	-411.04	448.29	1050.00	601.70	8239.99	8430.66	190.67
20	1	180	12.5 / 0.5 C	7142.93	7156.33	13.40	531.77	751.91	220.14	7674.69	7908.24	233.54
20	10	180	8 / 0.1	3165.20	2952.56	-212.64	723.73	1105.88	382.16	3888.92	4058.44	169.52
20	10	180	12.5 / 0.5	7722.19	7317.39	-404.80	670.07	1265.85	595.78	8392.26	8583.23	190.97
20	10	180	12.5 / 0.5 C	7123.37	7168.63	45.26	947.80	1230.19	282.39	8071.17	8398.82	327.65
20	20	180	8 / 0.1	3107.54	2976.65	-130.90	864.47	1280.37	415.90	3972.01	4257.01	285.00
20	20	180	12.5 / 0.5	7872.81	7596.89	-275.91	1137.34	1670.04	532.70	9010.15	9266.94	256.79
20	20	180	12.5 / 0.5 C	6917.72	6934.25	16.53	1503.71	1793.49	289.78	8421.42	8727.73	306.31
20	40	180	8 / 0.1	3146.12	2955.58	-190.54	727.83	1341.52	613.69	3873.95	4297.10	423.15
20	40	180	12.5 / 0.5	7590.35	7336.49	-253.86	754.60	1657.86	903.26	8344.95	8994.34	649.39
20	40	180	12.5 / 0.5 C	6941.21	6814.09	-127.12	1286.42	1972.23	685.82	8227.62	8786.33	558.70
20	80	180	8 / 0.1	3117.82	3234.53	116.71	819.29	1439.54	620.25	3937.11	4674.07	736.96
20	80	180	12.5 / 0.5	7651.02	7208.34	-442.68	670.49	2174.84	1504.34	8321.51	9383.18	1061.66
20	80	180	12.5 / 0.5 C	7353.32	7167.55	-185.77	1072.08	2192.70	1120.63	8425.40	9360.25	934.86
40	20	180	8 / 0.1	3076.92	3327.81	250.89	506.59	640.66	134.07	3583.52	3968.47	384.96
40	20	180	12.5 / 0.5	7670.12	7224.58	-445.54	892.01	1943.72	1051.71	8562.13	9168.30	606.18
40	20	180	12.5 / 0.5 C	6966.81	6935.04	-31.77	1300.79	1876.55	575.76	8267.60	8811.59	543.99

4.5.3.3 Stored Strain Energy Density

Lastly, Table 4-CCLXXIX through Table 4-CCLXXXII contain the segmented stored strain energy density arranged based on the loading parameters, and Figure 4-275 through Figure 4-286 provide the relevant cyclic plots for the sample data set.

For the strain energy density accumulated during the unloading segment, the two 12.5 MPa tests were larger than that for the 8 MPa testing for the 2nd and final cycle. Whereas for the difference between the two cycles was observed to be larger for the 8 MPa condition. The 12.5 MPa non-continuous was larger than the continuous for the 2nd and 180th cycle, while the continuous was larger for the difference between the cycles.

Evaluating the stored strain energy density during the recovery hold, the two 12.5 MPa tests were larger in magnitude than the 8 MPa tests. This was observed to be true for the majority of the tests and cycles evaluated, except for the change over the course of testing for the 8 MPa continuous tests which was larger for a slim majority over the 12.5 MPa continuous. Comparing the two 12.5 MPa testing scenarios, the continuous was observed to be larger than the non-continuous testing for the 2nd and 180th cycle, while the difference between the cycles was larger for the non-continuous.

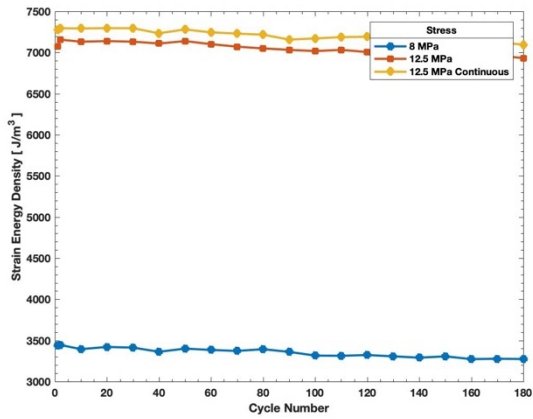


Figure 4-275: 120 °C - 1s - Stored Strain Energy Density (Unloading)

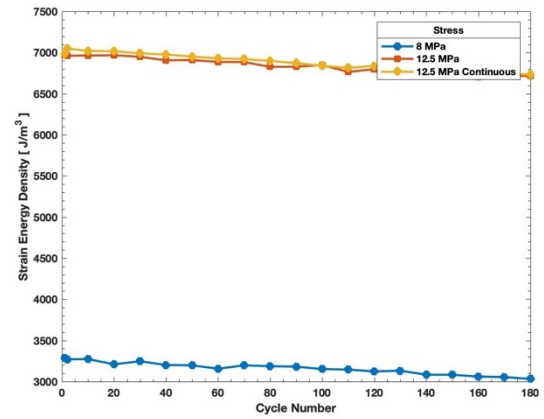


Figure 4-276: 120 °C - 10s - Stored Strain Energy Density (Unloading)

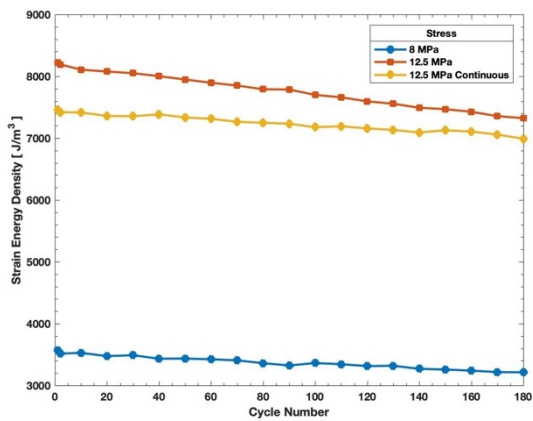


Figure 4-277: 120 °C - 20s - Stored Strain Energy Density (Unloading)

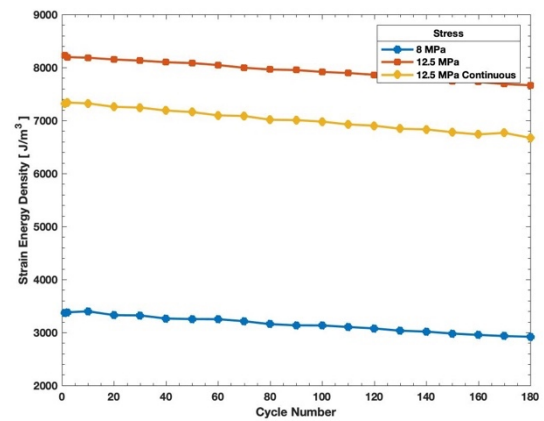


Figure 4-278: 120 °C - 40s - Stored Strain Energy Density (Unloading)

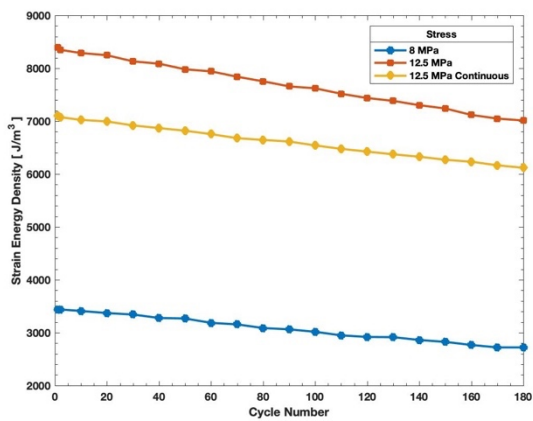


Figure 4-279: 120 °C - 80s - Stored Strain Energy Density (Unloading)

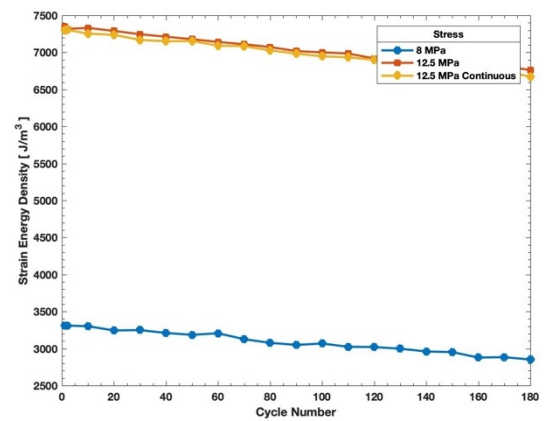


Figure 4-280: 120 °C - 20s (40s Creep) - Stored Strain Energy Density (Unloading)

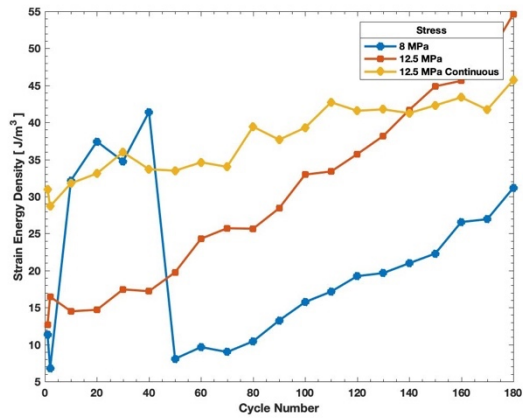


Figure 4-281: 120 °C - 1s - Stored Strain Energy Density (Recovery)

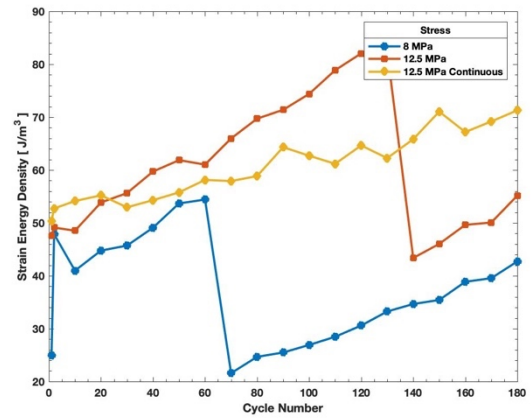


Figure 4-282: 120 °C - 10s - Stored Strain Energy Density (Recovery)

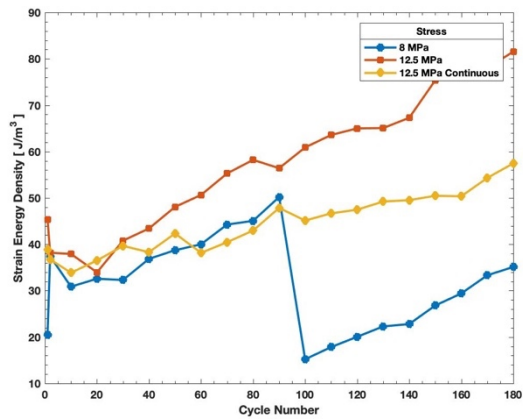


Figure 4-283: 120 °C - 20s - Stored Strain Energy Density (Recovery)

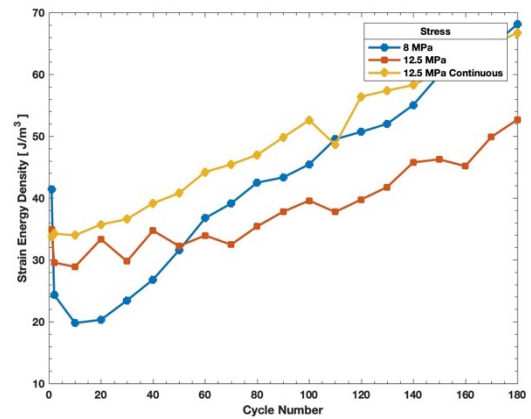


Figure 4-284: 120 °C - 40s - Stored Strain Energy Density (Recovery)

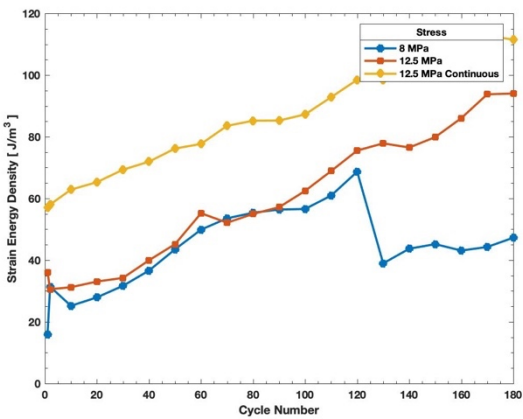


Figure 4-285: 120 °C - 80s - Stored Strain Energy Density (Recovery)

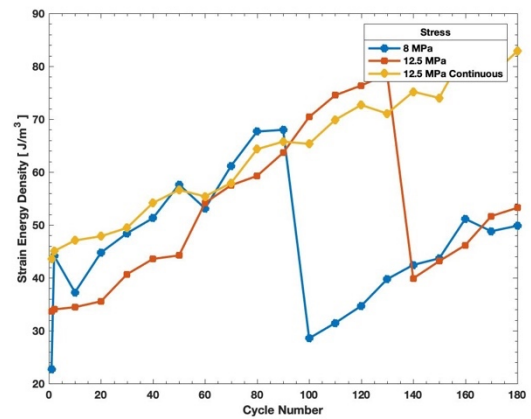


Figure 4-286: 120 °C - 20s (40s Creep) - Stored Strain Energy Density (Recovery)

Table 4-CCLXXIX: Applied Load - Room Temperature - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Stored - Unloading			Stored - Recovery			Stored - Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	RT	8 / 0.1	3577.69	3410.58	-167.11	14.65	10.15	-4.50	3592.34	3420.74	-171.60
20	1	RT	12.5 / 0.5	6629.45	6469.29	-160.16	17.71	20.01	2.30	6647.17	6489.31	-157.86
20	1	RT	12.5 / 0.5 C	7012.63	6801.91	-210.73	14.40	26.77	12.37	7027.03	6828.67	-198.36
20	10	RT	8 / 0.1	3390.12	3129.58	-260.54	8.20	33.95	25.74	3398.32	3163.53	-234.80
20	10	RT	12.5 / 0.5	6368.59	6125.22	-243.37	26.02	30.43	4.41	6394.60	6155.65	-238.96
20	10	RT	12.5 / 0.5 C	6741.82	6422.23	-319.59	50.99	71.37	20.38	6792.81	6493.60	-299.20
20	20	RT	8 / 0.1	3545.68	3188.17	-357.51	9.91	44.34	34.43	3555.59	3232.51	-323.09
20	20	RT	12.5 / 0.5	6787.87	6337.17	-450.70	13.70	60.39	46.69	6801.57	6397.56	-404.01
20	20	RT	12.5 / 0.5 C	7043.85	6641.49	-402.36	27.55	51.04	23.49	7071.40	6692.53	-378.87
20	40	RT	8 / 0.1	3376.58	2872.79	-503.79	17.91	57.21	39.30	3394.49	2930.00	-464.49
20	40	RT	12.5 / 0.5	7020.26	6814.74	-205.52	17.86	22.47	4.61	7038.12	6837.22	-200.91
20	40	RT	12.5 / 0.5 C	7060.77	6450.56	-610.21	29.69	64.26	34.58	7090.46	6514.82	-575.64
20	80	RT	8 / 0.1	3296.04	2515.51	-780.53	21.14	73.18	52.04	3317.17	2588.69	-728.48
20	80	RT	12.5 / 0.5	6969.81	5923.12	-1046.69	11.76	56.09	44.33	6981.58	5979.21	-1002.37
20	80	RT	12.5 / 0.5 C	6937.14	5988.54	-948.59	29.58	84.93	55.35	6966.72	6073.47	-893.25
40	20	RT	8 / 0.1	3338.22	2845.23	-492.99	16.53	56.81	40.28	3354.75	2902.05	-452.70
40	20	RT	12.5 / 0.5	6257.15	5753.35	-503.80	54.96	73.47	18.51	6312.11	5826.82	-485.29
40	20	RT	12.5 / 0.5 C	6759.81	6170.80	-589.02	64.63	102.08	37.45	6824.44	6272.88	-551.56

Table 4-CCLXXX: Applied Load - 80 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Stored - Unloading			Stored - Recovery			Stored - Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	80	8 / 0.1	3505.31	3324.94	-180.37	9.86	8.95	-0.91	3515.17	3333.89	-181.28
20	1	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	1	80	12.5 / 0.5 C	7104.54	6893.50	-211.04	26.27	37.50	11.22	7130.82	6931.00	-199.82
20	10	80	8 / 0.1	3153.67	2937.00	-216.68	29.97	29.43	-0.54	3183.64	2966.42	-217.22
20	10	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
20	10	80	12.5 / 0.5 C	7177.32	6875.33	-301.99	64.29	83.47	19.18	7241.62	6958.80	-282.81
20	20	80	8 / 0.1	3339.41	3017.88	-321.53	13.78	47.40	33.61	3353.20	3065.28	-287.92
20	20	80	12.5 / 0.5	7765.86	7161.89	-603.97	21.30	78.64	57.33	7787.16	7240.52	-546.64
20	20	80	12.5 / 0.5 C	7516.25	7092.79	-423.46	54.55	76.80	22.26	7570.80	7169.59	-401.20
20	40	80	8 / 0.1	3326.31	2845.01	-481.30	23.81	62.39	38.57	3350.13	2907.40	-442.73
20	40	80	12.5 / 0.5	7873.83	7007.00	-866.83	25.16	116.33	91.17	7898.98	7123.33	-775.66
20	40	80	12.5 / 0.5 C	7149.42	6534.05	-615.37	64.72	94.46	29.74	7214.14	6628.51	-585.63
20	80	80	8 / 0.1	3185.74	2473.56	-712.18	45.08	59.17	14.09	3230.82	2532.73	-698.09
20	80	80	12.5 / 0.5	7652.01	6414.56	-1237.44	9.44	86.80	77.35	7661.45	6501.36	-1160.09
20	80	80	12.5 / 0.5 C	7128.56	6129.77	-998.79	53.92	108.56	54.64	7182.48	6238.33	-944.15
40	20	80	8 / 0.1	3475.49	2989.64	-485.84	15.35	59.96	44.61	3490.84	3049.60	-441.23
40	20	80	12.5 / 0.5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	20	80	12.5 / 0.5 C	7322.35	6722.74	-599.60	52.38	90.81	38.44	7374.72	6813.56	-561.17

Table 4-CCLXXXI: Applied Load - 120 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Stored - Unloading			Stored - Recovery			Stored - Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	120	8 / 0.1	3445.10	3273.29	-171.82	6.79	31.17	24.38	3451.89	3304.45	-147.44
20	1	120	12.5 / 0.5	7157.02	6932.78	-224.24	16.46	54.65	38.18	7173.48	6987.42	-186.06
20	1	120	12.5 / 0.5 C	7295.73	7095.57	-200.16	28.68	45.74	17.06	7324.41	7141.30	-183.10
20	10	120	8 / 0.1	3269.99	3031.13	-238.86	47.86	42.71	-5.16	3317.85	3073.84	-244.01
20	10	120	12.5 / 0.5	6961.51	6714.30	-247.21	49.11	55.17	6.05	7010.62	6769.47	-241.15
20	10	120	12.5 / 0.5 C	7047.57	6735.03	-312.53	52.73	71.29	18.56	7100.30	6806.32	-293.97
20	20	120	8 / 0.1	3514.46	3211.51	-302.95	37.41	35.12	-2.30	3551.87	3246.62	-305.25
20	20	120	12.5 / 0.5	8192.38	7322.51	-869.87	38.19	81.56	43.37	8230.57	7404.07	-826.51
20	20	120	12.5 / 0.5 C	7420.30	6989.72	-430.58	36.75	57.46	20.71	7457.05	7047.18	-409.87
20	40	120	8 / 0.1	3379.36	2917.99	-461.37	24.34	68.09	43.76	3403.70	2986.08	-417.62
20	40	120	12.5 / 0.5	8195.99	7665.26	-530.73	29.54	52.67	23.13	8225.53	7717.93	-507.60
20	40	120	12.5 / 0.5 C	7337.21	6671.90	-665.31	34.22	66.72	32.50	7371.43	6738.62	-632.81
20	80	120	8 / 0.1	3438.72	2719.92	-718.80	31.39	47.27	15.89	3470.11	2767.19	-702.91
20	80	120	12.5 / 0.5	8349.82	7012.45	-1337.37	30.57	94.03	63.46	8380.39	7106.48	-1273.91
20	80	120	12.5 / 0.5 C	7075.14	6117.95	-957.19	58.04	111.48	53.44	7133.18	6229.43	-903.75
40	20	120	8 / 0.1	3310.41	2850.75	-459.66	44.13	49.83	5.70	3354.54	2900.58	-453.95
40	20	120	12.5 / 0.5	7317.93	6762.38	-555.55	34.01	53.24	19.22	7351.95	6815.61	-536.33
40	20	120	12.5 / 0.5 C	7305.44	6671.30	-634.14	45.05	82.88	37.82	7350.50	6754.17	-596.32

Table 4-CCLXXXII: Applied Load - 180 °C - Stored Strain Energy Density

Creep Duration [s]	Recovery Duration [s]	Temperature [°C]	Stress [MPa]	Strain Energy Density [J/m ³]								
				Stored - Unloading			Stored - Recovery			Stored - Overall		
				Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2	Cycle 2	Cycle 180	Cycle 180 - 2
20	1	180	8 / 0.1	3369.67	3180.73	-188.94	26.01	55.92	29.91	3395.67	3236.65	-159.02
20	1	180	12.5 / 0.5	7751.35	7478.61	-272.74	17.10	61.29	44.19	7768.45	7539.90	-228.55
20	1	180	12.5 / 0.5 C	7851.57	7655.44	-196.14	27.51	42.87	15.36	7879.09	7698.31	-180.78
20	10	180	8 / 0.1	3353.44	3102.66	-250.78	31.41	62.39	30.98	3384.85	3165.05	-219.80
20	10	180	12.5 / 0.5	7820.30	7414.74	-405.56	33.11	76.20	43.09	7853.41	7490.94	-362.47
20	10	180	12.5 / 0.5 C	7599.48	7335.89	-263.59	48.25	70.30	22.05	7647.73	7406.19	-241.54
20	20	180	8 / 0.1	3448.00	3139.26	-308.74	41.62	74.55	32.93	3489.62	3213.81	-275.81
20	20	180	12.5 / 0.5	8479.60	7901.57	-578.02	47.92	98.99	51.07	8527.52	8000.56	-526.95
20	20	180	12.5 / 0.5 C	7923.81	7505.05	-418.76	83.32	116.46	33.13	8007.13	7621.51	-385.63
20	40	180	8 / 0.1	3555.57	3043.01	-512.56	28.00	75.43	47.43	3583.57	3118.43	-465.13
20	40	180	12.5 / 0.5	8096.87	7422.15	-674.73	37.71	95.79	58.08	8134.59	7517.94	-616.64
20	40	180	12.5 / 0.5 C	7881.02	7234.19	-646.83	79.32	122.81	43.49	7960.34	7357.00	-603.34
20	80	180	8 / 0.1	3386.23	2616.04	-770.19	37.89	101.56	63.67	3424.13	2717.61	-706.52
20	80	180	12.5 / 0.5	7982.88	6855.01	-1127.88	36.63	121.49	84.86	8019.51	6976.49	-1043.01
20	80	180	12.5 / 0.5 C	7488.67	6518.85	-969.81	57.53	117.25	59.72	7546.20	6636.11	-910.09
40	20	180	8 / 0.1	3722.88	3273.34	-449.54	19.44	59.72	40.27	3742.32	3333.06	-409.27
40	20	180	12.5 / 0.5	7695.78	7004.28	-691.49	40.95	107.52	66.57	7736.73	7111.81	-624.92
40	20	180	12.5 / 0.5 C	7544.92	6973.56	-571.36	71.70	109.96	38.26	7616.62	7083.52	-533.10

Chapter 5 Conclusions

The effect of recovery duration on the cyclic creep response of carbon fibre reinforced polymer composites with fibre orientation of 90° was experimentally evaluated. The material was subjected to 180 cycles of tensile-tensile cyclic creep loading and the strain response of the material was recorded and analyzed. Using a creep hold duration of 20 seconds, five recovery durations were utilized, varying from 1 second to 80 seconds. Additionally, the effect that the peak load, and test temperature, and creep hold duration were investigated to evaluate their effects on the response as well. Performing the testing described and analyzing the results, the objectives outlined in section 2.5 have been successfully accomplished. The following sections shall summarize the results obtained for the objectives, identify the conclusions which can be drawn, and provide recommendations for future work in the subject matter.

5.1 Summary

Based upon the experimentation performed, the following summarizes the outcomes of the objectives of the research.

- Cyclic Creep loading was performed on a unidirectional carbon fibre reinforce polymer composite with varying recovery duration. Based upon changes in the recovery duration the following trends were identified for the creep and creep recovery of a polymer composite at a given peak load and temperature:
 - A marginally increasing trend in loading and unloading moduli with number of cycles was observed. The unloading modulus was marginally higher than the loading moduli. Effect of recovery duration was not discernible.
 - The magnitude increase in the strains during creep and recovery increased with number of cycles.
 - As the recovery duration increased, the maximum creep and recovered strains increased. Additionally, the change in the creep and recovered strains over the duration of testing showed greater increases for the longer recovery durations.
 - The unrecovered strain increased with increase in number of cycles, for a recovery duration. However, with the increase in the recovery duration, the total

unrecovered strain was found to decrease, at a given cycle.. With the shorter recovery duration tests showing a larger increase in the total unrecovered strain, over 180 cycles, in comparison to the longer recovery duration tests.

- Changes in both instantaneous moduli (loading and unloading) as a result of the cyclic loading, both showed a marginally increasing trend with increase in the recovery duration.
 - Both the total and the dissipated strain energy densities were found to increase as a result of the cyclic loading. However, they increased with increase in the recovery duration, for a given cycle.
 - Conversely, both the stored and the unrecovered strain energy densities showed a decreasing trend with an increase in the recovery duration. Additionally, the stored energy density showed a decreasing trend with increase in the number of cycles in contrast to increasing trend observed in total, dissipated, and unrecovered energies.
 - Segmenting the total and stored energy densities, the total energy accumulated during the creep hold and stored energy accumulated during the recovery hold were found to increase with recovery duration. While the energy accumulated during the stored energy accumulated during the unloading segment was found to decrease.
- Extending the study to investigate the interaction between the other variables and the recovery duration the following trends were observed:
 - As has been demonstrated in previous literature, with an increase in the temperature, the measured strains increased for a given recovery duration. This included the creep, recovered, and unrecovered creep, unrecovered strains. However, with increase in creep duration, the effect of temperature on unrecovered strain was decreasing.
 - The effect of temperature on energy densities was similar to that on strains.
 - The increase in applied load increased both the creep strains, unrecovered strains, and unrecovered strain energy density with increase in cycles. However, it did not have any effect on creep recovery, for the range of stresses investigated in this study.

- Similar trend was observed for all recovery durations.
- With increase in creep duration, both the creep and recovered strains increased for the same recovery duration; however, the unrecovered strains and energies decreased with increase in creep duration. Further testing for various creep durations and recovery periods is required to validate this tentative inference,

5.2 Conclusions

Based on the trends identified in the preceding section, the following can be concluded:

- The recovery duration was found to play a significant role in cyclic creep response of a carbon fibre reinforced epoxy composite.
- The unrecovered elastic strain accumulated between cycles was found to influence the viscoelastic response during subsequent loading cycles and this influence varied with recovery duration

5.3 Recommendations for Future Work

Based upon the results obtained via the experimentation performed, the following recommendations are made with respect to future work into the subject matter:

- Owing to only a single cyclic creep test being performed per load-temperature-hold, statistical validation of the trends observed is recommended.
- Additional testing using various creep durations, peak and minimum loads, and recovery durations longer than 80s.
- Extension of the performed study to evaluate additional fibre orientations, and their influence on the investigated parameters.
- Investigation into whether there is a critical strain energy with which the accumulation of the unrecovered stored elastic strain energy can be used to predict failure.

References

- [1] S. Chekurthi, "Fracture Criterion to Predict Strain-Rate Dependent Failure of Unidirectional Carbon Fiber Composites under Multi-axial State of Stress," University of Manitoba, Winnipeg, 2018.
- [2] A. Hao, Y. Chen and J. Y. Chen, "Creep and Recovery Behavior of Kenaf/Polypropylene Nonwoven Composites," *Journal of Applied Polymer Science*, vol. 131, no. 17, 2014.
- [3] J. Raghavan and M. Meshii, "Creep Rupture of Polymer Composites," *Composites Science and Technology*, vol. 57, pp. 375-388, 1997.
- [4] M. Xu, D. N. Futaba and M. Yumura, "Carbon Nanotubes with Temperature-Invariant Creep and Creep-Recovery from -190 to 970 C," *Advanced Materials*, vol. 23, no. 32, pp. 3686-3691, 2011.
- [5] A. K. Shojaei and A. R. Wedgewood, "An anisotropic cyclic plasticity, creep and fatigue predictive toll for unfilled polymers," *Mechanics of Materials*, no. 106, pp. 20-34, 2017.
- [6] R. Jayaraman, "Time-Dependent Damage Evolution in Unidirectional and Multidirectional Polymer Composite Laminates," in *Creep and Fatigue in Composite-Laminates*, Second ed., Elsevier/Woodhead Publishing, 2019, pp. 303-321.
- [7] X. Wang, L.-X. Gong, L.-C. Tang, K. Peng, Y.-B. Pei, L. Zhao, L.-B. Wu and J.-X. Jiang, "Temperature dependence of creep and recovery behaviors of polymer composites filled with chemically reduced graphene oxide," *Composites*, vol. Part A, no. 69, pp. 288-298, 2015.
- [8] M. Kawai and Y. Masuko, "Creep behavior of unidirectional and angle-ply T800H/3631 laminates at high temperature and simulations using a phenomenological viscoplasticity model," *Composites Science and Technology*, no. 64, pp. 2373-2384, 2004.
- [9] J. H. Almeida Jr., H. L. Ornaghi Jr., N. Lorandi, G. Marinucci and S. Amico, "On Creep, Recovery, and Stress Relaxation of Carbon Fiber-Reinforced Epoxy Filament Wound Composites," *Polymer Engineering and Science*, no. 58, pp. 1837-1842, 2018.
- [10] J. B. Sturgeon, "Creep, repeated loading, fatigue and crack growth in +- 45 oriented carbon fibre reinforced plastics," *Journal of Materials Science*, no. 13, pp. 1490-1498, 1978.
- [11] S. P. Zaoutos, G. C. Papanicolaou and A. Cardon, "On the non-linear viscoelastic behaviour of polymer-matrix composites," *Composites Science and Technology*, no. 58, pp. 883-889, 1998.
- [12] M. I. Faraz, N. A. Besseling, A. V. Korobko and S. J. Picken, "Characterization and Modeling of Creep Behavior of a Thermoset Nanocomposite," *Polymer Composites*, pp. 322-329, 2015.
- [13] S. P. Zaoutsos and G. C. Papanicolaou, "On the influence of preloading in nonlinear viscoelastic-viscoplastic response of carbon-epoxy composites," *Composites Science and Technology*, pp. 922-929, 2010.
- [14] Y. Zhu, F. Lu, C. Yu and G. Kang, "A Rate-Type Nonlinear Viscoelastic-Viscoplastic Cyclic Constitutive Model for Polymers: Theory and Application," *Polymer Engineering and Science*, pp. 1375-1381, 2016.

- [15] M. Eftekhari and A. Fatemi, "Tensile, creep and fatigue behaviours of short fibre reinforced polymer composites at elevated temperatures: a literature survey," *Fatigue & Fracture of Engineering Materials & Structures*, no. 38, pp. 1395-1418, 2015.
- [16] M. Kawai and T. Sagawa, "Temperature dependence of off-axis tensile creep rupture behavior of a unidirectional carbon/epoxy laminate," *Composites*, vol. A, no. 39, pp. 523-539, 2008.
- [17] K. Banik, J. Karger-Kocsis and T. Abraham, "Flexural Creep of All-Polypropylene Composites: Model Analysis," *Materials Science*, pp. 941-948, 2008.
- [18] W.-H. Wang, H.-B. Huang, H.-H. Du and H. Wang, "Effects of Fiber Size on Short-Term Creep Behavior of Wood Fiber/HDPE Composites," *Polymer Engineering and Science*, vol. 55, pp. 693-700, 2015.
- [19] Y. Jia, K. Peng, X.-l. Gong and Z. Zhang, "Creep and recovery of polypropylene/carbon nanotube composites," *International Journal of Plastics*, no. 27, pp. 1239-1251, 2011.
- [20] X. Zheng, X. Wen, W. Wang, J. Gao, W. Lin, L. Ma and J. Yu, "Creep-ratcheting behavior of PTFE gaskets under various temperatures," *Polymer Testing*, pp. 229-235, 2017.
- [21] G. C. Papanicolaou, S. P. Zaoutsos and A. H. Cardon, "Prediction of the non-linear viscoelastic response of unidirectional fibre composites," *Composites Science and Technology*, no. 59, pp. 1311-1319, 1999.
- [22] S. Zaoutsos, "Effect of multiple step creep/creep recovery loading on non-linear viscoelastic response of carbon fibre reinforced polymers," *Plastics, Rubber and Composites*, vol. 42, no. 8, 2013.
- [23] E. M. Wu, R. J. Sanches and N. Q. Nguyen, "Matrix-Dominated time-dependent deformation and damage of graphite/epoxy composite experimental data under creep and recovery," Lawrence Livermore National Laboratory, Livermore, 1983.
- [24] O. Starkova, K. Aniskevich, J. Sevcenko, O. Bulderberga and A. Aniskevich, "Relationship between the residual and total strain from creep-recovery tests of polypropylene/multiwall carbon nanotube composites," *Journal of Applied Polymer Science*, no. 138, 2020.
- [25] S. B. Adalja and J. U. Otaigbe, "Creep and Recovery Behavior of Novel Organic-Inorganic Polymer Hybrids," *Polymer Composites*, vol. 23, no. 2, pp. 171-181, 2002.
- [26] Y.-L. Li, M.-Y. Shen, W.-J. Chen, C.-L. Chiang and M.-C. Yip, "Tensile creep study and mechanical properties of carbon fiber nano-composites," *Journal of Polymer Research*, pp. 1-8, 2012.
- [27] A. V. Movahedi-Rad, T. Keller and A. P. Vassilopoulos, "Modelling of fatigue behavior based on interaction between time- and cyclic- dependent mechanical properties," *Composites Part A*, no. 124, 2019.
- [28] D. Lemme and L. Smith, "Ratcheting in a nonlinear viscoelastic adhesive," *Mechanics of Time-Dependent Materials*, no. 22, pp. 519-532, 2018.
- [29] X. Shen, Z. Xia and F. Ellyin, "Cyclic Deformation Behavior of an Epoxy Polymer. Part I: Experimental Investigation," *Polymer Engineering and Science*, vol. 44, no. 12, pp. 2240-2246, 2004.
- [30] G. Kang, Y. Liu, Y. Wang, Z. Chen and W. Xub, "Uniaxial ratchetting of polymer and polymer matrix composites: Time-dependent experimental observations," *Materials Science and Engineering A*, no. 523, pp. 13-20, 2009.

- [31] Z. Liu, L. Gao and H. Gao, "Quasi-static and ratcheting properties of PEEK reinforced by carbon fibers under uniaxial and cyclic compression," *Polymer Composites*, no. 41, pp. 729-739, 2020.
- [32] H. Jiang, J. Zhang, G. Kang, C. Xi and C. Jiang, "A test procedure for separating viscous recovery and accumulated unrecoverable deformation of polymer under cyclic loading," *Polymer Testing*, pp. 1445-1451, 2013.
- [33] K. Chen, G. Kang, C. Yu, F. Lu and H. Jiang, "Time-Dependent Uniaxial Ratchetting of Ultrahigh Molecular Weight Polyethylene Polymer: Viscoelastic-Viscoplastic Constitutive Model," *Journal of Applied Mechanics*, vol. 83, 2016.
- [34] W. Liu, Z. Gao and Z. Yue, "Steady ratcheting strains accumulation in varying temperature fatigue tests of PMMA," *Materials Science and Engineering A*, no. 492, pp. 102-109, 2008.
- [35] V. N. Paimushin and S. A. Kholmogorov, "Residual deformations in obliquely reinforced fibrous composites: experiments on cyclic stretching," *Journal of Physics: Conference Series*, 2019.
- [36] S. Chekurthi, Artist, *Adapted From: "Exploded view of simulated autoclave components with laminate lay-up."* [Art]. University of Manitoba, 2018.
- [37] Henkel, "Hysol® EA9673," [Online]. Available: <https://www.rudolphbros.com/customer/docs/SKUDocs/hy-9673-tds.pdf>. [Accessed June 2019].
- [38] A. Asadi, "A Model For Time-Independent And Time- Dependent Damage Evolution And Their Influence On Creep Of Multidirectional Polymer Composite Laminates," University of Manitoba, Winnipeg, 2013.
- [39] Vishay Precision Group, "General Purpose Strain Gages—Linear Pattern," 15 July 2014. [Online]. Available: <http://www.vishaypg.com/docs/11294/250bg.pdf>. [Accessed June 2019].
- [40] Micro-Measurements, "Precision Strain Gages and Sensors Databook," 26 August 2015. [Online]. Available: <http://www.vishaypg.com/docs/50003/precsg.pdf>. [Accessed June 2019].
- [41] Micro-Measurements, "Instruction Bulletin B-130," 29 September 2017. [Online]. Available: <http://www.vishaypg.com/docs/11130/11130B130.pdf>. [Accessed June 2019].
- [42] L. Struik, *Physical Aging in Amorphous Polymers and Other Materials*, New York: Elsevier Scientific Publishing Company, 1978.

Appendices

Additional Figures

Appendix A Effect of Recovery Duration

The following sections present the generated plots showing the parameters as a function of cycles for all recovery durations for a given load-temperature combination.

A.1 Strain

A.1.1 Creep / Recovered

A.1.1.1 Creep

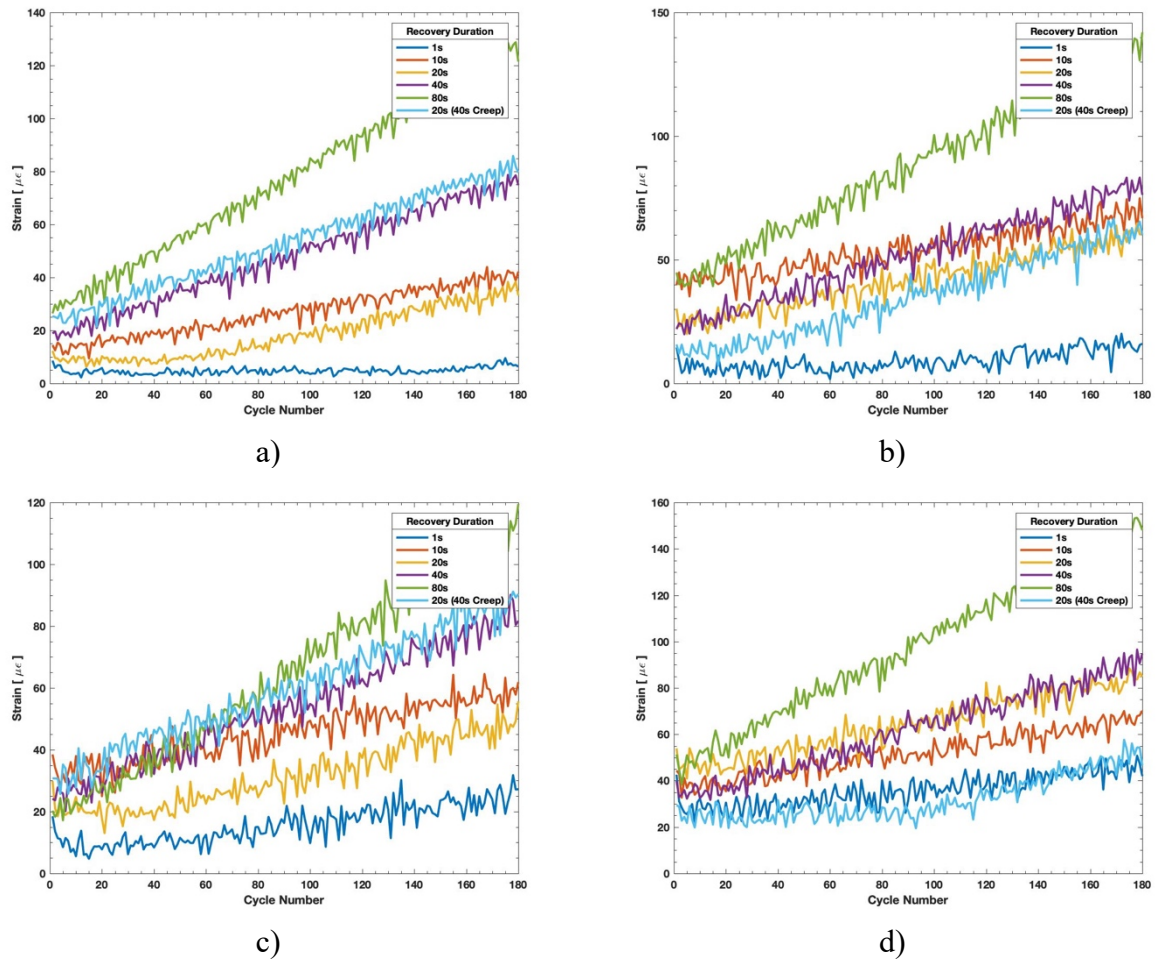
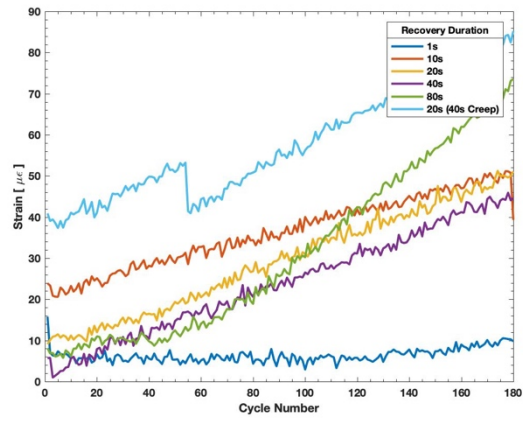
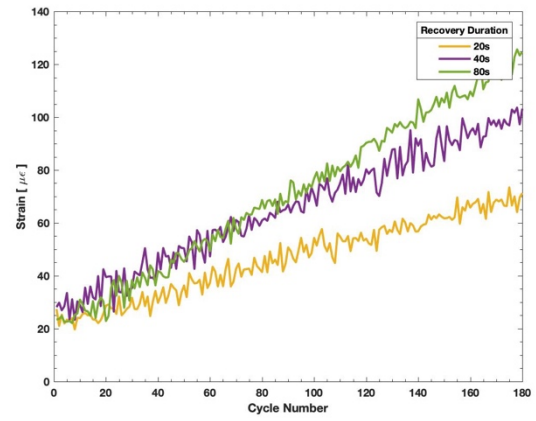


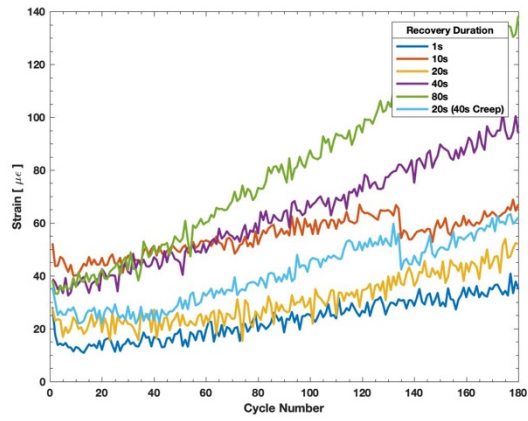
Figure A-1: 8 MPa - Creep Strain vs Cycle vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



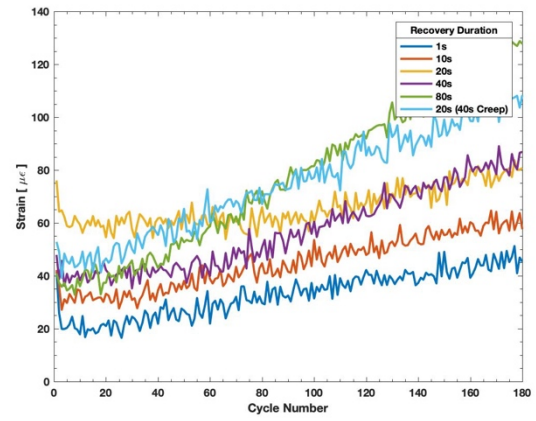
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b)

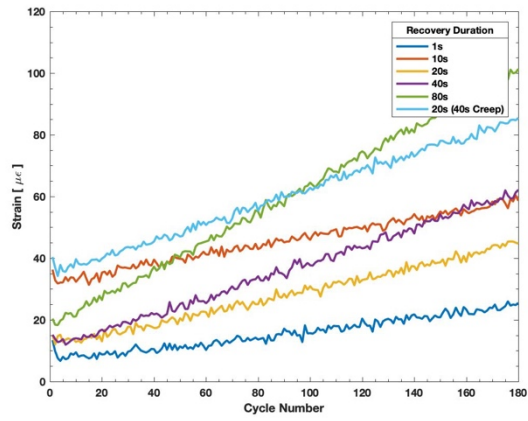


c)

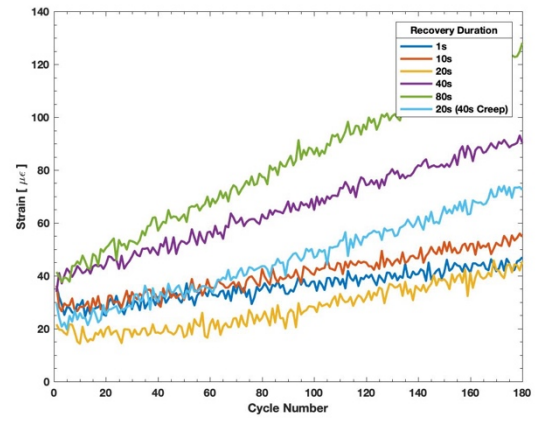


d)

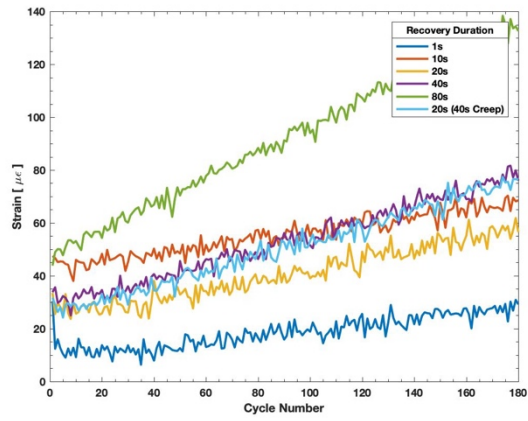
Figure A-2: 12.5 MPa – Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



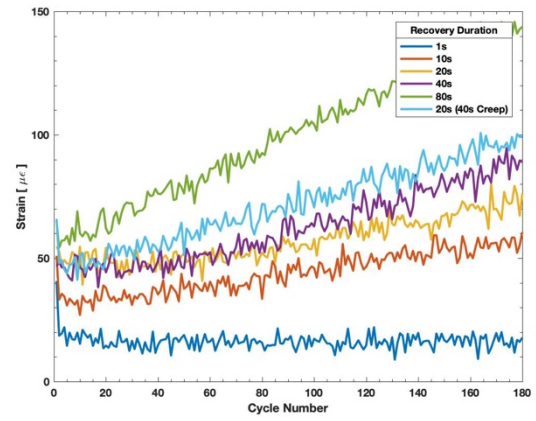
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b)



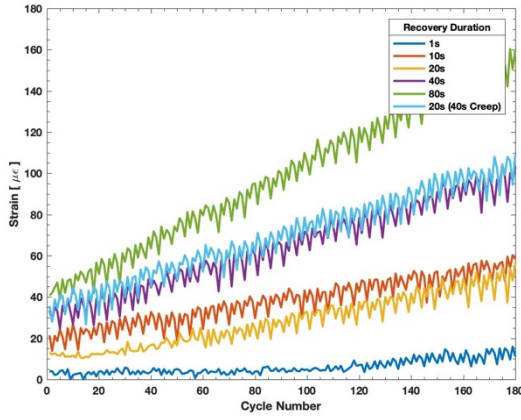
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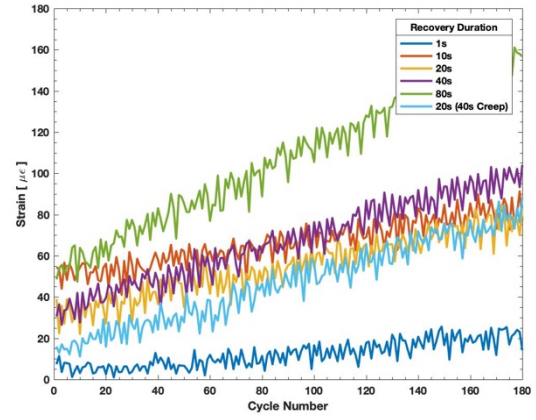
d)

Figure A-3: 12.5 MPa Continuous – Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

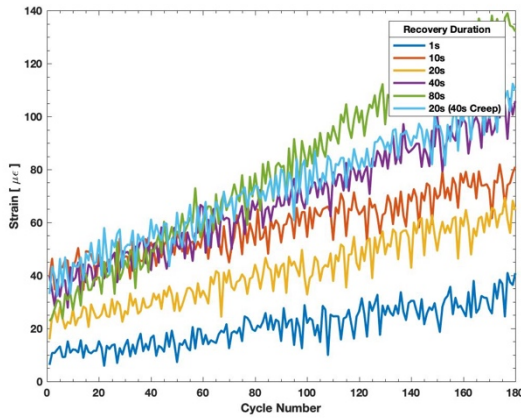
A.1.1.2 Recovered



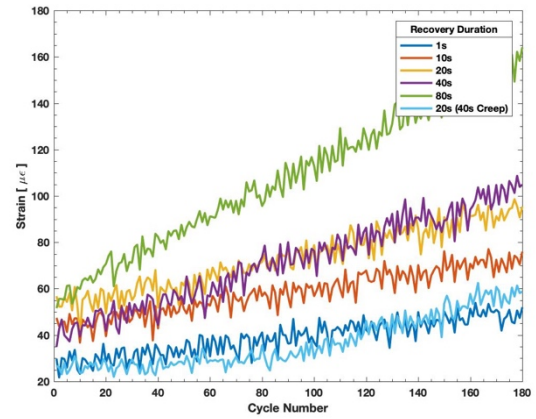
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b)

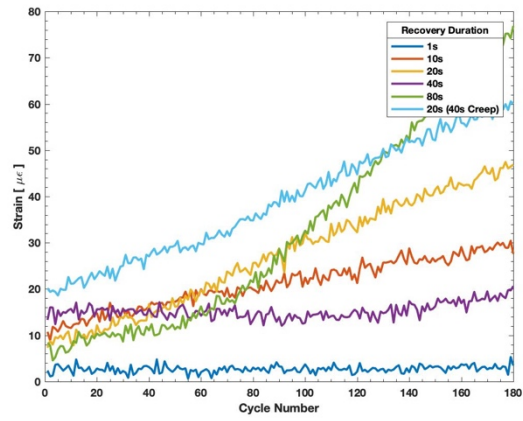


c)

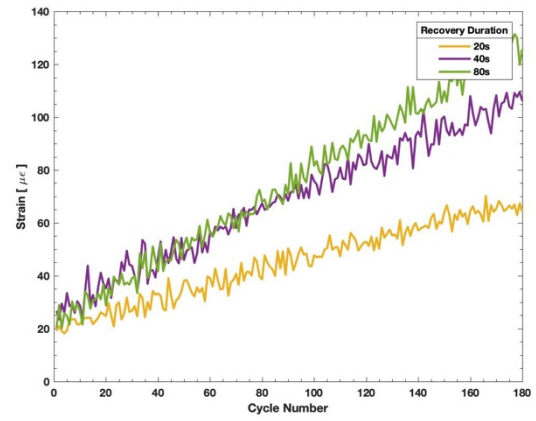


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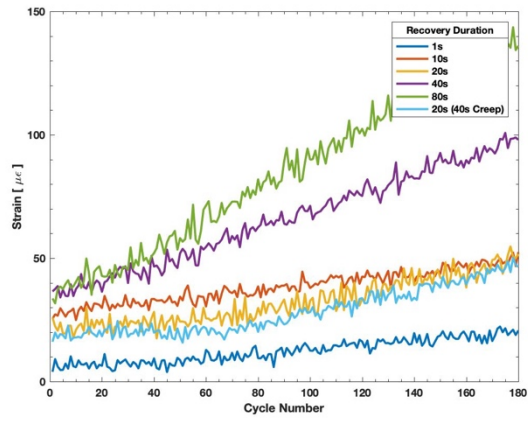
Figure A-4: 8 MPa - Recovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



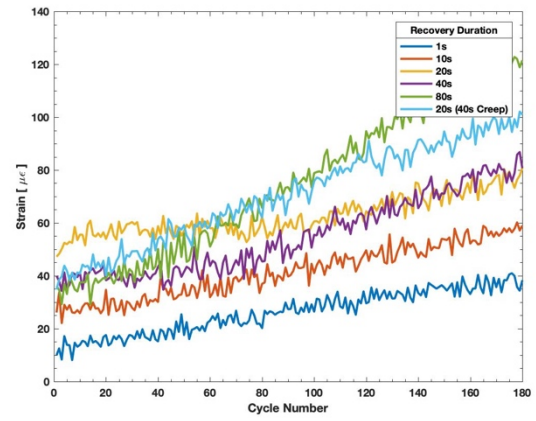
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b)

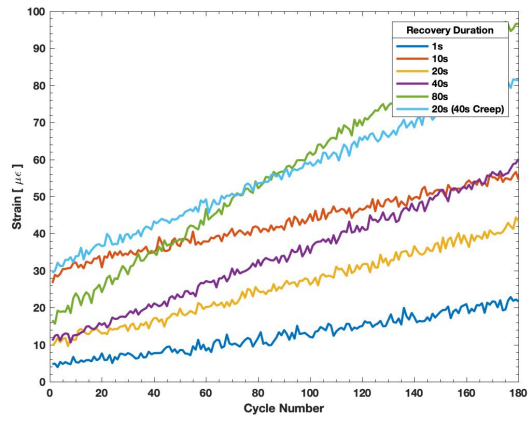


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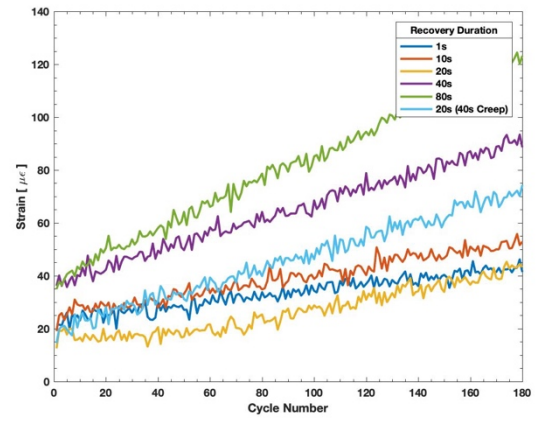


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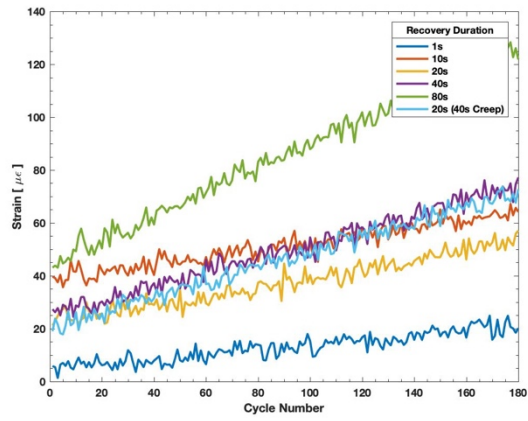
Figure A-5: 12.5 MPa - Recovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



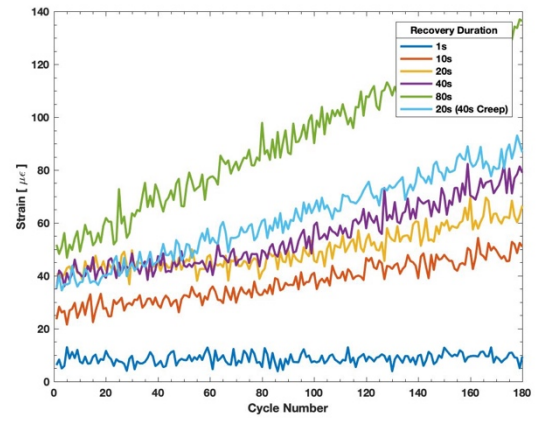
a)



b)



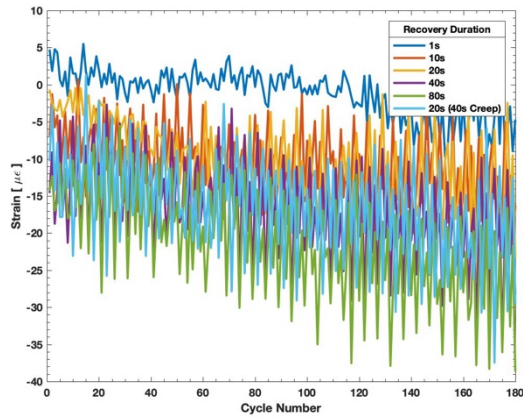
c)



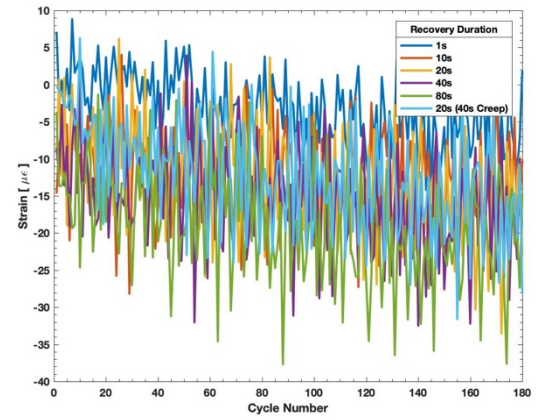
d)

Figure A-6: 12.5 MPa Continuous - Recovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

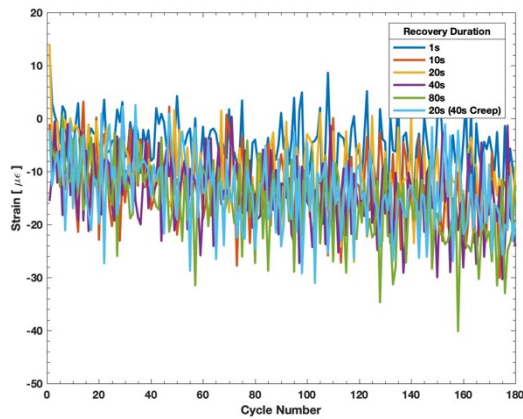
A.1.1.3 Unrecovered Creep Strain



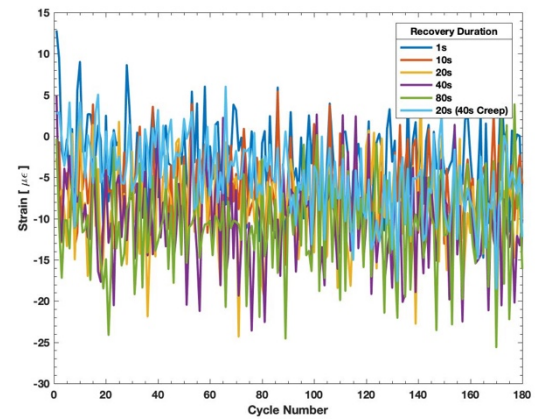
a)



b)

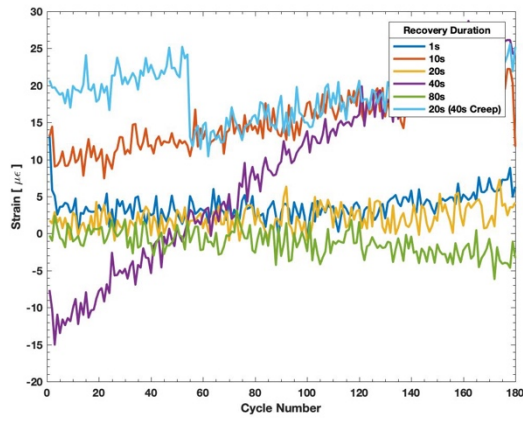


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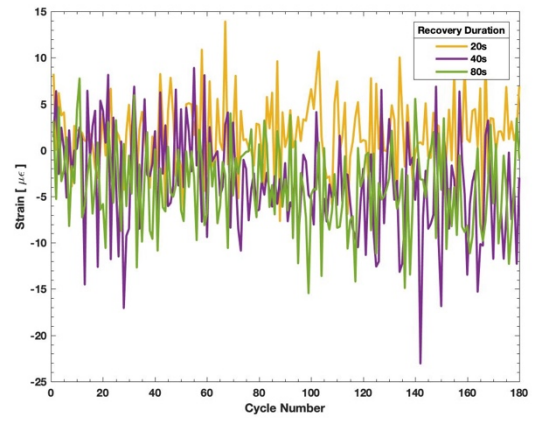


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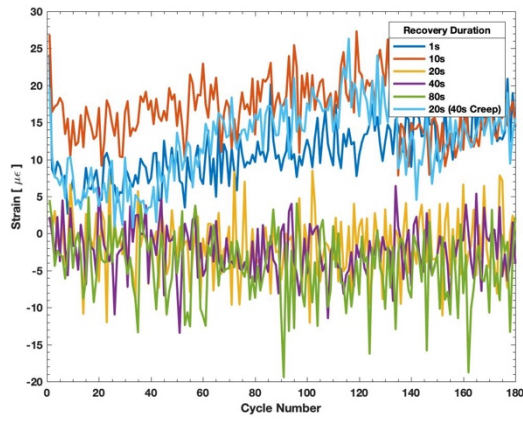
Figure A-7: 8 MPa - Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



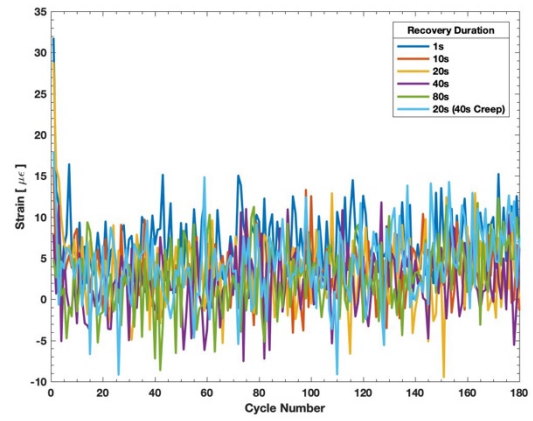
a)



b)

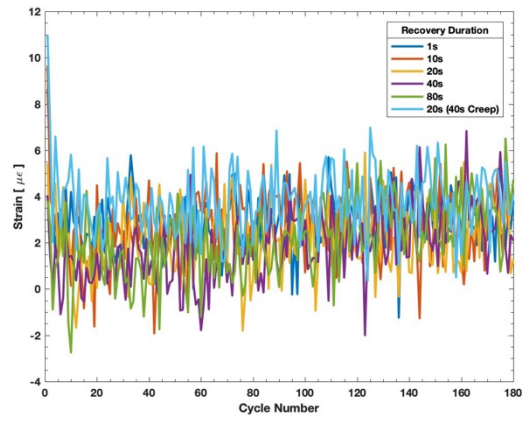


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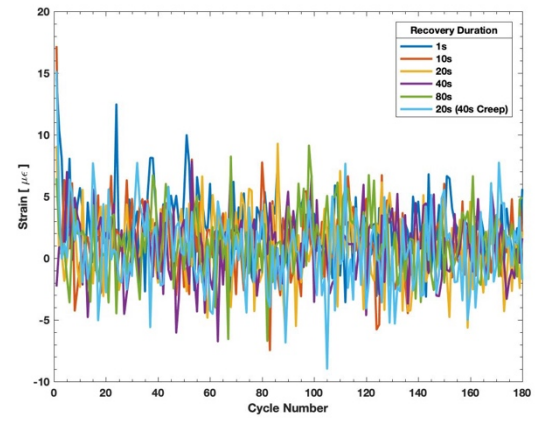


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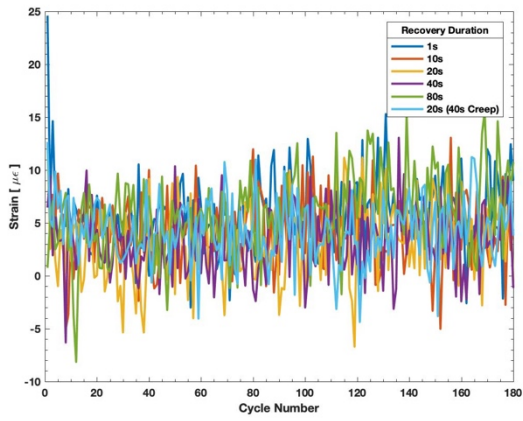
Figure A-8: 12.5 MPa - Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



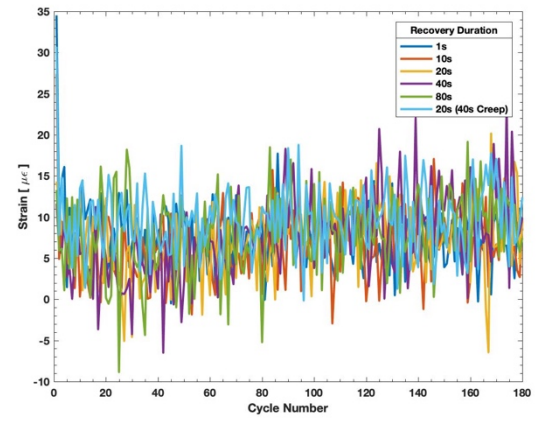
a)



b)



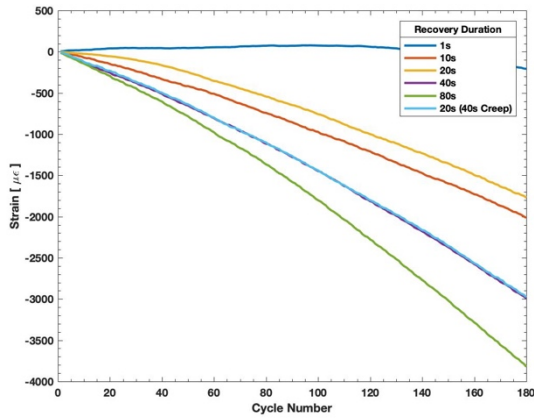
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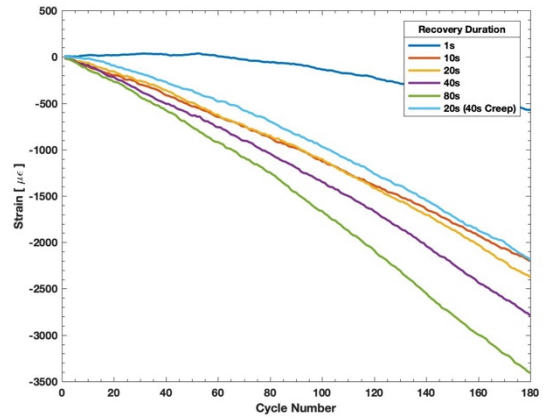
d)

Figure A-9: 12.5 MPa Continuous - Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

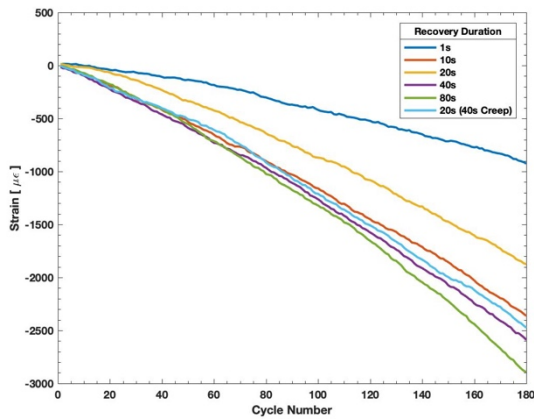
A.1.1.4 Accumulated Unrecovered Creep Strain



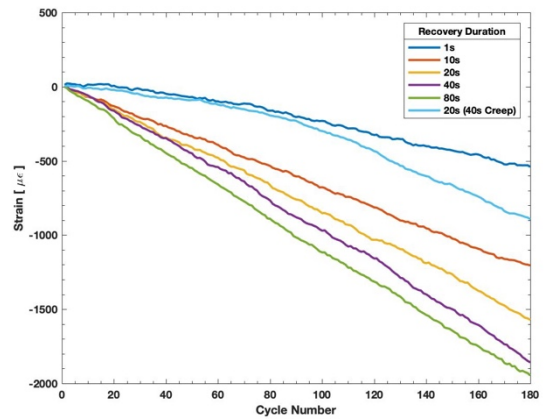
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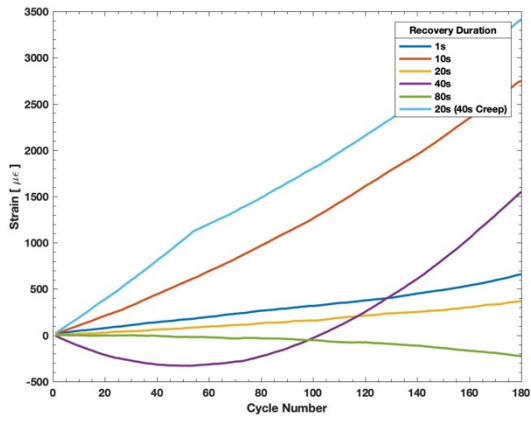


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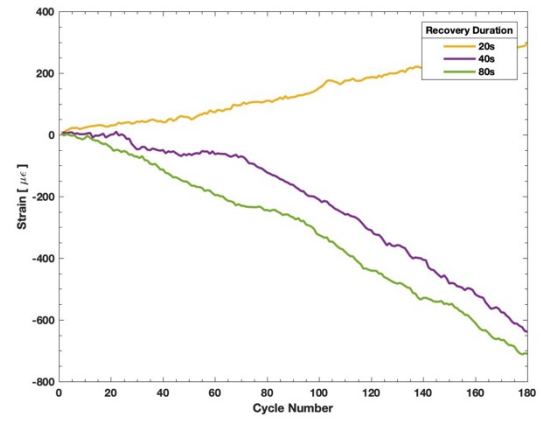


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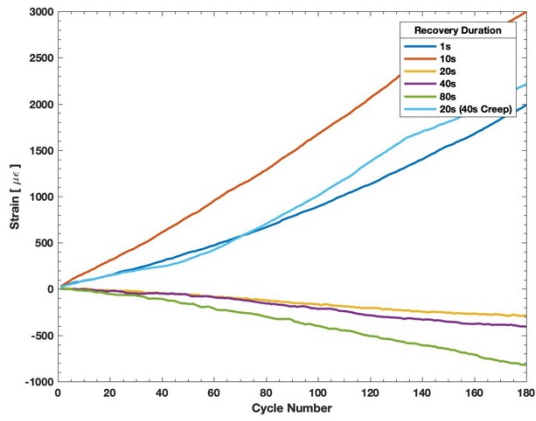
Figure A-10: 8 MPa - Accumulated Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



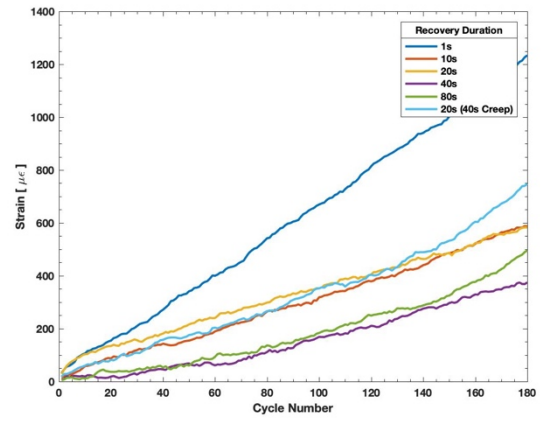
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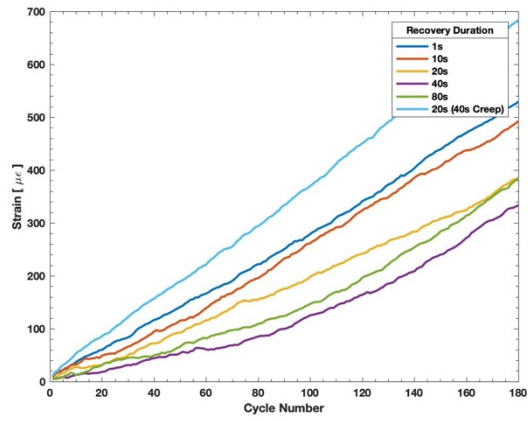


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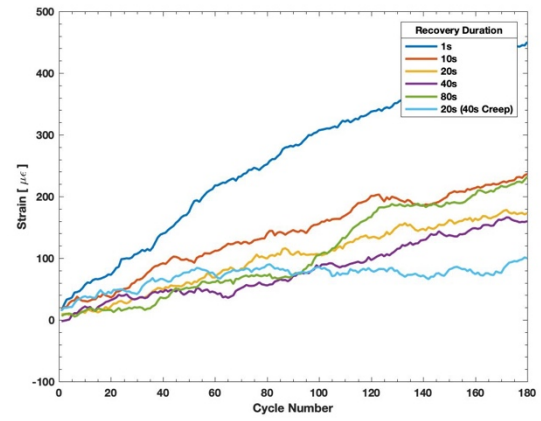


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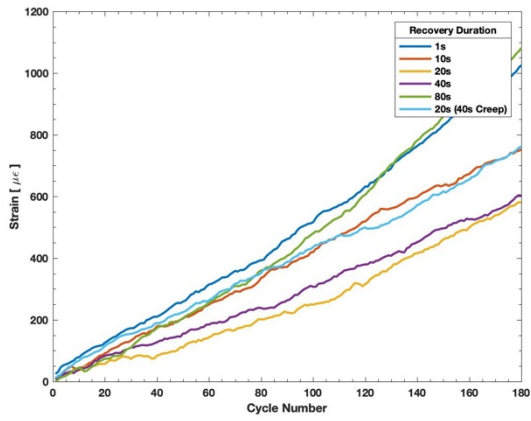
Figure A-11: 12.5 MPa - Accumulated Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



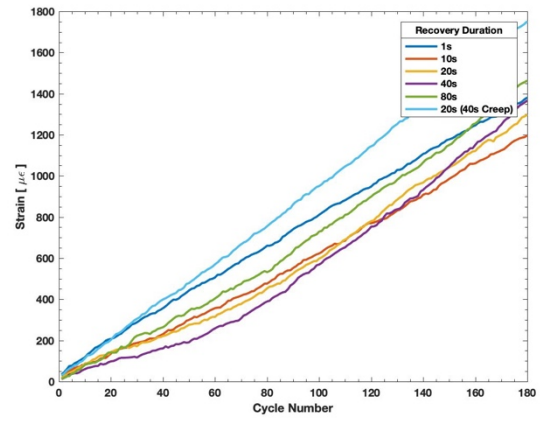
a)



b)



c)



d)

Figure A-12: 12.5 MPa Continuous - Accumulated Unrecovered Creep Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

A.1.2 Unrecovered

A.1.2.1 Total Unrecovered

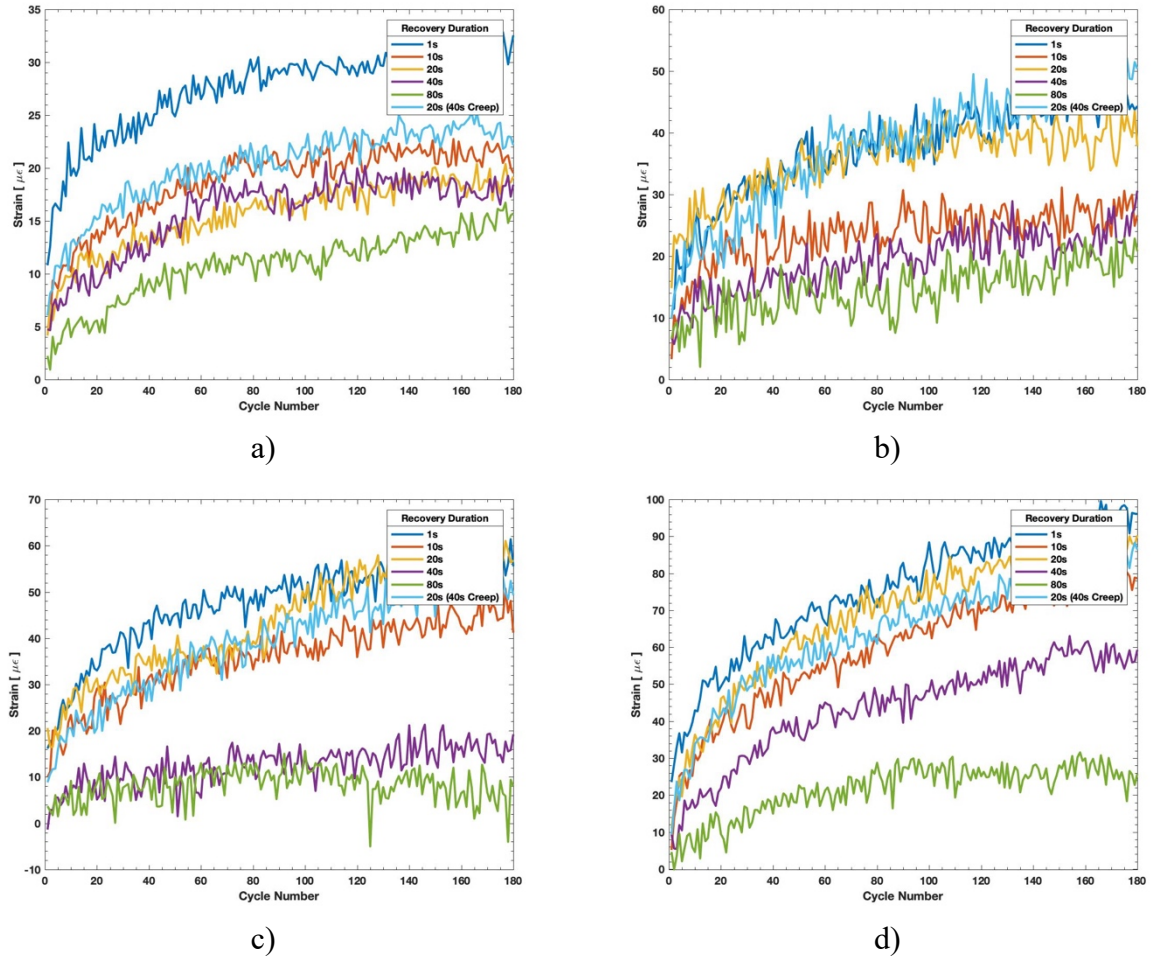
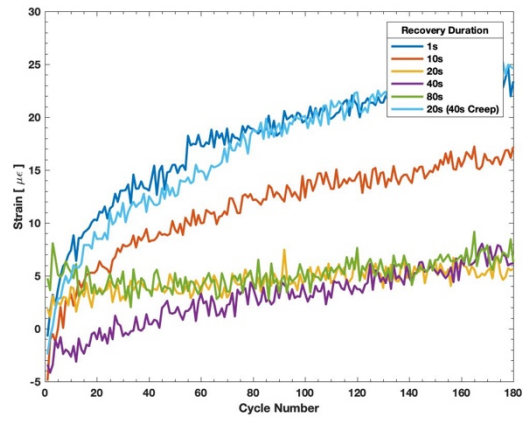
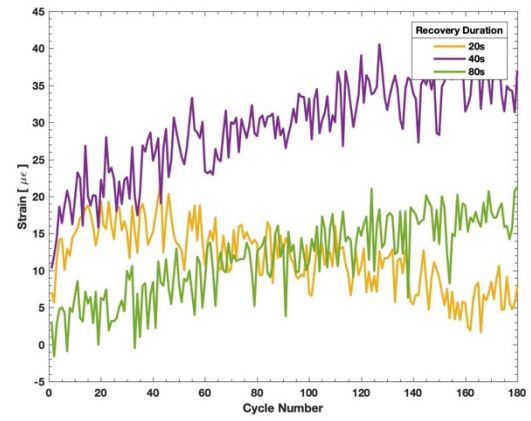


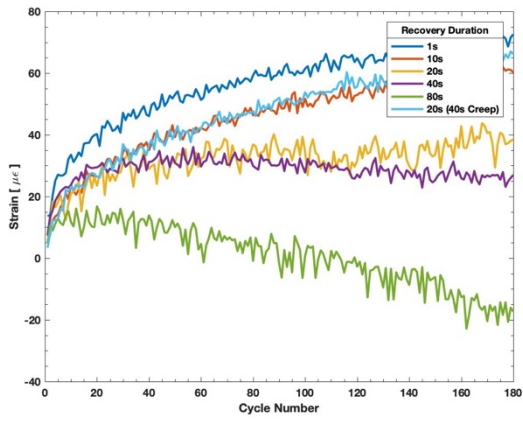
Figure A-13: 8 MPa - Total Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



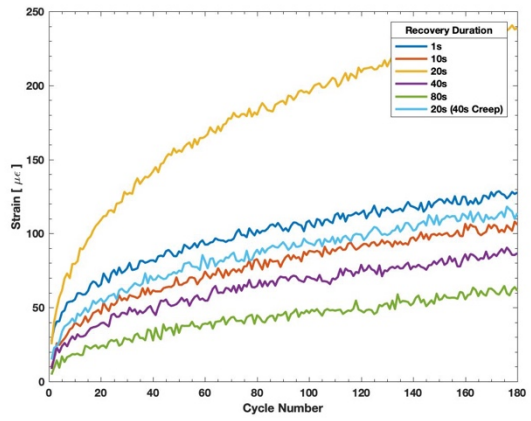
a)



b)

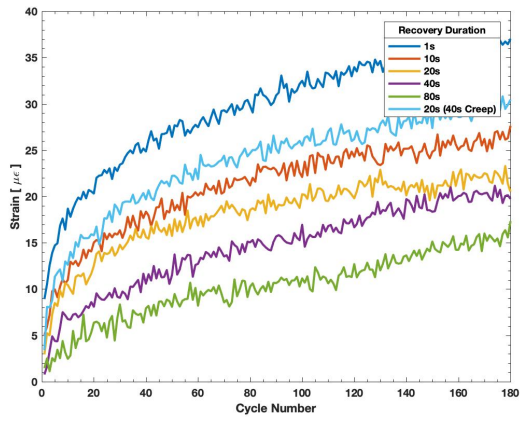


c)

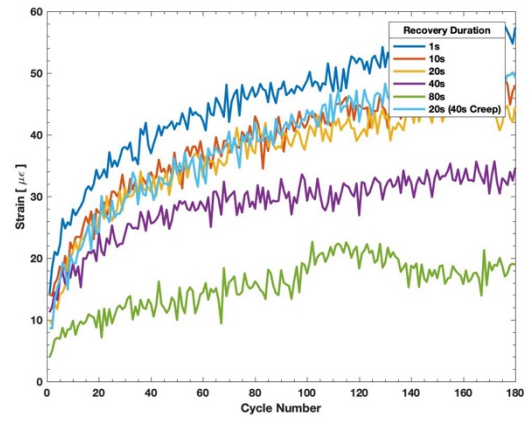


d)

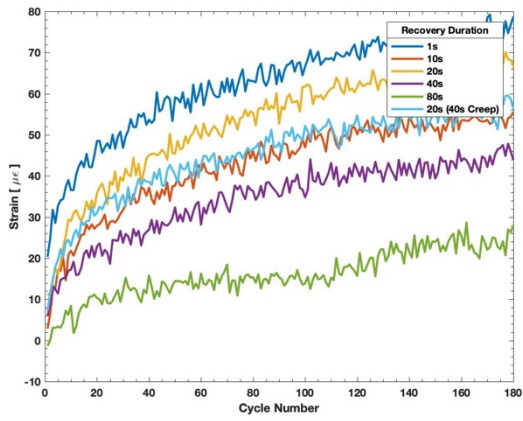
Figure A-14: 12.5 MPa - Total Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



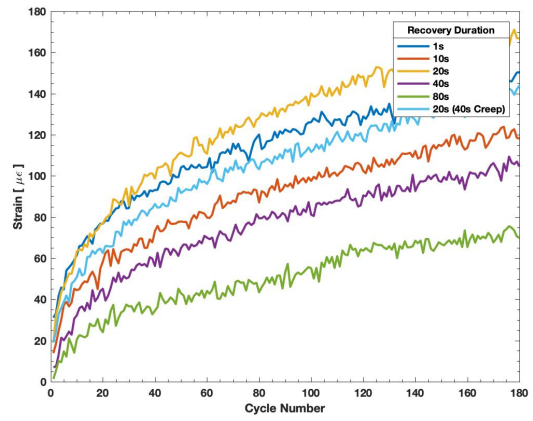
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b)



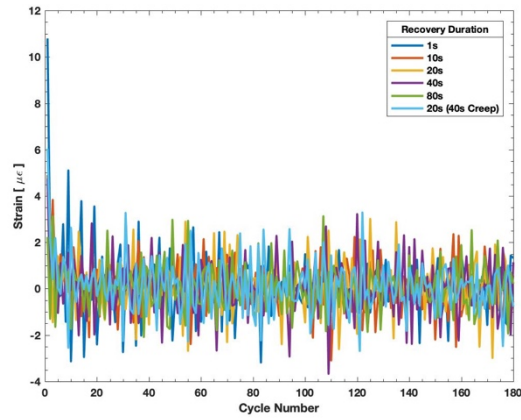
c)



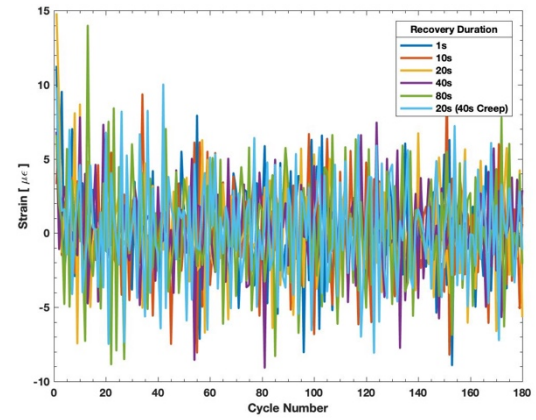
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Figure A-15: 12.5 MPa Continuous - Total Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

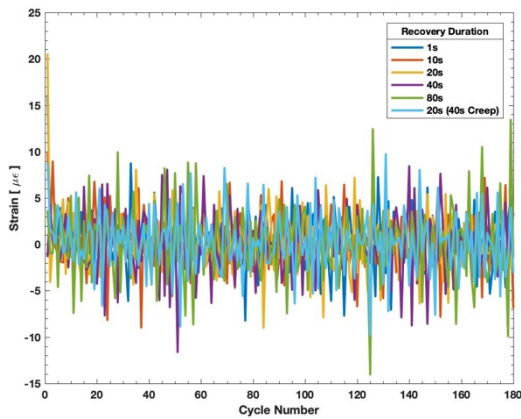
A.1.2.2 Cycle Unrecovered



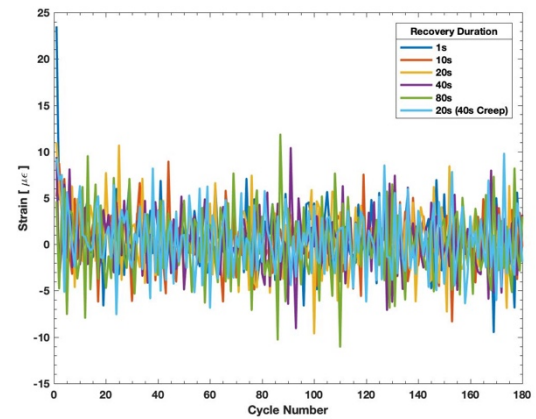
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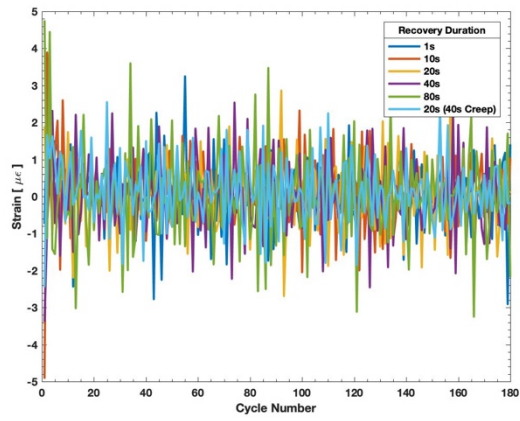


c)

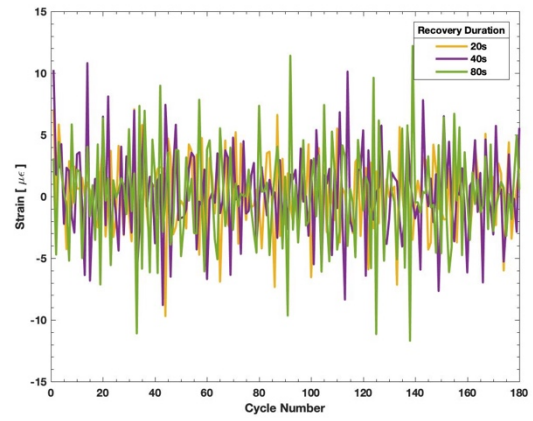


d)

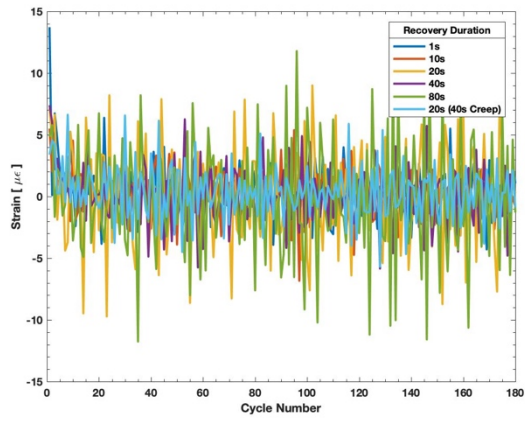
Figure A-16: 8 MPa - Cycle Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



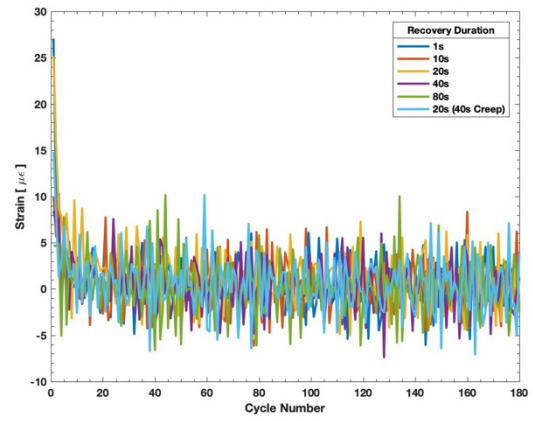
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b)

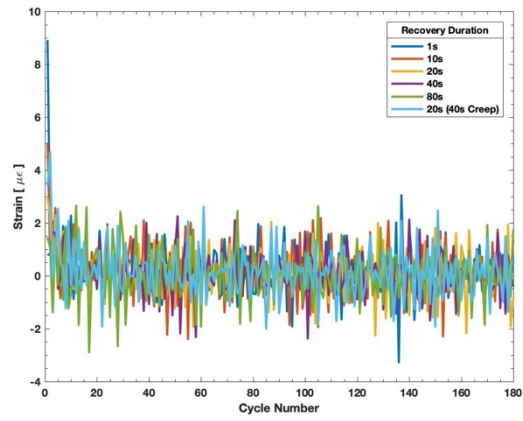


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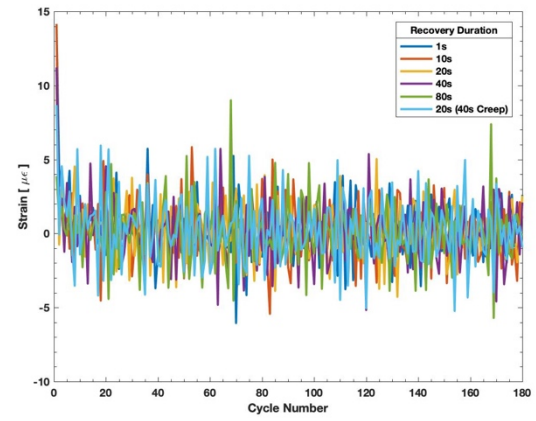


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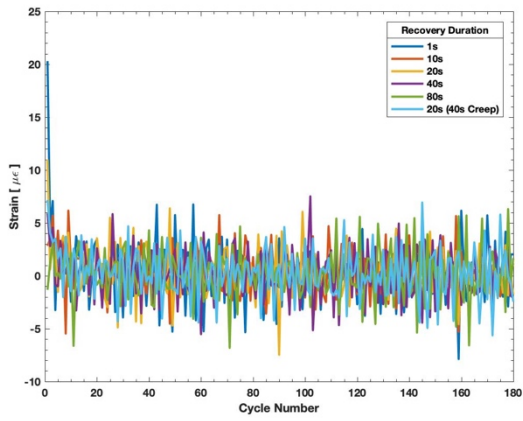
Figure A-17: 12.5 MPa - Cycle Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



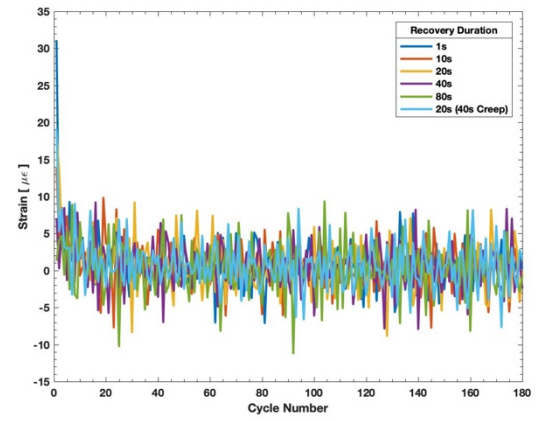
a)



b)



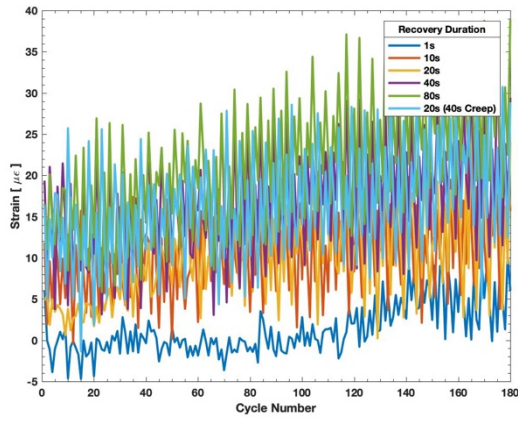
c)



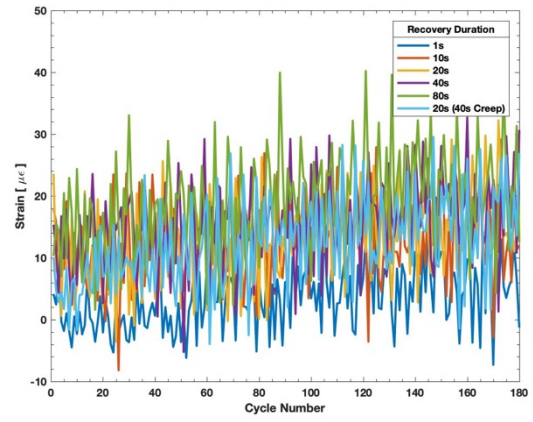
d)

Figure A-18: 12.5 MPa Continuous - Cycle Unrecovered Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

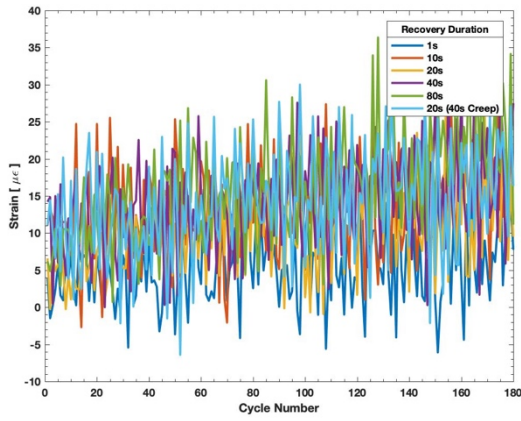
A.1.2.3 Unrecovered Instantaneous



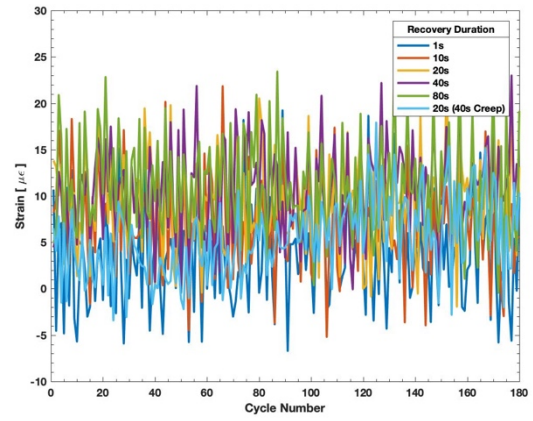
a)



b)

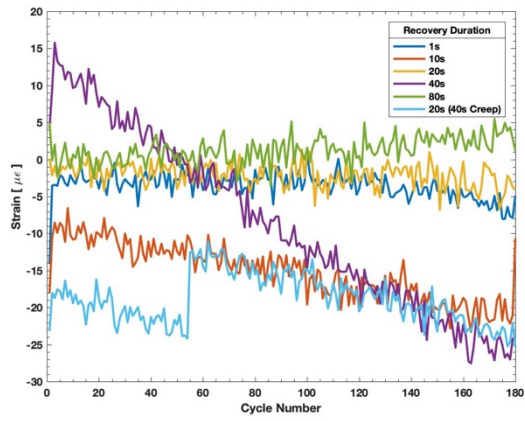


c)

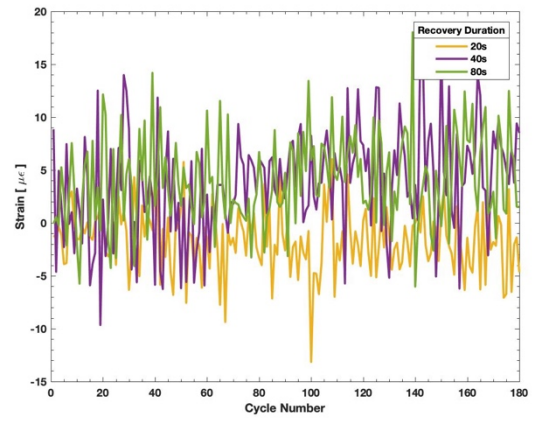


d)

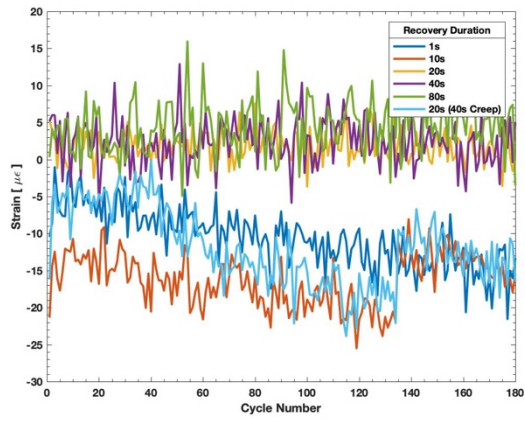
Figure A-19: 8 MPa - Unrecovered Instantaneous Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



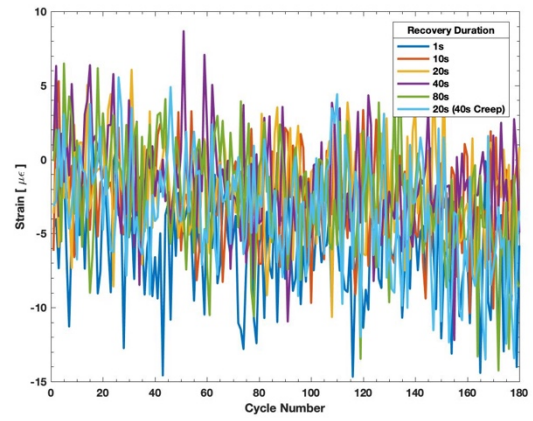
a)



b)

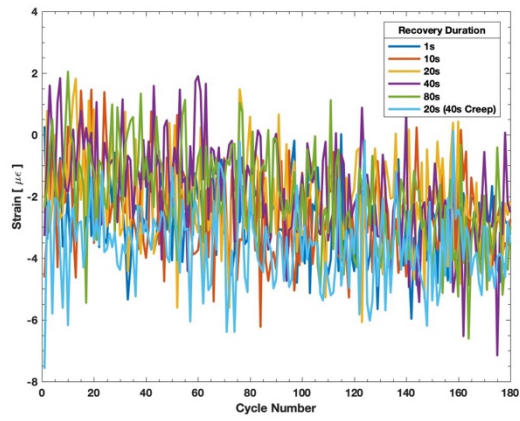


c)

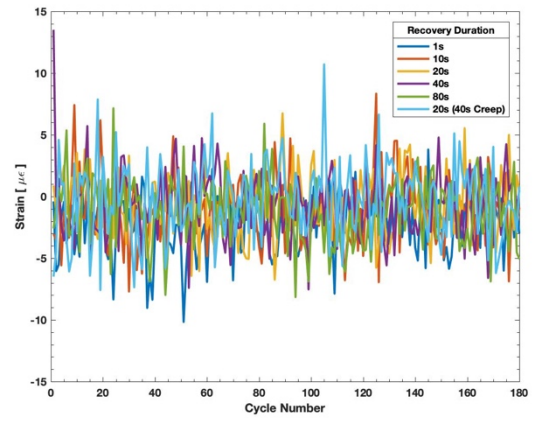


d)

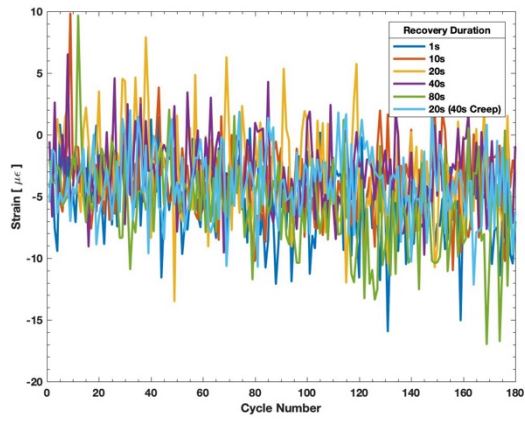
Figure A-20: 12.5 MPa - Unrecovered Instantaneous Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



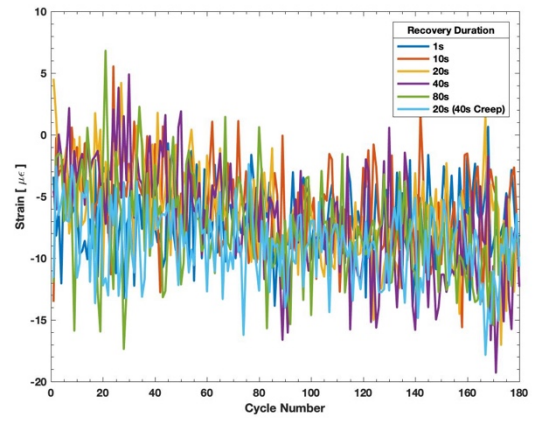
a)



b)



c)



d)

Figure A-21: 12.5 MPa Continuous - Unrecovered Instantaneous Strain vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

A.2 Modulus

A.2.1 Loading

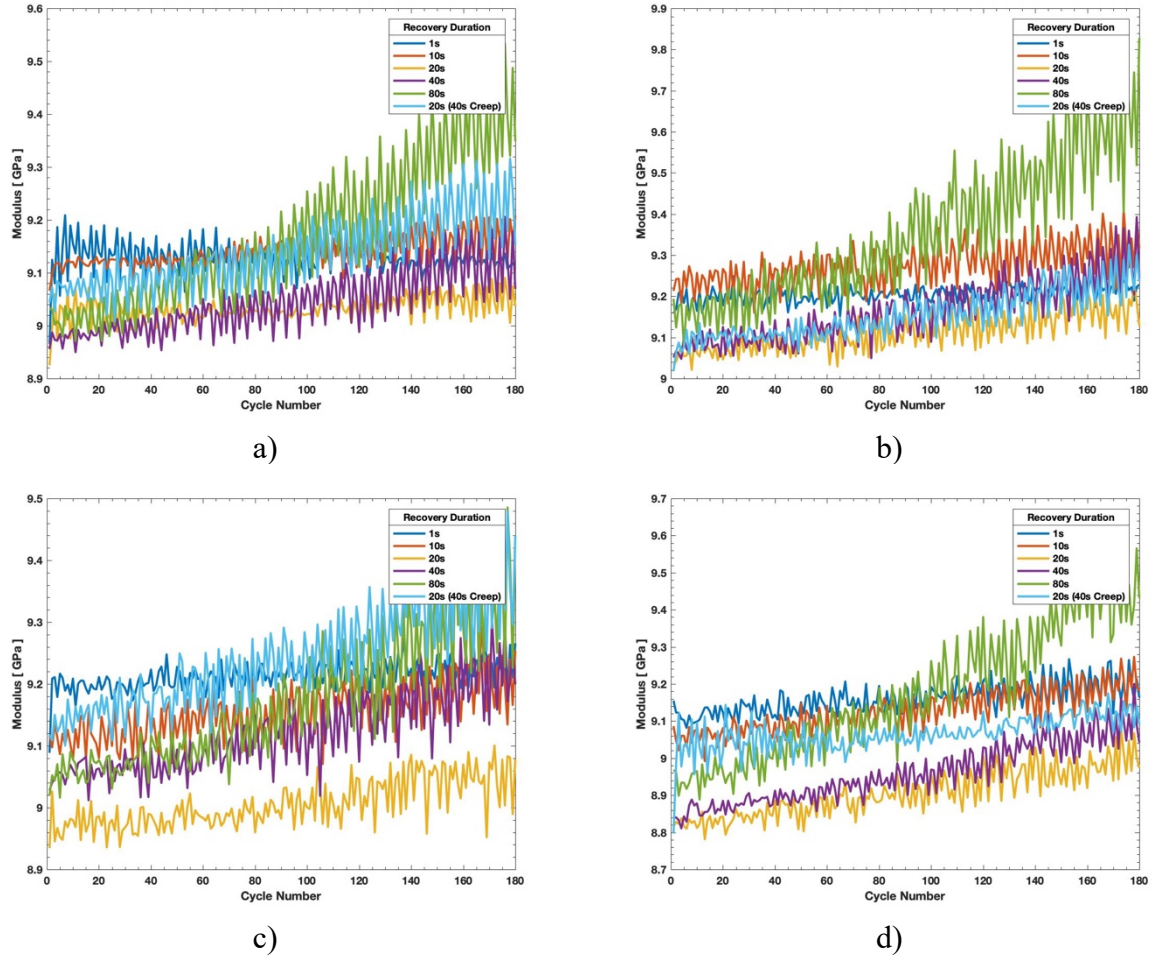
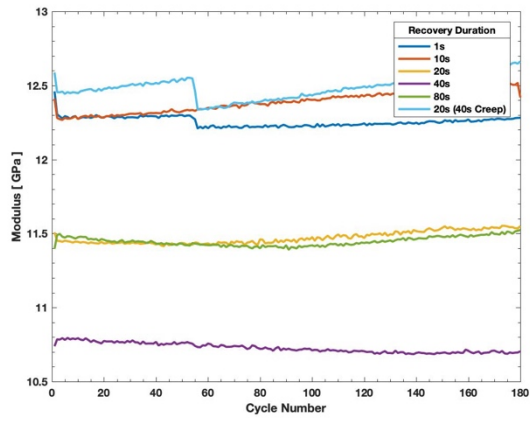
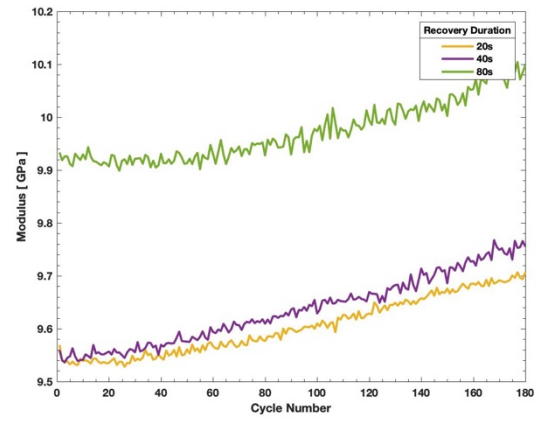


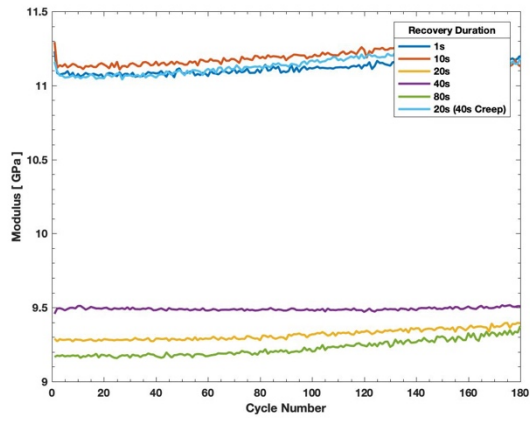
Figure A-22: 8 MPa - Instantaneous Modulus (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



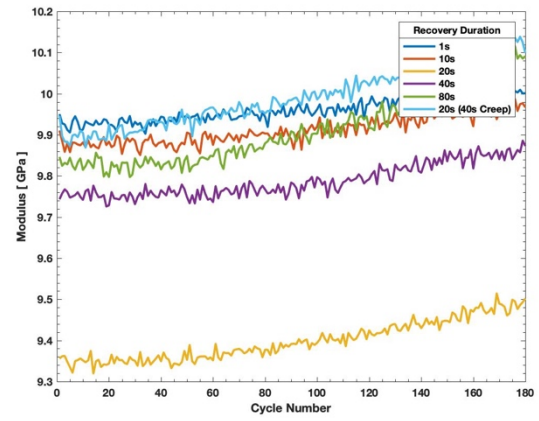
a)



b)

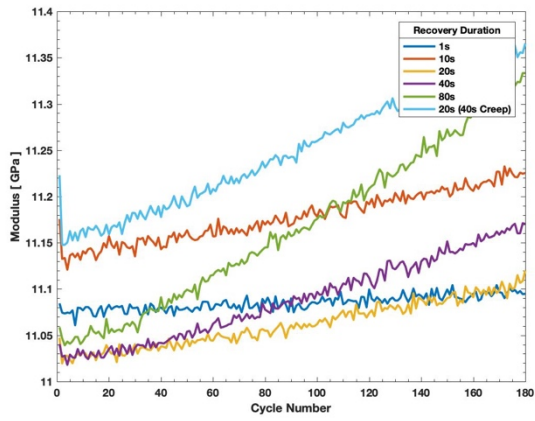


c)

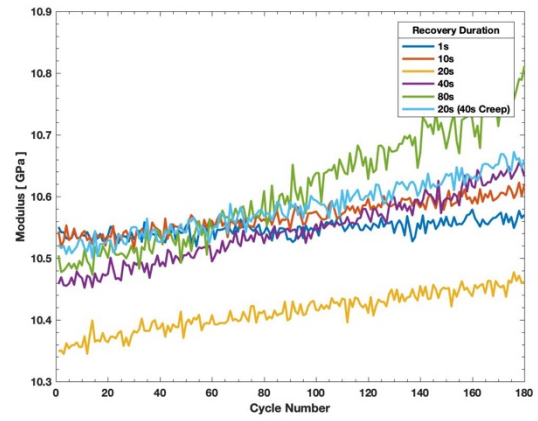


d)

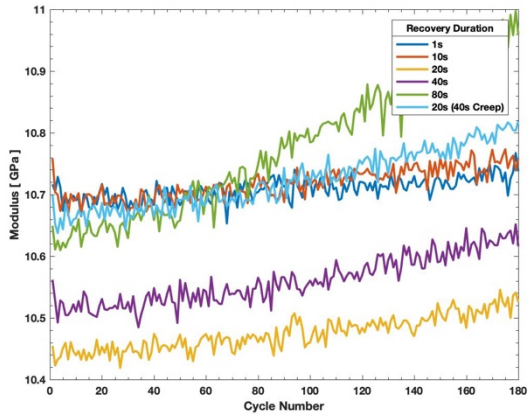
Figure A-23: 12.5 MPa - Instantaneous Modulus (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



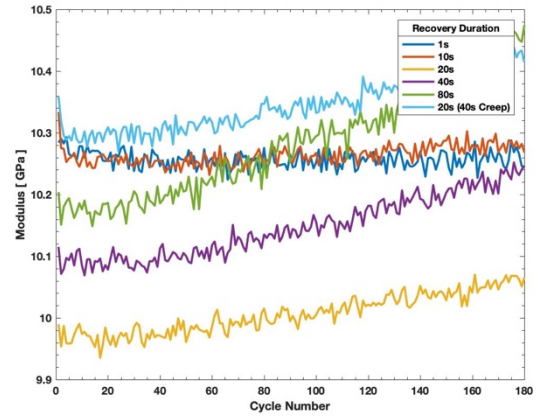
a)



b)



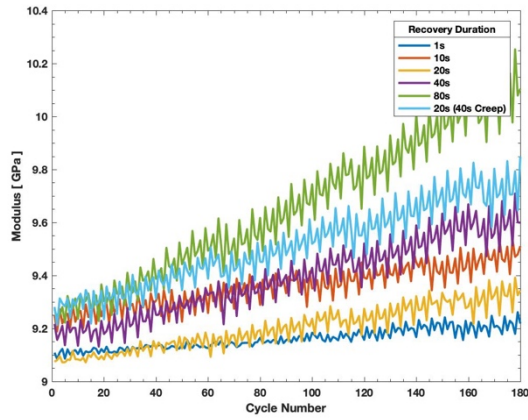
c)



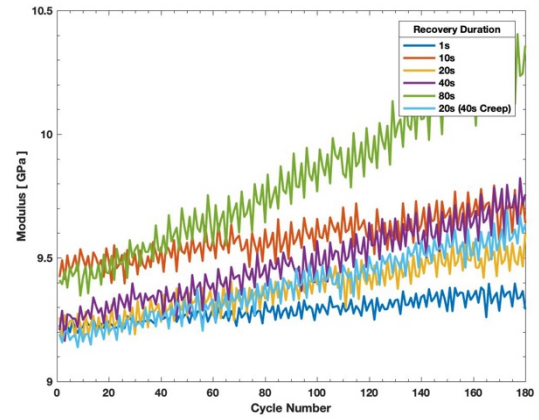
d)

Figure A-24: 12.5 MPa Continuous - Instantaneous Modulus (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

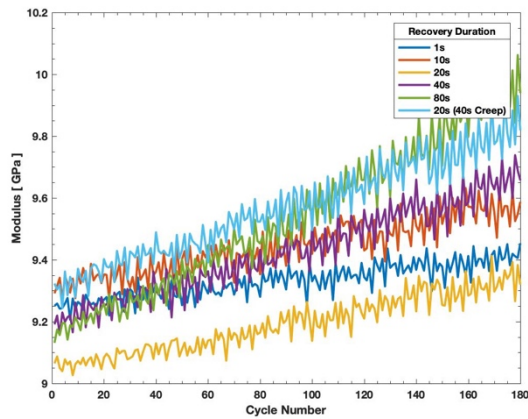
A.2.2 Unloading



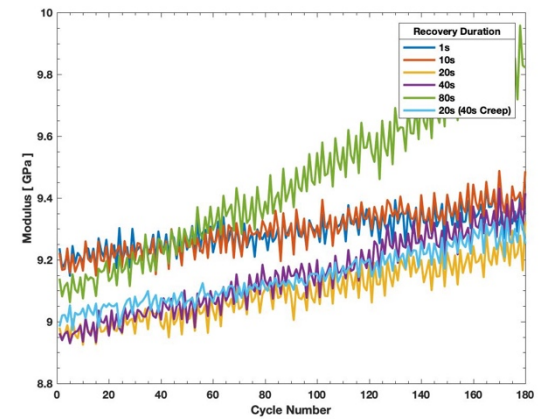
a)



b)

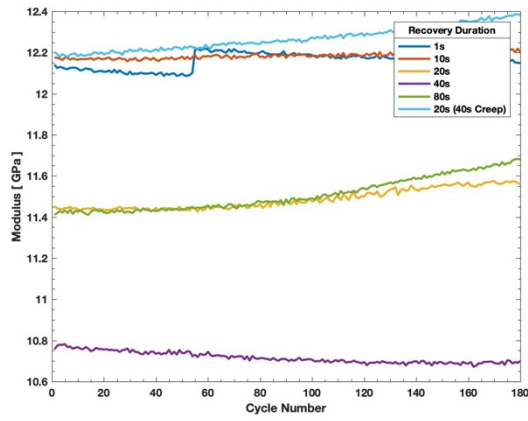


c)

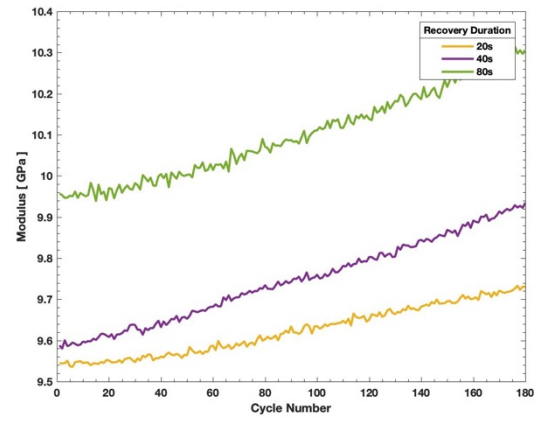


d)

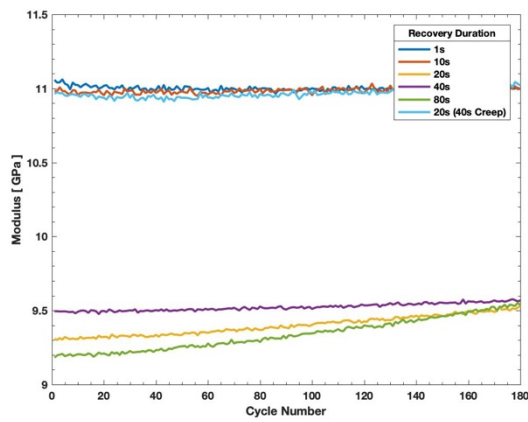
Figure A-25: 8 MPa - Instantaneous Modulus (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



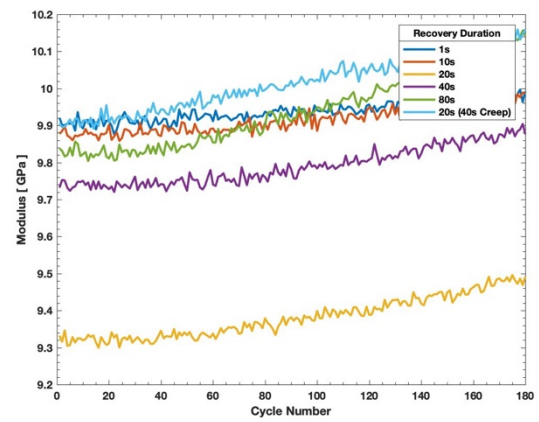
a)



b)

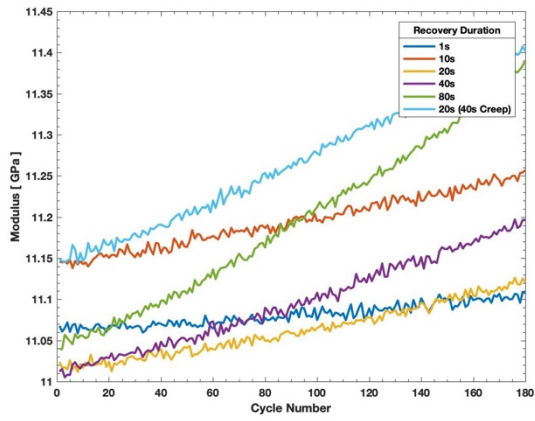


c)

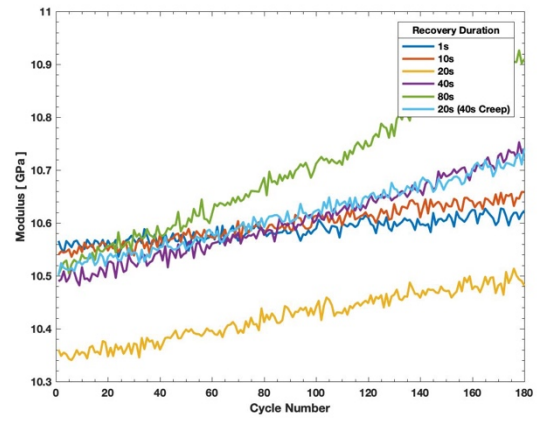


d)

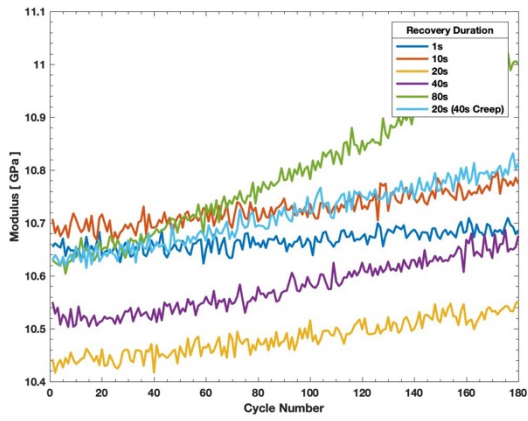
Figure A-26: 12.5 MPa - Instantaneous Modulus (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



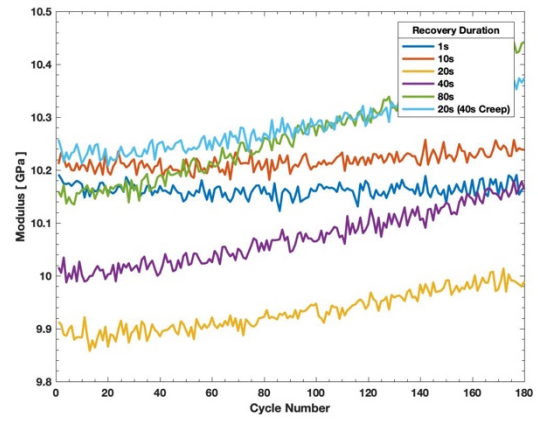
a)



b)



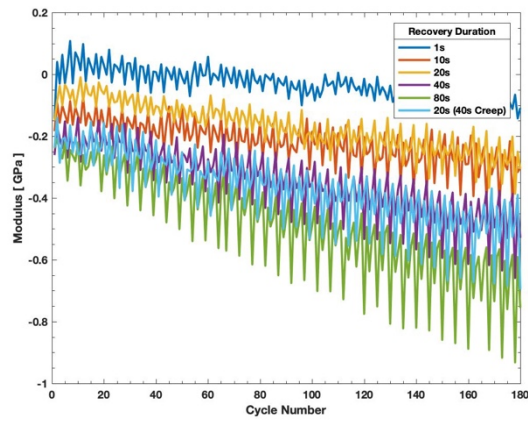
c)



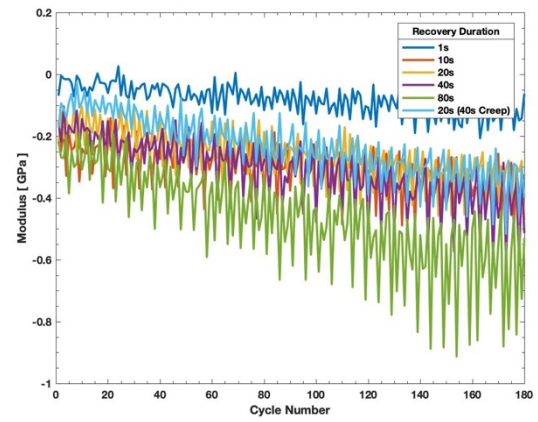
d)

Figure A-27: 12.5 MPa Continuous - Instantaneous Modulus (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

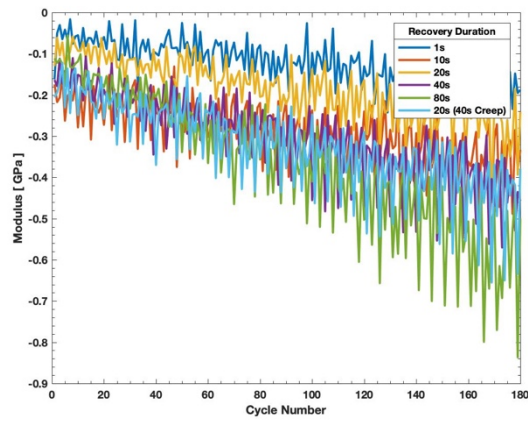
A.2.3 Difference



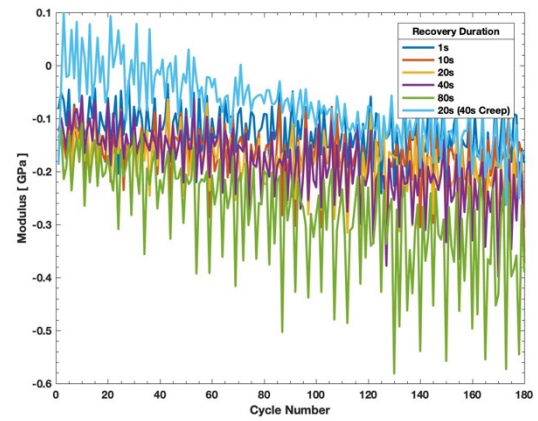
a)



b)

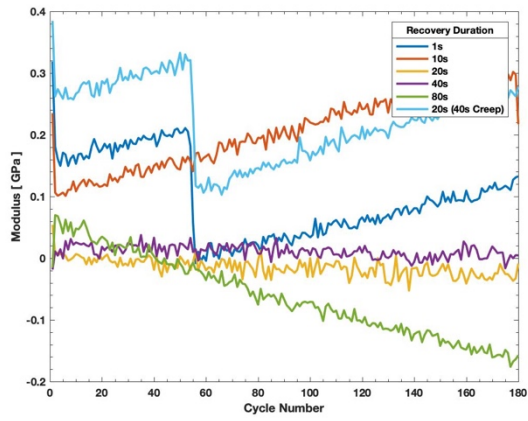


c)

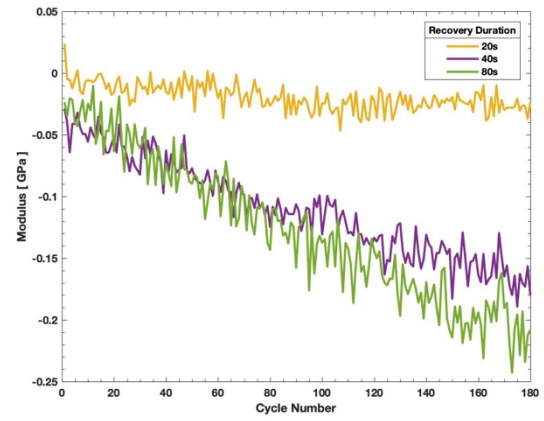


d)

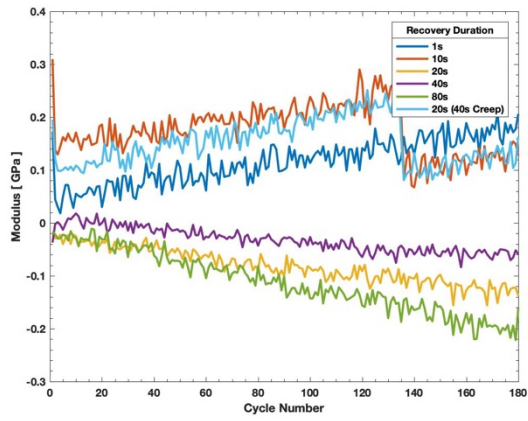
Figure A-28: 8 MPa - Instantaneous Modulus (Difference) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



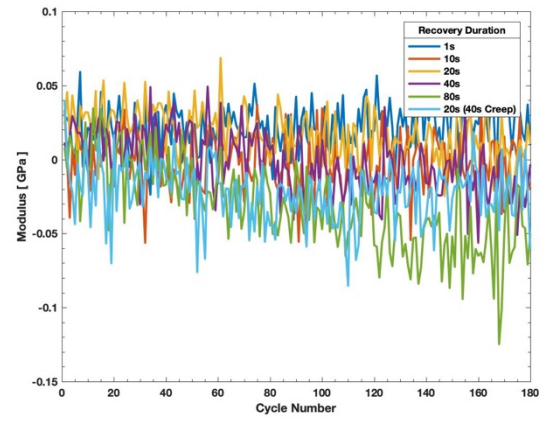
a)



b)

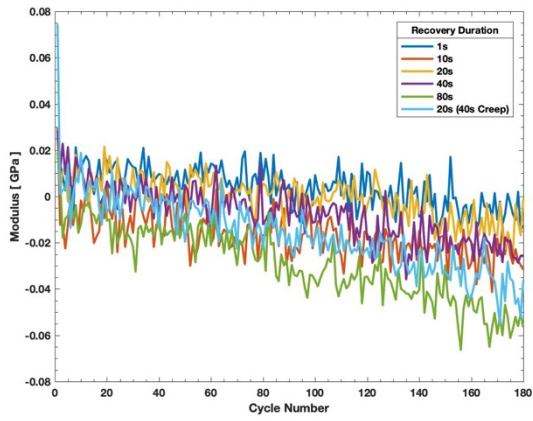


c)

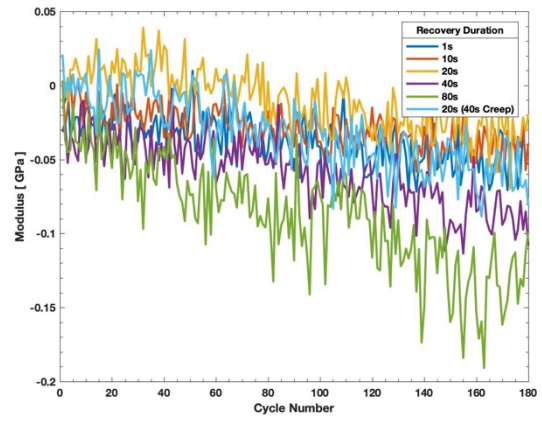


d)

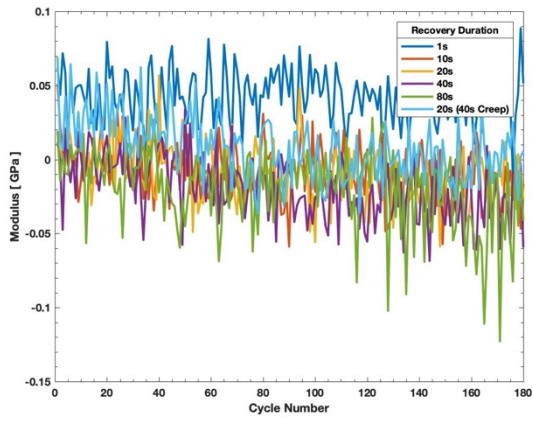
Figure A-29: 12.5 MPa - Instantaneous Modulus (Difference) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



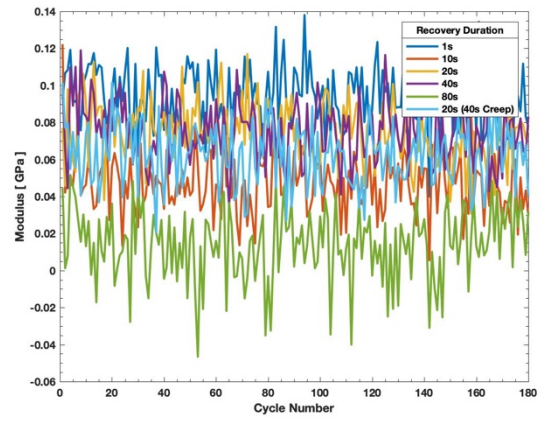
a)



b)



c)



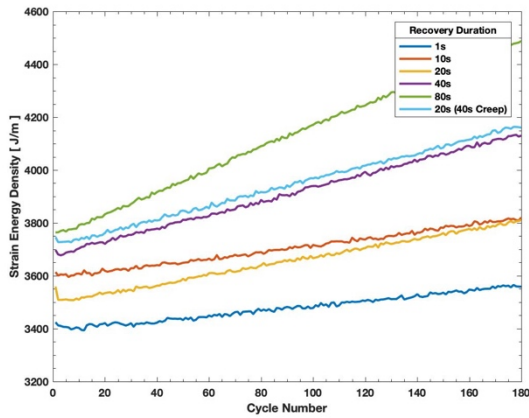
d)

Figure A-30: 12.5 MPa Continuous - Instantaneous Modulus (Difference) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

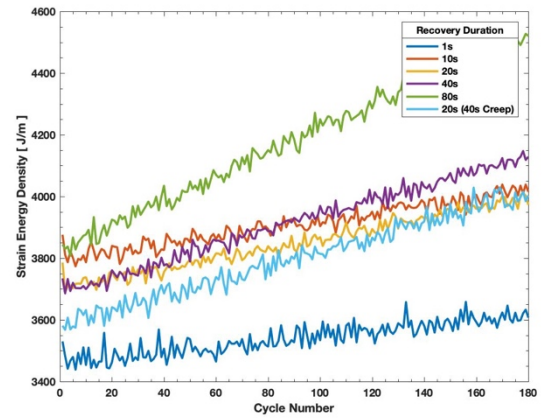
A.3 Strain Energy Density

A.3.1 Overall

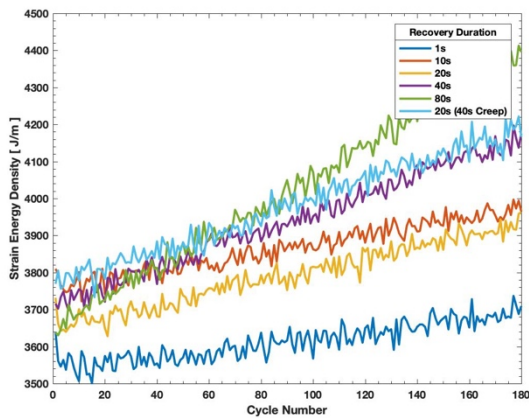
A.3.1.1 Total



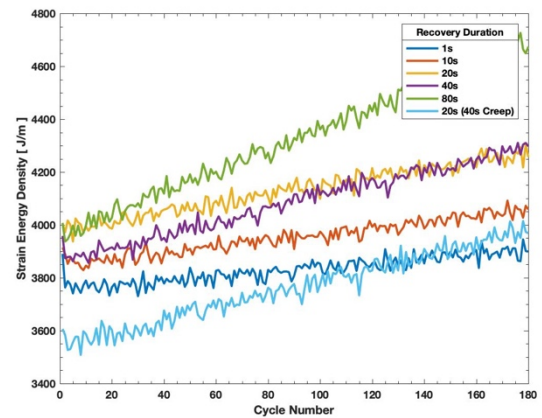
a)



b)

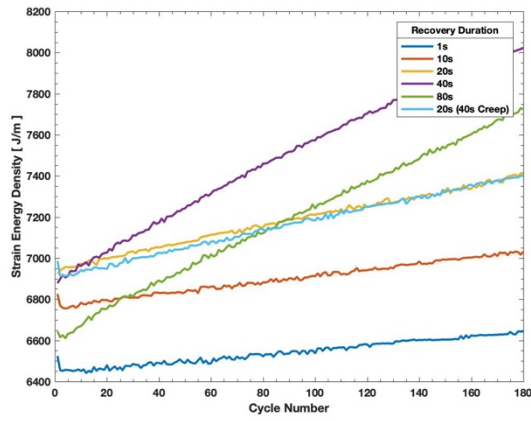


c)

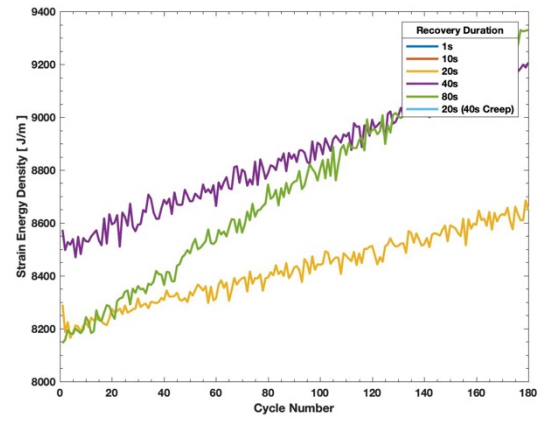


d)

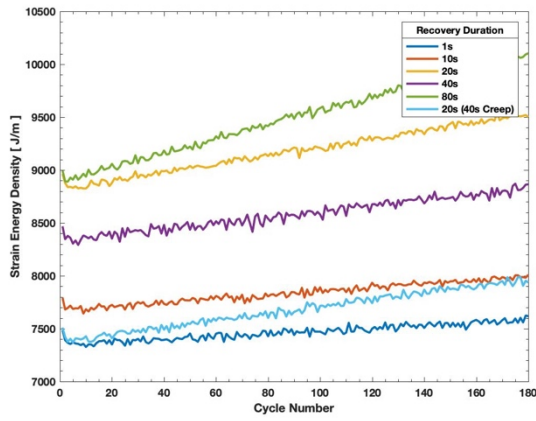
Figure A-31: 8 MPa - Total Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



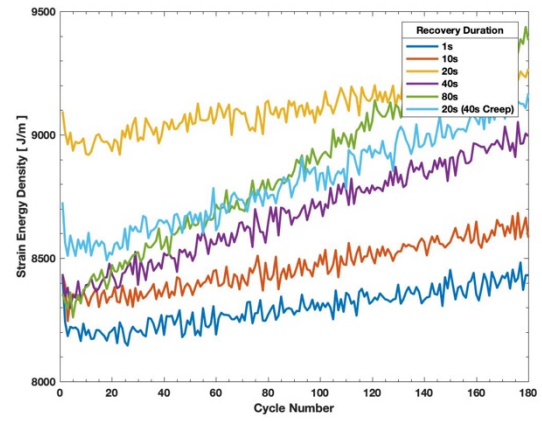
a)



b)

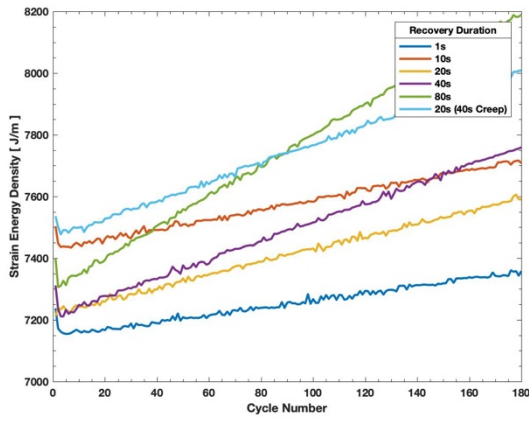


c)

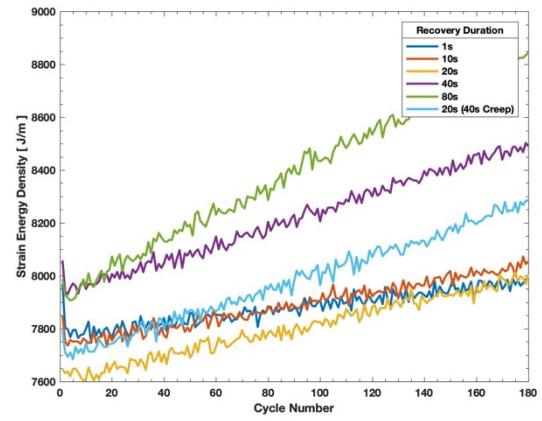


d)

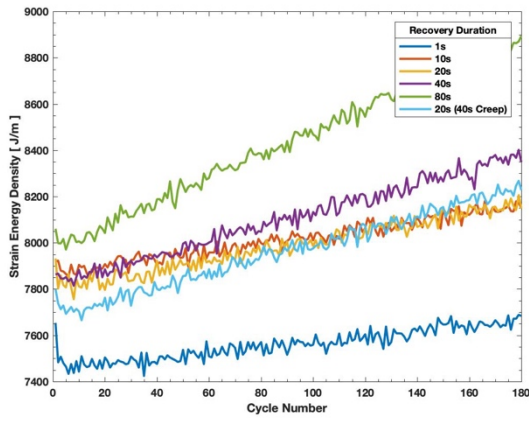
Figure A-32: 12.5 MPa - Total Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



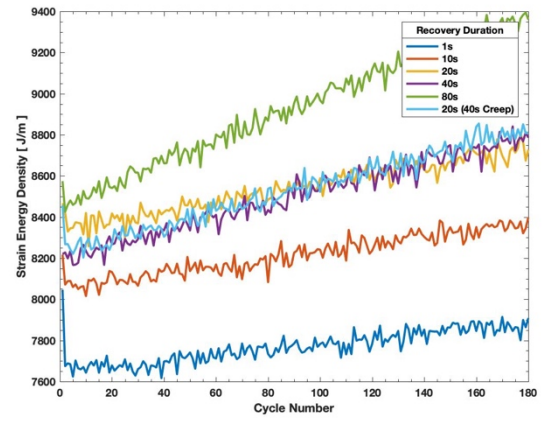
a)



b)



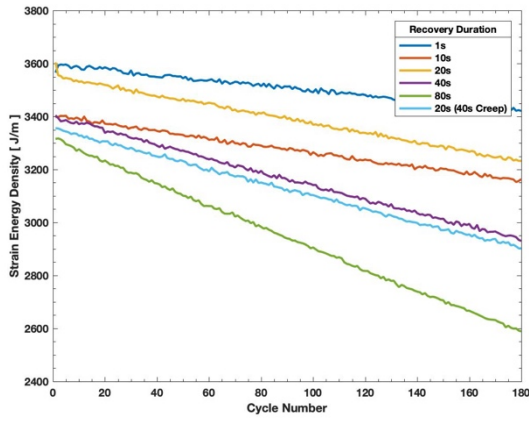
c)



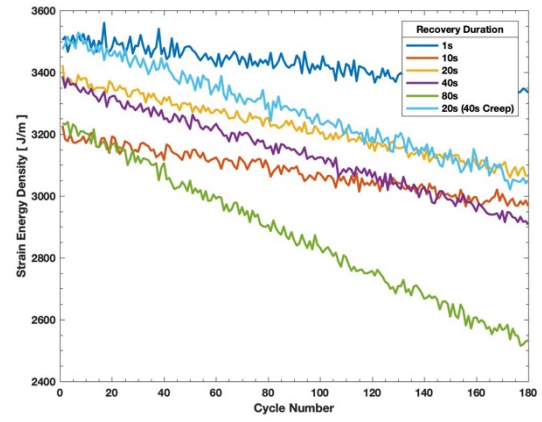
d)

Figure A-33: 12.5 MPa Continuous - Total Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

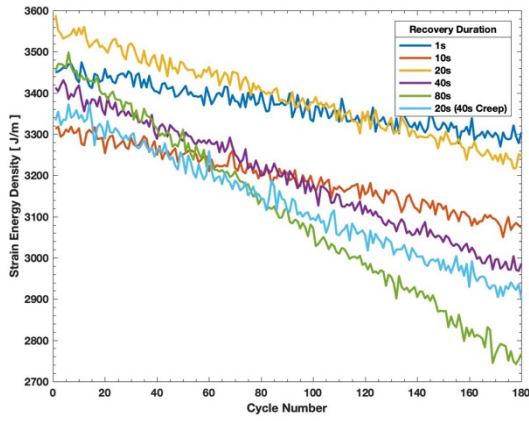
A.3.1.2 Stored



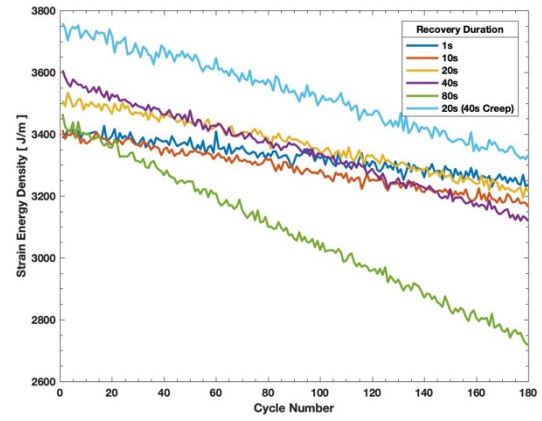
a)



b)

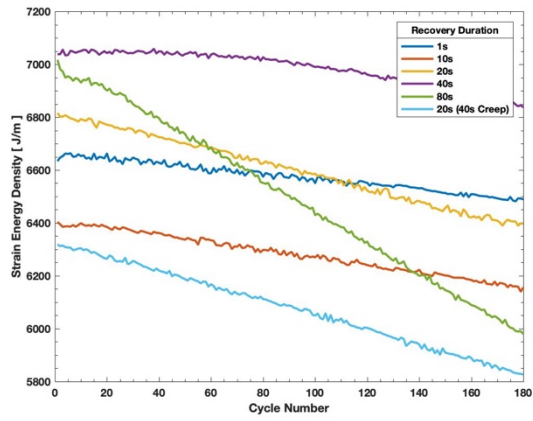


c)

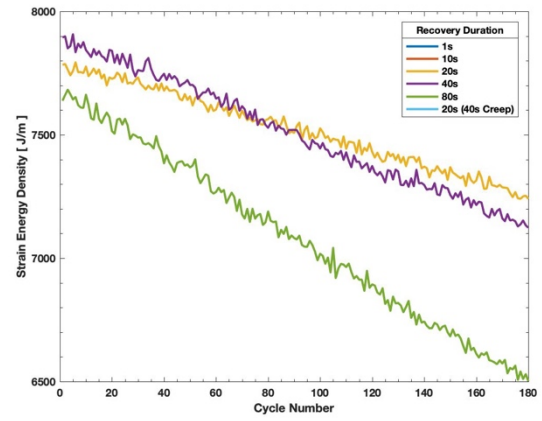


d)

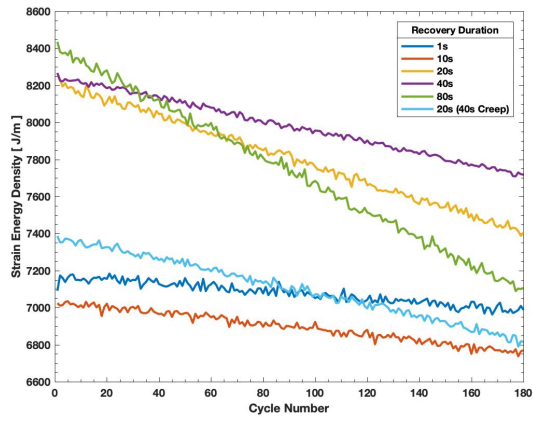
Figure A-34: 8 MPa - Stored Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



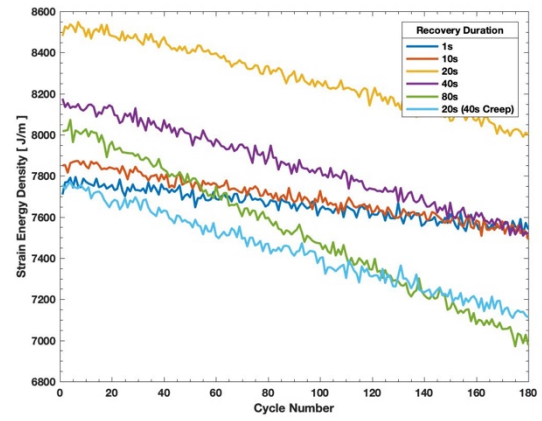
a)



b)

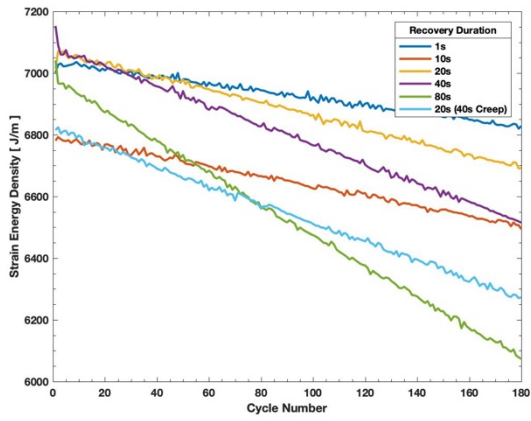


c)

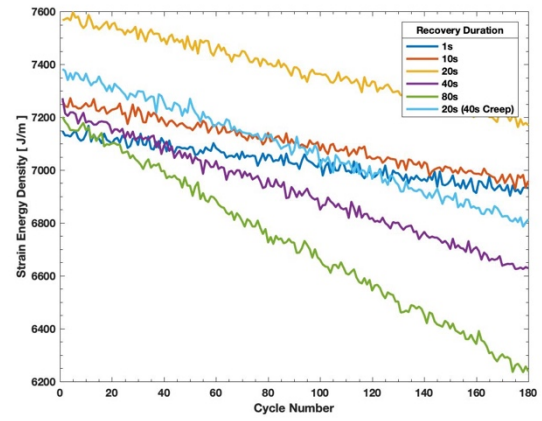


d)

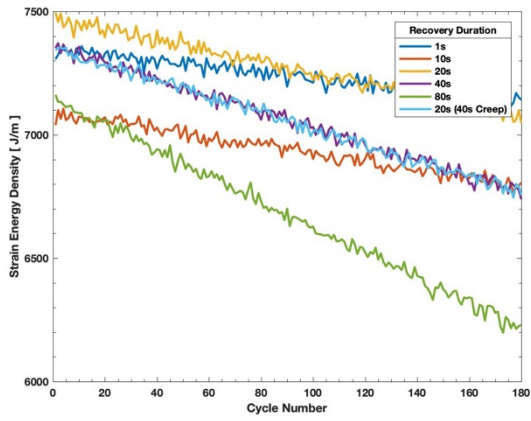
Figure A-35: 12.5 MPa - Stored Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



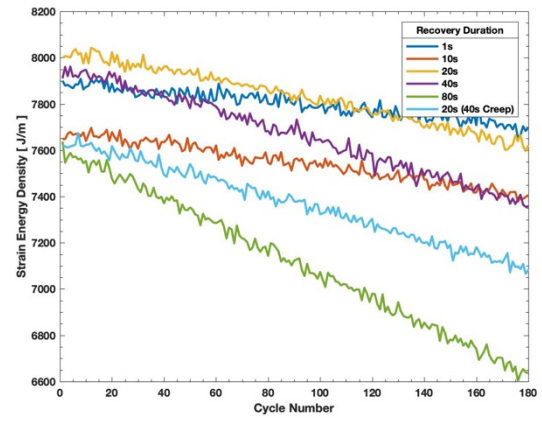
a)



b)



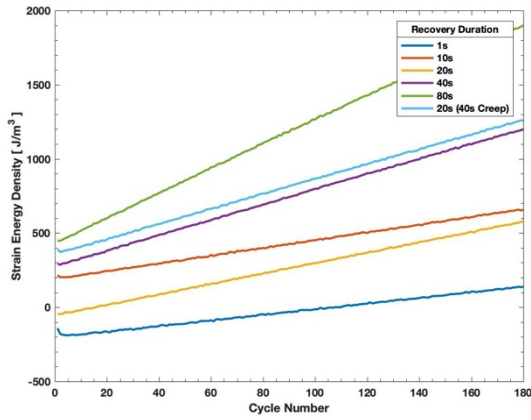
c)



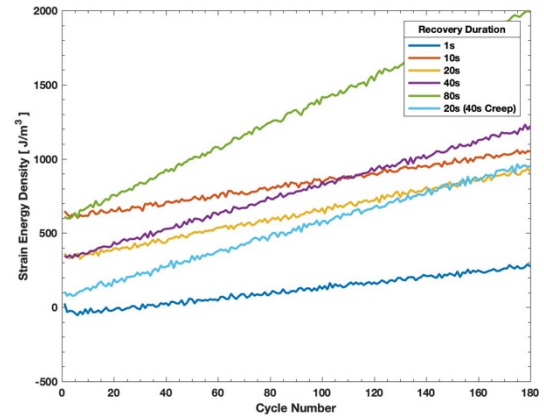
d)

Figure A-36: 12.5 MPa Continuous - Stored Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

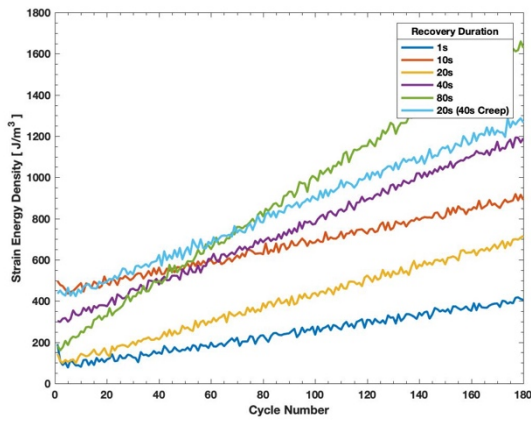
A.3.1.3 Dissipated



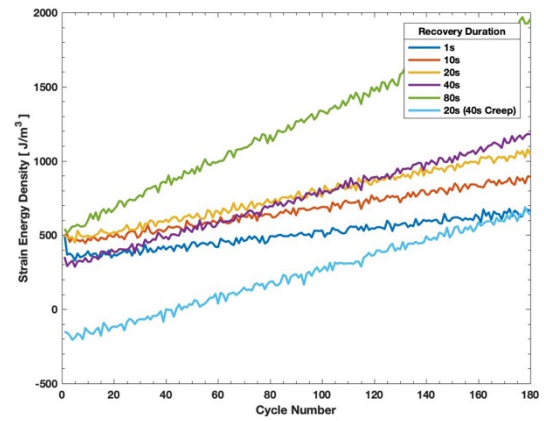
a)



b)

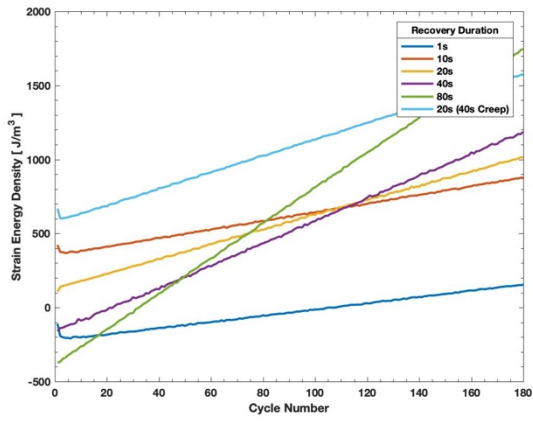


c)

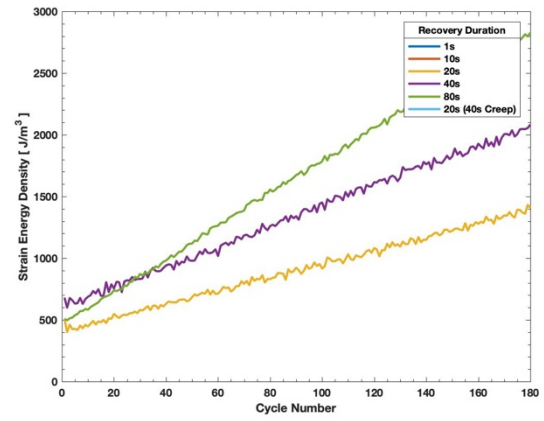


d)

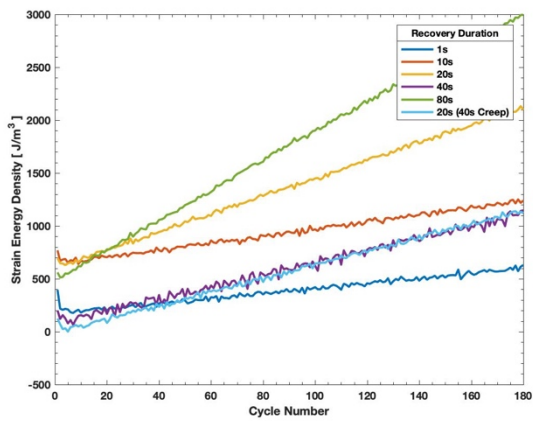
Figure A-37: 8 MPa - Dissipated Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



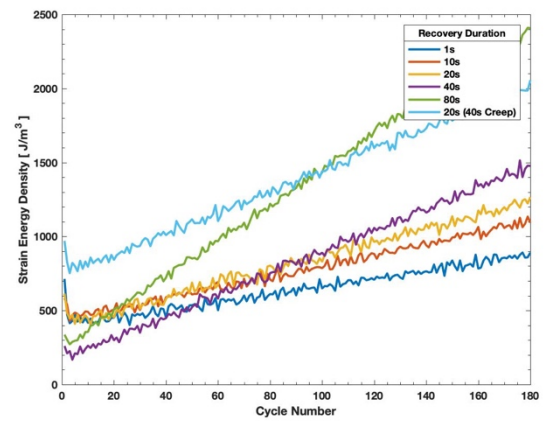
a)



b)

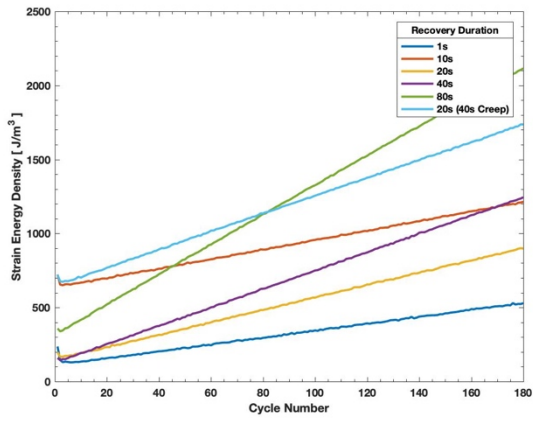


c)

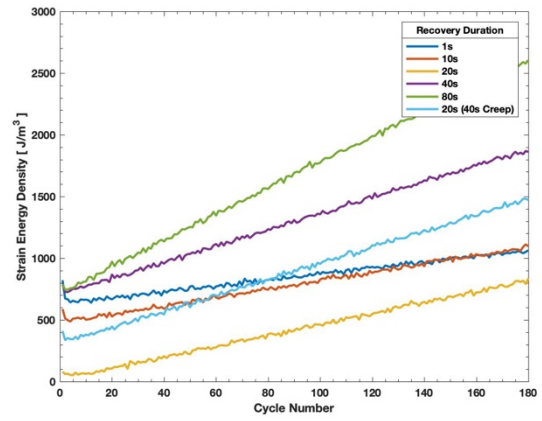


d)

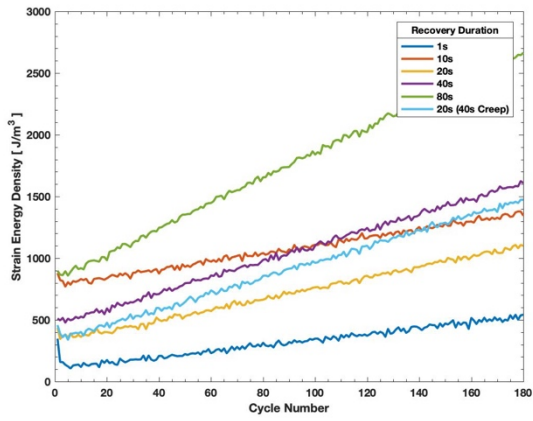
Figure A-38: 12.5 MPa - Dissipated Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



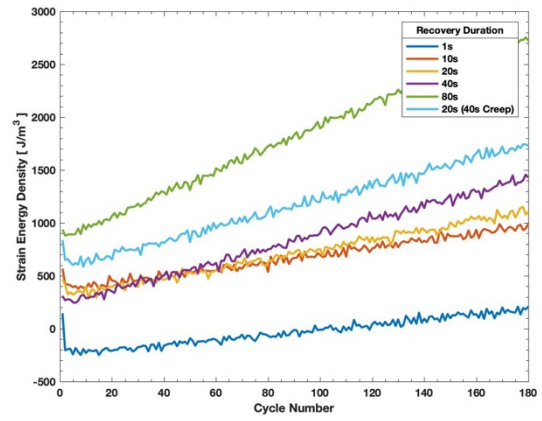
a)



b)



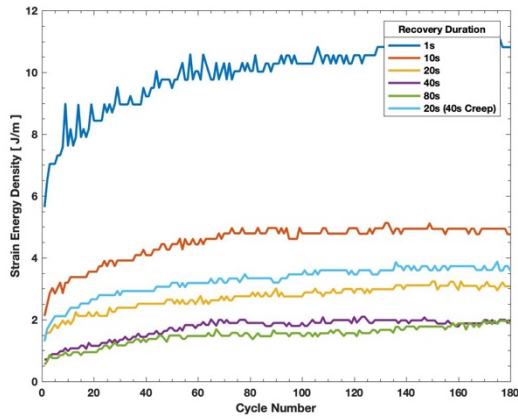
c)



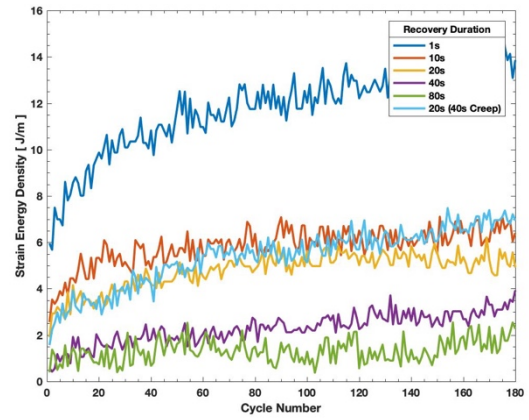
d)

Figure A-39: 12.5 MPa Continuous - Dissipated Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C
c) 120 °C d) 180 °C.

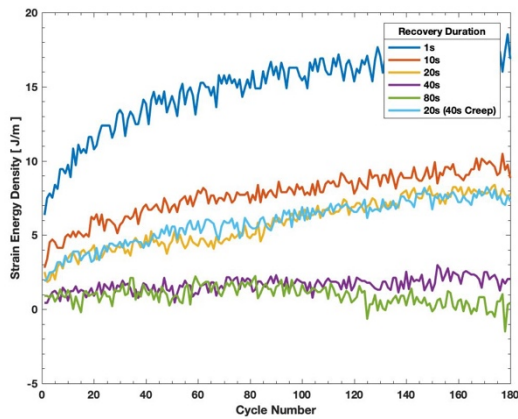
A.3.1.4 Unrecovered



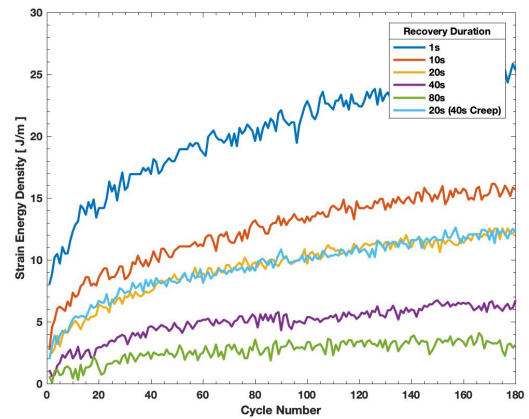
a)



b)

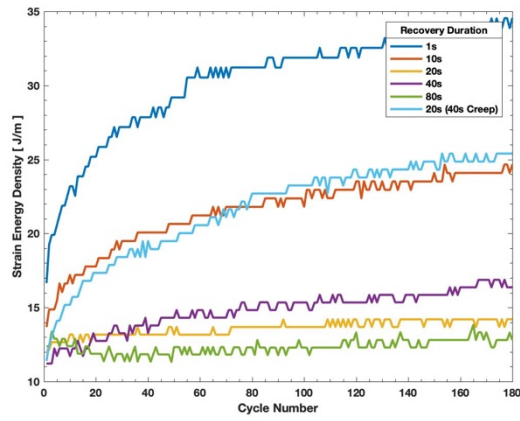


c)

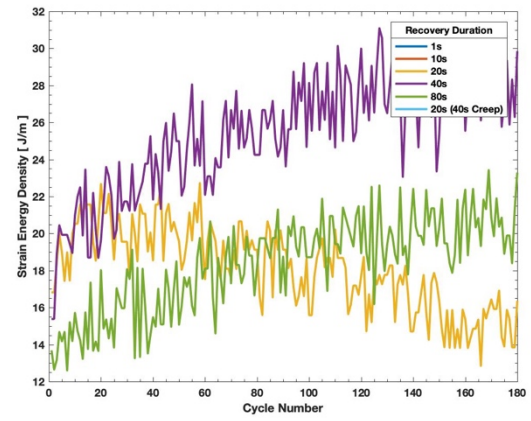


d)

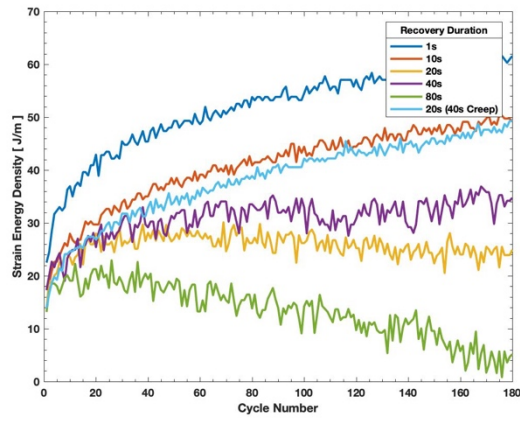
Figure A-40: 8 MPa - Unrecovered Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



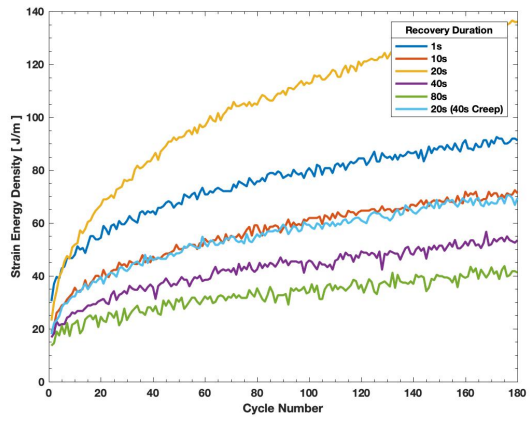
a)



b)

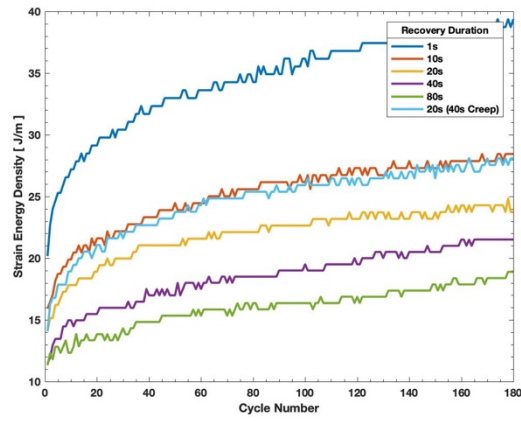


c)

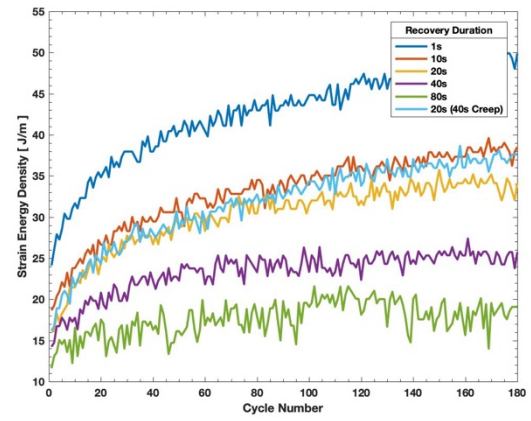


d)

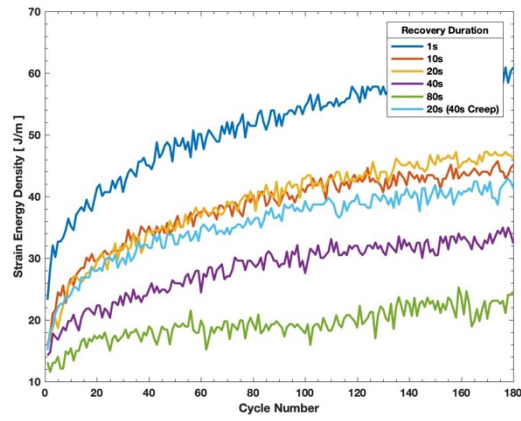
Figure A-41: 12.5 MPa - Unrecovered Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



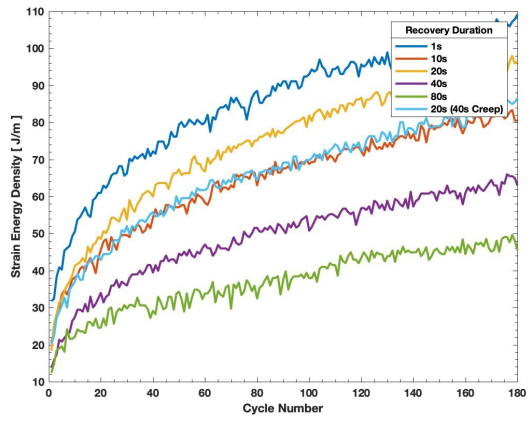
a)



b)



c)

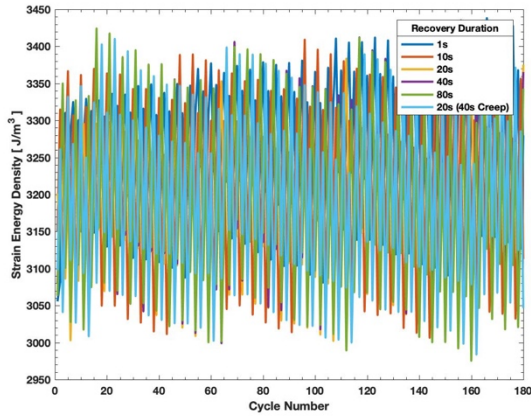


d)

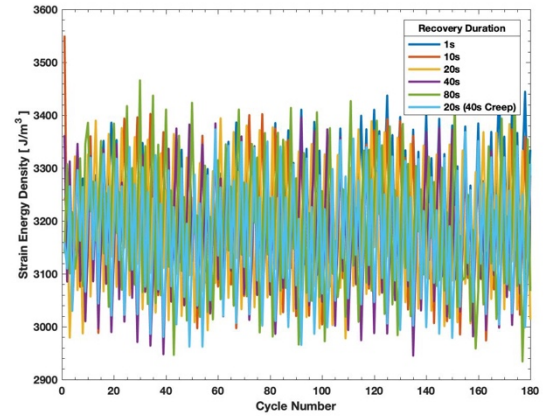
Figure A-42: 12.5 MPa Continuous - Unrecovered Strain Energy Density vs Cycle; a) Room Temperature b) 80 °C
c) 120 °C d) 180 °C.

A.3.2 Total

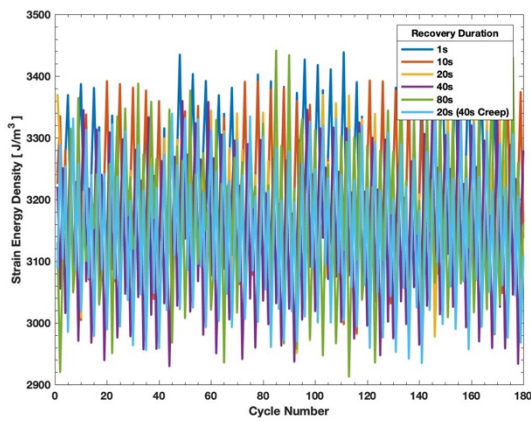
A.3.2.1 Loading



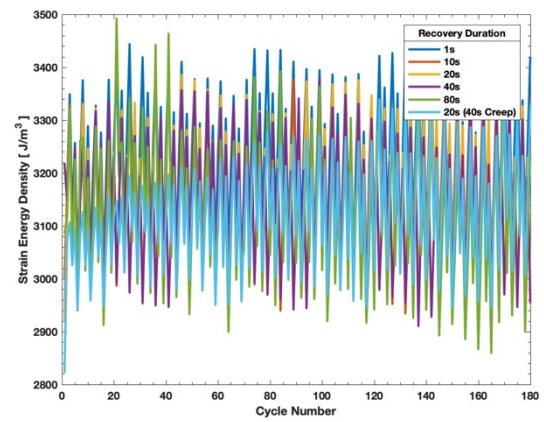
a)



b)

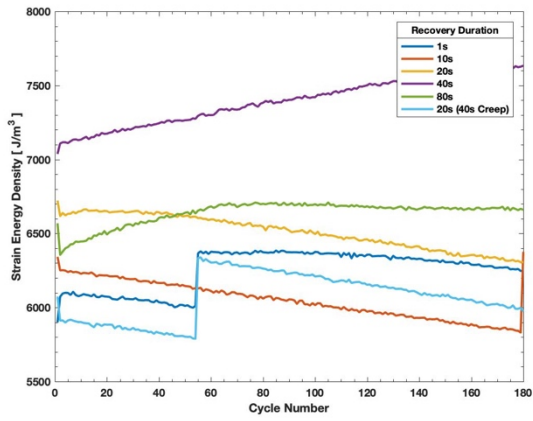


c)

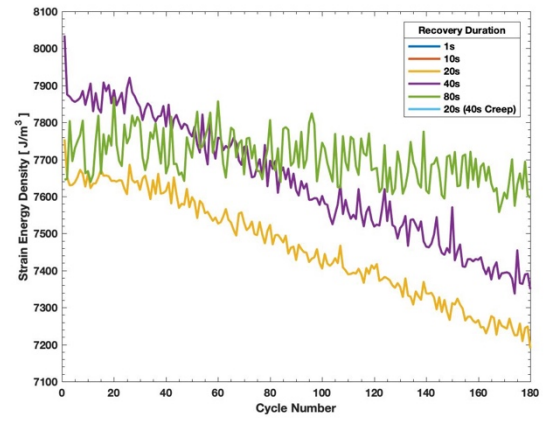


d)

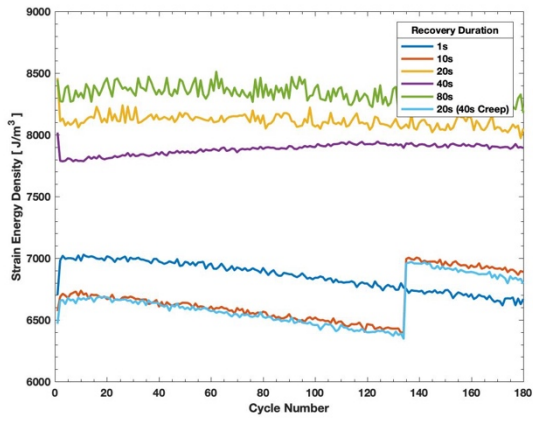
Figure A-43: 8 MPa - Total Strain Energy Density (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



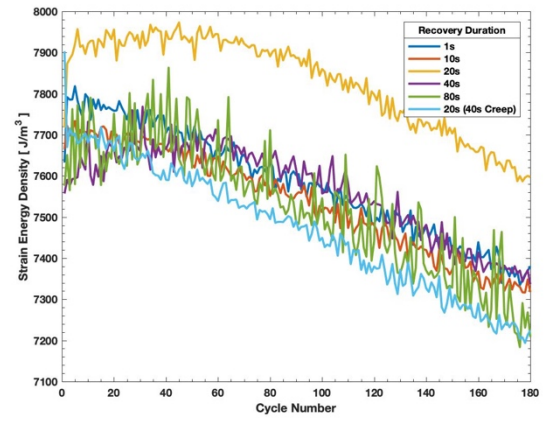
a)



b)

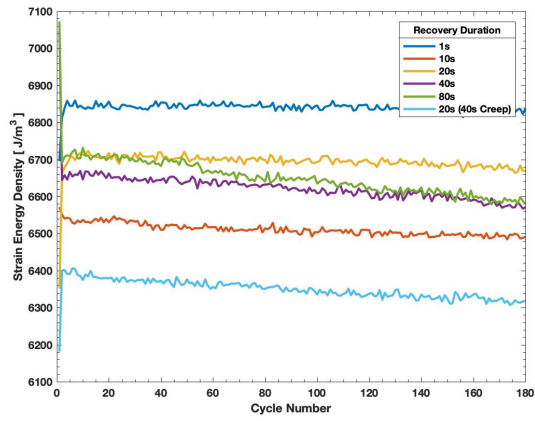


c)

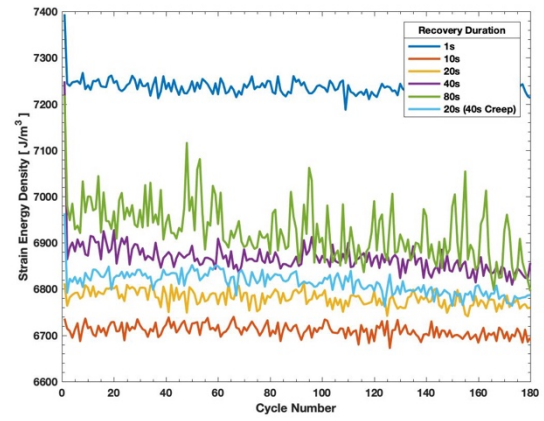


d)

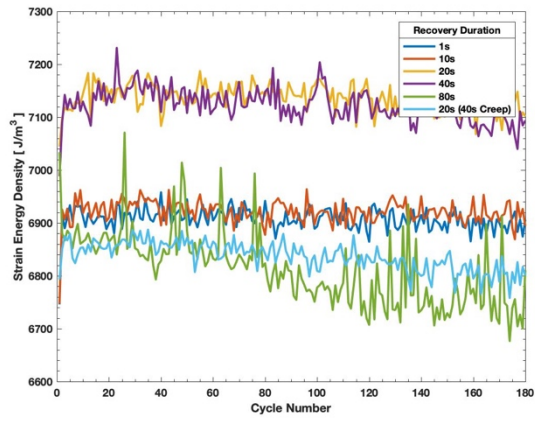
Figure A-44: 12.5 MPa - Total Strain Energy Density (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



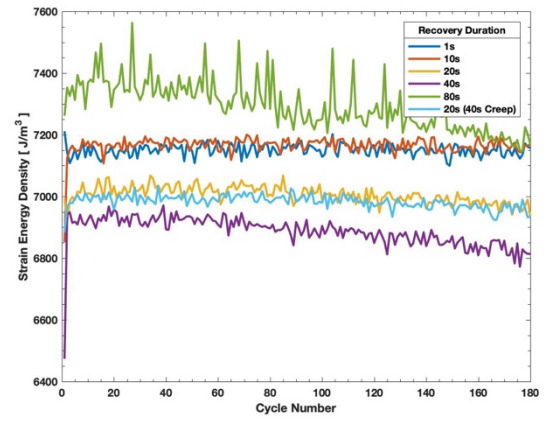
a)



b)



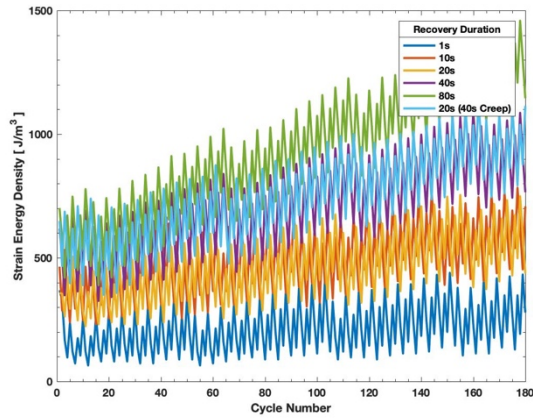
c)



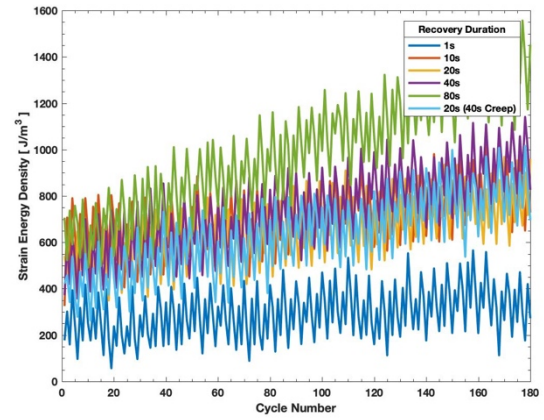
d)

Figure A-45: 12.5 MPa Continuous - Total Strain Energy Density (Loading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

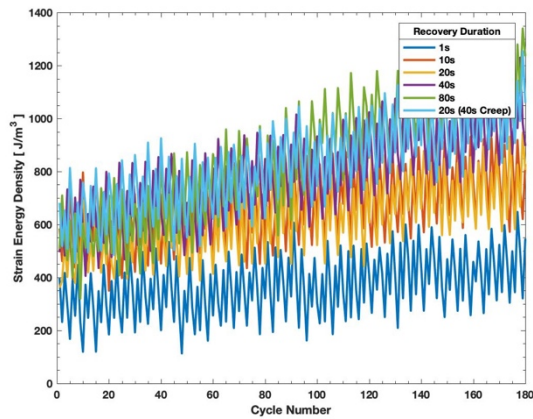
A.3.2.2 Creep



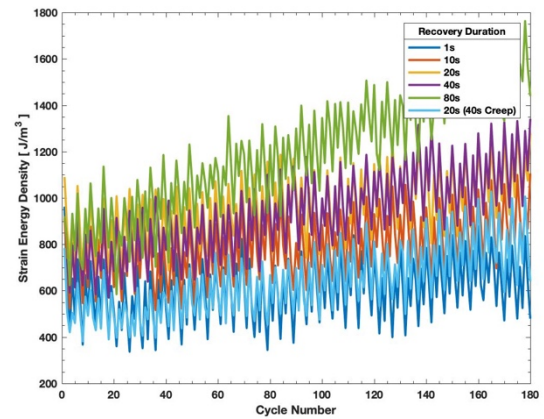
a)



b)

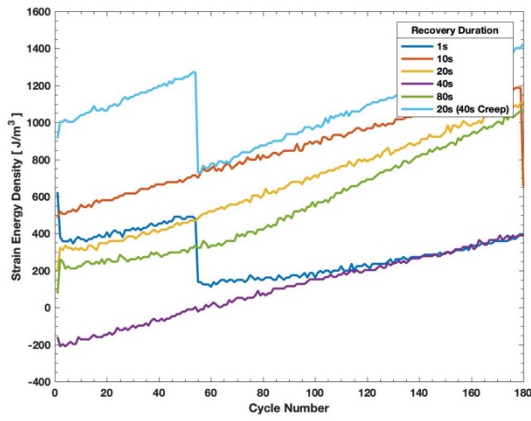


c)

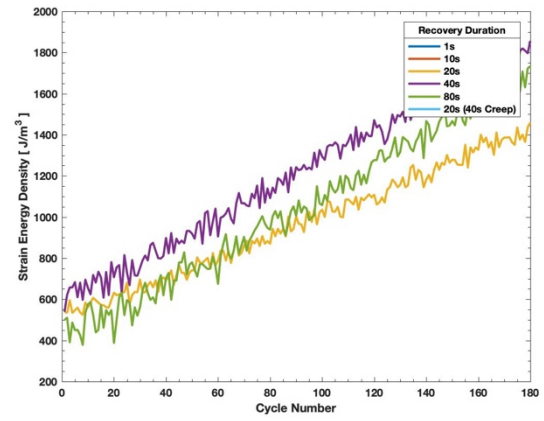


d)

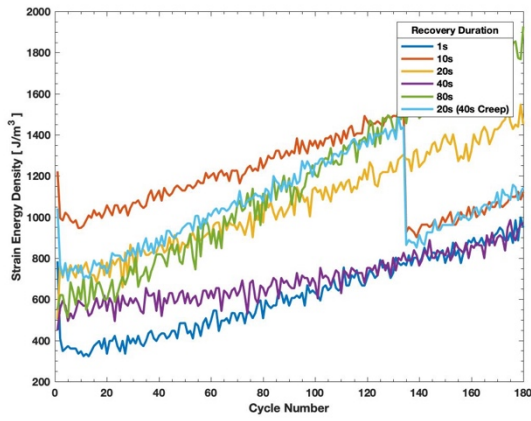
Figure A-46: 8 MPa - Total Strain Energy Density (Creep) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



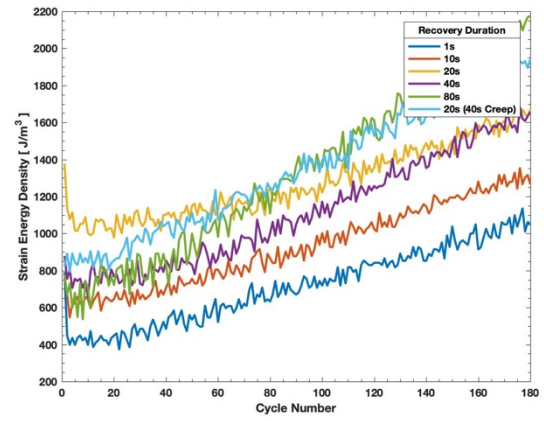
a)



b)

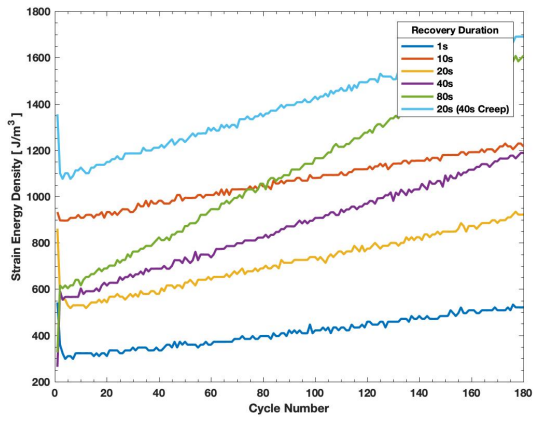


c)

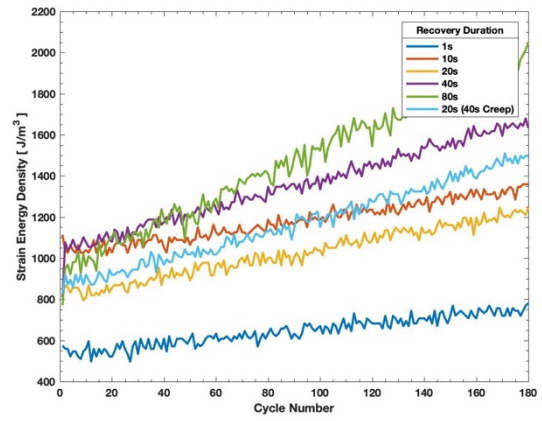


d)

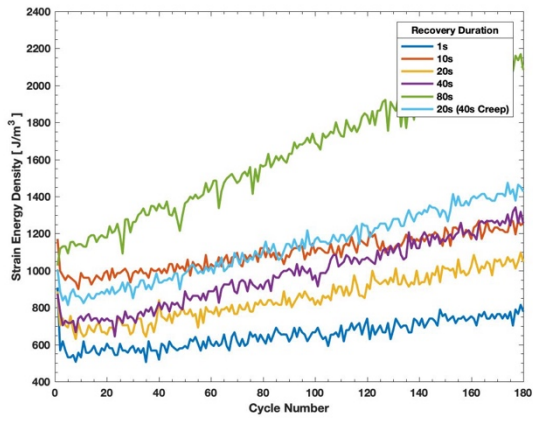
Figure A-47: 12.5 MPa - Total Strain Energy Density (Creep) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



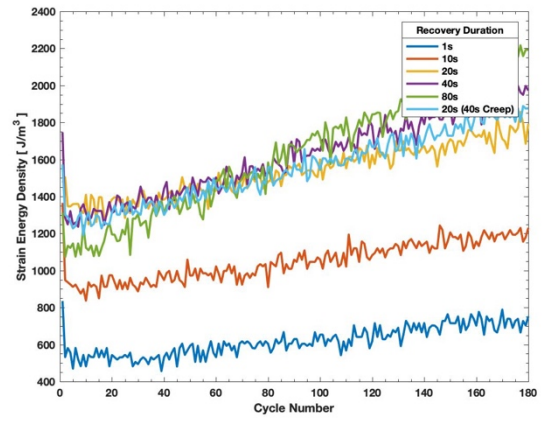
a)



b)



c)

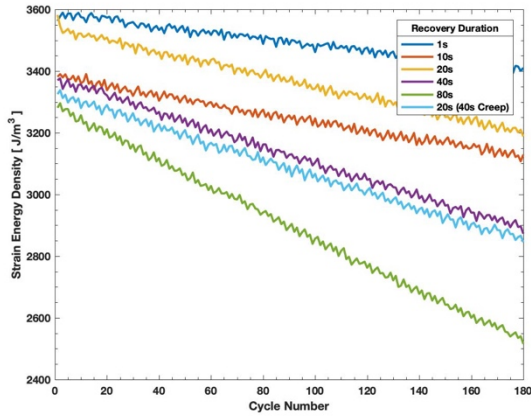


d)

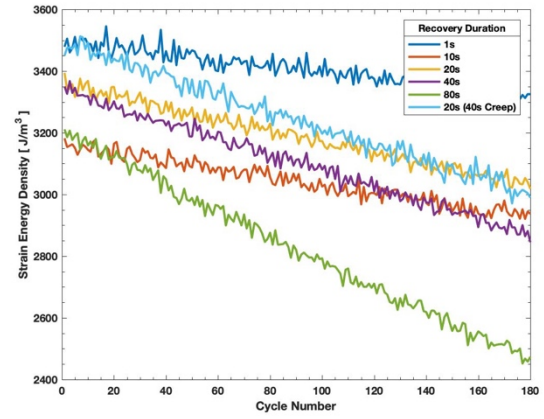
Figure A-48: 12.5 MPa Continuous - Total Strain Energy Density (Creep) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

A.3.3 Stored

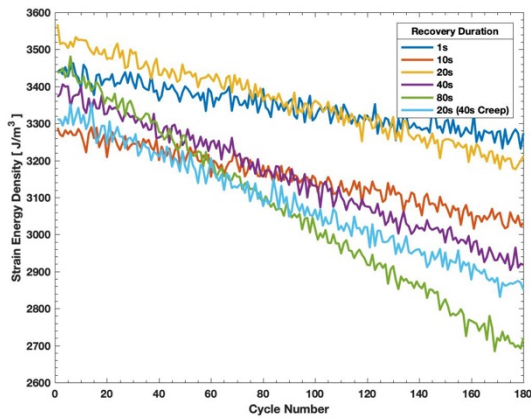
A.3.3.1 Unloading



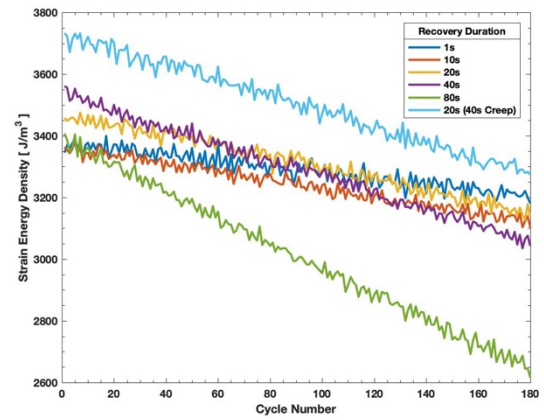
a)



b)

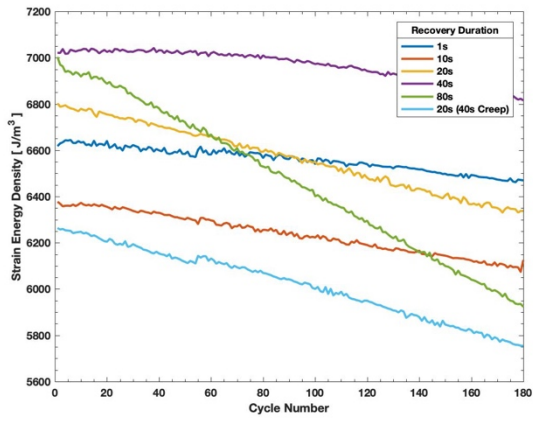


c)

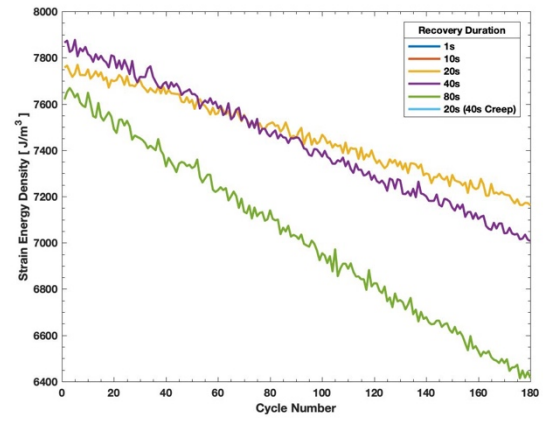


d)

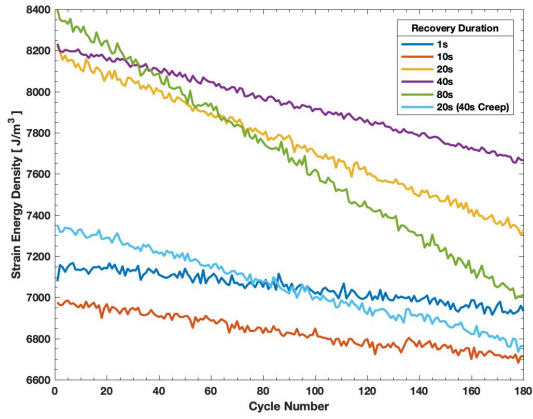
Figure A-49: 8 MPa - Stored Strain Energy Density (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



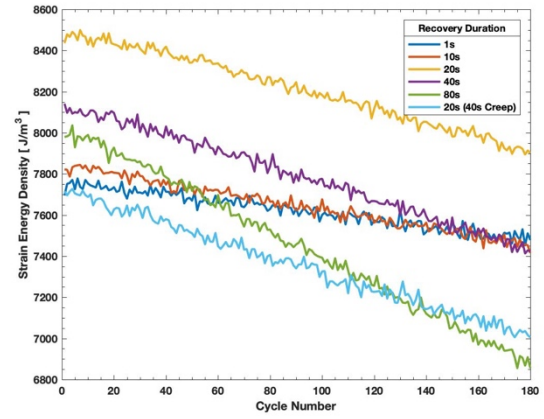
a)



b)

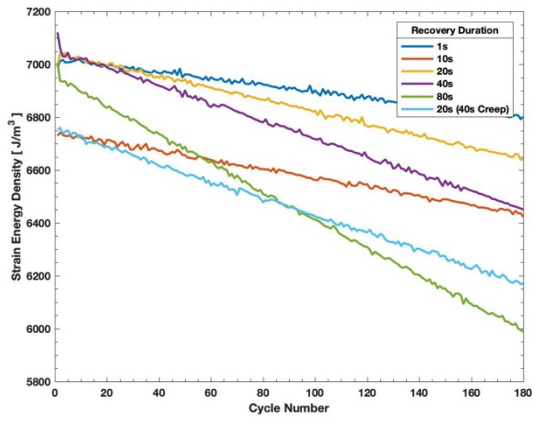


c)

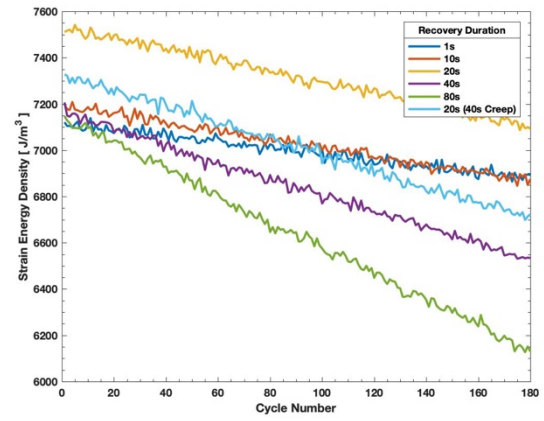


d)

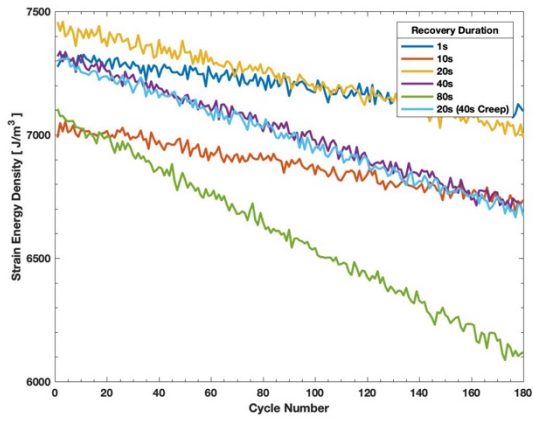
Figure A-50: 12.5 MPa - Stored Strain Energy Density (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



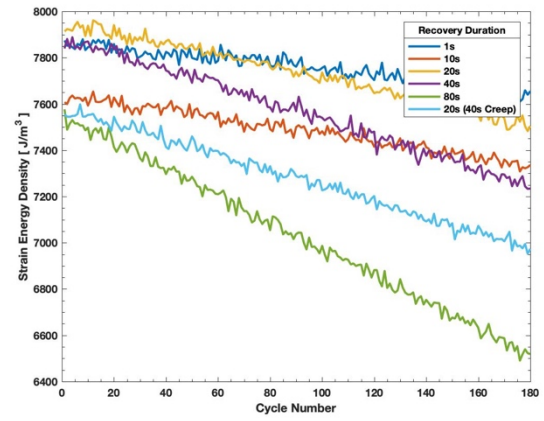
a)



b)



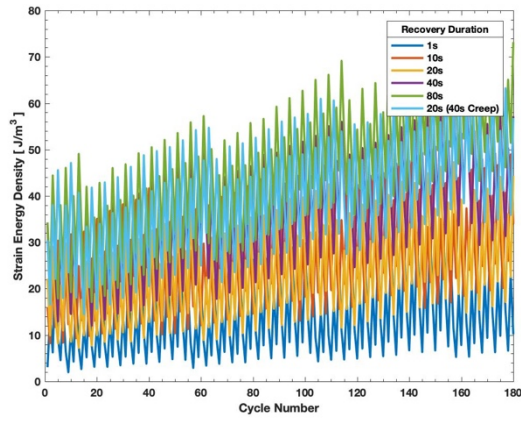
c)



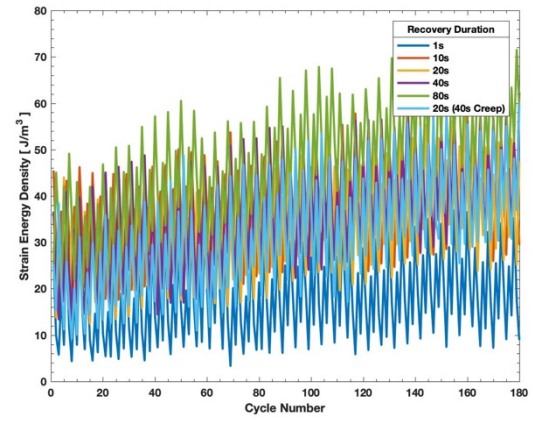
d)

Figure A-51: 12.5 MPa Continuous - Stored Strain Energy Density (Unloading) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

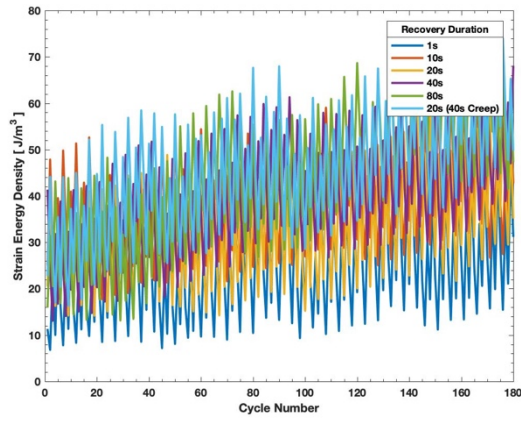
A.3.3.2 Recovery



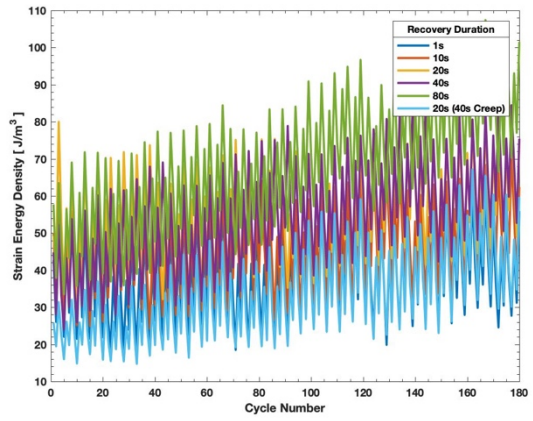
a)



b)

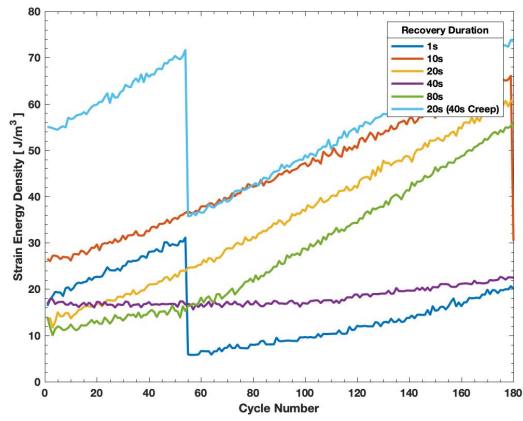


c)

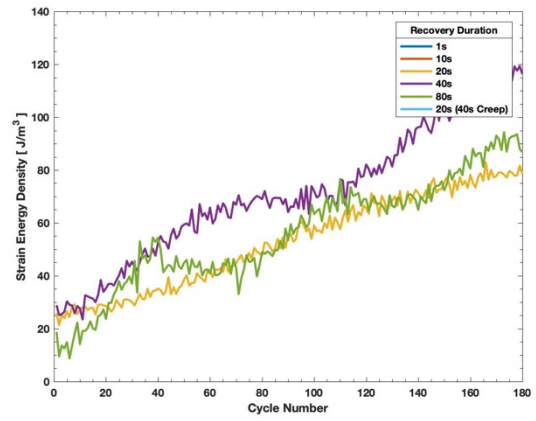


d)

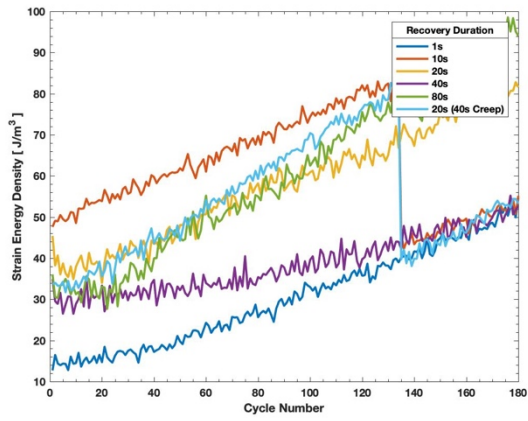
Figure A-52: 8 MPa - Stored Strain Energy Density (Recovery) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



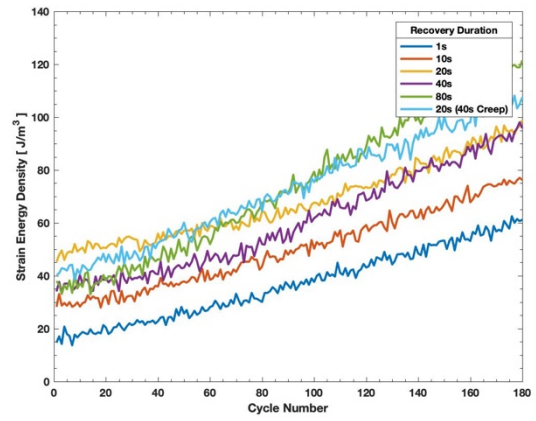
a)



b)

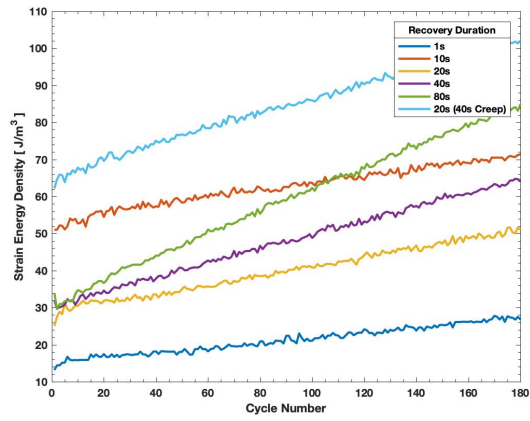


c)

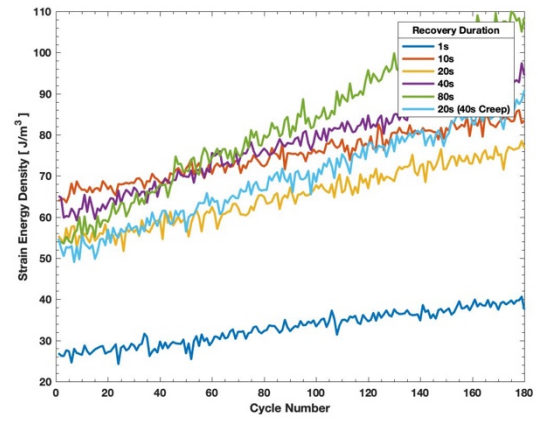


d)

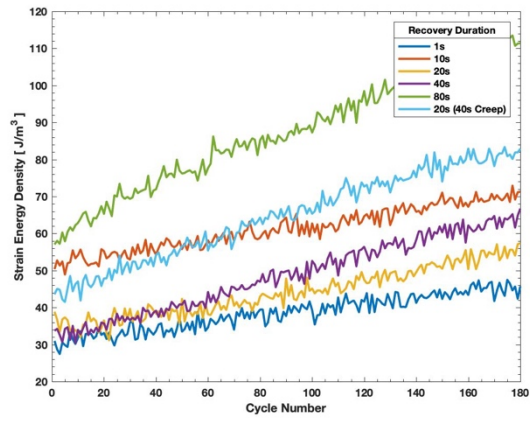
Figure A-53: 12.5 MPa - Stored Strain Energy Density (Recovery) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.



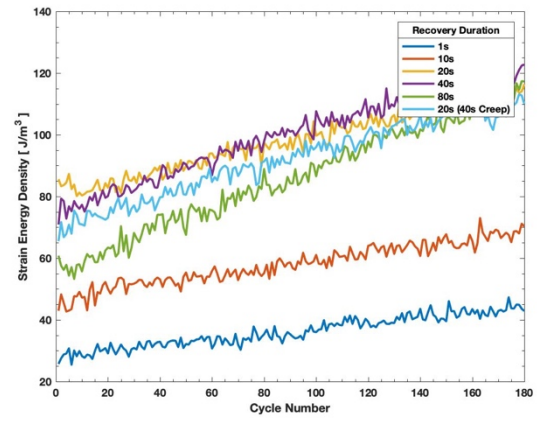
a)



b)



c)



d)

Figure A-54: 12.5 MPa Continuous - Stored Strain Energy Density (Recovery) vs Cycle; a) Room Temperature b) 80 °C c) 120 °C d) 180 °C.

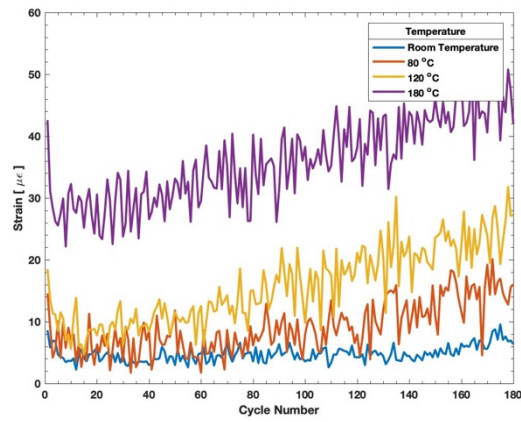
Appendix B Effect of Temperature

The following appendix shall present the generated plots showing the various parameters as a function of cycles for all temperatures for a given load-recovery duration combination.

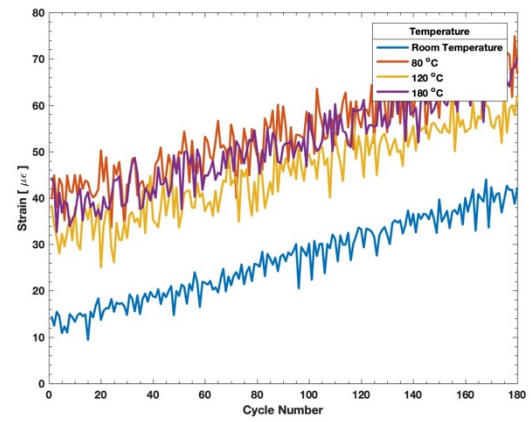
B.1 Strain

B.1.1 Creep / Recovered

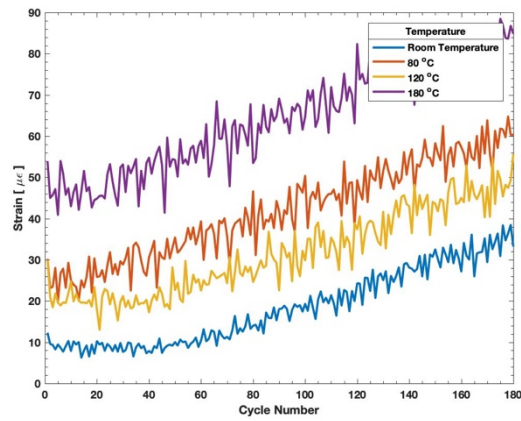
B.1.1.1.1 Creep



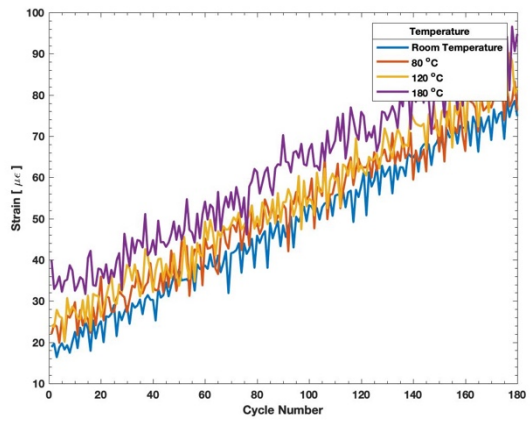
a)



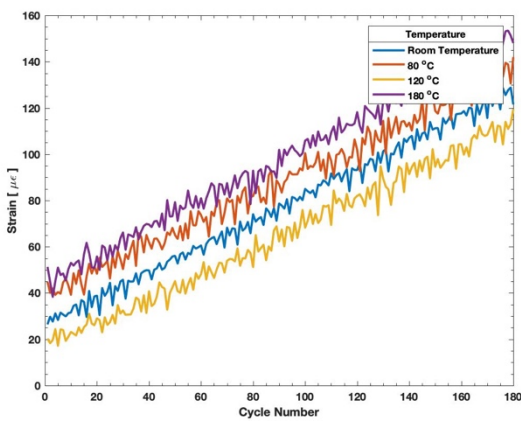
b)



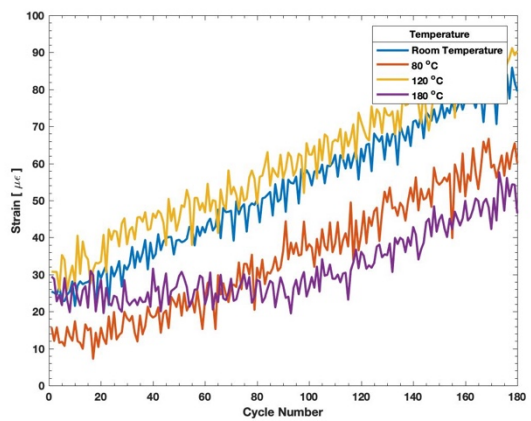
c)



d)

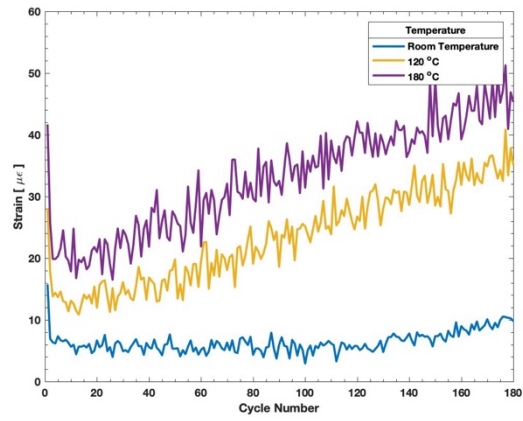


e)

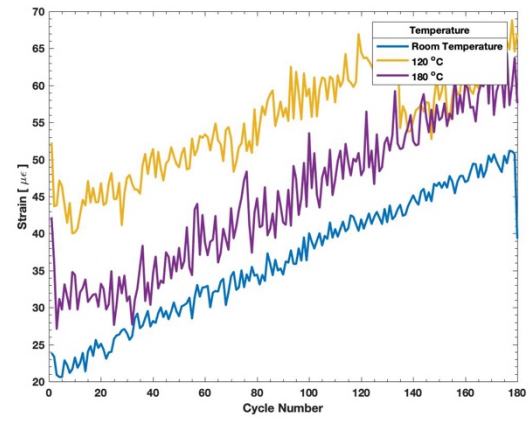


f)

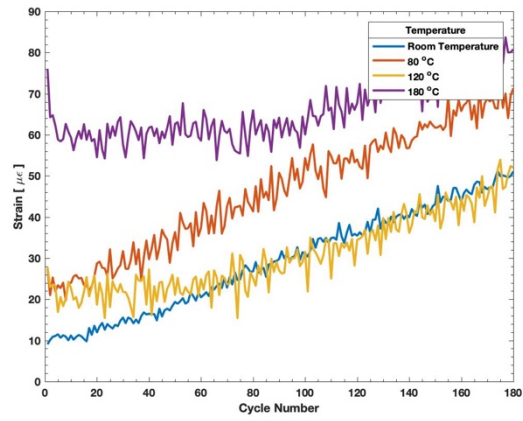
Figure B-1: 8 MPa – Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



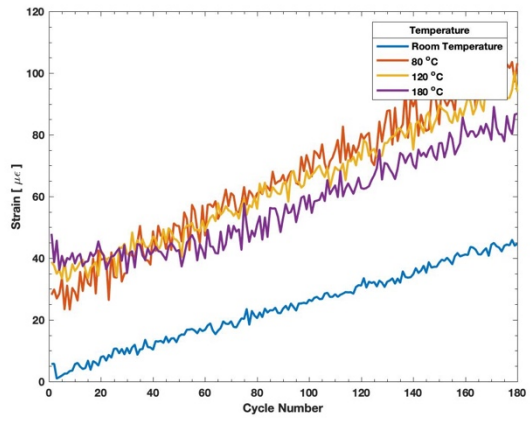
a)



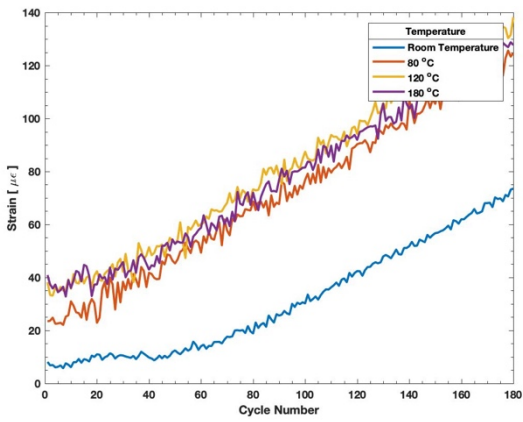
b)



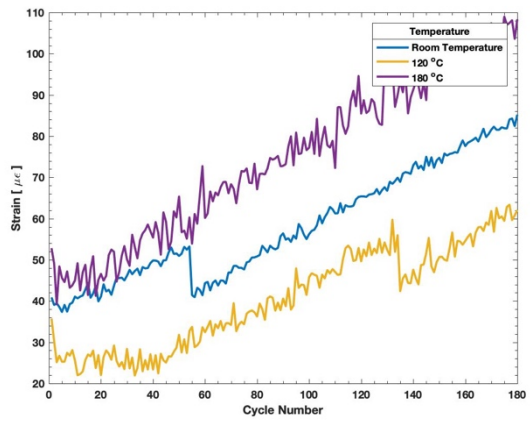
c)



d)

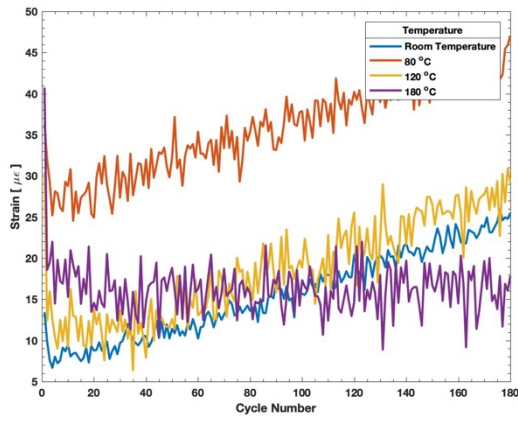


e)

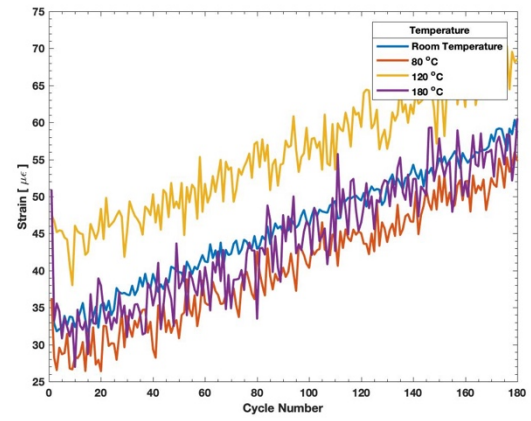


f)

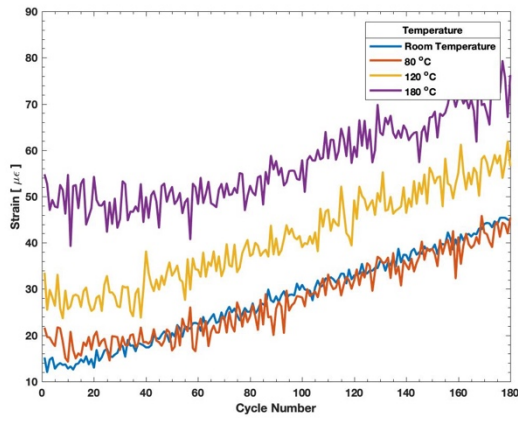
Figure B-2: 12.5 MPa – Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



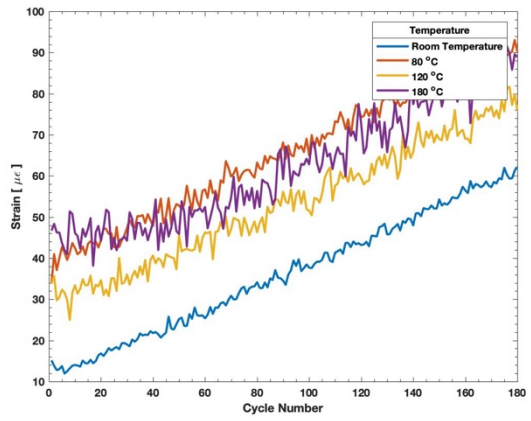
a)



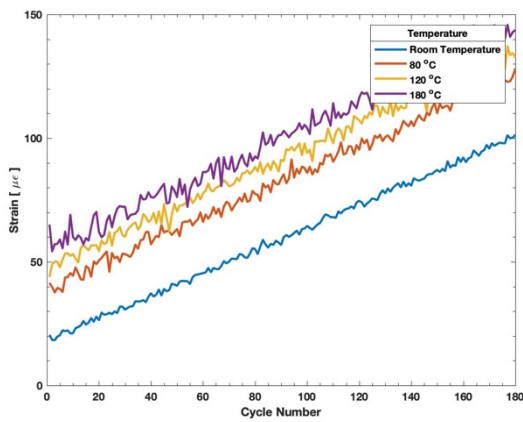
b)



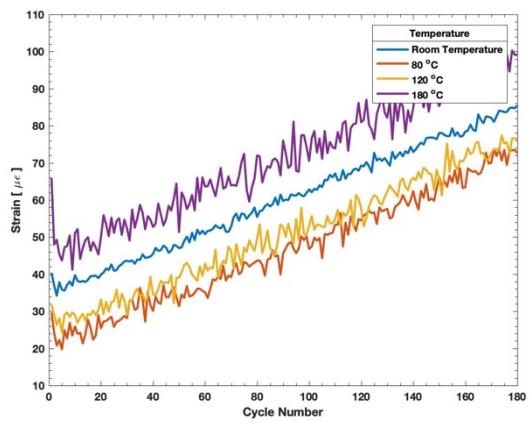
c)



d)



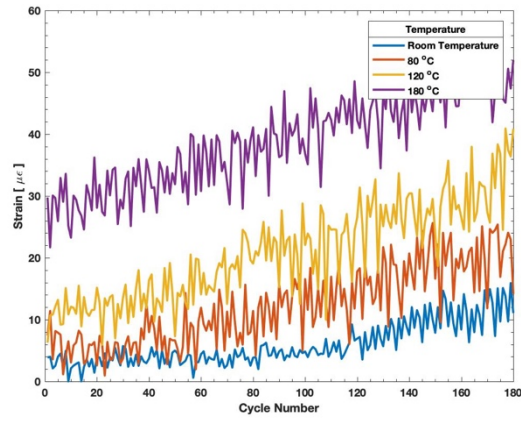
e)



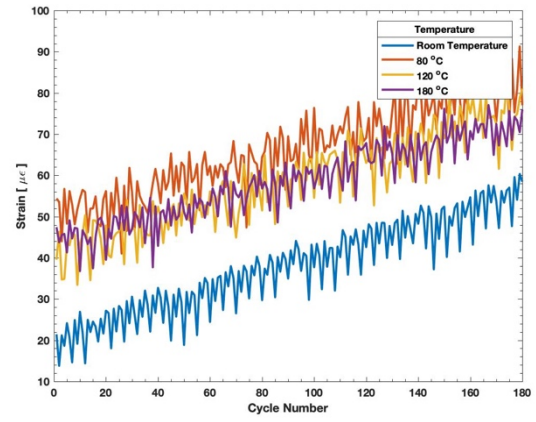
f)

Figure B-3: 12.5 MPa Continuous – Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

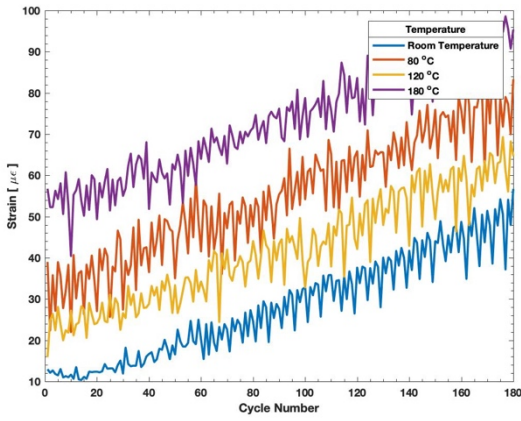
B.1.1.2 Recovered



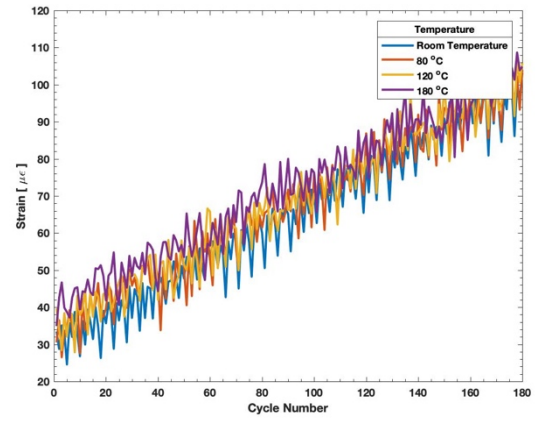
a)



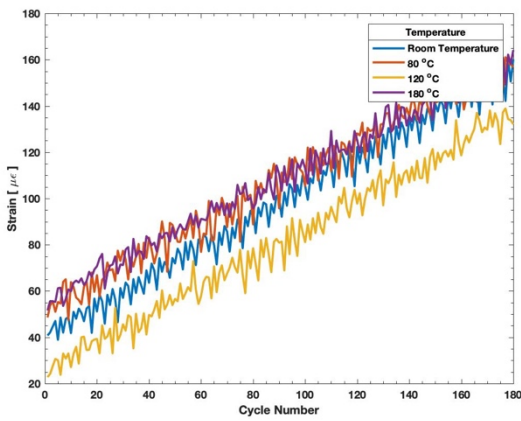
b)



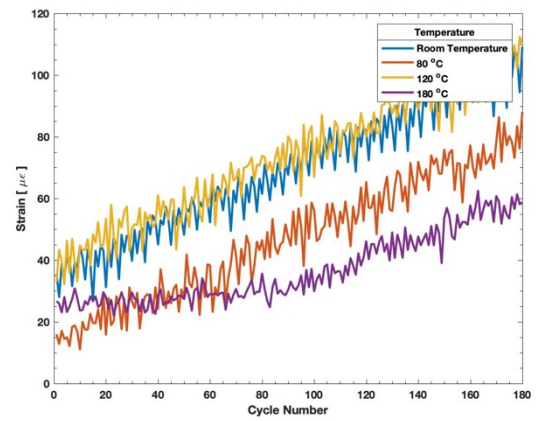
c)



d)

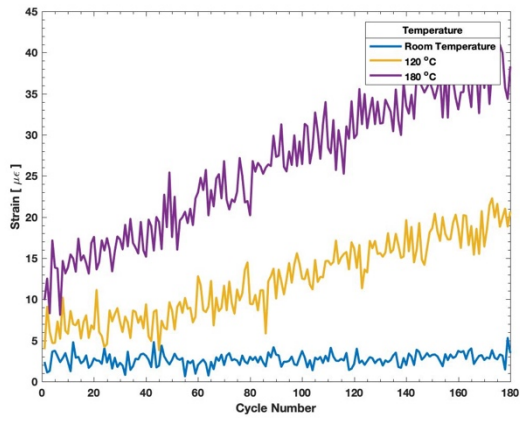


e)

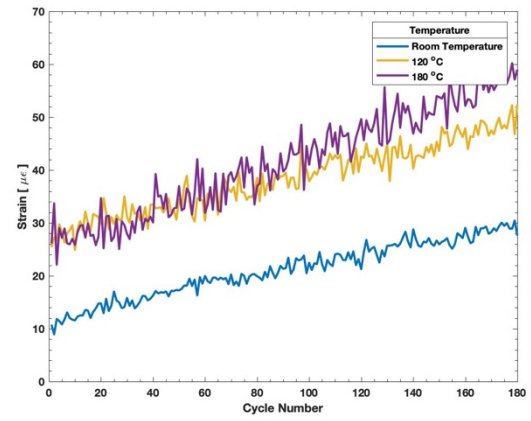


f)

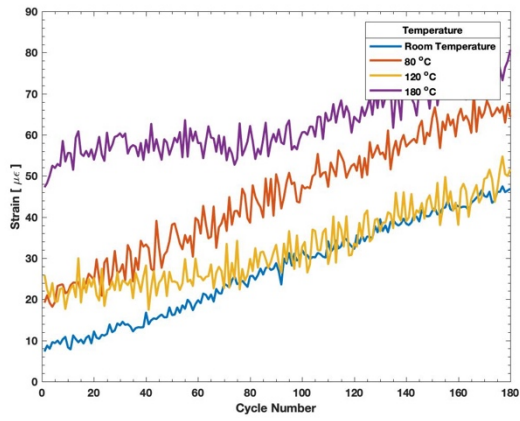
Figure B-4: 8 MPa - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



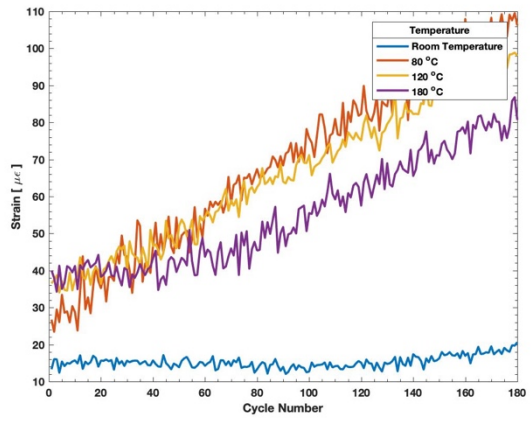
a)



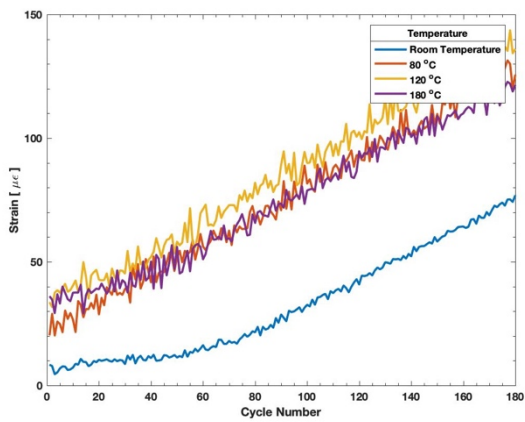
b)



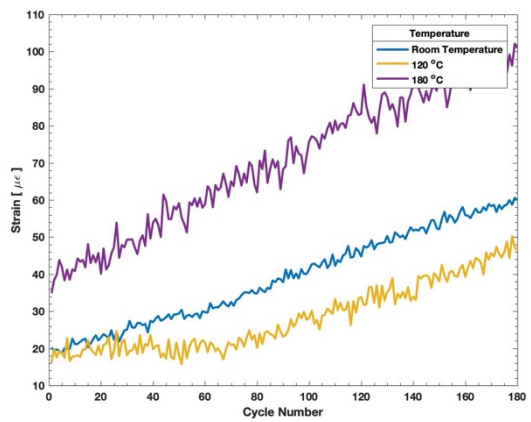
c)



d)

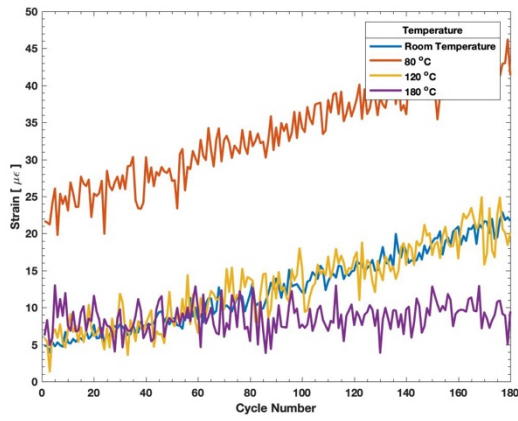


e)

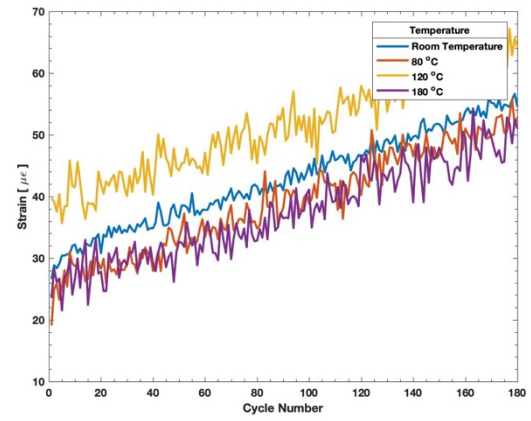


f)

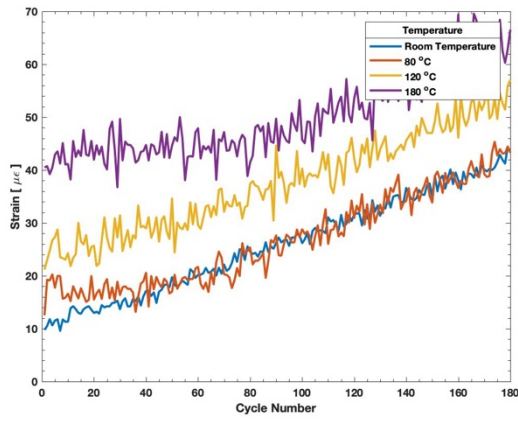
Figure B-5: 12.5 MPa - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



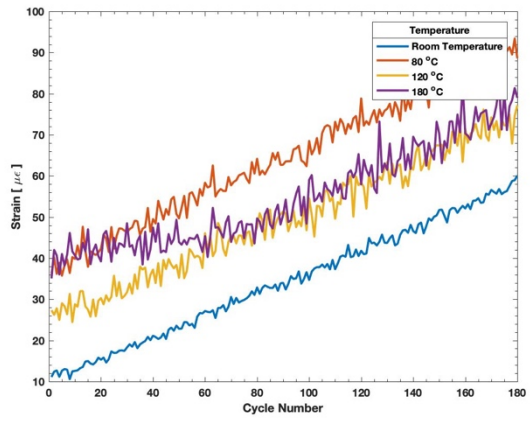
a)



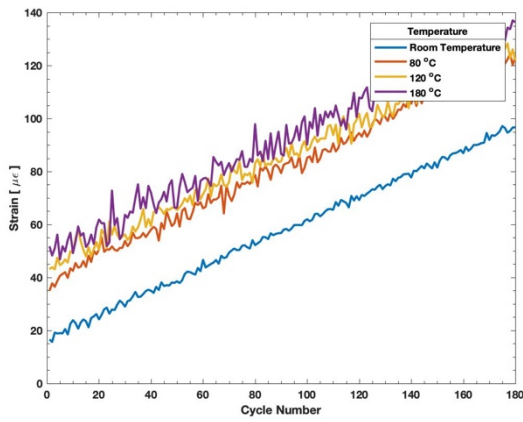
b)



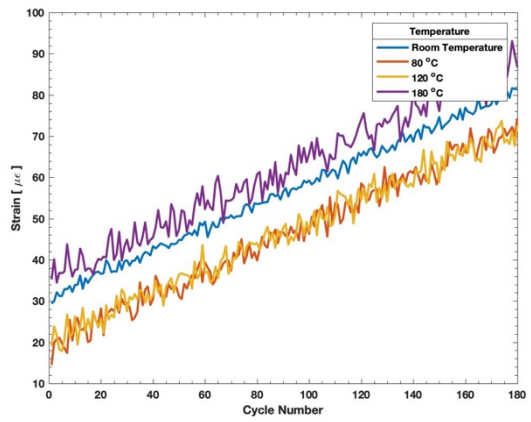
c)



d)



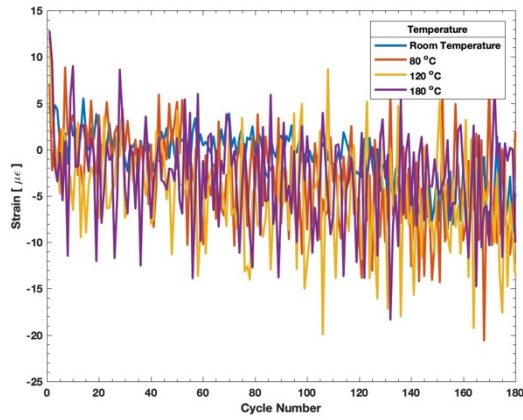
e)



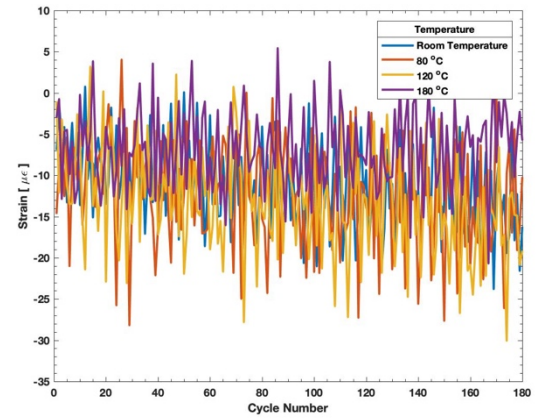
f)

Figure B-6: 12.5 MPa Continuous - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

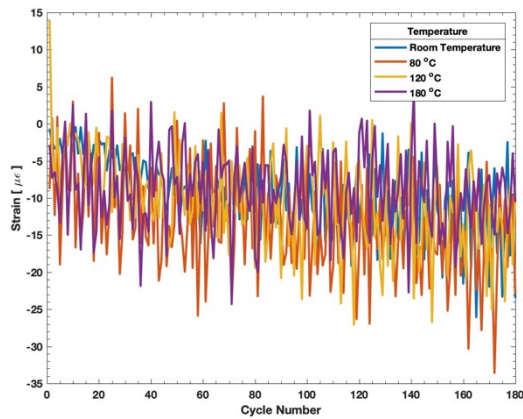
B.1.1.3 Unrecovered Creep Strain



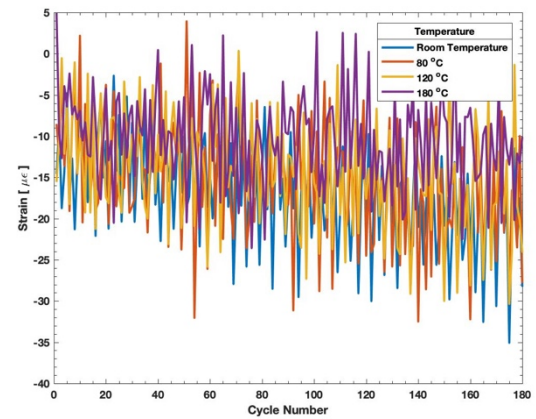
a)



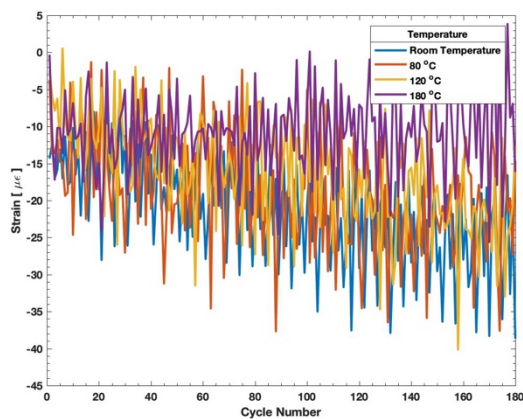
b)



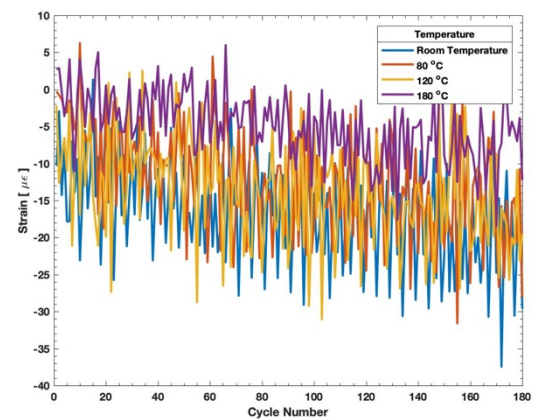
c)



d)

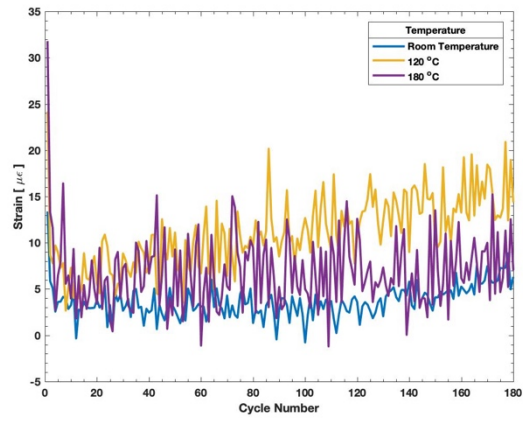


e)

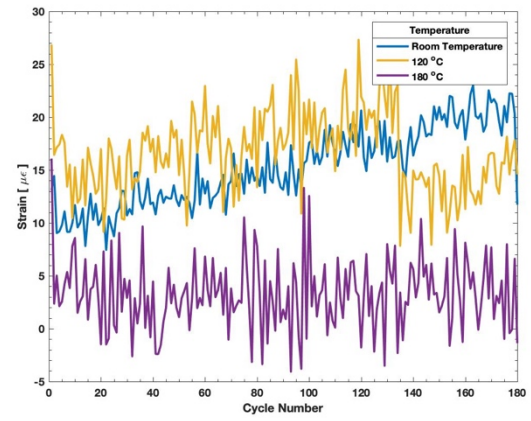


f)

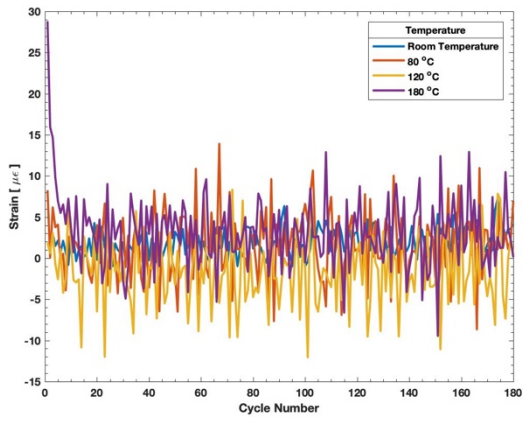
Figure B-7: 8 MPa - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



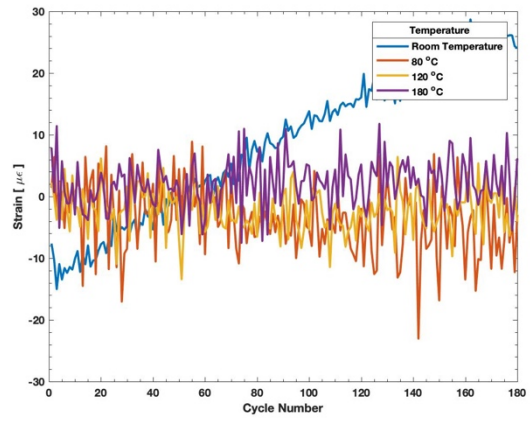
a)



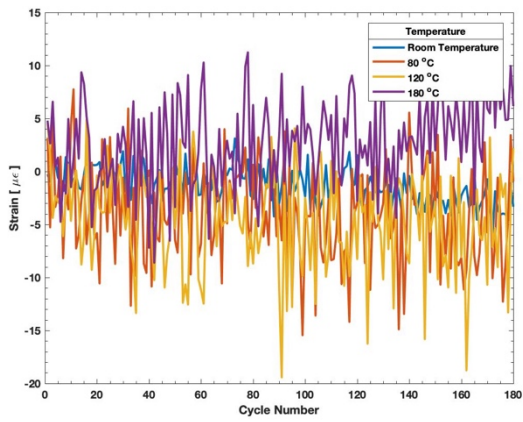
b)



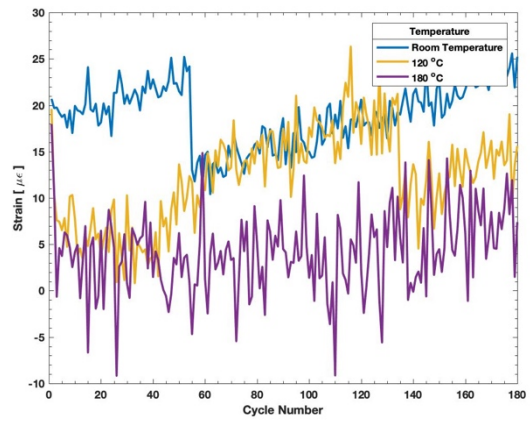
c)



d)

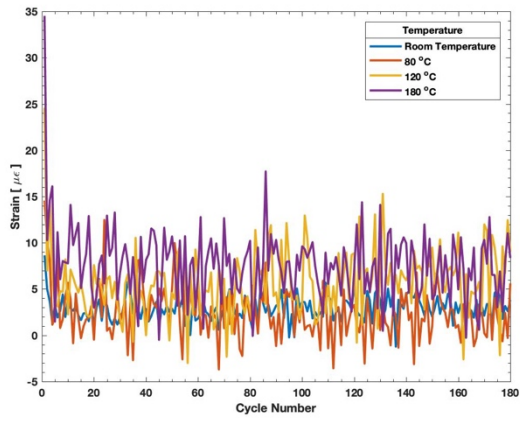


e)

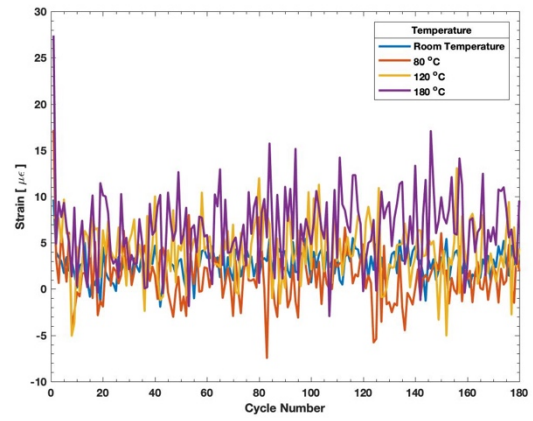


f)

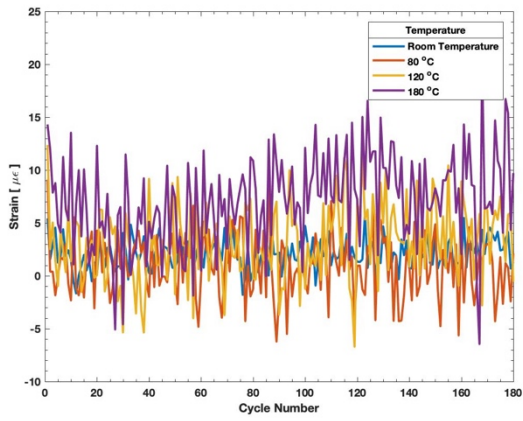
Figure B-8: 12.5 MPa - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



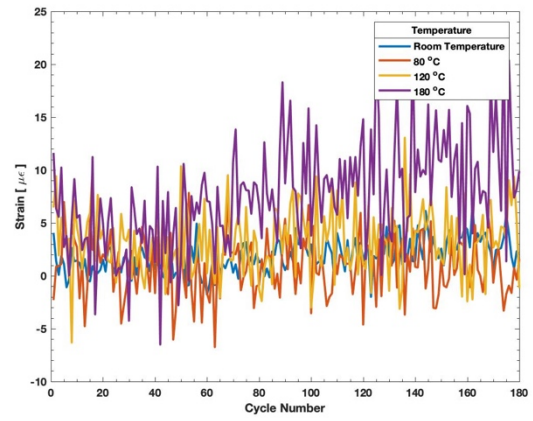
a)



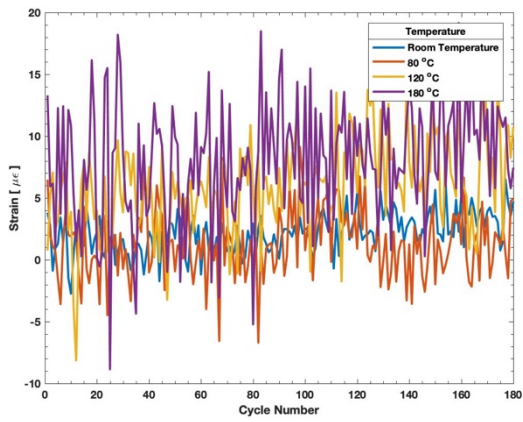
b)



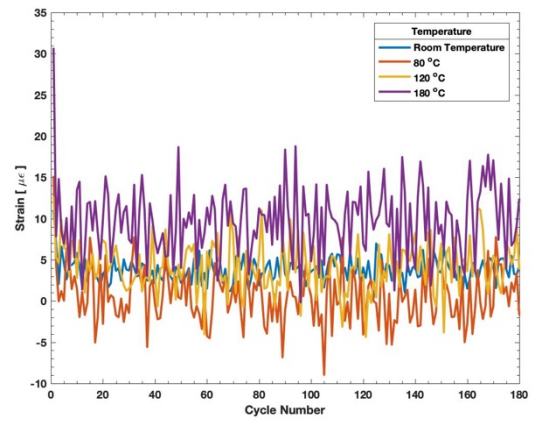
c)



d)



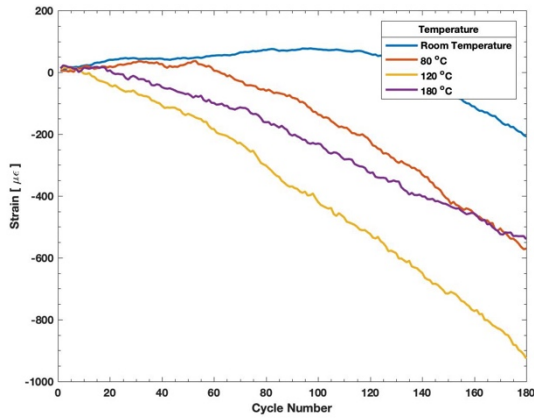
e)



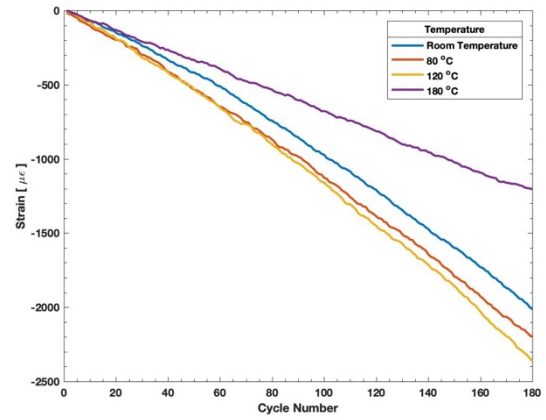
f)

Figure B-9: 12.5 MPa Continuous - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

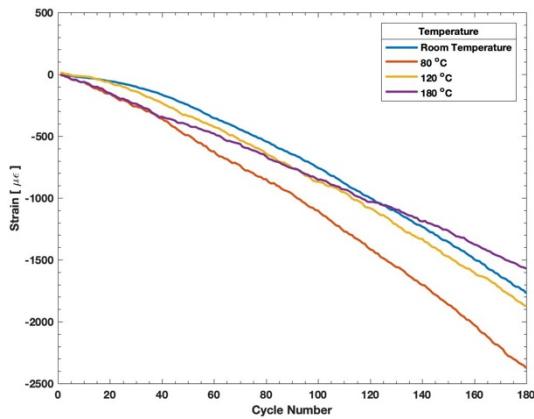
B.1.1.4 Accumulated Unrecovered Creep Strain



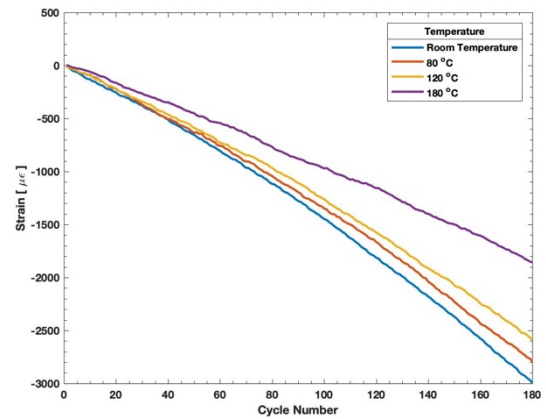
a)



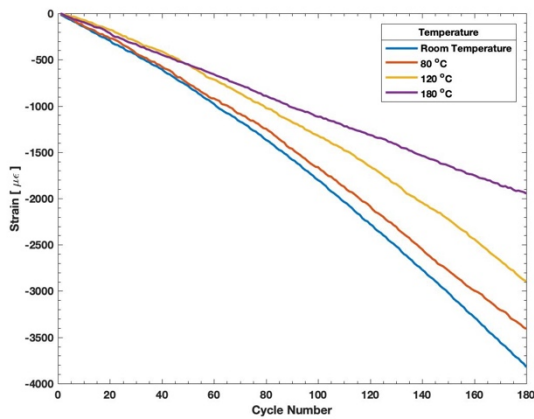
b)



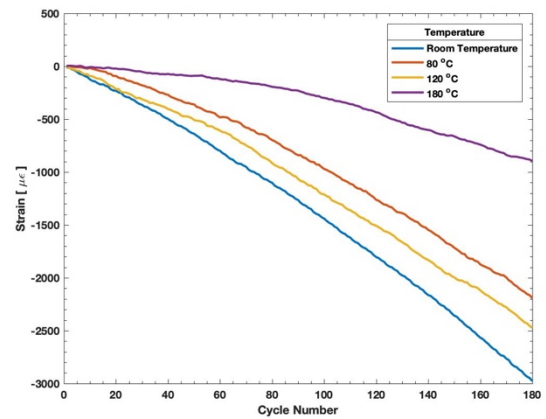
c)



d)

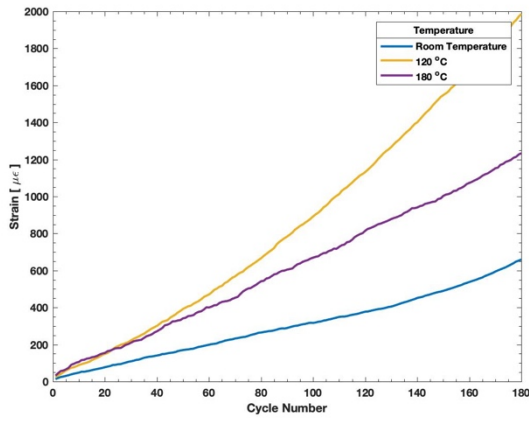


e)

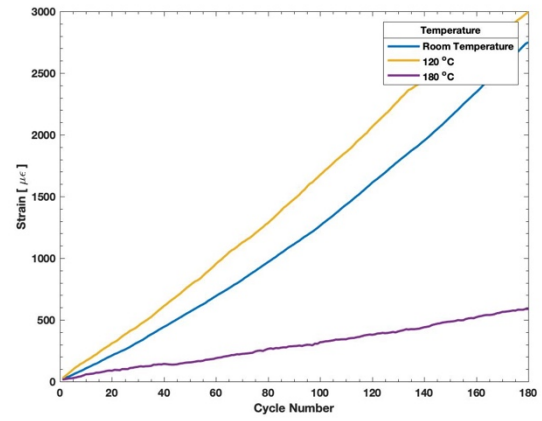


f)

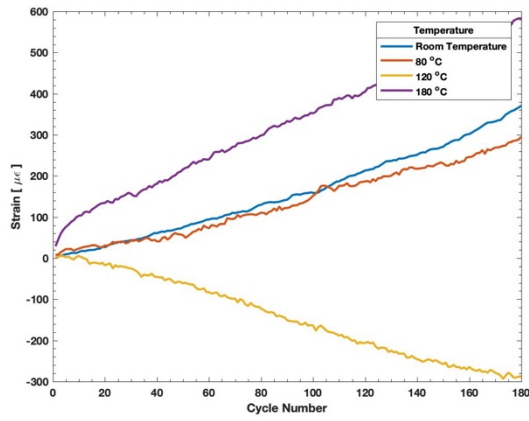
Figure B-10: 8 MPa - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



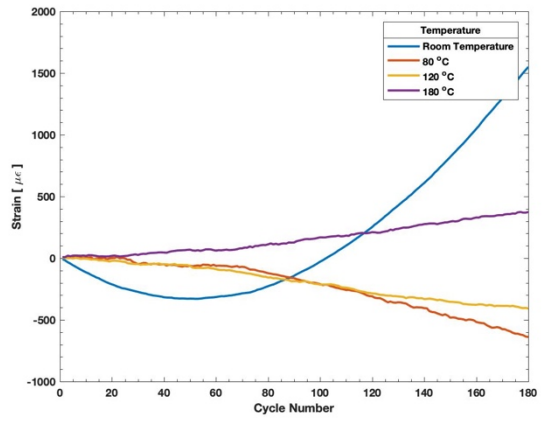
a)



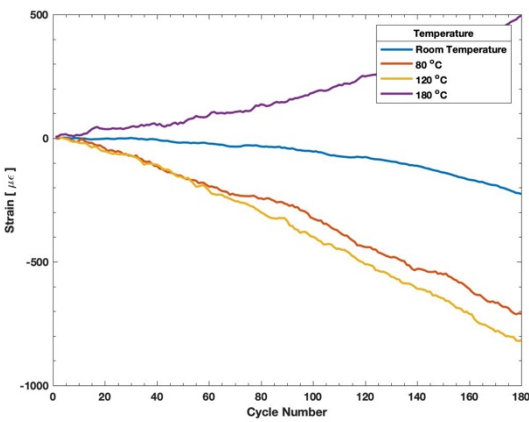
b)



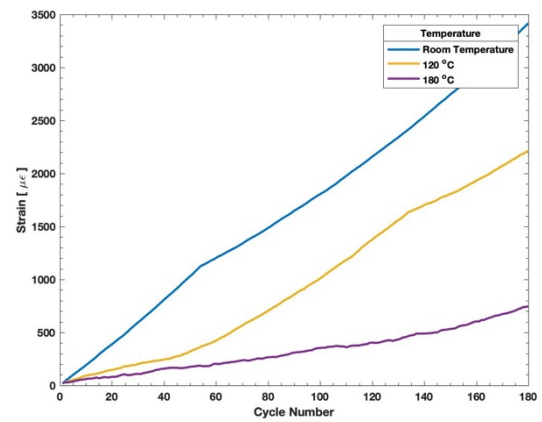
c)



d)

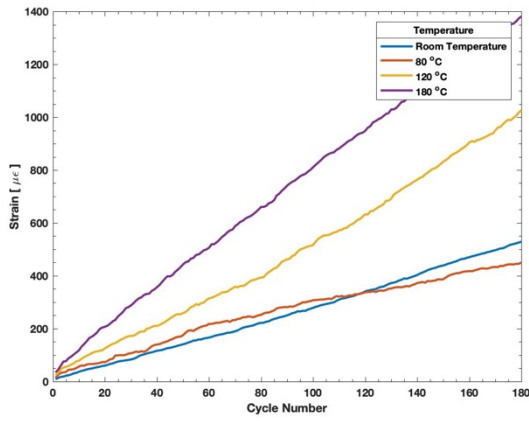


e)

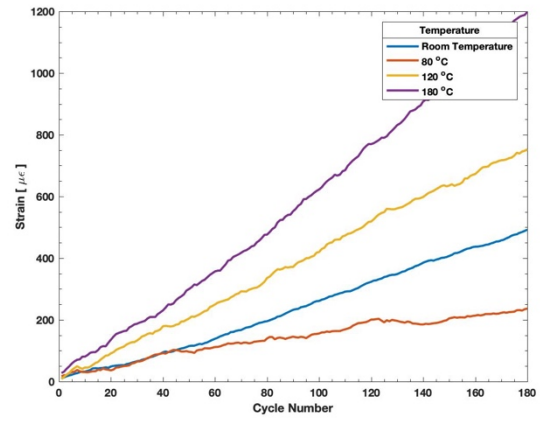


f)

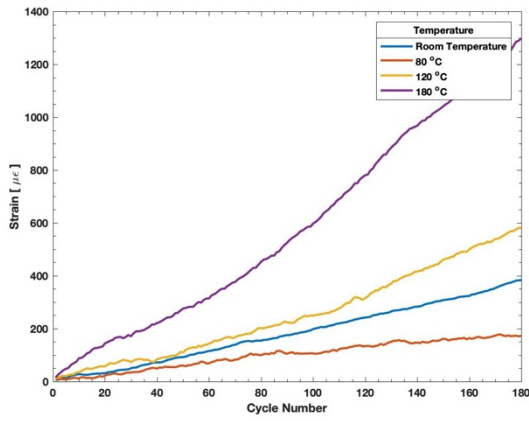
Figure B-11: 12.5 MPa - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



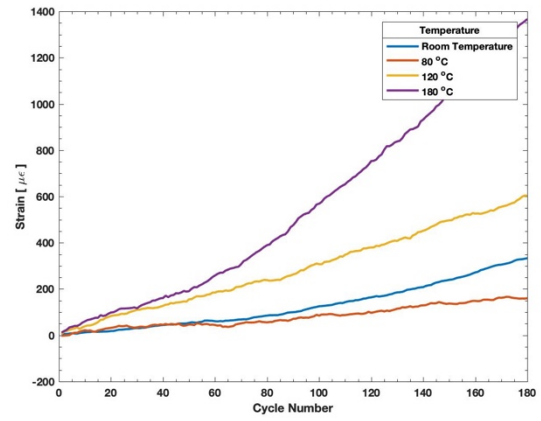
a)



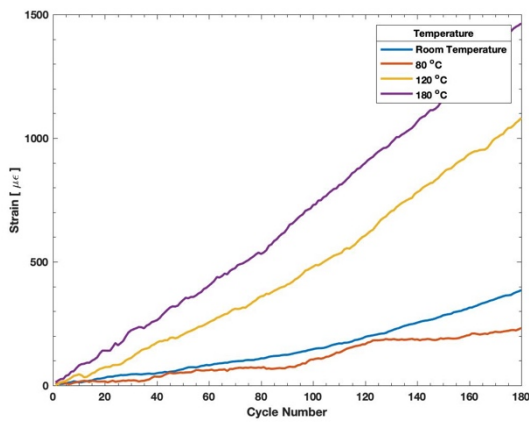
b)



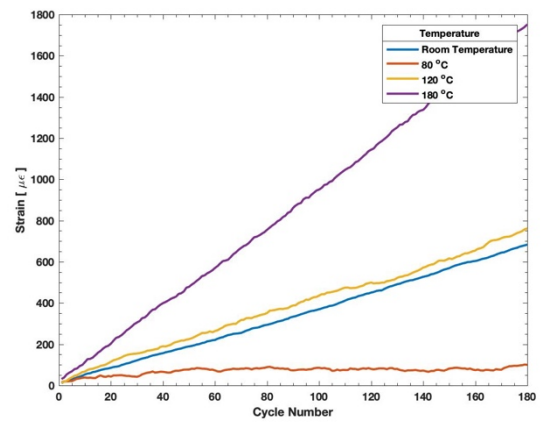
c)



d)



e)



f)

Figure B-12: 12.5 MPa Continuous - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.1.2 Unrecovered

B.1.2.1 Total Unrecovered Strain

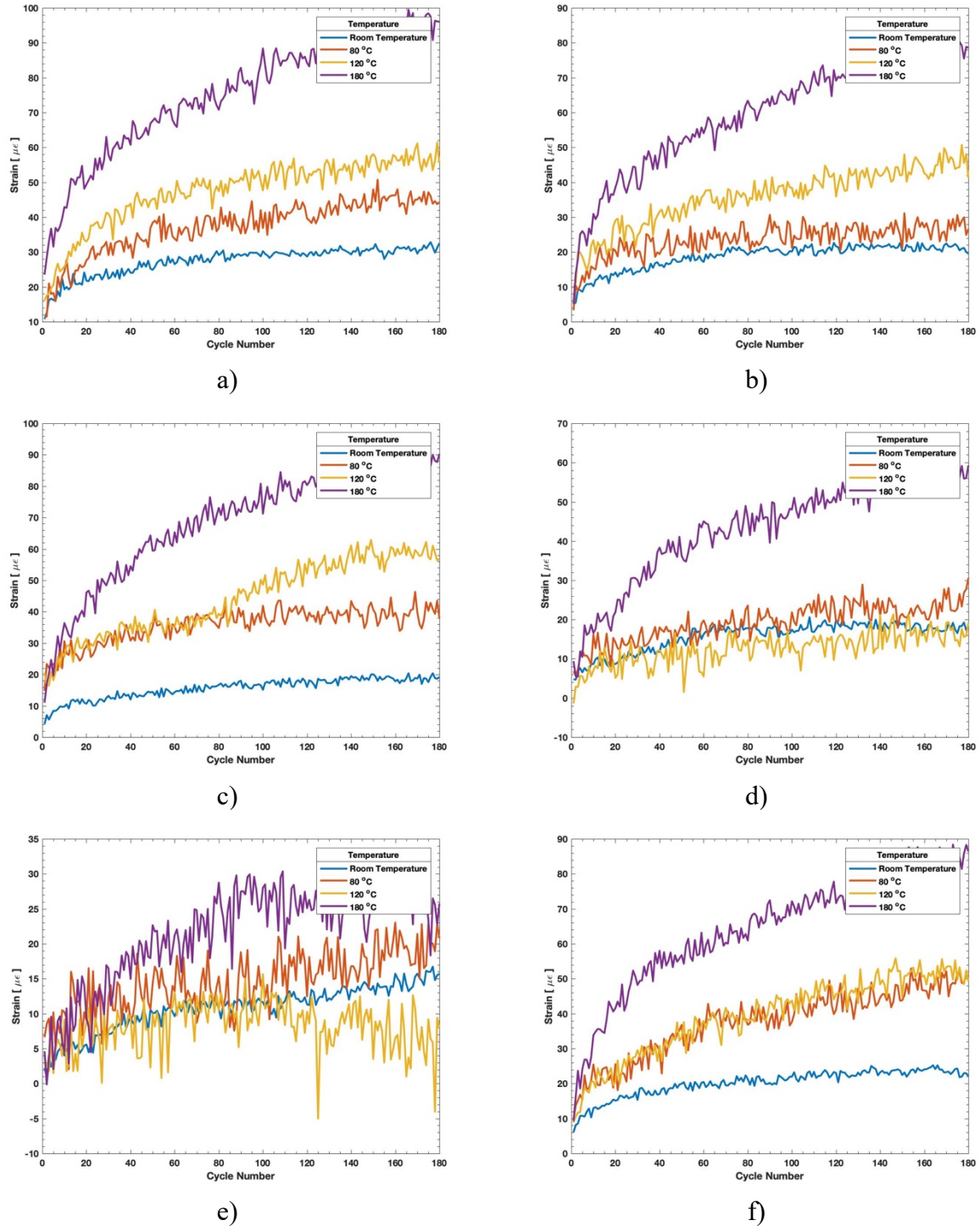
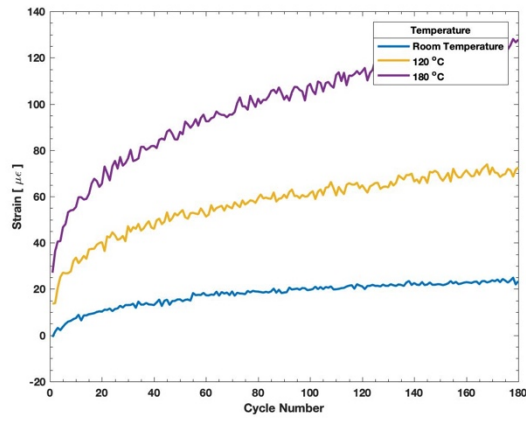
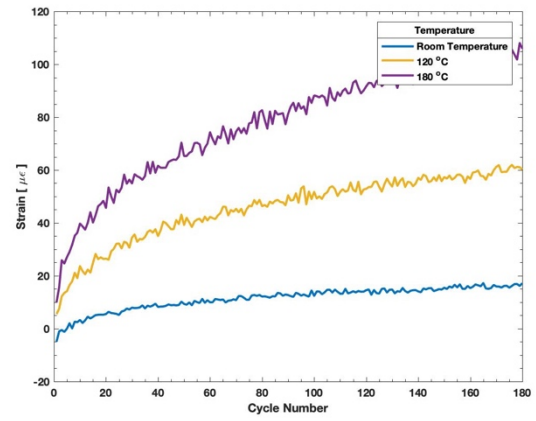


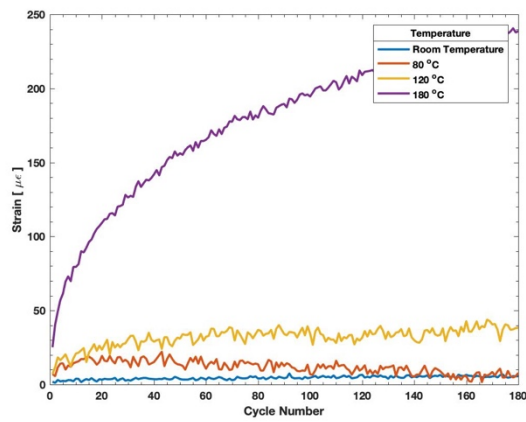
Figure B-13: 8 MPa - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



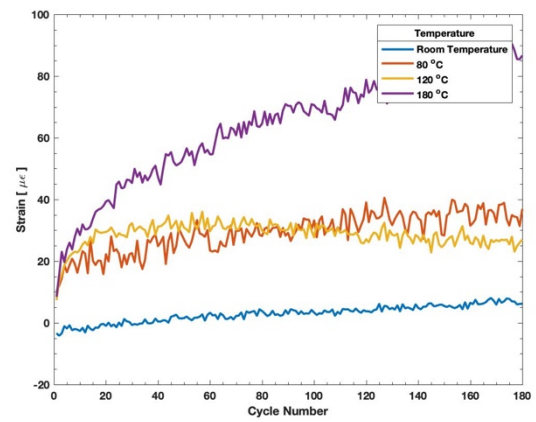
a)



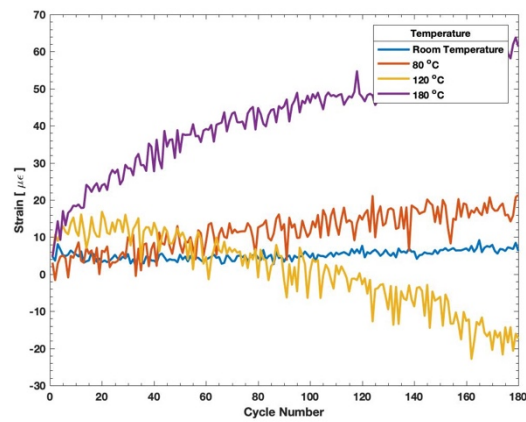
b)



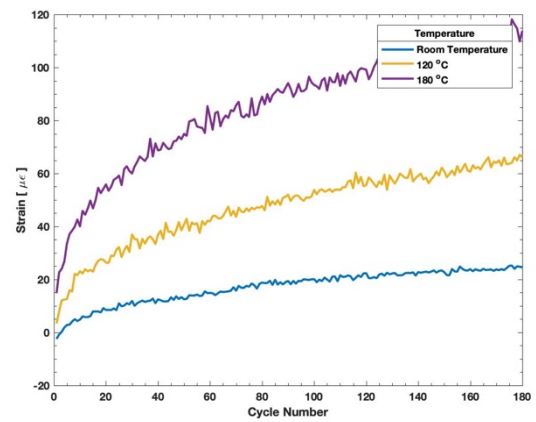
c)



d)

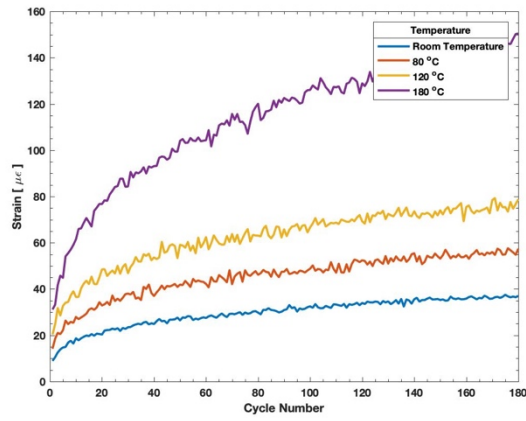


e)

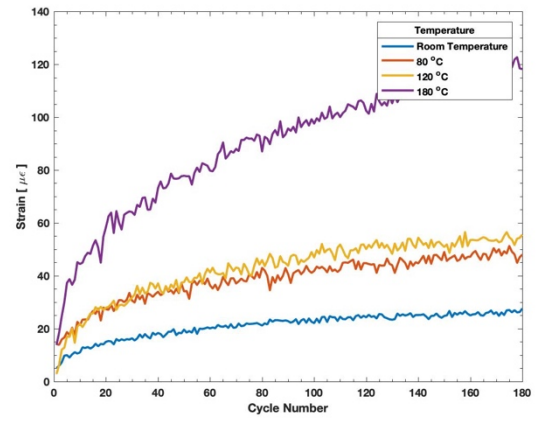


f)

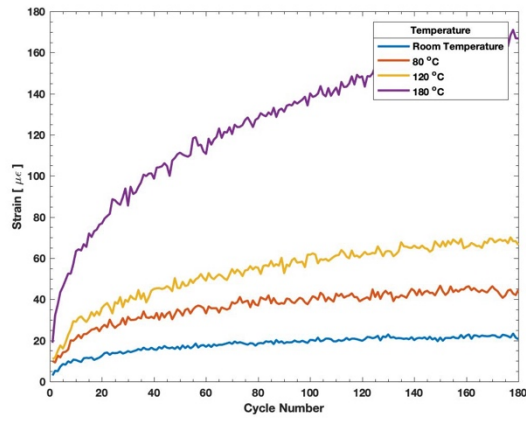
Figure B-14: 12.5 MPa - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



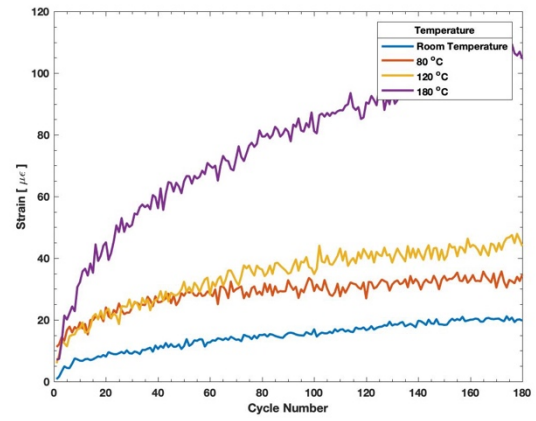
a)



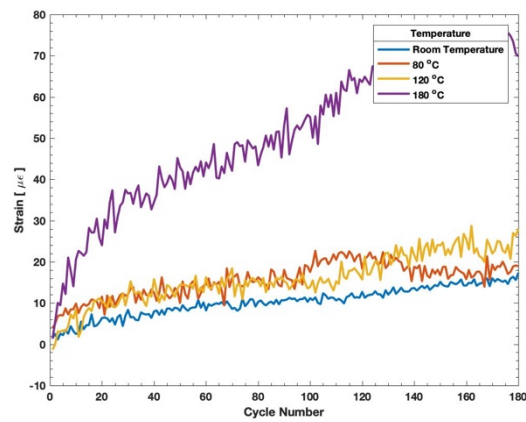
b)



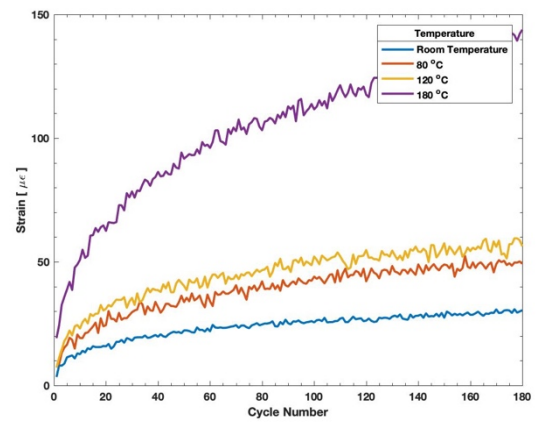
c)



d)



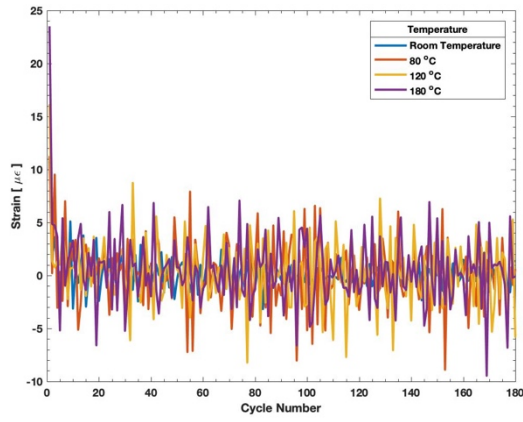
e)



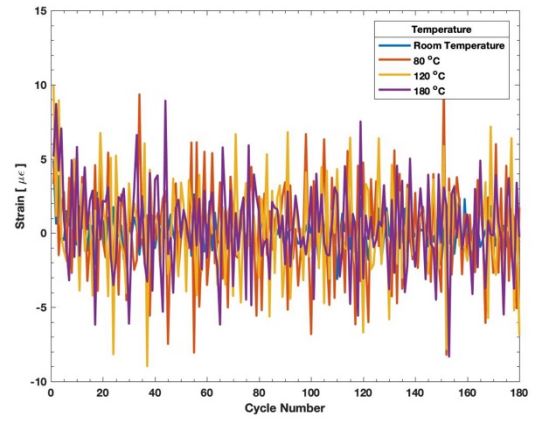
f)

Figure B-15: 12.5 MPa Continuous - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

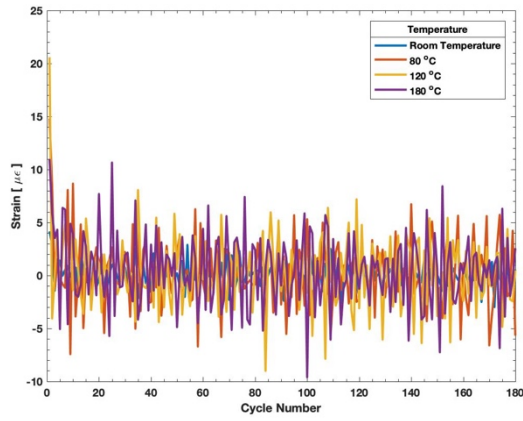
B.1.2.2 Cycle Unrecovered Strain



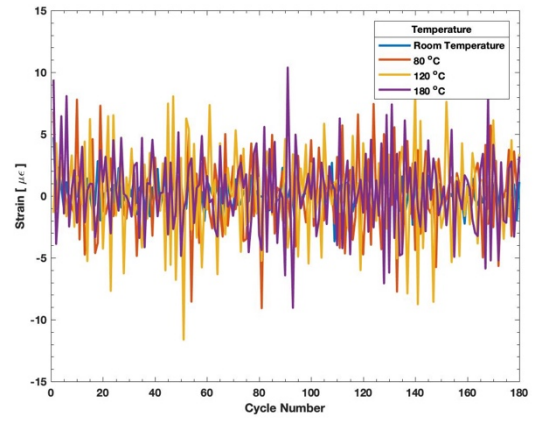
a)



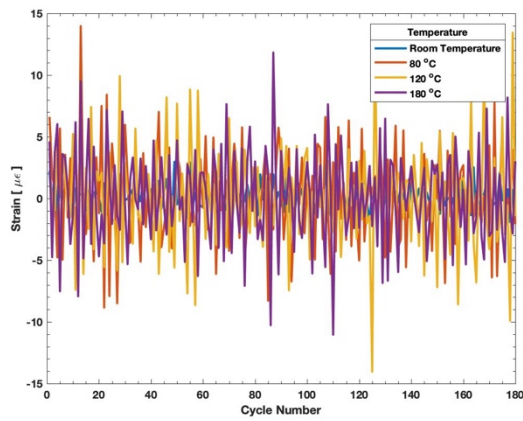
b)



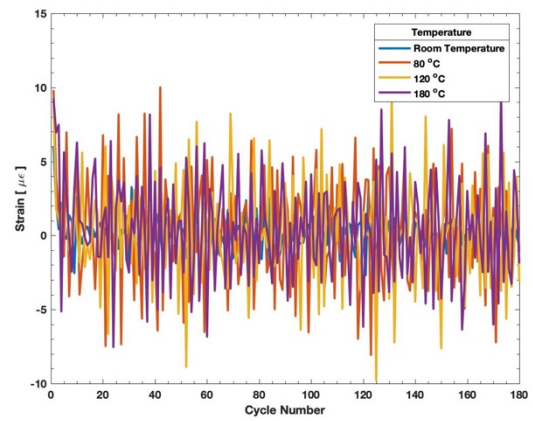
c)



d)

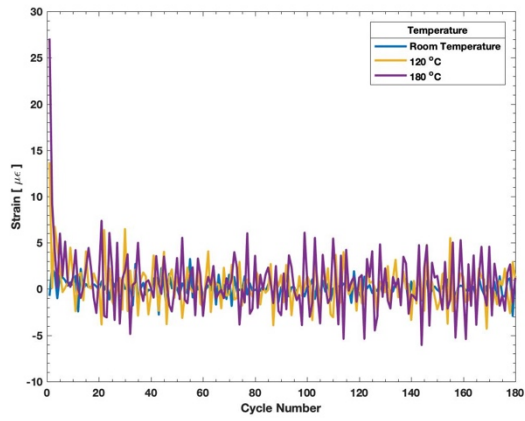


e)

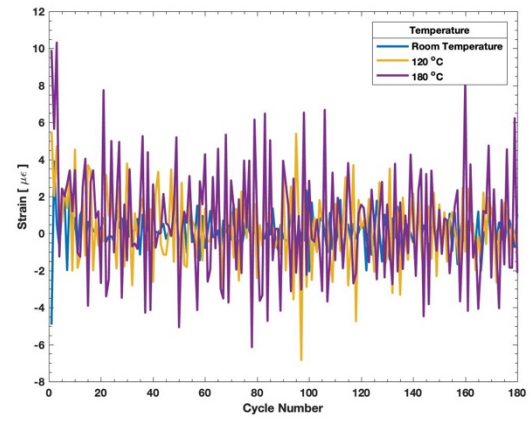


f)

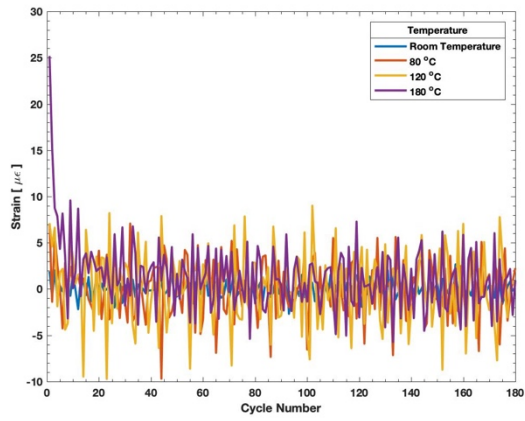
Figure B-16: 8 MPa - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



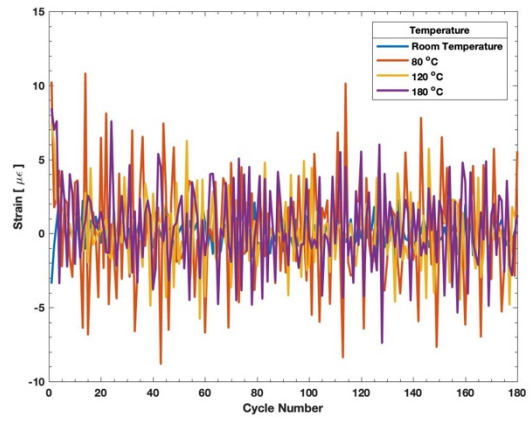
a)



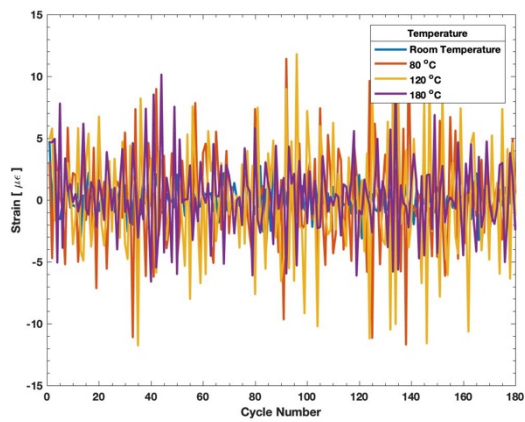
b)



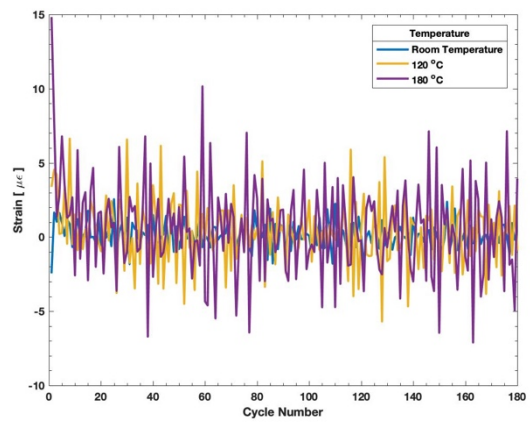
c)



d)

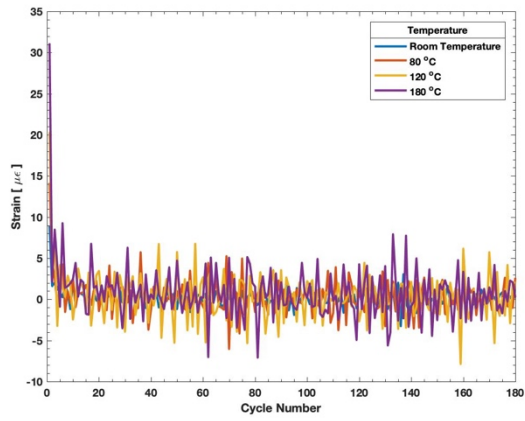


e)

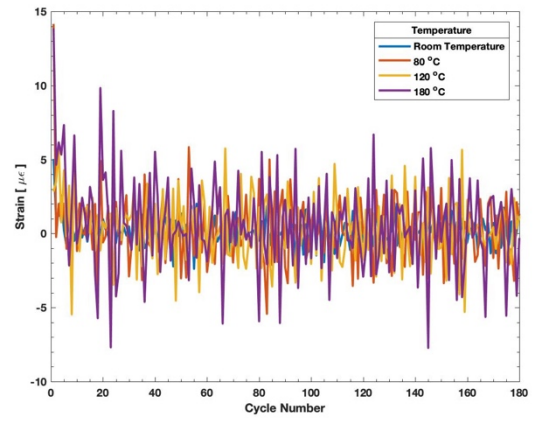


f)

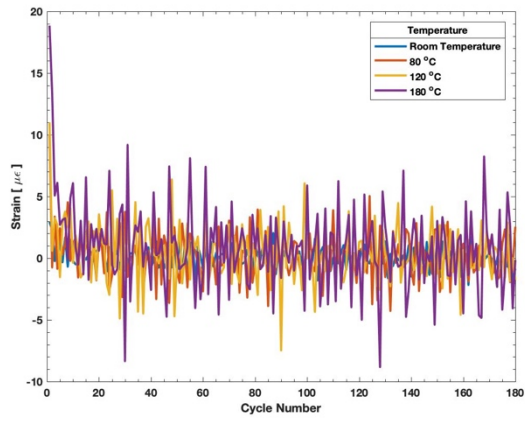
Figure B-17: 12.5 MPa - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



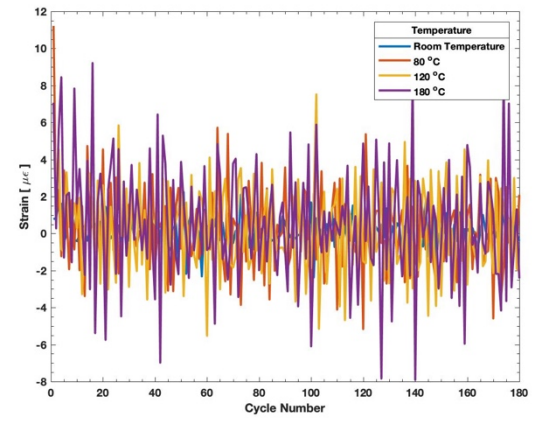
a)



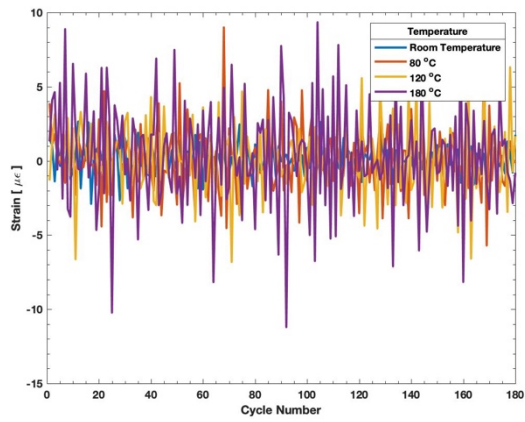
b)



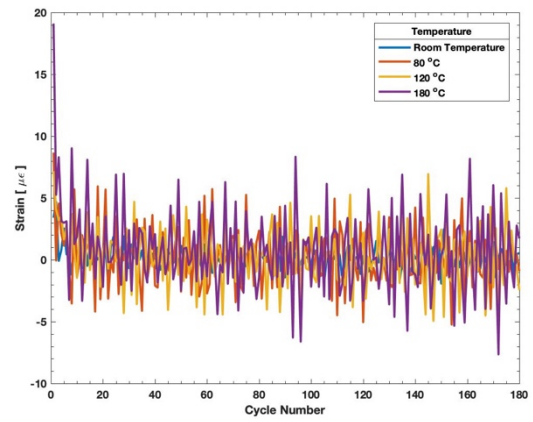
c)



d)



e)



f)

Figure B-18: 12.5 MPa Continuous - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.1.2.3 Unrecovered Instantaneous Strain

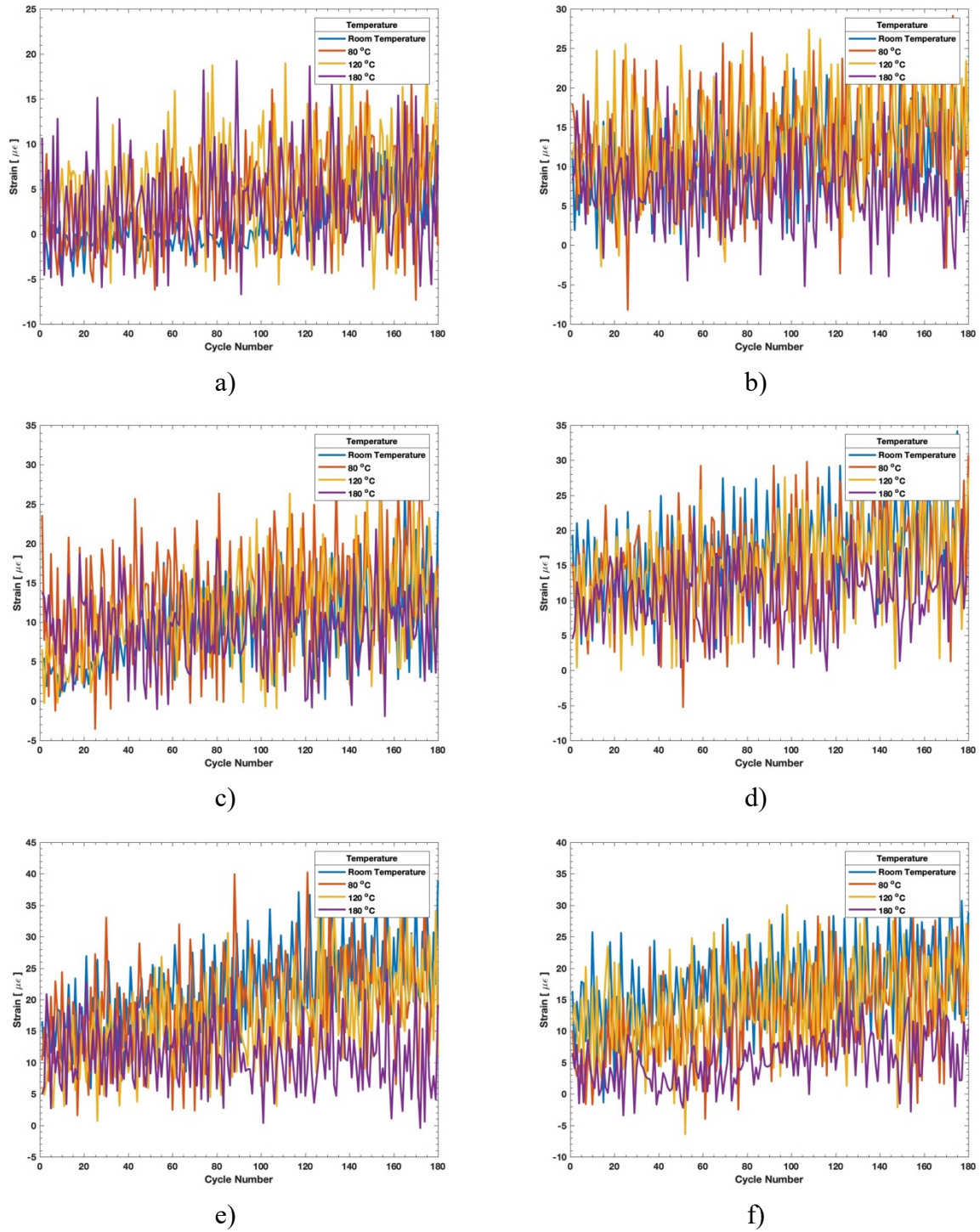
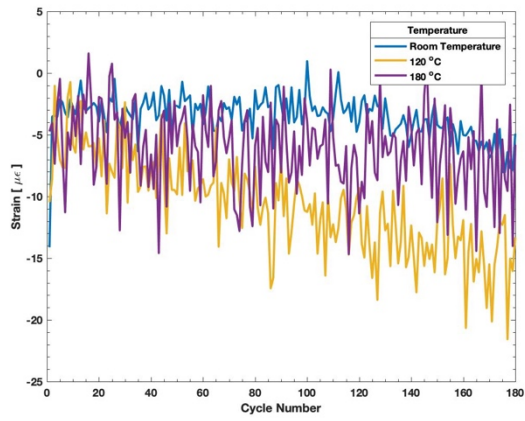
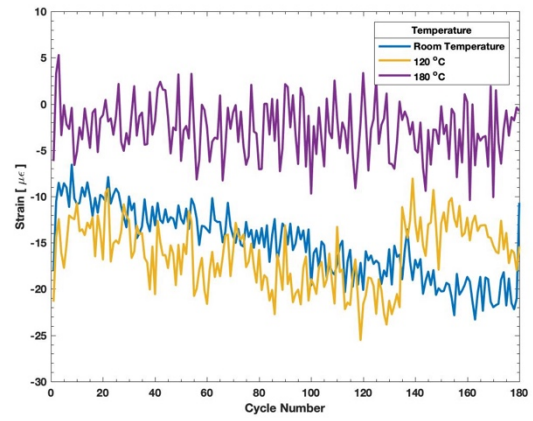


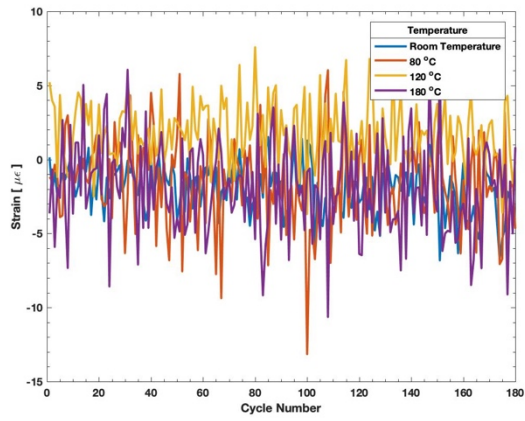
Figure B-19: 8 MPa – Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



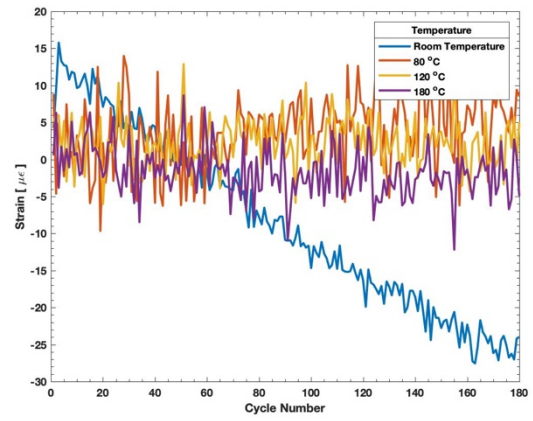
a)



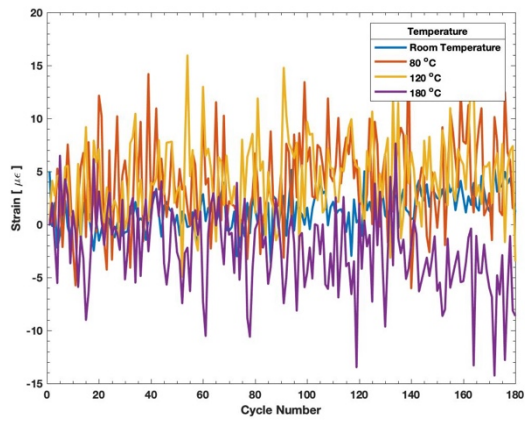
b)



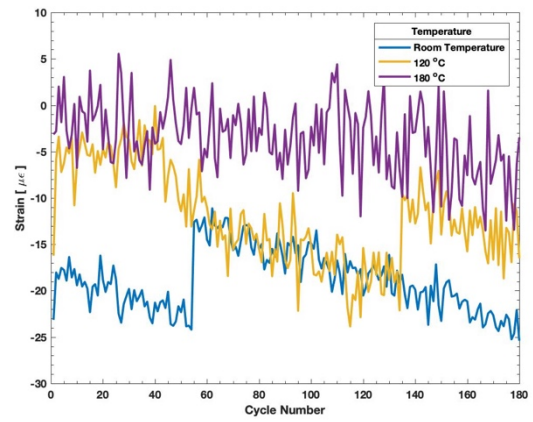
c)



d)

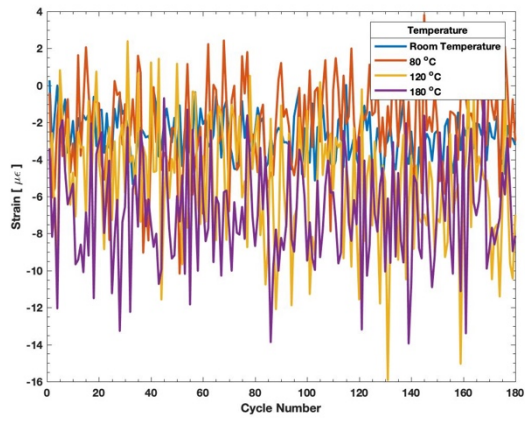


e)

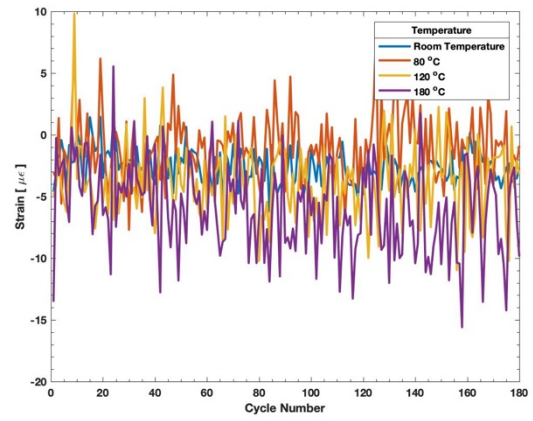


f)

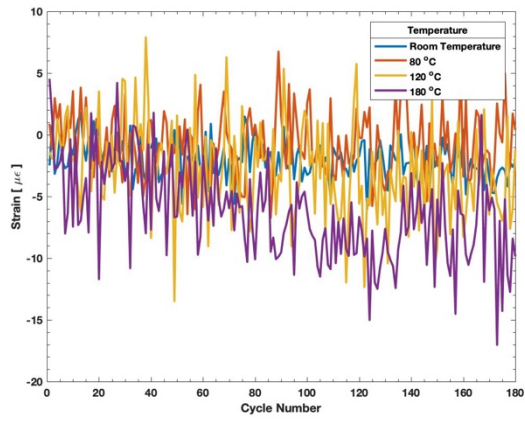
Figure B-20: 12.5 MPa – Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



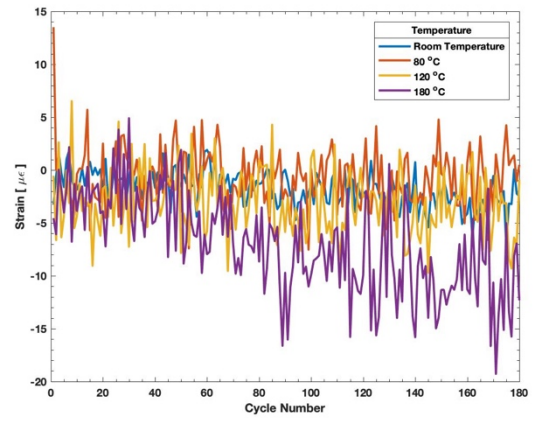
a)



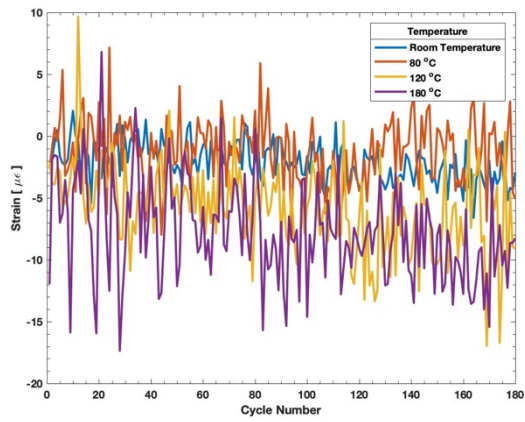
b)



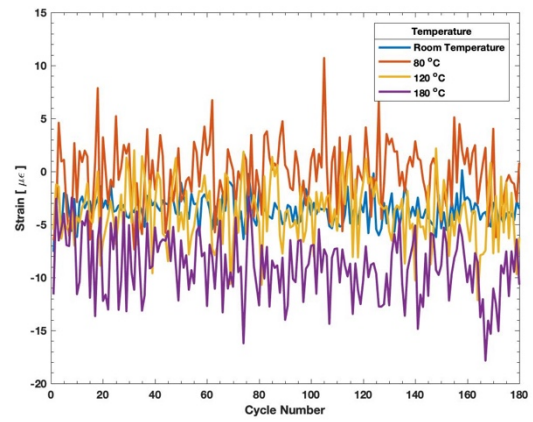
c)



d)



e)



f)

Figure B-21: 12.5 MPa Continuous – Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.2 Modulus

B.2.1 Loading

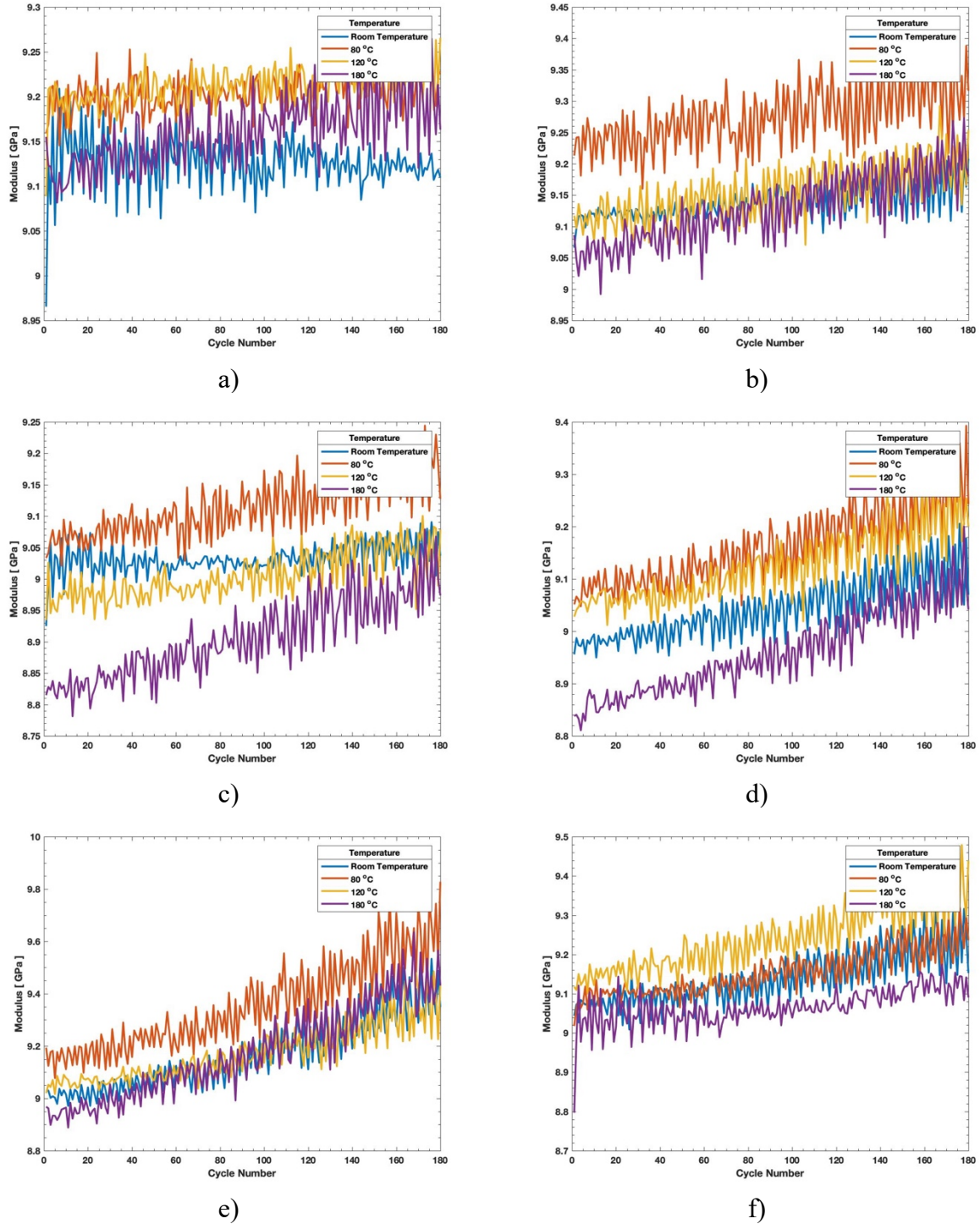
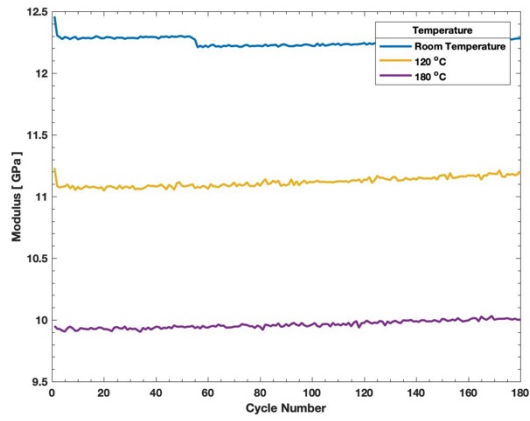
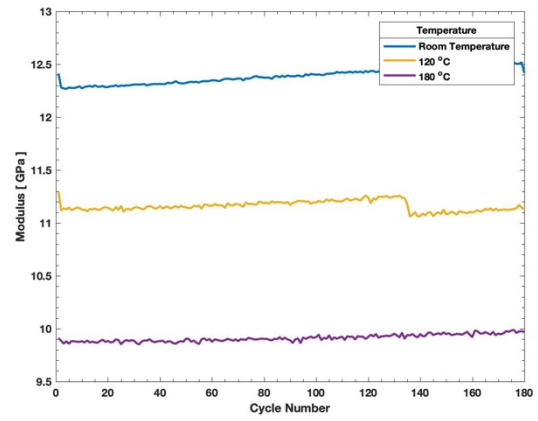


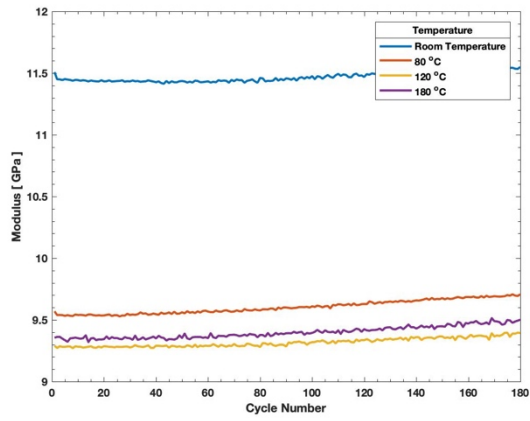
Figure B-22: 8 MPa - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



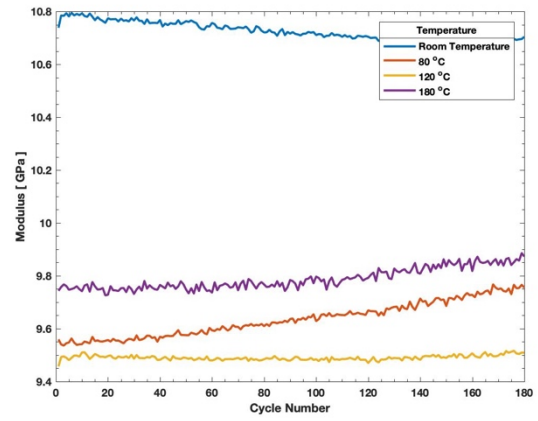
a)



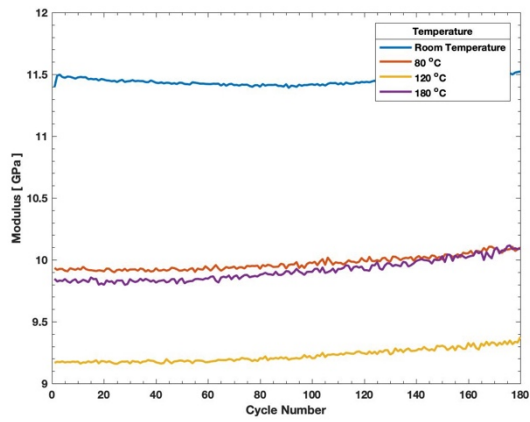
b)



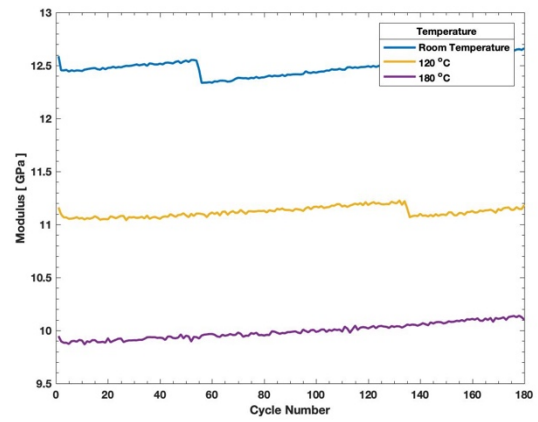
c)



d)

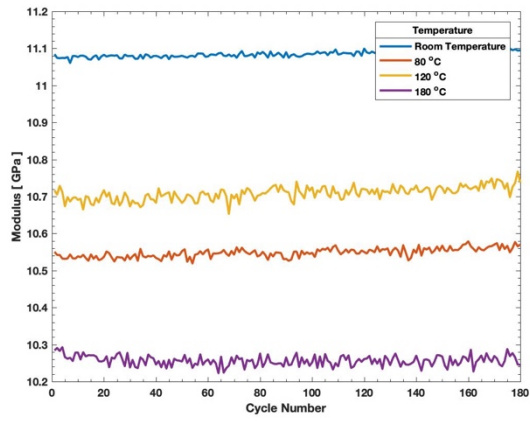


e)

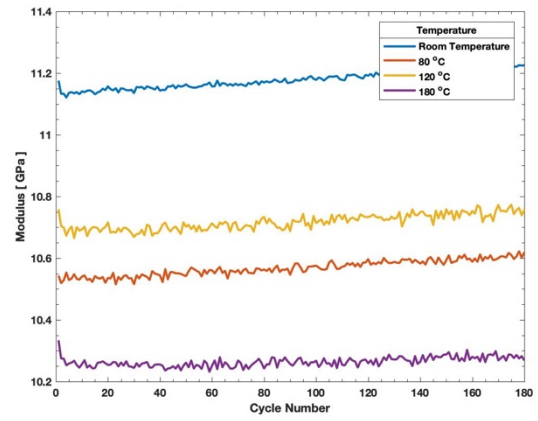


f)

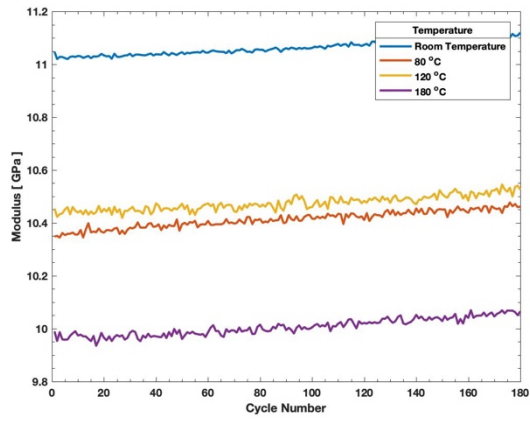
Figure B-23: 12.5 MPa - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



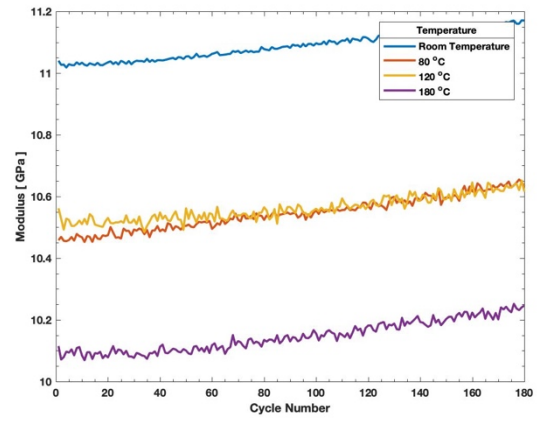
a)



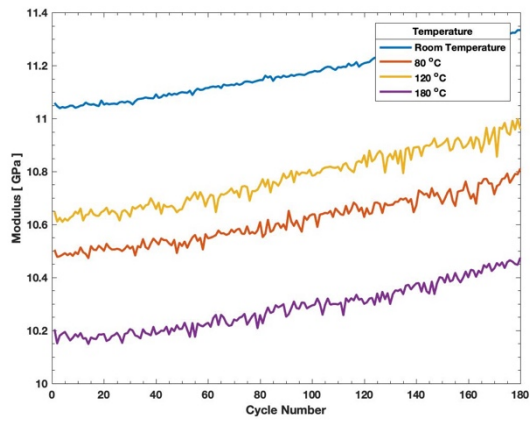
b)



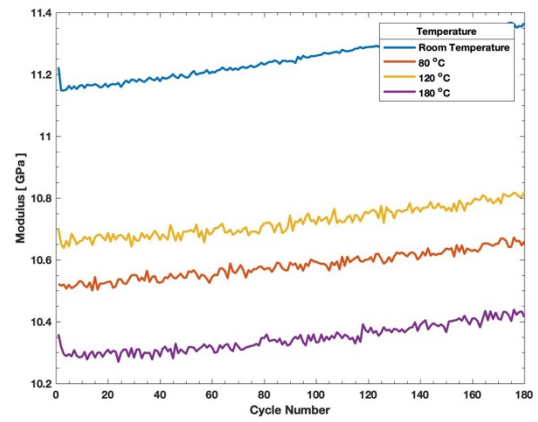
c)



d)



e)



f)

Figure B-24: 12.5 MPa Continuous - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.2.2 Unloading

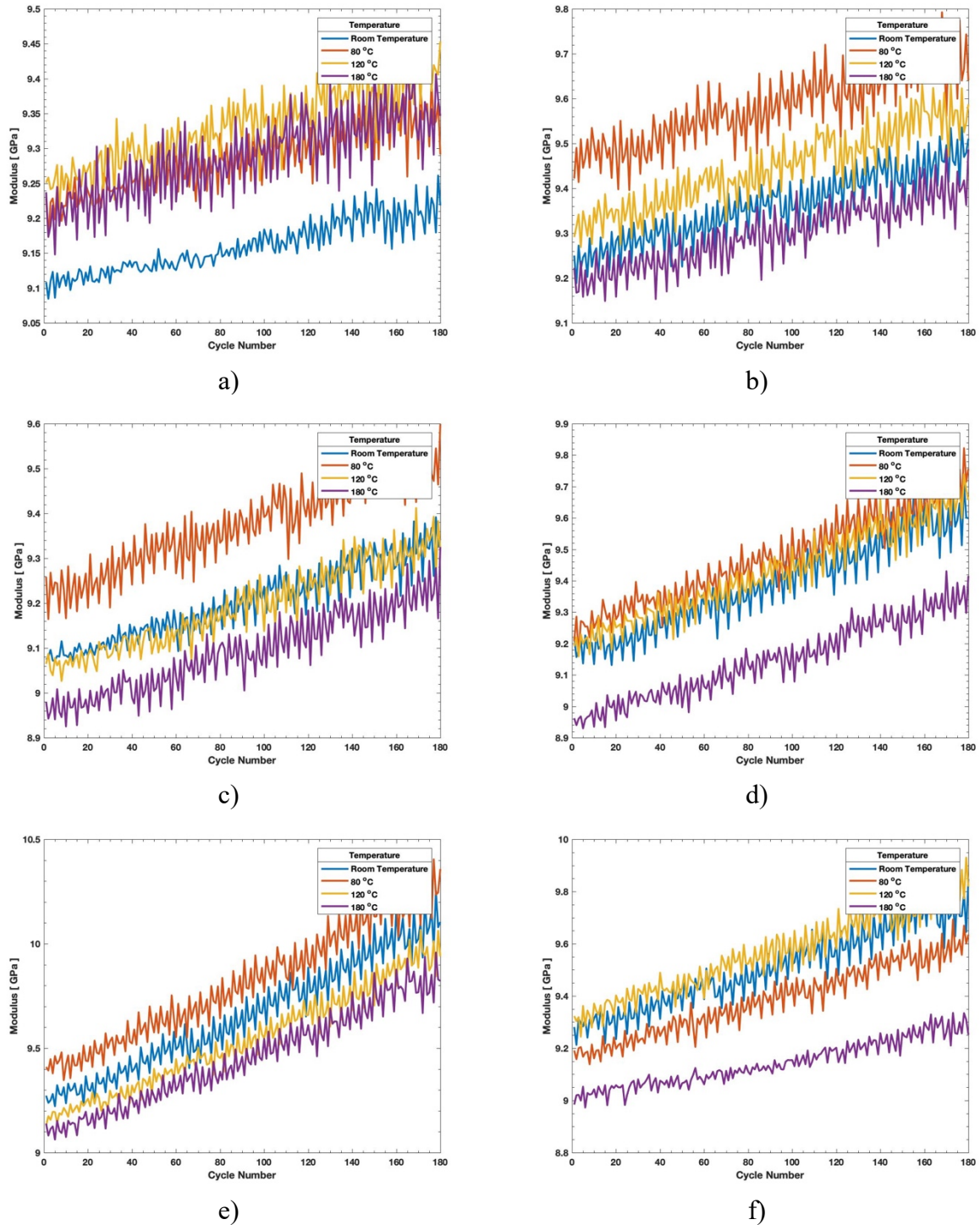
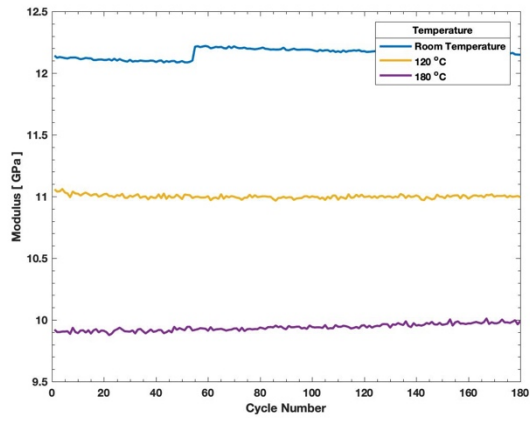
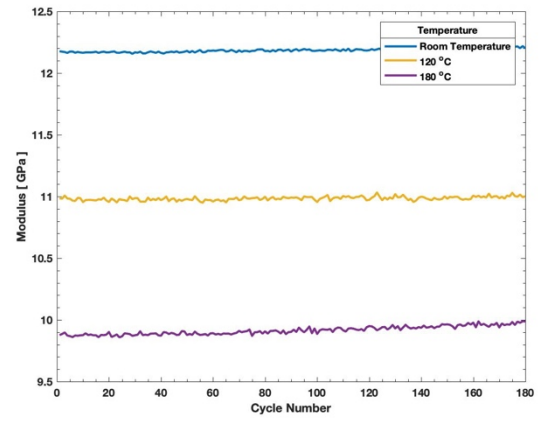


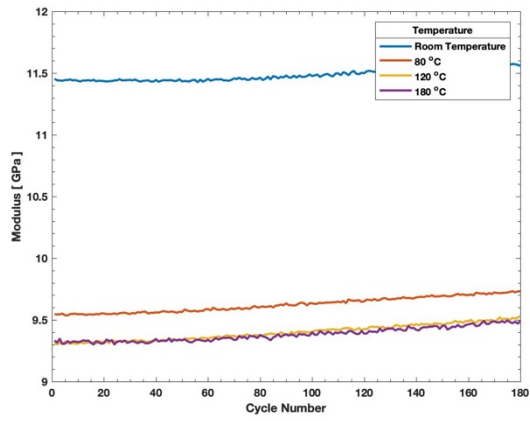
Figure B-25: 8 MPa - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



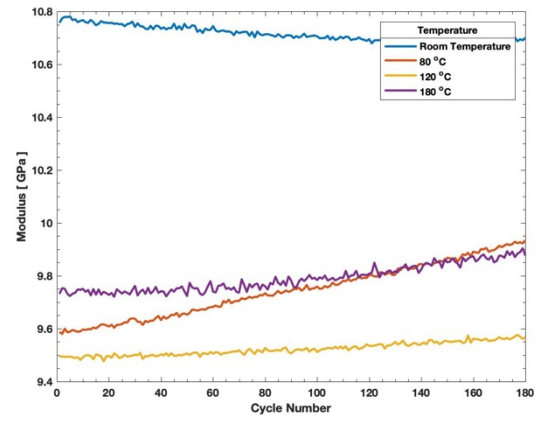
a)



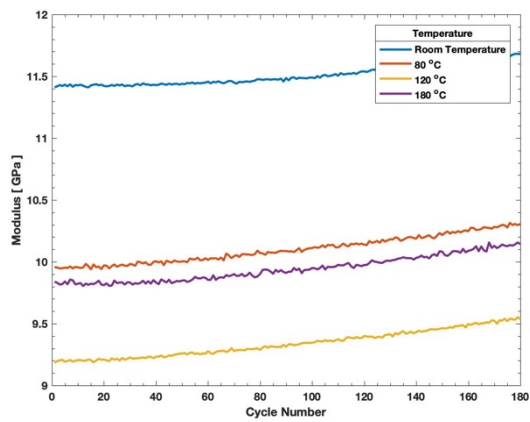
b)



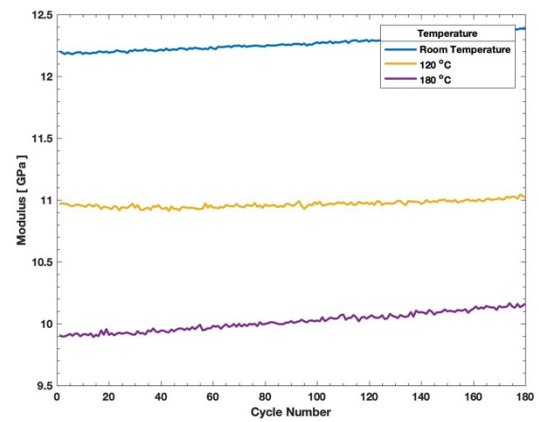
c)



d)

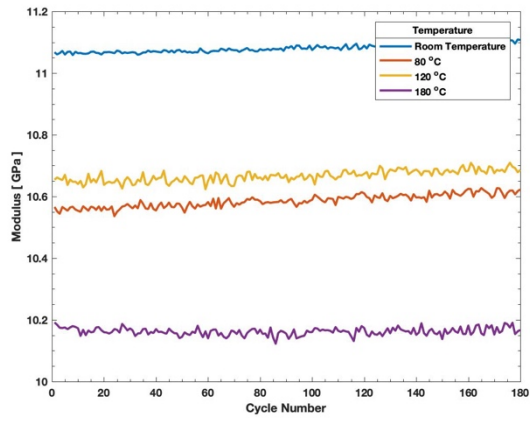


e)

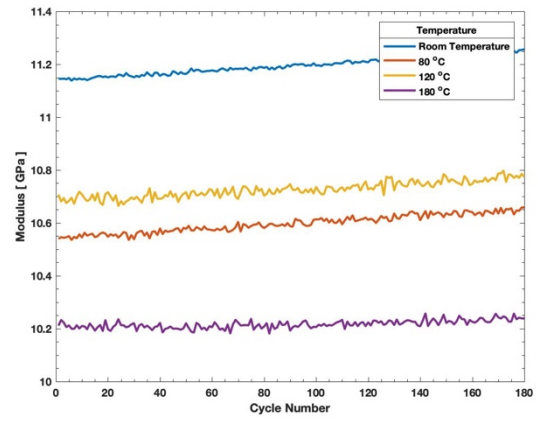


f)

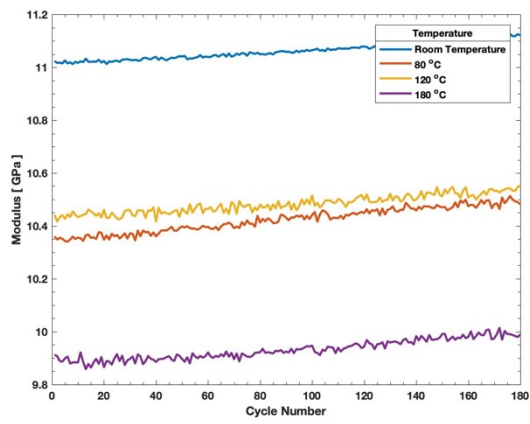
Figure B-26: 12.5 MPa - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



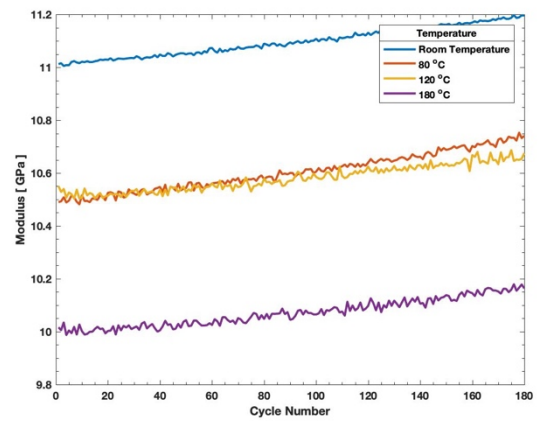
a)



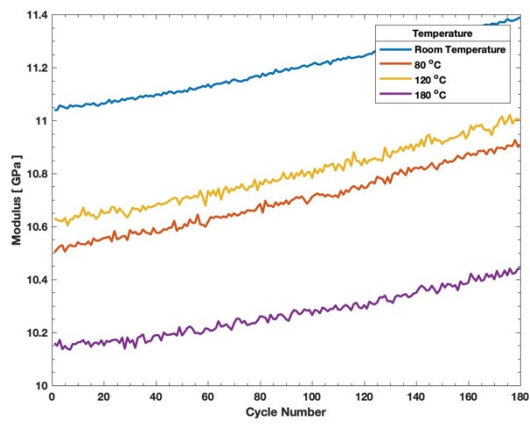
b)



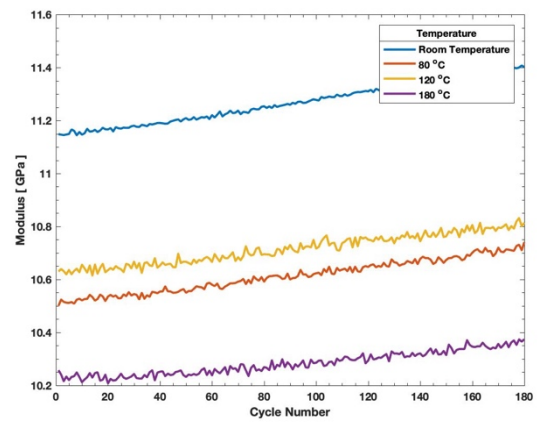
c)



d)



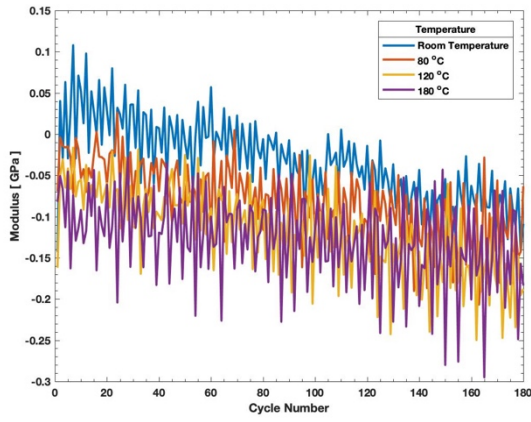
e)



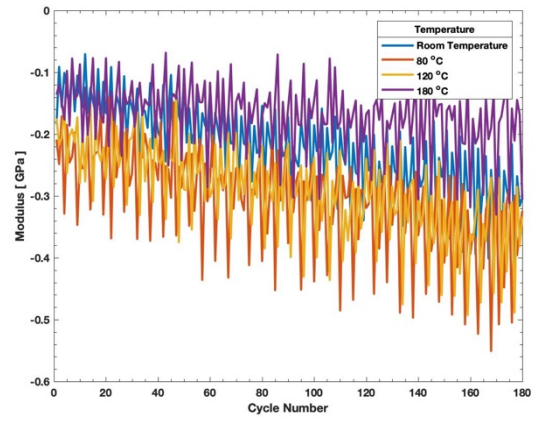
f)

Figure B-27: 12.5 MPa Continuous - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

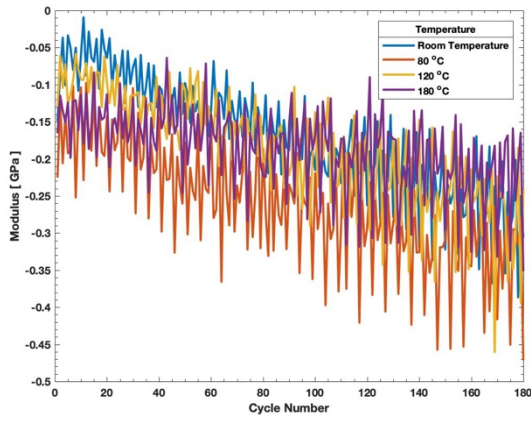
B.2.3 Difference



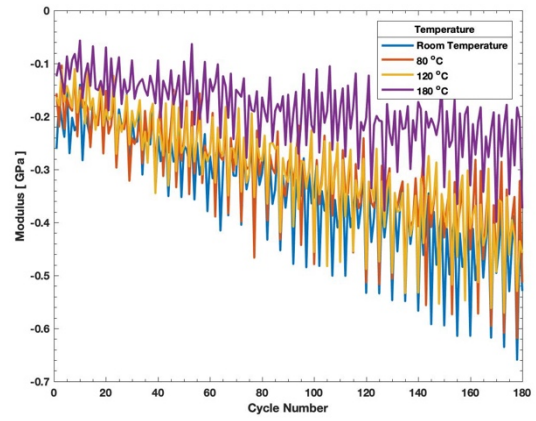
a)



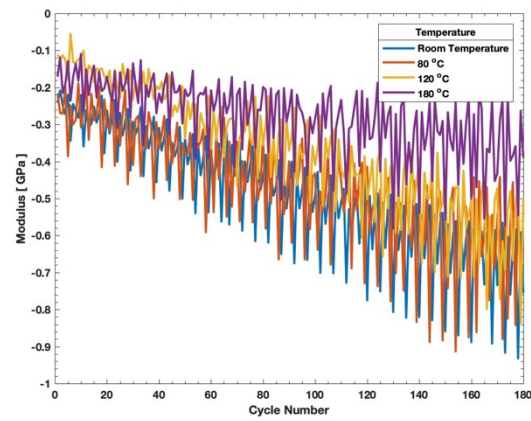
b)



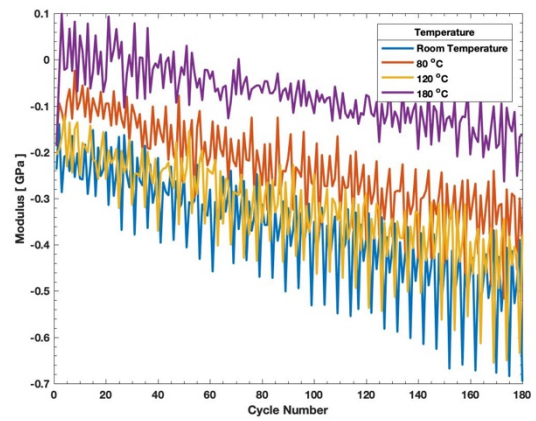
c)



d)

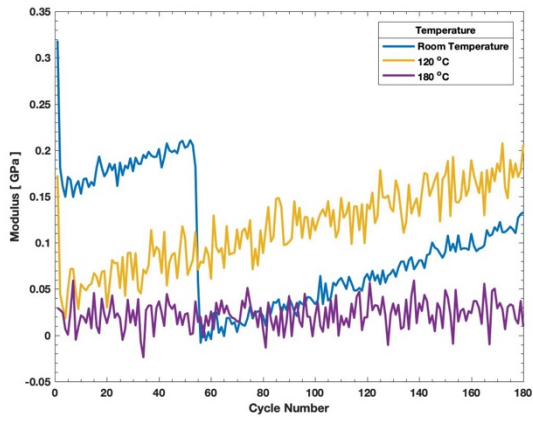


e)

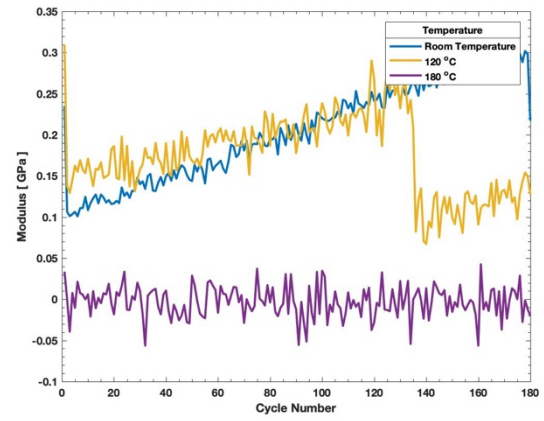


f)

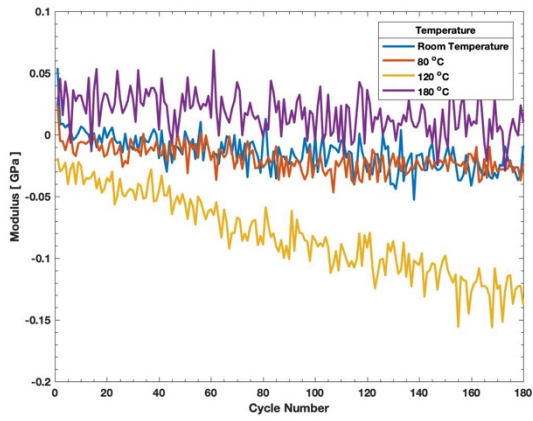
Figure B-28: 8 MPa - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



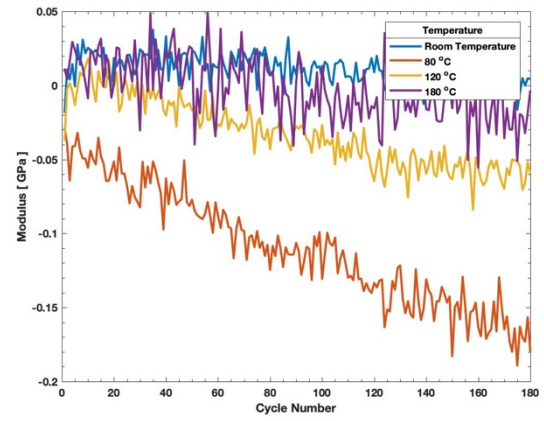
a)



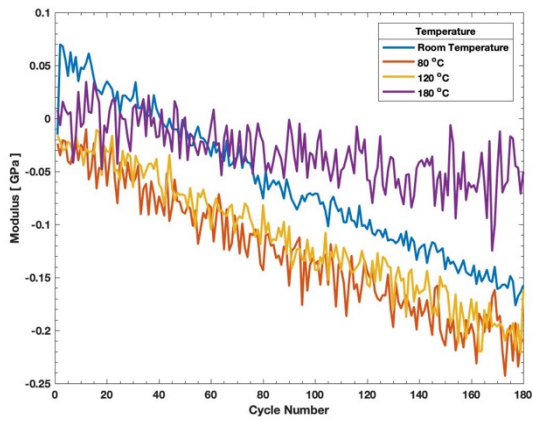
b)



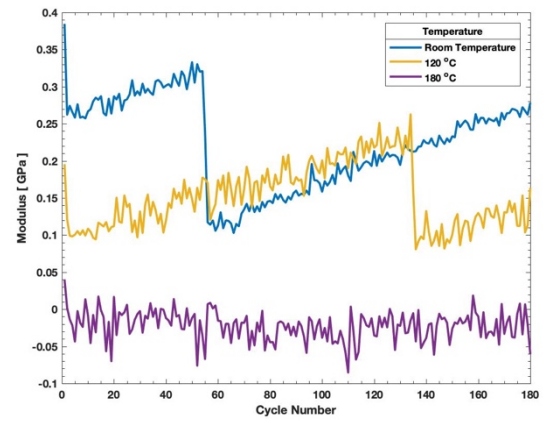
c)



d)

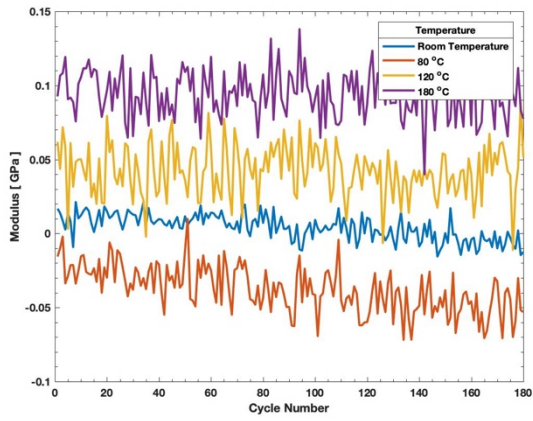


e)

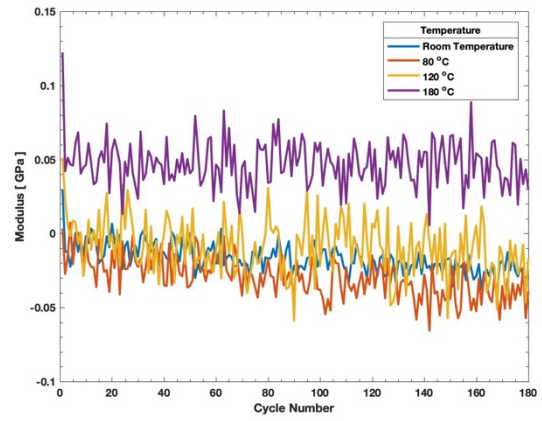


f)

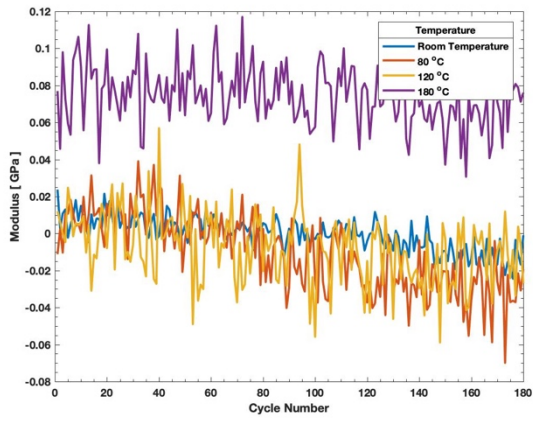
Figure B-29: 12.5 MPa - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



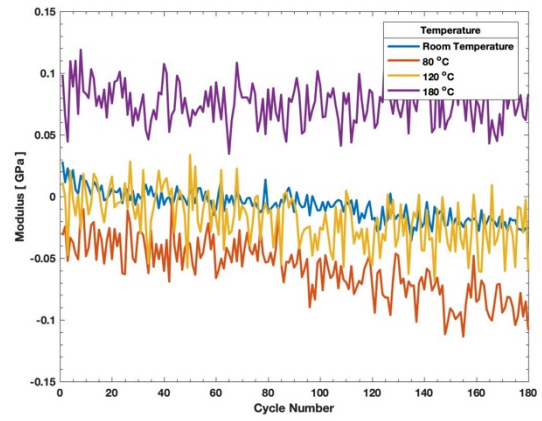
a)



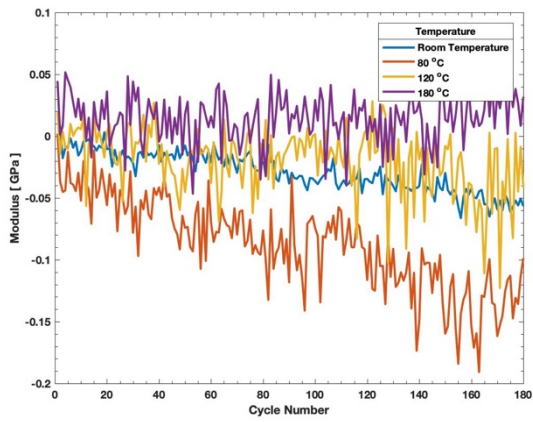
b)



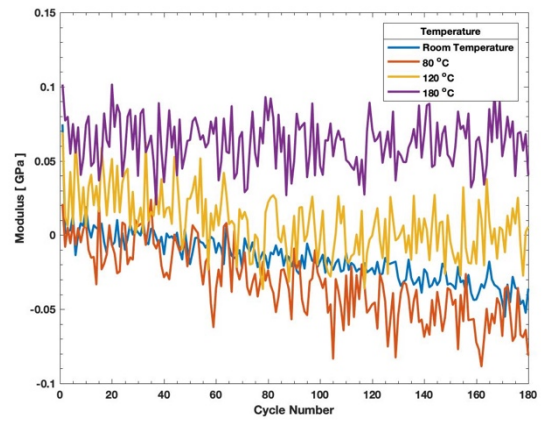
c)



d)



e)



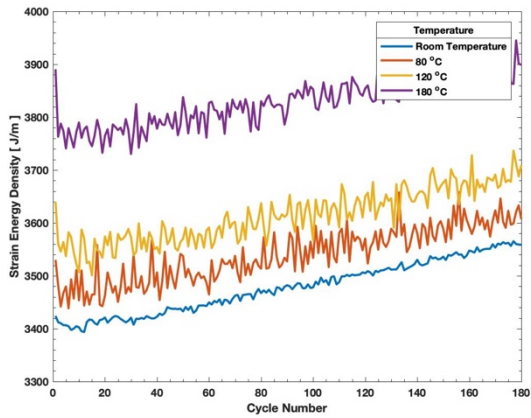
f)

Figure B-30: 12.5 MPa Continuous - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

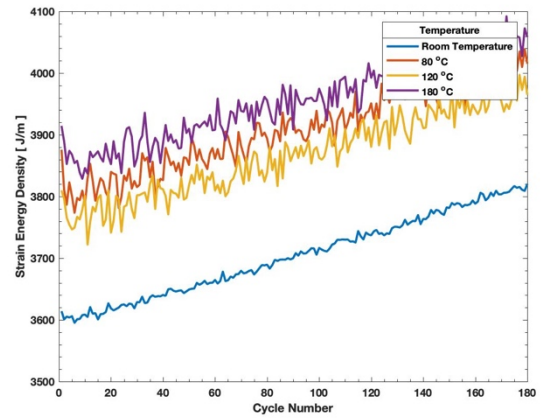
B.3 Strain Energy Density

B.3.1 Overall

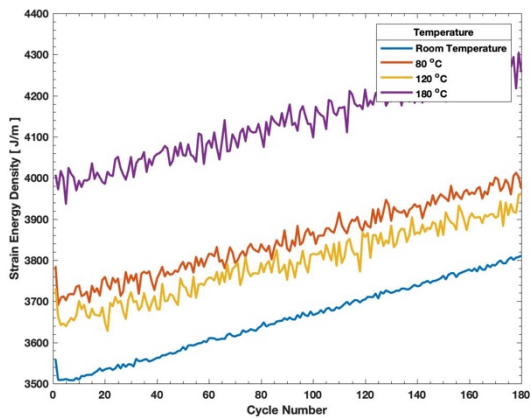
B.3.1.1 Total



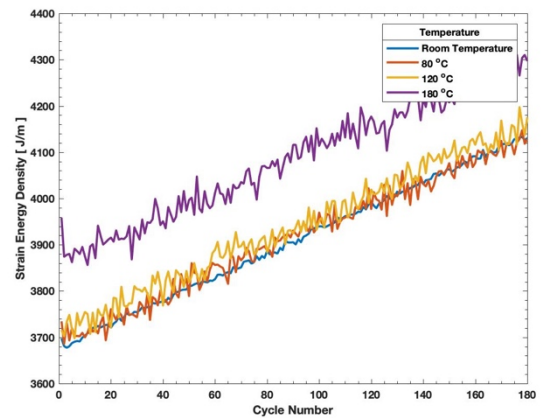
a)



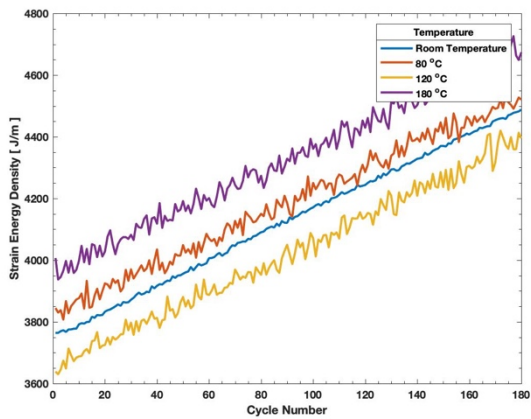
b)



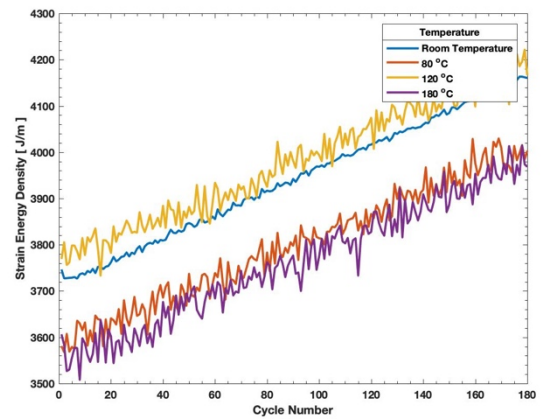
c)



d)

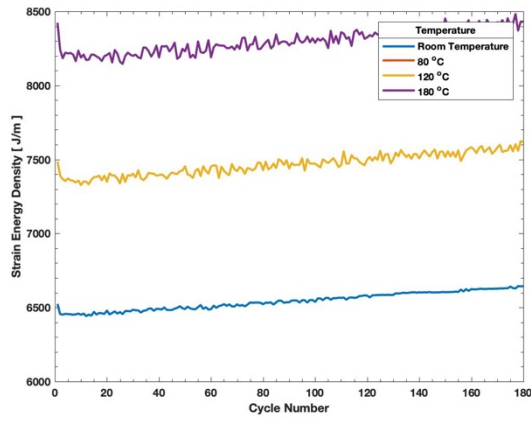


e)

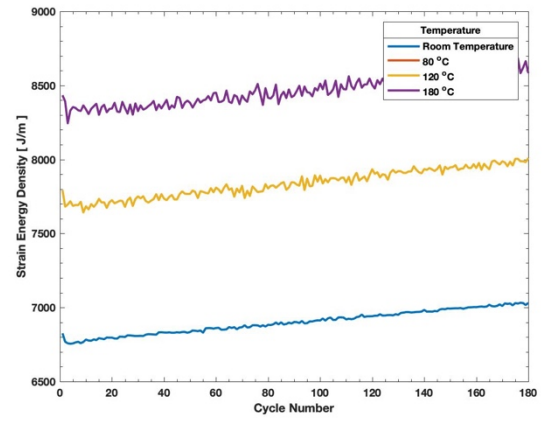


f)

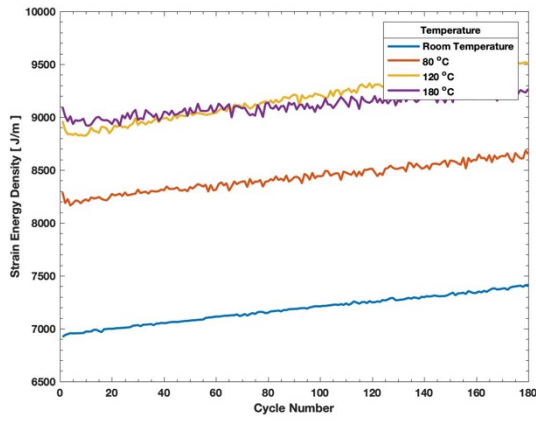
Figure B-31: 8 MPa - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



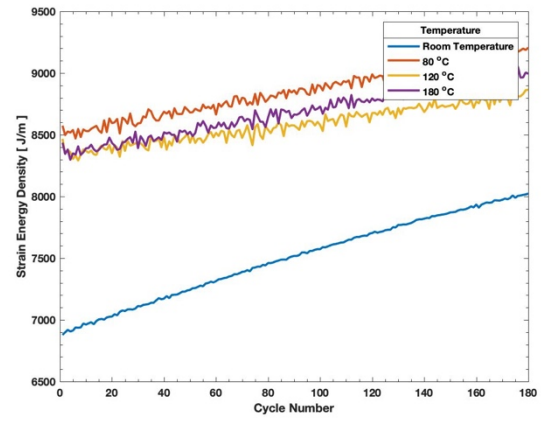
a)



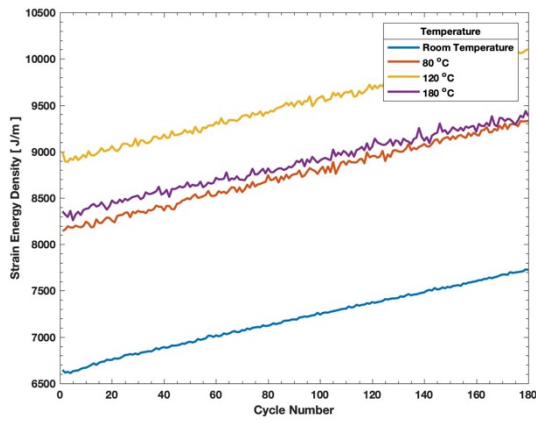
b)



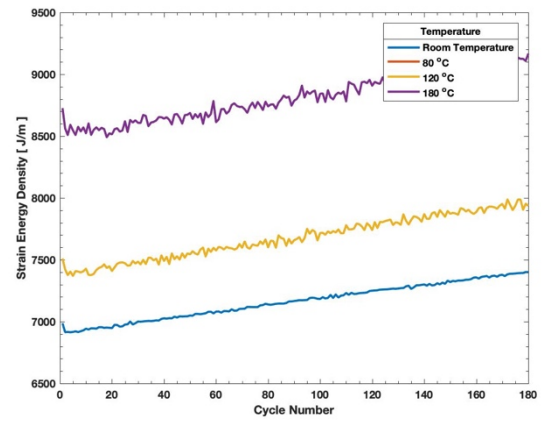
c)



d)

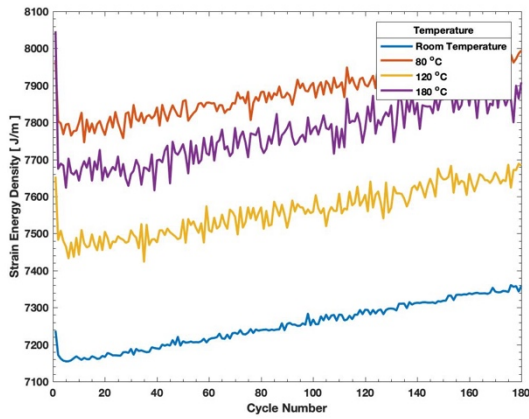


e)

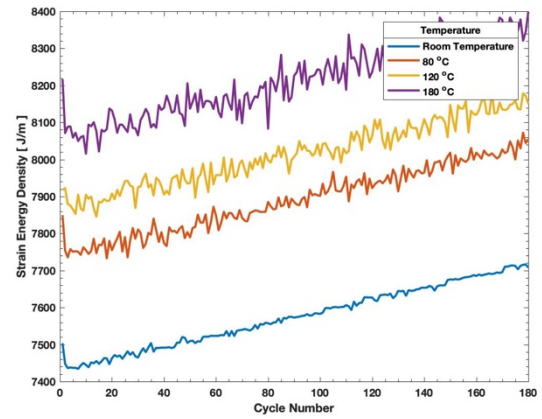


f)

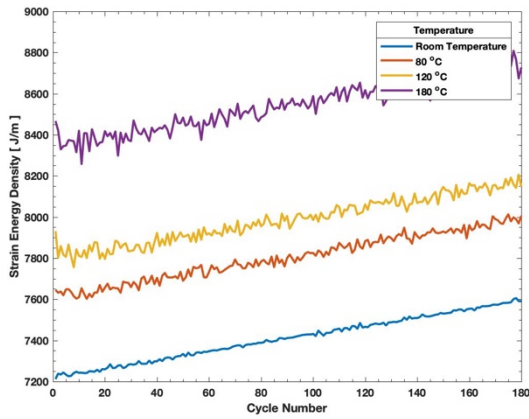
Figure B-32: 12.5 MPa - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



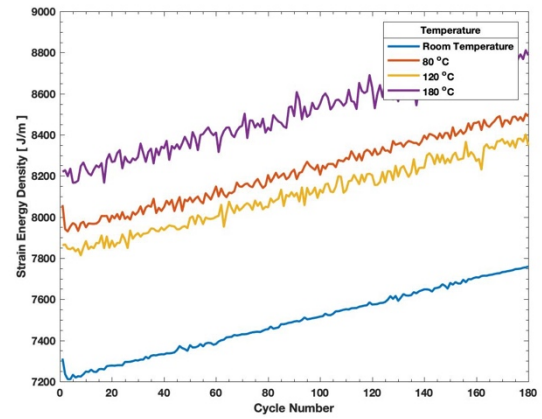
a)



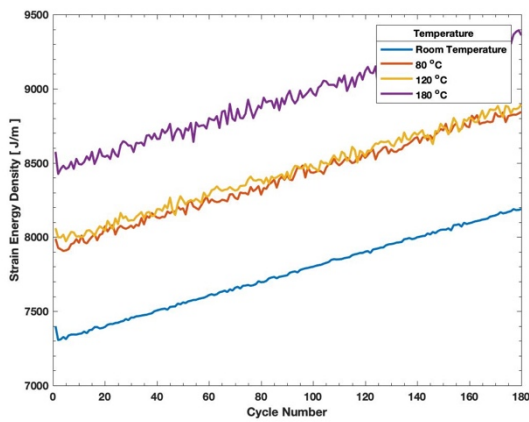
b)



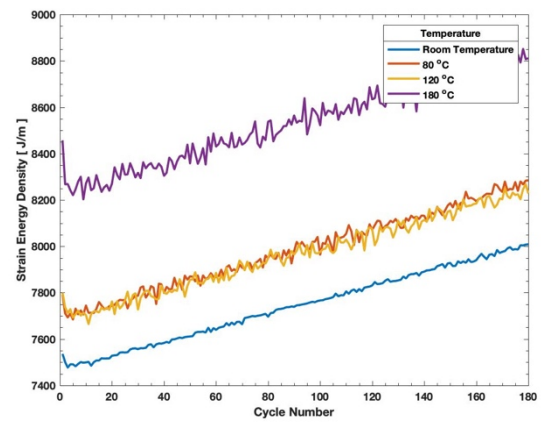
c)



d)



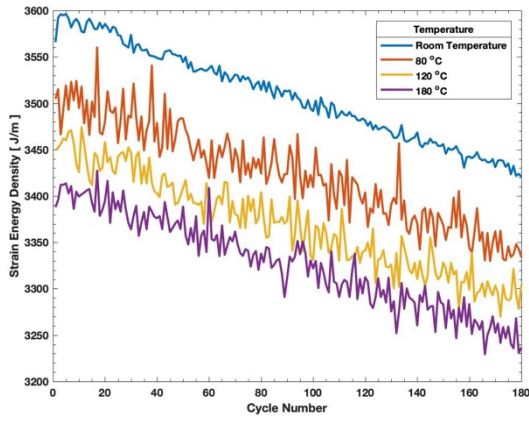
e)



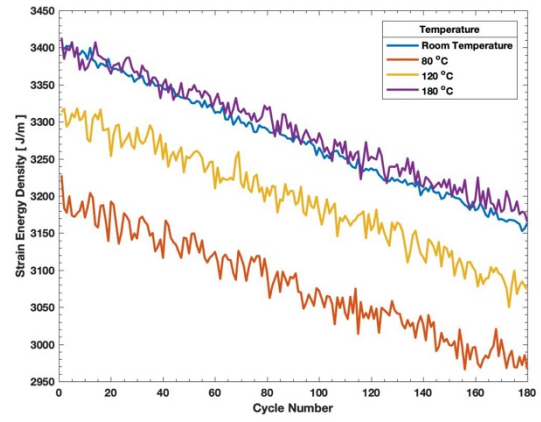
f)

Figure B-33: 12.5 MPa Continuous - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

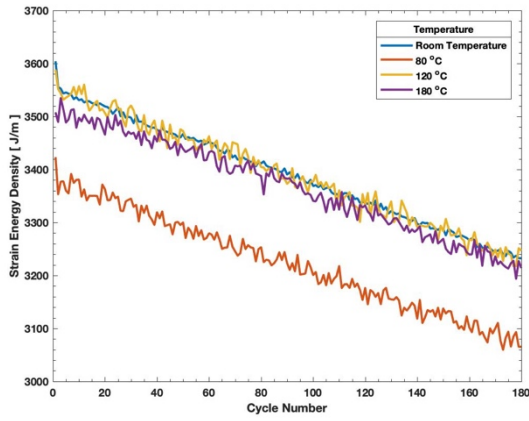
B.3.1.2 Stored



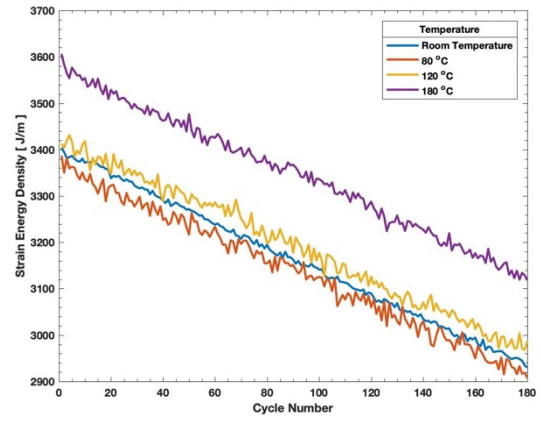
a)



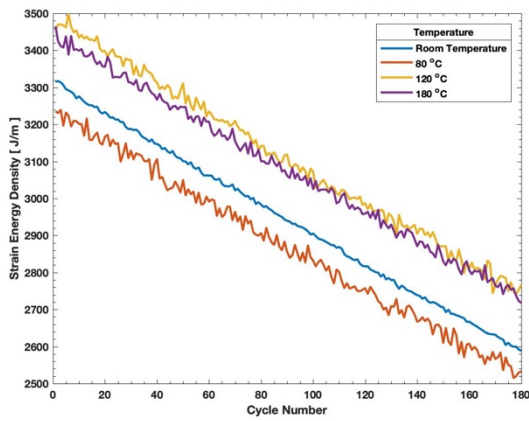
b)



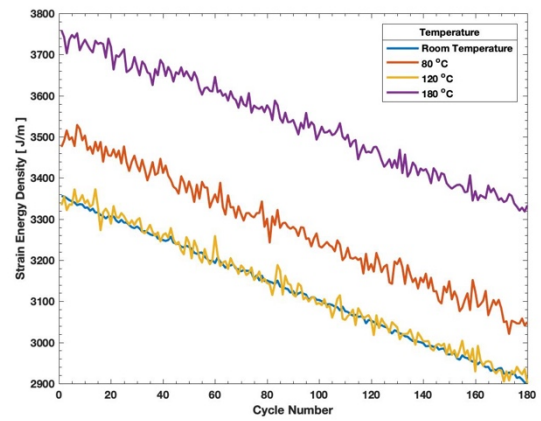
c)



d)

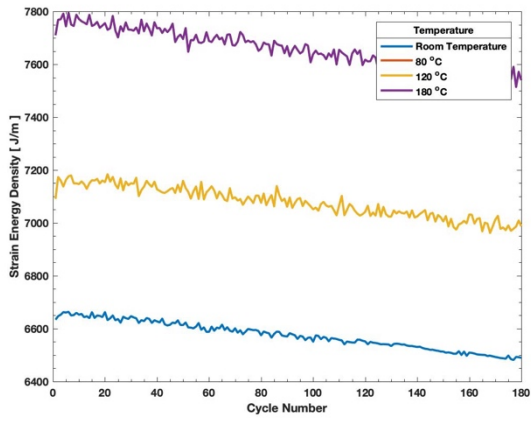


e)

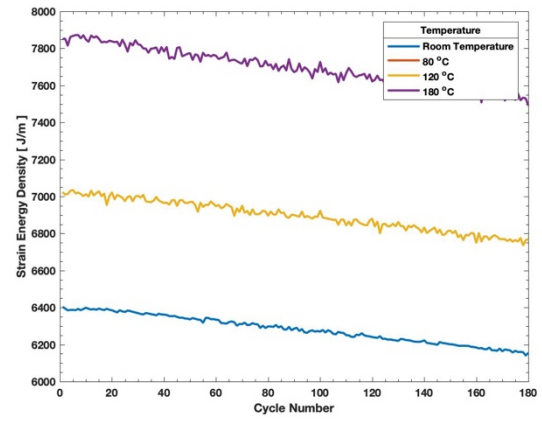


f)

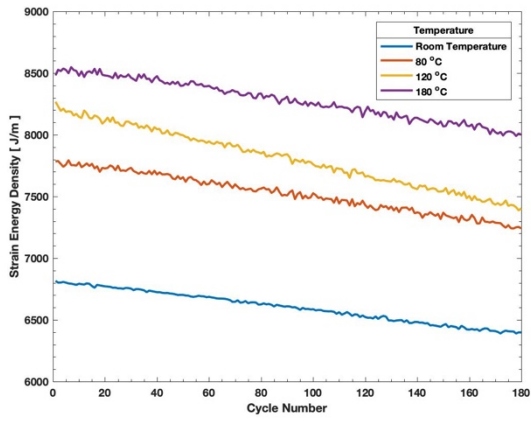
Figure B-34: 8 MPa - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



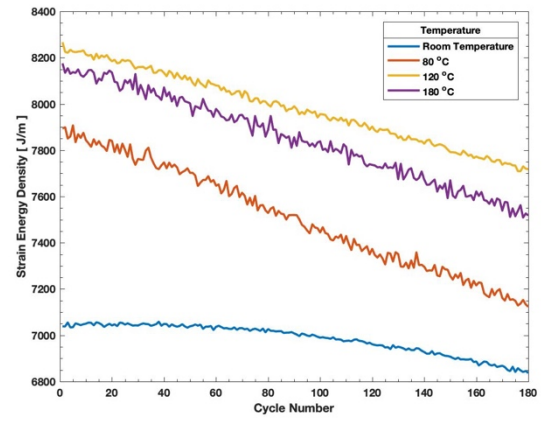
a)



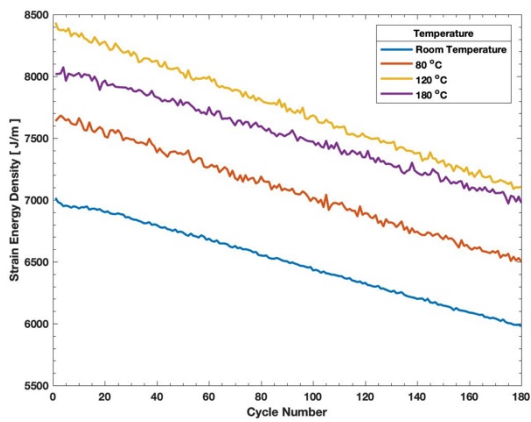
b)



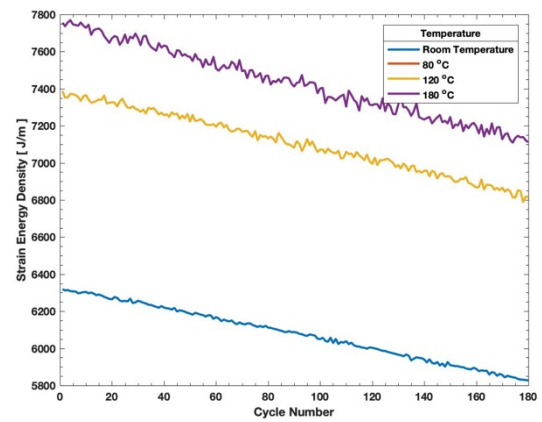
c)



d)

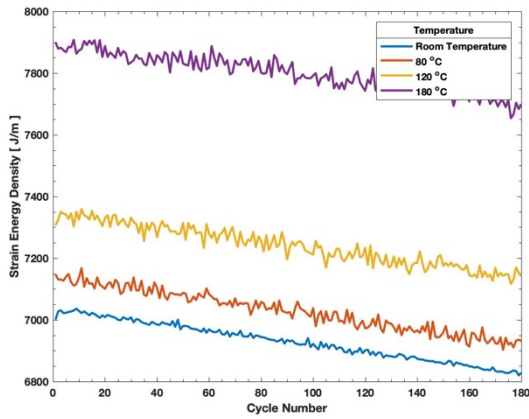


e)

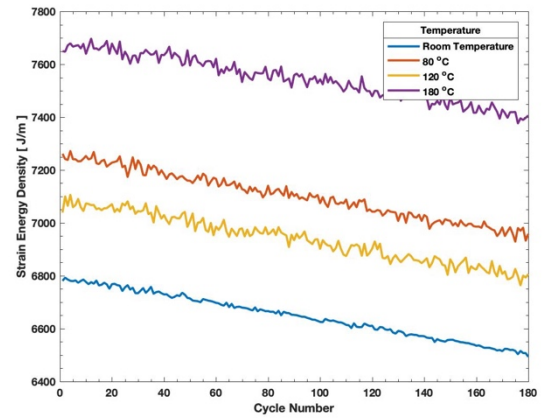


f)

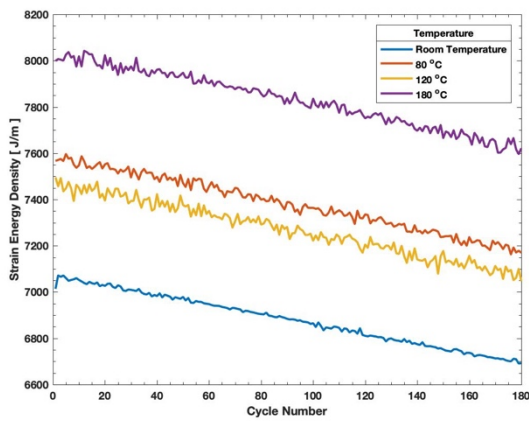
Figure B-35: 12.5 MPa - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



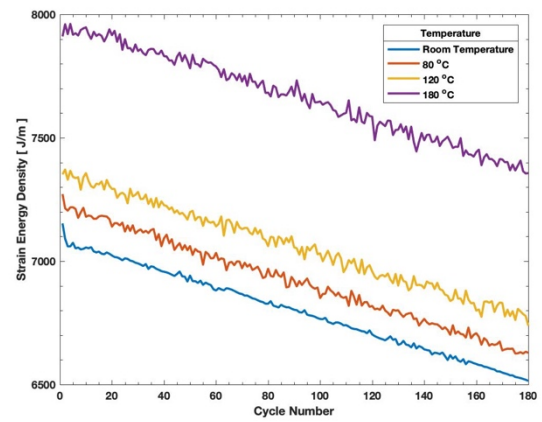
a)



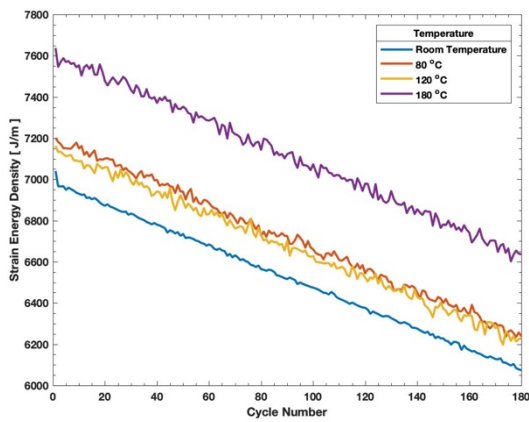
b)



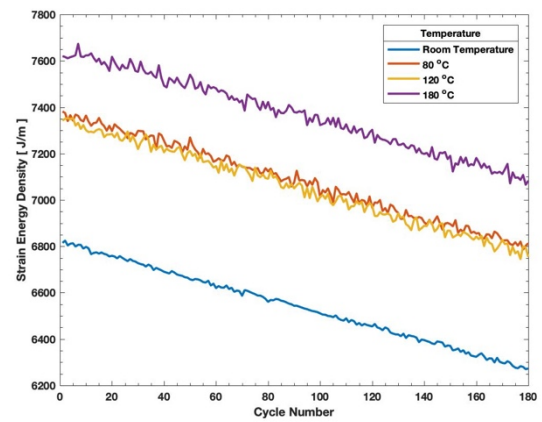
c)



d)



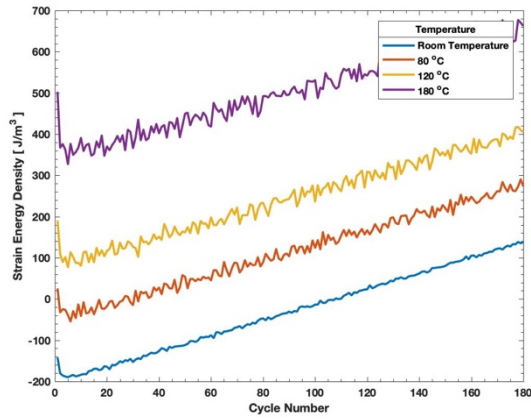
e)



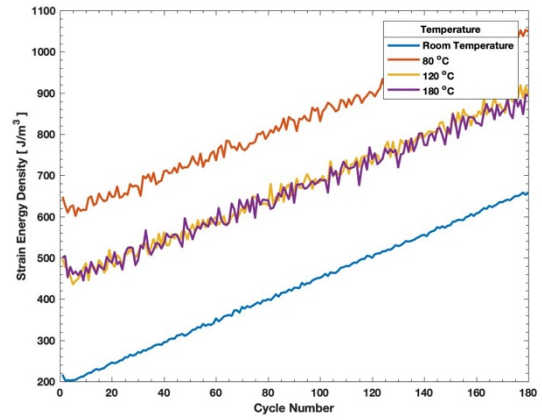
f)

Figure B-36: 12.5 MPa Continuous - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

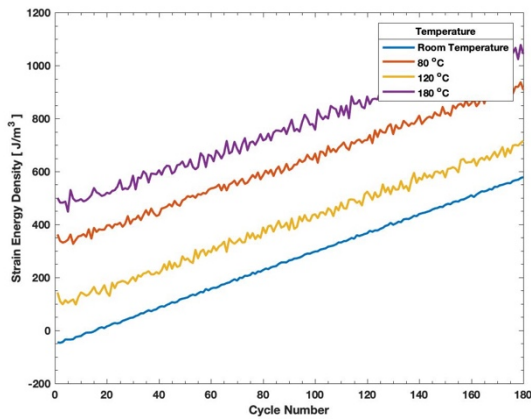
B.3.1.3 Dissipated



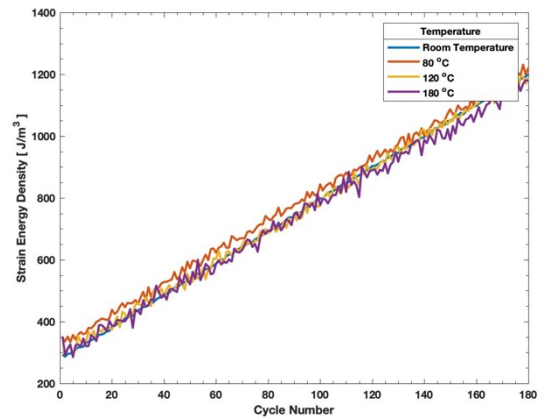
a)



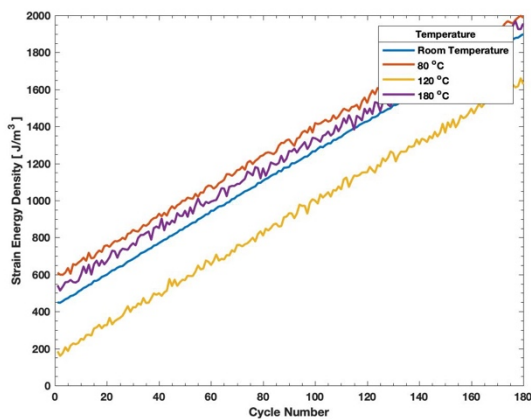
b)



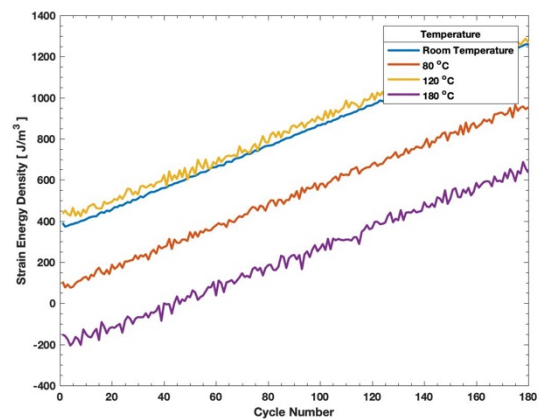
c)



d)

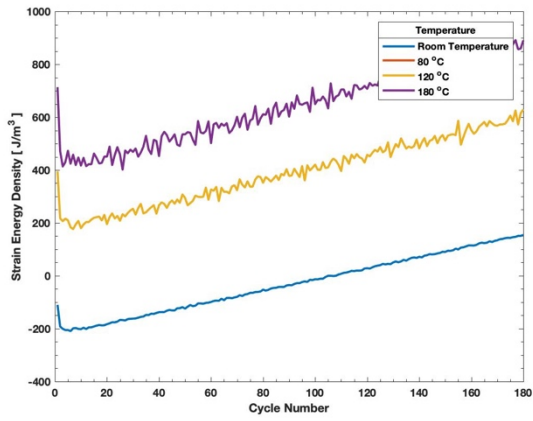


e)

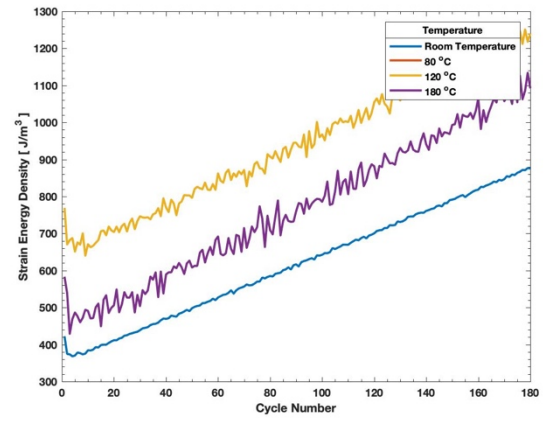


f)

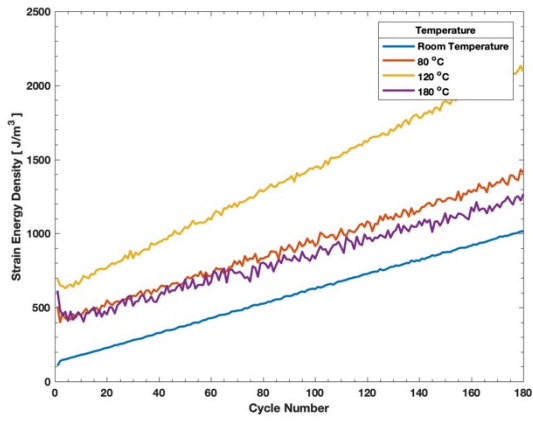
Figure B-37: 8 MPa - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



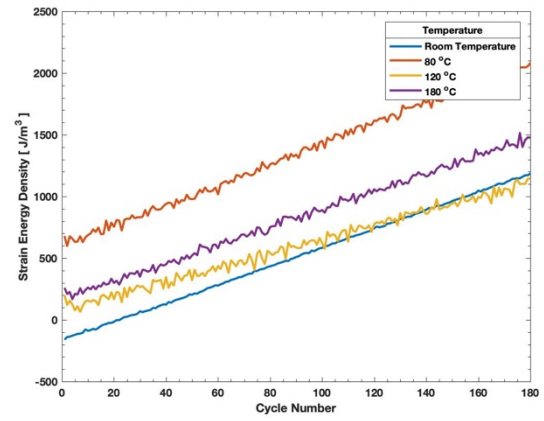
a)



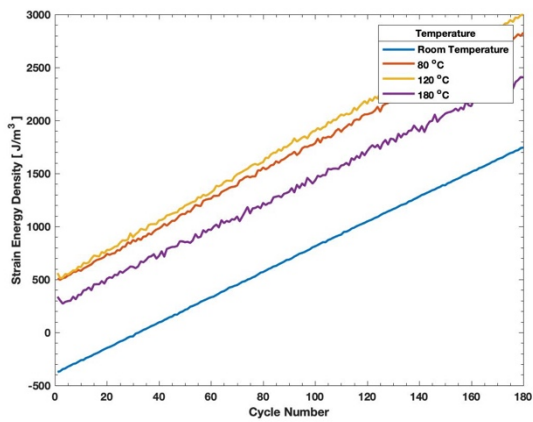
b)



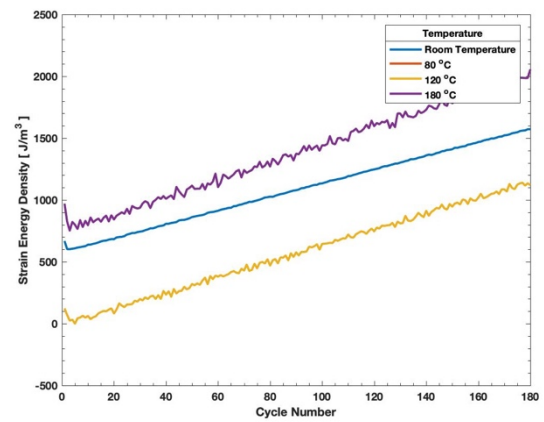
c)



d)

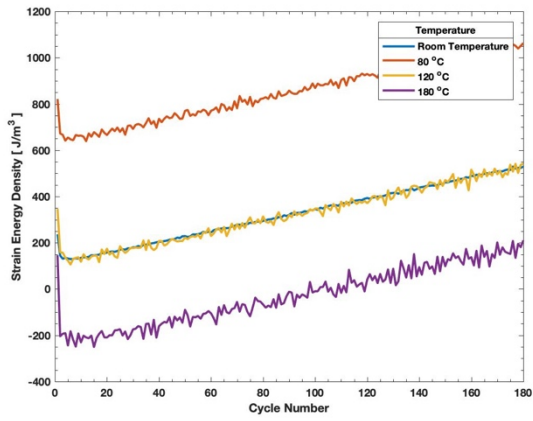


e)

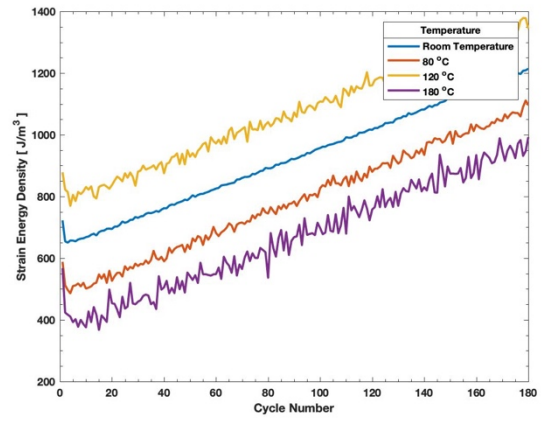


f)

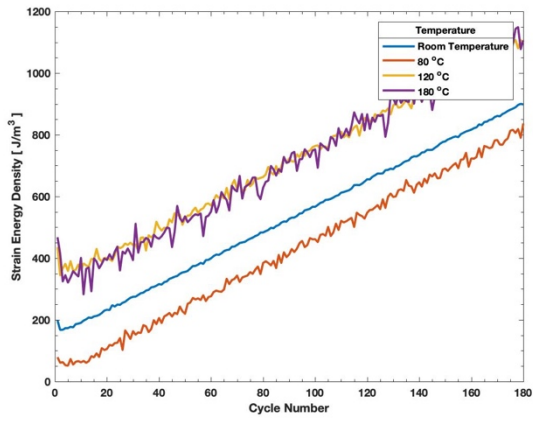
Figure B-38: 12.5 MPa - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



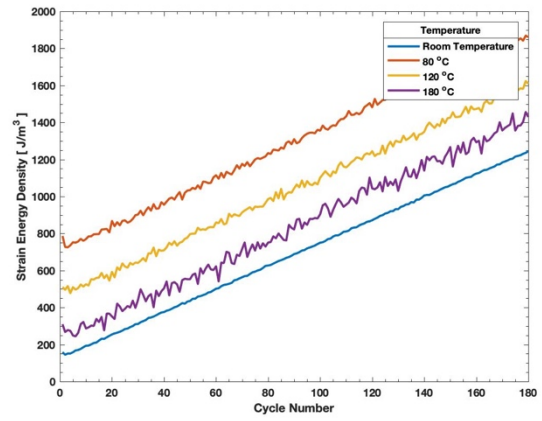
a)



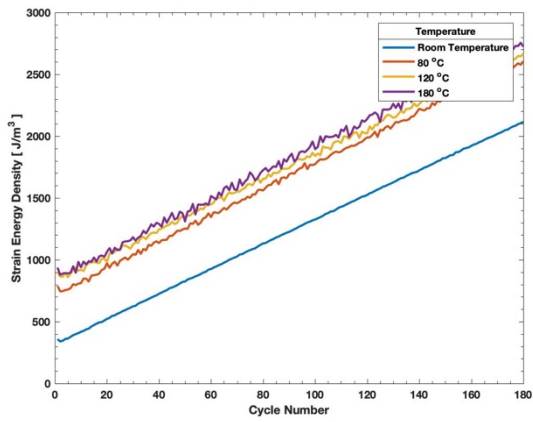
b)



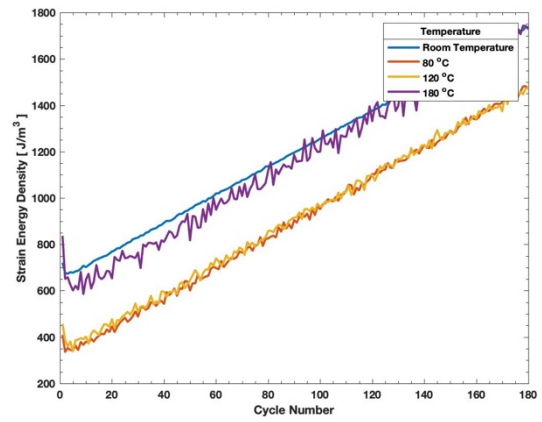
c)



d)



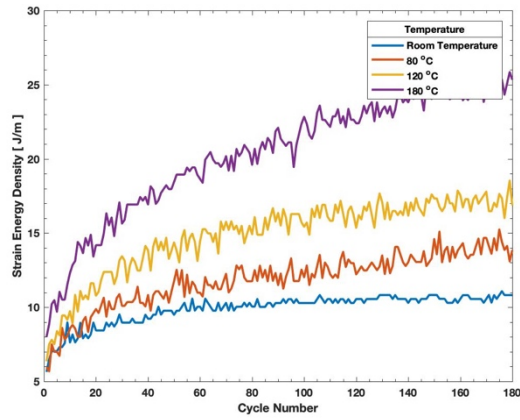
e)



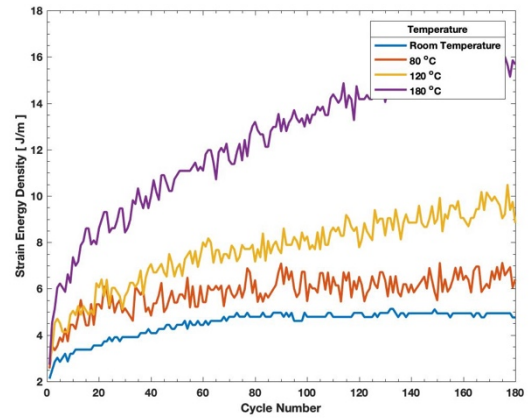
f)

Figure B-39: 12.5 MPa Continuous - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

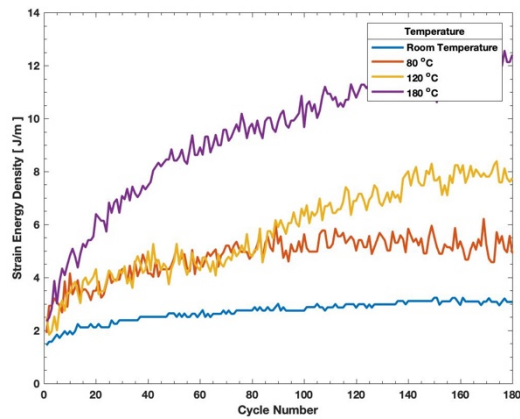
B.3.1.4 Unrecovered



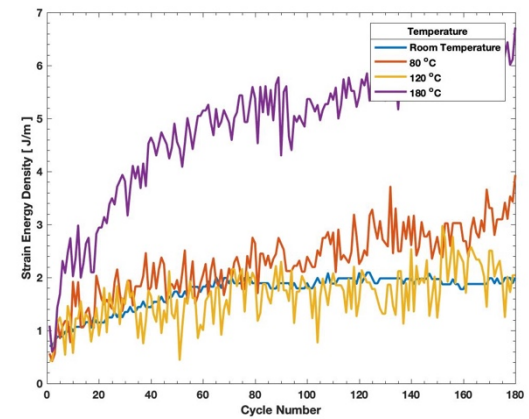
a)



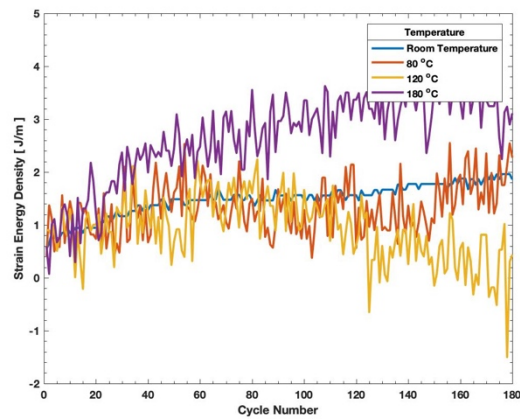
b)



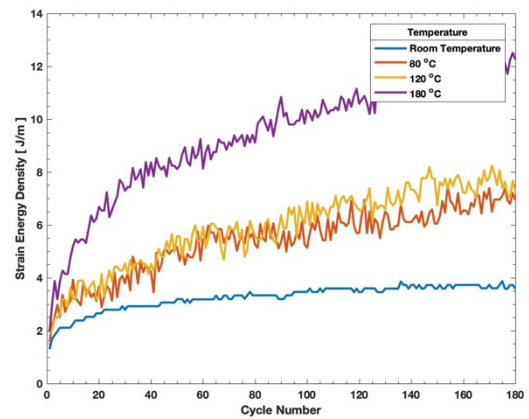
c)



d)

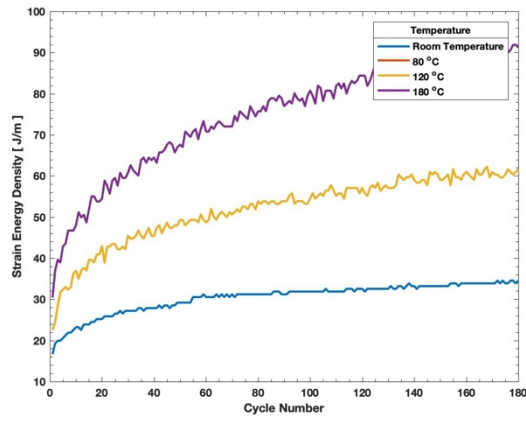


e)

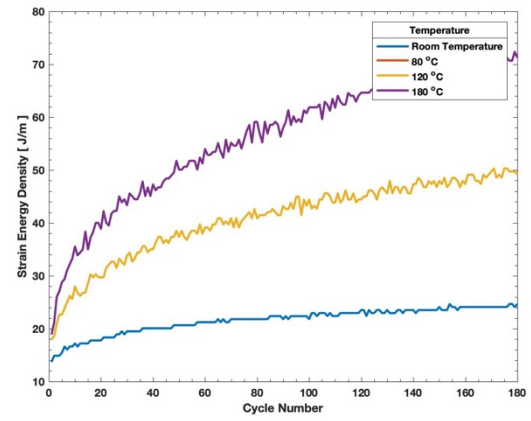


f)

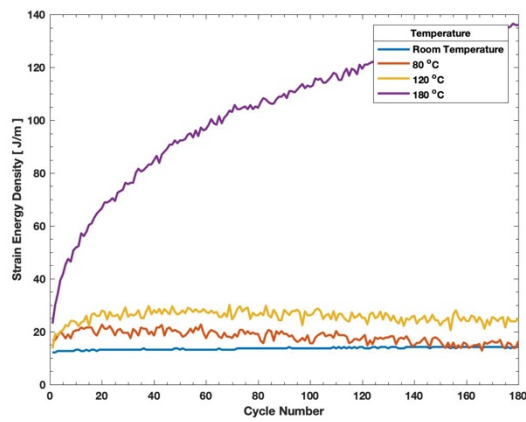
Figure B-40: 8 MPa - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



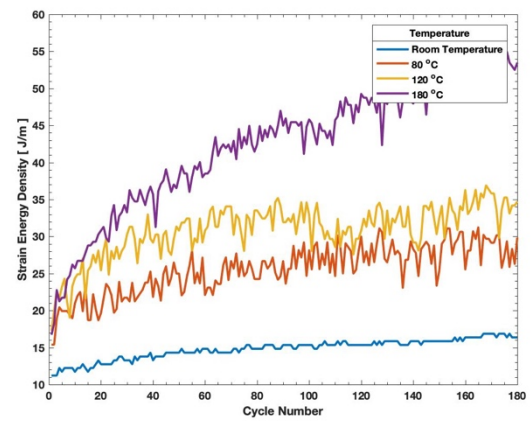
a)



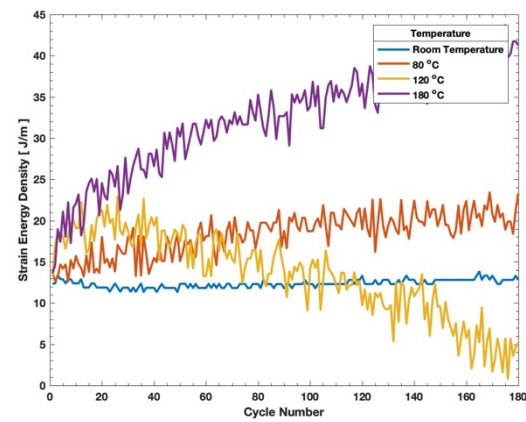
b)



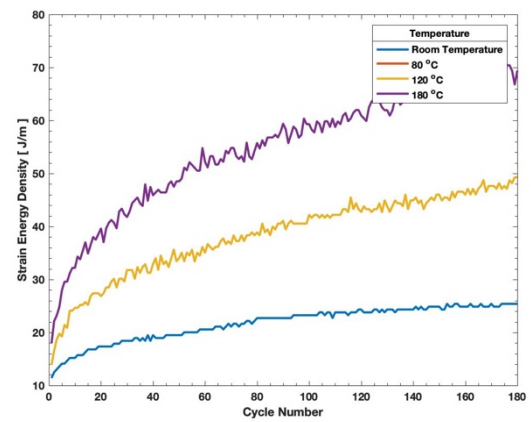
c)



d)

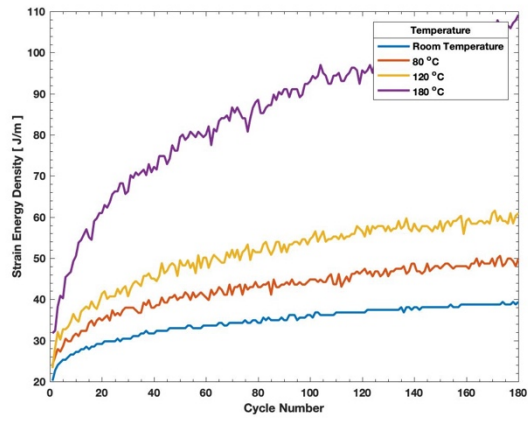


e)

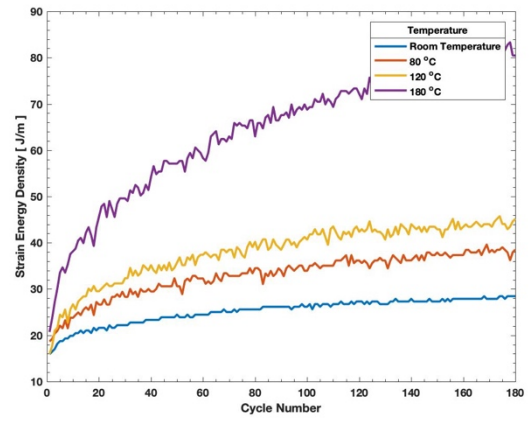


f)

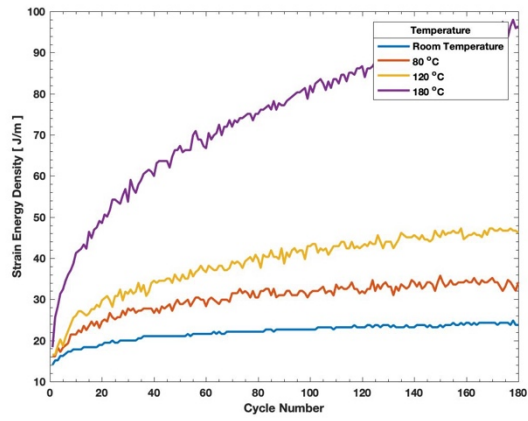
Figure B-41: 12.5 MPa - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



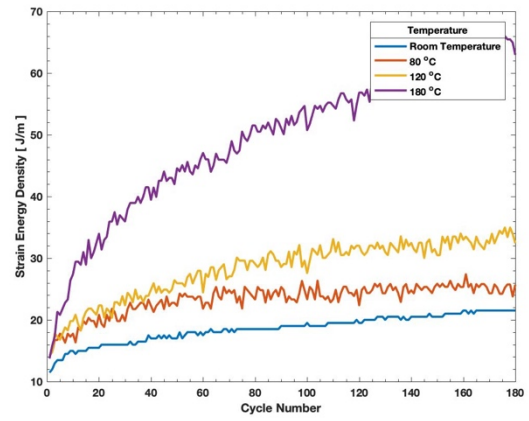
a)



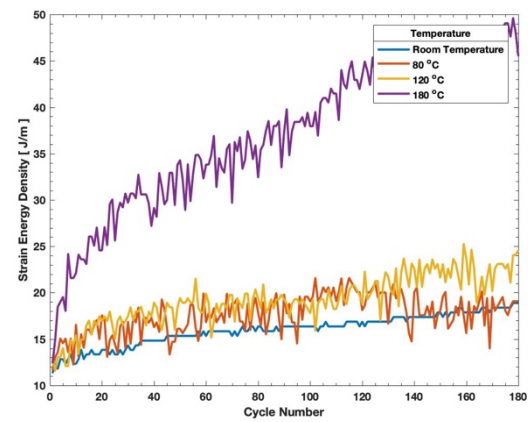
b)



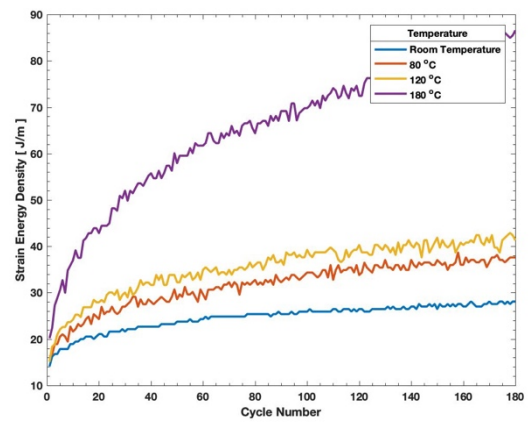
c)



d)



e)



f)

Figure B-42: 12.5 MPa Continuous - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.3.2 Total

B.3.2.1 Total - Loading

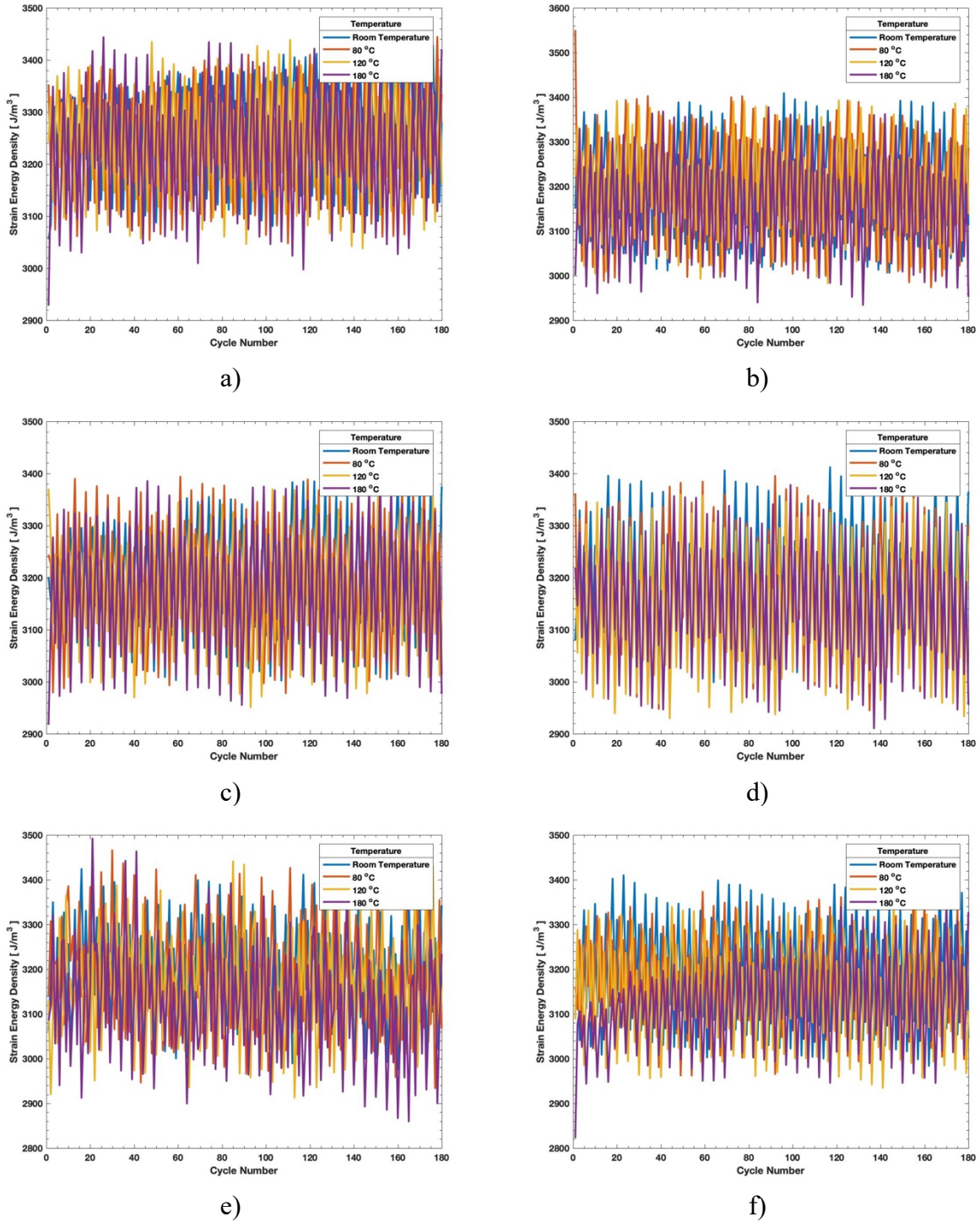
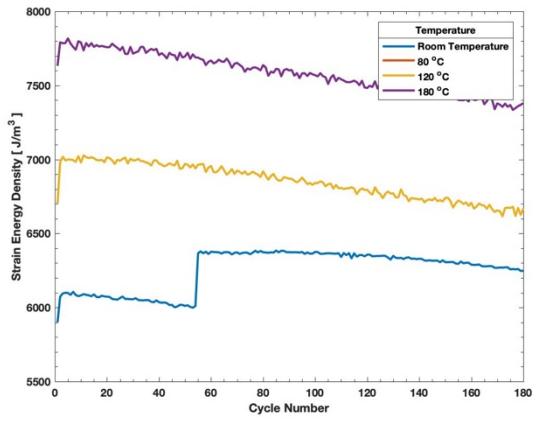
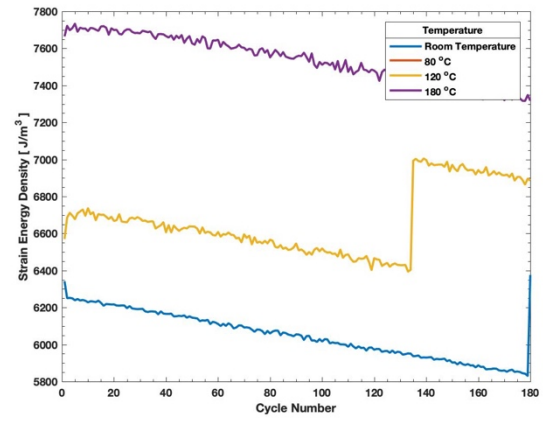


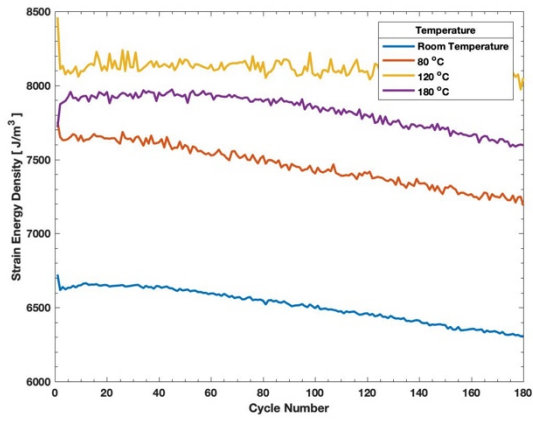
Figure B-43: 8 MPa - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



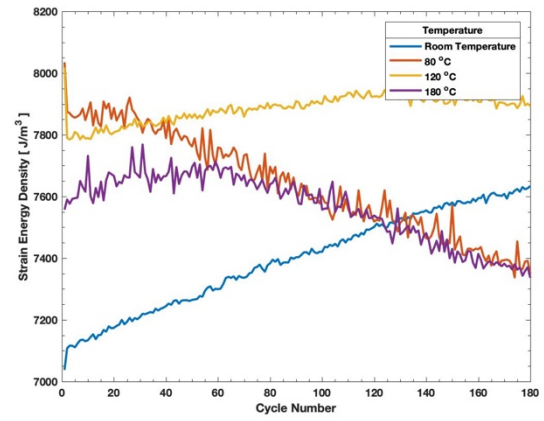
a)



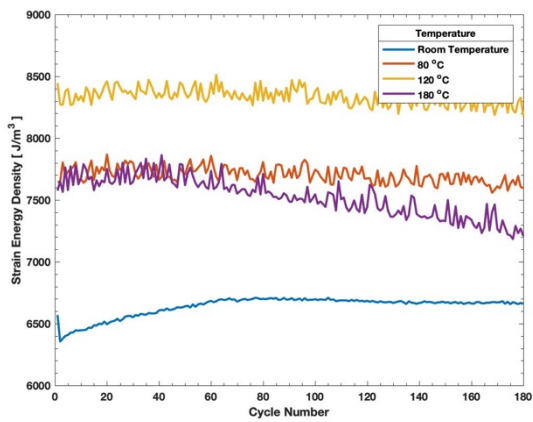
b)



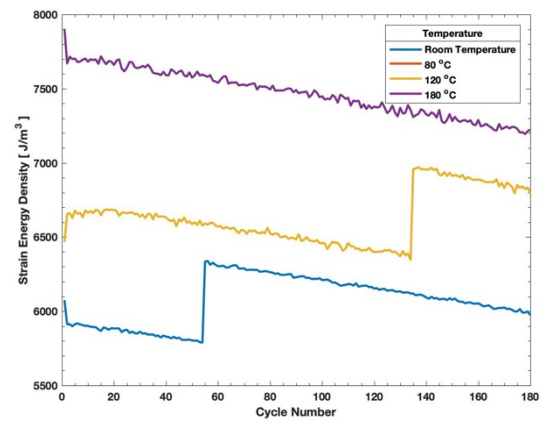
c)



d)

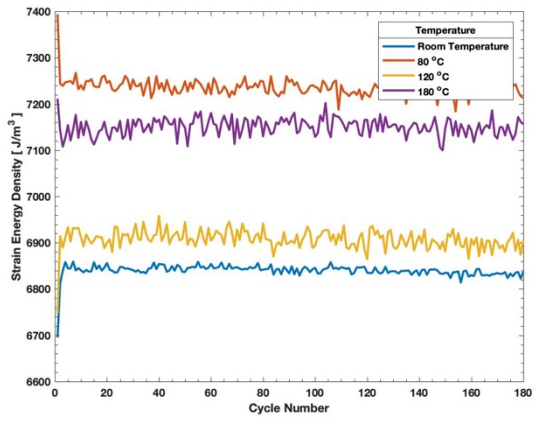


e)

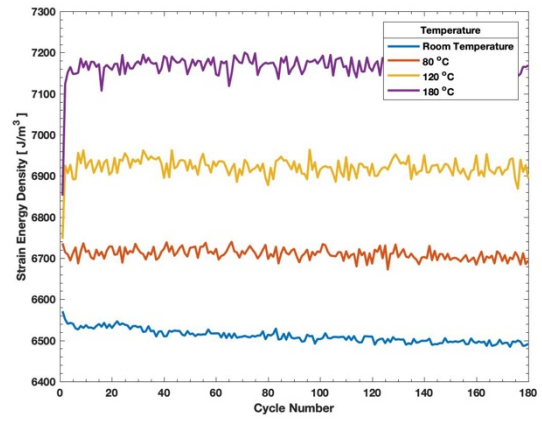


f)

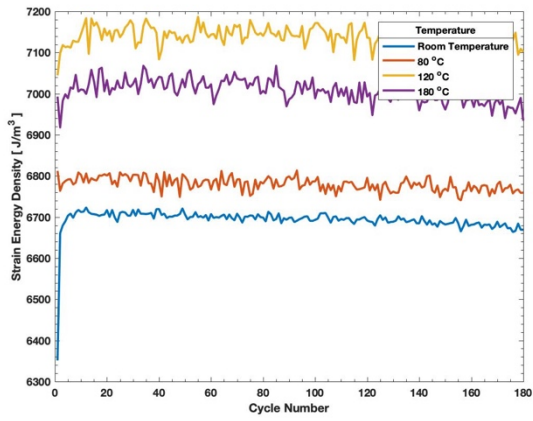
Figure B-44: 12.5 MPa - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



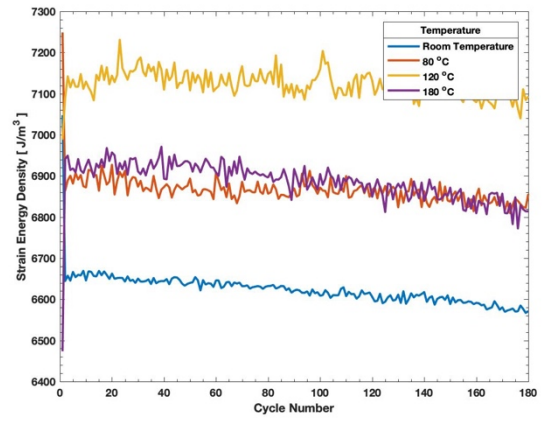
a)



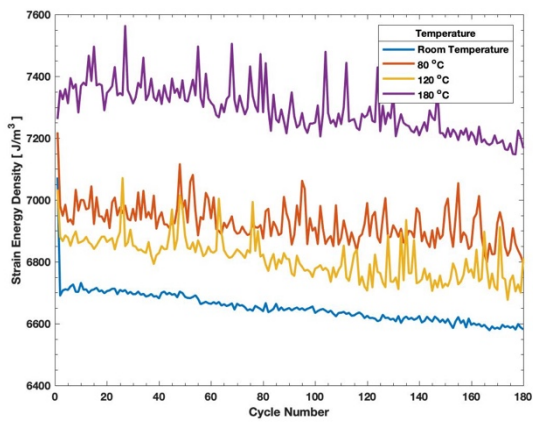
b)



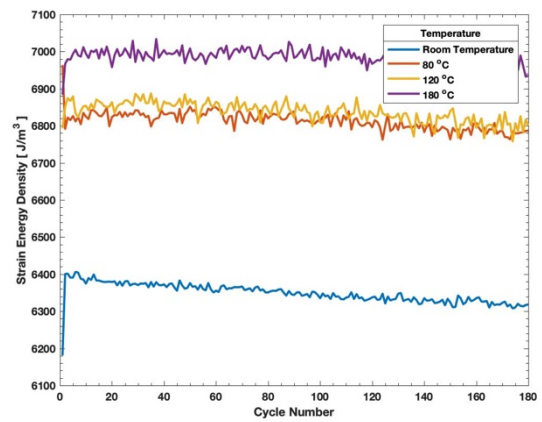
c)



d)



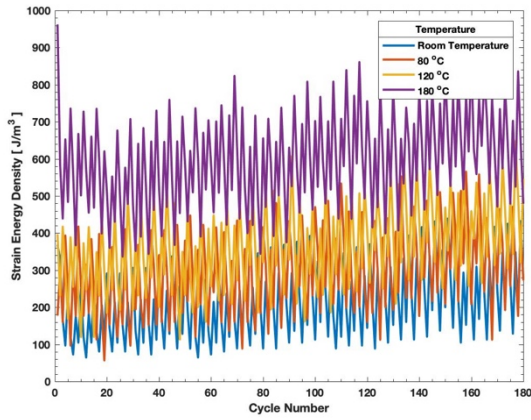
e)



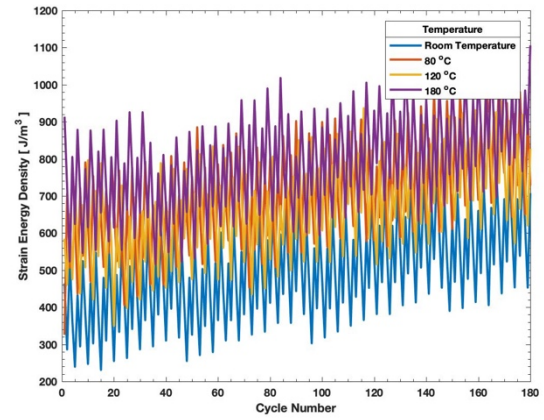
f)

Figure B-45: 12.5 MPa Continuous - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

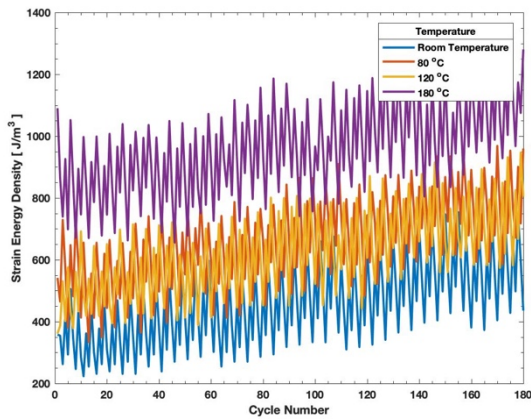
B.3.2.2 Total - Creep



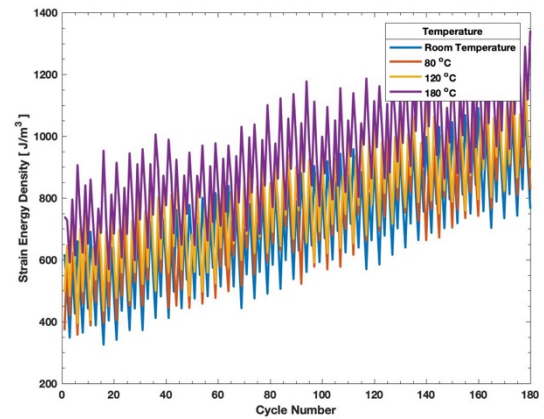
a)



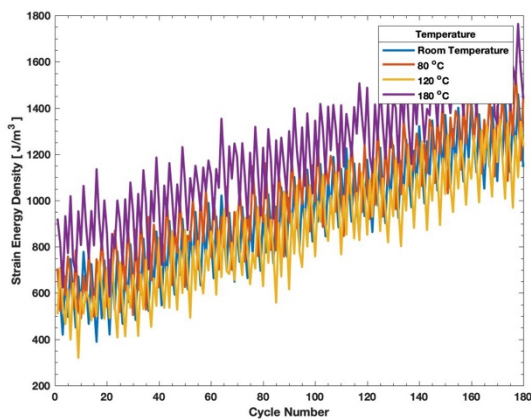
b)



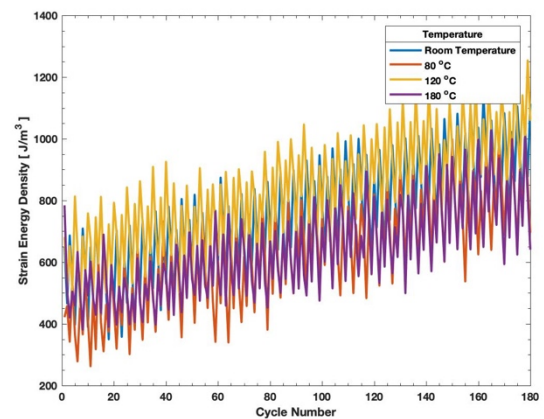
c)



d)

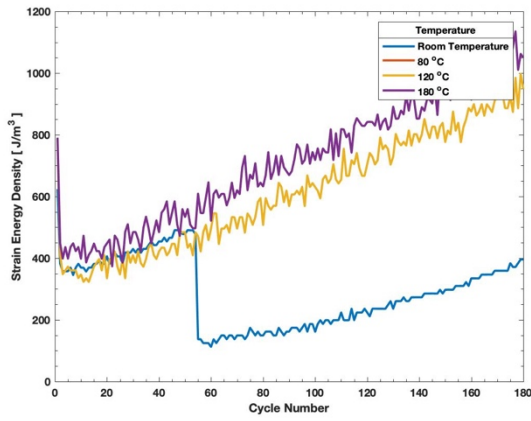


e)

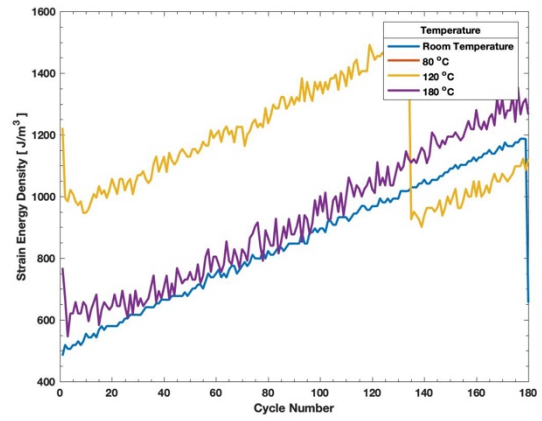


f)

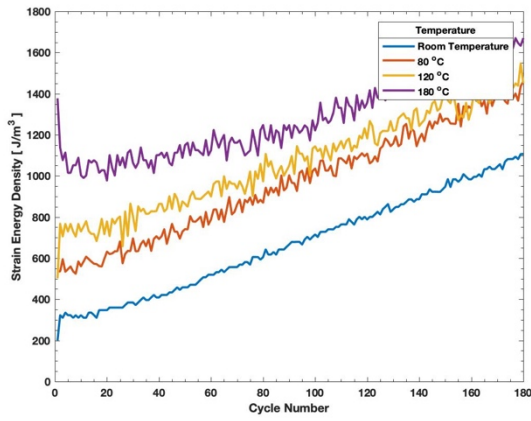
Figure B-46: 8 MPa - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



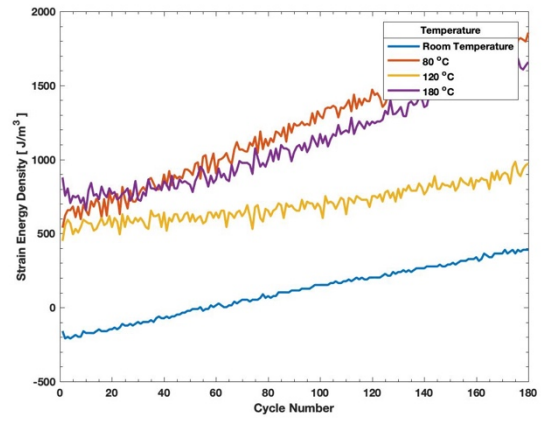
a)



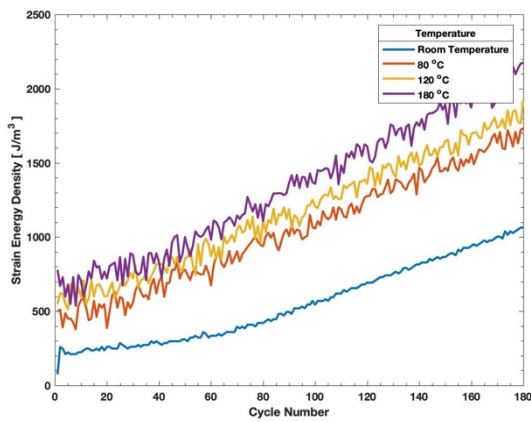
b)



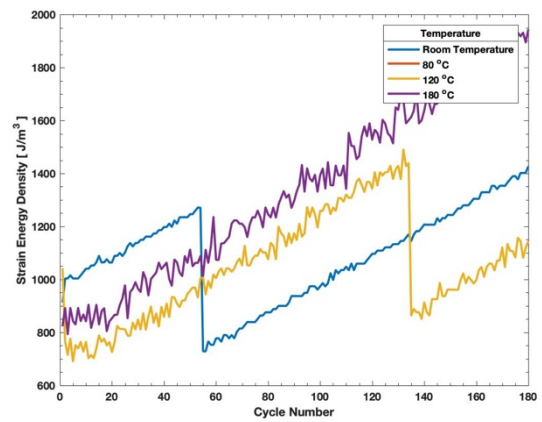
c)



d)

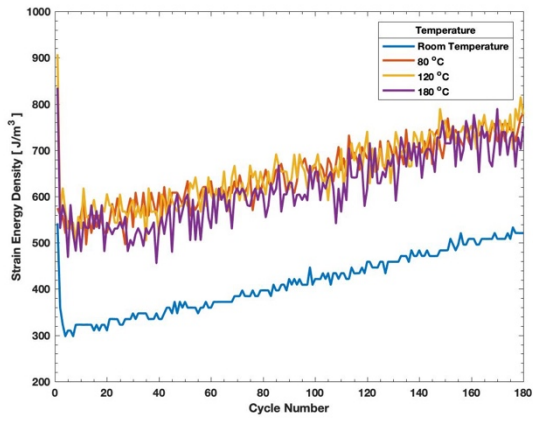


e)

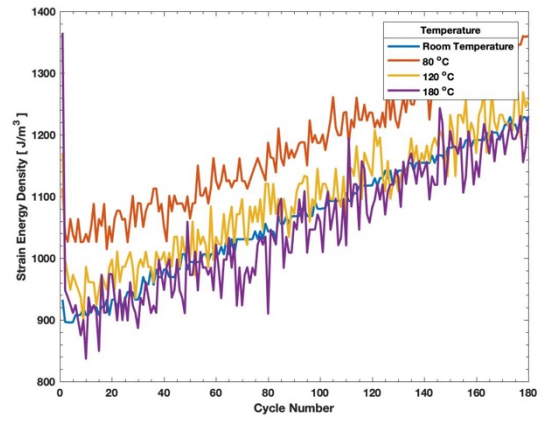


f)

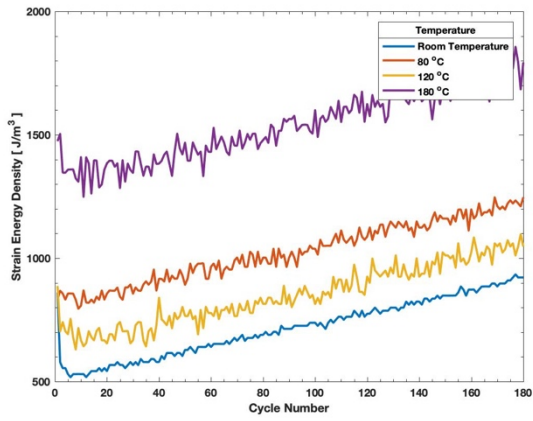
Figure B-47: 12.5 MPa - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



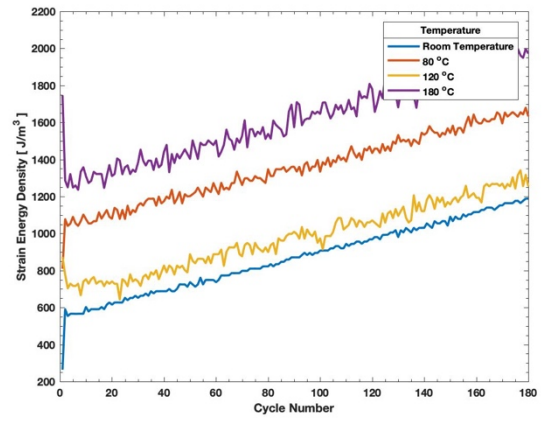
a)



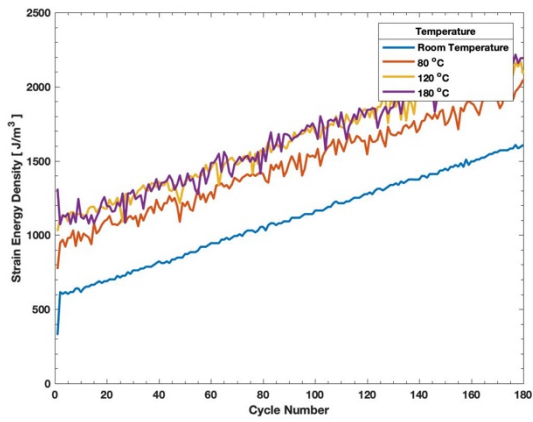
b)



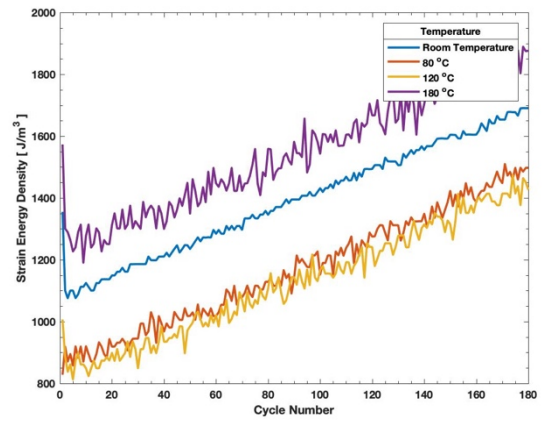
c)



d)



e)

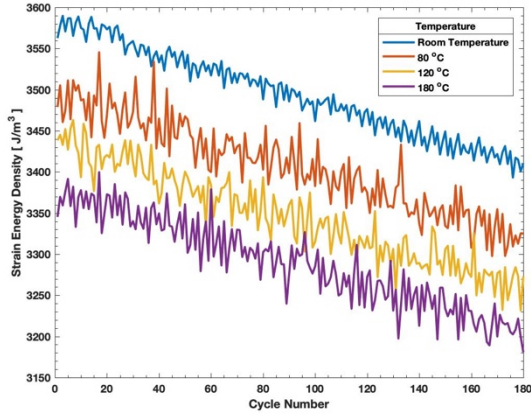


f)

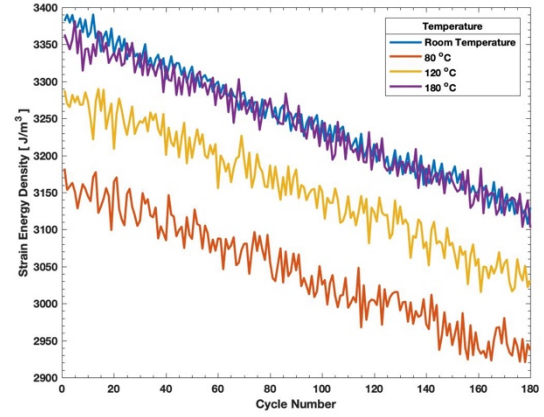
Figure B-48: 12.5 MPa Continuous - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

B.3.3 Stored

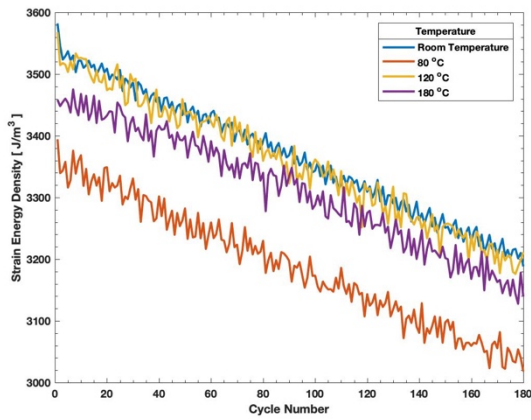
B.3.3.1 Stored - Unloading



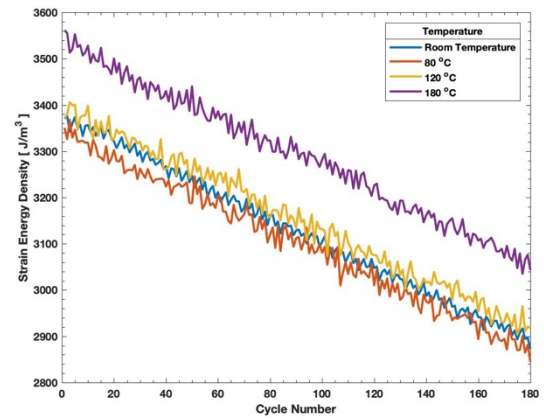
a)



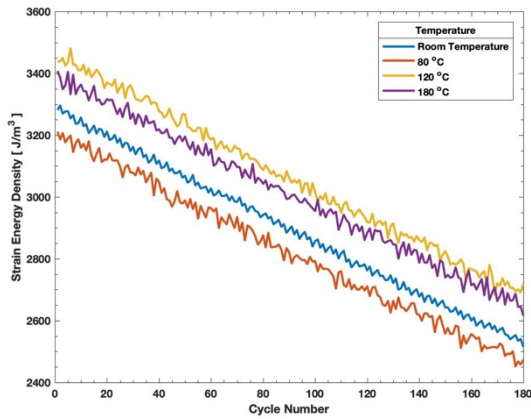
b)



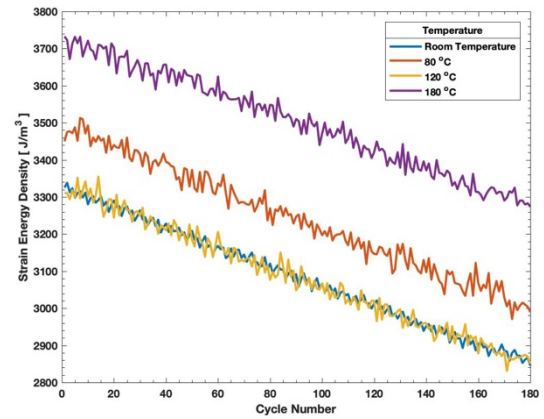
c)



d)

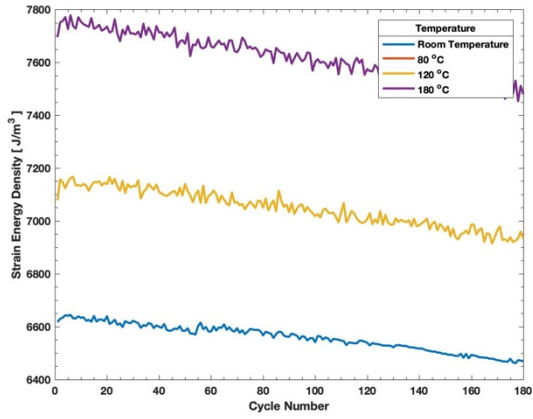


e)

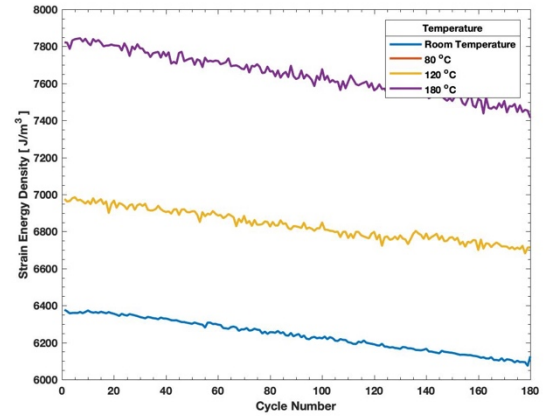


f)

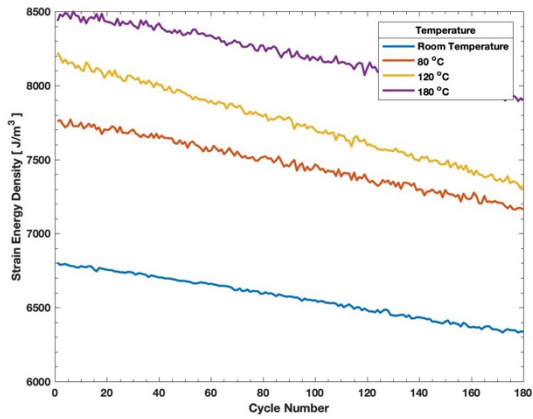
Figure B-49: 8 MPa - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



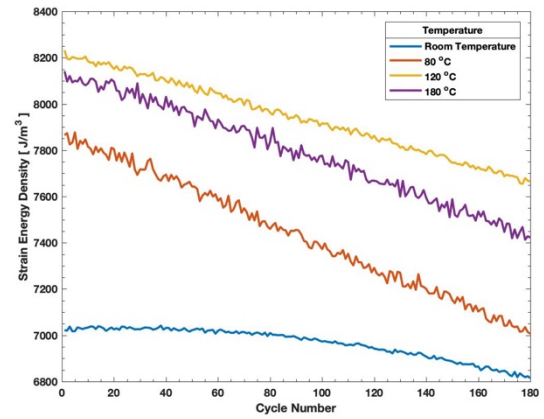
a)



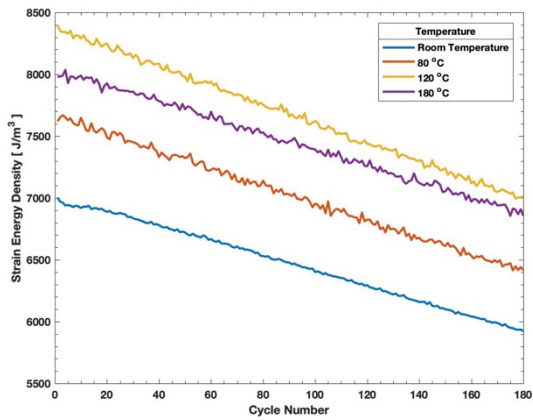
b)



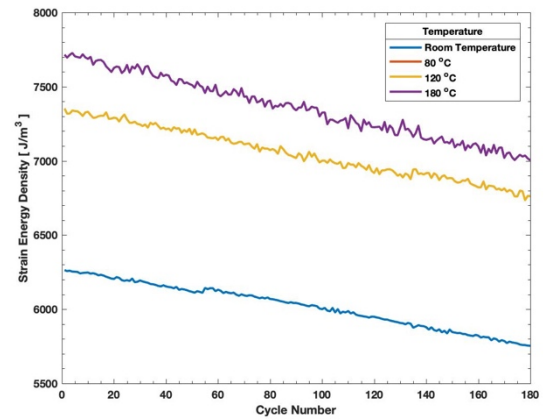
c)



d)

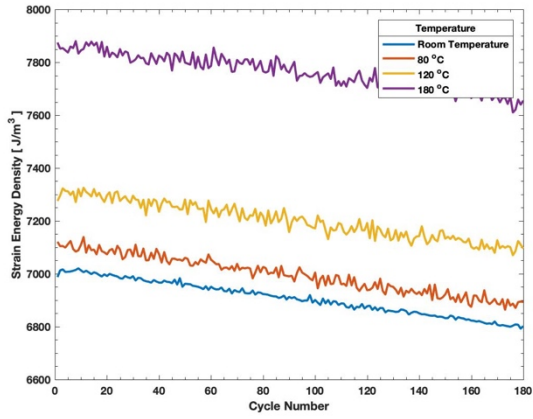


e)

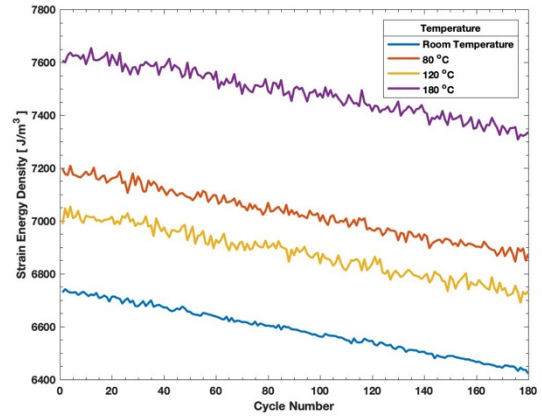


f)

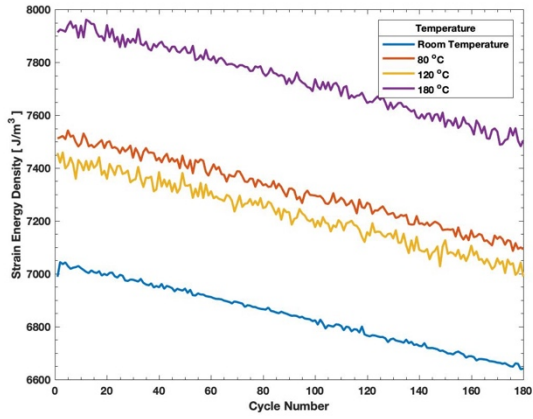
Figure B-50: 12.5 MPa - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



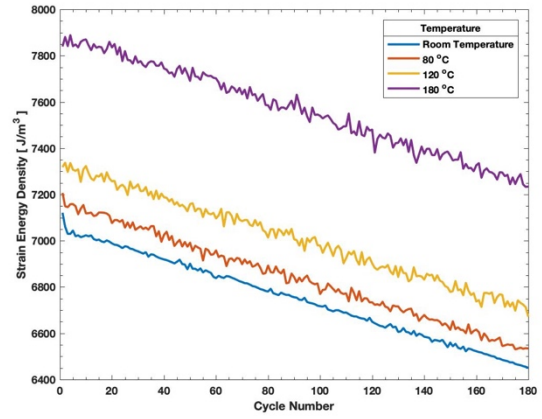
a)



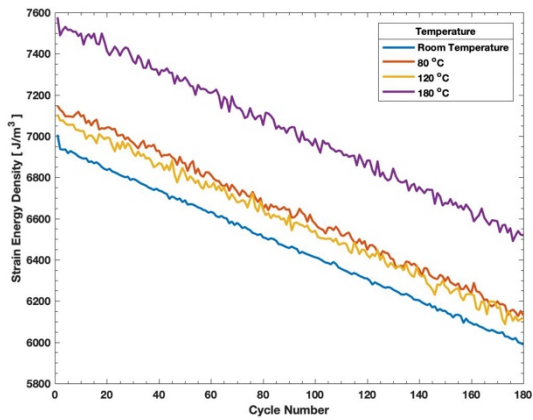
b)



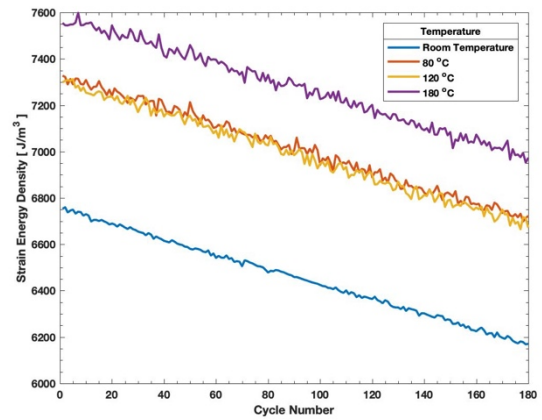
c)



d)



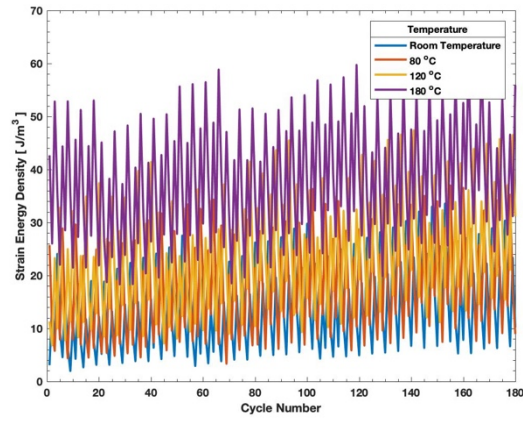
e)



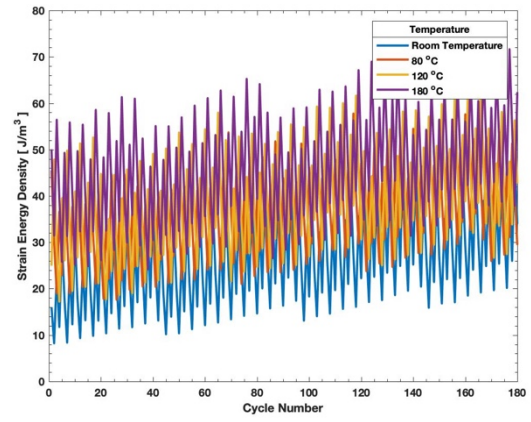
f)

Figure B-51: 12.5 MPa Continuous - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

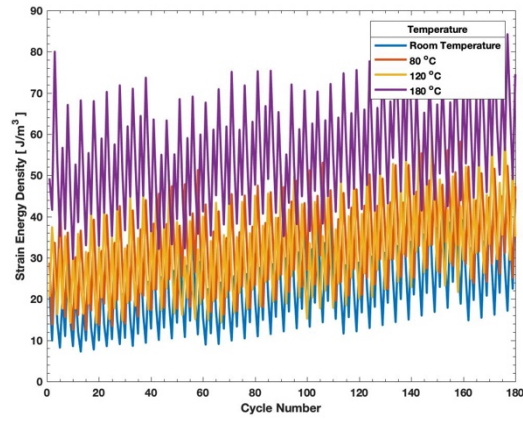
B.3.3.2 Stored - Recovery



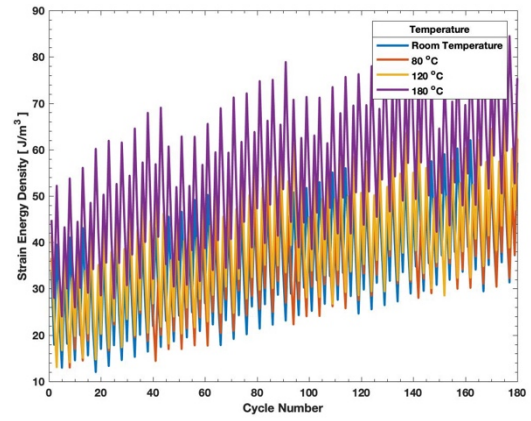
a)



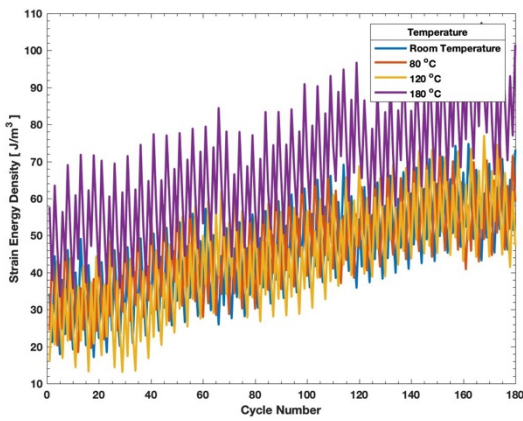
b)



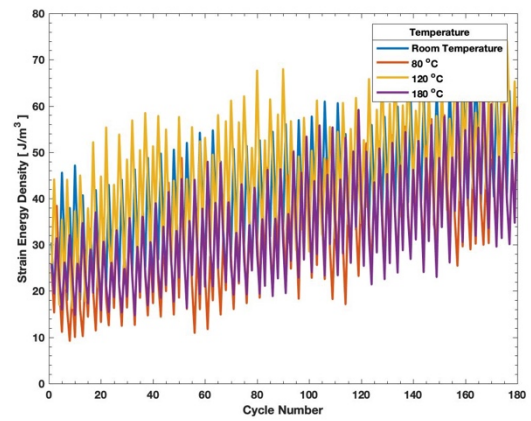
c)



d)

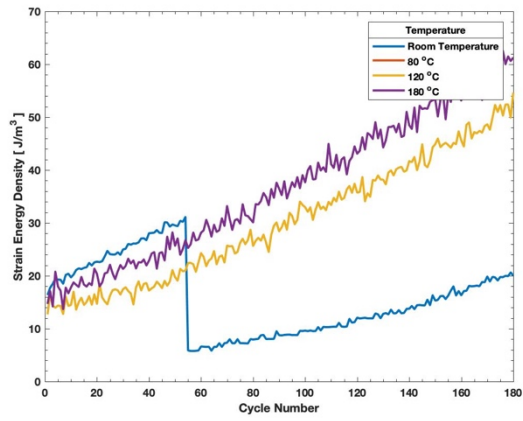


e)

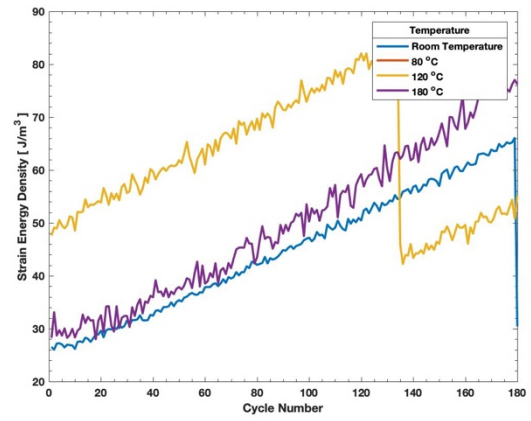


f)

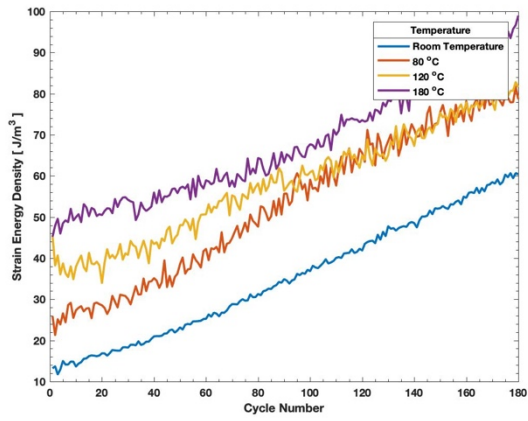
Figure B-52: 8 MPa - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



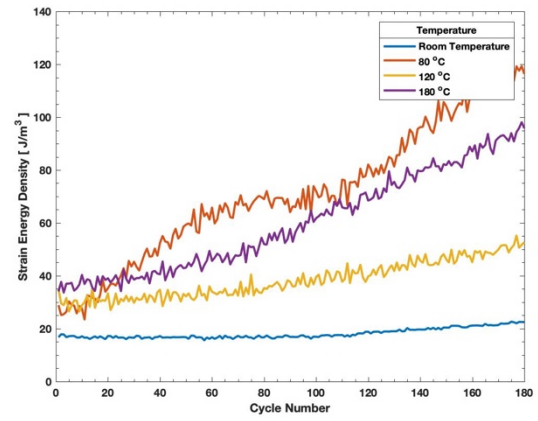
a)



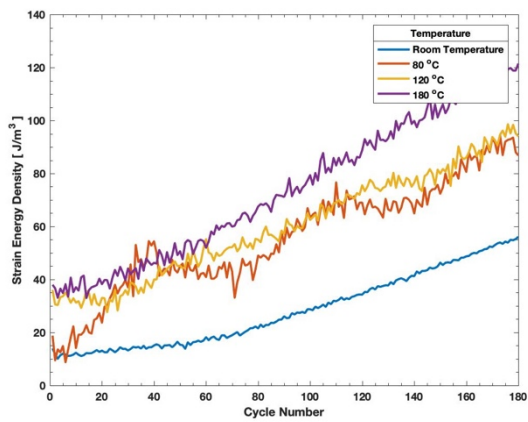
b)



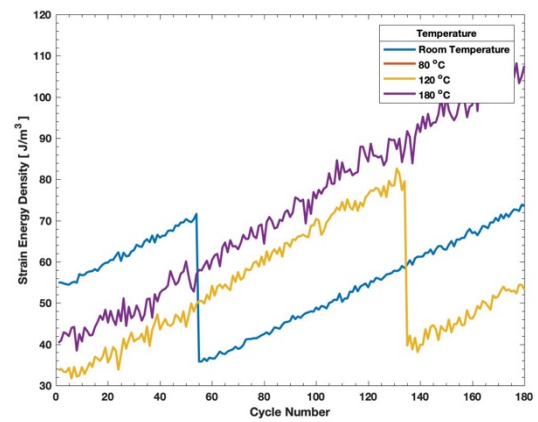
c)



d)

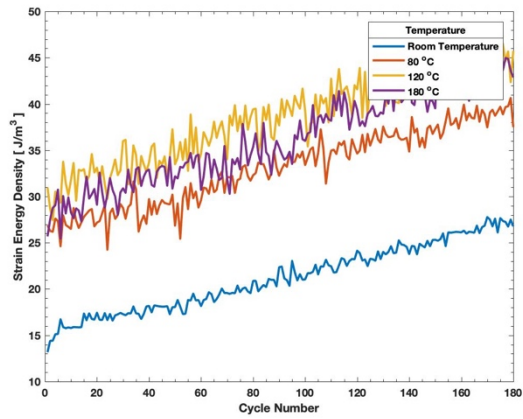


e)

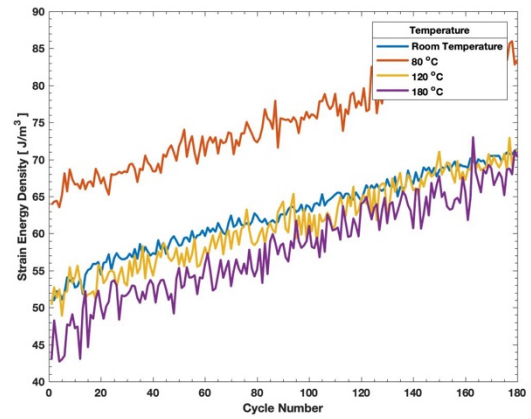


f)

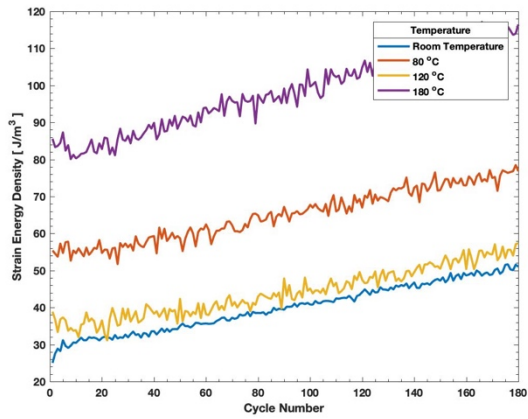
Figure B-53: 12.5 MPa - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



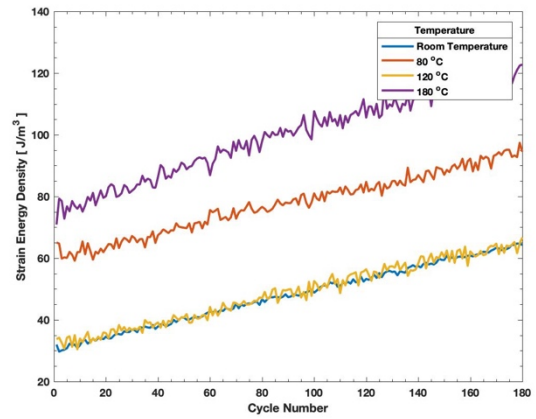
a)



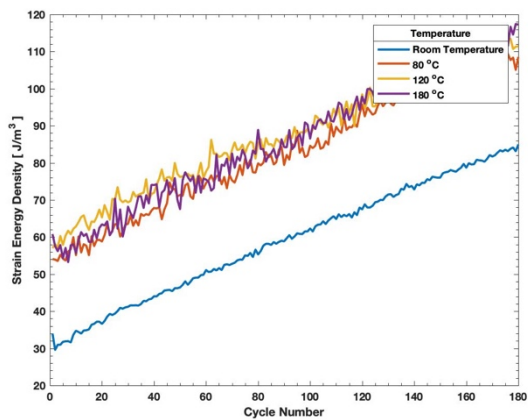
b)



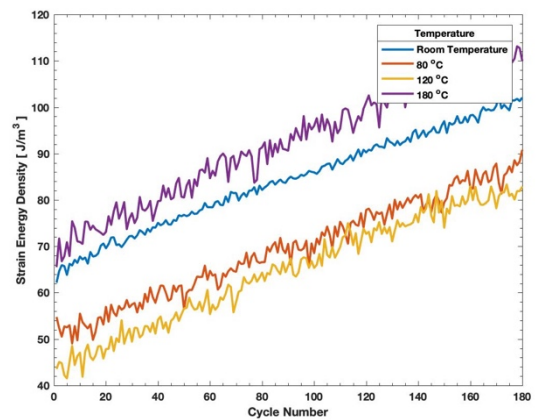
c)



d)



e)



f)

Figure B-54: 12.5 MPa Continuous - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

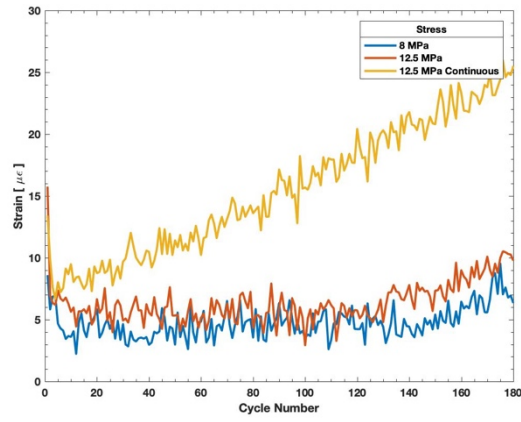
Appendix C Effect of Applied Load

The following appendix presents the generated plots showing the various properties as a function of cycles for all applied loads for a given recovery duration-temperature combination.

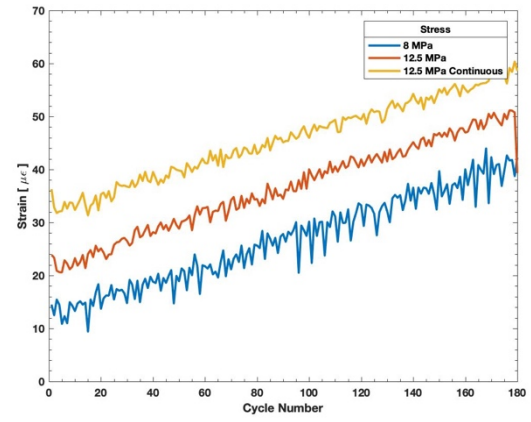
C.1 Strain

C.1.1 Creep / Recovered

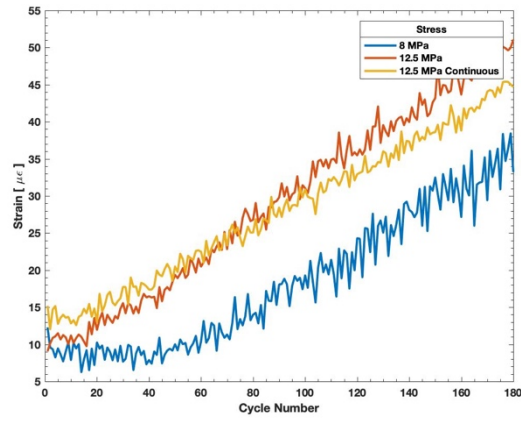
C.1.1.1 Creep Strain



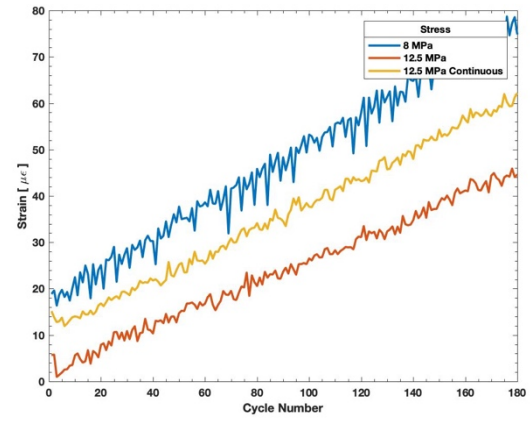
a)



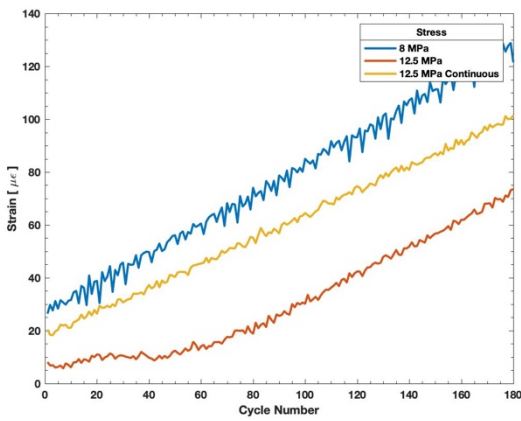
b)



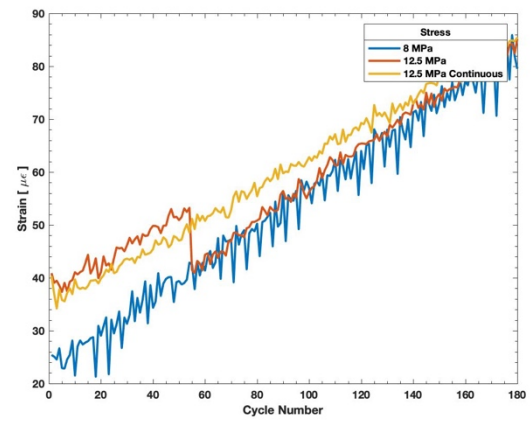
c)



d)

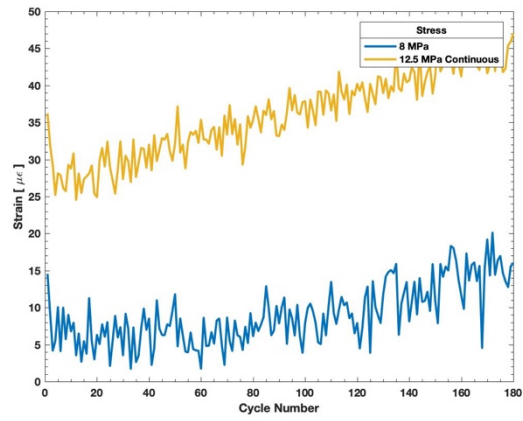


e)

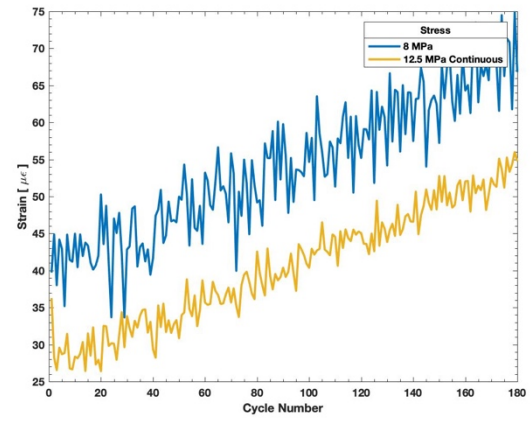


f)

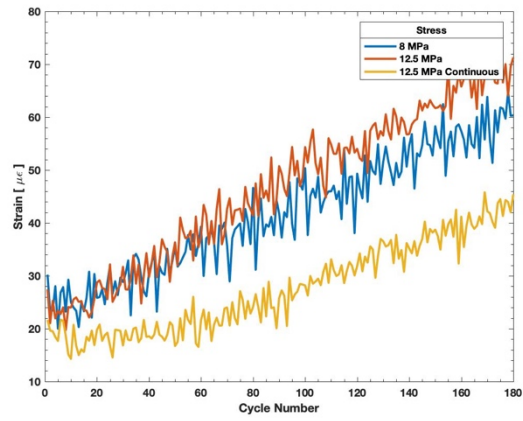
Figure C-1: Room Temperature - Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



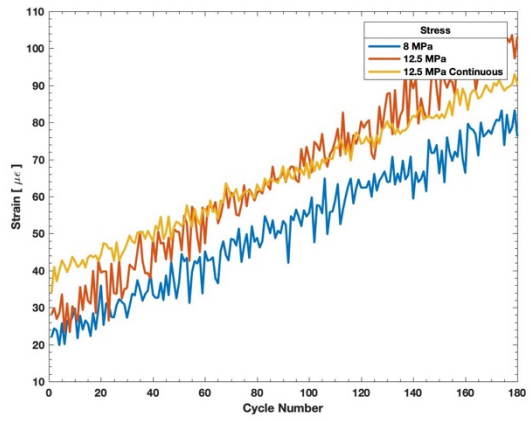
a)



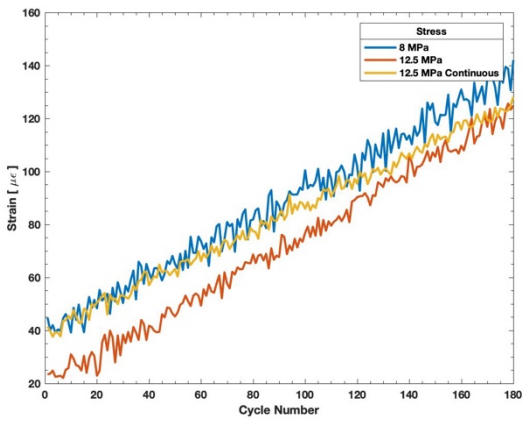
b)



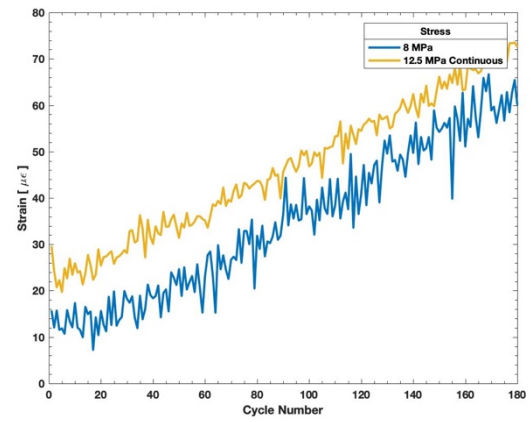
c)



d)

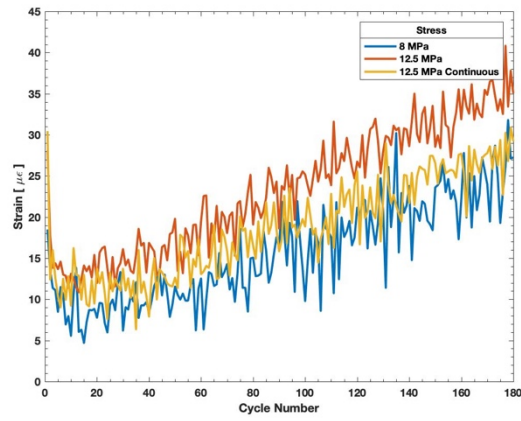


e)

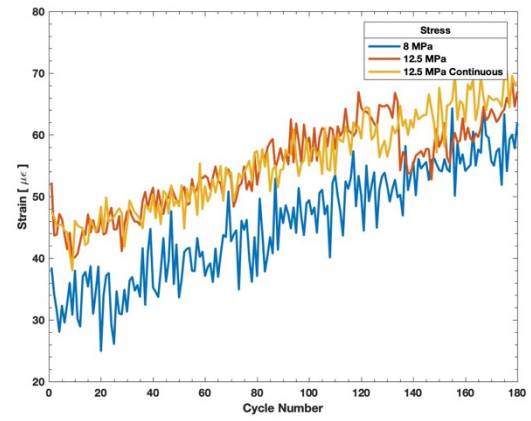


f)

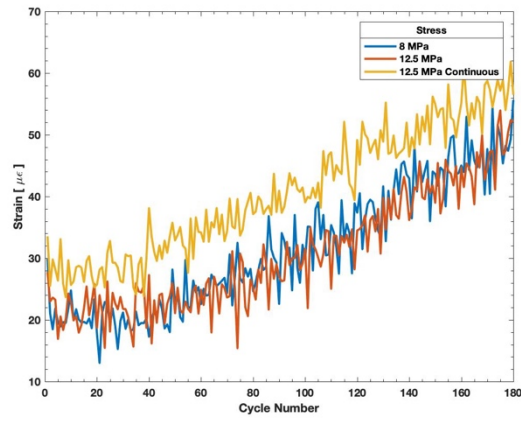
Figure C-2: 80 °C - Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



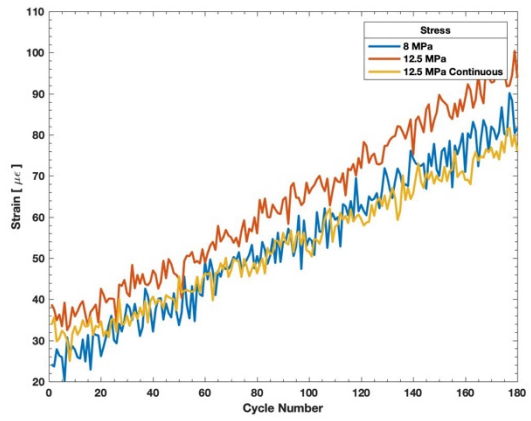
a)



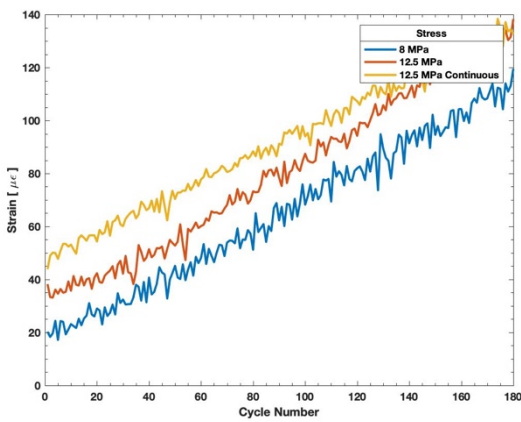
b)



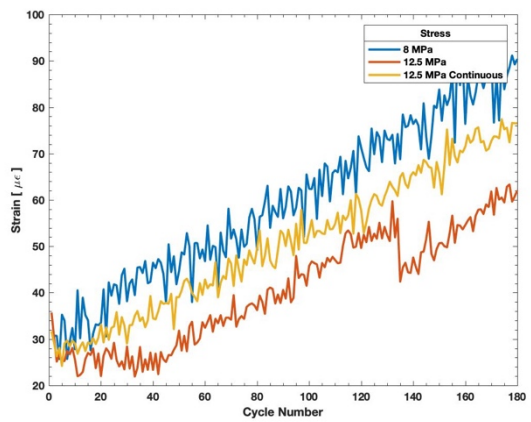
c)



d)

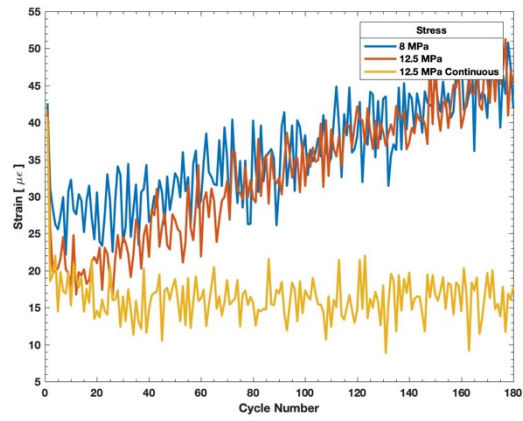


e)

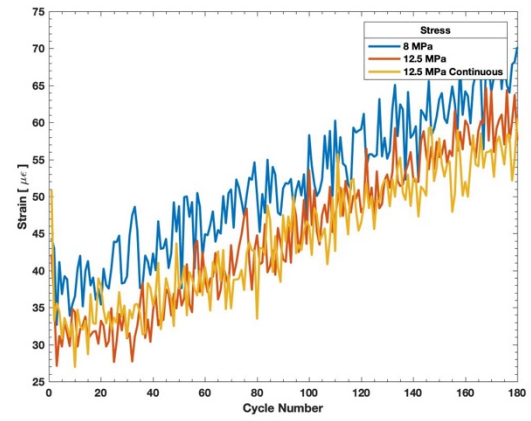


f)

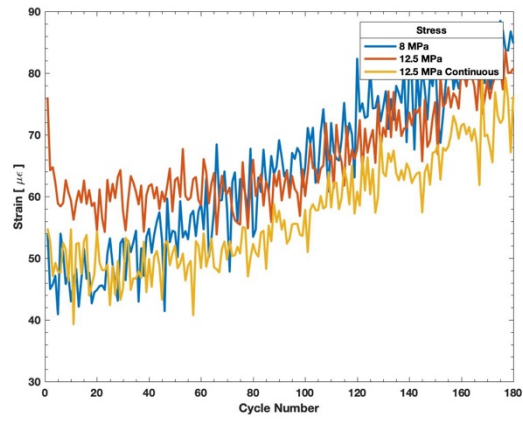
Figure C-3: 120 °C - Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



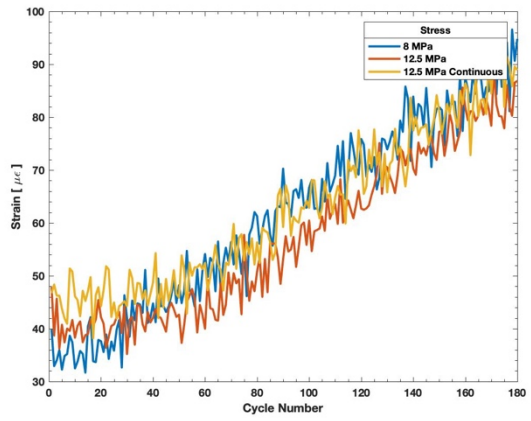
a)



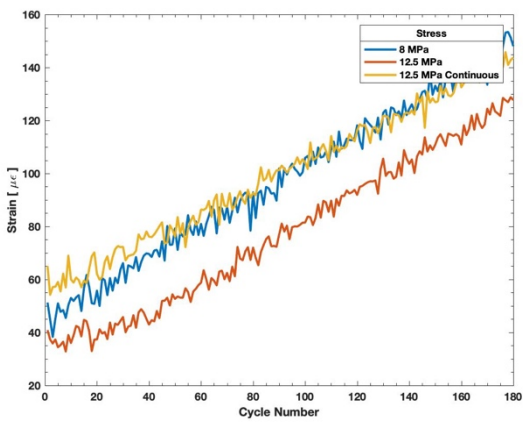
b)



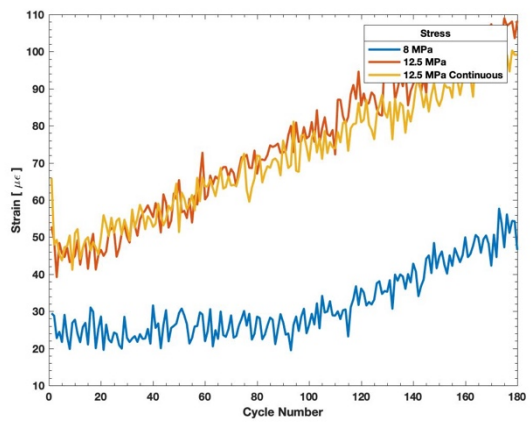
c)



d)



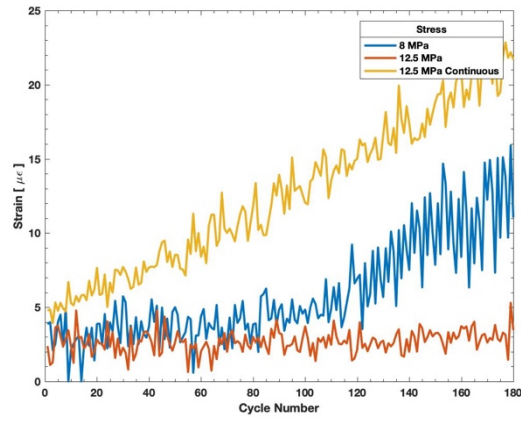
e)



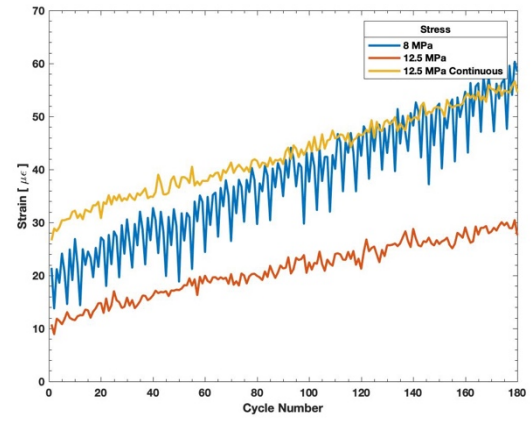
f)

Figure C-4: 180 °C - Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

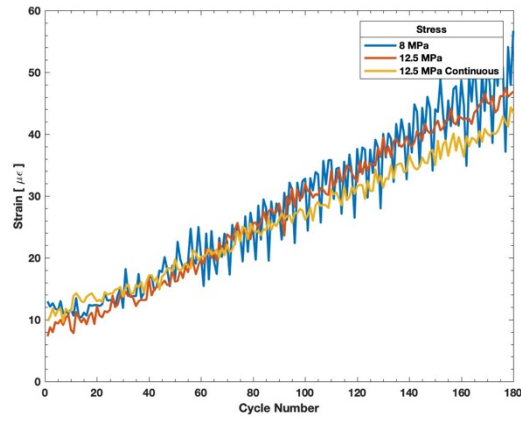
C.1.1.2 Recovered Strain



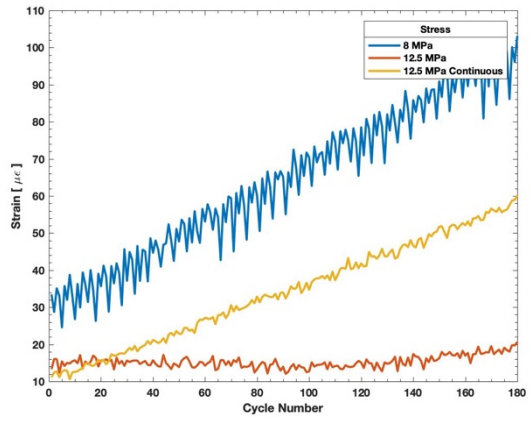
a)



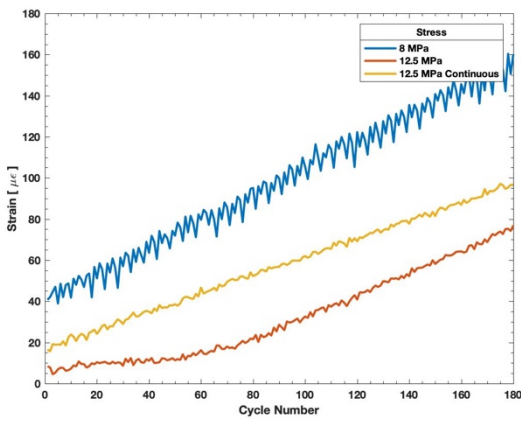
b)



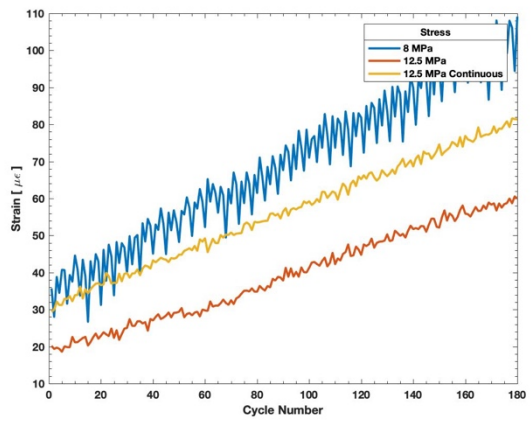
c)



d)

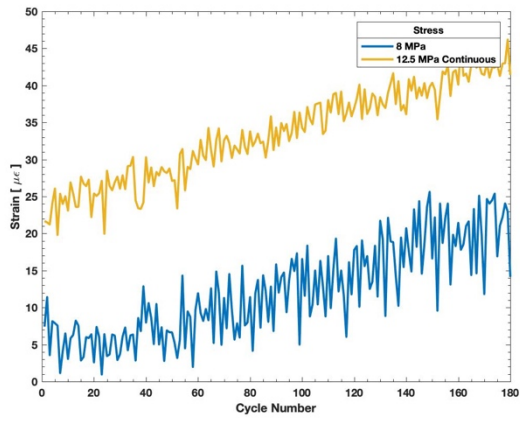


e)

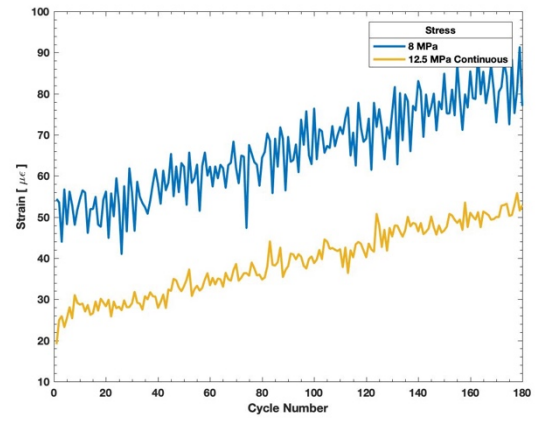


f)

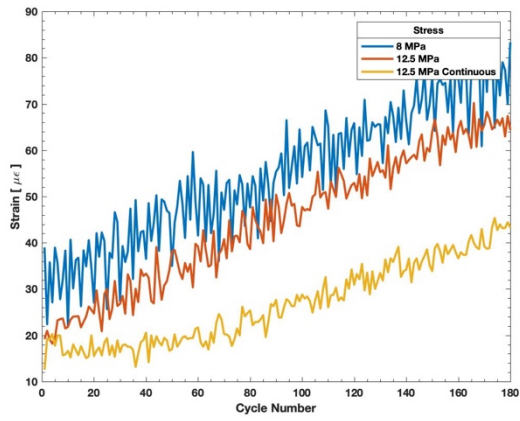
Figure C-5: Room Temperature - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



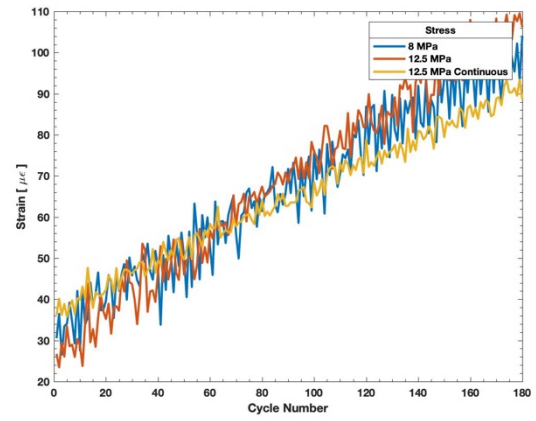
a)



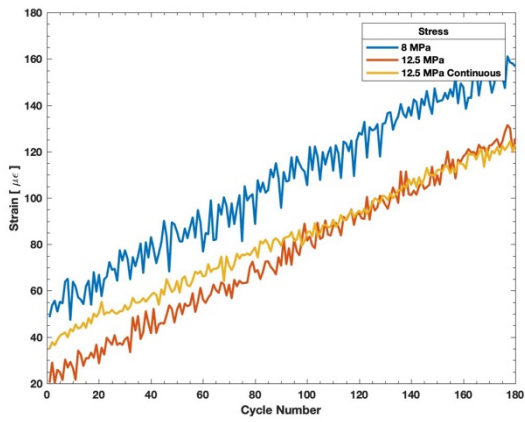
b)



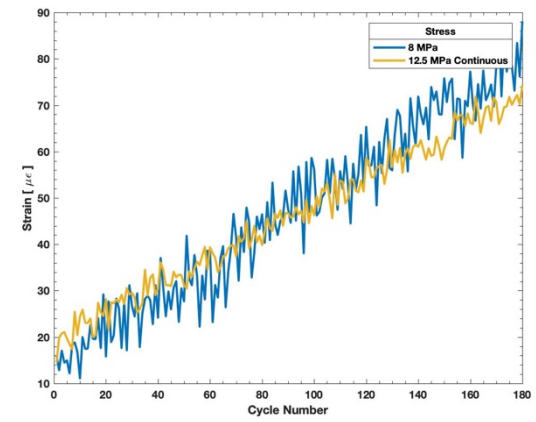
c)



d)

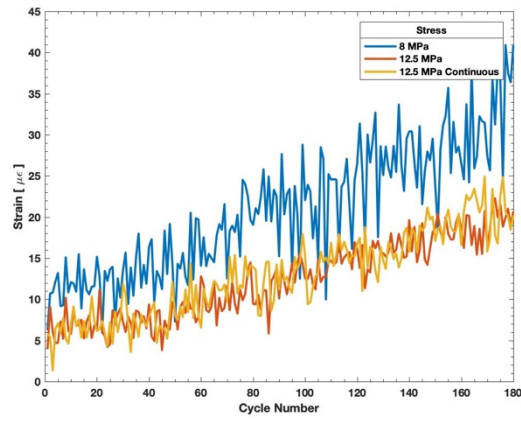


e)

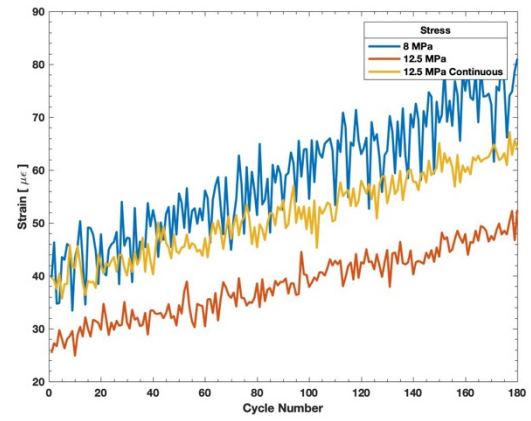


f)

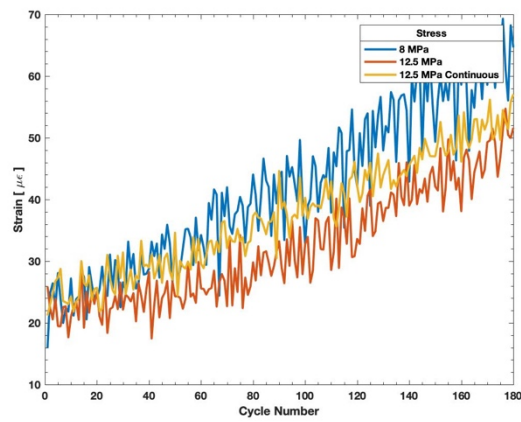
Figure C-6: 80 °C - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



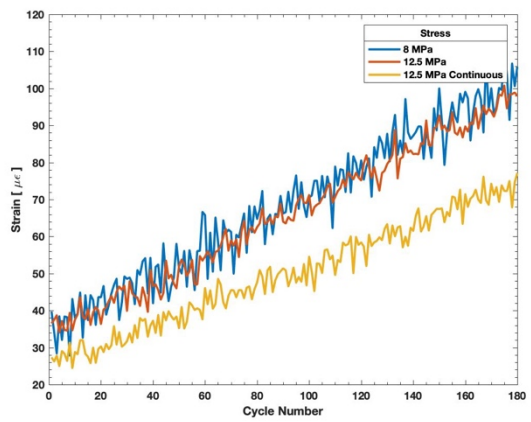
a)



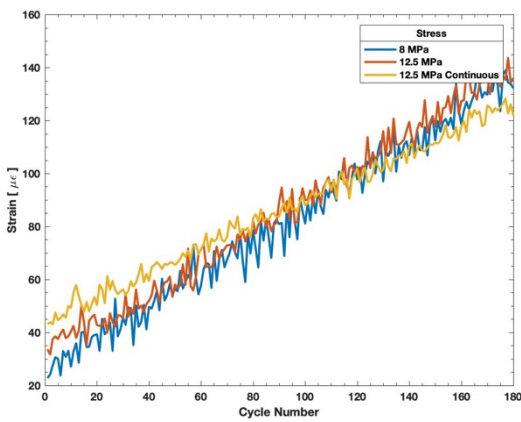
b)



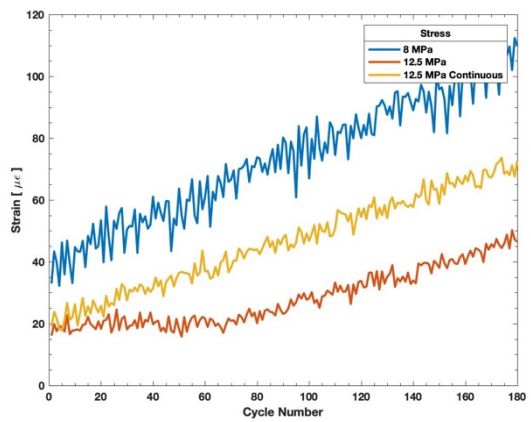
c)



d)

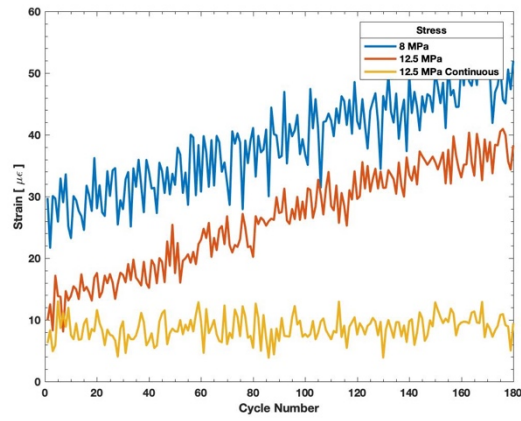


e)

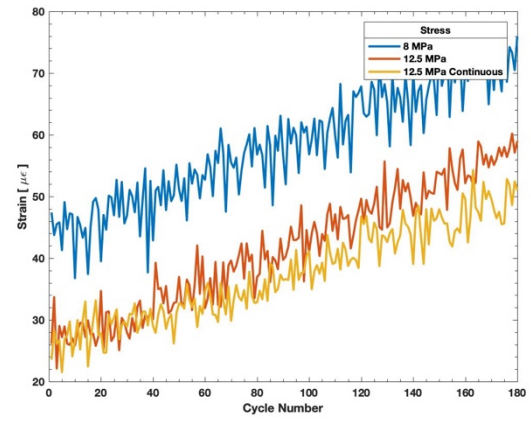


f)

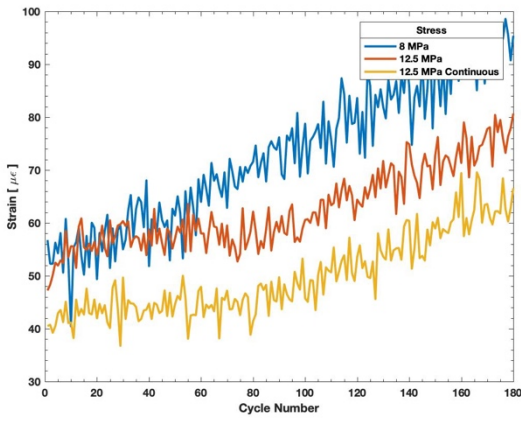
Figure C-7: 120 °C - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



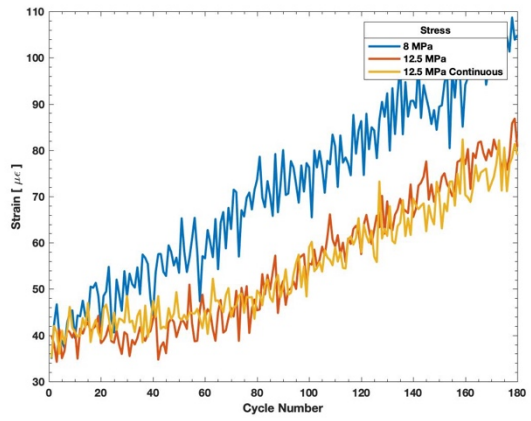
a)



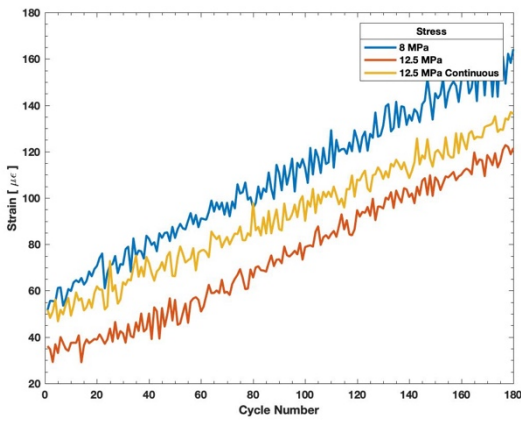
b)



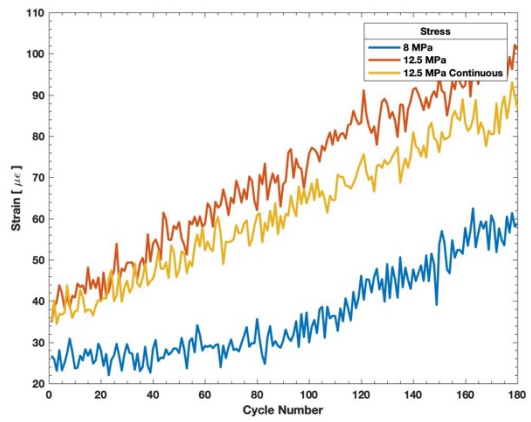
c)



d)



e)



f)

Figure C-8: 180 °C - Recovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.1.1.3 Unrecovered Creep Strain

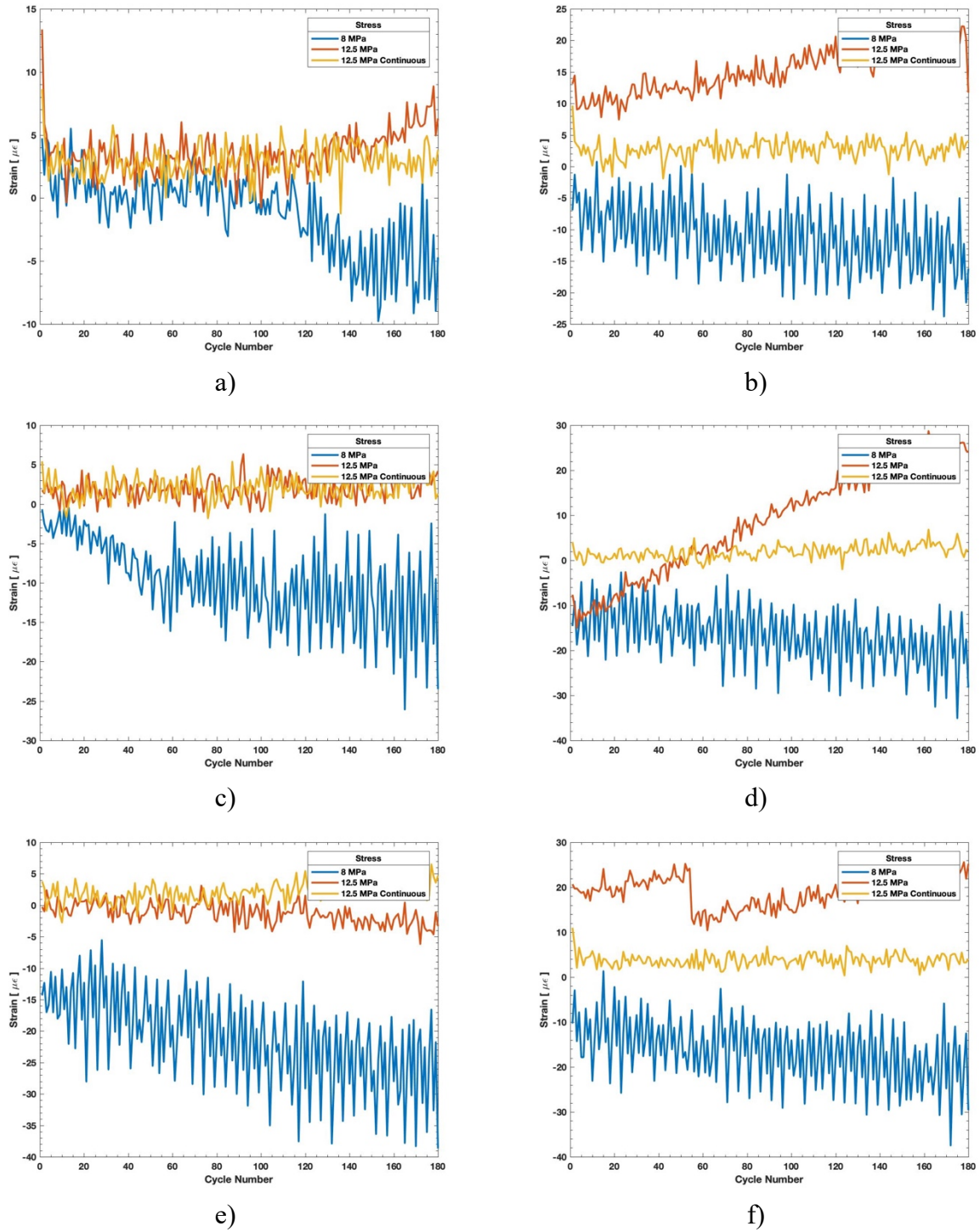
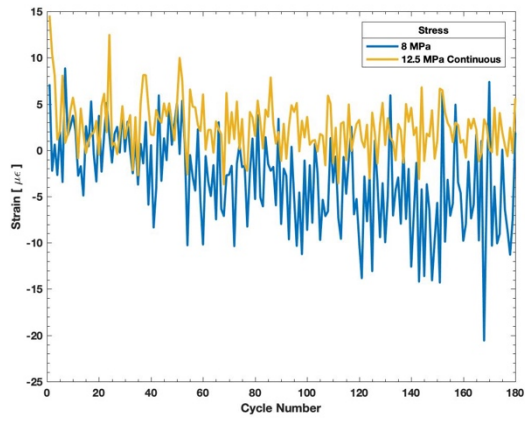
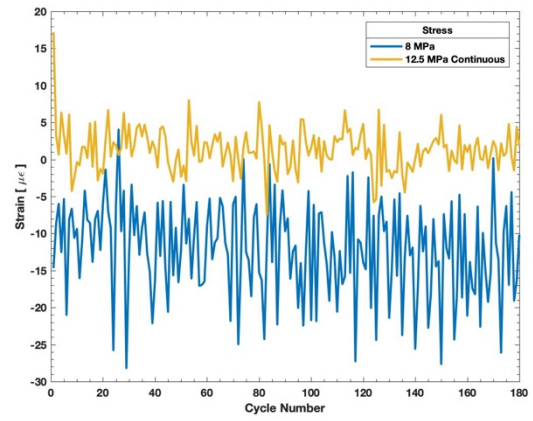


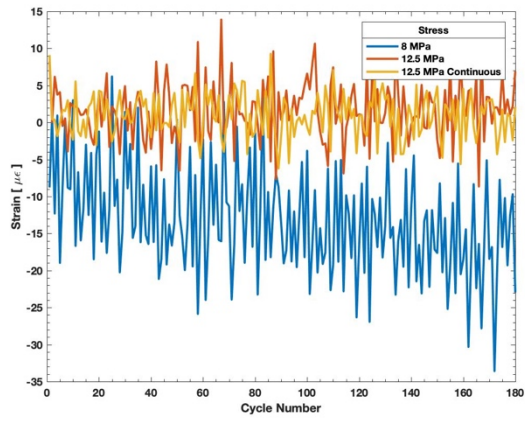
Figure C-9: Room Temperature - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



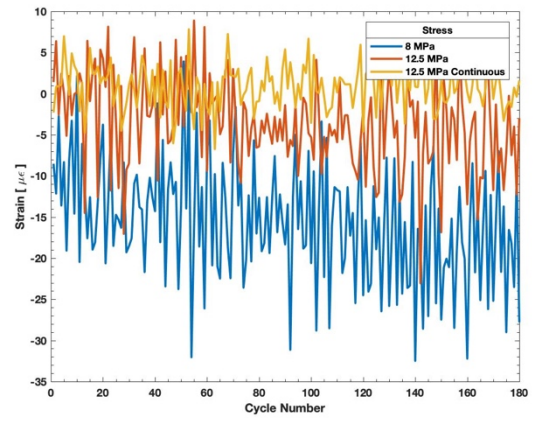
a)



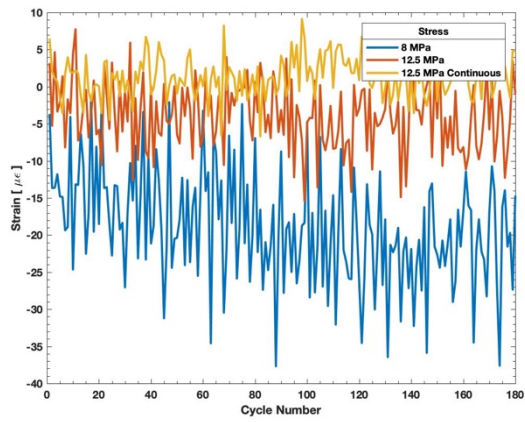
b)



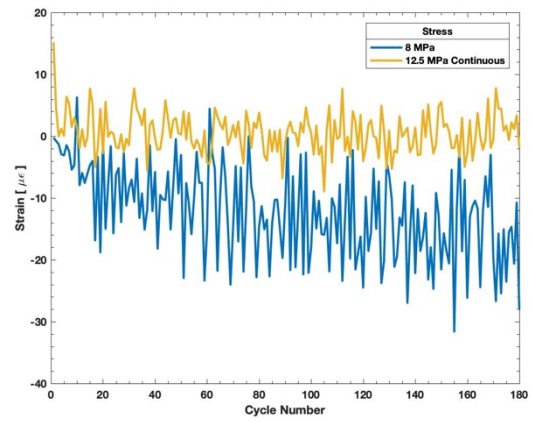
c)



d)

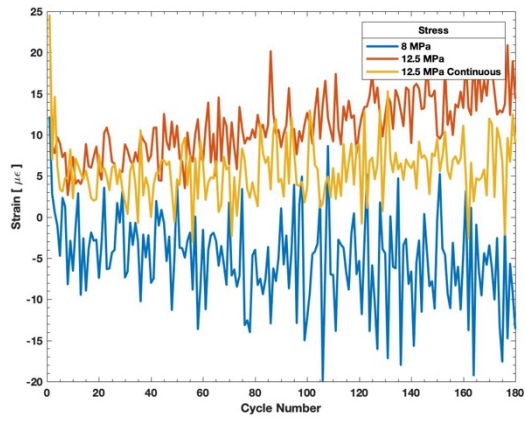


e)

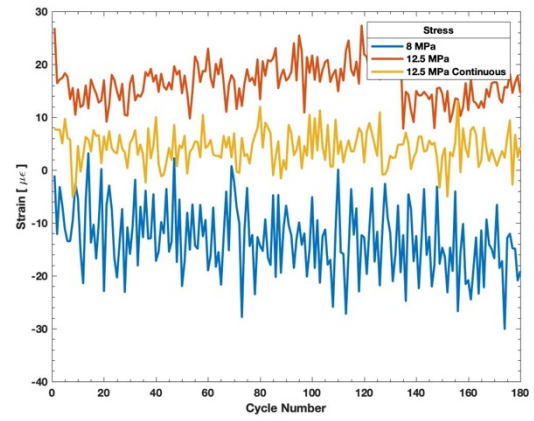


f)

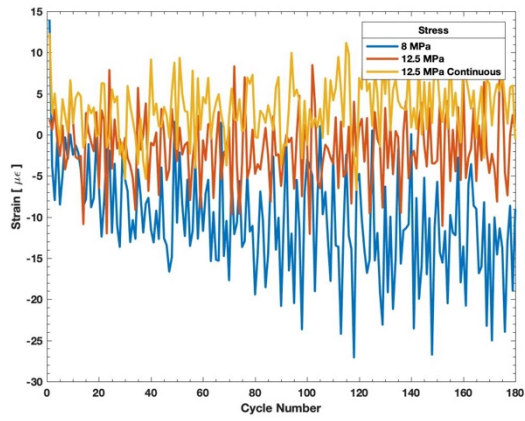
Figure C-10: 80 °C - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



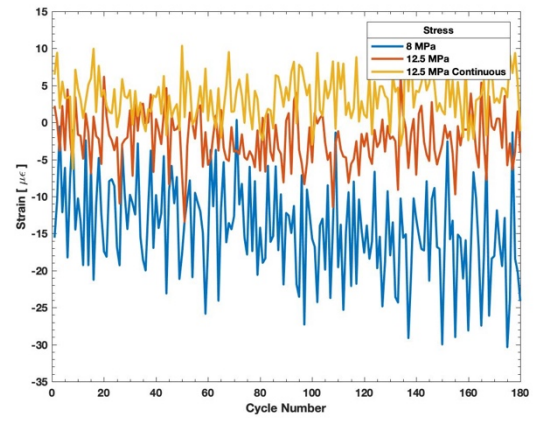
a)



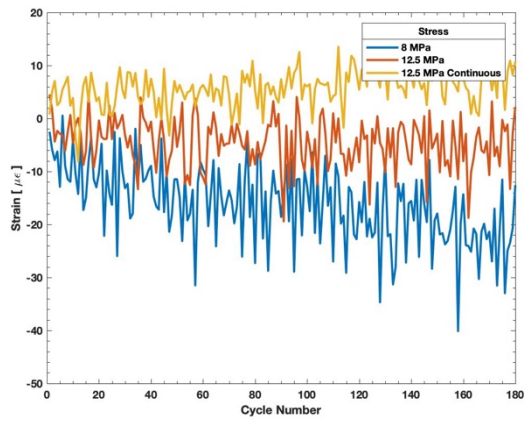
b)



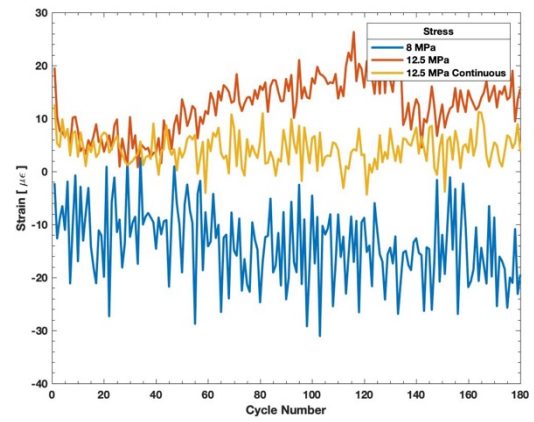
c)



d)

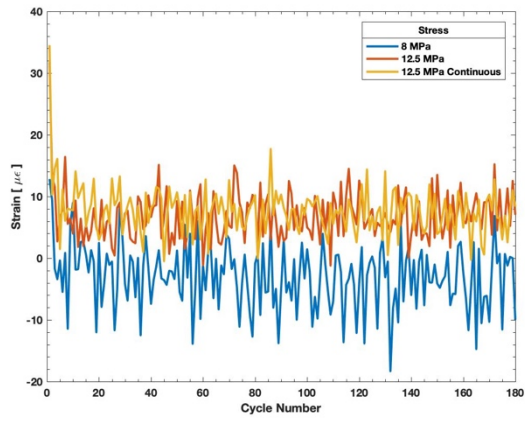


e)

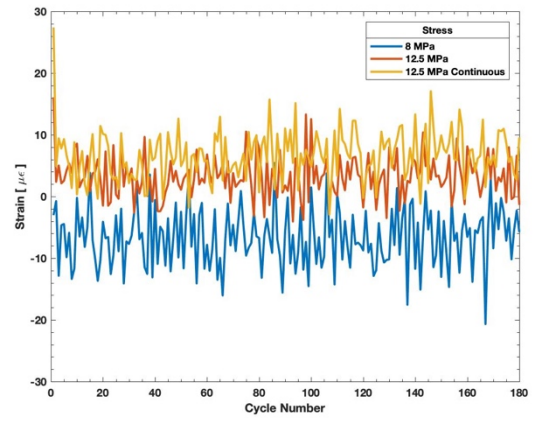


f)

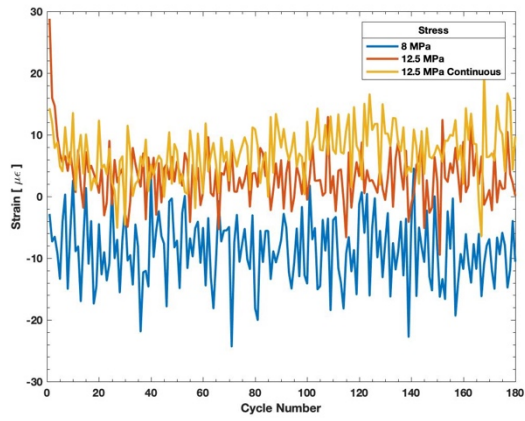
Figure C-11: 120 °C - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



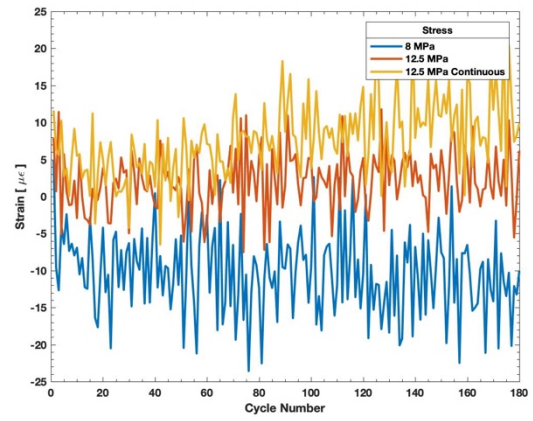
a)



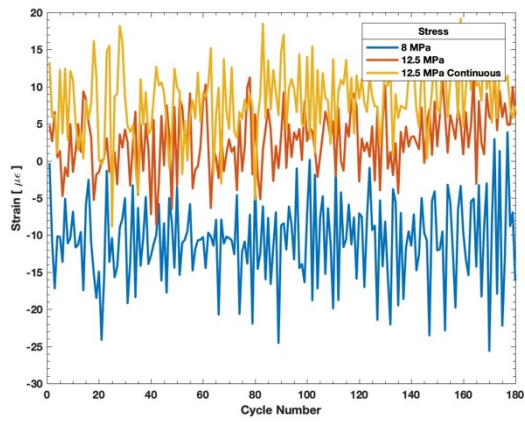
b)



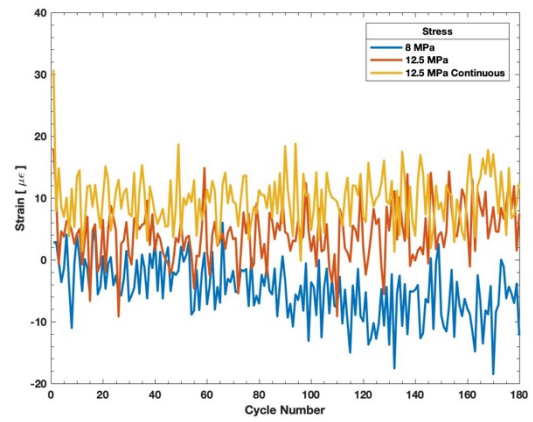
c)



d)



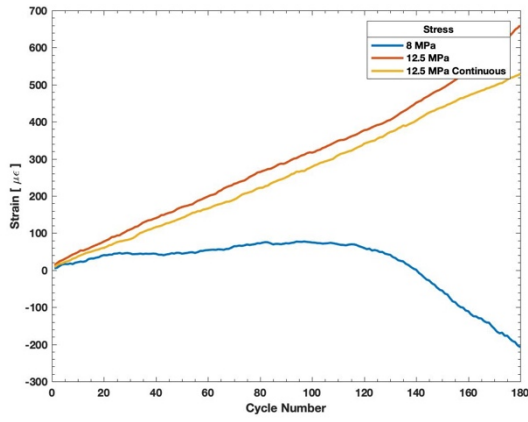
e)



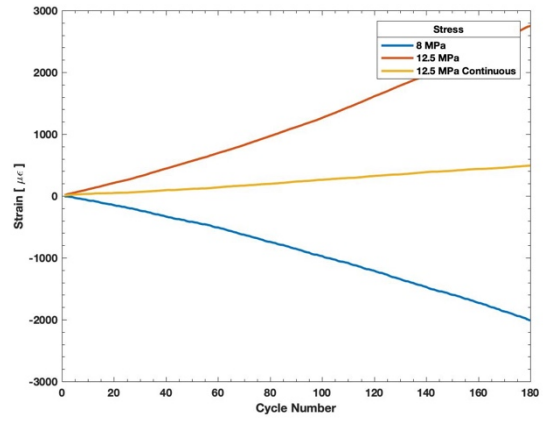
f)

Figure C-12: 180 °C - Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

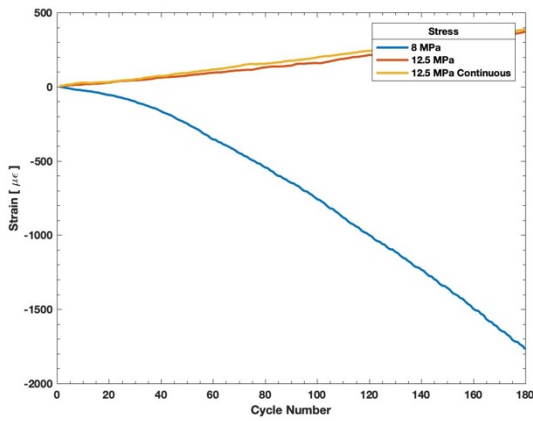
C.1.1.4 Accumulated Unrecovered Creep Strain



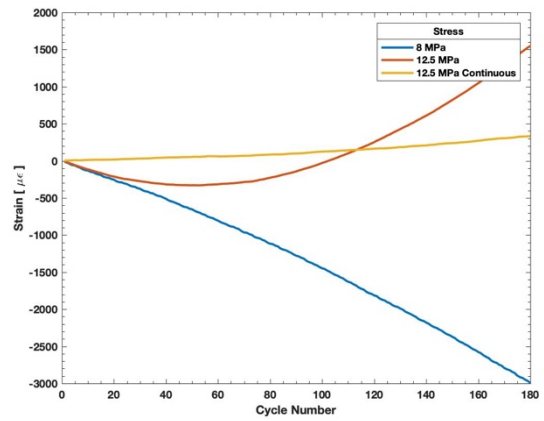
a)



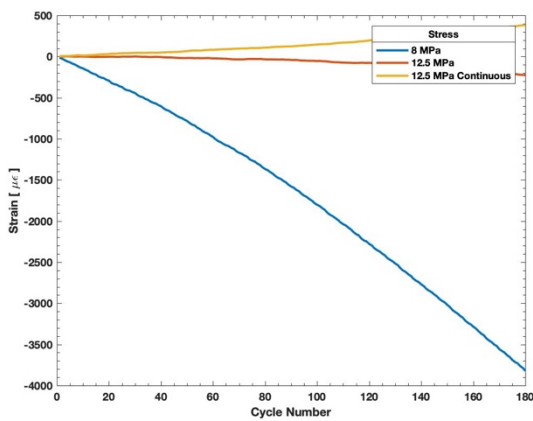
b)



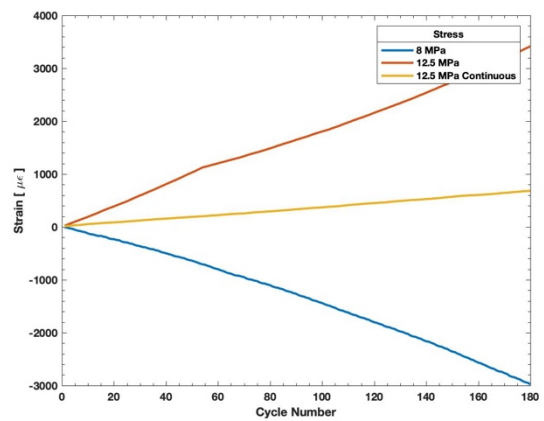
c)



d)

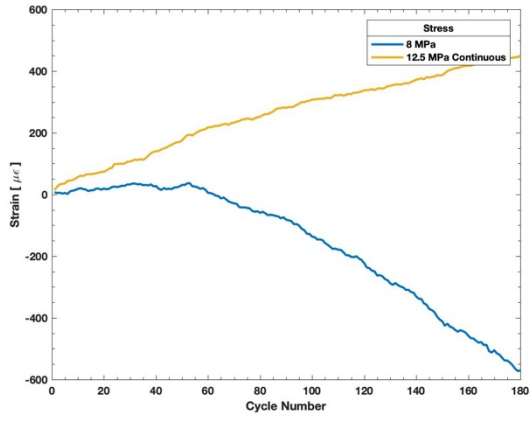


e)

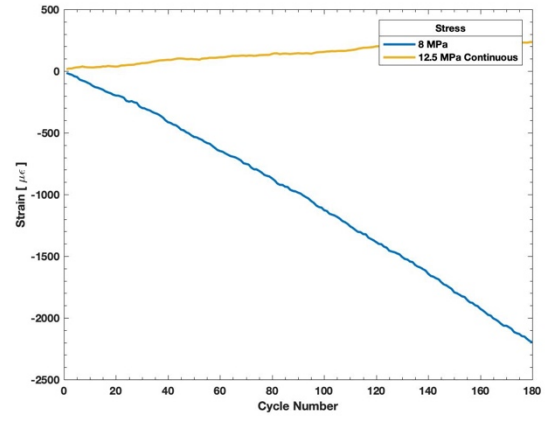


f)

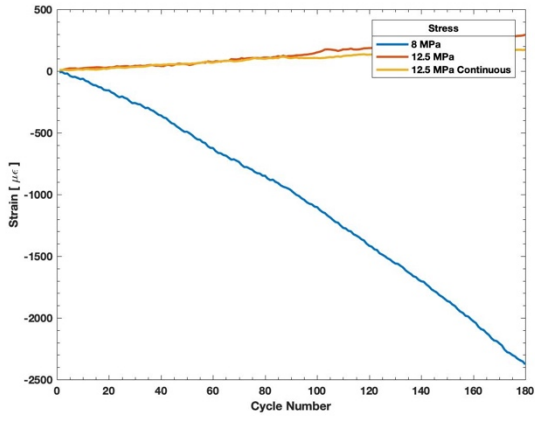
Figure C-13: Room Temperature - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



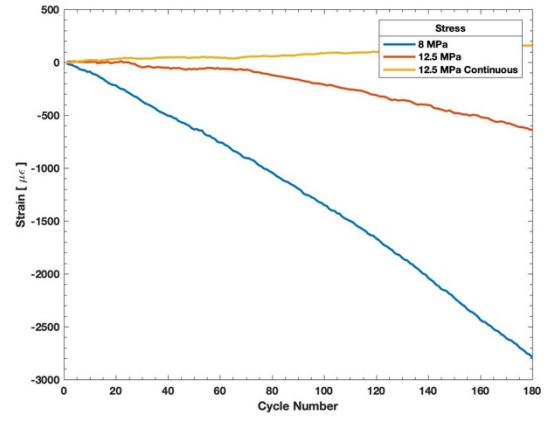
a)



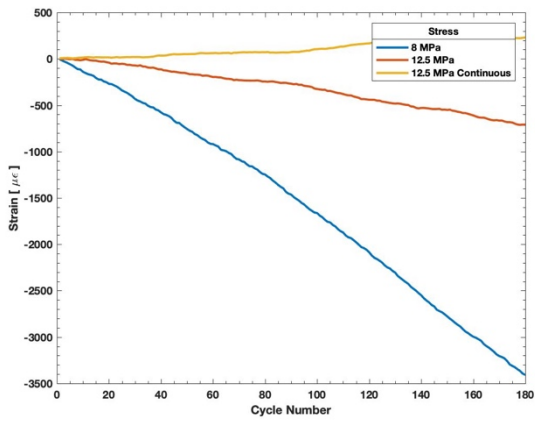
b)



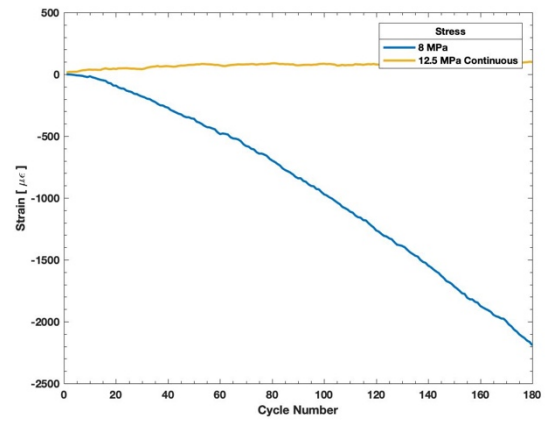
c)



d)

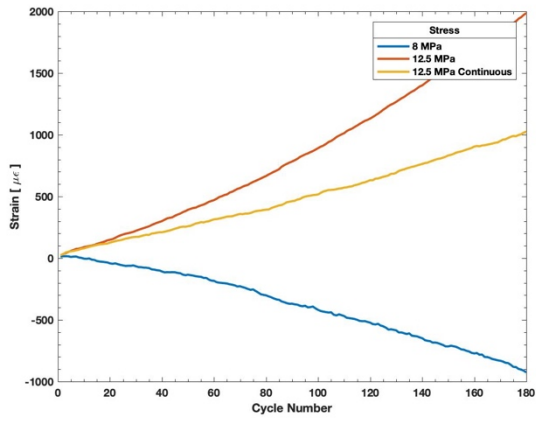


e)

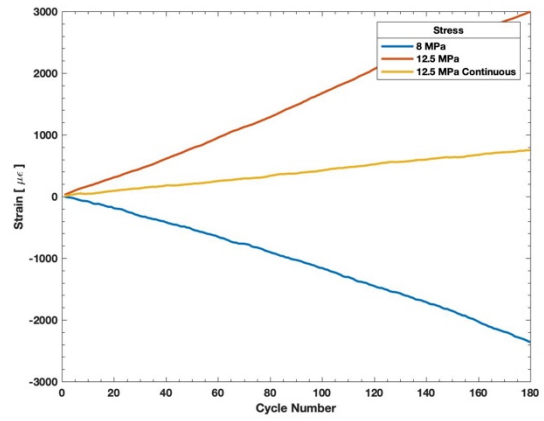


f)

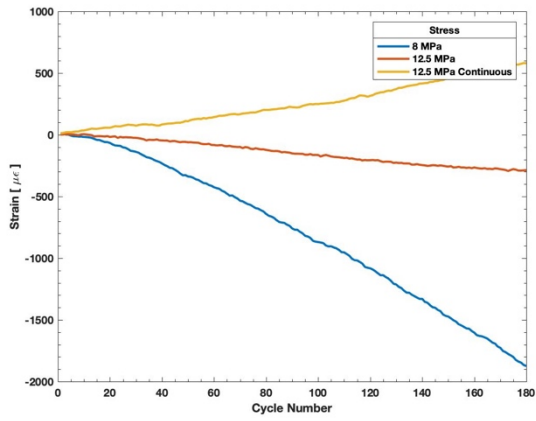
Figure C-14: 80 °C - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



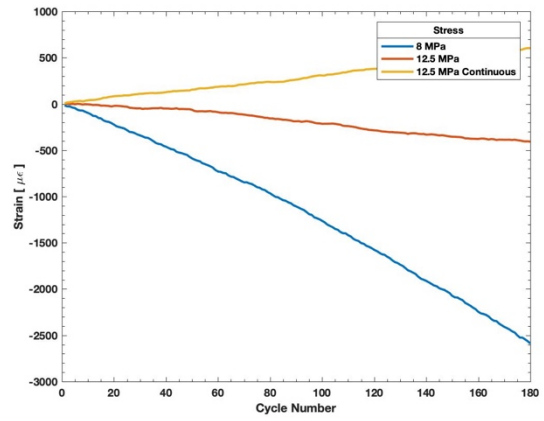
a)



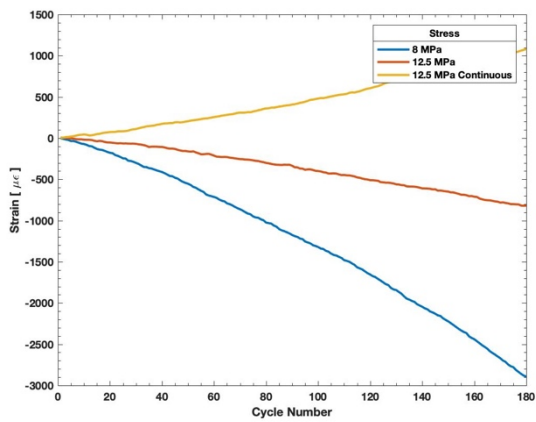
b)



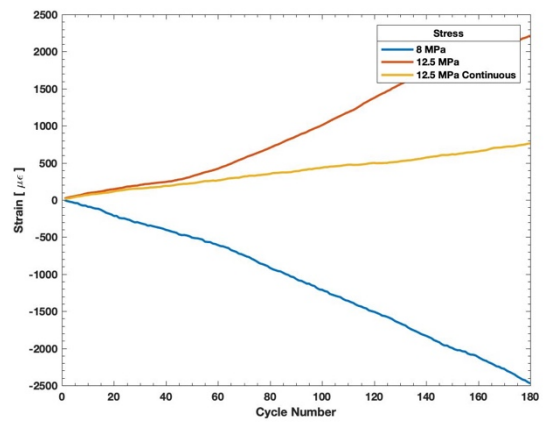
c)



d)

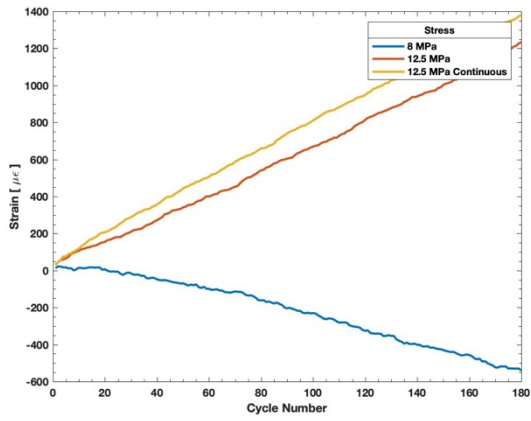


e)

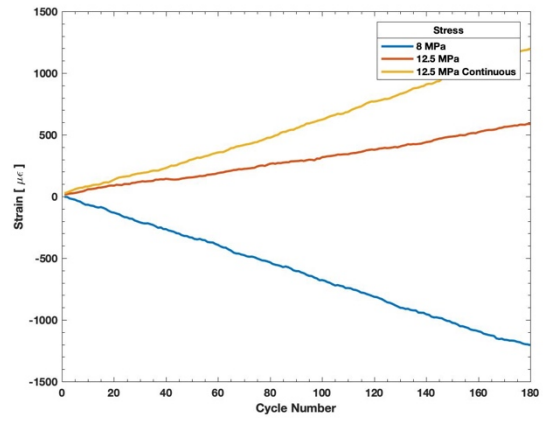


f)

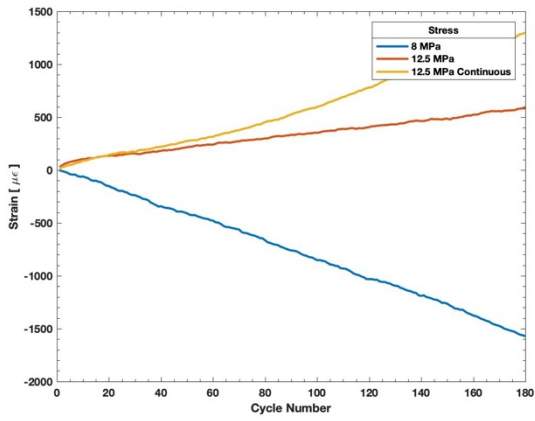
Figure C-15: 120 °C - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



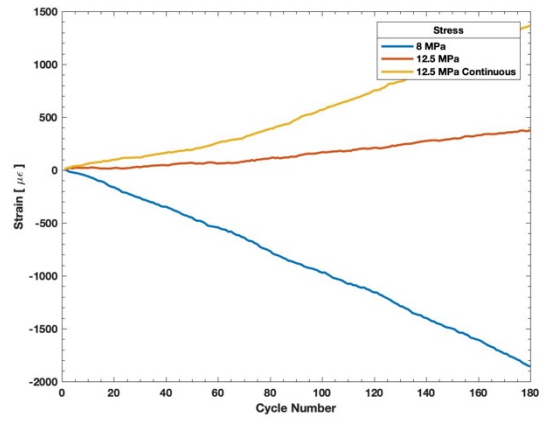
a)



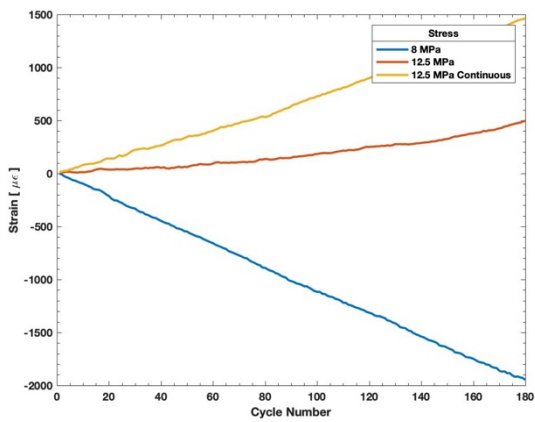
b)



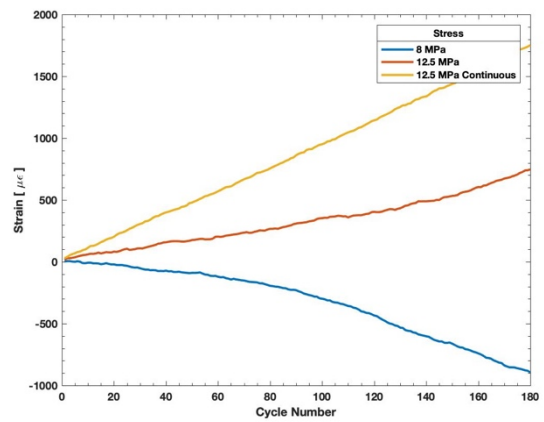
c)



d)



e)



f)

Figure C-16: 180 °C - Accumulated Unrecovered Creep Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.1.2 Unrecovered

C.1.2.1 Total Unrecovered Strain

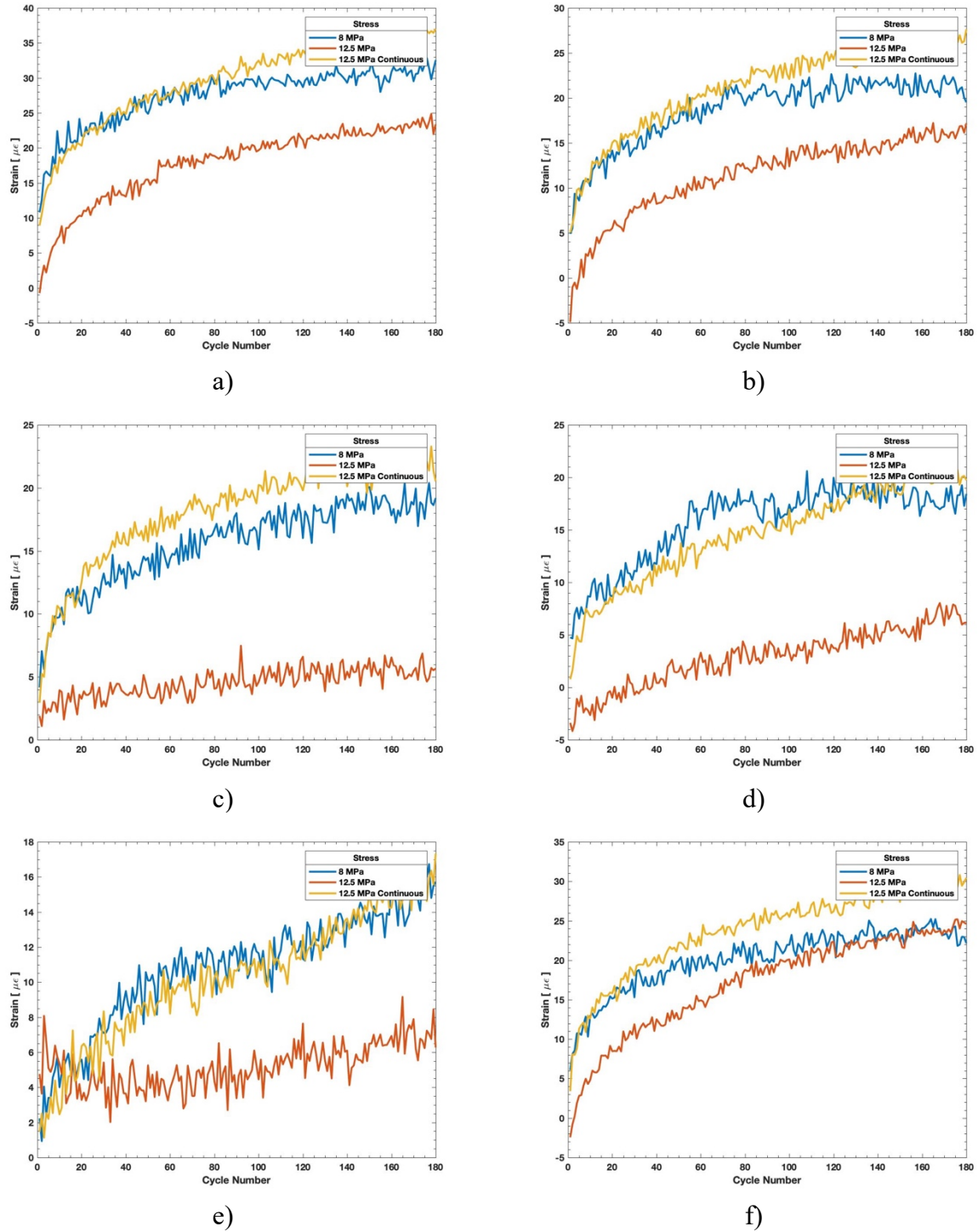
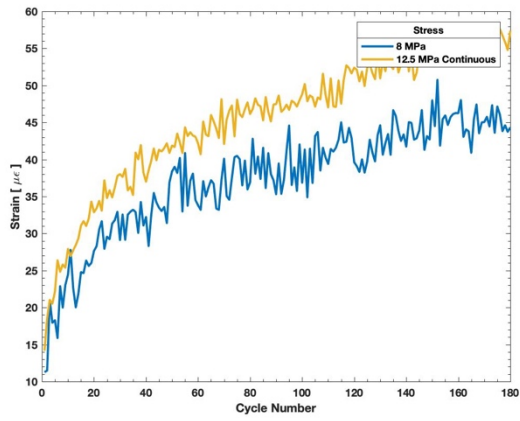
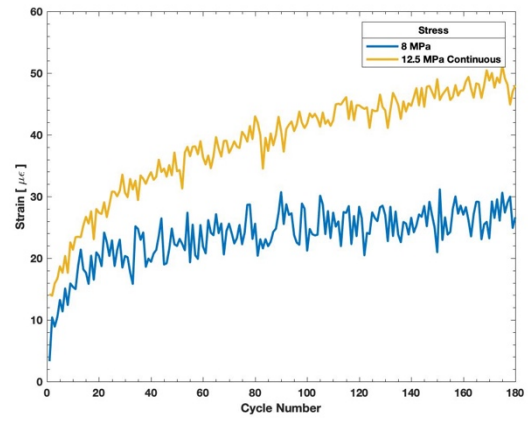


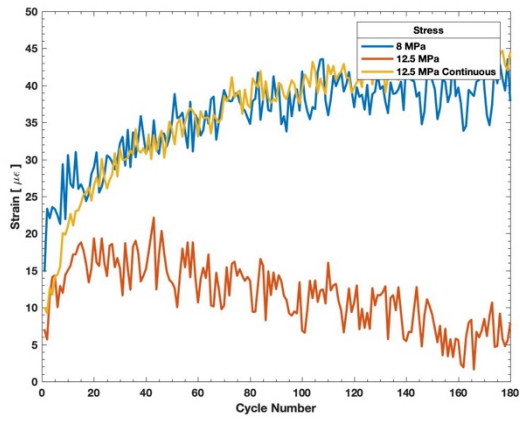
Figure C-17: Room Temperature - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



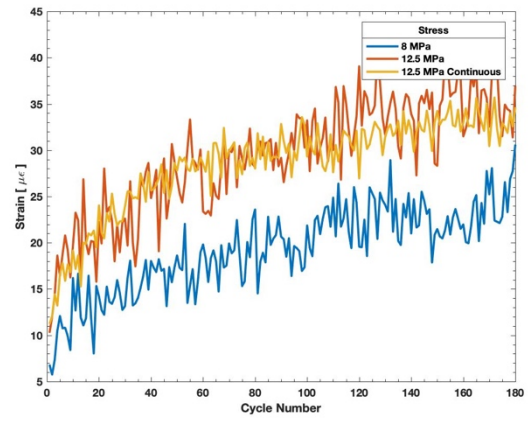
a)



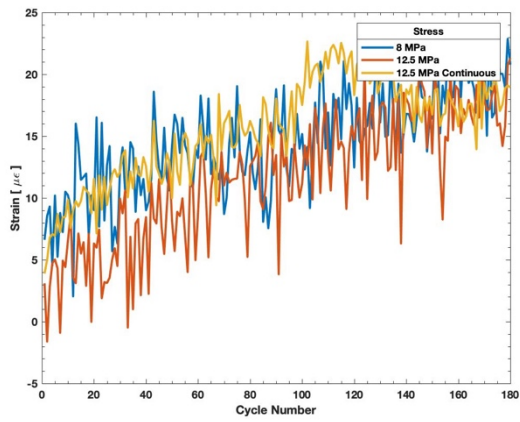
b)



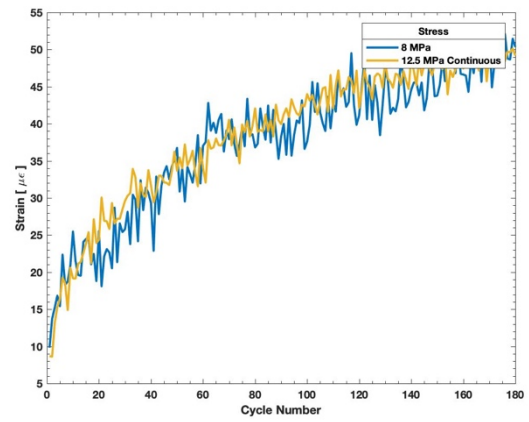
c)



d)

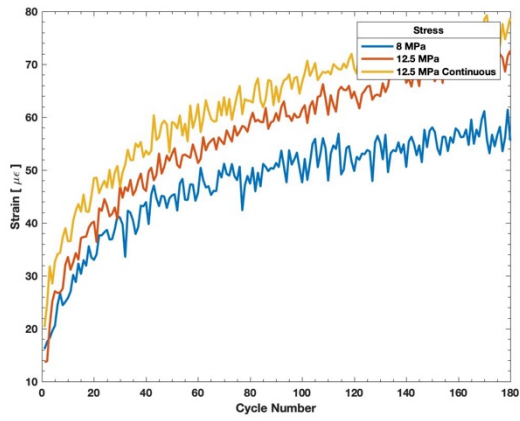


e)

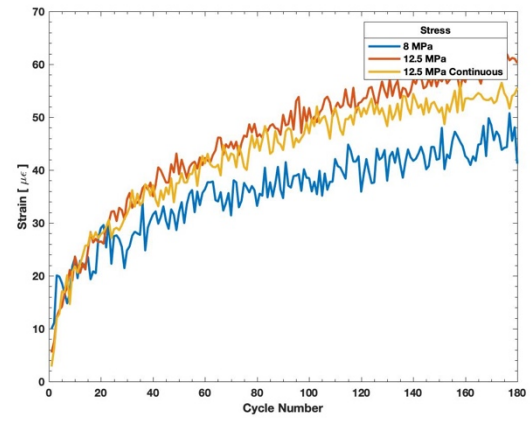


f)

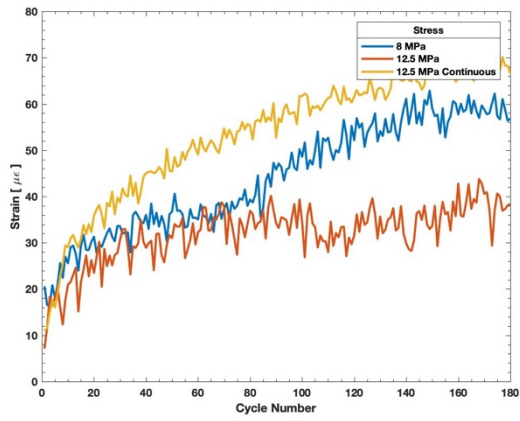
Figure C-18: 80 °C - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



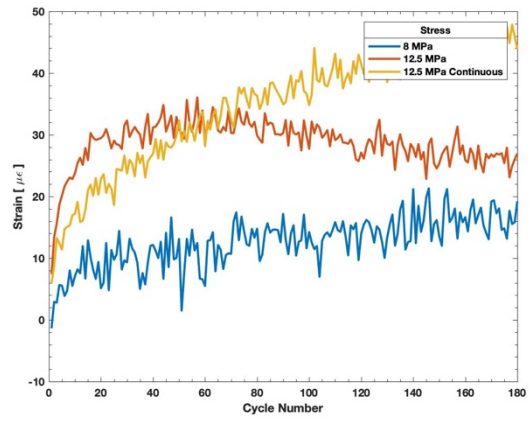
a)



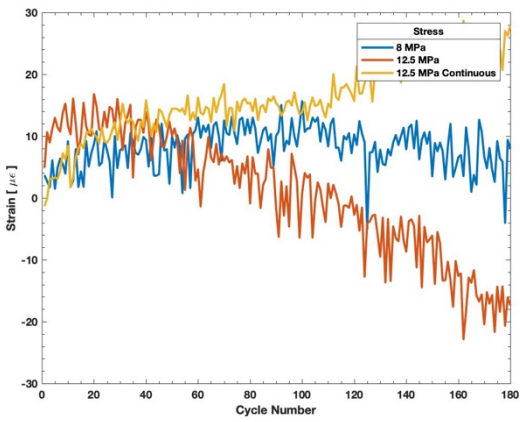
b)



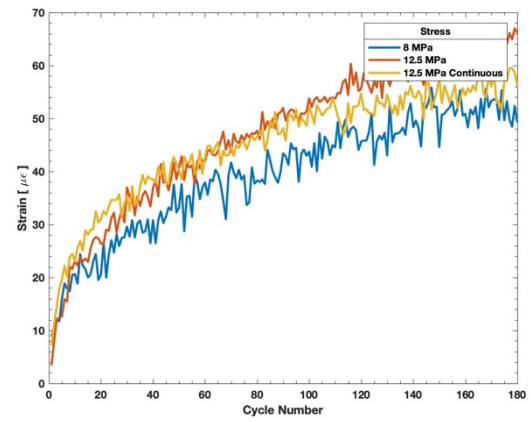
c)



d)

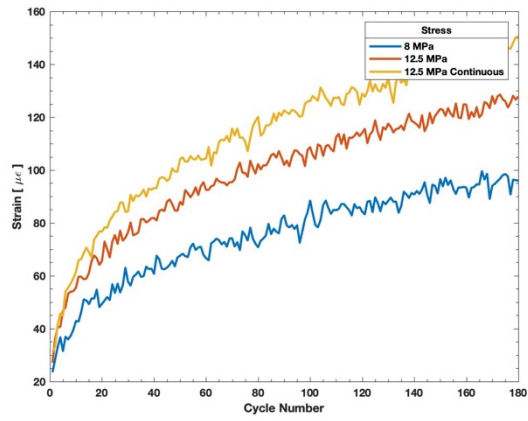


e)

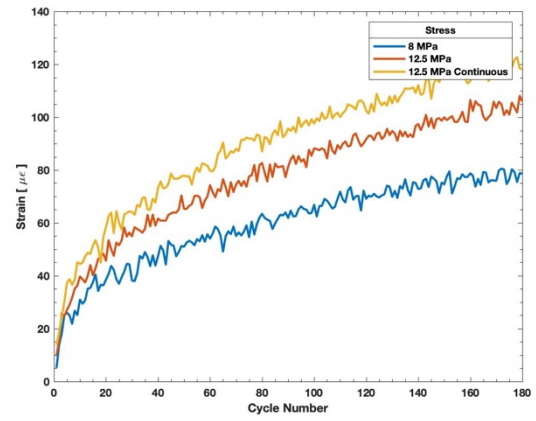


f)

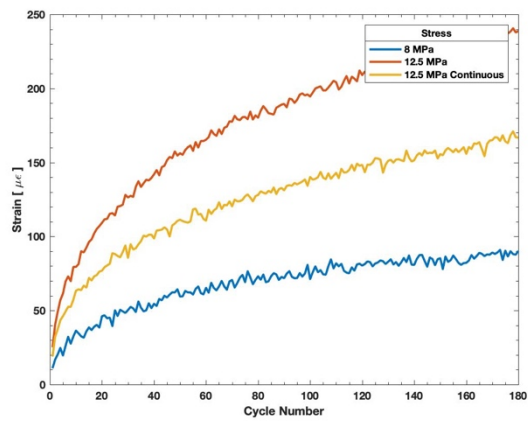
Figure C-19: 120 °C - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



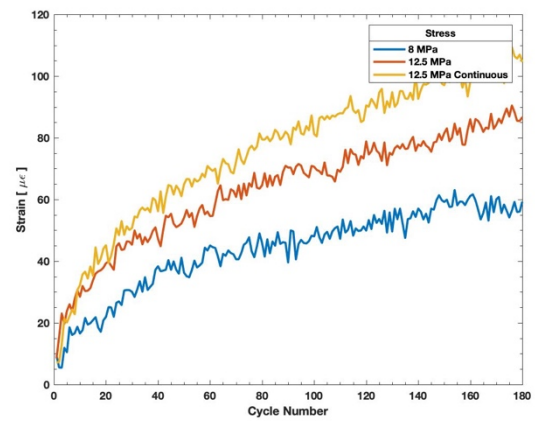
a)



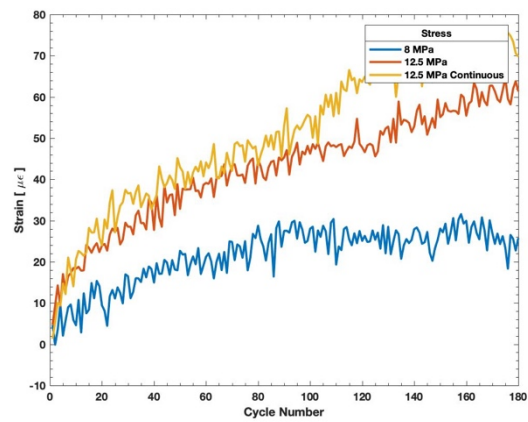
b)



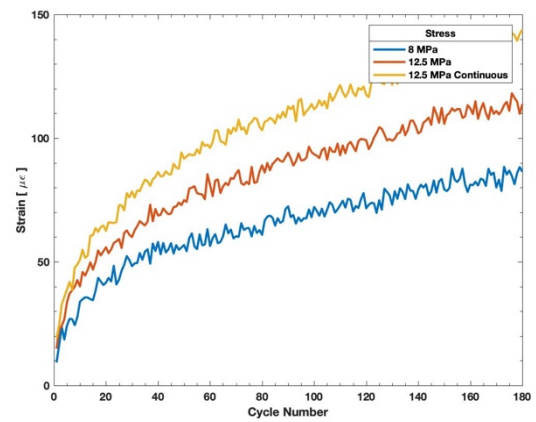
c)



d)



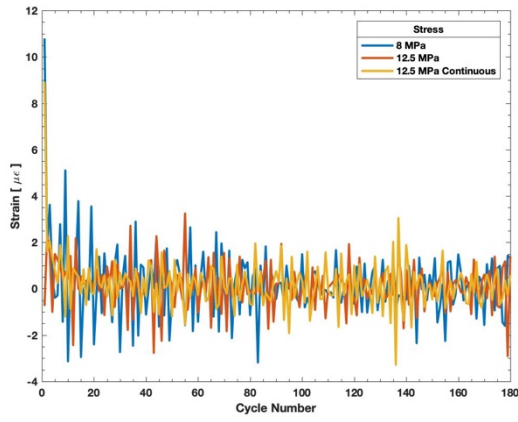
e)



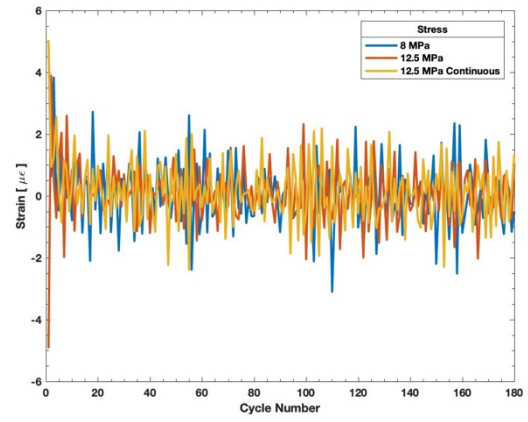
f)

Figure C-20: 180 °C - Total Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

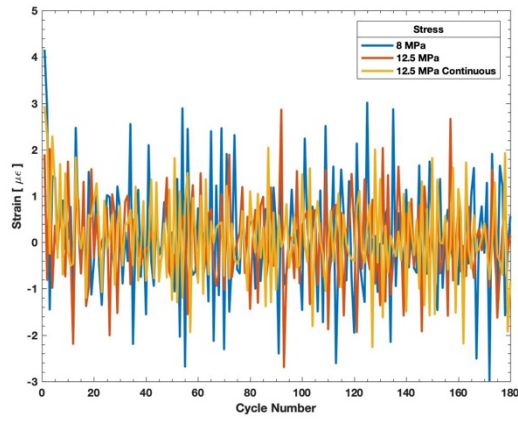
C.1.2.2 Cycle Unrecovered Strain



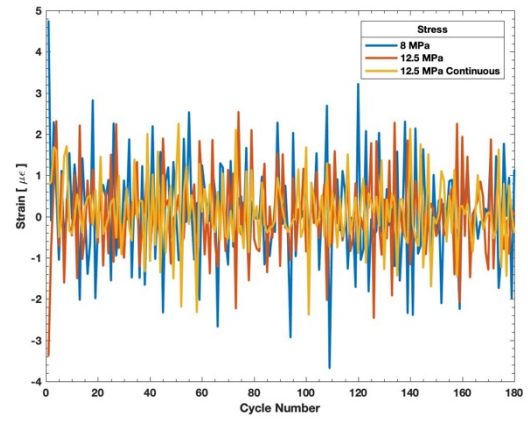
a)



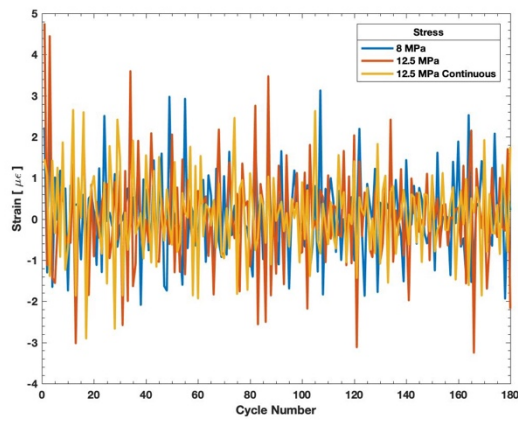
b)



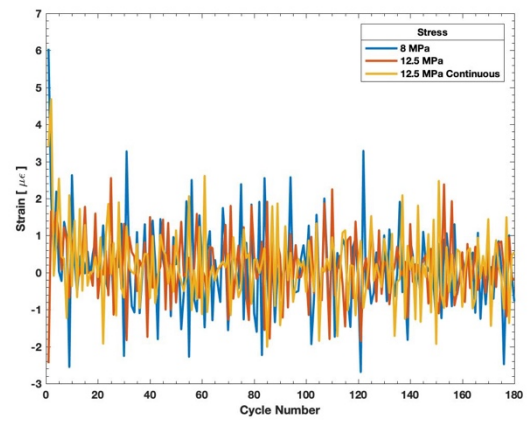
c)



d)

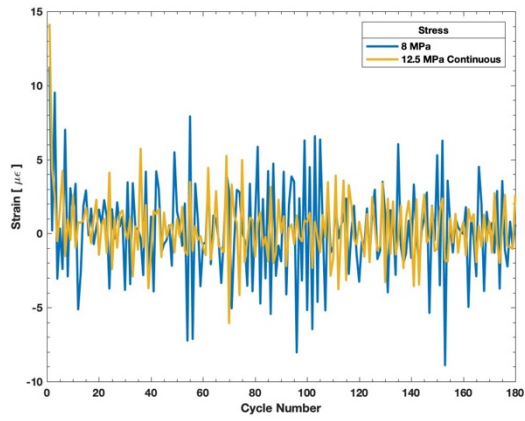


e)

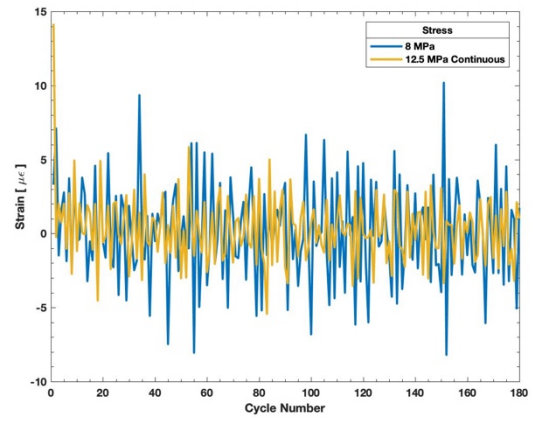


f)

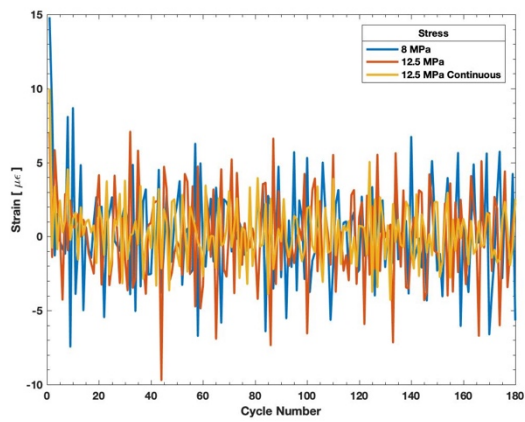
Figure C-21: Room Temperature - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



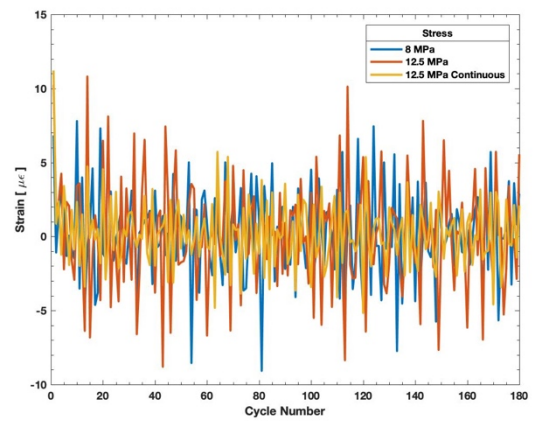
a)



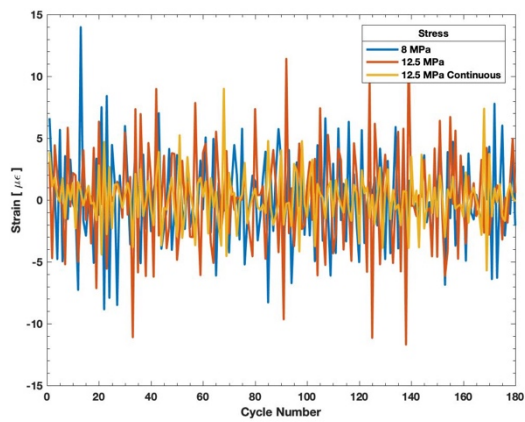
b)



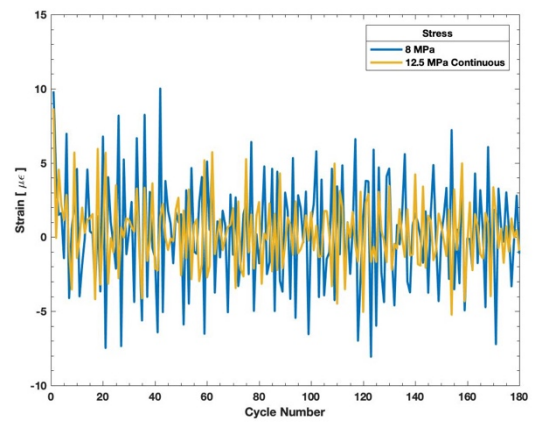
c)



d)

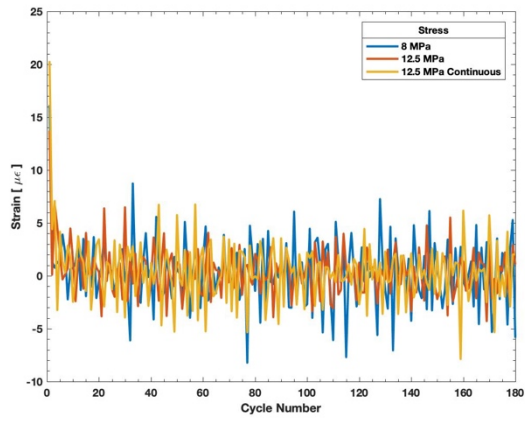


e)

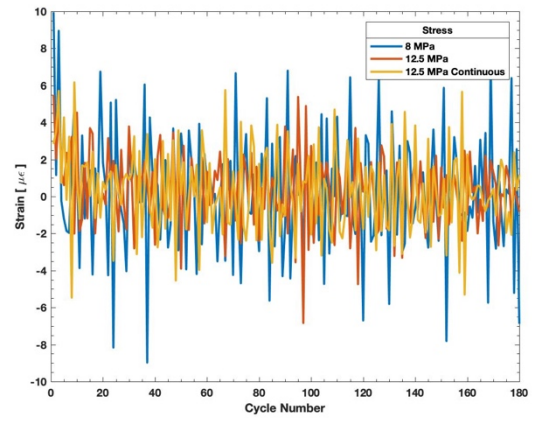


f)

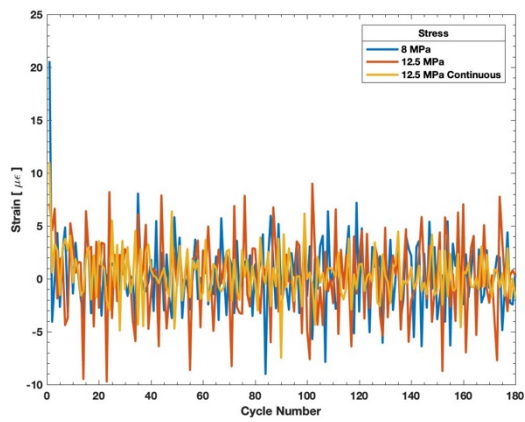
Figure C-22: 80 °C - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



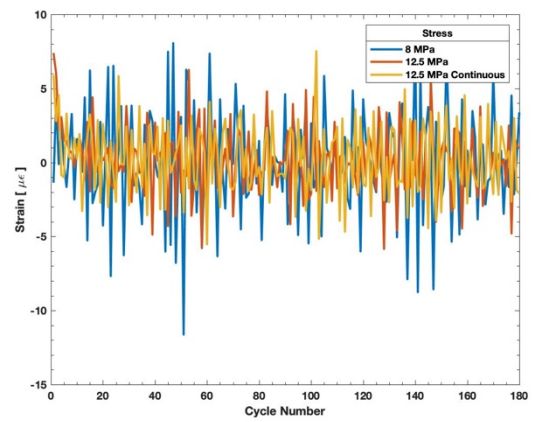
a)



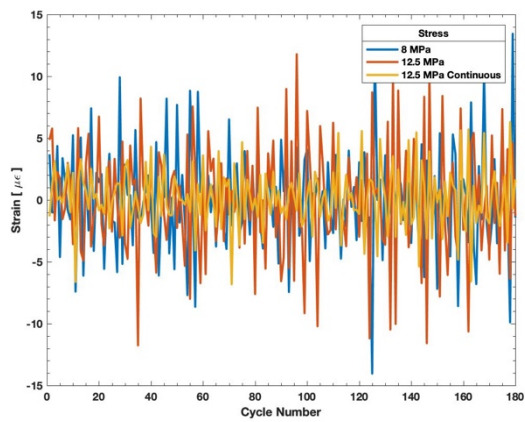
b)



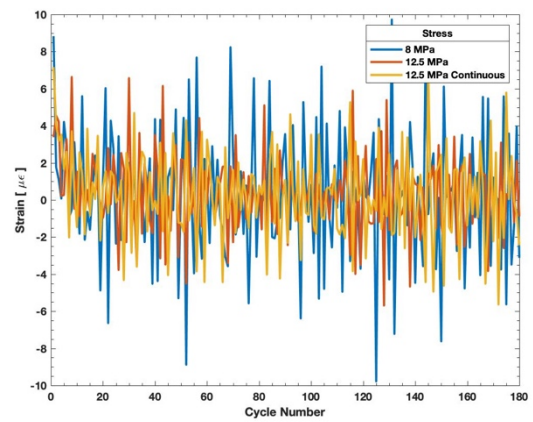
c)



d)

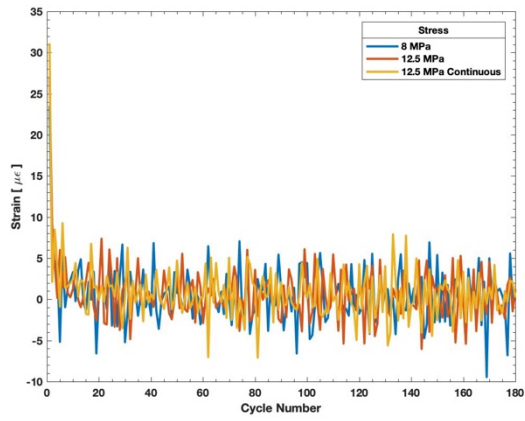


e)

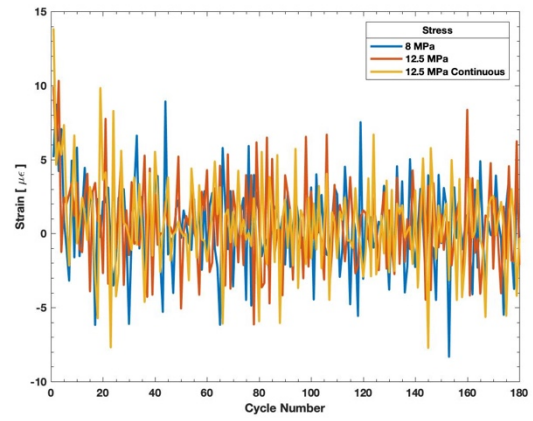


f)

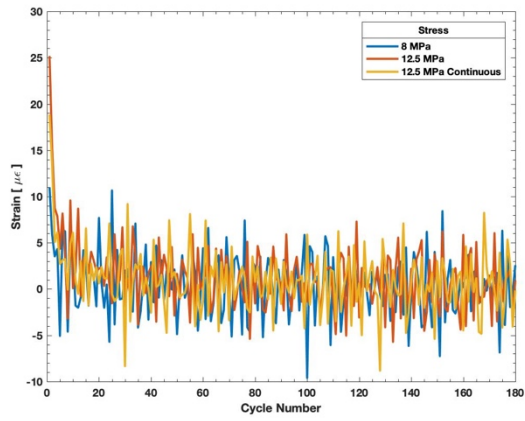
Figure C-23: 120 °C - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



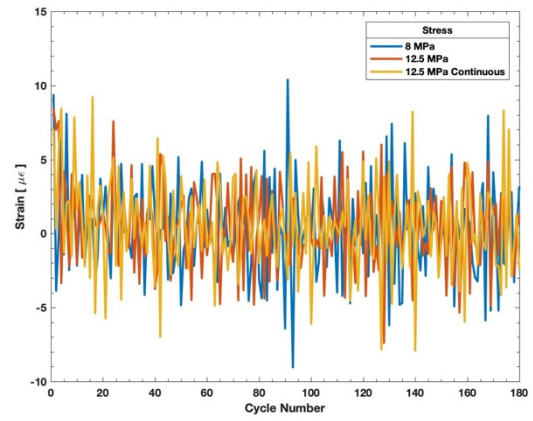
a)



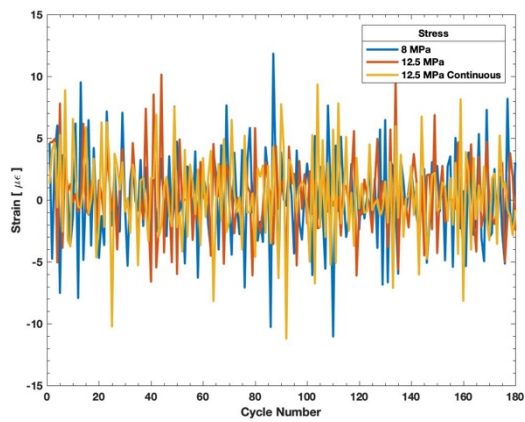
b)



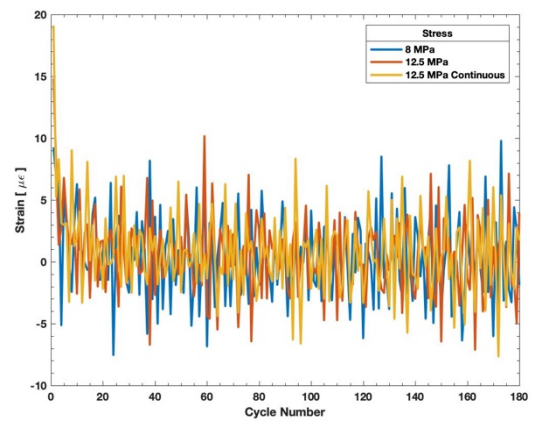
c)



d)



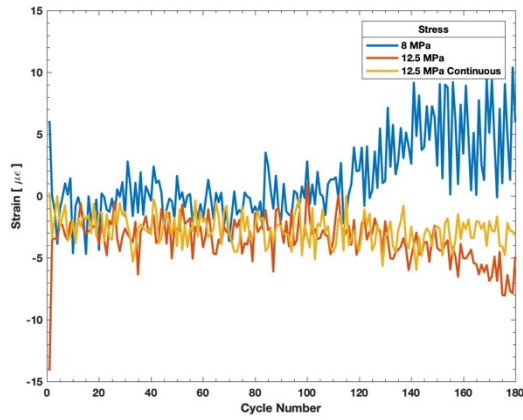
e)



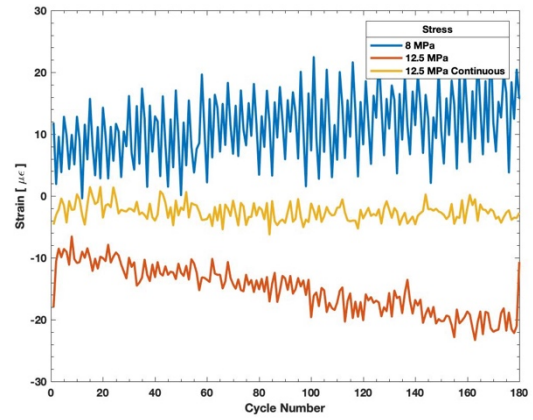
f)

Figure C-24: 180 °C - Cycle Unrecovered Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

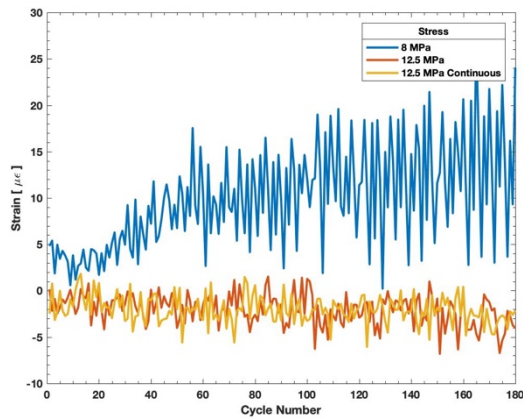
C.1.2.3 Unrecovered Instantaneous Strain



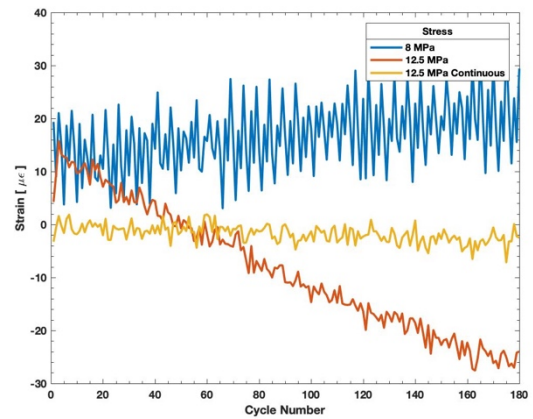
a)



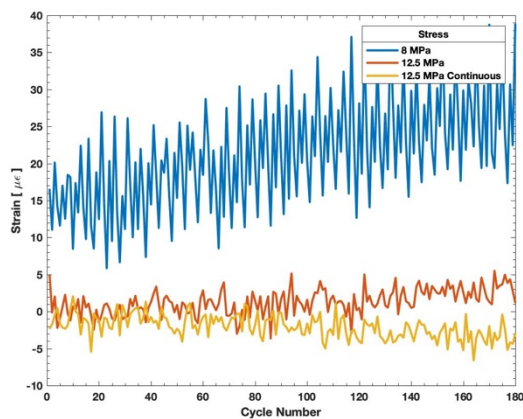
b)



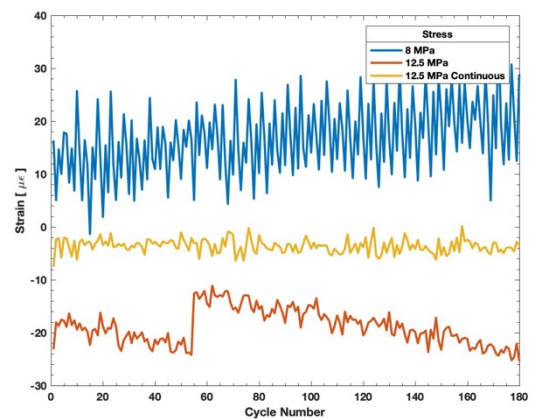
c)



d)

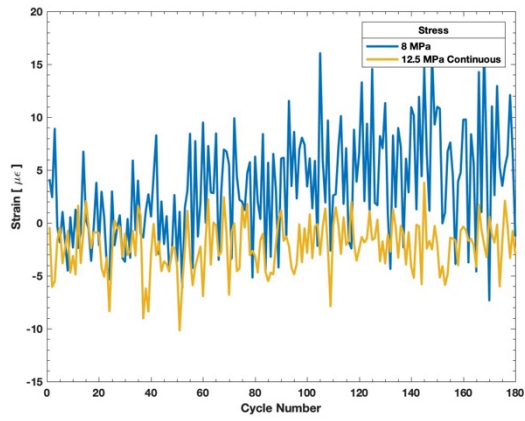


e)

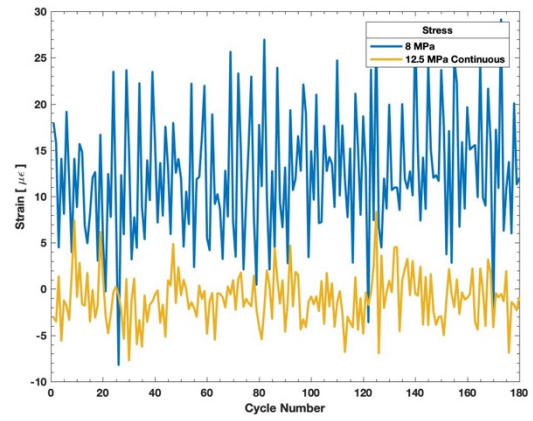


f)

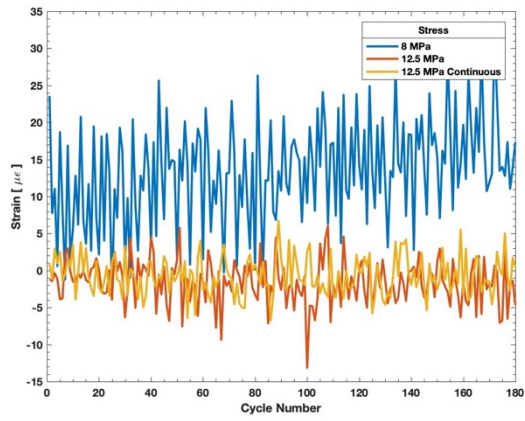
Figure C-25: Room Temperature - Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



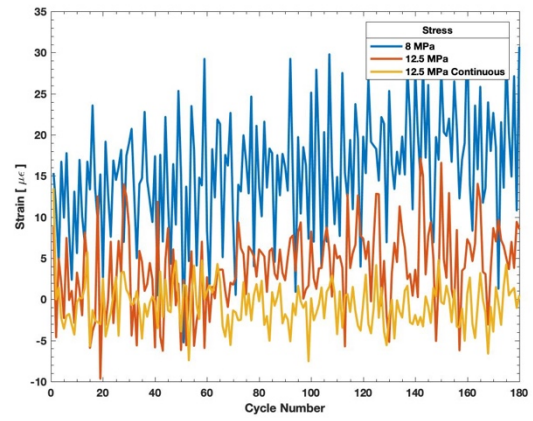
a)



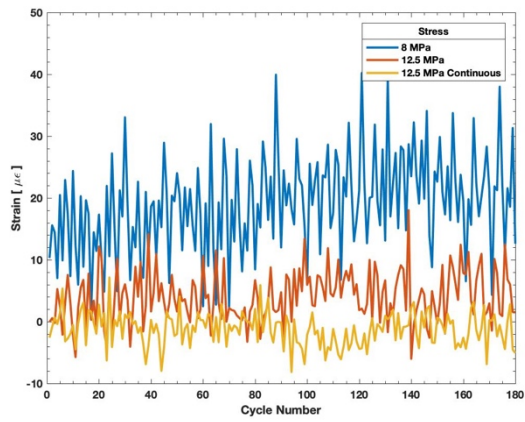
b)



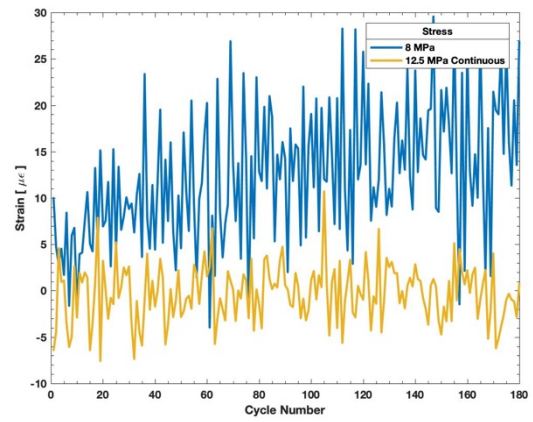
c)



d)

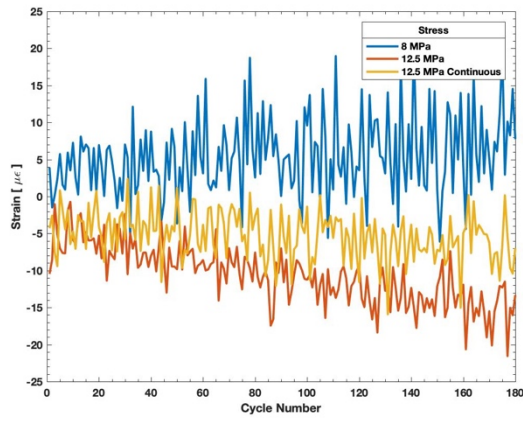


e)

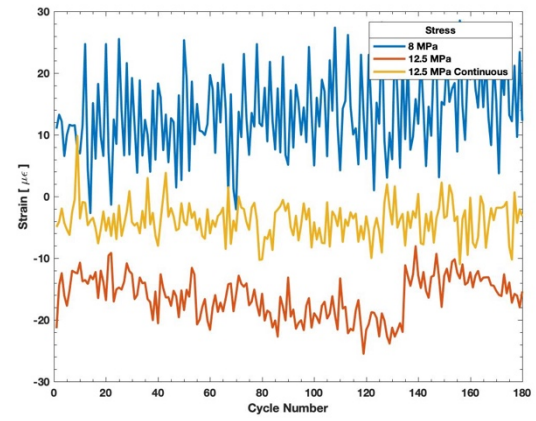


f)

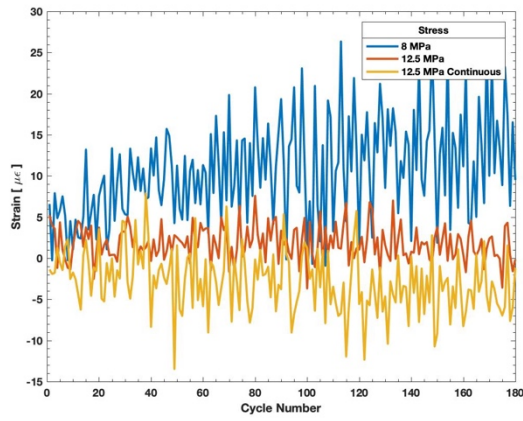
Figure C-26: 80 °C - Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



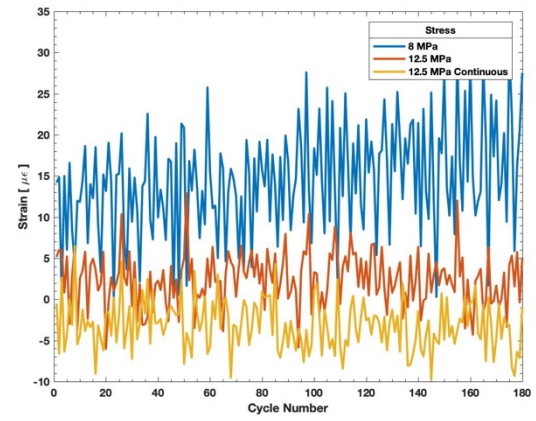
a)



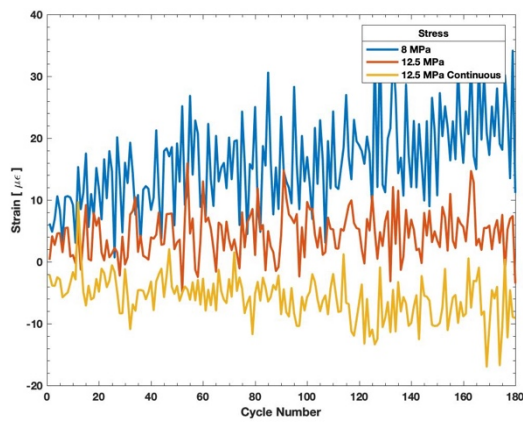
b)



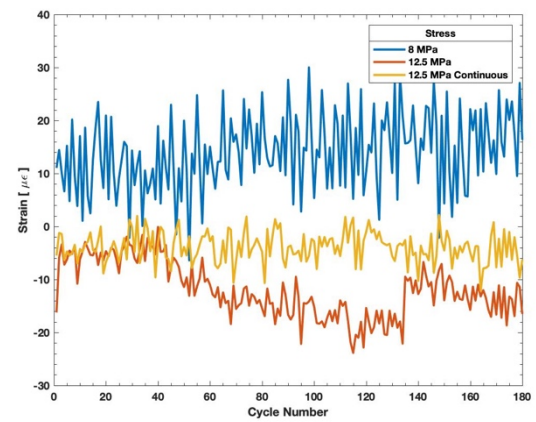
c)



d)

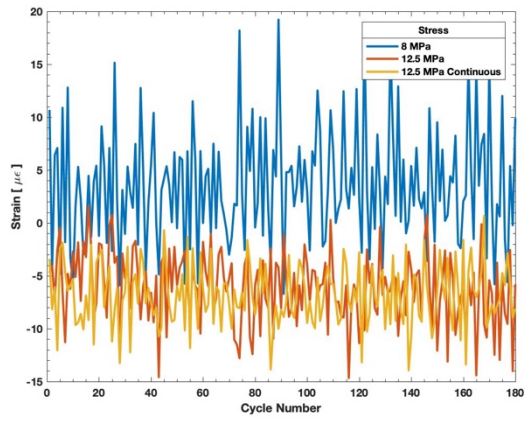


e)

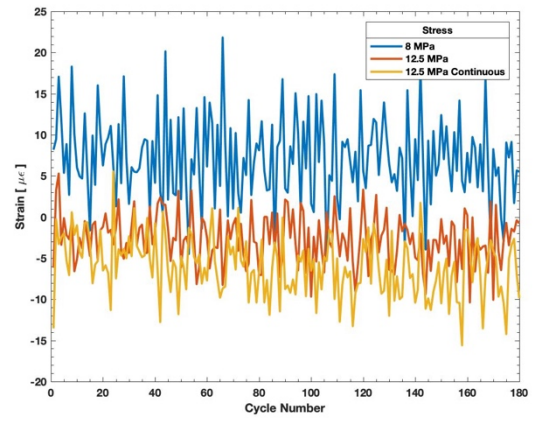


f)

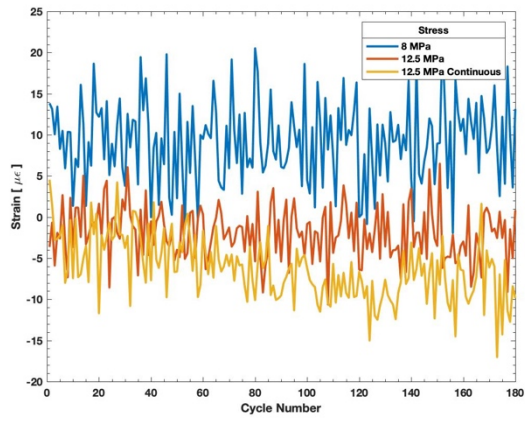
Figure C-27: 120 °C - Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



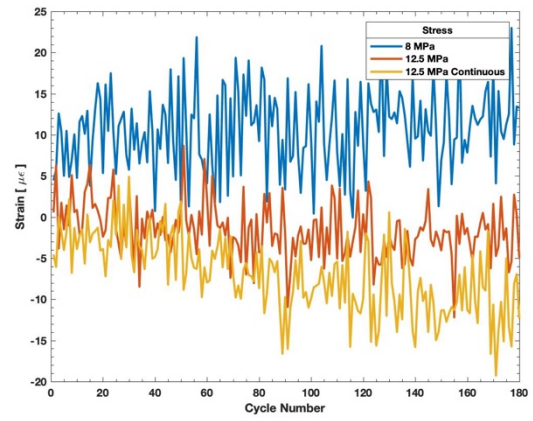
a)



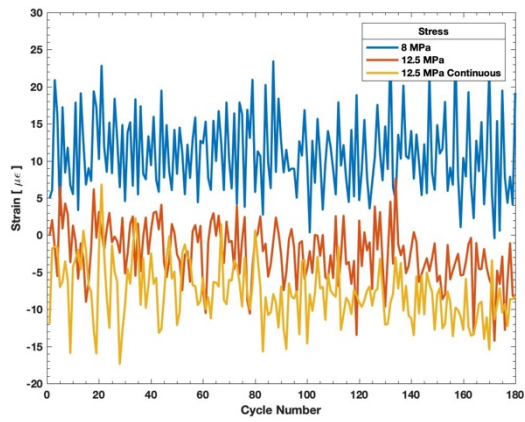
b)



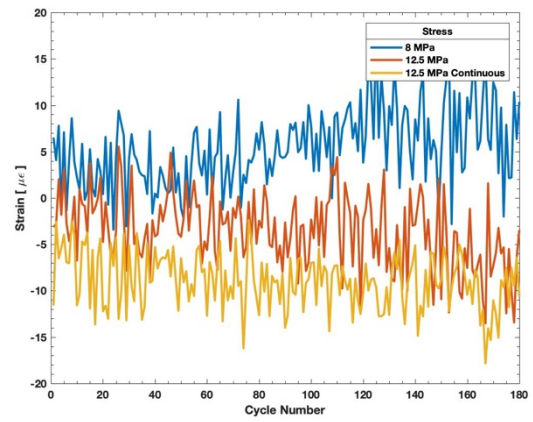
c)



d)



e)

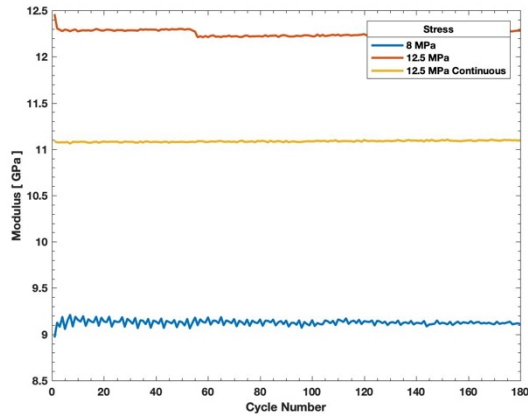


f)

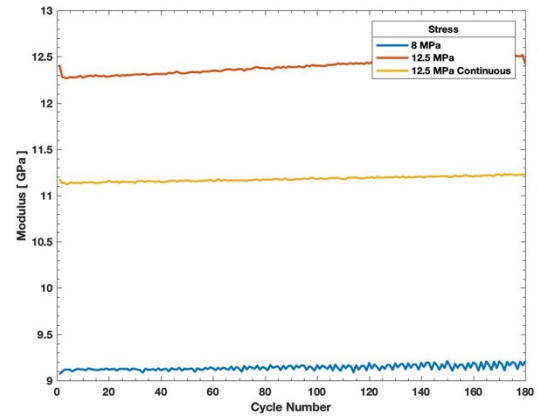
Figure C-28: 180 °C - Unrecovered Instantaneous Strain vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.2 Modulus

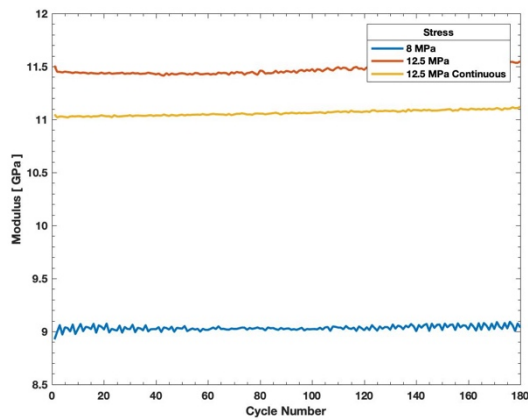
C.2.1 Loading



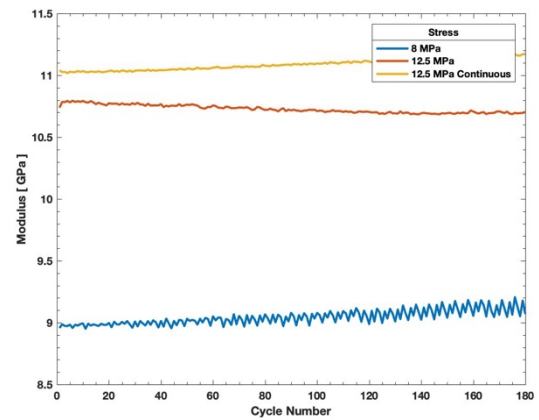
a)



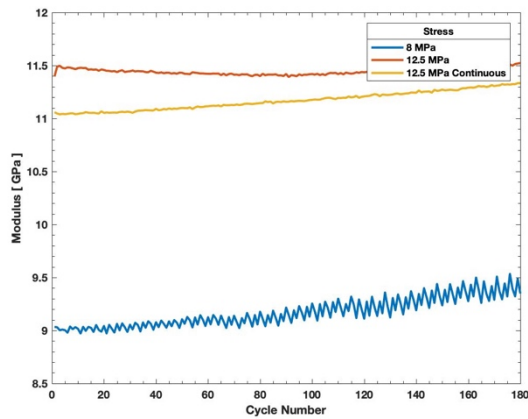
b)



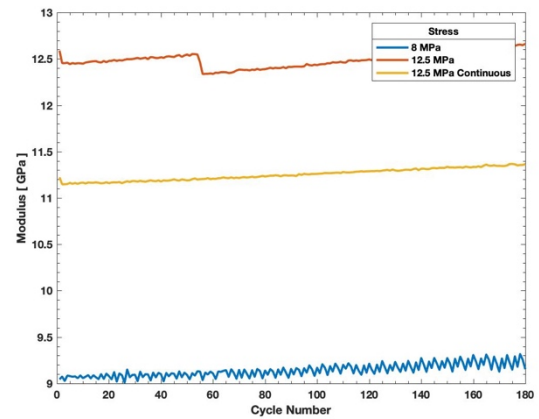
c)



d)

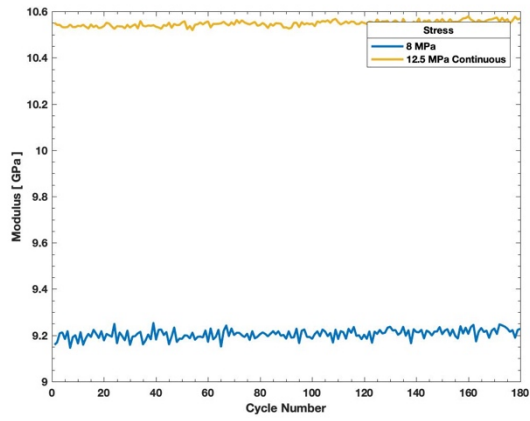


e)

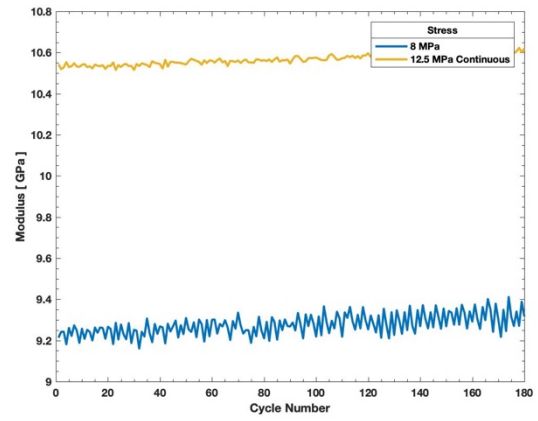


f)

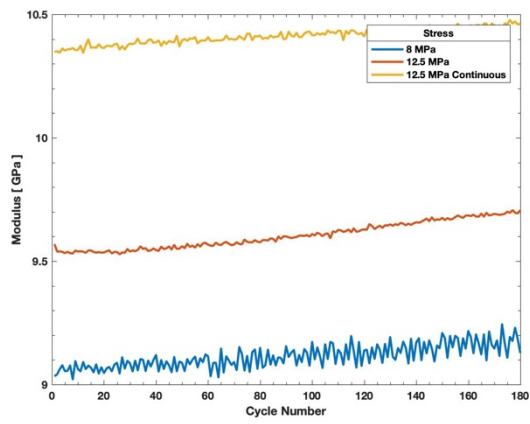
Figure C-29: Room Temperature - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



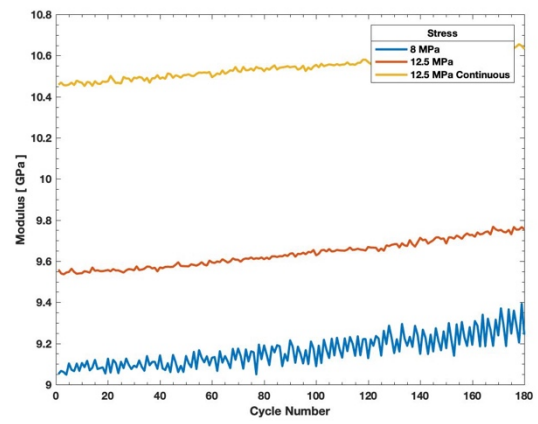
a)



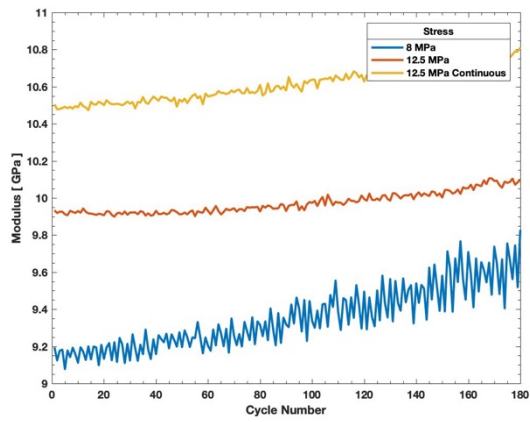
b)



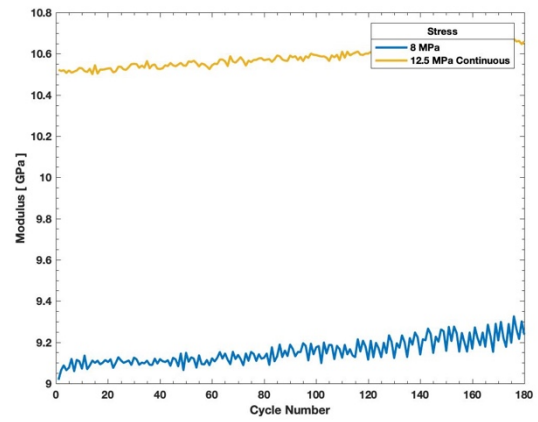
c)



d)

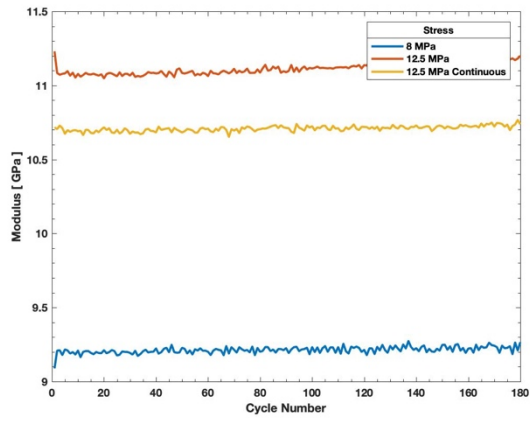


e)

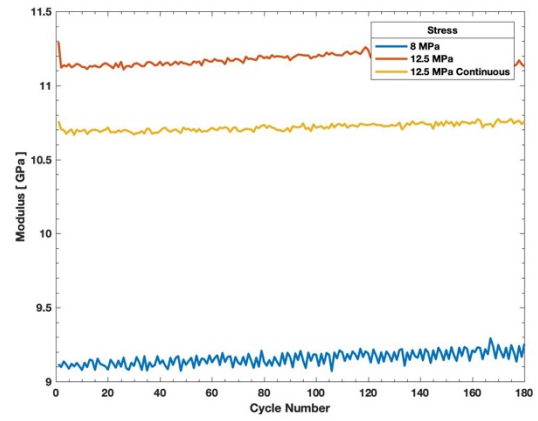


f)

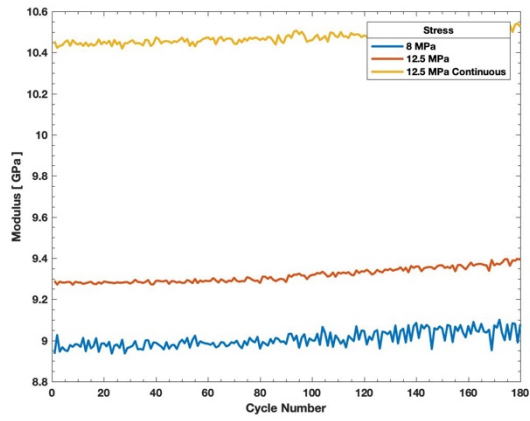
Figure C-30: 80 °C - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



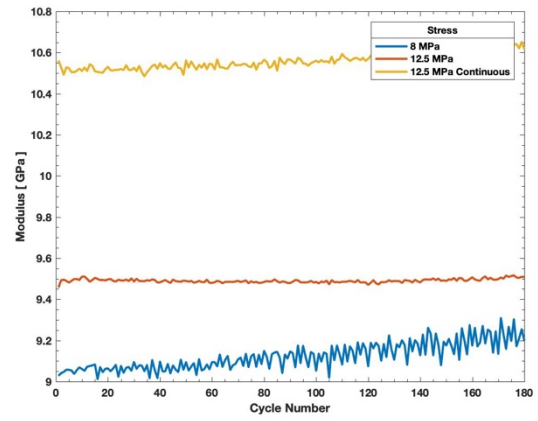
a)



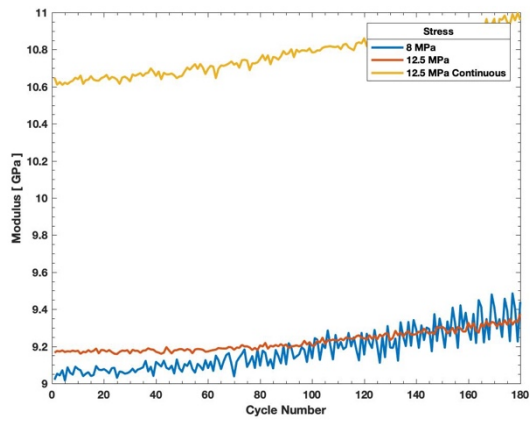
b)



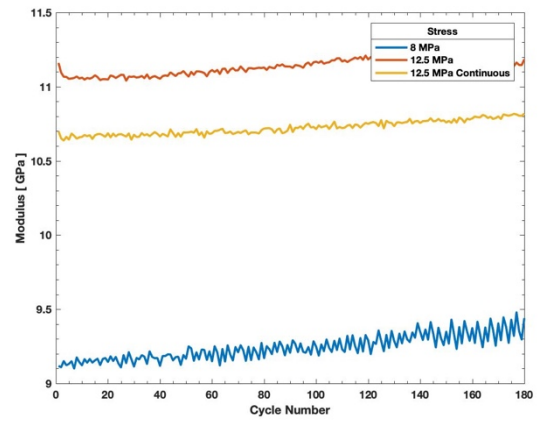
c)



d)

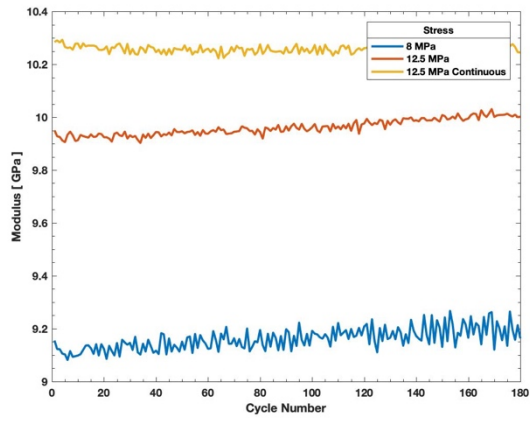


e)

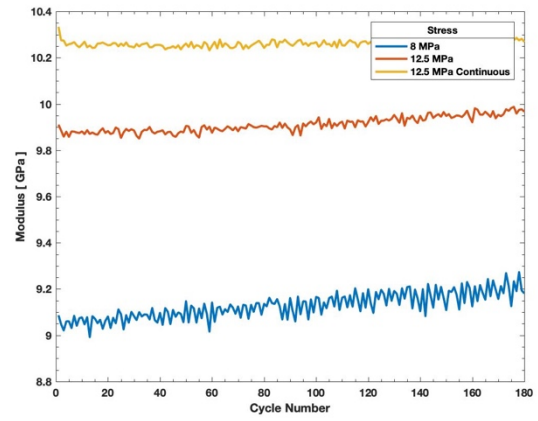


f)

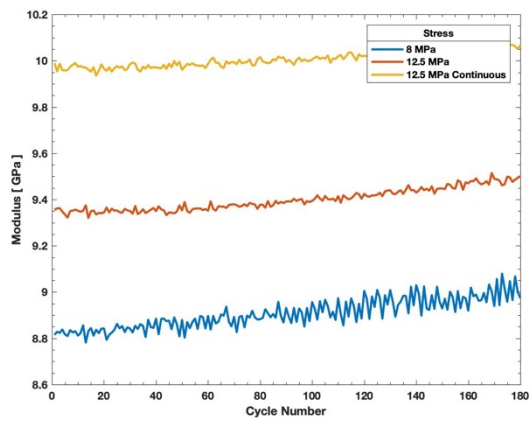
Figure C-31: 120 °C - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



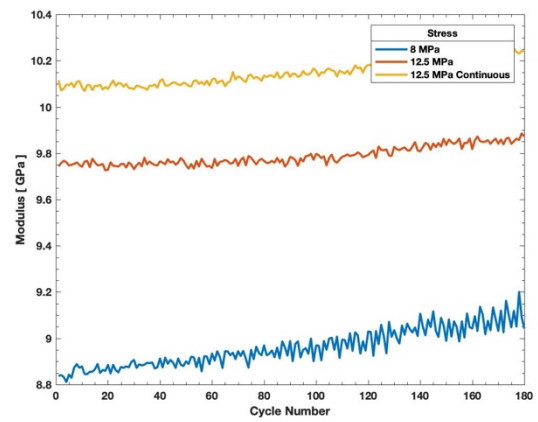
a)



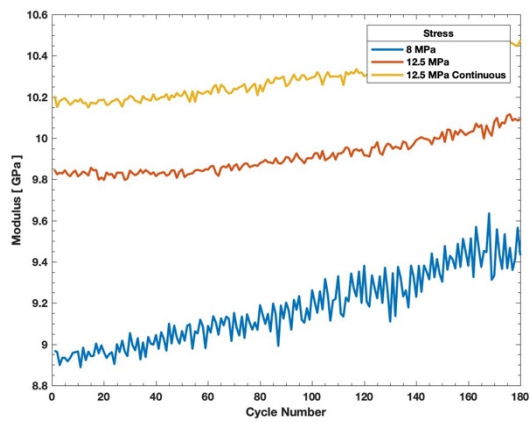
b)



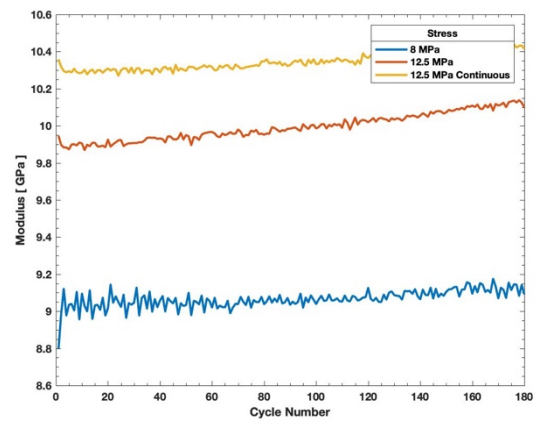
c)



d)



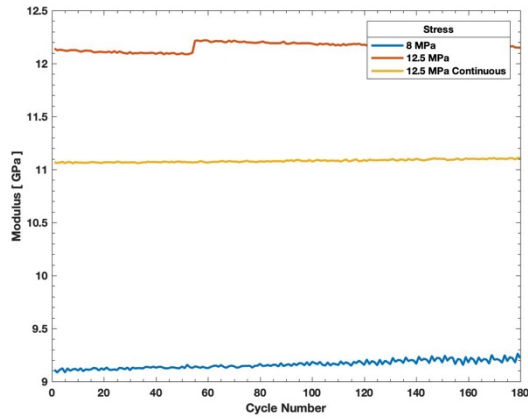
e)



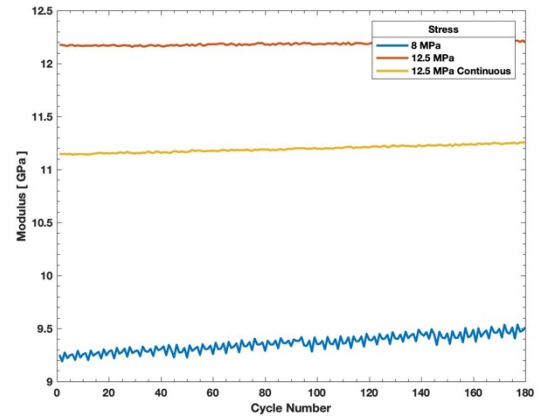
f)

Figure C-32: 180 °C - Instantaneous Modulus (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

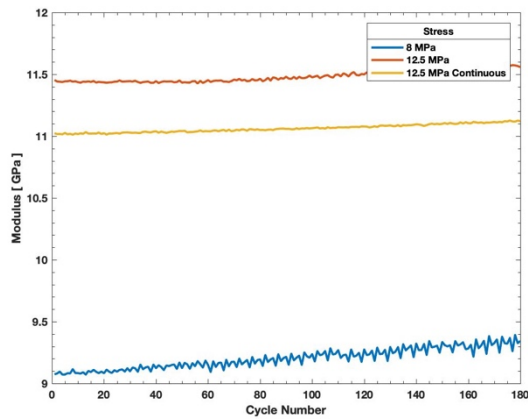
C.2.2 Unloading



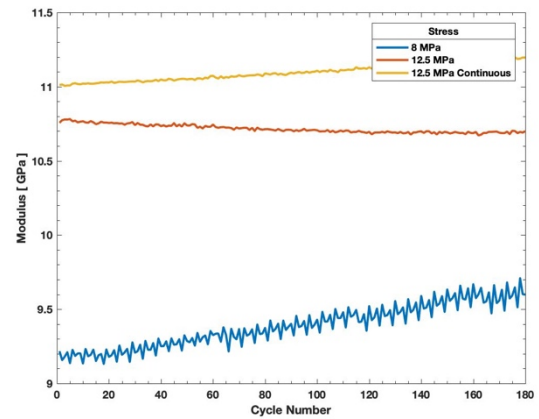
a)



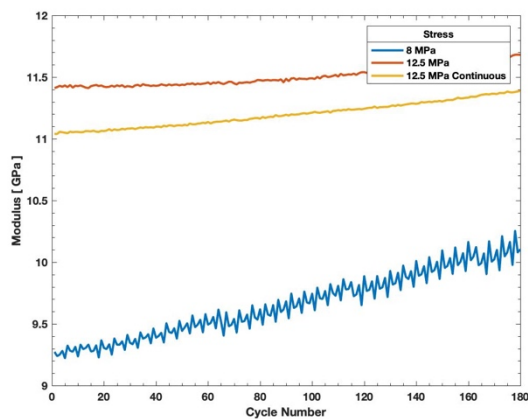
b)



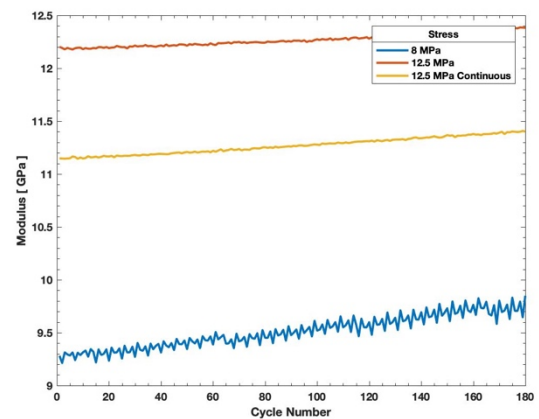
c)



d)

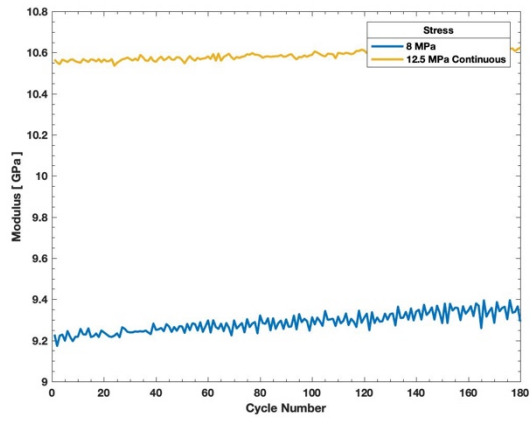


e)

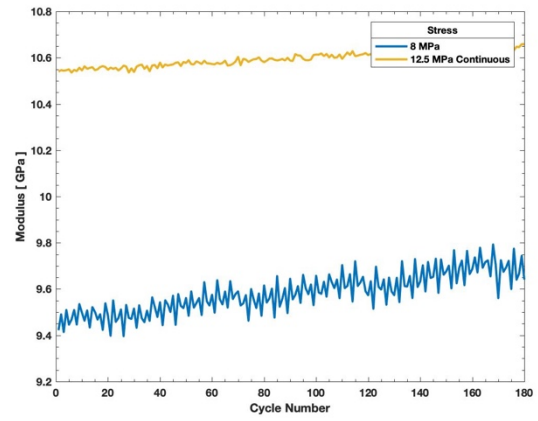


f)

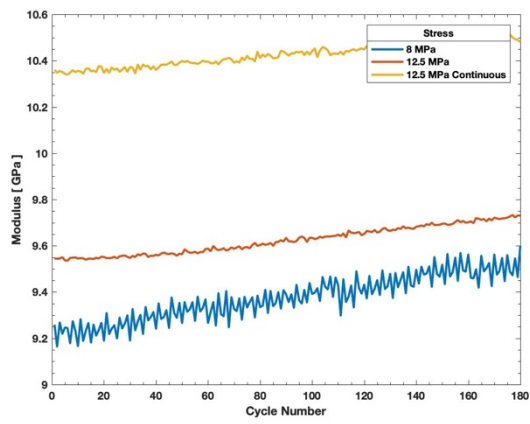
Figure C-33: Room Temperature - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



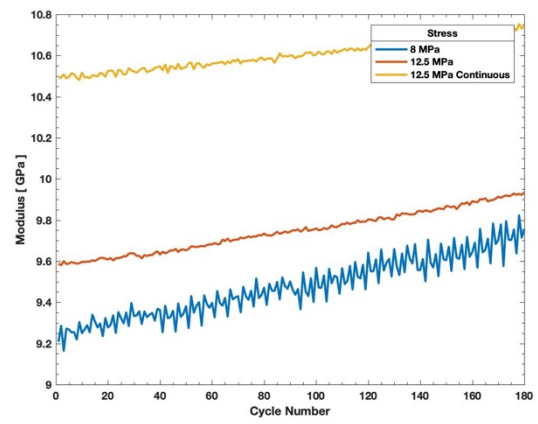
a)



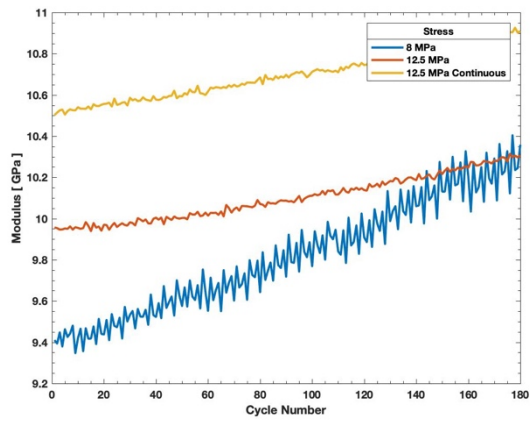
b)



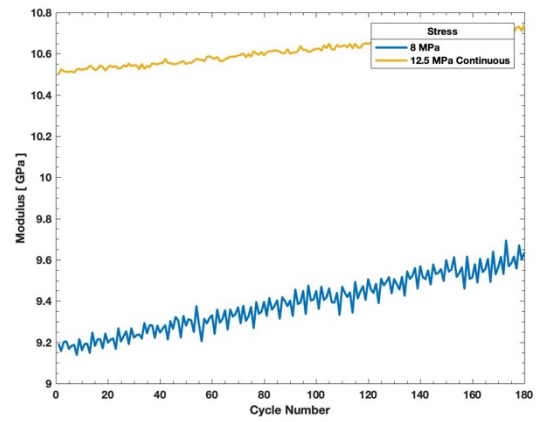
c)



d)

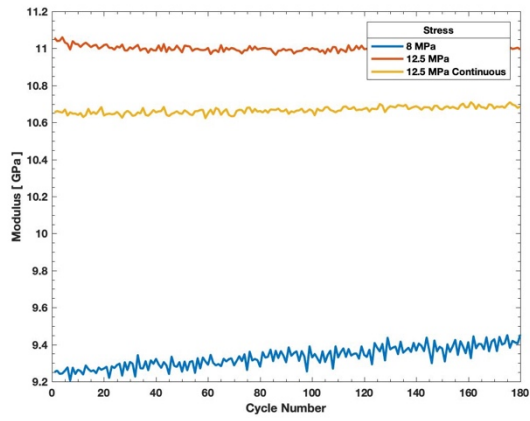


e)

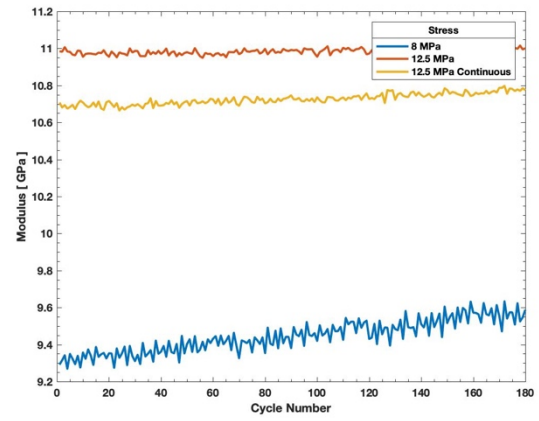


f)

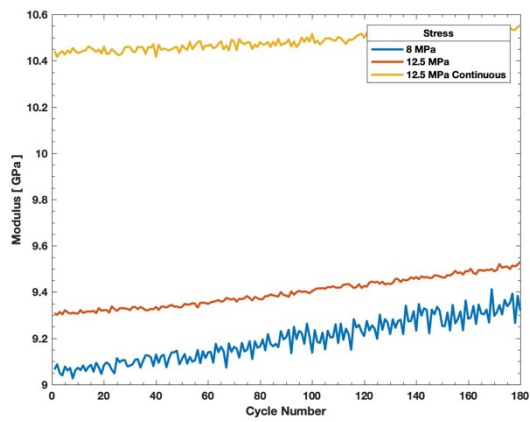
Figure C-34: 80 °C - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



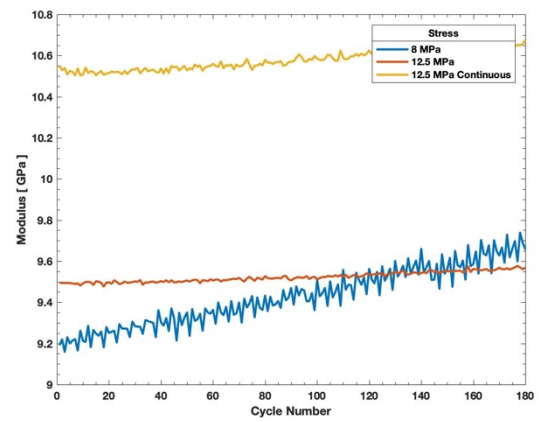
a)



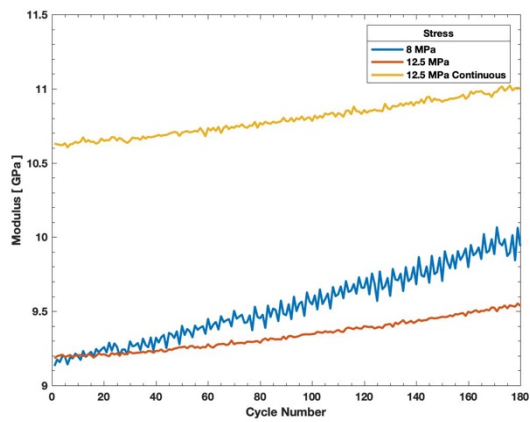
b)



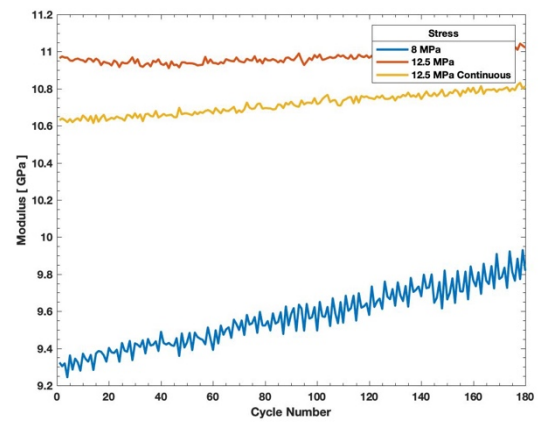
c)



d)

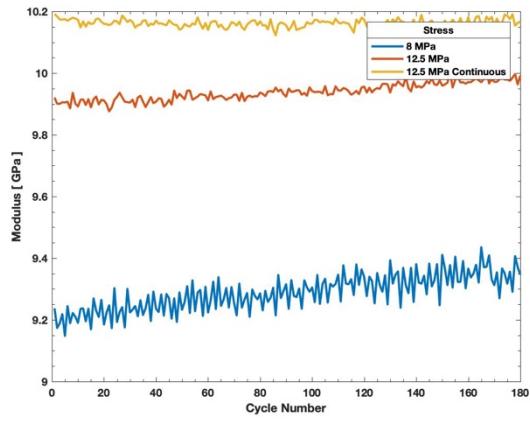


e)

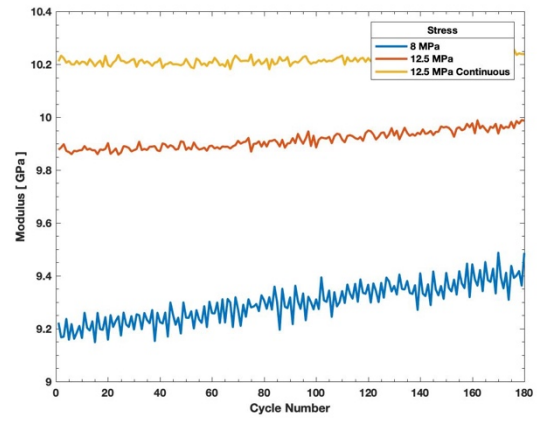


f)

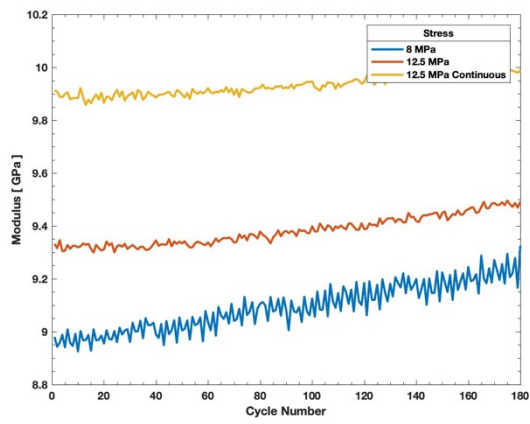
Figure C-35: 120 °C - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



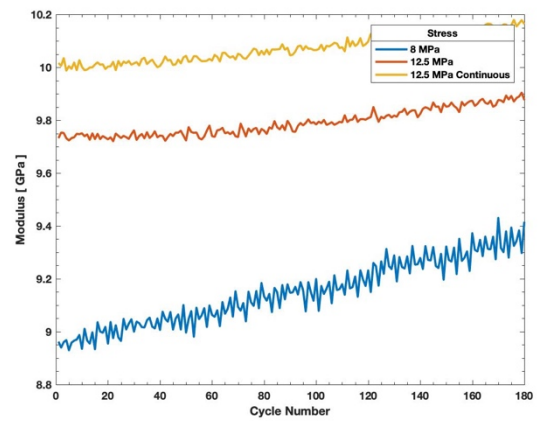
a)



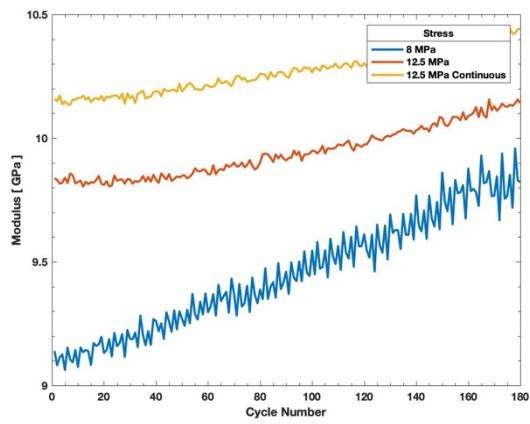
b)



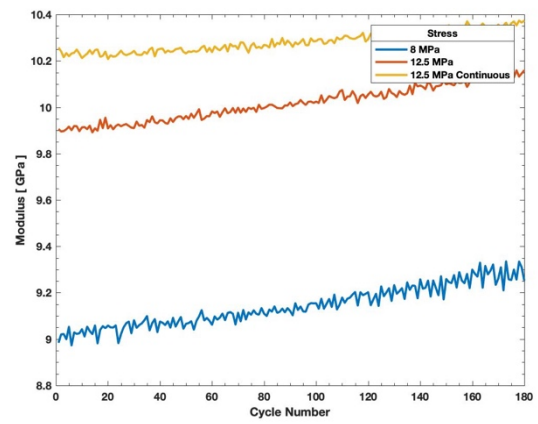
c)



d)



e)



f)

Figure C-36: 180 °C - Instantaneous Modulus (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.2.3 Difference

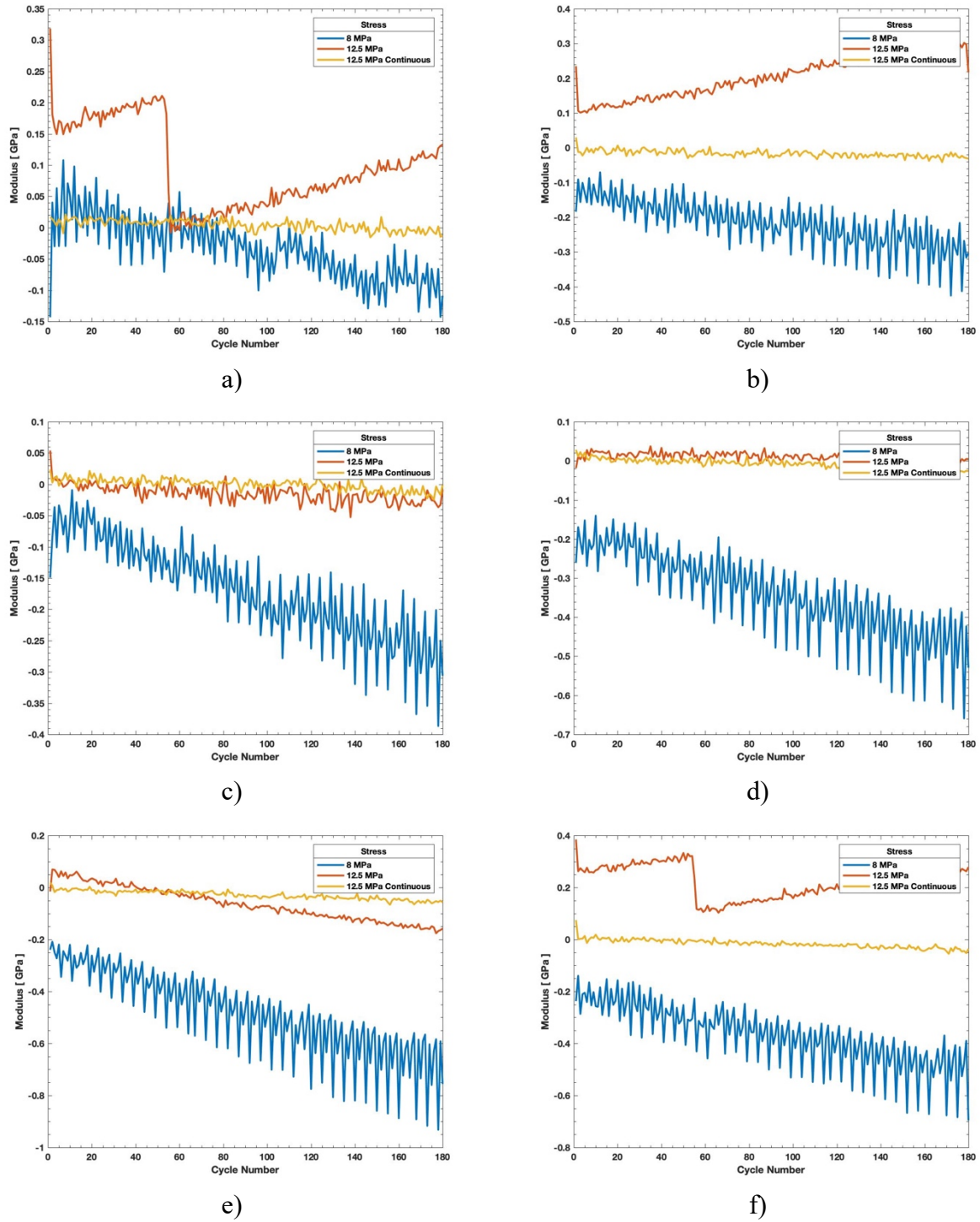
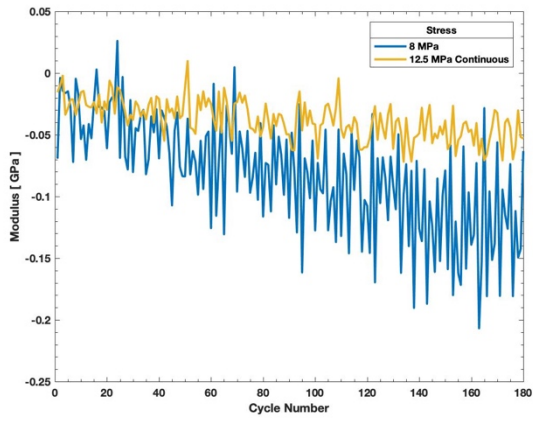
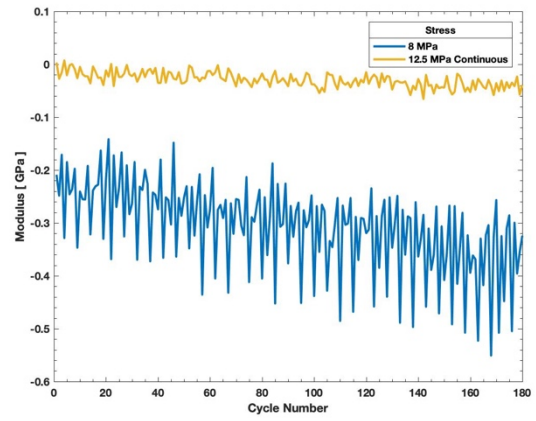


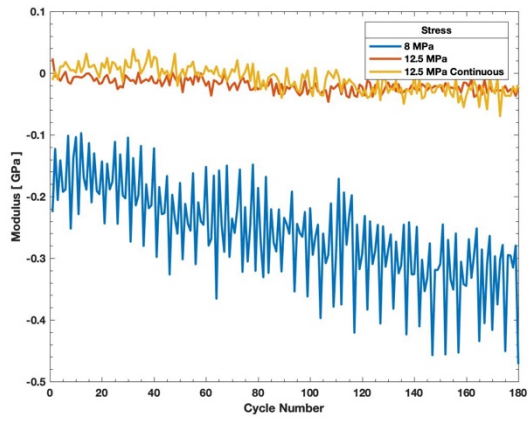
Figure C-37: Room Temperature - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



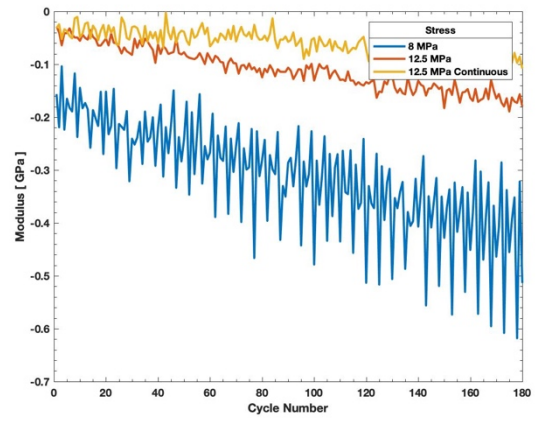
a)



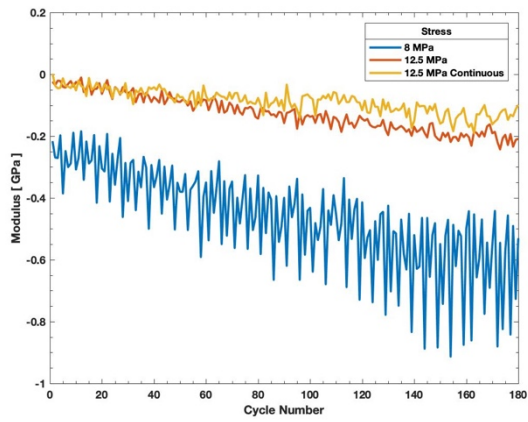
b)



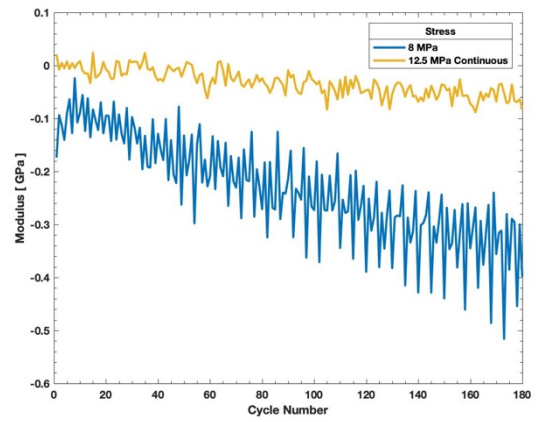
c)



d)

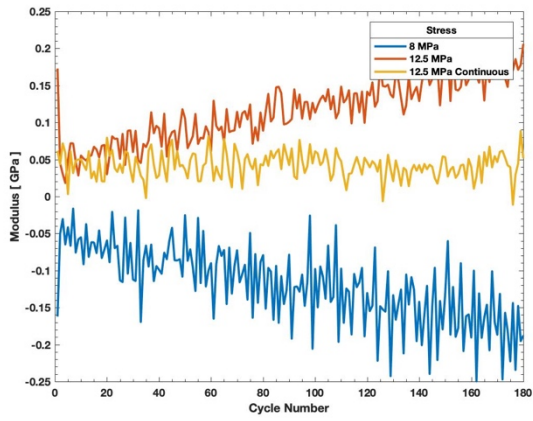


e)

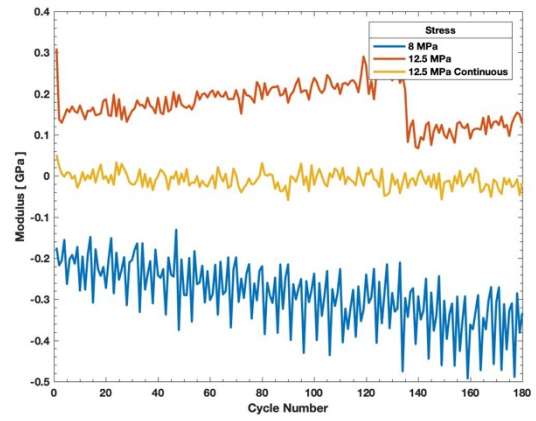


f)

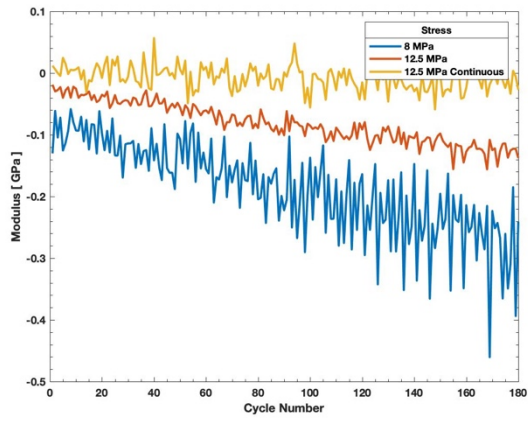
Figure C-38: 80 °C - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



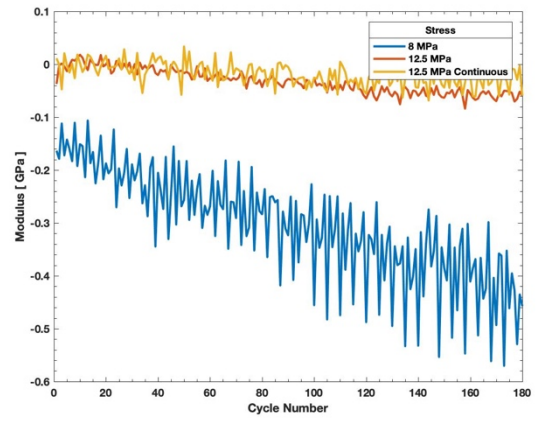
a)



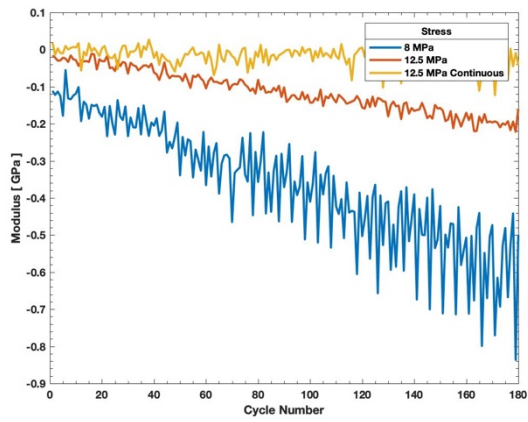
b)



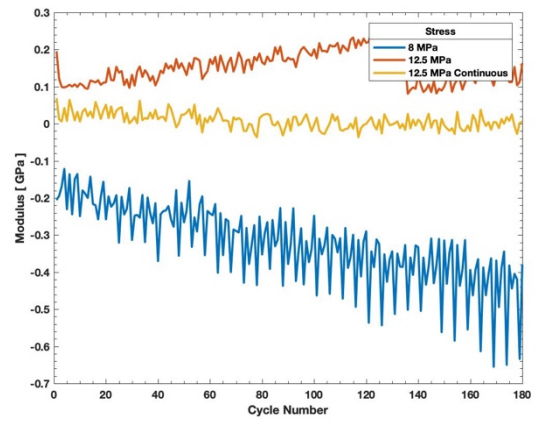
c)



d)

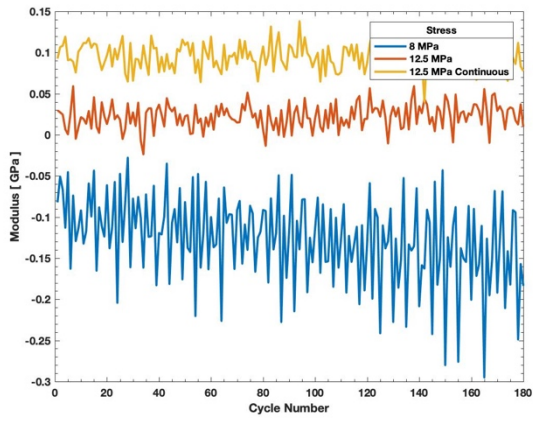


e)

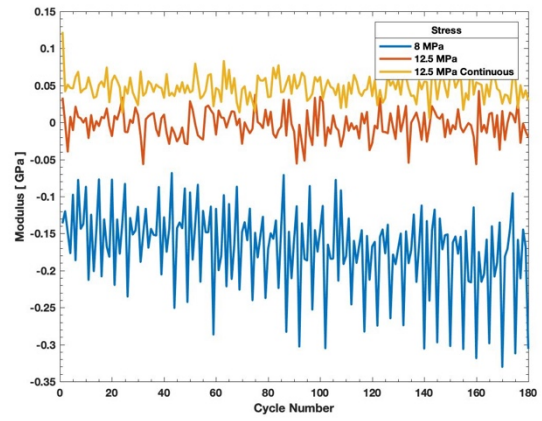


f)

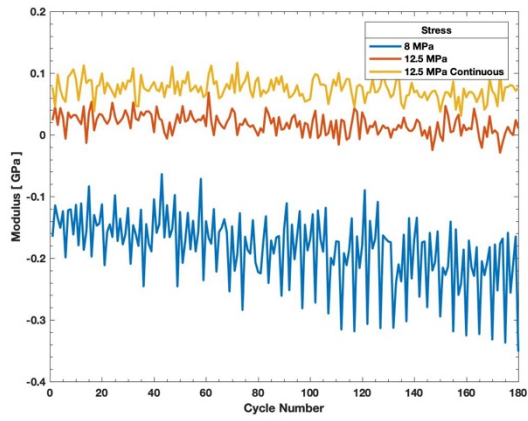
Figure C-39: 120 °C - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



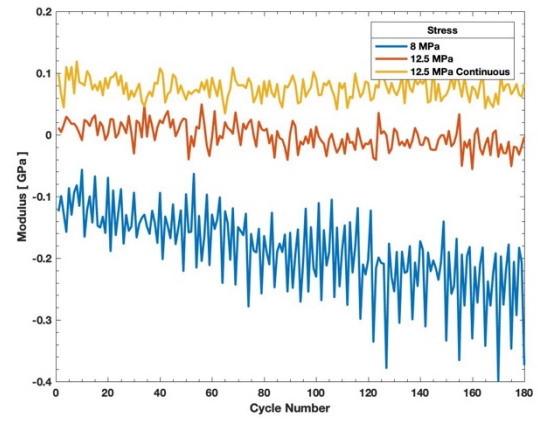
a)



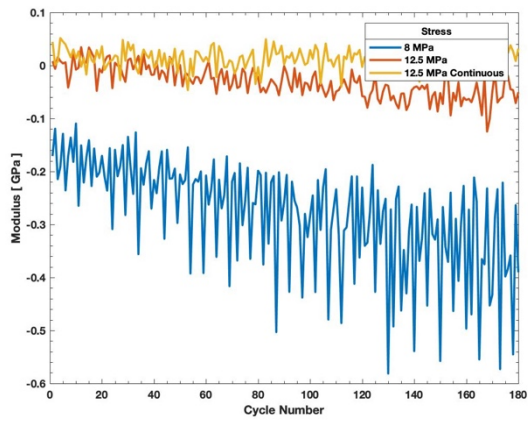
b)



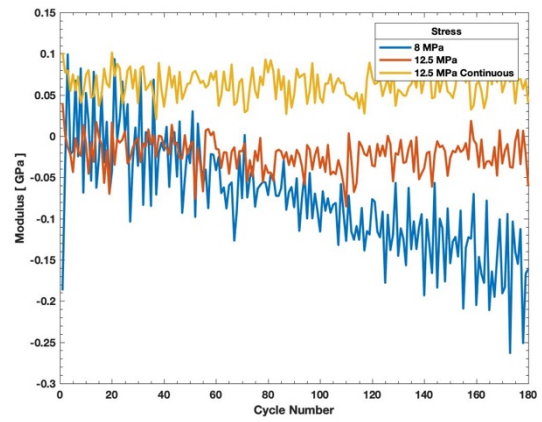
c)



d)



e)



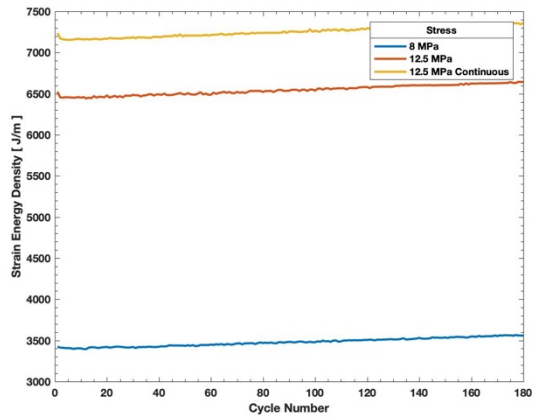
f)

Figure C-40: 180 °C - Instantaneous Modulus (Difference) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

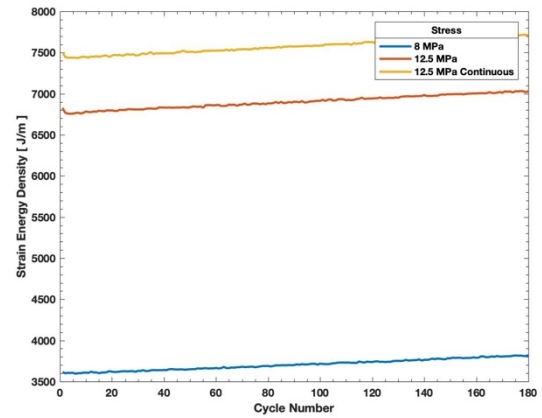
C.3 Strain Energy Density

C.3.1 Overall

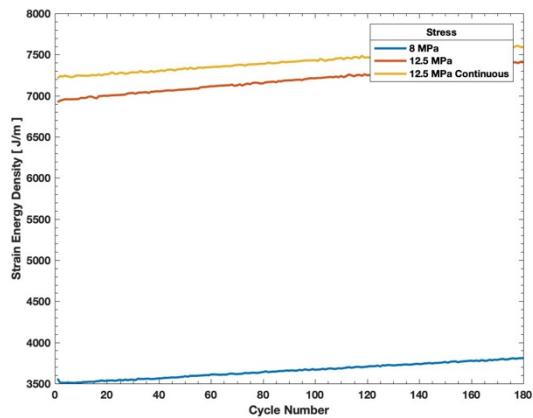
C.3.1.1 Total



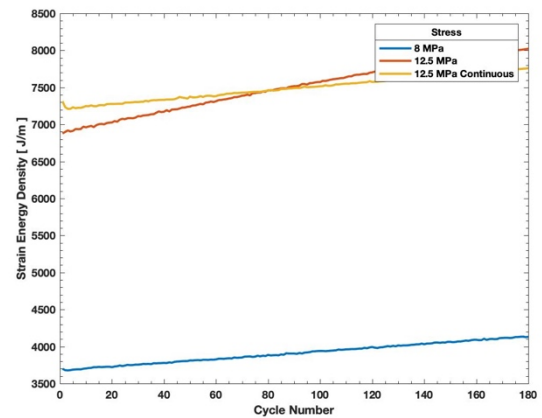
a)



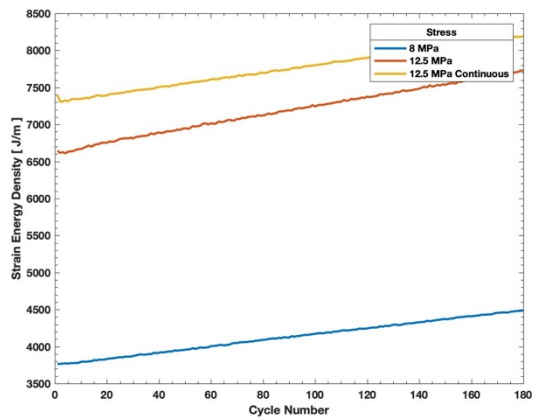
b)



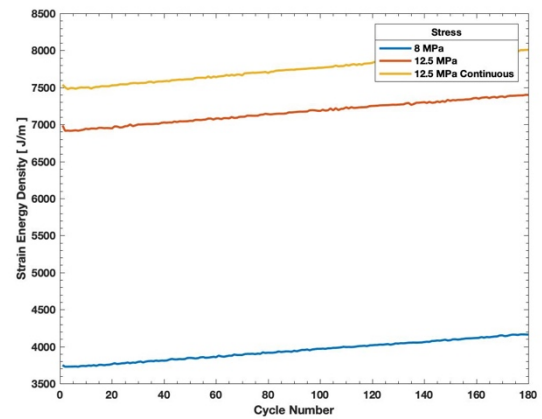
c)



d)

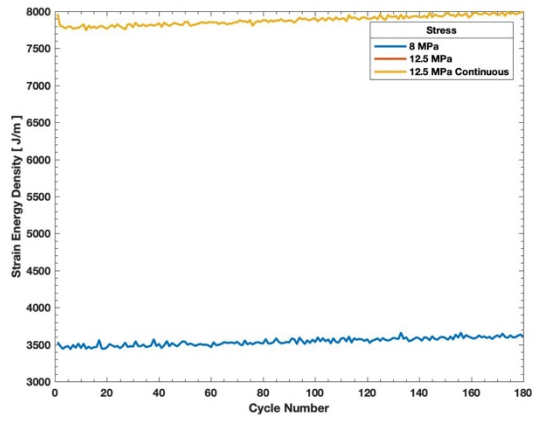


e)

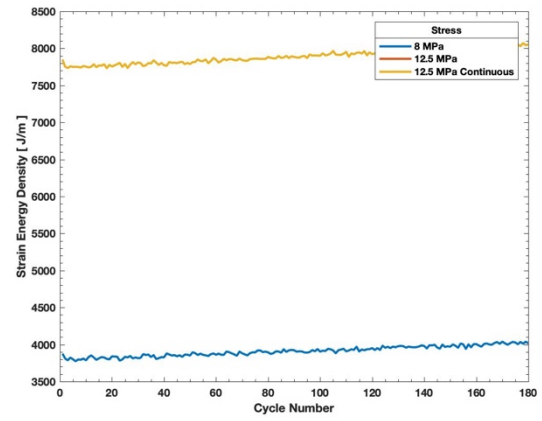


f)

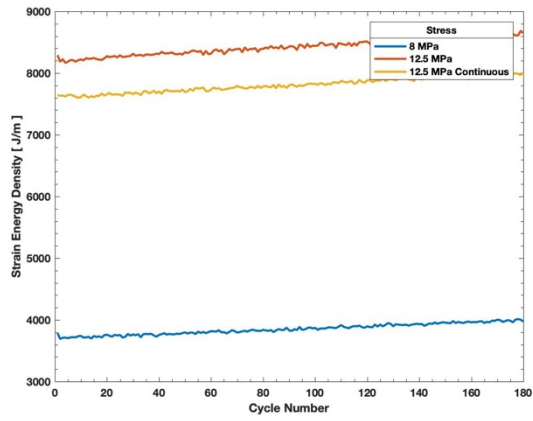
Figure C-41: Room Temperature - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



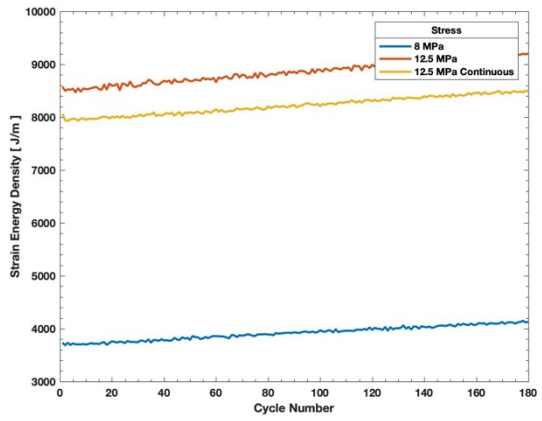
a)



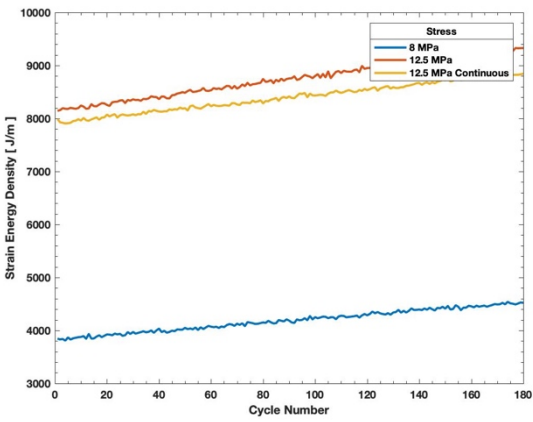
b)



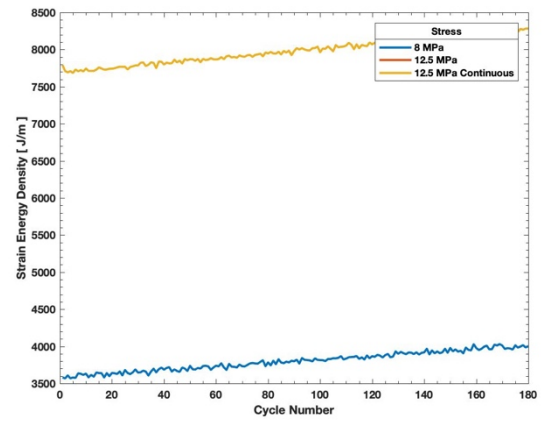
c)



d)

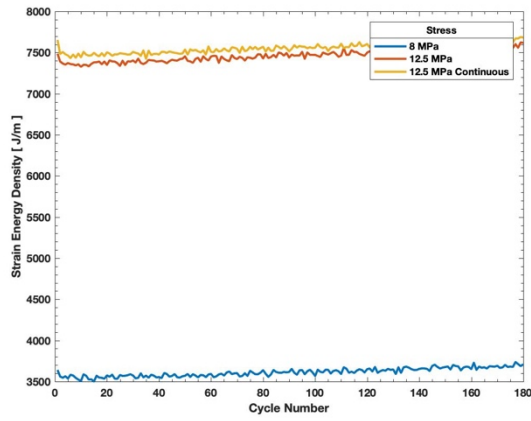


e)

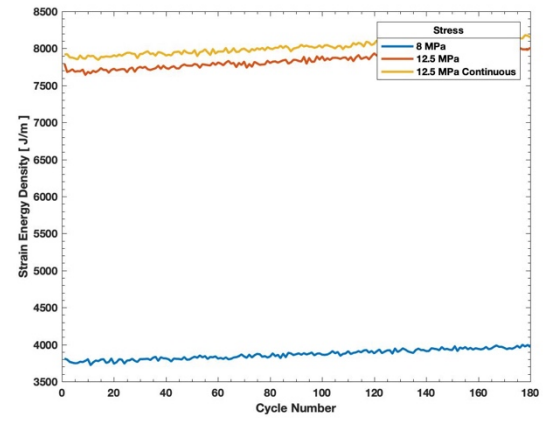


f)

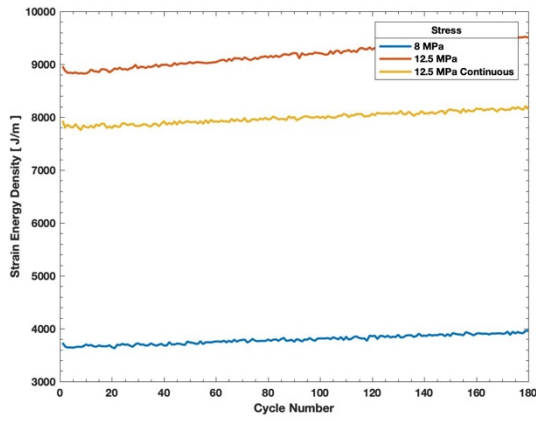
Figure C-42: 80 °C - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



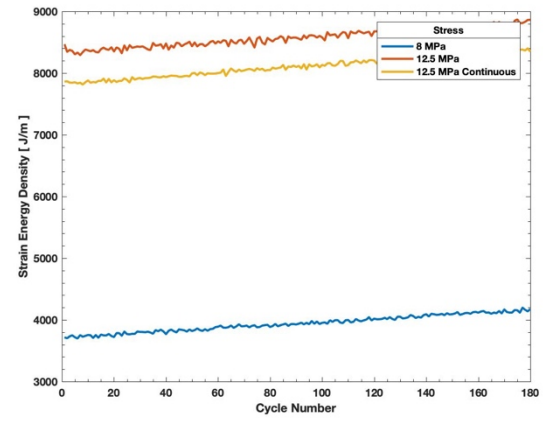
a)



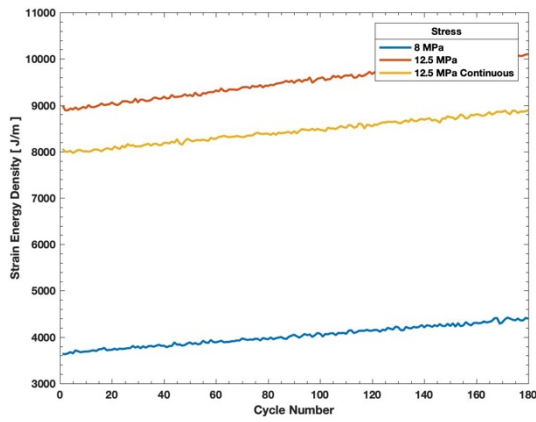
b)



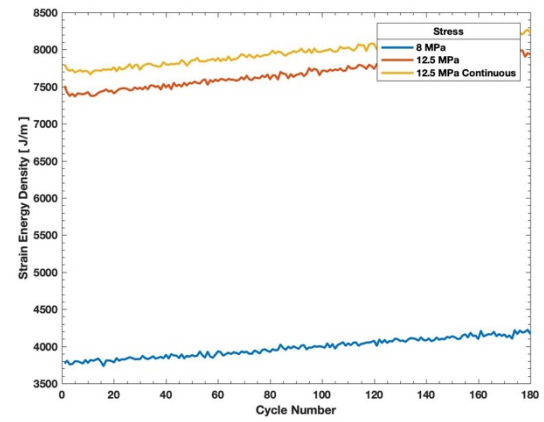
c)



d)

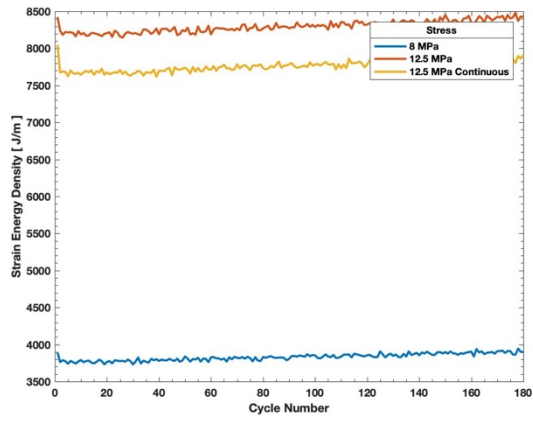


e)

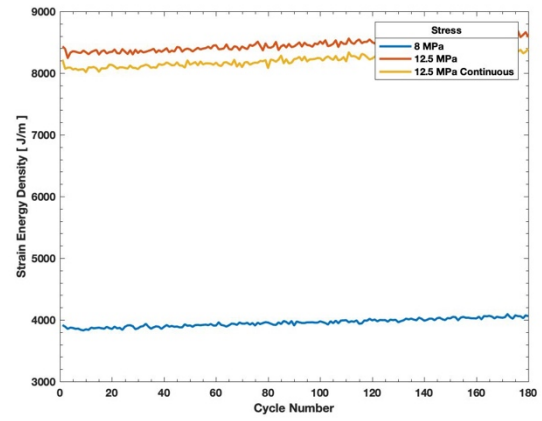


f)

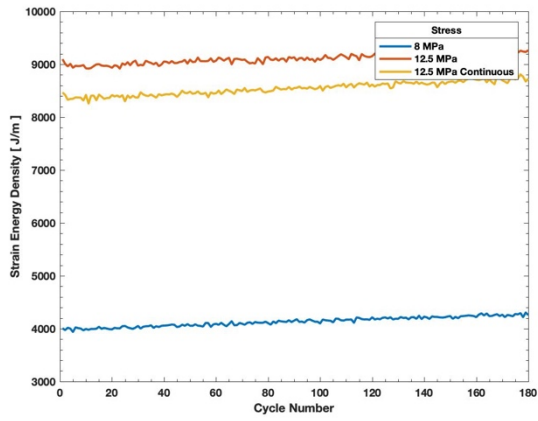
Figure C-43: 120 °C - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



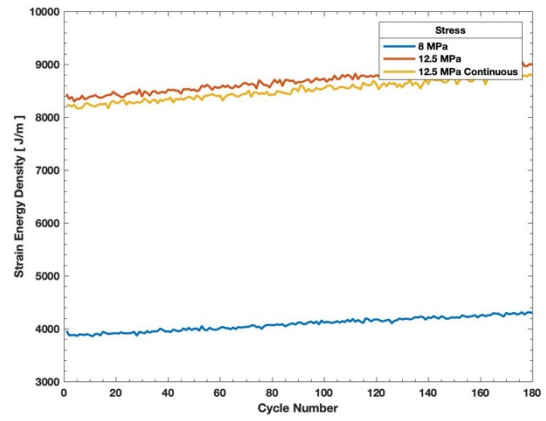
a)



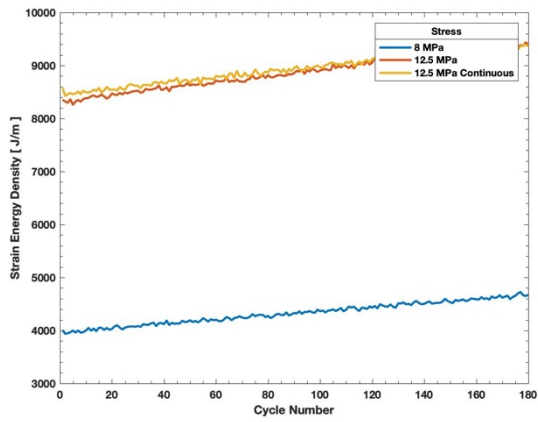
b)



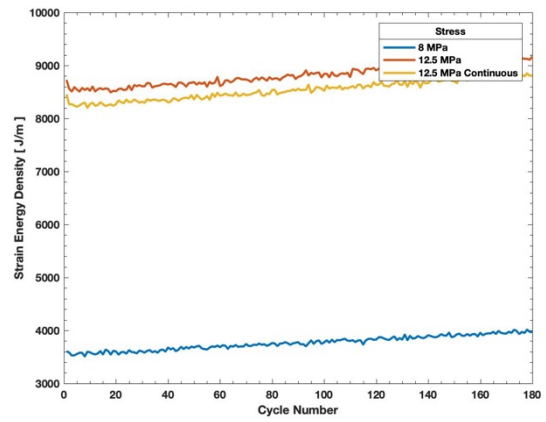
c)



d)



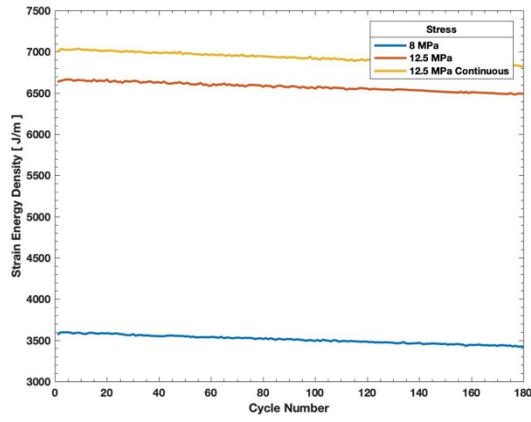
e)



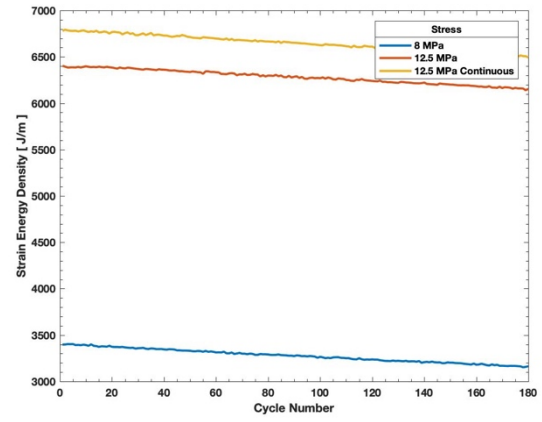
f)

Figure C-44: 180 °C - Total Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

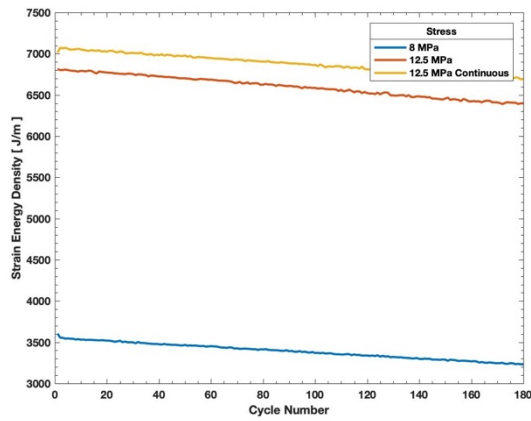
C.3.1.2 Stored



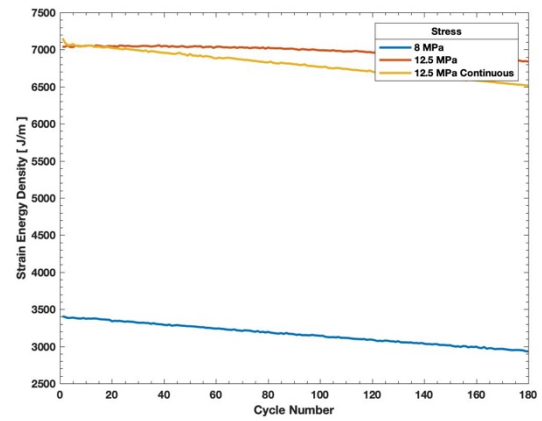
a)



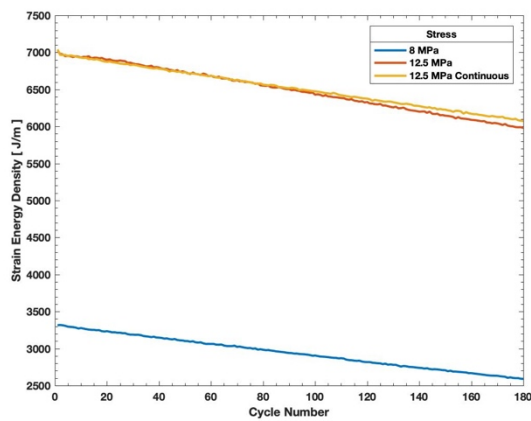
b)



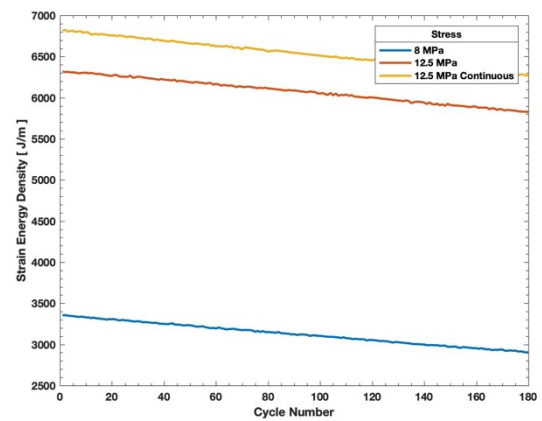
c)



d)

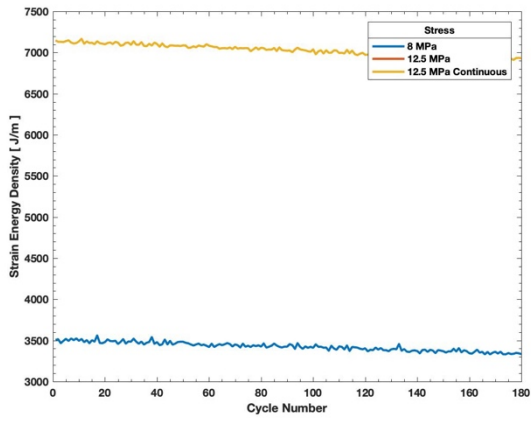


e)

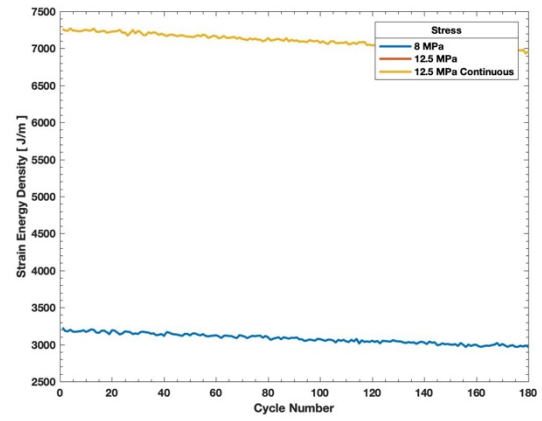


f)

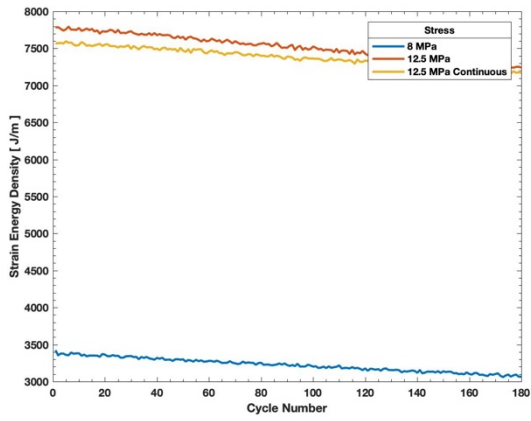
Figure C-45: Room Temperature - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



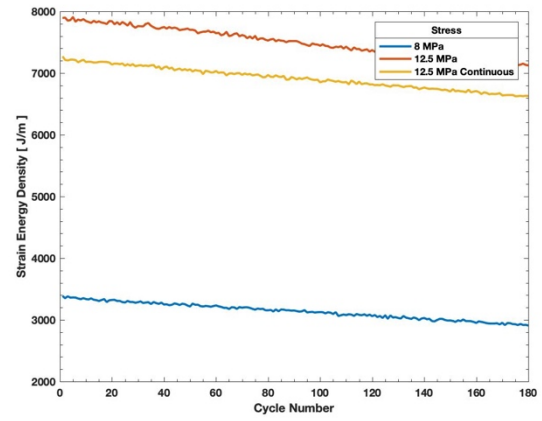
a)



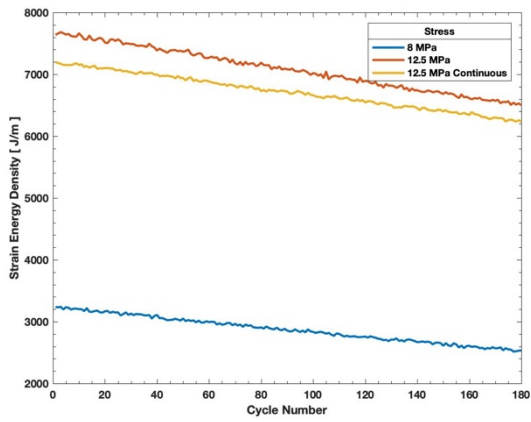
b)



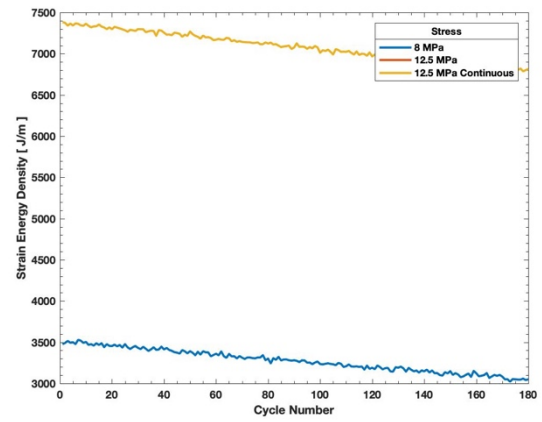
c)



d)

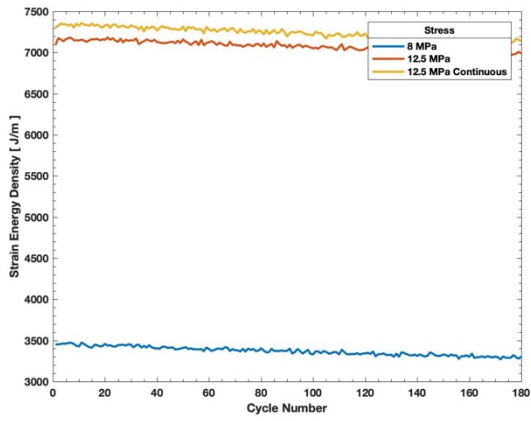


e)

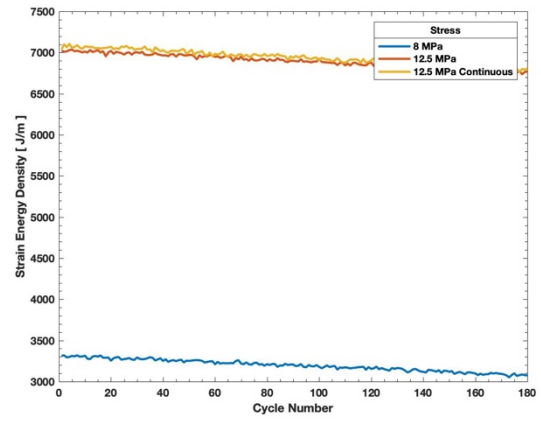


f)

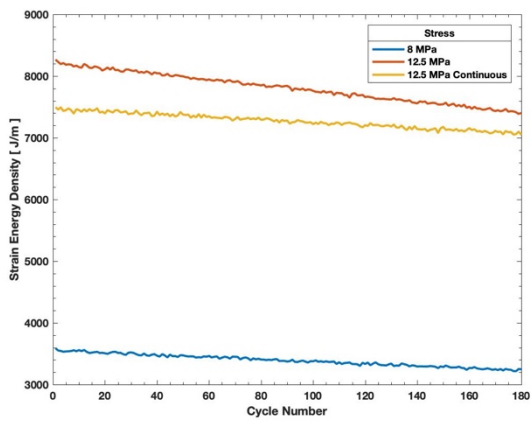
Figure C-46: 80 °C - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



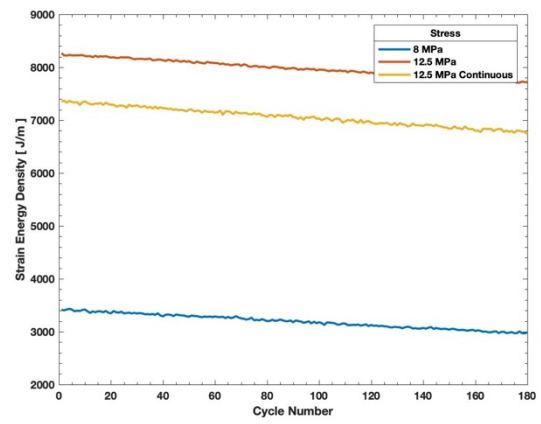
a)



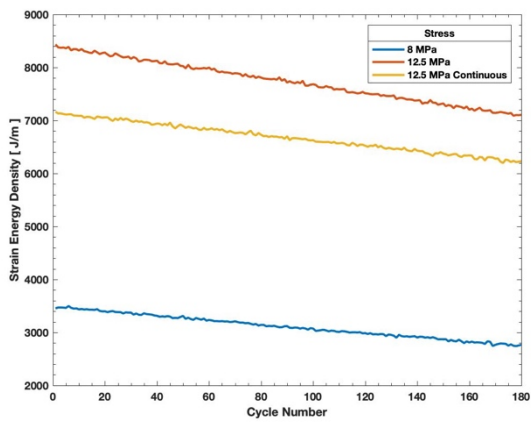
b)



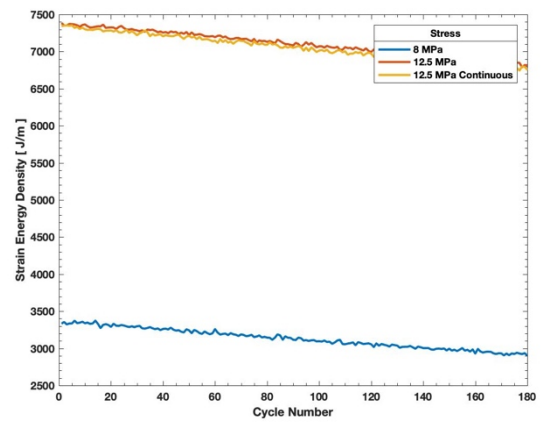
c)



d)

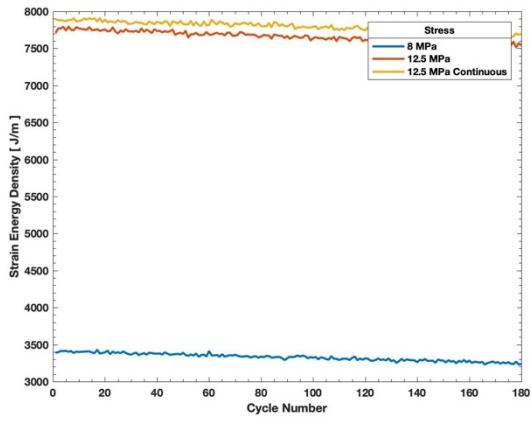


e)

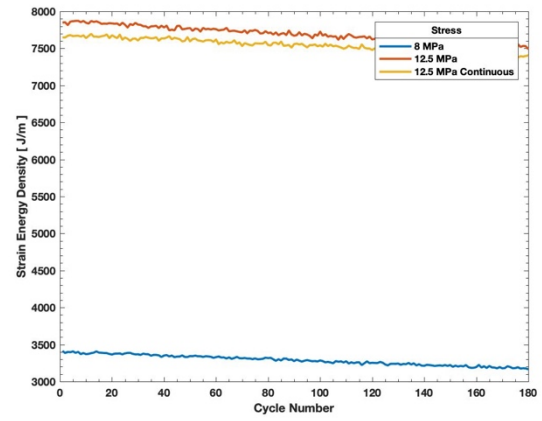


f)

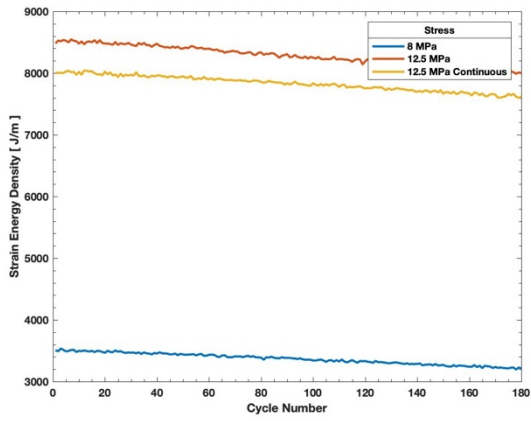
Figure C-47: 120 °C - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



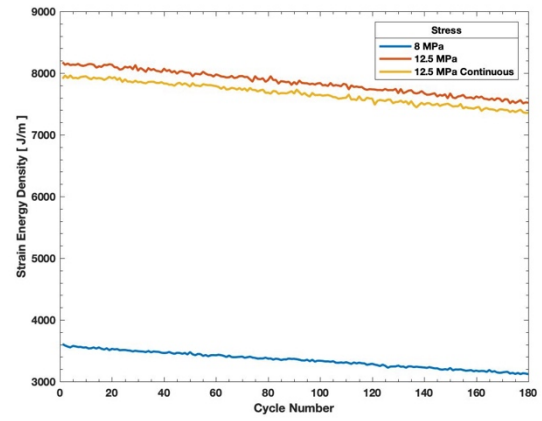
a)



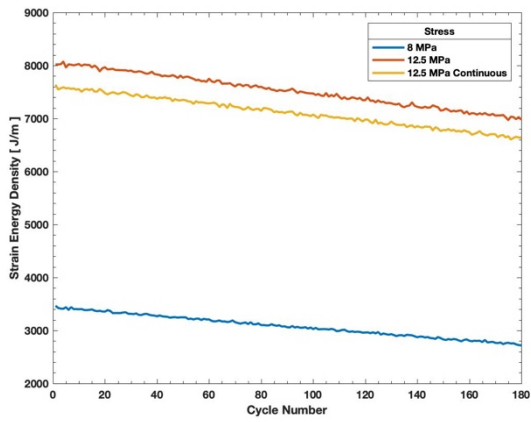
b)



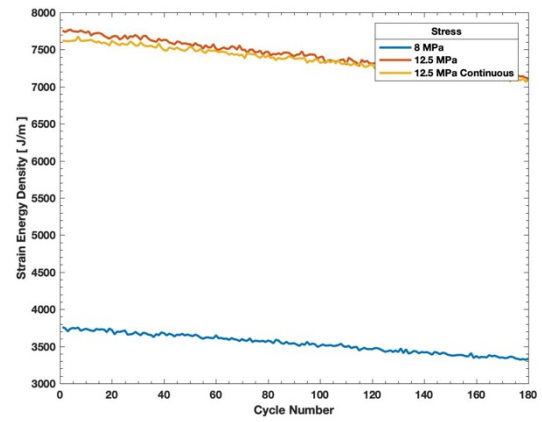
c)



d)



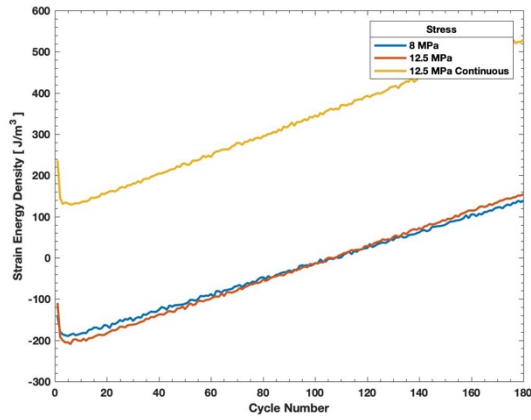
e)



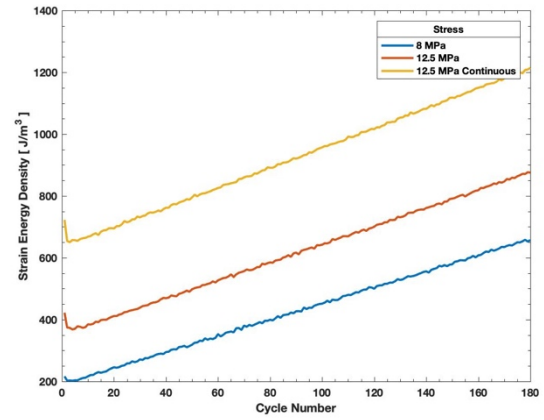
f)

Figure C-48: 180 °C - Stored Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

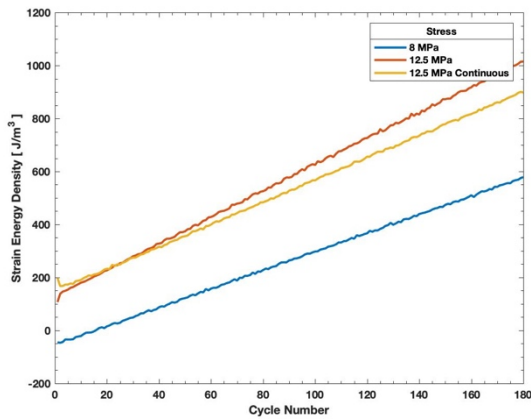
C.3.1.3 Dissipated



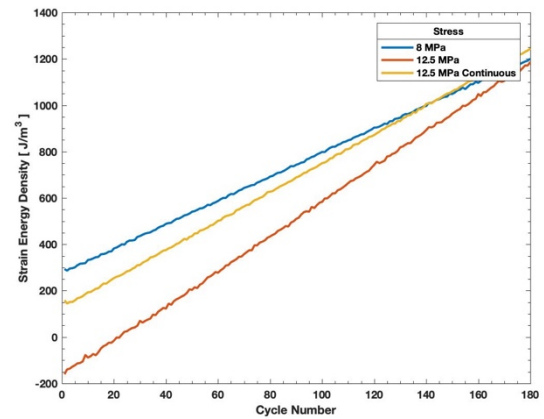
a)



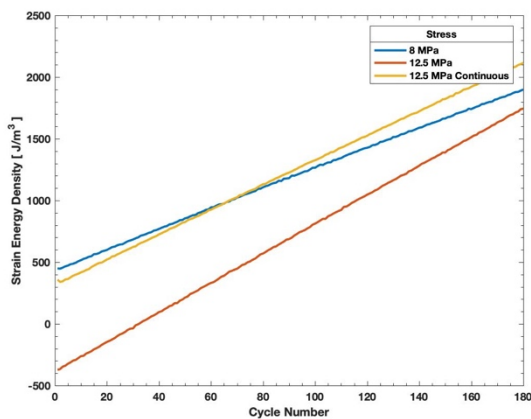
b)



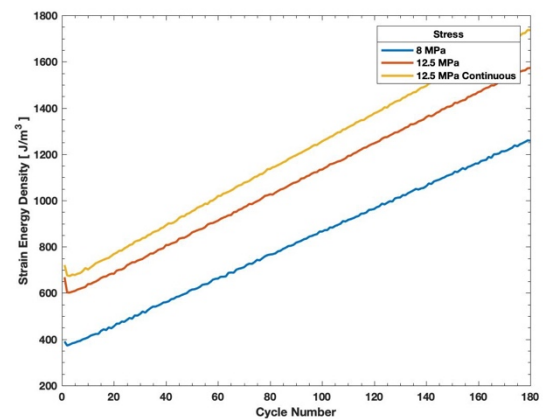
c)



d)

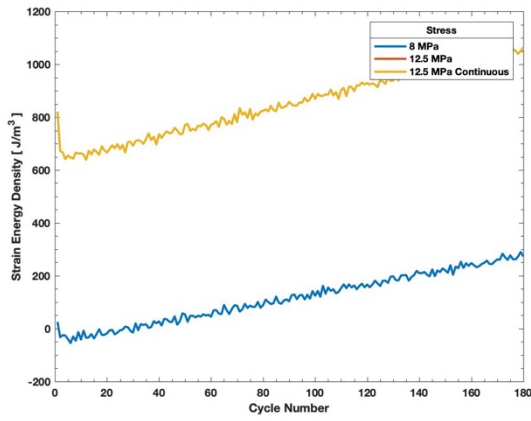


e)

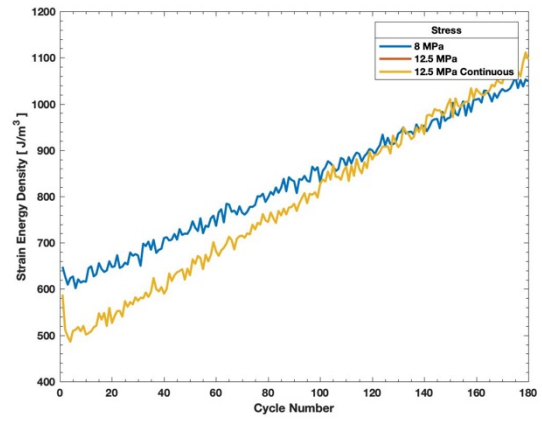


f)

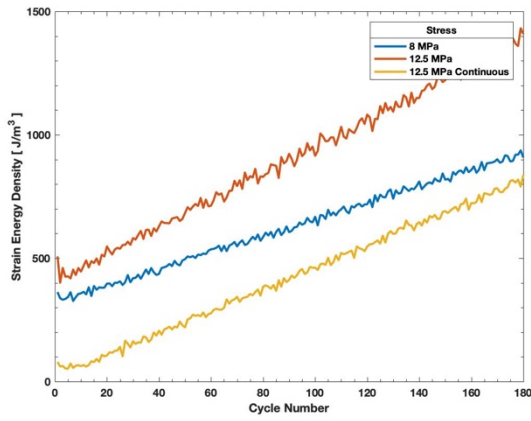
Figure C-49: Room Temperature - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



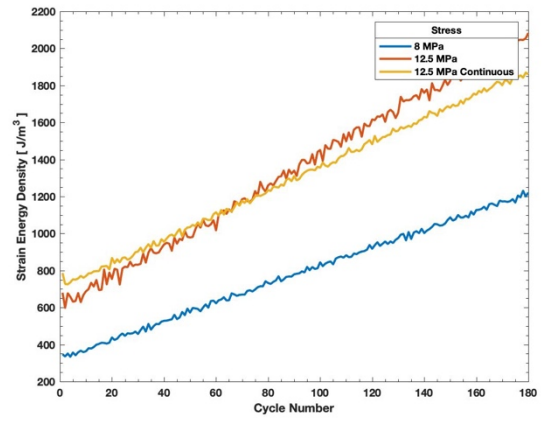
a)



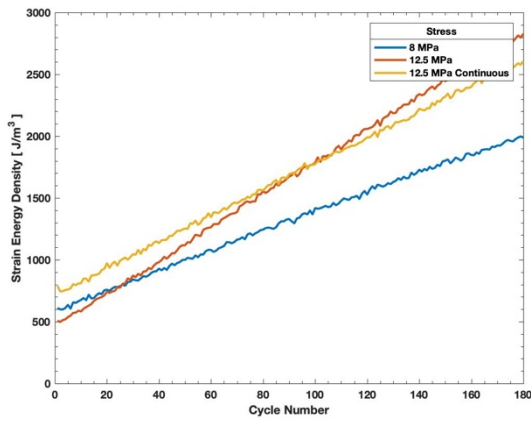
b)



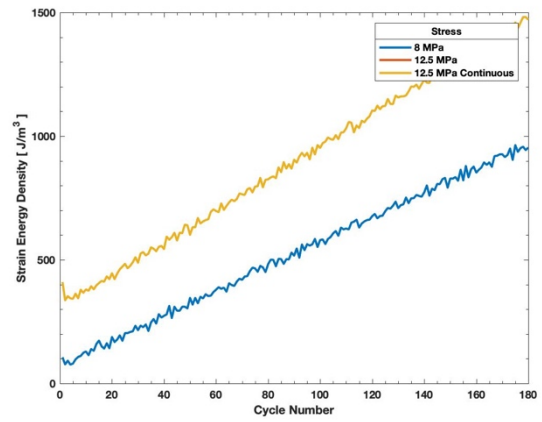
c)



d)

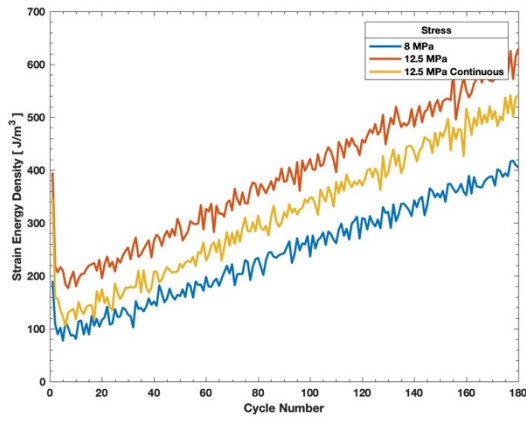


e)

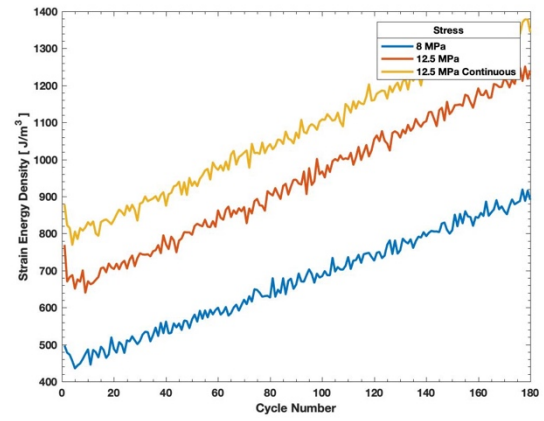


f)

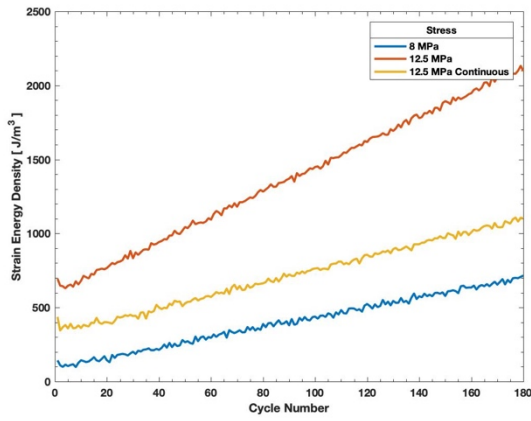
Figure C-50: 80 °C - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



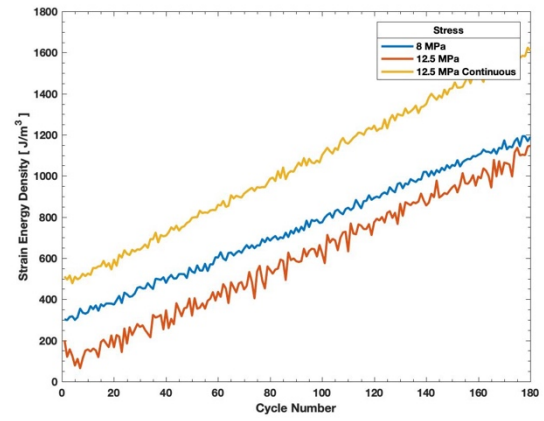
a)



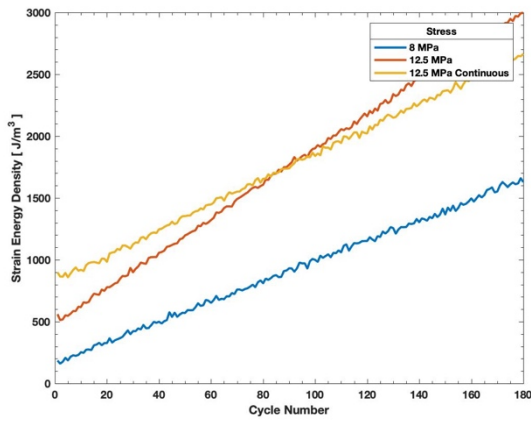
b)



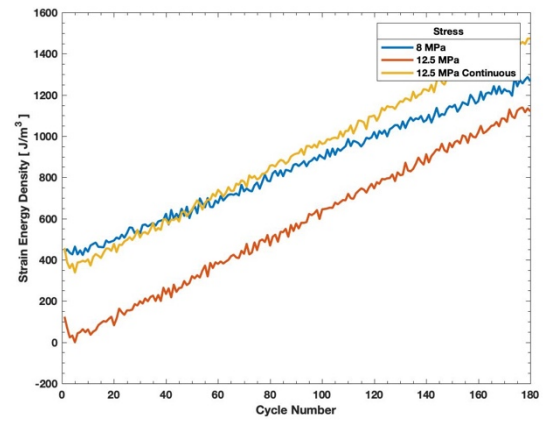
c)



d)

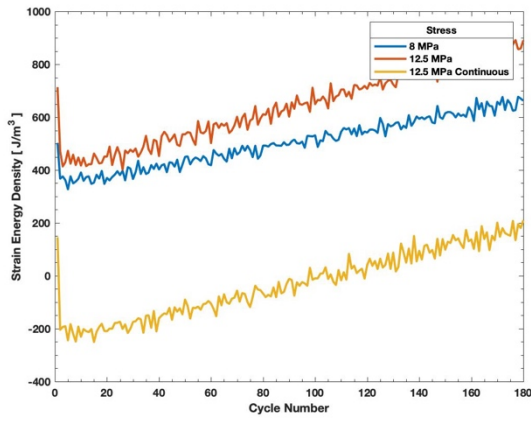


e)

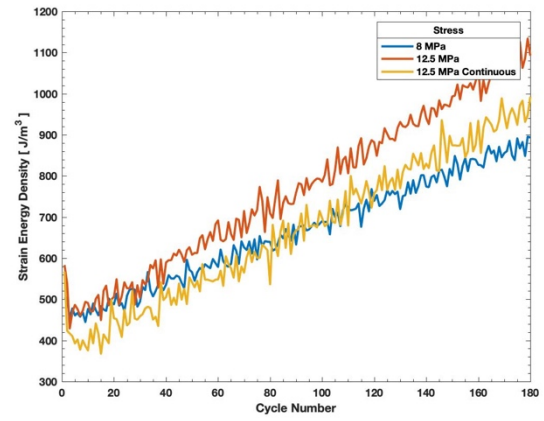


f)

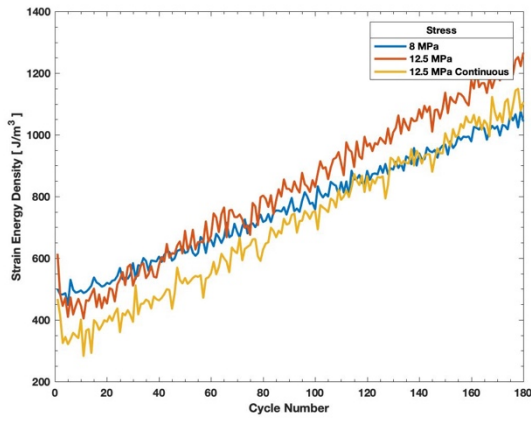
Figure C-51: 120°C - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



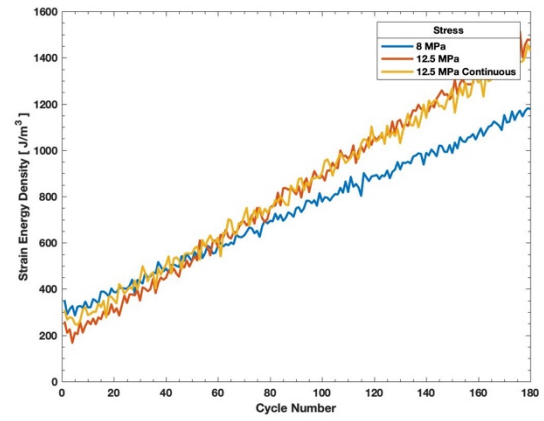
a)



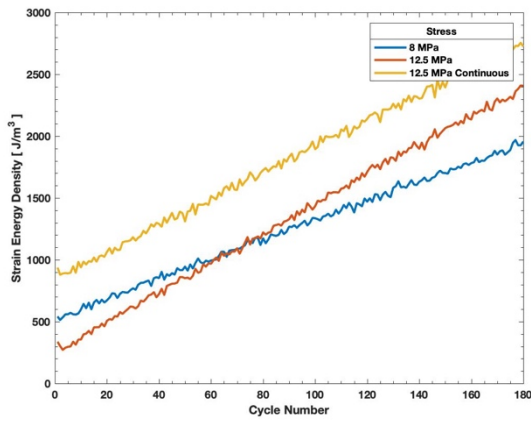
b)



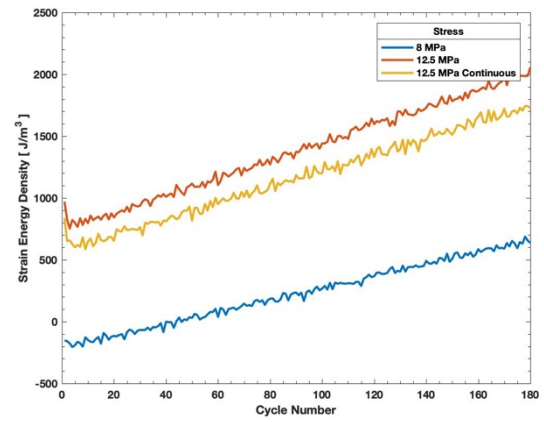
c)



d)



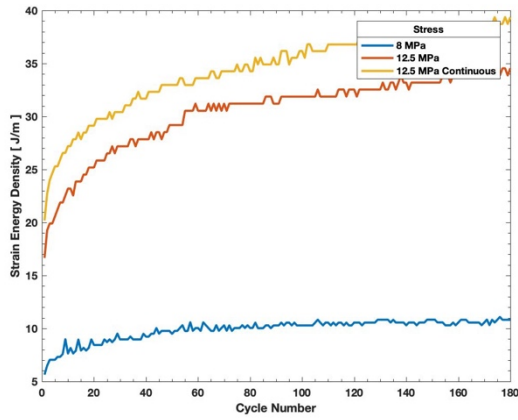
e)



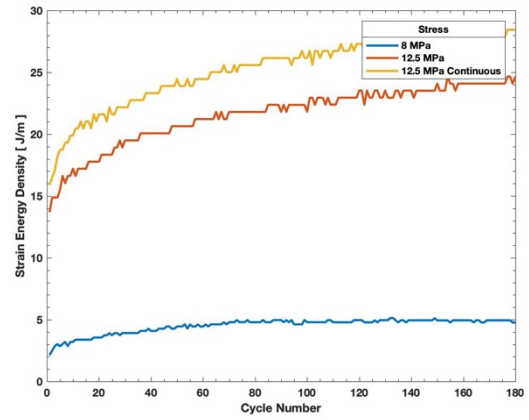
f)

Figure C-52: 180 °C - Dissipated Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

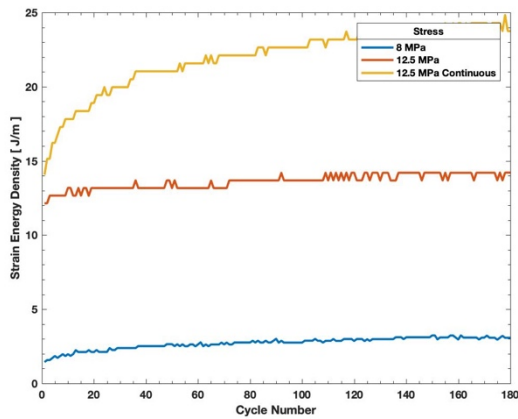
C.3.1.4 Unrecovered



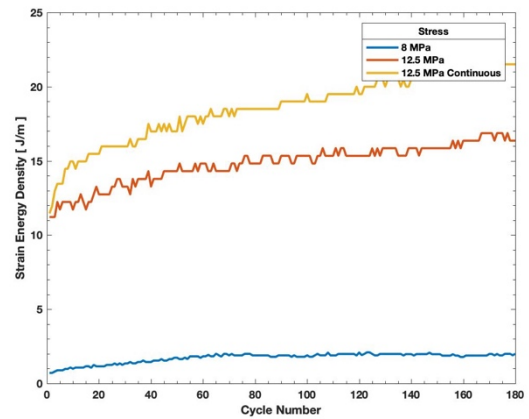
a)



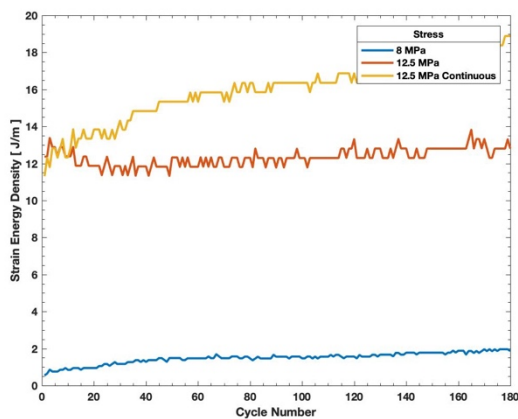
b)



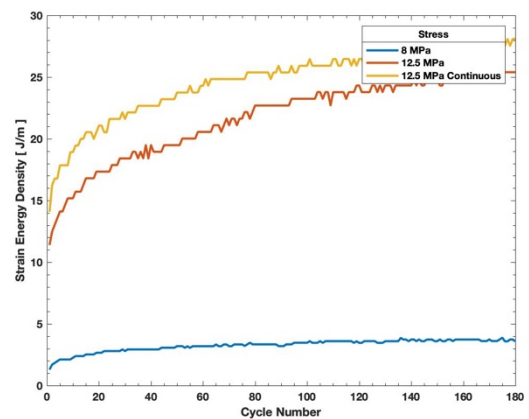
c)



d)

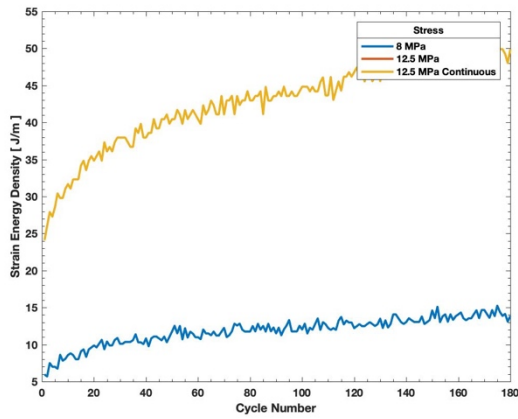


e)

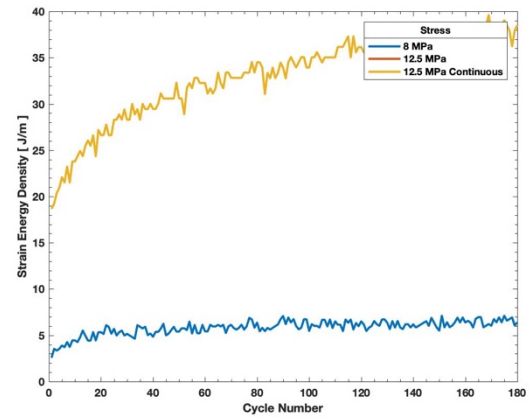


f)

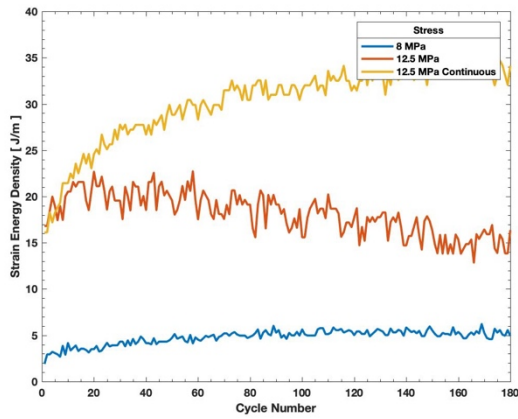
Figure C-53: Room Temperature - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



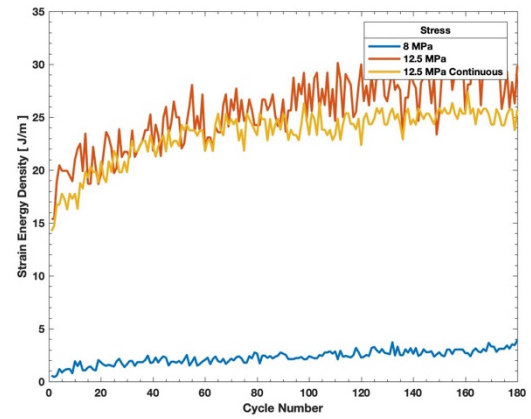
a)



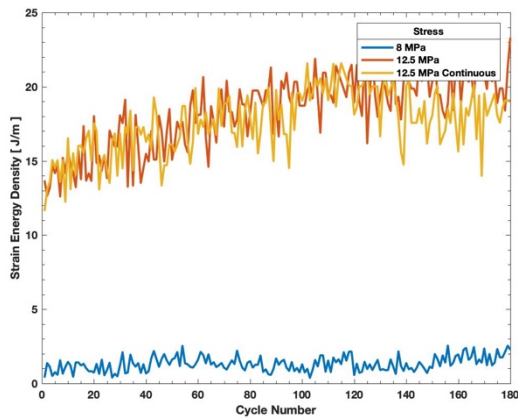
b)



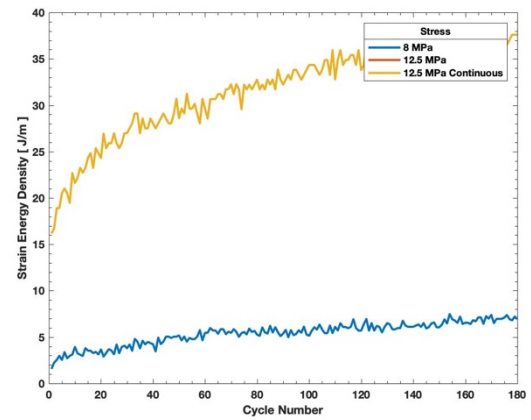
c)



d)

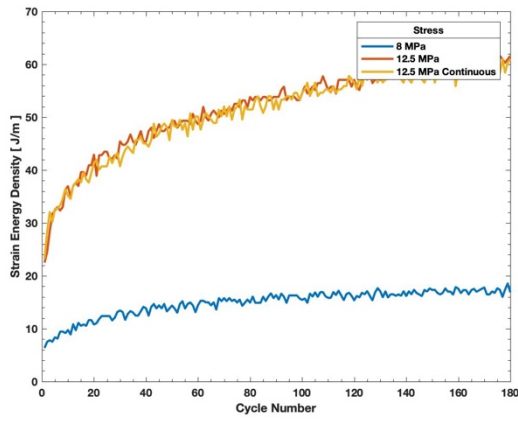


e)

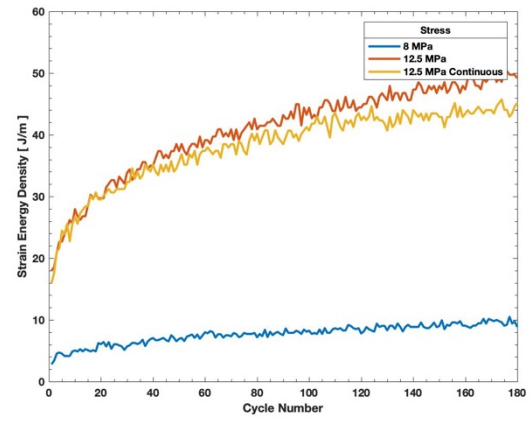


f)

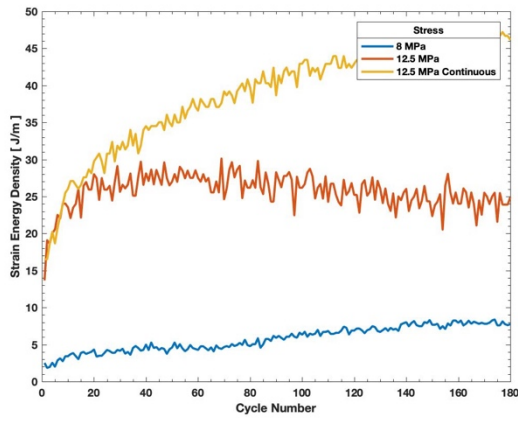
Figure C-54: 80 °C - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



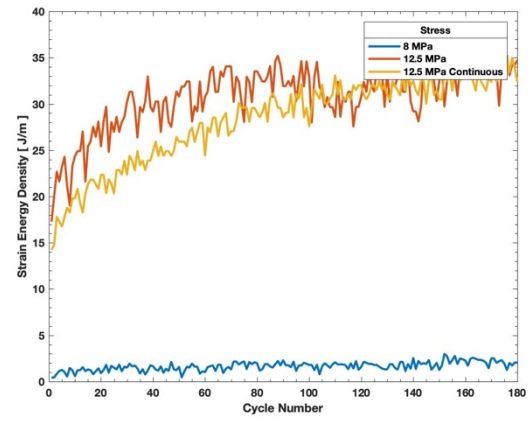
a)



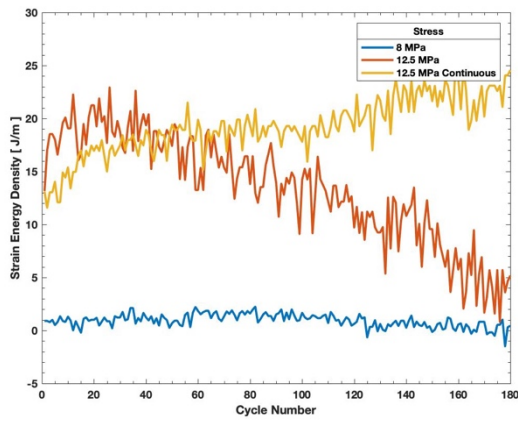
b)



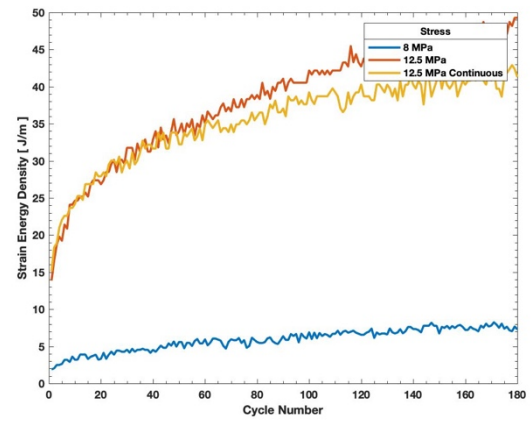
c)



d)

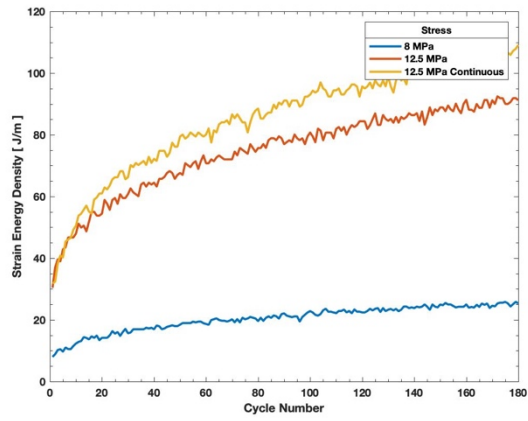


e)

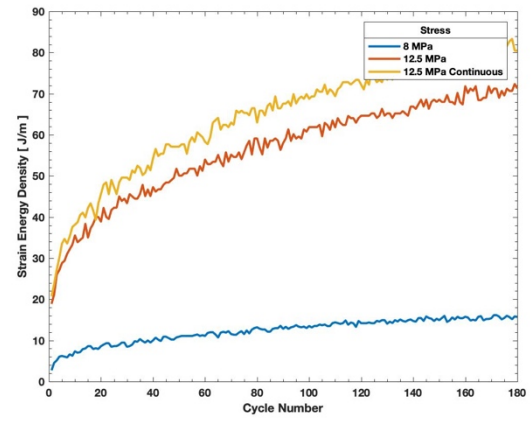


f)

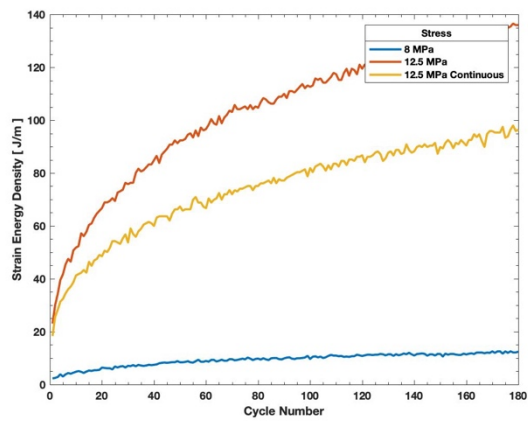
Figure C-55: 120 °C - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



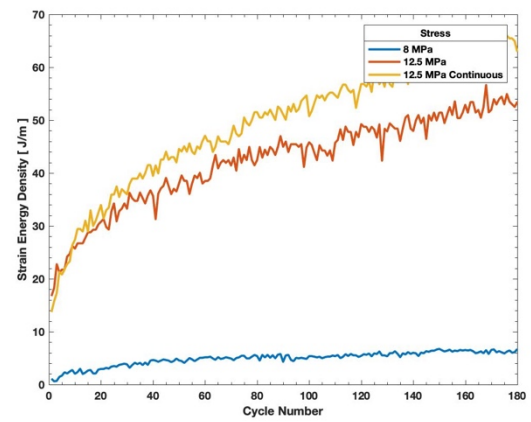
a)



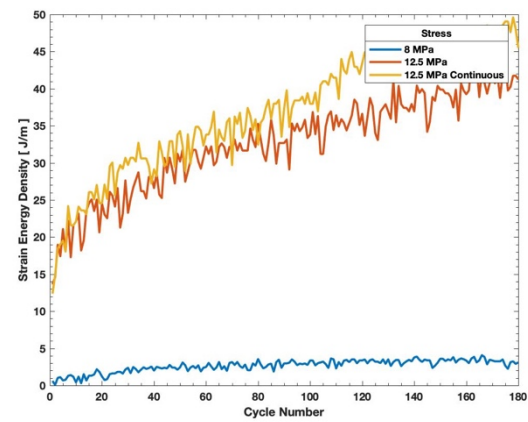
b)



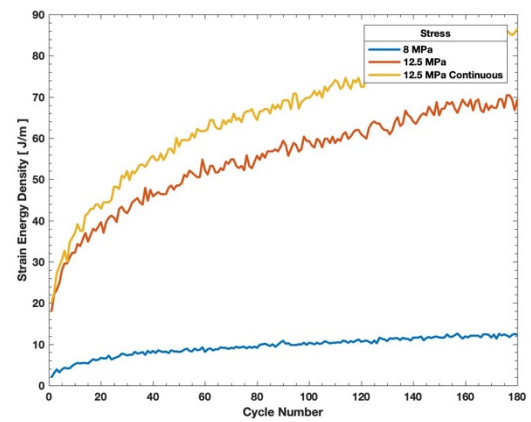
c)



d)



e)



f)

Figure C-56: 180 °C - Unrecovered Strain Energy Density vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.3.2 Total

C.3.2.1 Total - Loading

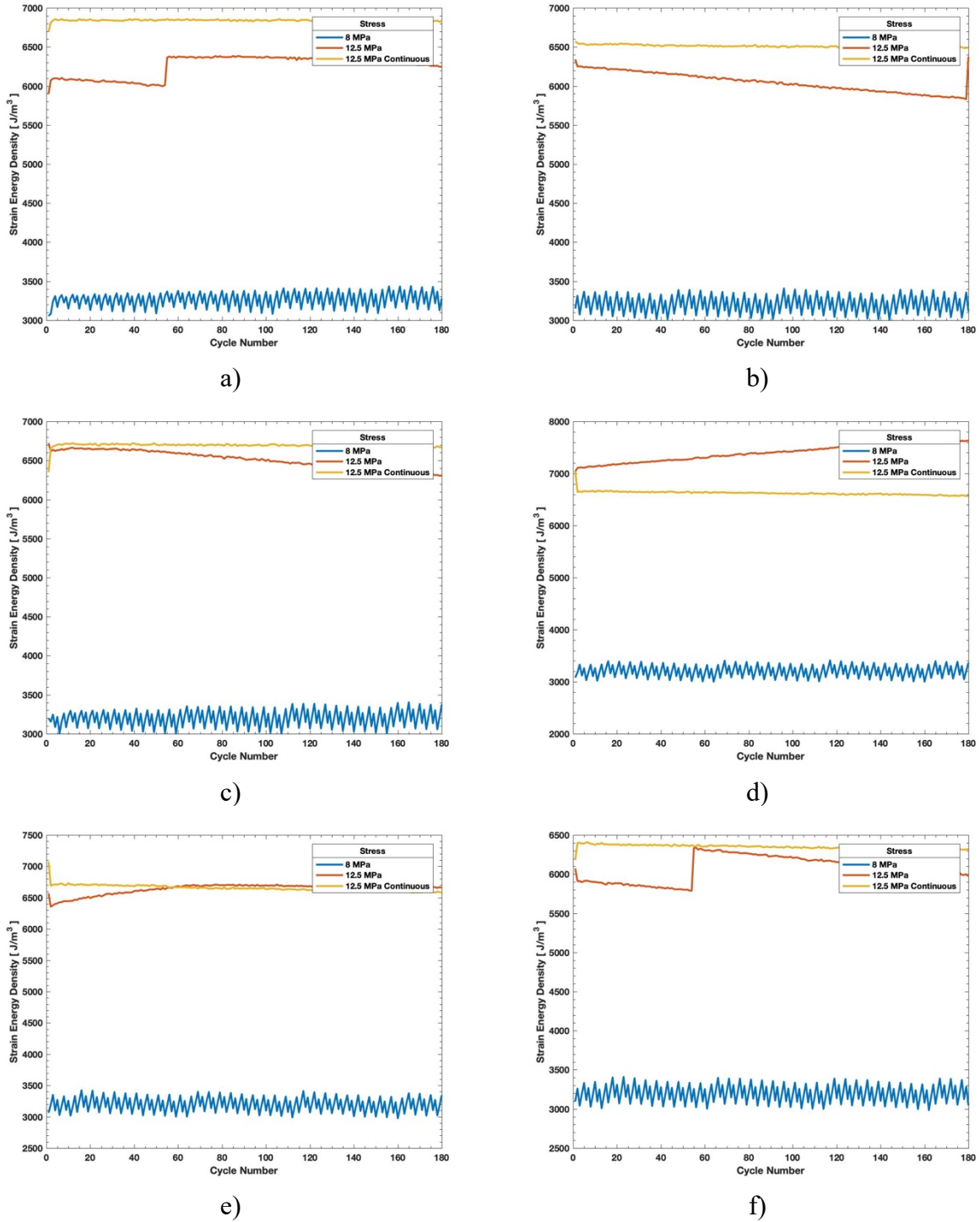
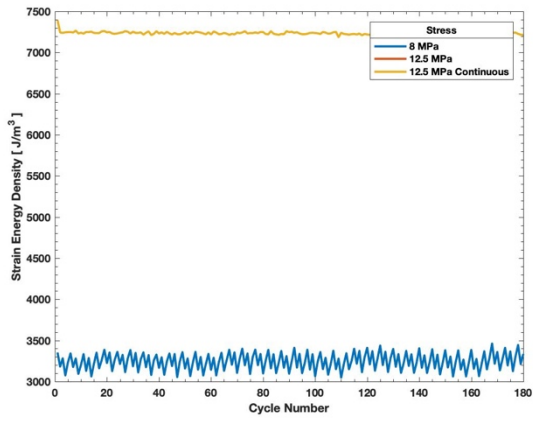
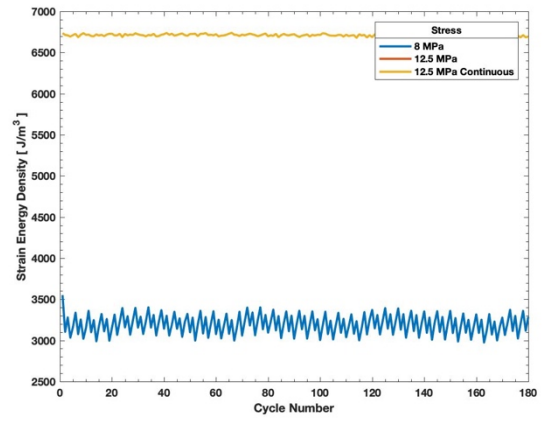


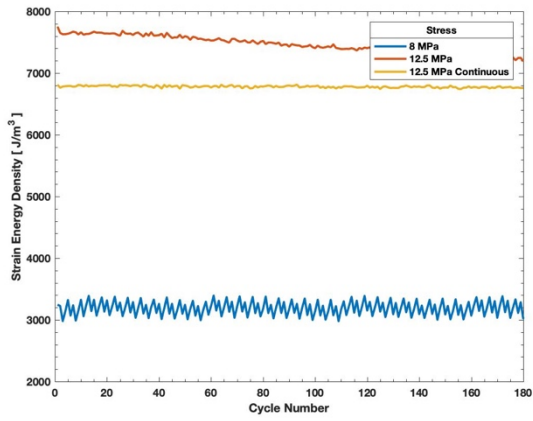
Figure C-57: Room Temperature - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



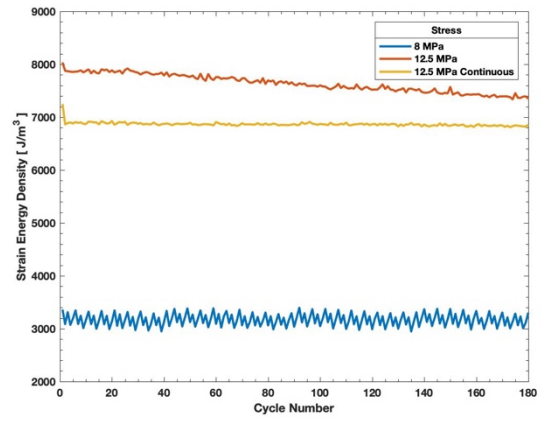
a)



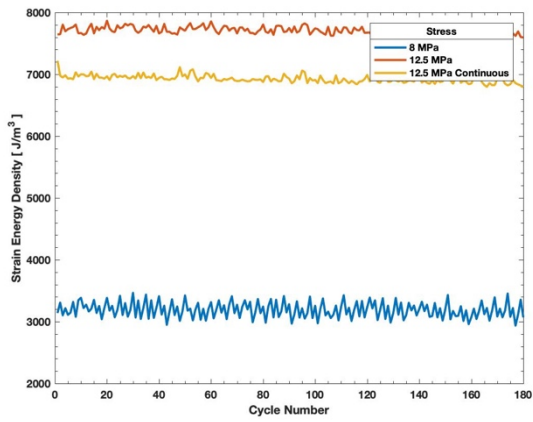
b)



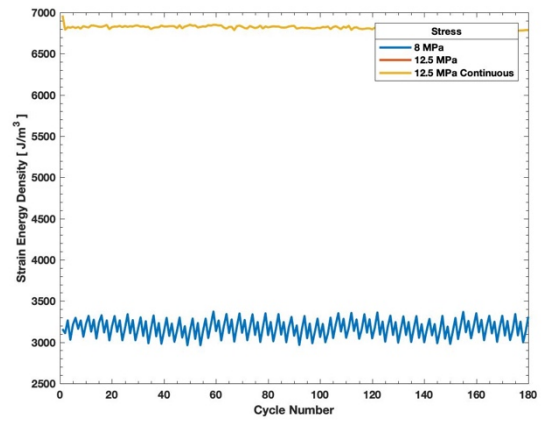
c)



d)

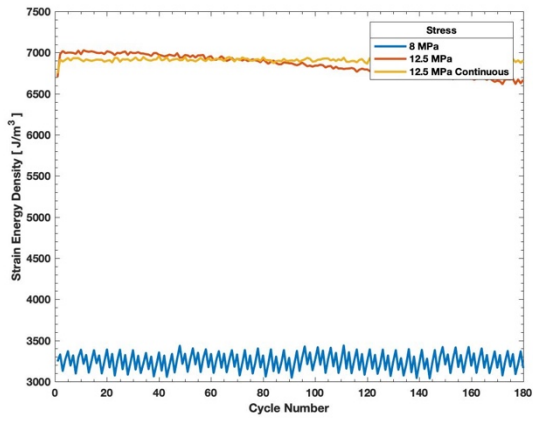


e)

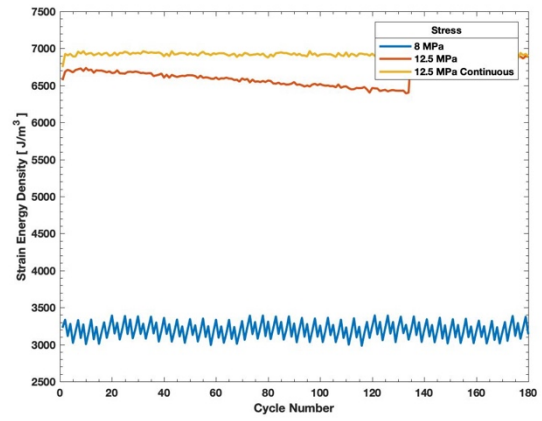


f)

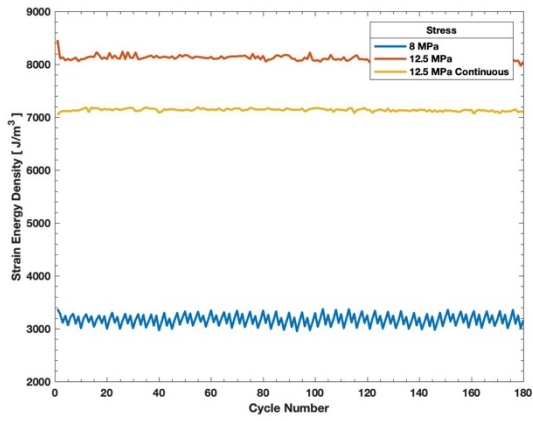
Figure C-58: 80 °C - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



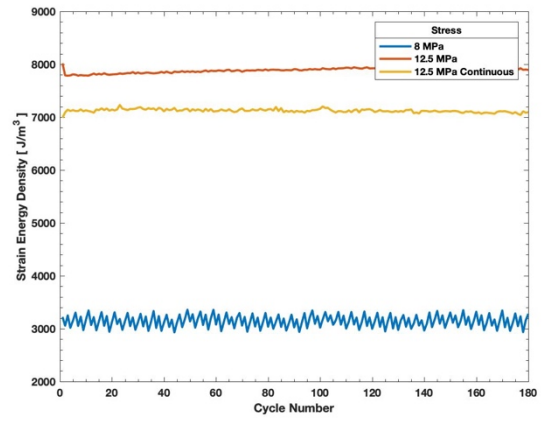
a)



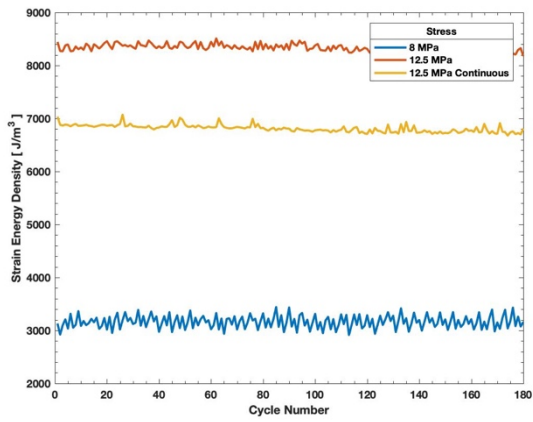
b)



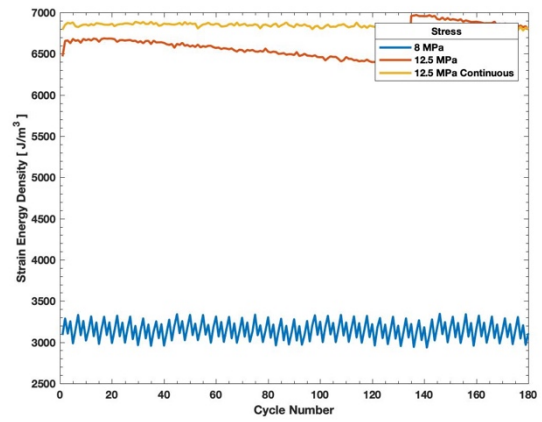
c)



d)

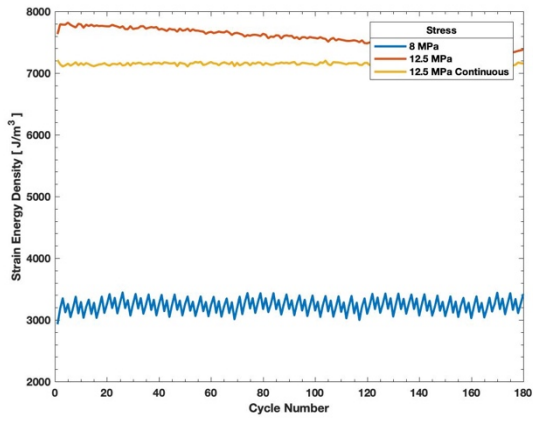


e)

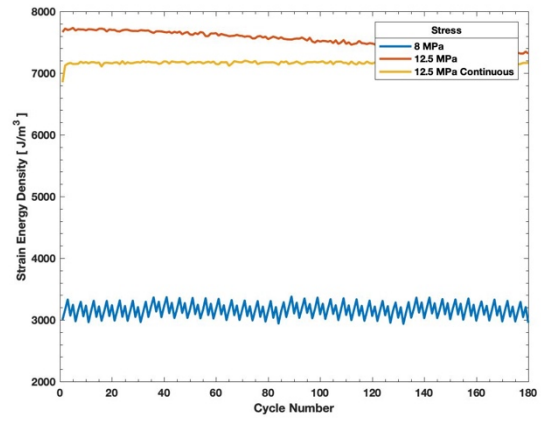


f)

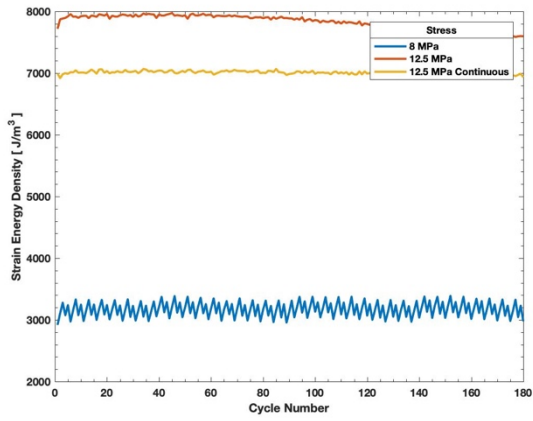
Figure C-59: 120 °C - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



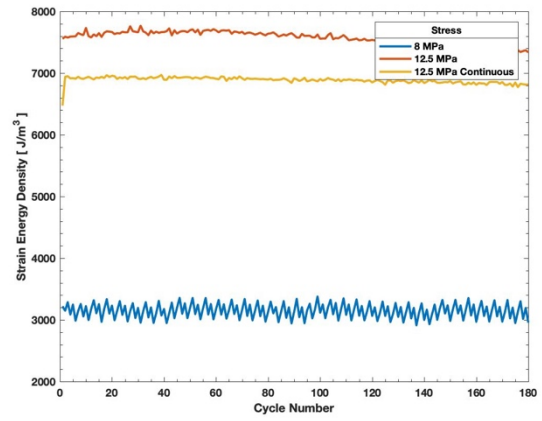
a)



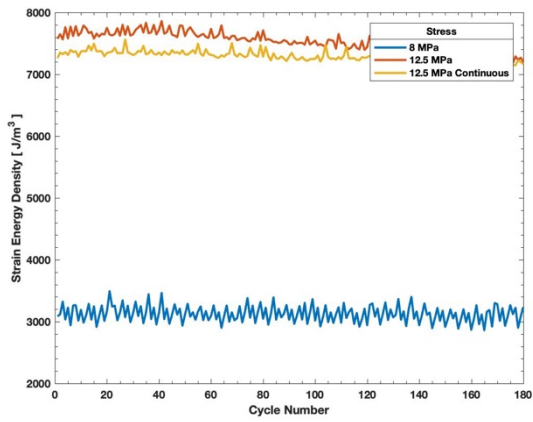
b)



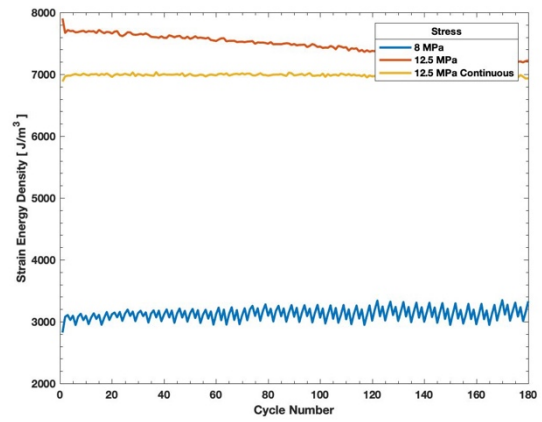
c)



d)



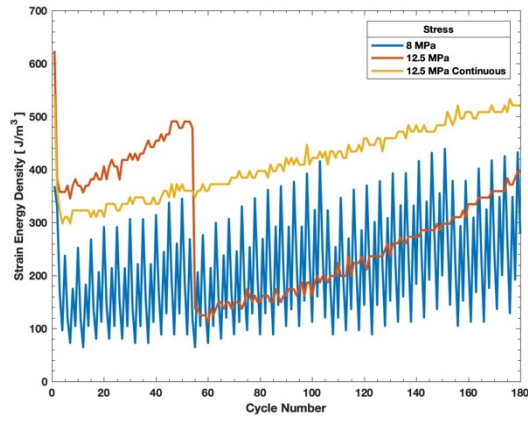
e)



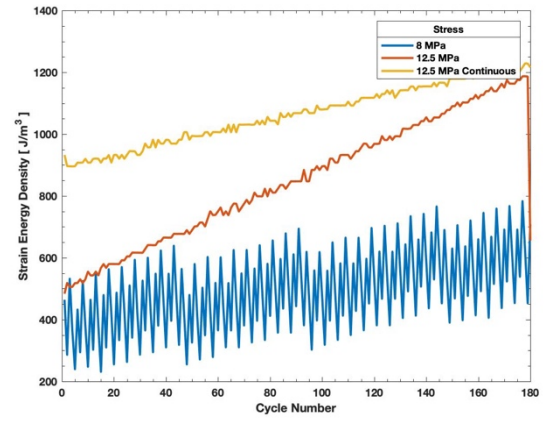
f)

Figure C-60: 180 °C - Total Strain Energy Density (Loading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

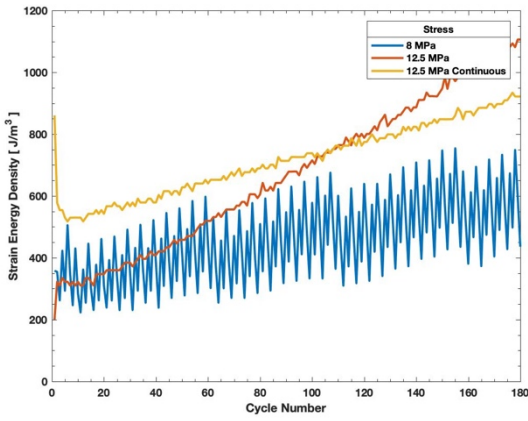
C.3.2.2 Total - Creep



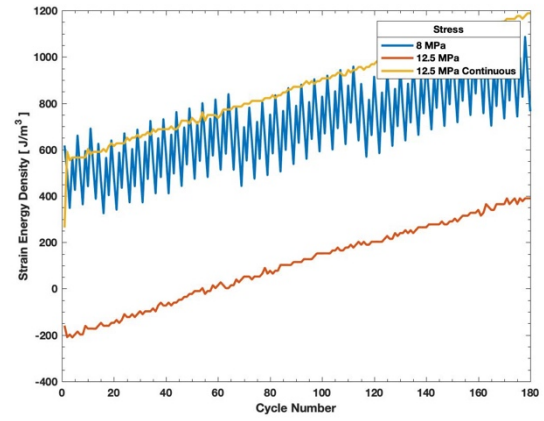
a)



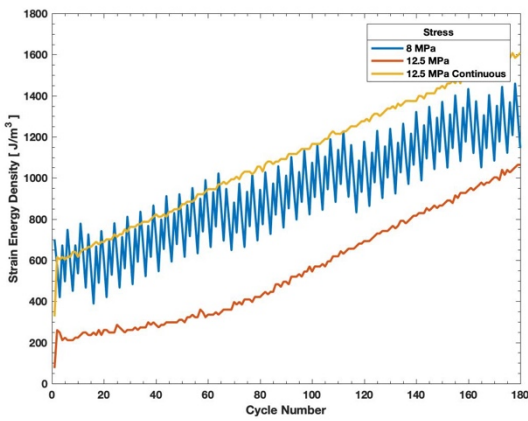
b)



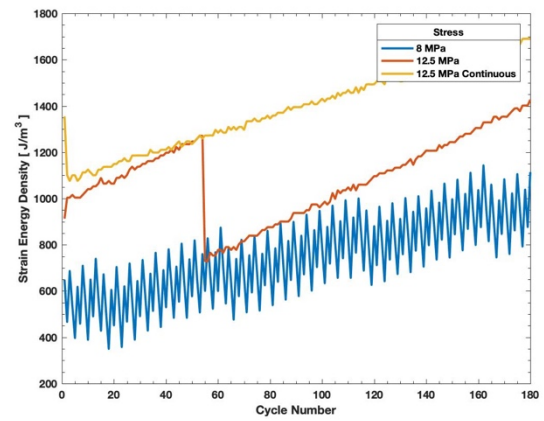
c)



d)

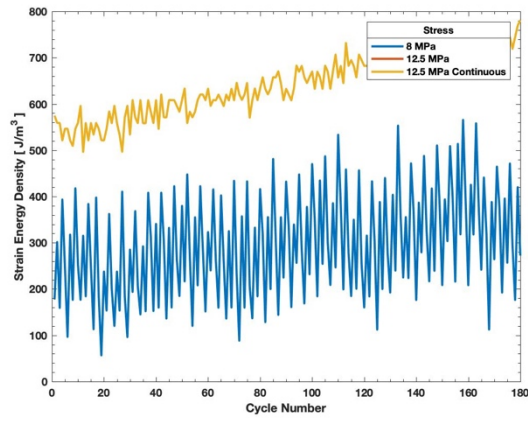


e)

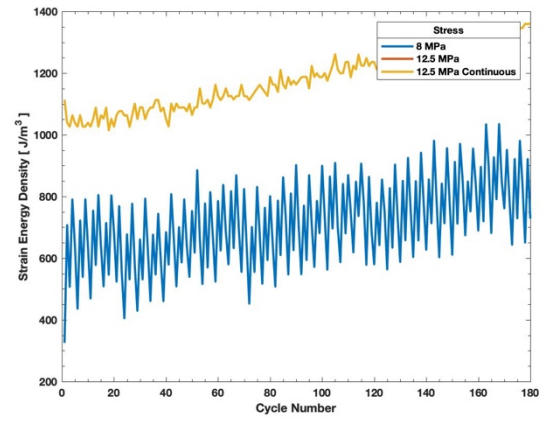


f)

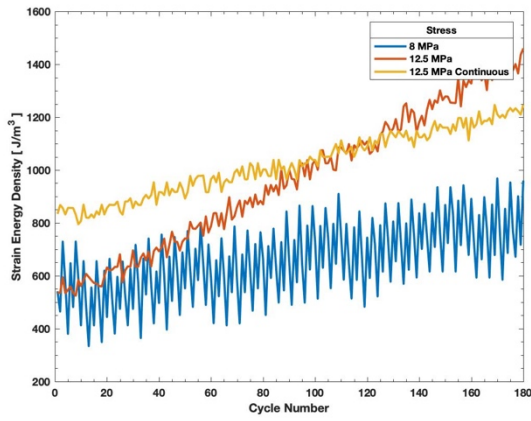
Figure C-61: Room Temperature - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



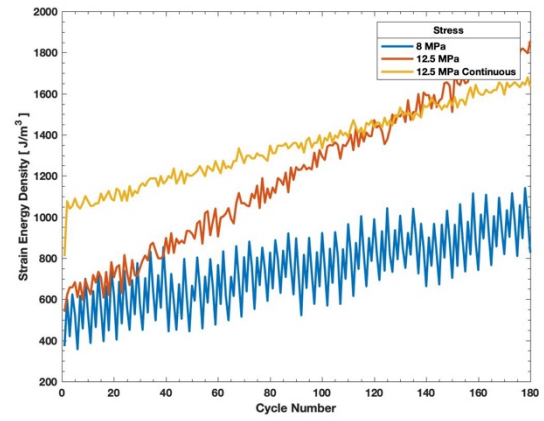
a)



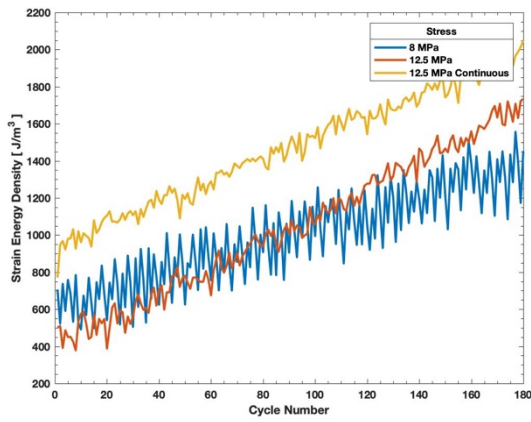
b)



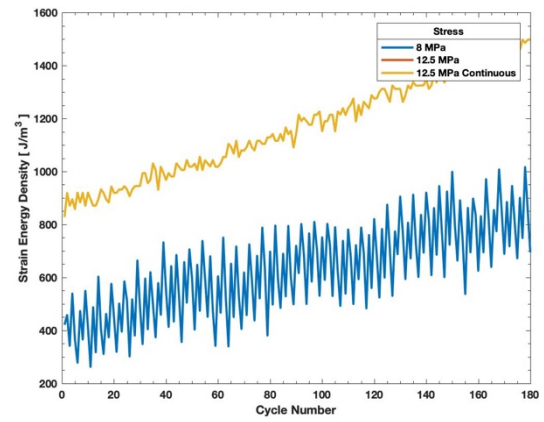
c)



d)

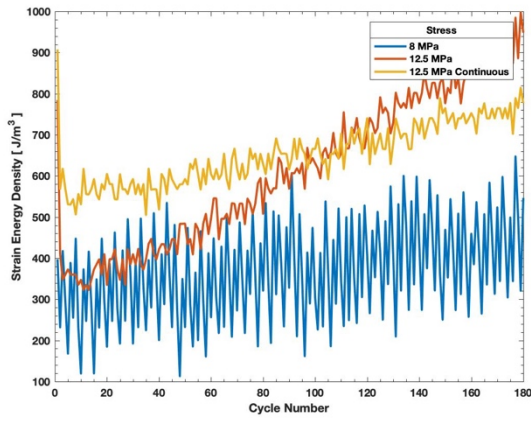


e)

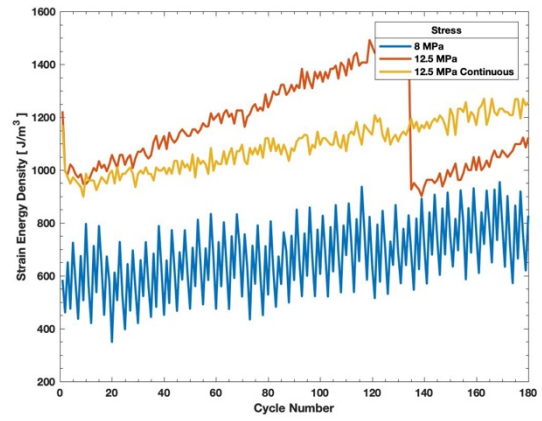


f)

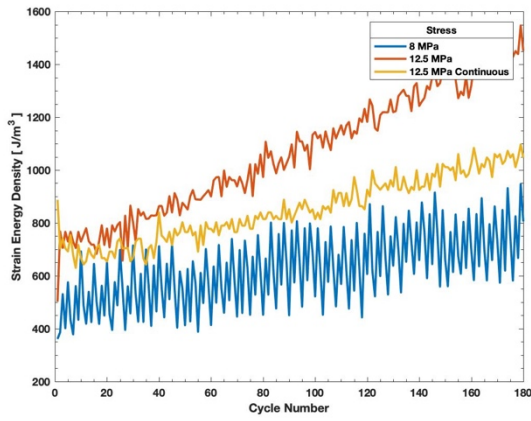
Figure C-62: 80 °C - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



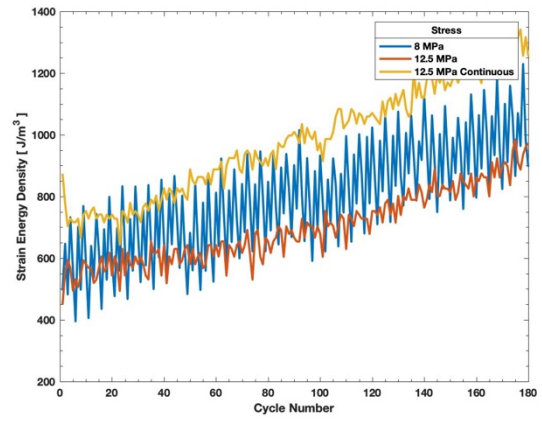
a)



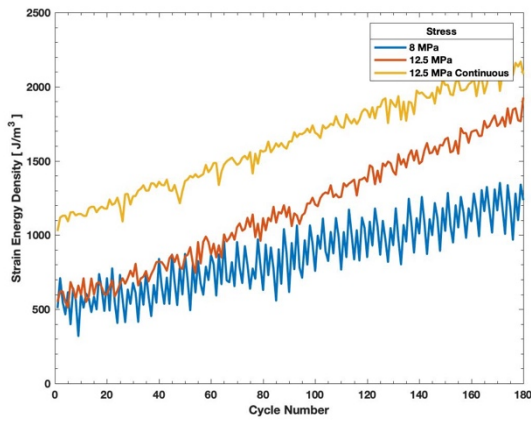
b)



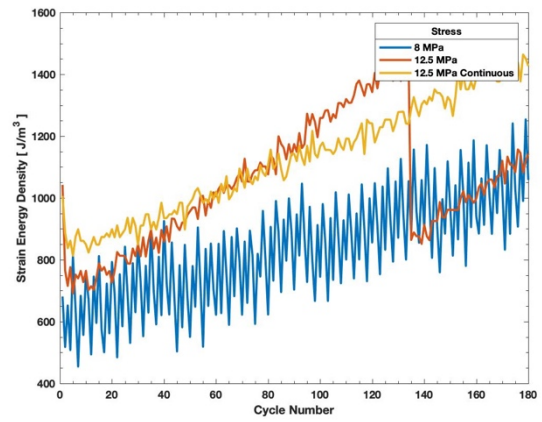
c)



d)

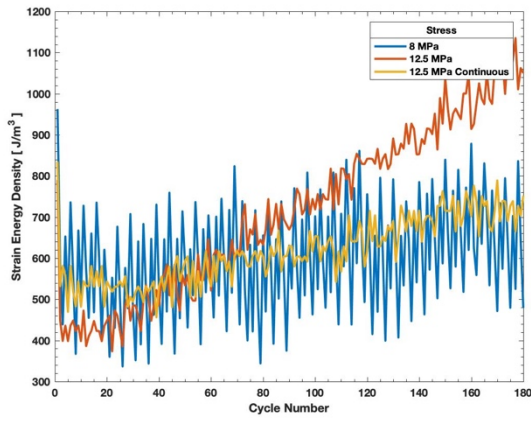


e)

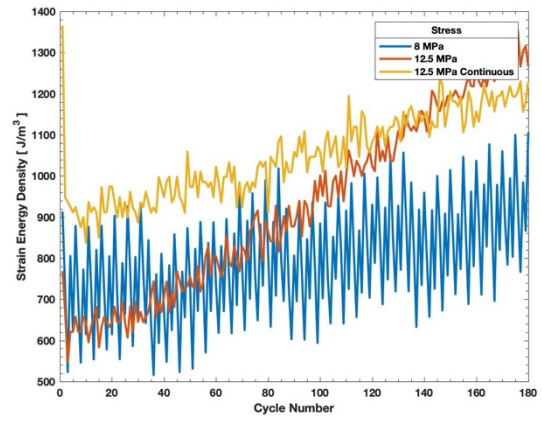


f)

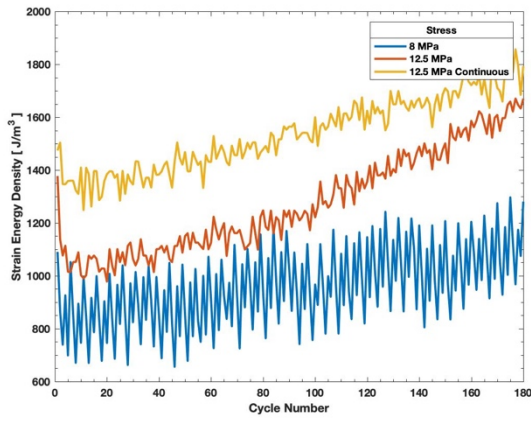
Figure C-63: 120 °C - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



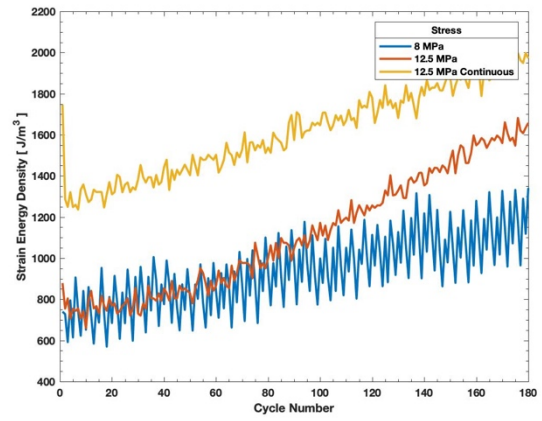
a)



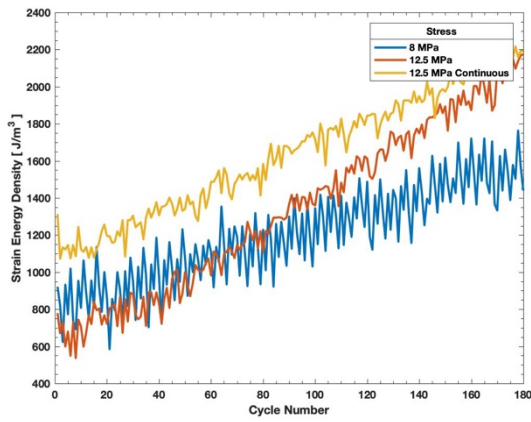
b)



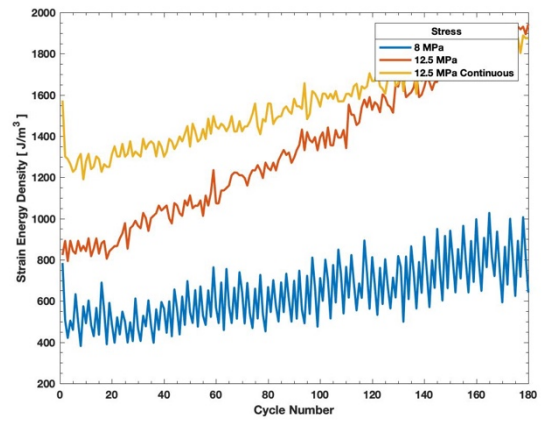
c)



d)



e)

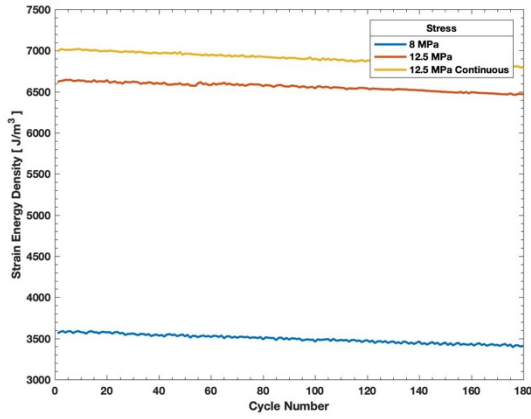


f)

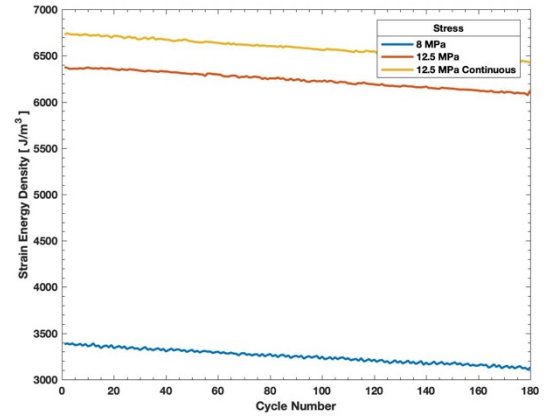
Figure C-64: 180 °C - Total Strain Energy Density (Creep) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.3.3 Stored

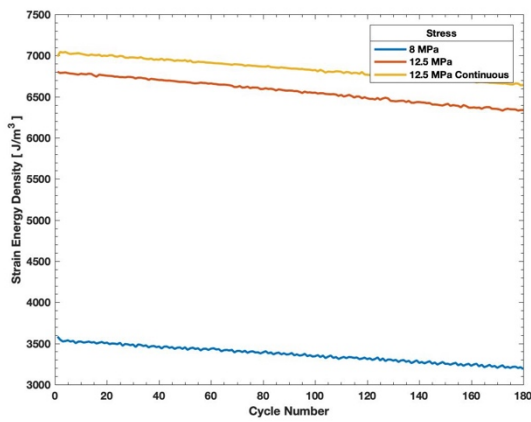
C.3.3.1 Stored - Unloading



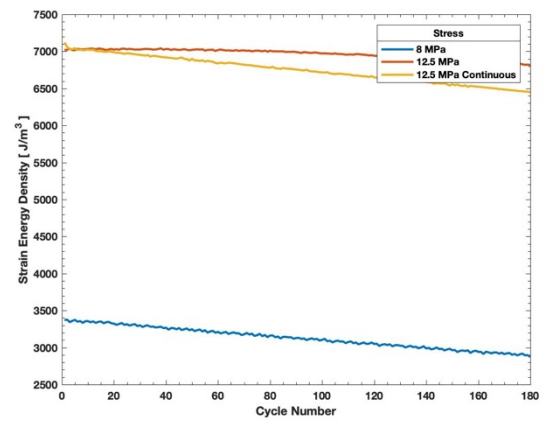
a)



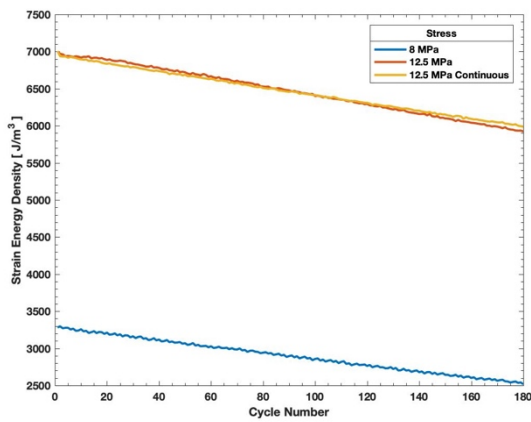
b)



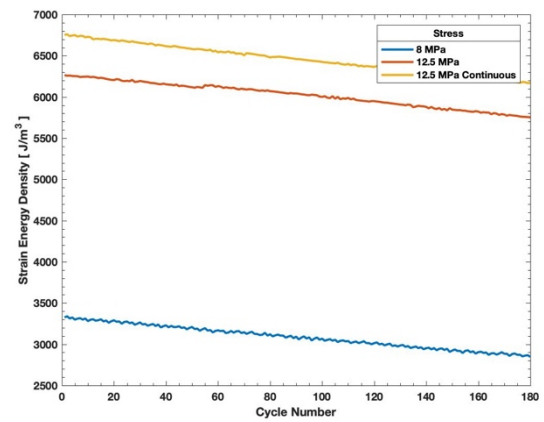
c)



d)

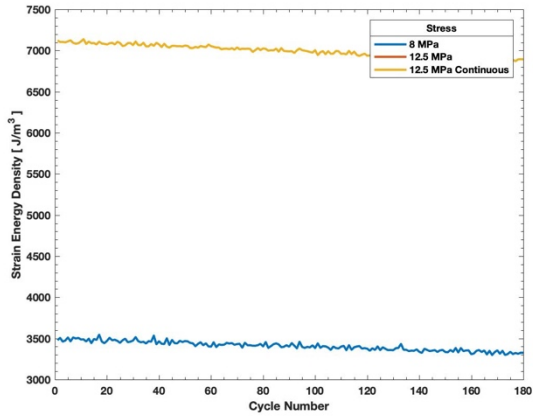


e)

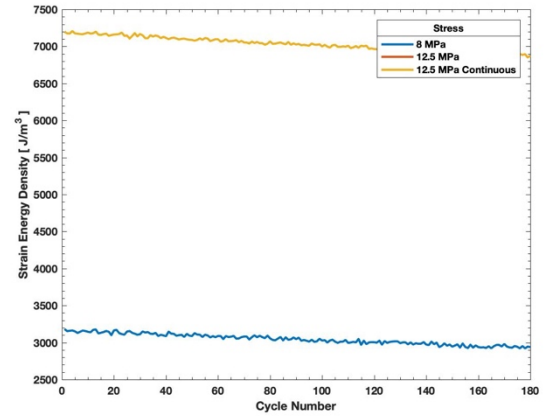


f)

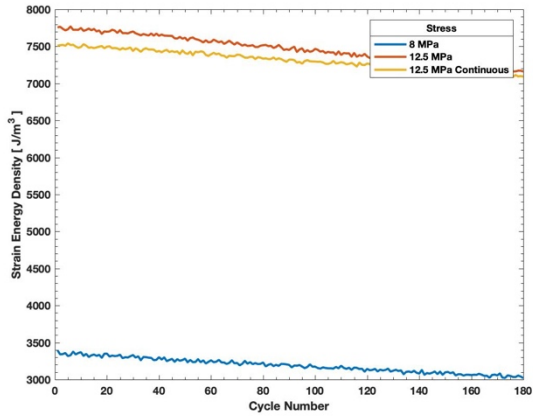
Figure C-65: Room Temperature - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



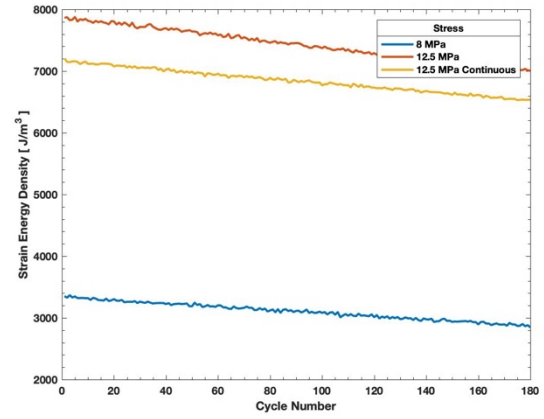
a)



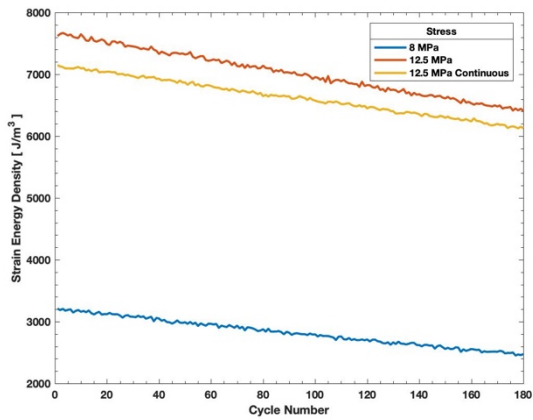
b)



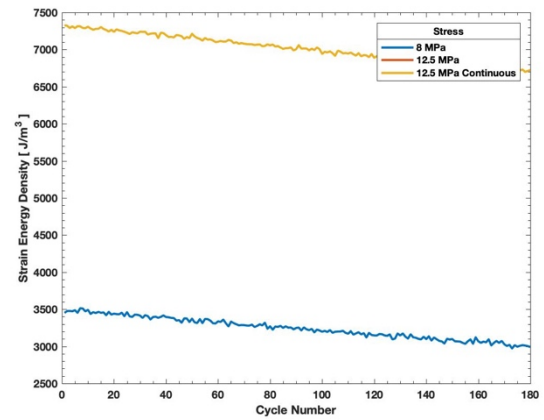
c)



d)

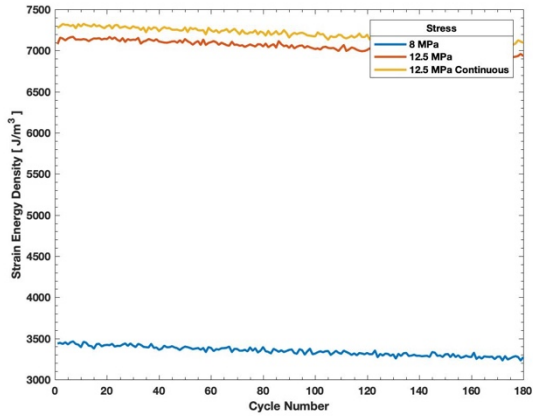


e)

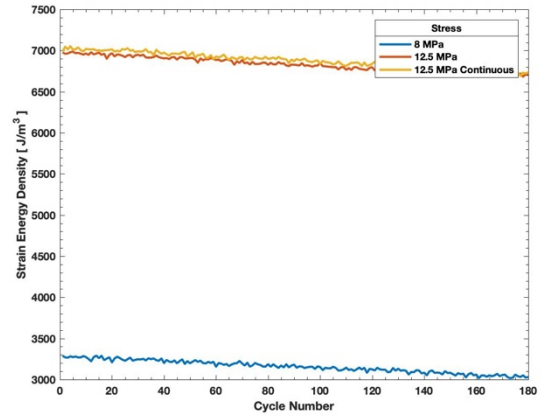


f)

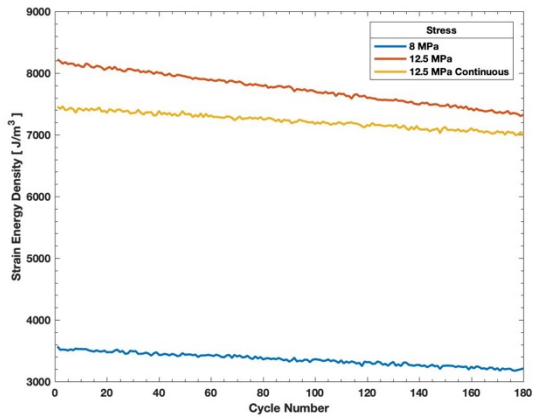
Figure C-66: 80 °C - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



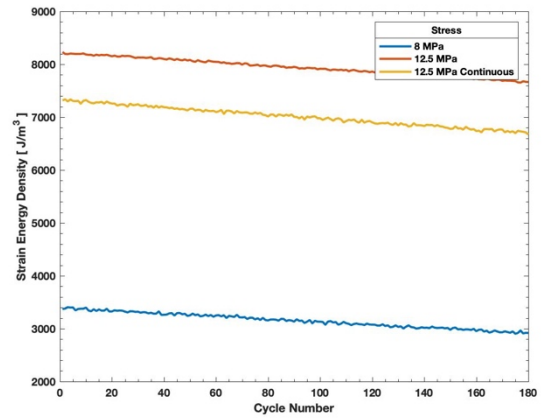
a)



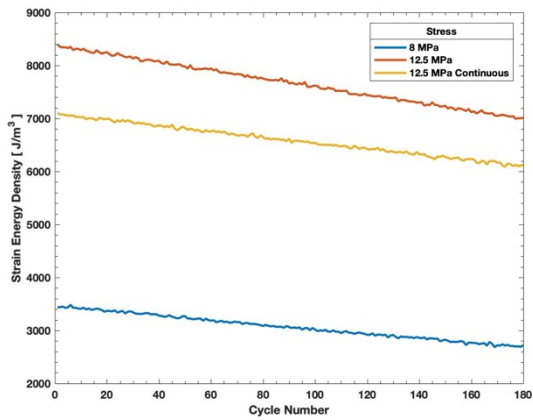
b)



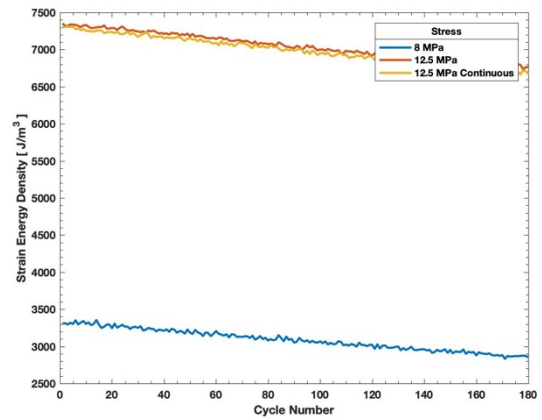
c)



d)

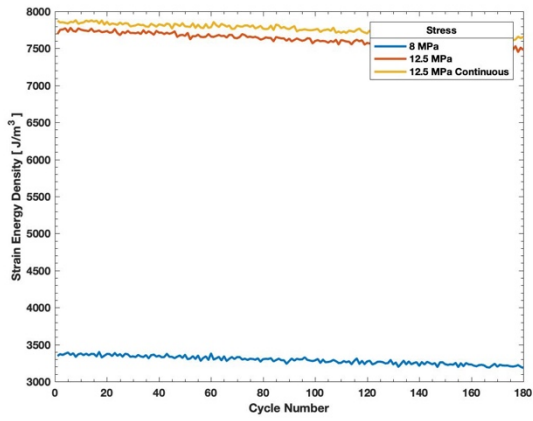


e)

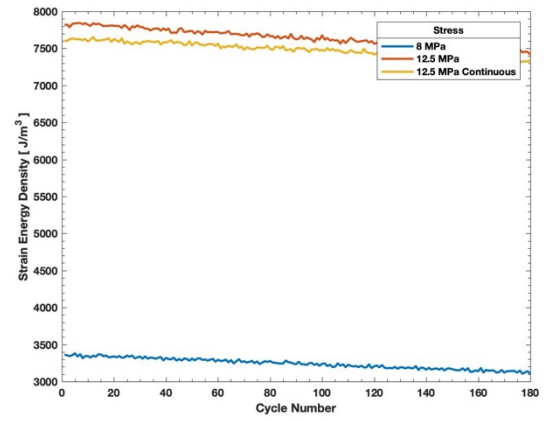


f)

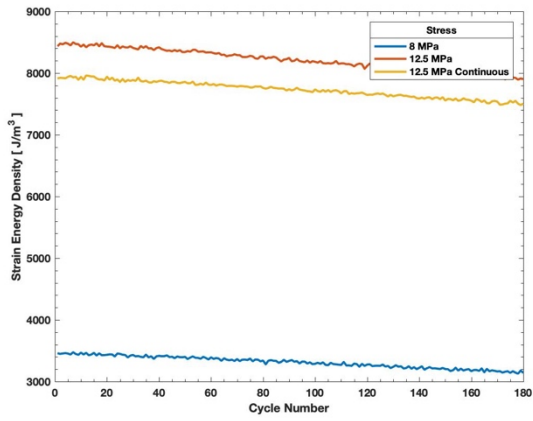
Figure C-67: 120 °C - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



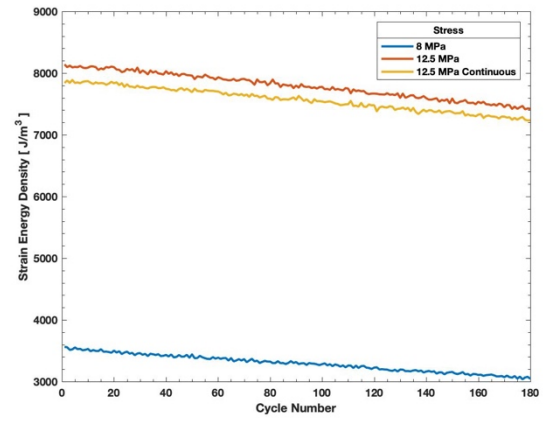
a)



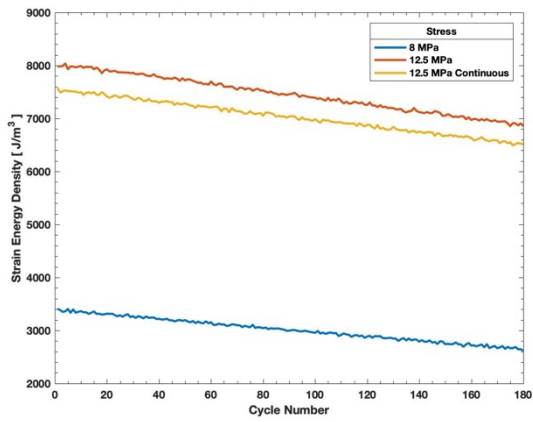
b)



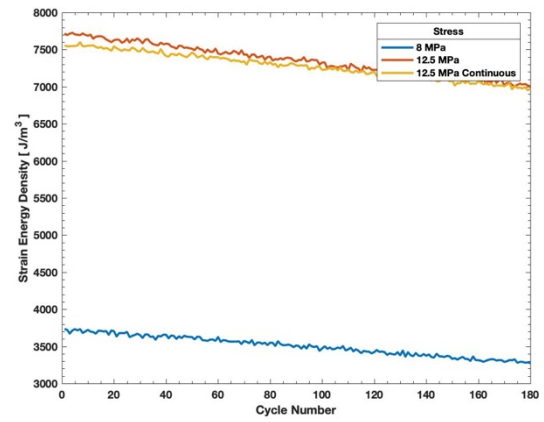
c)



d)



e)



f)

Figure C-68: 180 °C - Stored Strain Energy Density (Unloading) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).

C.3.3.2 Stored - Recovery

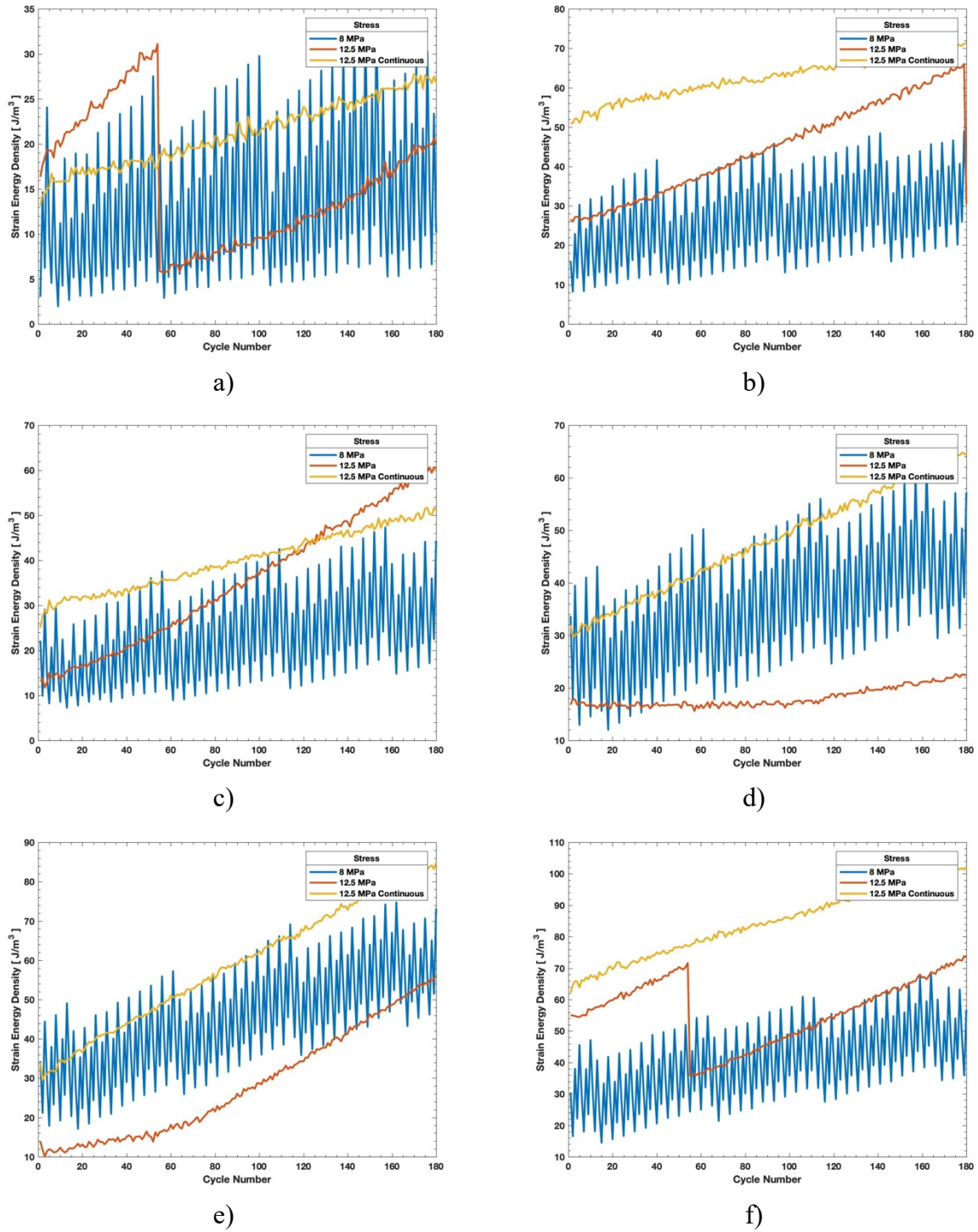
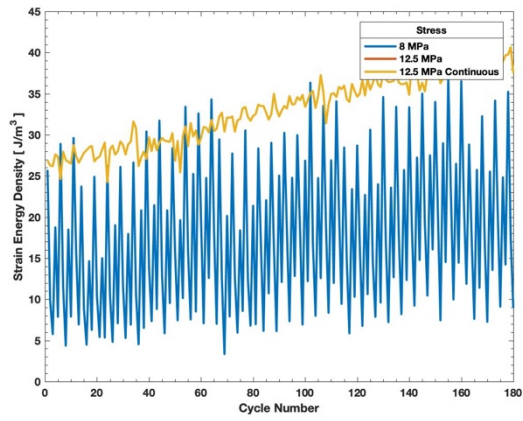
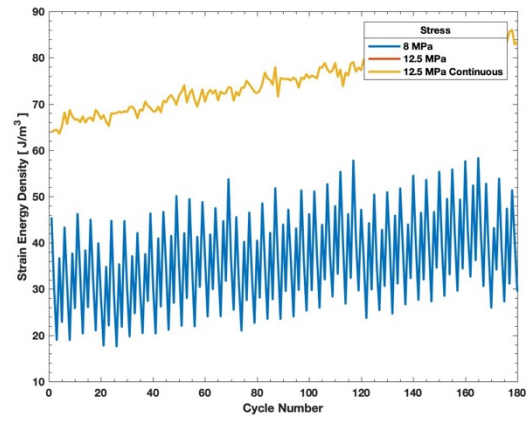


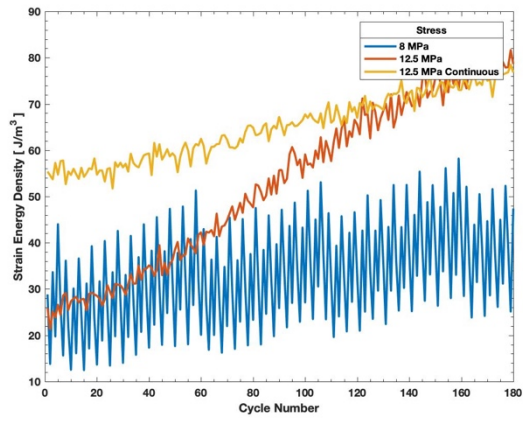
Figure C-69: Room Temperature - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



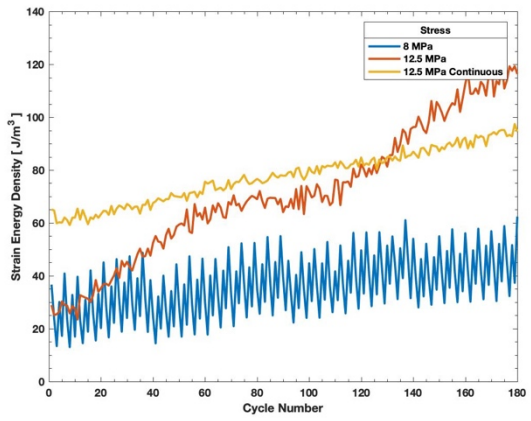
a)



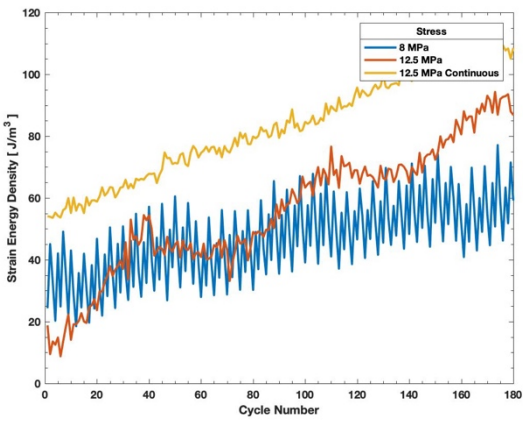
b)



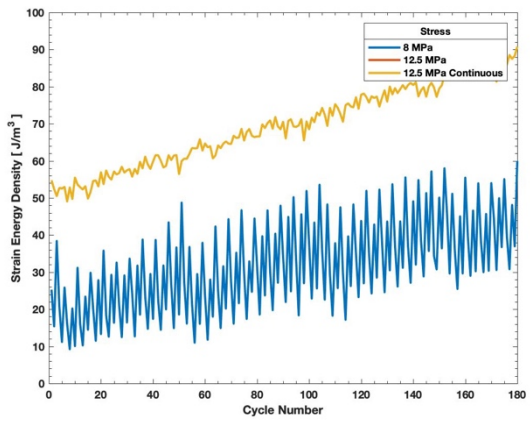
c)



d)

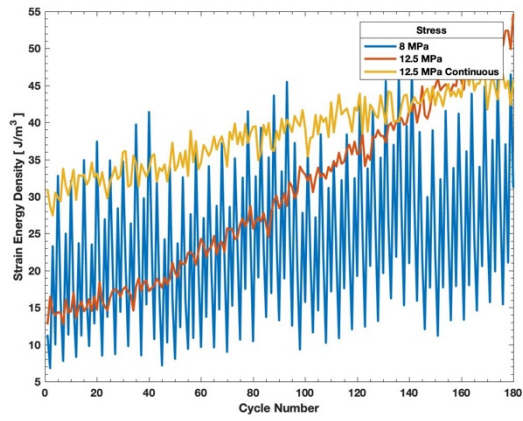


e)

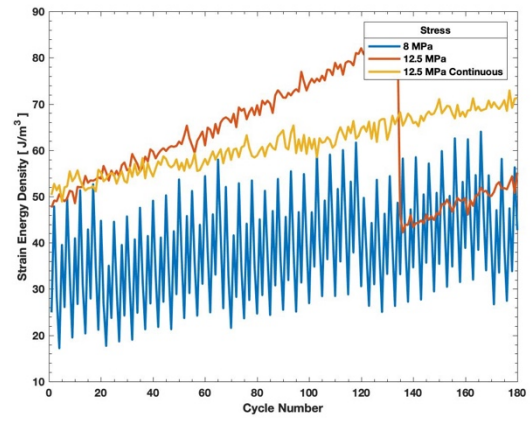


f)

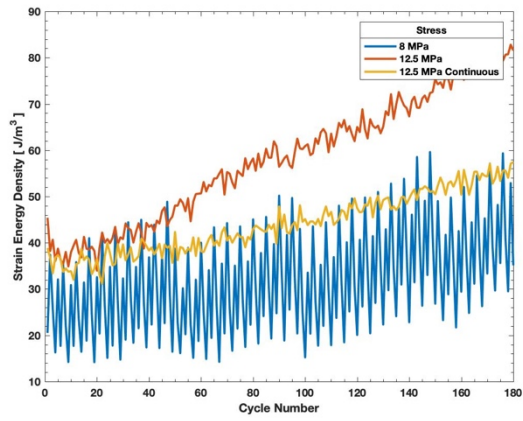
Figure C-70: 80 °C - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



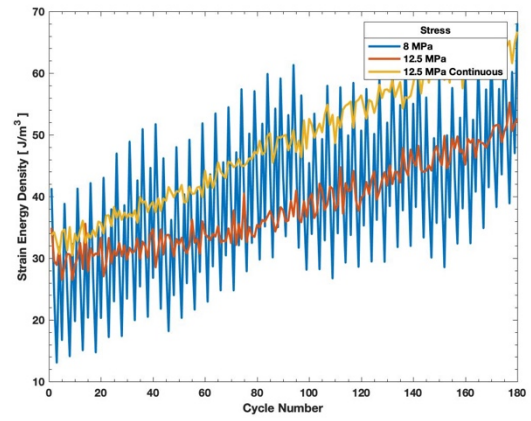
a)



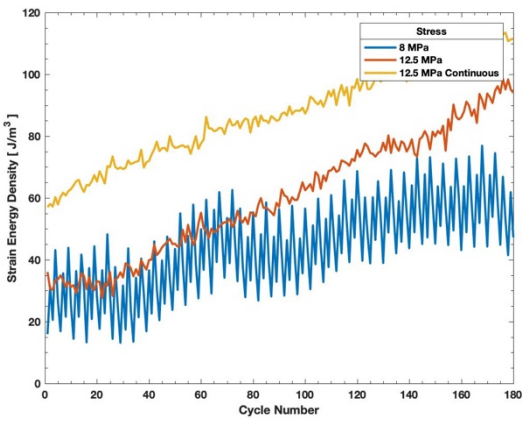
b)



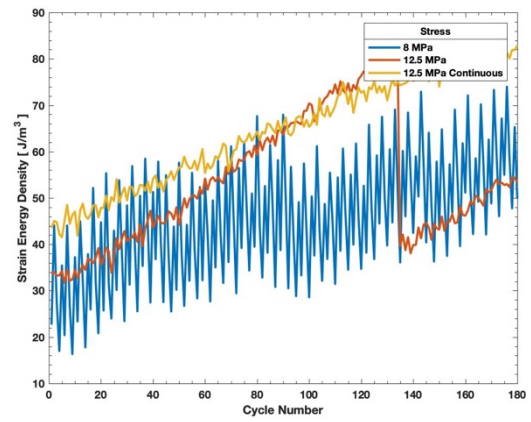
c)



d)

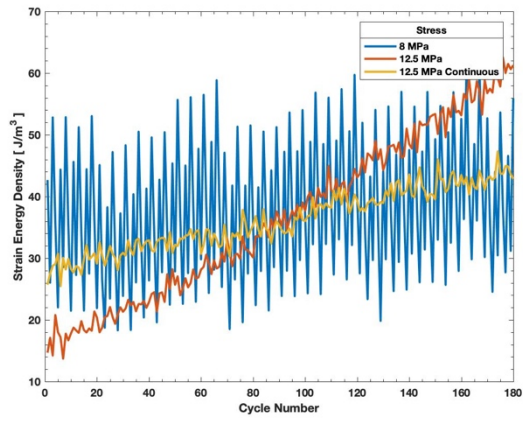


e)

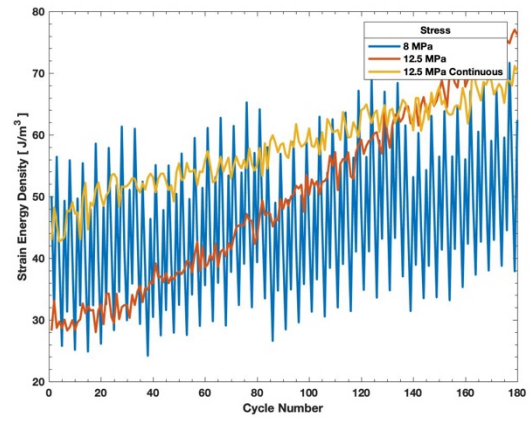


f)

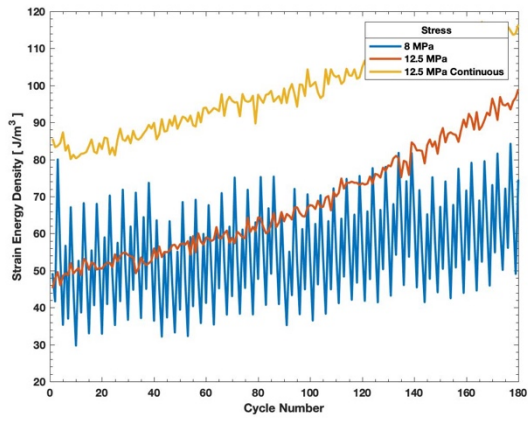
Figure C-71: 120 °C - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).



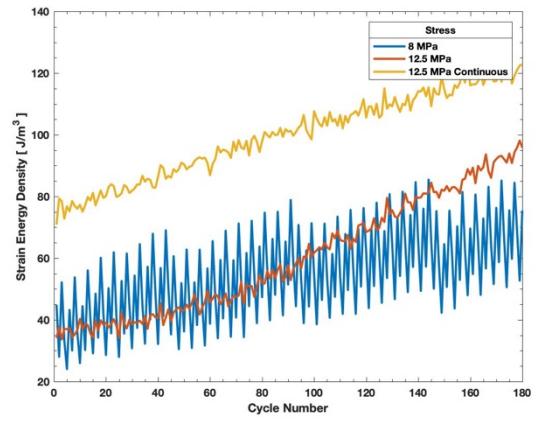
a)



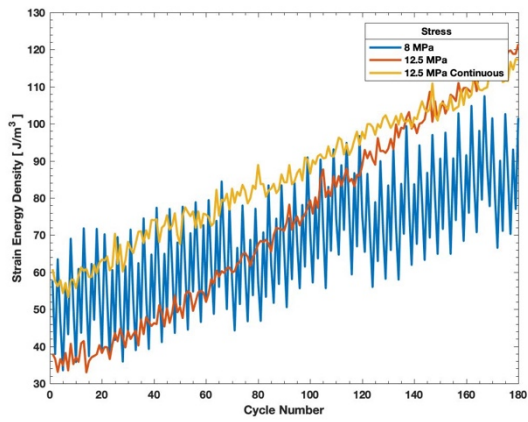
b)



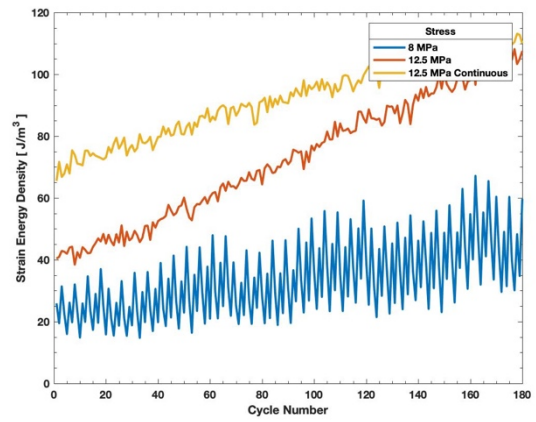
c)



d)



e)



f)

Figure C-72: 180 °C - Stored Strain Energy Density (Recovery) vs Cycle; a) 1s b) 10s c) 20s d) 40s e) 80s f) 20s (40s Creep).