THE MECHANICAL PROPERTIES OF RAW POTATO TISSUES AS MEASURED BY UNIAXIAL COMPRESSION AND SMALL STRAIN OSCILLATORY SHEAR TESTS

BY

CHAN HOI PANG

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ABSTRACT

The rheological properties of potatoes from two harvest years were examined by small strain oscillatory shear and uniaxial compression tests. A sectioning technique was developed to obtain slices and cylinders of tissue from the geometric centre of potato tubers in three directions. Slice samples with and without hypotonic/hypertonic mannitol treatment were subjected to small strain oscillatory shear at three frequencies (0.02, 0.2 and 2 Hz). Cylindrical samples with and without hypotonic/hypertonic mannitol treatments were subjected to three cycles of compression at two strain rates (2 and 20 cm min^{-1}) to a final strain of 10.5% in uniaxial compression. In terms of the variability of the measurements, the coefficient of variation ranged on average from below 10% for the new crops to above 25% for the old crops. Tissue slices obtained along the longitudinal length of the pith were found to be stiffer than those obtained transversely (higher apparent G* and G' values). Tissues slices obtained from the pith were found to be stiffer than those from the vascular ring/perimedullary regions as assessed by oscillatory shear but the reverse was observed after the sample were subjected to hypotonic/hypertonic treatments. The discrepancy was thought to be due to different responses in different potato tissues to artificial osmotic adjustment. Tissue cylinders obtained transversely to the pith were found to be stiffer than those obtained along the longitudinal length of the pith in uniaxial compression. The difference in rheological

response compared to small strain oscillatory shear was believed to be related to differences in the cellular structure and parenchyma cell size between the slices and the cylinders. Tissues from potato crops of 8 months storage were found to be more prone to changes in their mechanical properties after hypotonic/hypertonic mannitol treatments than freshly harvested crops. An increase in strain rate from 2 to 20 cm min^{-1} generally increased the Young's modulus (calculated at 1% deformation), deformation energy and energy recovered, but decreased the Young's modulus (calculated at 9% deformation) in compression. Energy dissipated was not affected by strain rate. An increase in oscillation frequency from 0.02 to 2 Hz at a given amplitude generally increased values of G*, G' and energy recovered but decreased G", δ and energy dissipated. The first cycle of 3 cyclic compressions was found to be significantly different from the subsequent large deformation cycles in both modulus and energy terms.

1. INTRODUCTION

Rheology is defined as "the study of deformation and flow of matter" (Mohsenin, 1986). When applied to foods, it has been defined as "the study of the deformation and flow of the raw materials, the intermediate products, and the final products of the food industry" (White, 1970). Studies of the rheological properties of food are of prime importance not only for engineering process design (Ashby, 1983; Loh, 1992; Mohsenin, 1986; Voisey, 1971; Voisey and deMan, 1976) and assessment of the textural attributes of the product (Szczesniak, 1963; 1971; 1972; 1977; Szczesniak and Kahn, 1971), but also for a better understanding of the structure and conformation of the molecular constituents of the foods (Biliaderis and Zawistowski, 1990; Kokini and Plutchok, 1987; Rochefort and Middleman, 1987; Vincent, 1989;).

The potato is the most important dicotyledonous source of human food and it ranks as the fourth major food crop of the world, exceeded only by wheat, rice and maize (Salunkhe and Kadam, 1991). Global potato production and the consumption of potato products have increased steadily since 1960 (Horton and Anderson, 1992). The average annual world production of potato from 1981 to 1990 was estimated to be nearly 280 million metric tonnes. Canadian production in 1989 was estimated to be 60.7 million Cwt, whereas the production in Manitoba in the same year was 5.4 million Cwt, comprising approximately 9% of the Canadian production (Anonymous, 1991).

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It has been observed since the early 70's that the consumption patterns of potato in developed countries such as Canada, the United States and the United Kingdom have been shifting from mainly fresh use to mainly processed products (frozen french fries, chips..etc) (Horton and Anderson, 1992; Kadam et al., 1991; Thorton and Sieczka, 1980). This change in consumption pattern, coupled with increasing production worldwide, requires tremendous effort to minimize loss and improve the keeping quality of potato during long term storage. It also necessitates efforts to develop objective techniques in order to measure and monitor at a cellular level the changes of potato firmness during storage. Questions have been raised as to the suitability and capability of traditional mechanical testing involving large deformation of the food specimens to meet this demand (Peterson and Hall, 1974; Tijskens, 1979).

This study was undertaken to assess the applicability of small strain oscillatory shear testing for evaluation of the mechanical properties of raw potato tissue flesh. Since the usual mode of testing of the textural properties of potato is under large deformation (Mohsenin, 1986), the mechanical properties determined by small strain oscillatory testing will be compared with uniaxial compression of raw potato tissue flesh.

2. REVIEW OF LITERATURE

2.1 Morphological and Histological Structures of Potato Tuber

Potato (Solanum tuberosum L.) belongs to the family Solanaceae and is an annual, herbaceous dicotyledonous plant (Smith, 1977). The edible parts, the tubers, are botanically modified, thickened, underground stems (Kadam et al., 1991). Tuberization does not occur until the end of the period of flower development. The tuber is formed at the tip of the stolen (rhizome) as a lateral proliferation of storage tissue resulting from rapid cell division and enlargement. The size, shape and colour of the tubers are primarily determined by the variety and growing conditions (Kadam et al., 1991). A typical tuber shape of the variety Russet Burbank is shown in Figure 1.

The histological structure of a potato tuber are shown in Figures 2 and 3. The principal regions in the mature tuber are (from the exterior inward): the periderm, cortex, vascular ring, perimedullary zone, and central pith (water core). The periderm is the outermost layer of the tuber which acts as a protective coating over the surface of the tuber. In a mature tuber the periderm is usually six to ten cell layers thick (Fedec et al., 1977) but may vary considerably among varieties (Smith, 1977). The cortex is a narrow band of storage tissue next to the periderm but its width increases generally

Figure 1. Typical Shape of the Potato Variety Russet Burbank (French Fries Processing Grade)

Figure 2.   Transverse Cross-Section View of a Potato Tuber Stained with Periodic Acid; a. Periderm; b. Cortex; c. Vascular Ring; d. Perimedullary Zone; e. Pith; f. Internal Phloem

I II III

IV V VI
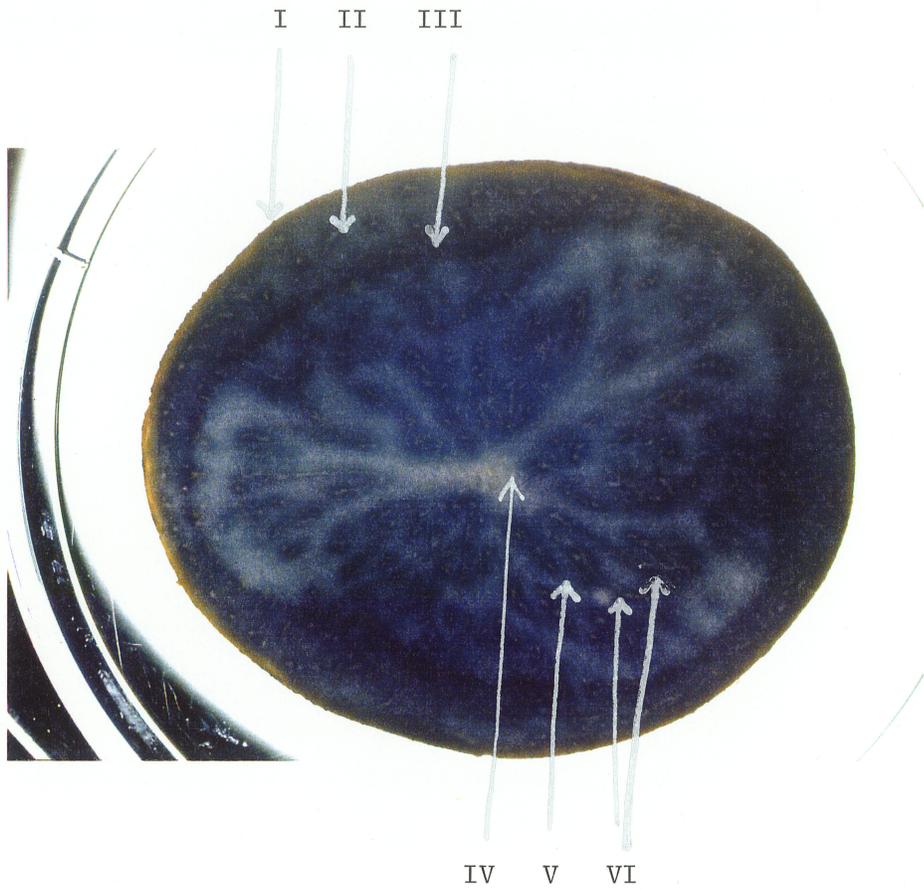
Figure 3.   Longitudinal Cross-Section View of a Potato Tuber Stained
with Periodic Acid; a. Periderm; b. Cortex; c. Vascular Ring; d.
Perimedullary Zone; e. Pith; f. Internal Phloem
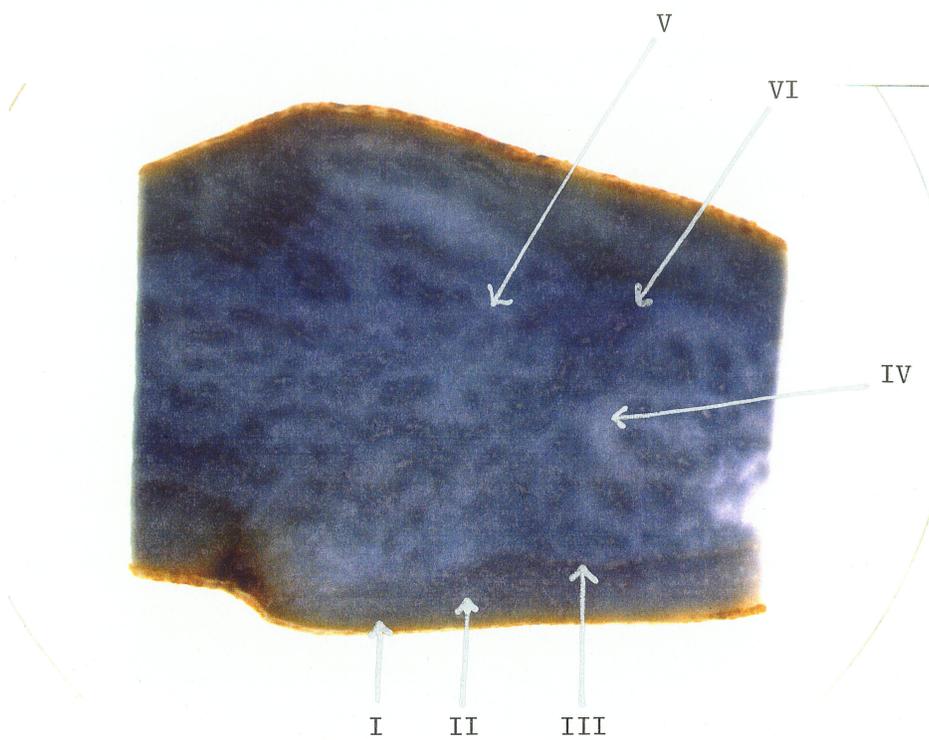
with the size of the tuber (Reeve et al., 1973b). The vascular ring is narrow and contains xylem and external phloem. The perimedullary zone contains numerous internal phloems which are separated by storage tissues. The pith or water core consists of a small central core with arms of medullary storage tissue radiating from it (Smith, 1977). The moisture content of the pith is generally 4-7% (wet basis) higher than the outer region (Anzaldúa-Morales et al., 1992) and the cells are more translucent than other tissues (Smith, 1977). The periderm accounts for 1.5-2.5% of the fresh weight of the tuber. The cortex accounts for approximately 15-20% of the fresh weight, the perimedullary zone for a further 60-75% and the pith the remainder (i.e. approximately 10%) (Burton, 1989).

2.2 Cellular Structure

The five major histological regions listed in section 2.1 are composed of different tissues which can be divided into 3 categories in accordance with their functions.

2.2.1 Parenchyma (Storage Tissue)

Parenchyma is the predominant tissue present in potato tuber. It can be found in all parts of the tuber except the periderm (Fedec et al., 1977). Parenchyma cells are mature, inactive cells that are not dividing, dying or enlarging (Bourne, 1976) but are capable of resuming meristematic activity (Fahn, 1974). The shape of mature parenchyma cells varies. They can be oval, round or polygonal (Aguilera and Stanley, 1990; Fedec et al., 1977). The size of parenchyma cells in a mature tuber also varies,

depending on their anatomical locations. They are generally 50-300 μm across and the largest cells are often found in the perimedullary zone (Fedec et al., 1977; Reeve, 1967; Reeve et al., 1973a). Parenchyma cells are thin-walled and are separated by very small intercellular spaces (Fedec et al., 1977; Falk et al., 1958). The air volume in newly harvested tubers has been reported to vary from 0.92-1.7% of the tuber volume (Davis, 1962).

Mature parenchyma cells usually contain a single large vacuole that accounts for most of the cell volume. The vacuole is surrounded by a membrane (tonoplast) and filled with an aqueous solution of sugars and salts which is referred to as the "cell sap" (Bourne, 1976). Amyloplasts containing starch granules of different sizes and shapes are embedded inside the cytoplasm (Fedec et al., 1977; Huang et al., 1990). Reeve (1967) reported that over 50% of the granules extracted from whole tubers are less than 28 μm in length. The cortex was found to contain numerous granules and the most starch per unit volume. The largest granules were primarily found in the perimedullary zone and the smallest in the vascular ring. A later study by Fedec et al. (1977) reported a similar observation. Anzaldúa-Morales et al. (1992) reported that cortex tissue has 3-6 % higher dry matter than pith tissue.

Parenchyma cells usually consist of thin cell walls (primary cell wall) surrounding the living protoplast (Bourne, 1976). The primary cell wall does not undergo secondary wall formation upon maturation (Fedec et al., 1977; Hoff and Castro, 1969). Individual parenchyma cells are cemented together by an amorphous layer external to the primary wall. This layer is known as the middle lamella, or the interlamellar layer (Bourne,

1976). The primary cell wall and middle lamella have been major research foci for decades and it has been suggested that the mechanical properties of potato tissues are principally derived from them (Falk et al., 1958; Frey-Wyssling, 1952; Mohsenin, 1977; Van Buren, 1979). The cell wall content of mature tubers has been reported to be approximately 1.2% (wet basis) and consists primarily of pectic substances, hemicellulose, cellulose and water (Hoff and Castro, 1969). The thickness of the cell wall has been reported to be 0.24 ± 0.02 μm (Fedec et al., 1977). The ultra-structure of the primary cell wall has been shown to consist of randomly oriented cellulose microfibrils interwoven with each others, forming a non-directional, three-dimensional network embedding in an amorphous matrix that is composed mainly of pectic substances and other hemicelluloses (Fedec et al., 1977; Steward and Mühlethaler, 1953). The pectic substances found in the middle lamella have been reported to consist of mainly polygalacturonic acids present in the form of calcium pectate (Bettelheim and Sterling, 1955; Hoff and Castro, 1969). The width of the middle lamella in a mature tuber has been estimated to be approximately 0.08 μm (Fedec et al., 1977). Warren and Woodman (1973) reported that the concentration of pectic substances extracted from potato tissues is higher in the periderm and cortex region. The possible function of pectic substances in the middle lamella is to act as a cementing agent between adjoining parenchyma cells (Jaswal, 1969; Van Buren,1979).

2.2.2 Collenchyma and Sclerenchyma (Supporting Tissues)

Collenchyma consists of living, elongated cells which exhibit angular wall

thickening (Aguilera and Stanley, 1990). Collenchyma usually forms immediately below the periderm (Reeve, 1970) or towards the outside of the cortex (Aguilera and Stanley, 1990; Fahn, 1974). The major function of collenchyma is to provide support at the outer region of the tuber.

Sclerenchyma consists of cells with thickened secondary cell walls, some of which may be lignified. Like collenchyma, sclerenchyma is primarily a supporting tissue and it constitutes the integral part of vascular bundle or strands of vascular tissues (Fahn, 1974; Reeve, 1970). Sclerenchyma may also exist in the form of stone cells at the periderm in some potato varieties such as Russet Burbank (Artschwager, 1924).

2.2.3 Xylem and Phloem (Conducting Tissues)

Phloem acts as conducting tissue which carries necessary nutrients to the growing cells. Two types of phloem can be found in a mature tuber: the external phloem which is located between the cortex and the vascular ring, and the internal phloem which is located in the perimedullary zone immediately next to the vascular ring (see Figure 2). Both the external and internal phloem occurs in strands and each strand is separated from the others by parenchyma cells (Artschwager, 1924). The strand consists primarily of sieve elements and companion cells (Cutter, 1992). The phloem strands in a mature tuber have been reported to comprise about 5% of its volume (Reeve et al., 1973b).

Xylem found in a mature tuber is located exclusively in the vascular ring region. Like phloem, individual xylem is separated from one another by layers of parenchyma cells (Artschwager, 1924; Cutter, 1992). The xylem cells are large, mostly porous

vessels with side walls which are heavily pitted. The proportion of xylem in a mature tuber is relatively small (Artschwager, 1924).

The supporting and conducting tissues form an inter-connected branching network throughout the fresh parenchyma tissue to give overall support to the tuber (Bourne, 1976).

2.3 Structural Changes with Respect to Physiological Changes During Storage

Potatoes are subjected to storage loss owing to their continuous metabolism (Burton et al., 1992). Transpiration and respiration continue at harvest and storage resulting in a net loss of moisture, though the rate can be minimized by controlling the storage temperature and humidity (Jadhav et al., 1991). The decrease in moisture content results in a concomitant decrease in turgor pressure inside the cells (Bourne, 1983). Conversion of starch to soluble (reduced) sugars or vice versa during storage is a function of storage temperature. Generally, for a given cultivar, storage at higher temperature (7-10°C) causes lower reducing sugar accumulation than storage at lower temperature (2-4°C) (Burton et al., 1992). Nevertheless, weight loss due to a decrease in starch content consumed in respiration is inevitable (Aguilera and Stanley, 1990). In this respect, small starch granules are more susceptible to enzymatic digestion during storage (Reeve, 1967). Pectic substances also undergo change from water-insoluble protopectin to water-soluble pectin during long term storage (Bourne, 1983; Kadam et

al., 1991; Van Buren, 1979). The air cell in the intercellular spaces of potato also decreases with prolong storage (Davis, 1962).

2.4 Viscoelastic Nature of Biomaterials

Classical theory describing the mechanical properties of matter was developed based on ideal elastic (Hooke's law) and ideal viscous (Newton's law) materials (Ferry, 1970). In a Hookean body, stress within the body is always directly proportional to strain for small deformations but is independent of the rate of strain (time-independent). That is (Mohsenin, 1986)

$$\sigma = E\,\epsilon \quad\dots\dots\dots\dots\dots\dots\dots (1)$$

where σ = tensile stress (Pa)

ϵ = tensile strain (dimensionless)

and E = tensile (Young's) modulus (Pa)

A Hookean body will return to its original shape instantly upon the removal of stress, with all the applied stress recovered as work during the returning process. In a Newtonian fluid, stress is always directly proportional to the rate of strain but independent of strain (time-dependent). That is

$$\tau = \eta\,\dot{\gamma} \quad\dots\dots\dots\dots\dots\dots\dots (2)$$

where τ = shear stress (Pa)

η = shear viscosity (Pas)

$\dot{\gamma}$ = shear rate (s^{-1})

A Newtonian fluid is not capable of sustaining the applied stress and the stored energy is completely lost as heat.

In reality, most biomaterials exhibit mechanical behaviour that deviates from the above two ideals; i.e., they exhibit behaviour which combines solid-like and liquid-like characteristics. These combined behaviours are collectively known as *viscoelastic behaviour* (Rao, 1992). The degree of viscoelasticity of any given biomaterial is governed by the relative magnitude of elasticity and viscosity it possesses, the time-scale of the deformation and measurement, and for living tissues their physiological states (Mohsenin, 1986; Pitt, 1992). The mathematical models describing various viscoelastic behaviours have been derived from constitutive equations which take into account variables such as elastic recovery, viscous and plastic flow, inhomogeneity... etc during deformation (Ferry, 1970).

2.5 Viscoelastic Properties of Potato as Measured by Uniaxial Compression Tests

Under uniaxial deformation, a potato specimen is placed between two parallel plates and its viscoelastic properties can be characterized using a number of testing conditions. Some of these conditions are: strain rate (the rate of deformation with respect to the change of the dimensions of the specimen to its original dimensions), final strain (the final magnitude of deformation of the specimen with respect to the change in dimensions of the specimen relative to its original dimensions), final stress (the final

magnitude of stress attained in the deformation), sample shape (cylindrical, rectangular, circular, etc), and type of testing, e.g., tension (stretching along the longitudinal axis of the specimen), compression (compressing along the longitudinal axis of the specimen), and radial compression (compressing along the diameter of specimen), etc. It is important to note that results obtained from a given biomaterial under a particular testing condition and geometry may not be comparable to those obtained from the same material tested under other testing conditions and geometries (Mohsenin, 1986; Peleg, 1977).

Finney et al. (1964) compressed whole potato tubers between parallel plates at different constant strain-rates to a pre-set stress level and then measured the relaxation time of the tuber. Differences in relaxation pattern were observed at different strain rates, implying that the stress relaxation function of potato was dependent on the strain-rate used for loading. At higher strain-rate, more energy was dissipated in the first few seconds of the measurement. It was also observed that potato tissue was capable of sustaining a large portion of the applied stress over a relatively long period of time, as characterized by having one relaxation time constant as large as 10^8s (Finney et al., 1964).

Finney and Hall (1967) studied the elasticity of potato flesh in cyclic compression. In their study, cylindrical columns of potato tissue were placed between parallel plates and then compressed at a constant strain-rate to 3 ascending final strain levels in 3 loading-unloading cycles. It was observed that pronounced hysteresis occurred in every loading-unloading cycle and the degree of elasticity calculated declined from 0.6 at a strain level of 0.1 to 0.46 at a strain level of 0.28; the corresponding hysteresis loss

increased from 72 to 90%. It was observed that pre-loading increased the modulus of elasticity in subsequent loading cycles, implying that substantial structural damage occurred in the first loading.

Since potatoes are frequently bruised or damaged during harvest and post-harvest operations, such as bulk transportation and storage, cyclic loading techniques (which simulate bulk transportation) and static loading techniques (which simulate bulk storage) are frequently used by researchers to study the susceptibility of potato to mechanical damage. Pitt (1984) applied multiple cyclic compressions to cylinders of potato tissue to assess the failure mechanism under cyclic loading. It was reported that under repeated compression potato tissue would eventually fail at a stress level insufficient to cause failure initially. By studying and comparing the probability of different failure models widely used in the field of materials science, the author concluded that potato tissues failed by a random degradation in strength, not by an accumulation of localized damage as in fatigue of engineering materials. The author also suggested that the hysteresis loss that occurred during loading-unloading cycles might be due to cell wall plasticity, cell fluid migration and plastic flow in the intercellular spaces. Brusewitz et al. (1989) studied the effect of static pre-loading in conjunction with cold storage of potato tissue. It was reported that cold storage increased cell wall stiffness which in turn resulted in a rise in tissue stiffness. Static pre-loading was observed to cause an increase in unrecovered strain, and to decrease the volume and turgor pressure in potato tissue, and the effect was more pronounced as the static pre-loading stress increased.

The change in potato firmness during storage at different temperatures has been

reported by Jindal (1986). In his study, moduli of elasticity, as calculated from uniaxial, radial and Hertz compression tests, were used to compare potato samples stored at 4 temperatures for 4 periods of time. It was reported that at each storage temperature, the modulus of elasticity decreased as storage time increased from 1 to 8 weeks, and at each storage period, the modulus of elasticity decreased with an increase in storage temperature from 5 to 30°C. In addition, specimen dimension and compression rate were also observed to affect the values of elasticity modulus. A higher length to diameter (l/d) ratio in the cylindrical specimen resulted in decreased values of the elasticity modulus in uniaxial and radial compression tests. An increase in loading rate from 50 to 500 mm min^{-1} in four stages resulted in progressive decrease in the value of the elasticity modulus in uniaxial compression. It was suggested by the author that radial compression might be more sensitive than uniaxial compression for monitoring the change in firmness of potato during storage.

Canet and Sherman (1988) also investigated the effects of sample dimension, deformation rate and friction on raw potato flesh. In their study, cylindrical potato specimens with various l/d ratios were subjected to uniaxial compression at different strain-rates. Some tests were performed with lubrication or emery paper inserted between the specimen and the upper and lower plates. It was observed that the failure stress and strain generally decreased as the sample l/d ratio increased, but the rate of compression did not appear to exert a pronounced effect on the failure strain. The failure stress was observed to be generally decreased with increasing rate of compression and sample lubrication, but increased with the use of emery paper. Diehl and Hamann

(1979) reported that varying the l/d ratio of the potato specimen had a negligible effect on the modulus of elasticity in uniaxial compression but affected the shear failure stress. Failure stress was observed to increase as the diameter of the samples increased (with the sample length kept at constant) and decrease as the length of the sample increased (with the sample diameter kept at constant). Niklas (1988) reported that tensile modulus increased as the transverse area of potato tissue specimen increased.

It has been well recognized that plant tissues are highly inhomogeneous, anisotropic and discontinuous in nature (Mohsenin, 1986; Van Buren, 1979). An early study by Huff (1967) showed that the mechanical properties of potato tissue varied among different histological regions during 4 months of storage: tensile strength, strain at failure and unit strain energy were observed to increase in the pith and decrease in the cortex, whereas no apparent changes was observed in the perimedullary zone. However, a majority of later studies either failed to report the location at which the specimen was obtained or focused only on the center pith region (Brusewitz et al., 1989; Canet and Sherman, 1988; Diehl et al., 1979; Lin and Pitt, 1986; Qiong et al., 1989) or considered potato tissue as isotropic (Khan and Vincent, 1993). It has been reported recently by Anzaldúa-Morales et al. (1992) that the cortex tissue of raw mature tuber has a significantly higher puncture force than the pith tissue, implying that different stress-strain responses exist in these two different regions.

Turgor pressure is a physiological status of plant tissue and is governed by the maturity of the plant cells and environmental conditions that the plant cells are subjected to (Burton, 1989; Pitt, 1992). Early studies of potato parenchyma by Falk et al. (1958)

and Nilsson et al. (1958) investigated the relationship between turgor pressure and tissue rigidity. In their studies, slices of potato parenchyma tissue were cut from the perimedullary zone and subjected alternatively to 0.0 M and 0.4 M mannitol solutions. It was observed that the parenchyma tissue did not return to its original diameter after the first cycle of swelling (at 0.0 M mannitol) and contraction (at 0.4 M mannitol) and the changes in diameter in subsequent swelling and contraction cycles remained at 2 constant values (i.e diameters at 0.0 and 0.4 M mannitol). The authors suggested that the irreversible increase in diameter in the first cycle was attributed to the plastic component of the parenchyma cell wall and the constant changes in diameter thereafter represented the elastic component. The mannitol treated specimens were also subjected to resonance and it was observed that the elasticity modulus of parenchyma was directly proportional to the turgor pressure.

A later study by Lin and Pitt (1986) indicated that the effect of turgor pressure on elasticity modulus was more complex. In their study, cylindrical parenchyma tissues were soaked in mannitol solutions with incremental concentrations ranging from 0.0 M to 0.5 M. The soaked specimens were then axially loaded to compressive failure at 4 different strain-rates. It was reported that above 0.4M mannitol concentration (corresponding to plasmolysis state) the elasticity modulus was very low and was independent of mannitol concentration and strain-rate. At 0.2-0.4 M mannitol concentration (the physiological turgor pressure of fresh potato corresponded to about 0.3 M mannitol concentration) the elasticity modulus decreased proportionally as mannitol concentration increased, with strain-rate having little or no effect. Below 0.2 M mannitol

concentration (corresponding to high turgor pressure) the elasticity modulus no longer decreased with mannitol concentration, reaching a plateau at about 0.15 M. Thereafter, the elasticity modulus decreased as mannitol concentration decreased. The elasticity modulus was not affected by strain-rate for samples treated at 0.5 to 0.3 M mannitol concentration. Below 0.3 M mannitol, higher stain-rate was observed to result in a higher elasticity modulus.

Qiong (1989) subjected potato tissue to various concentrations of mannitol solutions (ranging from 0 to 0.55 M at 0.02 M increments). Cell wall stretch ratio and wall tension were then calculated and plotted against each other. It was observed that at higher stretch levels significant irreversible deformation occurred upon subsequent plasmolysis. An inflection point on the stretch ratio to wall tension curve corresponding to 8% stretching induced by mannitol was observed. The authors suggested that elastic deformation occurred in parenchyma cell wall below 8% stretching (as characterized by an upward concave slope), and the stretching was plastic in nature above 8% (as characterized by an upward convex slope).

Niklas (1989) suggested that the mechanical properties of living tissues are dependent on the magnitude of turgor pressure. At higher turgor pressure, the cell wall was being stretched, creating tension along the cell wall plane. This reduces the magnitude of cell wall deformation under an applied stress, and thus increases the apparent elasticity modulus of the tissue. A similar suggestion was advanced by Pitt (1982) and Pitt and Chen (1983) based on a mechanics model. On the other hand, at reduced turgor pressure, the cell wall will respond as linear elastic, nonlinear elastic, or

densifying material, depending on the magnitude of the applied stress (Niklas, 1989).

2.6 Viscoelastic Properties of Potato as Measured by Dynamic Rheometry

Unlike uniaxial compression tests which are principally destructive, dynamic tests cause little or no destruction of the food specimen structure. In a dynamic shear test, a food specimen is subjected to a sinusoidally varying stress or strain, depending on the instrument geometry, and the resulting shear strain or stress is measured as a function of wave cycle. Since the strain imposed on the specimen in dynamic tests is extremely small, linear viscoelastic behaviour can be assured throughout the measurement (Rao, 1992).

If a small sinusoidal varying strain is applied to a biomaterial at a frequency ω, the shear strain at the bottom surface of the material can be expressed as (Biliaderis, 1992)

$$\gamma(t) = \gamma_o \sin (\omega t) \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where γ_o = strain amplitude or maximum strain (dimensionless)

ω = radial oscillatory frequency (rad.s^{-1} or Hz)

t = time (s)

The shear rate will be the first derivative of strain with respect to time.

$$d\gamma/dt = \dot{\gamma} = \omega \, \gamma_o \cos (\omega t) \ldots\ldots\ldots\ldots (4)$$

The resulting shear stress transmitted through the biomaterial to the top plate will also be sinusoidal but will lag behind the strain by an angle δ, which is usually referred

to as the phase angle (Figure 4)

$$\sigma(t) = \sigma_o \sin (\omega t + \delta) \dots\dots\dots\dots\dots (5)$$

where σ_o = maximum shear stress (MPa)

δ = phase angle (rad)

For viscoelastic materials, the phase angle lies between 0 to $\pi/2$ (0 for ideal elastic materials which are exactly in phase with the strain, whereas $\pi/2$ for ideal viscous fluids which are $\pi/2$ (or 90°) out of phase with the strain). Thus, the phase angle is a measure of the viscoelastic characteristics of a given material.

Expanding equation 5, we have

$$\sigma(t) = \sigma_o \left[\sin (\omega t) \cos \delta + \sin \delta \cos (\omega t) \right] \dots\dots\dots\dots\dots (6)$$

Since σ_o is proportional to γ_o for linear elastic materials, and for viscoelastic materials at small deformation, equation 6 can be further split into 2 components

$$\sigma(t) = \gamma_o \left[\sigma_o/\gamma_o \sin (\omega t) \cos \delta + \sigma_o/\gamma_o \sin \delta \cos (\omega t) \right] \dots\dots\dots (7)$$

The first component in equation 7 constitutes the part of stress in phase with the strain (elastic component), whereas the second component constitutes the part of stress 90° out of phase with the strain (viscous component). The ratio of in-phase stress to strain is the storage modulus, G', and the out-of-phase stress to strain is the loss modulus, G''.

$$G' = (\sigma_o/\gamma_o) \cos \delta \dots\dots\dots\dots\dots\dots (8)$$

$$G'' = (\sigma_o/\gamma_o) \sin \delta \dots\dots\dots\dots\dots\dots (9)$$

Equation 7 can then be expressed as

$$\sigma(t) = \gamma_o \left[G' \sin (\omega t) + G'' \cos (\omega t) \right] \dots\dots\dots (10)$$

Figure 4. Stresses and Strains in Dynamic Tests of Elastic, Viscous and Viscoelastic Bodies (Adapted from Peleg, 1987)

ELASTIC

STRESS &
STRAIN

VISCOUS

STRESS

STRAIN

$|\delta|$

VISCOELASTIC

STRESS

STRAIN
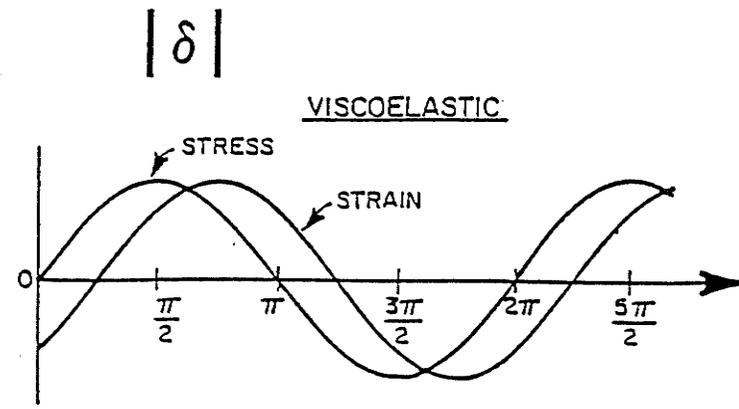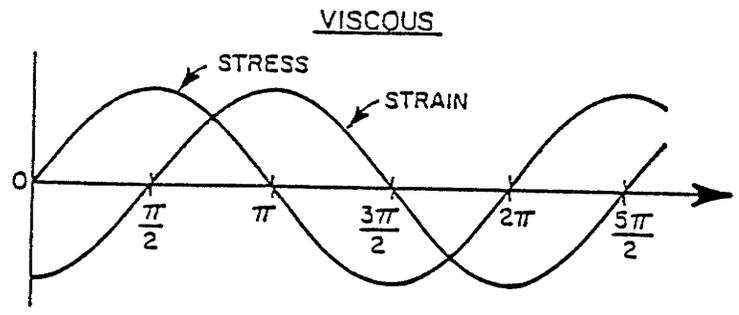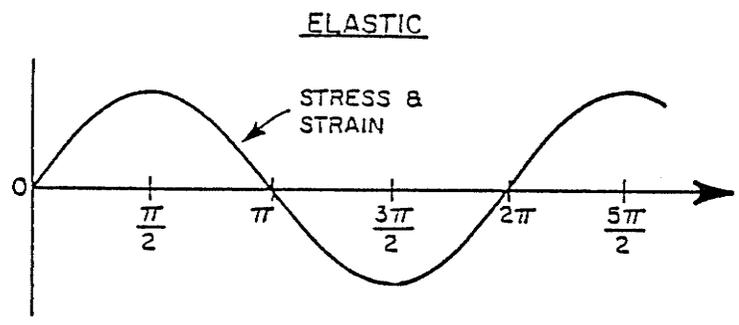
TIME

AMPLITUDE

The storage modulus relates to the energy stored and recoverable, whereas the loss modulus relates to the energy dissipated or lost per cycle of sinusoidal deformation. The storage modulus is taken as an indicator of the solid or elastic character of the material.

The relationship of stress to strain can be expressed as

$$|\sigma_o| = G^* (\omega) \ |\gamma_o| \ \dots\dots\dots\dots\dots\dots \ (11)$$

where G^* is the complex modulus, which includes the complete information of the viscoelastic properties of the materials. When G' and G'' are represented in absolute terms the complex modulus is represented as (Shoemaker, 1992)

$$G^* = G' + i \, G'' \dots\dots\dots\dots\dots\dots \ (12)$$

where $i = \sqrt{-1}$

From equations 8 and 9 the coefficient of internal friction (damping) can be derived as:

$$\tan \delta = G'' \, / \, G' \dots\dots\dots\dots\dots\dots \ (13)$$

Tan δ is a measure of the ratio of energy dissipated as heat to maximum energy that could have been stored in the material during one cycle of oscillation.

The application of dynamic testing such as resonance techniques on foods is not a new approach (Anonymous, 1966; Finney and Norris, 1968). However, it was not until recently with the increasing availability of commercial instruments, that dynamic rheometry has received much attention and gradually became a major technique for the mechanical and textural analysis of foods (though it is still somewhat limited to liquid and gel systems). Recent applications of dynamic rheometry on semi-solid foods include:

cheese (Diefes et al., 1993; Hsieh et al., 1993b; Nolan et al., 1989), butter (Rohm and Weidinger, 1993), whey and egg proteins (Hsieh et al., 1993a), flour dough (Dreese et al., 1988a, b; Navickis at al., 1982) and cooked pasta (Edwards et al., 1993).

Applications of dynamic rheometry to plant tissues have been scarce in the literature. An early study by Peterson and Hall (1974), using a self-assembled dynamic test instrument, investigated the influence of temperature and frequency on the dynamic rheological properties of potato. They reported that complex dynamic Young's modulus (E*), phase angle and storage modulus (E') of potato flesh were independent of temperature from 2-30°C but increased with frequency from 50-300 Hz. Specimens taken from the bud end were found to have a higher phase angle and lower complex modulus than those from the center and the stem end, indicating structural differences between these regions.

Petrell et al. (1980), using a self-assembled oscillatory shear rheometer, investigated the dynamic rheological properties of apple parenchyma tissue. By comparing the storage moduli of tissues obtained from different locations in the apple (from the cheek, stem and calyx ends) and at a particular stage of maturity, it was observed that the magnitude of the storage moduli was dependent on the sample location. It was also observed that dynamic testing was capable of differentiating the firmness of apple at the eating ripe and over ripe stages in some cases. The authors suggested that dynamic testing was capable of differentiating the cell size and intercellular spaces in apple tissues.

Vincent (1989), using a modified Deer rheometer, studied the effect of storage

and cell density of apple on the torsional stiffness of 9 apple varieties. In his study, apple flesh specimens were cut in a similar manner to those of Petrell at al. (1980) but the densities of the specimens were measured by vacuum and photographic techniques. Significant dependence of torsional stiffness on density was observed both within and between varieties at different stages of maturity. It was also observed that the outer parenchyma was stiffer than the inner parenchyma at any given density. The author attributed the observed differences to the differences in orientation of air spaces and parenchyma cells in apple tissues.

Jackman and Stanley (1992) investigated the resistance to puncturing and the dynamic viscoelastic properties of tomato pericarp tissue. Significant differences were observed in the mechanical properties of pericarp tissue from tomatoes subjected to different temperature treatments during storage, as measured by both puncture and dynamic tests. The results obtained from small strain testing were observed to be parallel to those from the puncture test, suggesting a possible relationship between the bioyielding strength of tomato pericarp and the stress function in the small strain test. Although not a cellular biomaterial, strong linear relationships between Instron measurements and parameters derived from small strain oscillatory shear measurements of cooked pasta have been reported later by Edwards et al., (1993).

Ramana and Taylor (1992a) studied the viscoelastic behaviour of a number of vegetables, including potato, during heating, in an attempt to establish the applicability of dynamic rheometry for monitoring textural changes of vegetable tissues during commercial cooking. In their study, cylindrical discs of vegetable tissue were placed

between parallel plates and subjected to pre-determined oscillatory frequency and strain at a heating rate of 20°C min^{-1}. A rapid decline of storage modulus (G') was observed at a temperature around 50-60°C in all vegetables investigated, indicating structural changes occurred which reduced the magnitude of the elastic component within the tissues. It was also observed in an initial experiment of their study that the storage modulus increased as sample thickness increased up to a certain thickness (Table 1). It is noted from Table 1 that G' increased as sample thickness increased from 1 to 7 mm. Beyond 7 mm, G' appeared to be no longer affected by sample thickness. The authors suggested that this phenomenon was attributed to the fixation effect (glue layer) or end effect; at smaller thickness the shear modulus functions should be reported in apparent, not absolute terms.

Ramana et al. (1992) later reported a similar pattern for the decline of G' of carrot tissues subjected to identical heating and dynamic shear tests. In their study carrot tissues of different maturity and histological origin were subjected to dynamic testing and heating. It was observed that the dynamic test was capable of differentiating the textural changes in the carrot tissues of different maturity and anatomical origin. In addition to dynamic testing, the authors also performed compression and sensory tests on the carrot tissues. The correlation coefficients between the Young's modulus, E, and the firmness score from the sensory test, and between G' and the firmness score were reported to be 0.93 and 0.86, respectively, indicating that the dynamic and compression tests were able to measure the same intensity of textural characteristics as perceived by the panellists.

Ramana and Taylor (1992b) subjected isolated carrot cells and cell wall materials

Table 1.   Effect of Potato Sample Thickness on Storage Modulus (G') at a
Frequency of 0.2 Hz (from Ramana and Taylor, 1992a)

Thickness (mm)	G' (MPa)
1	0.67±0.02
2	0.89±0.13
3	1.34±0.14
5	2.08±0.35
7	2.16±0.15
9	2.08±0.22

to dynamic shear using the parallel plate, concentric cylinder and cone and plate geometries. It was observed that parallel plate geometry did not provide linear results for carrot cells over a frequency range of 0.02 to 0.2 Hz, and a stress level of 0.1 to 20 Pa. For carrot cell wall materials all 3 geometries were observed to provide linear results. Shomer et al. (1993) studied the effect of heating and cellulase treatments on the dynamic rheological properties of potato cell suspensions. It was reported that elevating temperature from 20 to 70°C resulted in an increase in G' and decrease in G" and complex dynamic viscosity, η^* of cell suspensions. The addition of cellulase was observed to cause breakdown of the cell structure, resulting in reduction of G', G" and η^* of the cell suspensions.

In view of the research carried out by others that has been outlined above, the objectives of this study were:

1. To assess the applicability and reproducibility of small strain oscillatory shear rheometry for measuring the mechanical properties of raw potato tissues.

2. To assess the mechanical properties of raw potato tissues using cyclic uniaxial compression testing.

3. To map out the mechanical properties of the raw potato tissues at different physiological ages using these two techniques.

4. To map out the mechanical properties of the raw potato tissues taken from different histological regions of the tuber.

5. To map out the mechanical properties of the raw potato tissues taken from different histological regions of the tuber and subjected to hypotonic and hypertonic

mannitol treatments.

3. EXPERIMENTAL

3.1 Materials

The potatoes were of the cultivar, Russet Burbank, and of french fries processing grade. They were kindly supplied by Nestlé Simplot Foods (Carberry, Manitoba) and had been obtained from their contracted growers in Manitoba. The old and new crops were grown at different locations.

The old crops were harvested in early September, 1993 and arrived on September 24, 1993. Upon arrival the potatoes were pre-conditioned at 15°C with 90% relative humidity (R.H.) for one week. After the pre-condition treatment the temperature was reduced to 6°C at a rate of 1°C per week without changing the R.H. Thus, the storage temperature reached 6°C by the end of November, 1993. The potatoes were then kept under these conditions until use. Potatoes were not sprout inhibitor treated and the total storage time was approximately 10 months. It was observed that sprouting started to occur at the end of April, 1994. As a result, a considerable amount of potatoes with severe sprouting were discarded and any sprouts found on the remaining potatoes were manually removed.

The new crops were harvested in September, 1994 and arrived on September 23. Upon arrival the potatoes were promptly stored in the cold room at a temperature of 7 ± 1°C with controlled R.H. until use. Potatoes were not sprout inhibitor treated and the

total storage time was approximately one month.

D-mannitol (ACS reagent grade), nitric and periodic acid (basic) were obtained from Sigma chemical company (St.Louis, MO). Potassium phosphate (mono- and di-basic) were obtained from Fisher Scientific Limited (Ottawa, ON). Emery paper with grain size 280 and cyanoacrylate bonding agent were procured from a local store (Dominion Lumber).

The Bron slicer (model Mandoline) was procured from J.B. Prince Co. (New York, NY). The double blade cutting device, similar to that used by McLaughlin (1987), was manufactured by the physics workshop at the University of Manitoba. The cutting device consists of 2 parallel blades (with a clearance of 40 mm between them). Core borers of 15 and 30 mm diameters were supplied by the Food Science Department at the University of Manitoba.

3.2 Methods

3.2.1   Sampling and Selection of Potato Tubers

The old and new potato tubers were randomly sampled from the top to the bottom of five and three one-hundred-lb bags, respectively, prior to their use. The sampled tubers were then selected for use based on their size. Since tubers of the cultivar Russet Burbank have a typical elongated, oval shape (see Figure 1), care was taken in selection to ensure that during subsequent sectioning sufficient flesh portion would be obtained from the tubers. This was carried out by measuring the length of the tubers by a caliper

in 3 directions: the longitudinal, and 2 transverse directions perpendicular to each other. The point of measurement for the transverse directions was as close to the mid-point of the longitudinal length as possible. The longitudinal direction was arbitrarily assigned and referred to as the x-axis, the longest transverse direction as the y-axis and the shortest transverse direction as the z-axis. The length criteria of the tubers used were as follow: 100-150 mm at the x-axis, 55-65 mm at the y-axis and 50-55 mm at the z-axis. Potatoes were rejected if below bottom of these ranges. The weight of the tubers ranged from 225-300 g.

3.2.2 Overall Experimental Design

The whole project consisted of 4 parts. They were:

a.   Mapping of mechanical properties of potato tissues using small strain oscillatory rheometry - axis (x, y and z) and frequency (0.02, 0.2 and 2 Hz) were the main effects in this part. In addition, slices obtained at 2 different locations in the y and z-axes (inner and outer slices) would also be investigated.

b.   Examination of the effect of artificial turgor adjustment on the mechanical properties of potato tissues using small strain oscillatory shear rheometry - axis (x, y and z), frequency (0.02, 0.2 and 2 Hz) and mannitol concentration (3 and 7%) were the main effects in this part. Like in part a, slices obtained in 2 different locations along the y and z-axes would be investigated.

c.   Mapping of mechanical properties of potato tissues using uniaxial compression - axis (x, y and z) and strain rate (2 and 20 cm min^{-1}) and three cycles of

cyclic compression were the main effects in this part.

     d.   Examination of the effect of artificial turgor adjustment on the mechanical properties of potato tissues using uniaxial compression - axis (x, y and z), strain rate (2 and 20 cm min^{-1}), three cycles of compression, and mannitol concentration (3 and 7%) were the main effects in this part.

     Each of the above experiments were applied to both old and new potato crops to examine the effect of storage on the mechanical properties of potato tissues.

3.2.3   Preparation Procedures for Potato Flesh Slices Used in Small Strain Oscillatory Shear Test

3.2.3.1   X-Axis Samples

     A number of potato tubers were taken from the storage room, washed, dried with paper towels and equilibrated to room temperature ($22 \pm 2°C$) overnight. The length of the tubers at the x-axis were carefully measured with a caliper. A knife was used to discard equal portions (in length) of flesh from the stem and bud ends. Since the tubers used varied considerably in length along the x-axis, the length of the remaining center portion was kept as close as possible to 50 mm to facilitate later sectioning. A core borer of 30 mm diameter was carefully placed in the center of the top of the center portion. The core borer was then punched through the whole flesh to obtain a cylindrical flesh core (diameter 30 mm, length $\approx$ 50 mm) (see Figure 5). The length of the core was then measured with a caliper. To obtain a cylinder of 40 mm length, the double-blade cutting device was used to chop off equal portions from the ends.

Figure 5.   Sectioning of Potato Slice Samples for Small Strain Oscillatory Shear Test
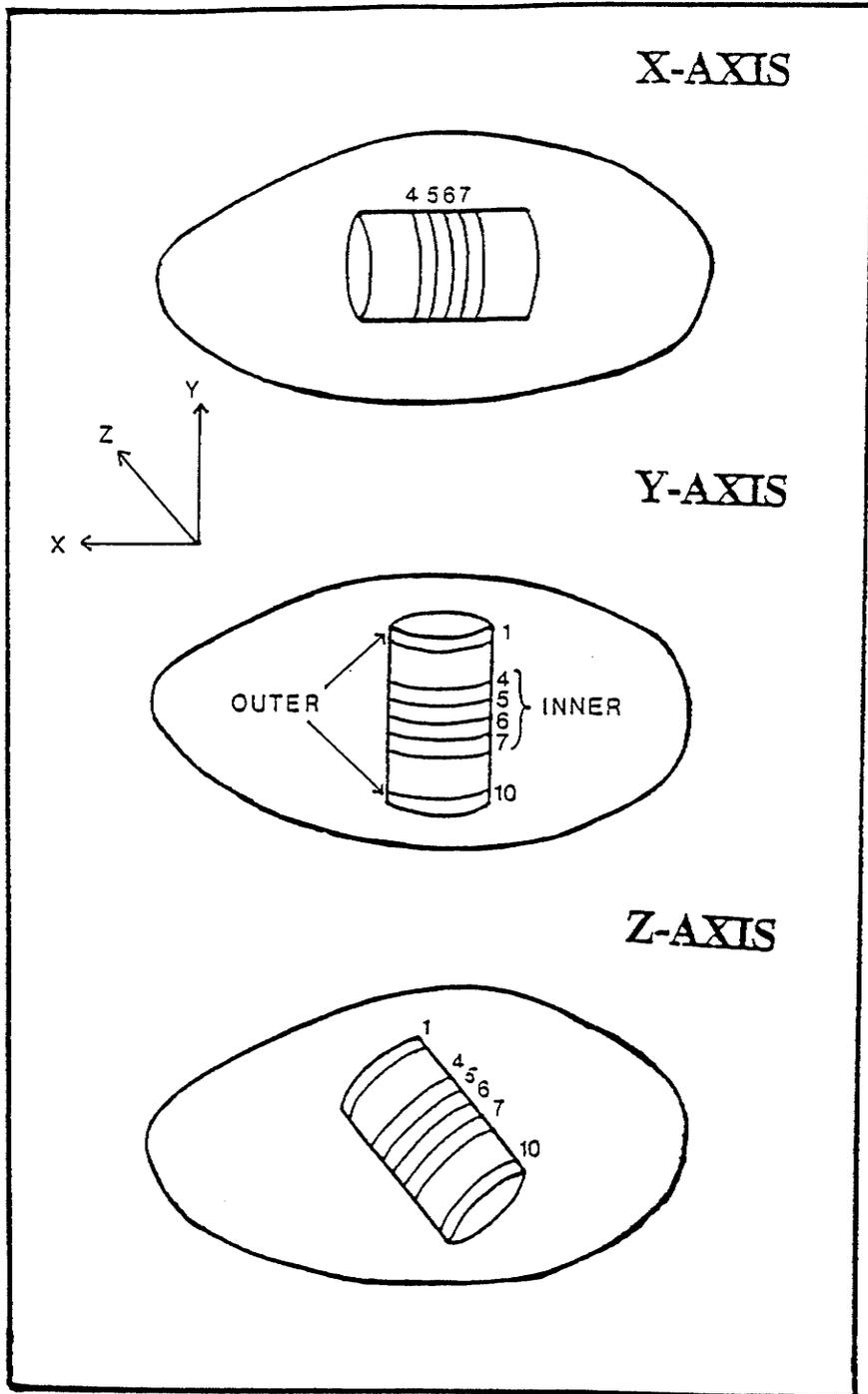
Therefore, the final cylindrical core of flesh had a diameter of 30 mm and length of 40 mm. The slicer was carefully set at a clearance of 4 mm between the sliding plate and the blade. The cylindrical flesh core was then manually pulled onto the blade. The slices obtained in this manner had a thickness of 4 mm and diameter of 30 mm. The first 3 slices obtained were discarded and only slices 4, 5, 6, and 7 were used for measurement. The portion remaining after slice 7 was also discarded. The slices obtained in this fashion were arbitrarily assigned and referred to as slice numbers 4, 5, 6, and 7, respectively (see Figure 5). To avoid dehydration, the slices were cut from the cylindrical core just prior to measurement and the remaining core was covered by a paper towel saturated with a small quantity of distilled water. The slices were rinsed with distilled water (to remove any cellular debris remaining on the surface) and dried with a clean paper towel prior to testing in the rheometer.

3.2.3.2   Y-axis Samples

A number of potato tubers were taken from the storage room, washed, dried with paper towels and equilibrated to room temperature (22 $\pm$ 2°C) overnight. The length of the tubers at the x-axis were carefully measured with a caliper. The core borer was placed as close as possible to the mid-point of the x-axis length and then punched through the whole flesh along the y-axis to obtain a cylindrical flesh core. To obtain a cylinder of 40 mm length, the double-blade cutting device was used to chop off equal portions from the ends. Therefore, the final cylindrical core of flesh had a diameter of 30 mm and length of 40 mm. The slicer was carefully set at a clearance of 4 mm between the

sliding plate and the blade. The cylindrical flesh core was then manually pulled onto the blade. The slices obtained in this manner had a thickness of 4 mm and diameter of 30 mm. The first slice obtained from the end of the cylindrical core was retained, as were slices 4, 5, 6 and 7, and also the last slice from the cylinder. Thus, the total number of slices measured were six. The slices obtained from the opposite ends were arbitrarily assigned and referred to as slices numbers 1 and 10 (the outer slices), while slices 4, 5, 6 and 7 were referred to as slices numbers 4, 5, 6 and 7, respectively, as for the x-axis slices (the inner slices) (see Figure 5). To avoid dehydration, the slices were cut from the cylindrical core just prior to measurement and the remaining core was covered by a paper towel saturated with a small quantity of distilled water. The slices were rinsed with distilled water (to remove any cellular debris remaining on the surface) and dried with a clean paper towel prior to testing in the rheometer.

3.2.3.3   Z-Axis Samples

Samples for the z-axis were obtained in an identical manner to those in the y-axis (section 3.2.3.2) except for the punching of the core borer which was performed along the z-axis (see Figure 5).

3.2.4   Preparation Procedure for Potato Flesh Samples Used in the Determination of the Effect of Sample Thickness on Storage Modulus

This experiment consisted of two parts and was performed on the old crops. The first part involved the use of sample thicknesses of 1, 2, 3, 4 and 4.5 mm, whereas the

second part involved the use of sample thicknesses of 3, 5 and 7 mm, respectively. The

total replicates (tubers) used in this experiment were 12; 9 for the first and 3 for the

second part. Since the combined thickness of the pre-selected thicknesses in the first part

was 14.5 mm (1, 2, 3, 4 and 4.5 mm) and the length of the cylindrical core was 40 mm,

2 sets of the 5 samples could be obtained from each potato (i.e. 18 sets could be obtained

from 9 tubers). The order of 5 sample thicknesses (1, 2, 3, 4 and 4.5 mm) for each set

was obtained by drawing randomly from a bag containing 5 pieces of papers with the

thicknesses written on them. This procedure was repeated to obtain the random order

of thicknesses of the slices for the second set of the tuber. Both these procedures were

repeated nine times (9 different tubers) to assign a total of 18 thickness combinations

The assignment of thickness order and sets pairing for the second part were carried out

in the same manner (with the exception that the combined thickness was 15 mm for each

set). The cylinder preparation and slicing procedure described in section 3.2.3.1 for the

x-axis was followed with one modification: for the x-axis samples only the center portion

(slices number 4, 5, 6 and 7) was used but for the thickness trials the first 30 mm portion

was used and the remaining portion was discarded.

3.2.5   Procedures for Mannitol Treatments for Potato Flesh Slices Used in Small Strain Oscillatory Shear Tests

Based on preliminary experimentation and the work of Lin and Pitt (1986), two

mannitol concentrations (3 and 7%) were employed to create hypotonic and hypertonic

conditions for potato flesh. The 3% mannitol solution was hypotonic whereas the 7%

mannitol was hypertonic to potato tissues. Fresh stock mannitol solutions at concentration of 3 and 7% (w/v) were prepared and kept in a refrigerator at least one day prior to use. Any solutions that had been kept for more than 7 days was discarded. To minimize cellular degradation, the mannitol solutions were buffered with 0.02 M K_2HPO_4 and 0.02 M KH_2PO_4 (Lin and Pitt, 1986). Potato slices for the 3 axes were obtained as described in sections 3.2.3.1, 3.2.3.2, and 3.2.3.3 (with the exception that no temperature equilibration of the tubers was performed prior to slicing). The slices were placed in petri dishes containing approximately 45 ml of a given mannitol solution. For the inner slices, two slices from the same tuber were kept in one labelled petri dish containing the 3% mannitol solution. The other two inner slices from the same tuber were kept in another labelled petri dish containing the 7% mannitol. For the outer slices, two outer slices each from different tubers were kept in one labelled petri dish containing the 3% mannitol solution. The remaining two outer slices were kept in another labelled petri dish containing the 7% mannitol. Based on preliminary experimentation and the work of Lin and Pitt (1986), sample slices were soaked for 12 h at room temperature prior to testing. Since the time required for measuring the mechanical properties of a sample slice in the dynamic shear test was approximately 5 min, slices from the same tubers were cut and soaked at intervals of 5 min to ensure equal mannitol soaking time was achieved. While awaiting slicing, the potato cylindrical core was covered with a paper towel saturated with a small quantity of distilled water.

3.2.6   Small Strain Oscillatory Shear Testing

A Bohlin Rheometer (Bohlin Reologi, Edison, NJ) with a parallel plate geometry was used for small strain oscillatory shear testing. The diameters of the upper and lower plates were 30 mm. Pre-cut circular discs of emery paper (diameter $\approx$ 30 mm) were glued on to the plates with cyanoacrylate bonding agent. The thickness of both pieces of emery paper was then measured by the dial gauge attached to the rheometer by lowering the upper plate until the upper and lower plates' emery papers touched. The value obtained was subtracted from all sample thickness measurements to obtain the true thickness of the sample slices in later measurement. The total thickness of the emery paper discs was approximately 0.5 mm. In most cases, the same emery paper discs were used throughout a given set of experiments. If a change of emery paper was required, the same procedure described above would be repeated prior to testing. Compression of the slices was necessary to provide contact over the maximum area between the slices and the upper and lower plates, and to prevent slipping during testing. The compression was maintained at less than 5% strain.

Rheological measurements were obtained using the oscillatory mode. All measurements were conducted at $22 \pm 2°C$ using a 2.74×10^{-3} kg.m torsion bar for the thickness trials (section 3.2.4) and a 9.31×10^{-4} kg.m torsion bar for the rest of the work. Small amplitude oscillation measurements were performed at strain amplitudes of 1.0% (for old crops) and 2.0% (for new crops), and at frequencies of 0.02, 0.2 and 2 Hz. Values for the apparent complex (G*), storage (G') and loss (G") moduli, as well as maximum strain (ϵ_o) were obtained using the software analysis program of the Bohlin

Rheometer. The energy stored and dissipated in each quarter cycle of oscillation were calculated from (Ferry, 1970):

$$\text{Energy stored per } \tfrac{1}{4} \text{ cycle } (U_{st}) = G' \, \epsilon_o{}^2 / 2$$

$$\text{Energy dissipated per } \tfrac{1}{4} \text{ cycle } (U_{dis}) = G'' \, \pi \, \epsilon_o{}^2 / 4$$

For the determination of the effect of sample thickness on G', strain amplitudes of 0.1 to 15% and a frequency of 0.2 Hz were used. The values of G' at 1.7% amplitude were taken for analysis. Unfortunately, the maximum slice thickness that could be measured by the dial gauge attached to the Bohlin Rheometer was 5 mm. This distance set a limit on maximum slice thickness if thicknesses used in the calculation of the dynamic shear moduli were to be measured accurately. Since the emery paper discs took up approximately 0.5 mm, the maximum thickness that could be measured by the dial gauge was reduced to 4.5 mm. Consequently, most of the slices used in the second part of the thickness trials (which had thicknesses over 4.5 mm) could only be measured by a caliper, and the slight compression of the slices during the lowering of the top plate prior to testing could only be estimated. The true thicknesses of the slices were obtained by subtracting the estimated compression distance from the thicknesses measured by the caliper.

3.2.7   Experimental Design for Small Strain Oscillatory Shear Testing

A completely randomized block design was not feasible since measurements were performed over a period of 4 weeks for old crops, and 4 weeks for the new crops at different times of the year (June and October, 1994, respectively). In all experiments

listed in 3.2.2, potato tubers were tested for the x-axis first, followed by the y and z-axes. Originally the effect of frequency was to be investigated on separate tubers (seven tubers for each frequency). However, it was observed that internal black spot and hollow heart had occurred quite extensively in the old crops. As a result, a number of tubers had to be discarded and the degree of replication was reduced. In order to maximize the number of results obtainable from the limited tubers available, a decision was made to employ pairing of frequencies on individual tubers. This was done by arranging the three frequencies investigated into two pairs. The first pair was 0.02 Hz and 0.2 Hz, and the second pair was 0.2 Hz and 2 Hz. Since the lower frequency pair required substantially longer analysis times than the higher frequency pair, it was important to consider whether errors were introduced by sample dehydration during testing (Vincent 1989), especially in the first pairing (i.e. 0.02 and 0.2 Hz). To investigate this effect consecutive slices from the same tuber were tested at alternating frequencies within a given pair of frequencies. Shown in Table 2 is an example of the application of the paired frequencies of 0.2 and 2 Hz on the slices obtained for the x, y and z-axes for tubers without mannitol treatments. On average, for each axis, 20 slices (from 5 tubers) were analyzed at 0.02 and 2 Hz, while for 0.2 Hz 40 slices (from 10 tubers) were analyzed. For tubers with mannitol treatments, the paired frequencies were also applied to consecutive slices from the same tuber in an alternating manner. However, the number of analyses obtained at 3 and 7% mannitol would be half of those without mannitol treatments (see Table 3). On average, for each mannitol concentration and each axis, 10 slices (from 5 tubers) were analyzed at 0.02 and 2 Hz, while for 0.2

Table 2.   Application of Paired Frequencies (0.2 and 2 Hz) on Potato Slices in
            Small Strain Oscillatory Shear Testing for the Old and New Crops
            without Mannitol Treatments

| Slice Number | | Frequency Applied | |
X-Axis	Y & Z-Axes	First	Second
	1	0.2 Hz	2 Hz
4	4	2 Hz	0.2 Hz
5	5	0.2 Hz	2 Hz
6	6	2 Hz	0.2 Hz
7	7	0.2 Hz	2 Hz
	10	2 Hz	0.2 Hz

Table 3. Application of Paired Frequencies (0.02 and 0.2 Hz) on Potato Slices in Small Strain Oscillatory Shear Testing for the Old and New Crops with Mannitol Treatments

Slice Number		Mannitol Concentration	Frequency Applied	
X-Axis	Y & Z-Axes	(% w/v)	First	Second
	1	3	0.02 Hz	0.2 Hz
4	4	7	0.2 Hz	0.02 Hz
5	5	3	0.02 Hz	0.2 Hz
6	6	7	0.2 Hz	0.02 Hz
7	7	3	0.02 Hz	0.2 Hz
	10	7	0.2 Hz	0.02 Hz

Hz 20 slices (from 10 tubers) were analyzed. The application of a particular frequency pair was carried out in an alternating manner on the tubers. For example, if 5 tubers were subjected to the frequency pair, 0.2 and 2 Hz, and tuber number one was subjected to the paired frequencies in the same sequence as that shown in Table 2, the first slice of tuber number 2 would be subjected to 2 Hz first then 0.2 Hz, and so on alternately for the rest of the slices remained in tuber number 2. This procedure was therefore self-repeated every 2 tubers in a given set of experiment.

In all measurements two full cycles of oscillation at a particular frequency were given to the sample slices for 'conditioning' (Vincent, 1989); the reading obtained from the third cycle was recorded. The 'conditioning' was necessary to overcome any inertia effect from the 4 mm thick slice samples, particularly at such a small strain level applied (0.04%). The total analysis times for the frequency pairing of 0.02 and 0.2 Hz, and the 0.2 and 2 Hz pair were approximately 5 and 3 min, respectively.

3.2.8 Preparation Procedures for Uniaxial Compression Testing of Potato Flesh Cylinders

3.2.8.1 X-Axis Samples

The samples were obtained as described in section 3.2.3.1 with the following modifications: a core borer of diameter of 15 mm was carefully placed as close as possible to the geometric center of the top of the center portion after chopping off 2 equal portions from the stem and bud ends. The core borer was then punched through the flesh and a cylindrical flesh core was obtained (diameter 15 mm; length $\approx$ 50 mm).

A second cylindrical core was obtained in close proximity to the first core in the same manner. The first and second cylindrical cores were always aligned on a straight line along the y-axis and the distance between the positions where the samples were obtained was approximately 5 mm (see Figure 6). After chopping off 2 equal portions from the ends of the cylinder by the double blade cutting device, the final cylindrical flesh core had a diameter of 15 mm and length of 40 mm. To avoid dehydration the second cylindrical sample was cored just prior to testing. The top and the bottom surfaces of the samples were rinsed with distilled water (to remove cellular debris remaining on the surfaces) and dried with a clean paper towel prior to loading on to the compression plates.

3.2.8.2   Y-Axis Samples

The samples were obtained as described in section 3.2.3.2 with the following modifications: two cylinders of flesh were obtained (diameter 15 mm, length 40 mm) along the y-axis instead of one 30 mm diameter cylindrical core. The cylinders were always aligned on a straight line along the x-axis and the distance between the positions where the samples were obtained was approximately 5 mm (see Figure 6). The same precautions and cleaning procedures described in section 3.2.8.1 were used prior to testing of the cylinders.

3.2.8.3.   Z-Axis Samples

Same as 3.2.8.2 except on z-axis (see Figure 6).

Figure 6. Sectioning of Potato Cylinder Samples for Uniaxial Compression Test

X-AXIS

Y

Z

X

Y-AXIS

Z-AXIS
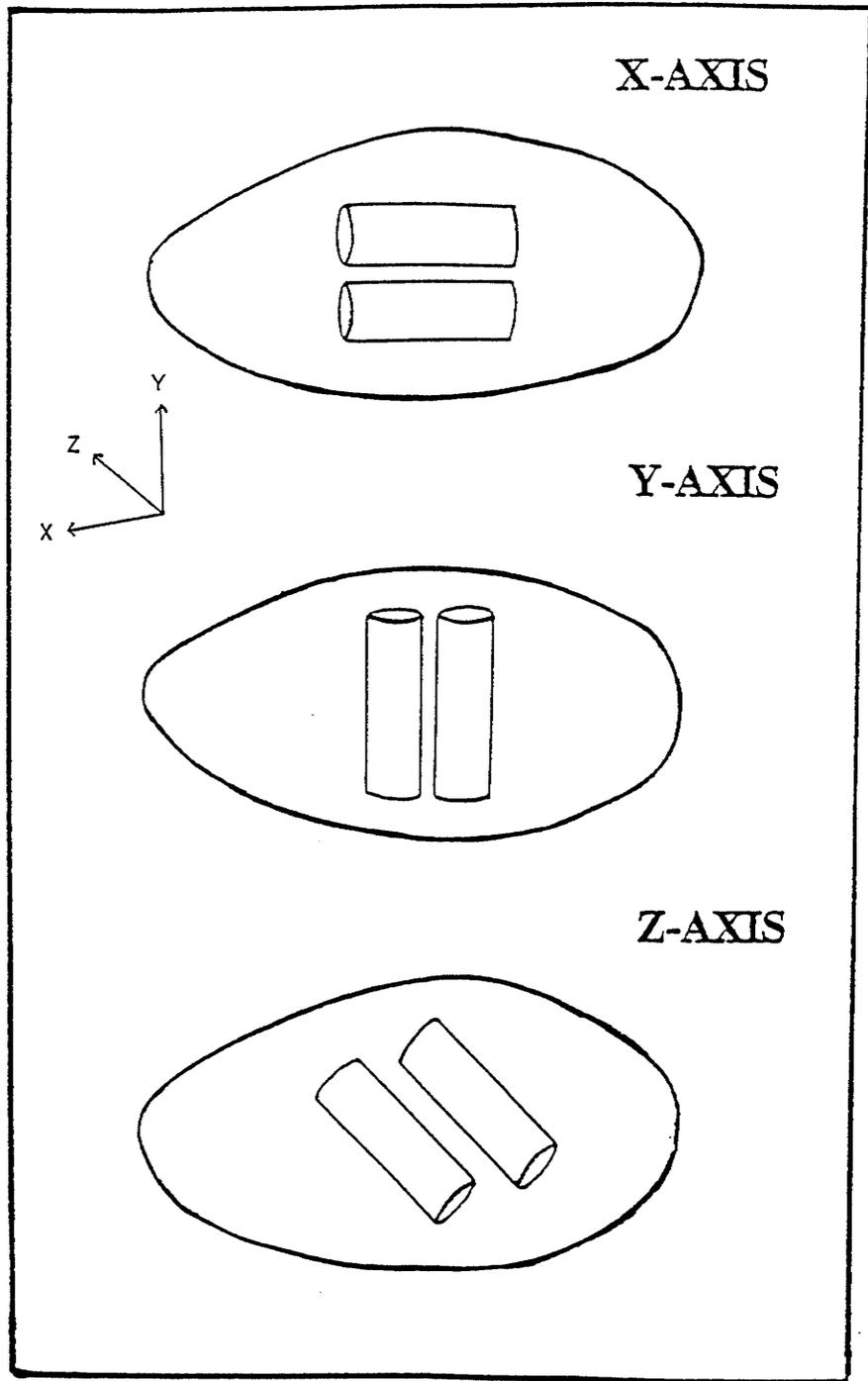
3.2.9 Procedures for Mannitol Treatment for Potato Cylindrical Flesh Samples Used in Uniaxial Compression Test

The mannitol solutions were prepared as described in section 3.2.5. The cylindrical samples were obtained in the same manner as in sections 3.2.8.1, 3.2.8.2 and 3.2.8.3 (with the exception that no temperature equilibration of the tubers was performed prior to sectioning). The cylinders were put into plastic bottles containing approximately 70 ml of a given mannitol solution. Only one sample was kept in each labelled bottle. Based on preliminary experimentation and the work of Lin and Pitt (1986), samples were soaked for approximately 17 h at room temperature prior to testing. Since the time required for measuring the mechanical properties of a cylinder sample in the compression test was approximately 5 min, the second cylinder sample from the same tuber was cored and soaked 5 min later to ensure equal mannitol soaking time was achieved.

3.2.10 Uniaxial Compression Testing

A Lloyd Instrument model 1000R (Omnitronix, Mississauga, ON) with a parallel plate geometry was used throughout. All measurements were carried out at room temperature (22 $\pm$ 2°C) with a calibrated 100 N load cell. The diameters of the upper and lower plates were 100.2 and 110.5 mm, respectively. Pre-cut, circular discs of emery paper (diameter $\approx$ 20 mm) were glued as close as possible on to the center of the plates with cyanoacrylate bonding agent. In all measurements the cylindrical samples were placed on the emery paper at the center of the lower plate and the upper plate

lowered to just touch the upper surface of the sample.

Two compression rates (strain rates) were used throughout the experiment: 2 cm min^{-1} and 20 cm min^{-1}. Each sample was subjected to three identical, consecutive compression cycles (i.e. three loading and unloading cycles) of 10.5% compression of the original length of the sample (or a distance of 4.2 mm). Deformation and force responses were recorded by the software analysis program of the Lloyd Instrument. A number of parameters were derived from the force-deformation curves for each cycle. At the strain rate of 2 cm min^{-1}, the initial and end moduli were calculated from linear regression analysis of the points within the strain region from 0.85 to 1.18 %, and from 8.81 to 9.14 %, respectively. For 20 cm min^{-1}, the initial and end moduli were calculated from linear regression analysis of the points within the strain region from 0.75 to 2.35%, and 7.83 to 9.40%, respectively. The areas under the loading and unloading curves were calculated by the Fig.P software program (Version 6.0, Biosoft®, NC) to obtain total energy and recovered energy, respectively; dissipated energy being obtained by subtraction.

The strain rates were applied to the cylinders in an alternating fashion. For example, if the first cylinder from tuber number 1 was subjected to 2 cm min^{-1}, the second cylinder from the same tuber would be subjected to 20 cm min^{-1}. For tuber number 2, the first cylinder would then be subjected to 20 cm min^{-1} whereas the second cylinder from tuber number 2 would be subjected to 2 cm min^{-1}. This procedure was therefore self-repeated every 2 tubers in a given set of experiment.

3.2.11   Experimental Design for Uniaxial Compression Testing

Like the small strain oscillatory shear testing, a completely randomized block design was not feasible for uniaxial compression testing due to differences in the period of measurement between the old and new crops. The number of replicate tubers analyzed was 11, although only 10 x-axis replicates were obtained for the old crops and 10 z-axis replicates for the new crops. In the mannitol treatment experiment, 10 replicates tubers were used for each axis. One cylinder form each tuber was soaked in 3% mannitol solution and the remaining cylinder from the same tuber was soaked in 7% mannitol. As a result, it was not possible to compare cylinders from the same tuber statistically. For both crops (with and without mannitol treatment) x-axis samples were tested first, followed by the y and z-axis samples.

3.2.12   Moisture Content Determination

Moisture content was determined in accordance with AOAC methods (32.082-32.084) with one modification: whole potato flesh slices were used instead of homogenization of potato tissues. The potato slices were obtained as described in sections 3.2.3.2 and 3.2.3.3. Two outer slices (numbers 1 and 10) and two inner slices (numbers 5 and 6) were obtained from each tuber. Ten tubers were used for both old and new crops. In each crop five out of ten tubers were used for the y-axis and the remaining five were used for the z-axis determinations.

3.2.13   Staining Procedure

Staining solution was prepared by dissolving 0.5 g periodic acid powder ($HIO_4.2H_2O$) in 100 ml of 3% (w/v) nitric acid (HNO_3) prior to staining. Potato slices of approximately 1 mm thickness obtained from the middle part of different tubers (transverse cross section and longitudinal cross section) were immersed in about 40 ml staining solution for 10-15 min to allow colour development.

3.2.14   Statistical Analysis

All statistical analyses were performed on a PC microcomputer using SAS statistical analysis software program package (SAS Institute, Version 6.09, 1989). Analyses of variance were carried out using the General Linear Model (GLM) Procedure. Significant differences among treatments were determined by the Duncan's multiple range test ($p \leq 0.05$).

4 RESULTS

4.1 Preliminary Experiments

4.1.1 Determination of the Linear Viscoelastic Region for Potato Flesh Tissue in Small Strain Oscillatory Shear Test

It is important that only if the potato tissue displays a linear viscoelastic region can useful results be obtained from small strain oscillatory shear tests (Biliaderis, 1992). Therefore, preliminary work was carried out on both old and new crops to determine if potato flesh tissue exhibited a linear viscoelastic response when subjected to oscillatory shear. Potato slices of 4 mm thickness and 30 mm diameter (obtained at the x-axis) were subjected to oscillatory shear at amplitudes from 0.1 to 50% and a frequency of 0.2 Hz. The new crop results are depicted in Figure 7, where it appears that potato flesh tissue does possess a linear viscoelastic response in a narrow strain region below 0.1%, as indicated by the dynamic shear function G'. Above 0.1% strain, G' starts to drop in a rather constant, shallow slope up to a strain of about 0.6%. Beyond 0.6% strain G' drops more sharply, indicating that considerable irreversible deformation has occurred in the tissue. The curve looks slightly different in terms of the other dynamic shear function, G". The value of G" rises initially and levels off at a strain of about 0.4%. Beyond 0.4% strain, G" starts falling in a similar manner to G'.

Figure 7.   Effect of Oscillatory Shear Strain on the Storage (G') and Loss (G")
of New Crops at a Frequency of 0.2 Hz
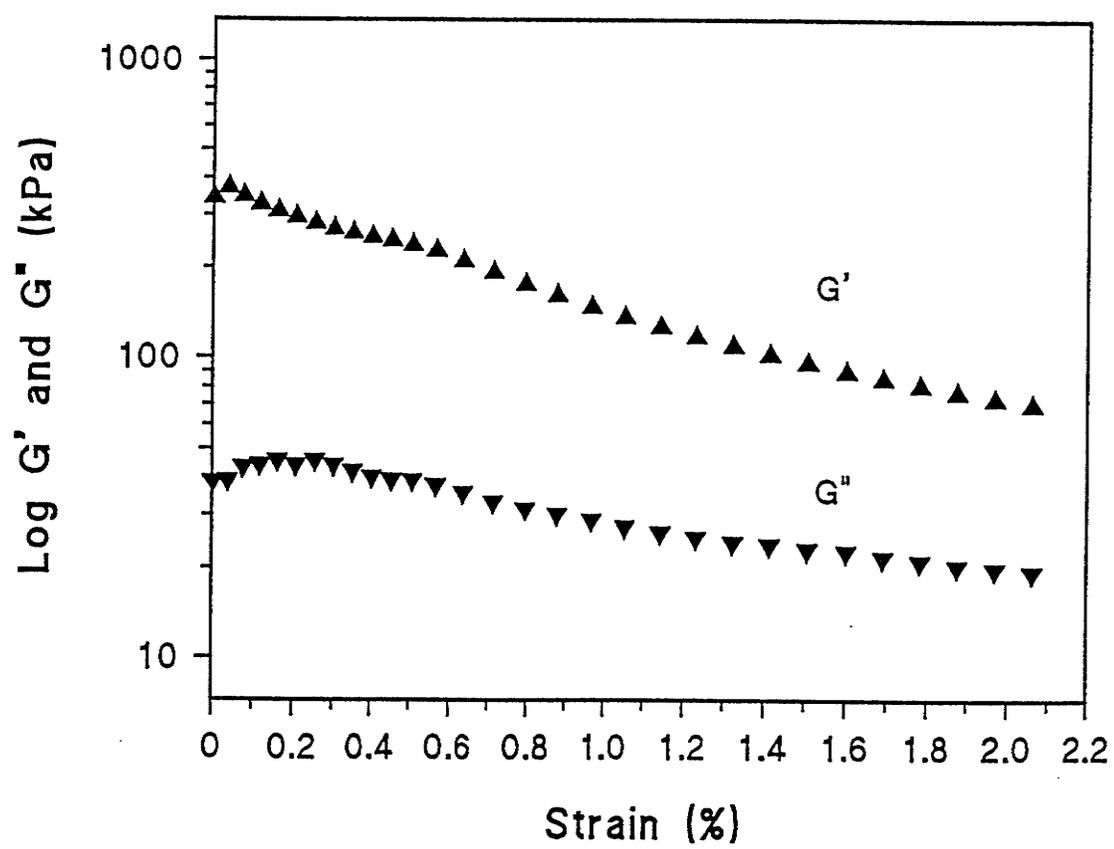
Subsequently, potato flesh slices were subjected to oscillatory shear at lower amplitude levels (0.1 to 2.5%) at a frequency of 0.2 Hz. The new crop results are depicted in Figure 8. It can be seen from Figure 8 that G' and G" are independent of oscillatory shear strain from 0.001 to 0.05%. The strain corresponding to 2% amplitude was about 4×10^{-4} (or 0.04%) which was slightly lower than that used by Ramana and Taylor (1992). Therefore, a linear viscoelastic region was established for potato flesh tissue for all subsequent experiments.

4.1.2   Effect of Slice Thickness on G' in Small Strain Oscillatory Shear Test

Since the value of the dynamic shear function, G' has been reported to increase with the thickness of potato tissue samples (Ramana and Taylor, 1992), preliminary work was carried out to (i) determine the extent that the dynamic shear function, G', was affected by sample thickness, and (ii) determine the sample thickness that would be used in subsequent work.

Potato slices of various thicknesses (section 3.2.4) were subjected to oscillatory shear at amplitudes from 0.1 to 15% at a frequency of 0.2 Hz. For each measurement the value of G' at an amplitude of 1.7% was taken to construct the plot of slice thickness against G' (Figure 9). It is apparent from Figure 9 that G' increased as sample thickness increased from 0.6 mm to about 4 mm. Beyond 4 mm, G' appears to level off towards a plateau at the largest thickness (7.5 mm). This observation concurs with that reported by Ramana and Taylor (1992) in which G' was reported to no longer increase as sample thickness was increased beyond 7 mm.

Figure 8. Effect of Oscillatory Shear Strain on the Storage (G') and Loss (G")
of New Crops at a Frequency of 0.2 Hz
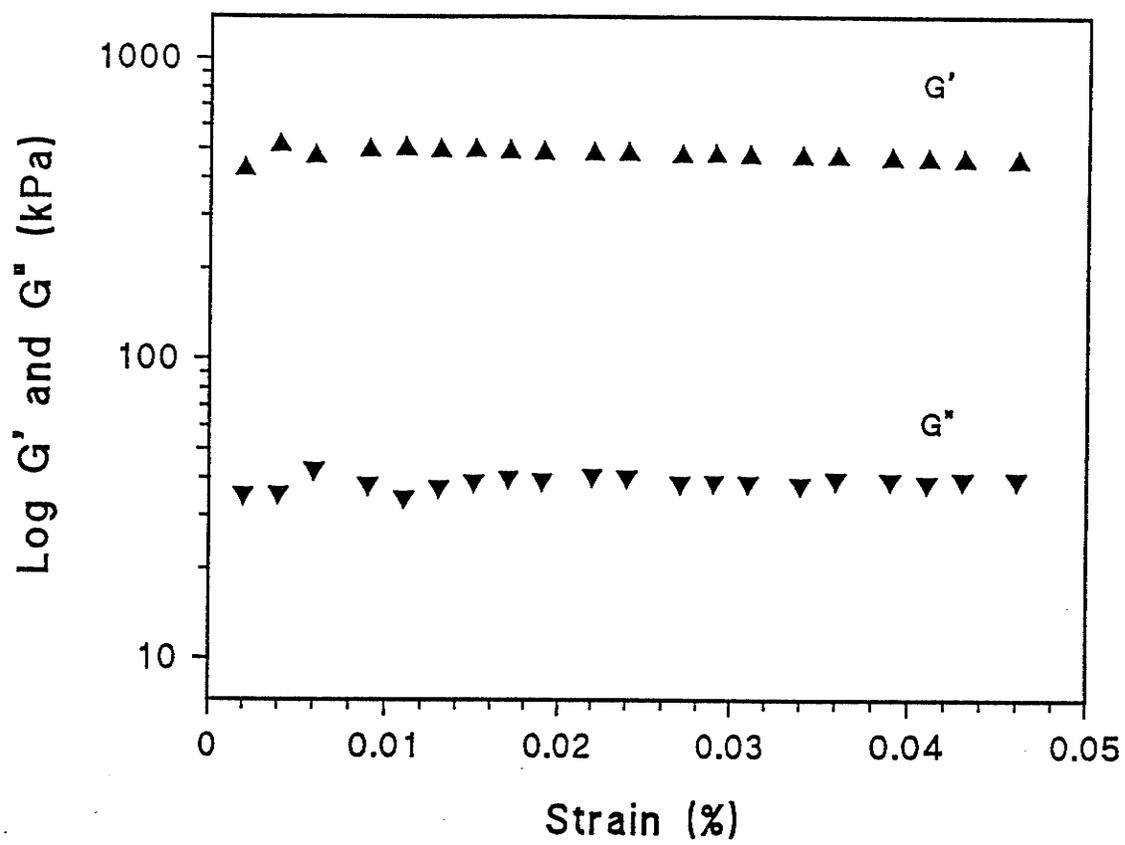
Figure 9. Effect of Slice Thickness on the Storage Modulus (G') of Old Crops at an Oscillatory Amplitude of 1% and Frequency of 0.2 Hz
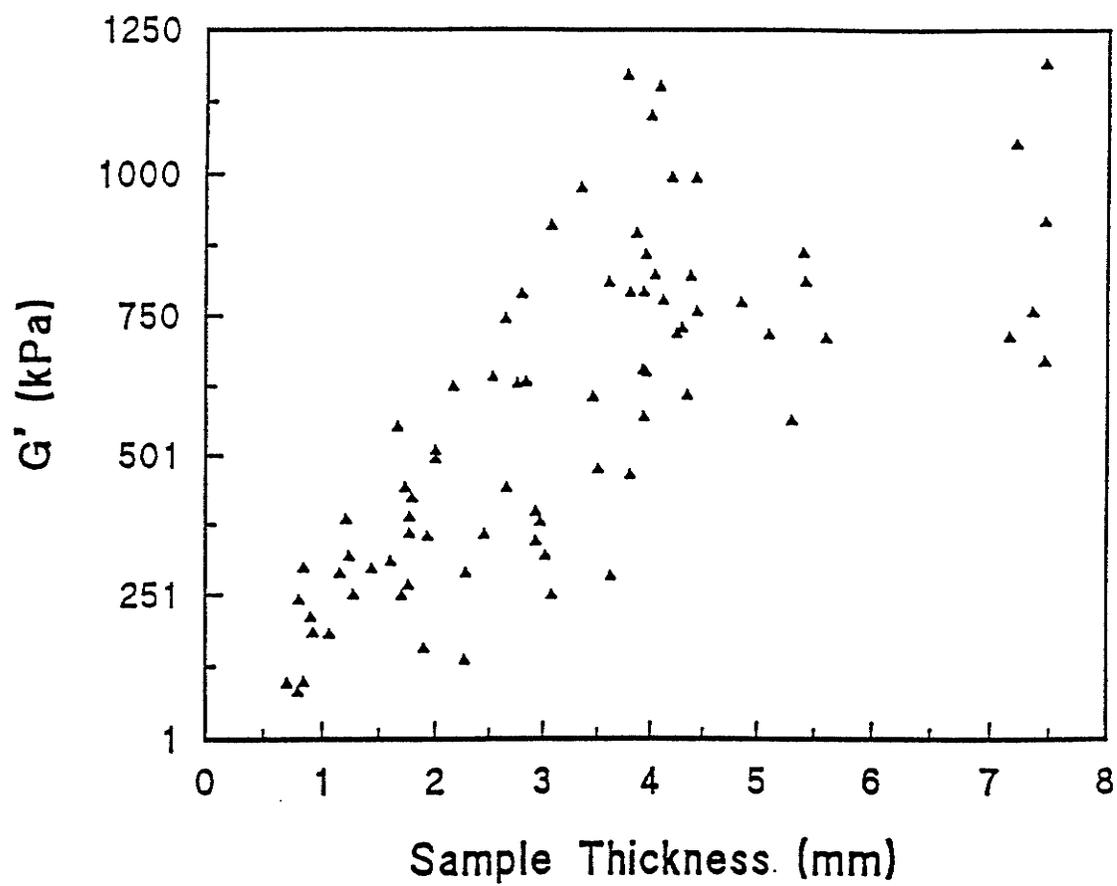
In regards to the sample thickness employed in this project, a choice of 7.5 mm appears rheologically sound as it would eliminate the variation in dynamic shear moduli caused by slice thickness. However, a thickness of 4 mm was chosen for all experiments due to uncertainty in measurement of sample thickness (section 3.2.6). As a result, the dynamic shear functions that are reported are apparent (at 4 mm), not absolute values (Ramana and Taylor, 1992).

4.1.3   Moisture Content of the Old and New Potato Tissues in Different Histological Regions

The mean moisture contents for 2 outer and 2 inner slices for the old and new crops are shown in Table 4. Since the old and new crops were grown at different sites and in different years, a direct comparison between their moisture contents could not be performed. For both the old and new crops, the difference between the inner and outer slices of the z-axis was higher than that of the y-axis (8.14% for the z-axis and 6.41% for the y-axis on average).

4.2 Preliminary Statistical Analysis of Results

4.2.1 Effect of Sample Dehydration During Measurement

Since the time required for sample preparation and oscillatory shear measurement was approximately 3 min for each slice at 0.2 and 2 Hz, and 7 min at 0.02 Hz, the total time elapsed from the measurement of the first slice to the last slice in each replicate was

TABLE 4. Moisture Content (M.C.) of the Inner and Outer Slices of the Old and New Crops

Potato	Axis	Slice Position	Mean M.C.[1] (% wet basis)
Old	Y	Outer	73.14
		Inner	79.82
	Z	Outer	73.97
		Inner	81.82
New	Y	Outer	78.54
		Inner	84.68
	Z	Outer	76.20
		Inner	84.62

1 Mean value for a particular axis was the average of 5 tuber replicates; 2 inner (slice numbers 5 and 6) and 2 outer (slice numbers 1 and 10) slices were used in each replicate for M.C. determination.

approximately 25 to 30 min for the x-axis and 40 to 45 min for the y and z-axes. It was thought that, despite the precautions taken, sample dehydration might occur in the cylindrical cores awaiting sectioning which would affect the results. Preliminary statistical analysis was carried out to verify if this was the case before a full statistical analysis was performed on the results.

The statistical analysis performed was to use the general linear model procedure to state that apparent G' or G" were dependent solely on the variable slice position in the cylindrical core (i.e. slice numbers 4, 5, 6 or 7). The means of the dependent variable (apparent G' or G") for each position were compared at a particular axis, frequency, crops (old and new), and mannitol treatment (3 and 7%), and for all combinations of these. For all cases, no significant difference at the 0.05 level or apparent pattern was observed among the means of slice position. This indicates that the preparation and measuring procedures did not cause any significant moisture losses that had affected the results, since it might be expected that slice numbers 6 and 7 which were sectioned last would have lost more moisture than slice numbers 4 and 5 which were sectioned earlier.

4.2.2 Effect of Frequency Pairing

As described in section 3.2.7 all slices were subjected to oscillatory shear at 2 frequencies. It was speculated that the frequency pairing procedure might introduce systematic errors in the results - the reading which was obtained from the first analysis in a pair at a particular frequency might be consistently higher than that obtained from the same frequency but from the second analysis in a pair (see Table 2 & 3), due to

longer time having elapsed which would have caused more dehydration of the sample (Vincent, 1989). This was thought to be more likely in the pairing of 0.02 Hz and 0.2 Hz where analysis times were longer. As a result, preliminary statistical analysis was performed to consider this hypothesis.

The General Linear Model Procedure was used to state that apparent G' or G" were solely dependent on the variable, order of frequency applied (i.e first or second order). The means of the dependent variable (apparent G' or G") for each order were then compared at a particular axis, frequency, crops (old and new), and mannitol treatment (3 and 7%), and for all combinations. In the majority of tests, no significant difference was observed between the 2 orders at the 0.05 level. Despite the absence of significant difference in the statistical analysis, a consistent but not statistically different trend was observed that apparent G' values were higher in the first order than in the second order for any given frequency used, indicating that dehydration may have affected the results.

Since frequency pairing was carried out by pairing 0.02 Hz with 0.2 Hz, and 0.2 Hz with 2 Hz, a decision had to be made whether the 0.2 Hz observations from both frequency pairs could be combined together. Two arguments were put forward to justify combining the results:

(i)   For 0.2 Hz analyzed as the first order of frequency pair, the time elapsed in the measurement at 0.2 Hz paired with 0.02 Hz is identical to that at 0.2 Hz paired with 2 Hz. Therefore, the means of apparent G' at 0.2 Hz should not be different from each other.

(ii)   For 0.2 Hz analyzed as the second order of frequency pair, the time elapsed for 0.2 Hz in the measurement at 0.2 Hz paired with 0.02 Hz is substantially longer than that at 0.2 Hz paired with 2 Hz. Therefore, the means of apparent G' at 0.2 Hz paired with 0.02 Hz should be different from that measured at 0.2 Hz paired with 2 Hz.

If the results of the preliminary statistical analysis agreed with these arguments, measurements at 0.2 Hz would need to be treated separately, according to the frequency with which it was paired. If not, then all observations obtained at 0.2 Hz would be combined.

Results from the statistical analysis indicated that no apparent pattern existed among the observations. At the second order of frequency pair, approximately half of the apparent G' values obtained at 0.2 Hz paired with 0.02 Hz were higher than those at 0.2 Hz paired with 2 Hz. Similar results were observed at the first order of frequency pair. As a result, all observations at 0.2 Hz were combined in later statistical analyses.

4.2.3   Effect of Cylinders Pairing with Strain Rates

As described in section 3.2.10 the two cylindrical samples obtained from each replicate were subjected to different strain rates, a given strain rate being applied to the first cylinder removed from the tuber number one, and then that strain rate applied to the second cylinder from the next tuber. This alternating fashion was performed throughout the replicates. Preliminary statistical analysis was performed to determine whether sample dehydration affected the results for the second cylinder. The samples were

grouped into 2 groups according to their order of strain rate application (i.e. whether first or second). The means of the 5 parameters measured (E_{in}, E_{end}, U_{tot}, U_{rec} and U_{dis}) at a particular order of strain rate were compared at a particular axis, strain rate, cycle, crops (old and new), and mannitol treatment (3 and 7%), and for all combinations. In most cases no significant differences were observed at the 0.05 level between the first and second cylinders, indicating that the application of strain rates in an alternating manner did not cause any significant systematic error.

4.3 Small Strain Oscillatory Shear Results- Old and New Crops without Mannitol Treatment

The overall coefficient of variation (c.v.) between replicates and between slices are shown in Table 5 to 6, respectively (see appendix 8.1 for the original c.v. at each frequency). Overall the c.v. values for apparent G' and G" were substantially lower in the new crops than in the old crops. Generally, the c.v. of apparent G' were higher than apparent G" c.v. The c.v. values were lower in the outer slices than in the inner slices.

The c.v. values between slices were comparable to those between replicates. In regards to axis, no particular pattern was observed in the between replicates c.v. values (Table 5), but x-axis samples showed the highest variation between slices for both apparent G' and G" (Table 6).

Statistical analysis revealed that in most cases no interactions were observed between axis and frequency for all experimental parameters (G^*, G', $G"$, δ, U_{st} and U_{dis}) at the 0.05 level. Therefore, the main effects of axis and frequency on the experimental

TABLE 5. Coefficient of Variation (C.V.) between Replicates as Measured by G' and G" Values[1,2]

Potato	Location	Axis	C.V. of G' (%)	C.V. of G" (%)
Old	Inner	X	28.18	31.23
		Y	23.34	14.37
		Z	29.60	22.16
	Outer	Y	22.40	22.30
		Z	19.11	10.51
New	Inner	X	17.27	17.94
		Y	21.14	21.36
		Z	19.30	16.32
	Outer	Y	15.75	14.37
		Z	13.75	8.83

1 Values were averaged over the 3 frequency ranges measured.
2 Means of G' and G" are shown in Table 7.

TABLE 6.   Coefficient of Variation (C.V.) between Slices as Measured by G' and
G" Values[1]

Potato	Location	Axis	C.V. of G' (%)	C.V. of G" (%)
Old	Inner	X	30.66	24.50
		Y	26.87	19.27
		Z	27.02	17.06
	Outer	Y	17.61	25.59
		Z	25.57	14.49
New	Inner	X	19.86	23.17
		Y	13.54	12.13
		Z	16.99	10.72
	Outer	Y	14.69	11.49
		Z	15.05	8.91

1 Values were averaged over the 3 frequency ranges measured.

parameters for old and new crops are shown separately in Table 7 to Table 10 (see appendix 8.2 for the significant interactions).

In regards to the effect of axis on the inner slices of the old crops (Table 7), x, y and z-axes were not significantly different from each other, though the values of apparent G^*, G', and G'', U_{st} and U_{dis} were slightly higher in the x-axis than in the other axes. For the new crops, the values of apparent G^*, G' and G'' were significantly higher in the x-axis than those in the y and z-axes, but the opposite was true for U_{st}. The values of δ were generally 2° higher in the old crops than in the new crops.

In regards to the effects of axis on the outer slices (Table 8), y and z-axes were not significantly different from each other at both physiological stages, though the values of U_{st} and U_{dis} were significantly higher for the y-axis than the z-axis in the old crops.

With respect to the effect of frequency on the inner slices (Table 9), an increase in frequency from 0.02 Hz to 2 Hz had a greater effect on apparent G'' and δ than the other parameters; an increase in frequency was inversely related to apparent G'' and δ. The values of apparent G'' and δ were all significantly different from each other as frequency increased from 0.02 to 0.2 Hz. In terms of apparent G^* and G', an increase in frequency from 0.02 Hz to 2 Hz did not cause any significant increase in those values for the old crops, but in the new crops an increase in frequency from 0.02 Hz to 0.2 Hz increased apparent G^* and G' significantly. However, a further increase in frequency from 0.2 Hz to 2 Hz did not cause any significant change in apparent G^* and G'. It is interesting to note that for the old crops although the values of apparent G^* and G' were not significantly different as frequency increased, they did follow a similar pattern to the

TABLE 7.   Effect of Axis on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	X	403.32	399.71	45.86	7.46	19.53	5.84
	Y	373.19	369.76	45.77	7.62	18.07	3.86
	Z	370.12	365.62	46.57	8.34	11.08	2.71
New[2]	X	682.57[a]	679.22[a]	61.80[a]	5.34	26.83[a]	4.18
	Y	625.93[b]	623.12[b]	52.70[b]	5.25	28.68[b]	4.29
	Z	605.50[b]	602.14[b]	55.87[b]	5.68	28.67[b]	4.60

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 frequency ranges measured

TABLE 8. Effect of Axis on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and New Potato Crops[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	Y	346.85	343.15	52.10	7.98	17.42[a]	3.89[a]
	Z	367.28	364.03	43.07	7.39	11.22[b]	2.54[b]
New[2]	Y	575.95	572.18	58.20	6.24	29.92	5.29
	Z	580.46	576.65	59.63	6.20	28.98	5.10

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 frequency ranges measured.

TABLE 9. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	0.02	370.25	361.90	76.25[a]	12.72[a]	24.83	9.00
	0.2	391.91	389.38	39.33[b]	6.54[b]	12.32	2.51
	2	374.89	373.05	28.15[c]	5.24[c]	15.18	2.34
New[2]	0.02	601.44[a]	594.20[a]	89.97[a]	8.95[a]	28.37	7.14[a]
	0.2	650.05[b]	648.01[b]	48.85[b]	4.62[b]	27.76	3.64[b]
	2	649.81[b]	648.83[b]	35.90[c]	3.17[c]	28.46	2.75[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 axes measured.

changes with frequency seen for the new crops. The values of U_{st} and U_{dis} were not significantly different as frequency increased for the old crops, but the values of U_{dis} were significantly different from each other in the new crops as frequency increased from 0.02 Hz to 2 Hz. The effect of frequency on the measured values in the outer slices (Table 10) were very similar to those observed in the inner slices.

In comparing inner and outer slices in their y and z-axes, no interactions were found between axis, frequency and slice position. The inner slices were not significantly different from the outer slices in the old crops, but the inner slices were significantly different from the outer slices in the new crops, as indicated by higher apparent G' and lower apparent G" values (Table 11).

4.4 Small Strain Oscillatory Shear Results - Old and New Crops with 3 and 7% Mannitol Treatments

The overall c.v between replicates for the inner and outer slices for old and new crops at 2 mannitol concentrations are shown in Table 12. The overall c.v. between slices for the inner slices at 2 mannitol concentrations are shown in Table 13 (see appendix 8.3 for the original c.v. at each axis and frequency).

Overall the apparent G' c.v. values were higher than apparent G" c.v. values. and the c.v. values were lower at 3% than at 7% mannitol (Table 12 & 13). The c.v values were lower in the new crops than in the old crops. The c.v. values between slices were comparable to those between replicates for the inner slices. The c.v. values were

TABLE 10. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and New Potato Crops[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	0.02	333.50	325.72	67.96[a]	12.51[a]	11.22[a]	4.01
	0.2	361.17	358.39	48.92[b]	7.03[b]	14.59[b]	3.17
	2	363.74	362.30	31.21[c]	5.20[c]	17.63[c]	2.97
New[2]	0.02	518.63[a]	510.17[a]	91.52[a]	10.40[a]	30.41	8.95[a]
	0.2	592.24[b]	589.91[b]	50.98[b]	5.12[b]	29.03	4.16[b]
	2	620.71[b]	619.50[b]	35.90[c]	3.47[c]	29.27	2.84[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the y and z-axes measured.

TABLE 11. Effect of Slice Location on Storage Modulus (G') and Loss Modulus
(G") of the Old and New Potato Crops[1]

Potato	G'		G"	
	(kPa)		(kPa)	
	Inner	Outer	Inner	Outer
Old[2]	369.80	352.32	48.43	48.13
New[2]	612.63[a]	574.33[b]	54.28[a]	58.89[b]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the y and z-axes, and 3 frequency ranges measured.

TABLE 12. Coefficient of Variation (C.V.) between Replicates as Measured by G' and G" Values for the Inner and Outer Slices of the Old and New Potato Crops at Two Mannitol Concentrations

Potato	Location	Mannitol Concentration (% w/v)	C.V. of G' (%)	C.V. of G" (%)
Old	Inner[1]	3	21.26	18.01
		7	20.80	21.63
	Outer[2]	3	28.23	20.84
		7	45.29	36.38
New	Inner[1]	3	16.86	18.43
		7	22.70	16.27
	Outer[2]	3	27.89	24.79
		7	38.08	31.20

1 Values were averaged over the x, y and z axes, and 3 frequency ranges measured.
2 Values were averaged over the y and z axes, and 3 frequency ranges measured.

TABLE 13. Coefficient of Variation (C.V.) between Slices as Measured by G' and G" Values[1] for the Inner Slices of the Old and New Potato Crops at Two Mannitol Concentrations

Potato	Mannitol Concentration (% w/v)	C.V. of G' (%)	C.V. of G" (%)
Old	3	25.27	28.55
	7	24.95	24.85
New	3	22.84	18.41
	7	32.62	22.46

1 Values were averaged over the 3 axes and 3 frequency ranges measured.

higher in the outer slices than in the inner slices at both mannitol concentrations, for both apparent G' and G".

Statistical analysis revealed that there were a number of interactions at the 0.05 level between mannitol concentration and the other 2 main effects of axis and frequency. Subsequent statistical analysis was carried out by separating mannitol concentration from axis and frequency. It revealed that interactions between axis and frequency were not significant at the 0.05 level in most cases (see appendix 8.4 for significant interactions). Therefore, the effects of axis and frequency on the inner and outer slices for old and new crops were reported for separate mannitol concentrations (Table 14 to Table 21).

In regards to the effect of axis on the inner slices, the values of apparent G^* and G' were significantly higher in the x-axis than the y and z-axes at both mannitol concentrations (Tables 14 & 16). The values of apparent G" were significantly higher in the x-axis than in the other axes for both old and new crops at 7% mannitol. No apparent difference in apparent G^* and G' was observed between the y and z-axes for the new crops but the y-axis showed higher apparent G^* and G' values than the z-axis for the old crops at both mannitol concentrations. Under the same mannitol treatment (3% or 7%), the values of apparent G^*, G' and G", U_{st} and U_{dis} were much higher in the new crops than the old crops. The values of δ were approximately 2 times higher at 7% mannitol than at 3% for all axes and for both crops. In terms of energy, the x-axis showed significantly lower U_{st} and U_{dis} values than the other axes for both old and new crops at 3% mannitol concentration. However, the x-axis showed significantly higher U_{dis} values than the other axes at 7% mannitol concentration for both old and new crops.

TABLE 14. Effect of Axis on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops at 3% Mannitol Concentration[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	X	454.26[a]	452.47[a]	23.39	3.16[a]	7.73[a]	0.68[a]
	Y	332.56[b]	330.53[b]	28.93	5.23[b]	8.76[b]	1.25[b]
	Z	285.22[c]	283.85[b]	25.79	5.90[b]	9.31[c]	1.51[b]
New[2]	X	548.68[a]	546.98[a]	37.83[a]	4.41[a]	30.04[a]	3.79[a]
	Y	468.27[b]	466.40[b]	39.57[b]	5.31[b]	31.42[b]	4.68[b]
	Z	466.27[b]	475.69[b]	34.85[c]	4.68[c]	31.10[b]	4.13[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were over the 3 frequency ranges measured.

TABLE 15. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops at 3% Mannitol Concentration[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	0.02	334.27	331.48	38.07[a]	7.13[a]	8.48[a]	1.69[a]
	0.2	361.69	359.89	24.62[b]	4.37[b]	8.52[b]	1.05[b]
	2	376.48	375.83	17.76[b]	3.28[b]	8.79[c]	0.83[b]
New[2]	0.02	445.60[a]	442.18[a]	53.28[a]	7.39[a]	31.60	6.56[a]
	0.2	495.64[b]	502.33[b]	34.58[b]	4.30[b]	30.65	3.72[b]
	2	542.34[c]	541.72[b]	23.59[c]	2.72[c]	30.51	2.36[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 axes measured.

TABLE 16. Effect of Axis on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops at 7% Mannitol Concentration[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	X	38.60[a]	38.06[a]	5.37[a]	8.35	5.11[a]	1.14
	Y	24.30[b]	24.02[b]	3.66[b]	8.75	4.17[b]	1.00
	Z	30.39[c]	30.08[c]	4.18[b]	8.43	5.11[a]	1.13
New[2]	X	107.80[a]	106.86[a]	13.83[a]	7.92[a]	32.02[a]	6.77[a]
	Y	80.53[b]	79.74[b]	11.08[b]	8.36[a]	28.43[b]	6.38[b]
	Z	74.68[b]	73.90[b]	10.78[b]	9.04[b]	27.24[b]	6.52[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 frequency ranges used.

TABLE 17. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Inner Slices of the Old and New Potato Crops at 7% Mannitol Concentration[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	0.02	25.59[a]	25.03[a]	5.31[a]	12.16[a]	4.05[a]	1.35[a]
	0.2	31.63[b]	31.29[b]	4.05[b]	7.51[b]	4.83[b]	0.99[b]
	2	36.60[c]	36.32[c]	4.33[b]	6.83[b]	5.52[c]	1.03[b]
New[2]	0.02	74.47[a]	73.21[a]	13.76[a]	11.28[a]	26.66[a]	8.11[a]
	0.2	87.78[b]	87.08[b]	11.15[b]	7.75[b]	29.28[b]	6.09[b]
	2	99.77[c]	99.18[c]	10.88[b]	6.57[c]	31.74[c]	5.64[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 axes measured.

TABLE 18. Effect of Axis on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and New Potato Crops at 3% Mannitol Concentration[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	Y	393.10	391.65	30.28	4.64	8.36	1.07
	Z	402.00	400.65	28.82	4.65	8.79	1.15
New[2]	Y	583.79	581.67	41.55	4.57	29.09	3.79
	Z	545.65	543.77	42.36	4.66	29.54	4.03

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 fequency ranges measured.

TABLE 19. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and New Potato Crops at 3% Mannitol Concentration[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} (10^{-3}Jm^{-3})	U_{dis} (10^{-3}Jm^{-3})
Old[2]	0.02	377.40	374.30	46.59[a]	7.25[a]	8.58	1.71[a]
	0.2	402.40	401.45	25.65[b]	3.99[b]	8.45	0.95[b]
	2	408.00	407.40	20.31[c]	3.34[b]	8.81	0.84[b]
New[2]	0.02	502.07	498.00	63.01[a]	7.62[a]	30.31	6.51[a]
	0.2	572.60	571.20	37.22[b]	4.04[b]	29.05	3.33[b]
	2	623.09	622.36	25.99[c]	2.09[c]	28.69	1.96[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the y and z-axes.

TABLE 20. Effect of Axis on Complex Modulus (G*), Storage Modulus
(G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st})
and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and
New Potato Crops at 7% Mannitol Concentration[1]

Potato	Axis	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	Y	43.47	43.06	5.74	8.01	5.77	1.23
	Z	46.85	46.44	6.22	8.31	6.30	1.35
New[2]	Y	126.43	125.30	17.01	8.23	33.15	7.34
	Z	127.18	126.05	16.37	7.85	33.05	7.09

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 3 frequency ranges measured.

TABLE 21. Effect of Frequency on Complex Modulus (G*), Storage Modulus (G'), Loss Modulus (G"), Phase Angle (δ), Energy Stored (U_{st}) and Energy Dissipated (U_{dis}) for the Outer Slices of the Old and New Potato Crops at 7% Mannitol Concentration[1]

Potato	Frequency (Hz)	G* (kPa)	G' (kPa)	G" (kPa)	δ (°)	U_{st} ($10^{-3}Jm^{-3}$)	U_{dis} ($10^{-3}Jm^{-3}$)
Old[2]	0.02	38.54	37.87	7.26	11.25[a]	5.24	1.60[a]
	0.2	45.35	45.04	5.44	7.24[b]	6.03	1.16[b]
	2	51.39	51.06	5.78	6.90[b]	6.83	1.24[b]
New[2]	0.02	106.26[a]	104.49[a]	18.94	10.68[a]	31.28[a]	9.15[a]
	0.2	127.87[b]	126.90[b]	15.90	7.36[b]	33.25[b]	6.69[b]
	2	150.59[c]	149.91[c]	15.55	6.20[c]	35.03[c]	5.91[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the y and z-axes.

In regards to the effect of frequency on the inner slices, an increase in frequency had a more pronounced effect on the measured parameters for the old crops at 7% than at 3% mannitol concentration (Table 15 & 17). In general, an increase in oscillation frequency was directly related to increase in apparent $G*$ and G', and U_{st} but inversely related to apparent G'', δ and U_{dis} at both mannitol concentrations. It was noted that the incremental increases in frequency from 0.02 Hz to 2 Hz resulted in significantly higher apparent $G*$ and G' values for both the old and new crops at 7% mannitol concentration. This phenomenon was not observed in potato tubers with no mannitol treatment (section 4.3).

In examining the effect of axis on the outer slices, y and z-axes were not different from each other at both mannitol concentrations (Table 18 & 20).

In regards to the effects of frequency on the outer slices, a more pronounced effect was observed in the new crops at 7% mannitol concentration as compared to 3%; at 7% mannitol the increase in apparent $G*$ and G' became significant as frequency increased from 0.02 to 2 Hz (Table 19 & 21). Like the inner slices, oscillation frequency was directly related to apparent $G*$ and $G,'$ and U_{st} but inversely related to apparent G'', δ and U_{dis} at both mannitol concentrations.

In comparing the inner and outer slices, statistical analysis revealed that significant interactions existed between mannitol concentration and axis, frequency and slice position at the 0.05 level. As a result, mannitol concentration was separated in subsequent statistical analyses. It was then observed that interactions between axis, frequency and slice location were not significant at the 0.05 level for a majority of the

cases (see appendix 8.5 for significant interactions). Therefore, the effect of slice location was reported for individual mannitol concentrations (Table 22). It was observed in Table 22 that the apparent G' and G" values were significantly higher in the outer slices than in the inner slices at both mannitol concentrations.

Generally speaking, under the same mannitol treatment the values of the parameters were far higher for the new crops than for the old crops for both inner and outer slices.

4.5 Uniaxial Compression Results - Old and New Crops without Mannitol Treatment

The overall c.v. between replicates as determined by E_{in} and U_{tot} measurements for the old and new crops are shown in Table 23 (see appendix 8.6 for the original c.v. at individual strain rates and cycles). Since only 2 cylindrical samples were obtained from each tuber and each sample was subjected to different strain rates, a comparison between cylinders within replicates was not possible.

Table 23 indicated that the x-axis showed the greatest variation, followed by the y-axis and the z-axis, as measured by E_{in}. In terms of U_{tot}, the x-axis showed the largest variation in the old crops but the least in the new crops. Overall, the c.v. values were lower in the new crops than in the old crops.

Statistical analysis revealed no 3-way interaction between axis, strain rate and cycle, and the majority of the 2-way interactions were insignificant at the 0.05 level (see appendix 8.7 for the significant interactions). The main effects of axis, strain rate and

TABLE 22. Effect of Slice Location on Storage Modulus (G') and Loss Modulus (G") of the Old and New Potato Crops at 3% and 7% Mannitol Concentration[1]

Potato	Mannitol Concentration (% w/v)	G' (kPa)		G" (kPa)	
		Inner	Outer	Inner	Outer
Old[2]	3	307.19[a]	396.15[b]	27.36[a]	34.66[b]
New[2]	3	471.23[a]	561.96[b]	37.11[a]	41.97[b]
Old[2]	7	27.05[a]	44.75[b]	3.92[a]	5.98[b]
New[2]	7	76.70[a]	125.69[b]	10.93[a]	16.67[b]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the y and z-axes.

TABLE 23. Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) and Total Energy (U_{tot}) Values[1] for the Old and New Potato Crops

Potato	Axis	C.V. of E_{in} (%)	C.V. of U_{tot} (%)
Old Crops	X	43.86	46.28
	Y	34.36	31.91
	Z	24.77	27.81
New Crops	X	25.93	8.31
	Y	24.26	15.00
	Z	15.52	10.39

1 Values were averaged over the 2 strain rates and 3 Cycles measured.

TABLE 24. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the Old Potato Crops[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} ($10^3 Jm^{-3}$)	U_{dis} ($10^3 Jm^{-3}$)	U_{rec} ($10^3 Jm^{-3}$)
Axis[2]					
X	0.42[a]	3.05[a]	2.92[a]	1.19[a]	1.73[a]
Y	0.57[b]	4.04[b]	4.05[b]	1.60[b]	2.45[b]
Z	0.53[b]	3.55[c]	3.40[c]	1.33[a]	2.07[c]
Strain Rate[3]					
2	0.44[a]	3.76[a]	3.27[a]	1.38	1.90[a]
20	0.58[b]	3.35[b]	3.67[b]	1.38	2.29[b]
Cycle[4]					
1	0.36[a]	2.84[a]	4.72[a]	2.57[a]	2.15
2	0.57[b]	3.85[b]	2.93[b]	0.86[b]	2.08
3	0.60[b]	3.98[b]	2.76[b]	0.71[b]	2.05

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

TABLE 25. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the New Potato Crops[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} ($10^3 Jm^{-3}$)	U_{dis} ($10^3 Jm^{-3}$)	U_{rec} ($10^3 Jm^{-3}$)
Axis[2]					
X	2.56[a]	5.92[a]	12.66[a]	5.50[a]	7.16[a]
Y	2.83[b]	6.30[b]	13.84[b]	5.93[b]	7.91[b]
Z	2.50[a]	5.83[a]	12.55[a]	5.14[a]	7.41[a]
Strain Rate[3]					
2	2.58	6.17[a]	12.62[a]	5.56	7.06[a]
20	2.68	5.88[b]	13.44[b]	5.50	7.94[b]
Cycle[4]					
1	3.76[a]	2.83[a]	20.77[a]	12.93[a]	7.83[a]
2	2.07[b]	7.48[b]	9.53[b]	2.09[b]	7.44[b]
3	2.07[b]	7.76[c]	8.79[c]	1.57[c]	7.22[b]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

cycle on the measured parameters for old and new crops are shown in Table 24 and Table 25, respectively.

In regards to the effect of axis, y-axis showed significantly higher values for both the elastic modulus and energy terms than the x and z-axes for old and new crops. In the old crops, x-axis showed the lowest values for both the elastic modulus and energy terms but the values were not significantly different from those of the z-axis in the new crops. The ratio of U_{dis}/U_{tot} for the x, y and z-axes in the old crops were slightly less than that in the new crops, though the magnitude of the energy terms were far greater in the new crops.

In regards to the effects of strain rate, the higher strain rate generally resulted in significantly higher values for both the elastic modulus and the energy terms for both the old and new crops except for U_{dis}. Higher strain rate also resulted in lower U_{dis}/U_{tot} and thus higher U_{rec}/U_{tot} ratios. For the new crops E_{in} was not affected by strain rate.

In considering the cycles in both the old and new crops, cycle 1 was significantly different from cycles 2 and 3 as assessed by the elastic modulus and energy terms (except U_{rec} in the old crops). Cycles 2 and 3 were not significantly different from each other in the old crops but they were significantly different from each other in the new crops in terms of E_{end}, U_{tot} and U_{dis}. The ratio of U_{dis}/U_{tot} was highest for cycle 1, followed by cycle 2, and the lowest for cycle 3 for both old and new crops. Shown in Figures 10 and 11 are representative curves for the old and new crops under 3 cyclic compressions. Since the shape of the compression curves at two deformation rates (2 and 20 cm min^{-1}) were very similar, only the deformation rate of 2 cm min^{-1} was chosen for presentation.

Figure 10. Representative Curves for the Old Crops under Uniaxial Compression Test (Strain Rate at 2 cm min^{-1}); a. First Cycle; b. Second Cycle; c. Third Cycle

Deformation (mm)
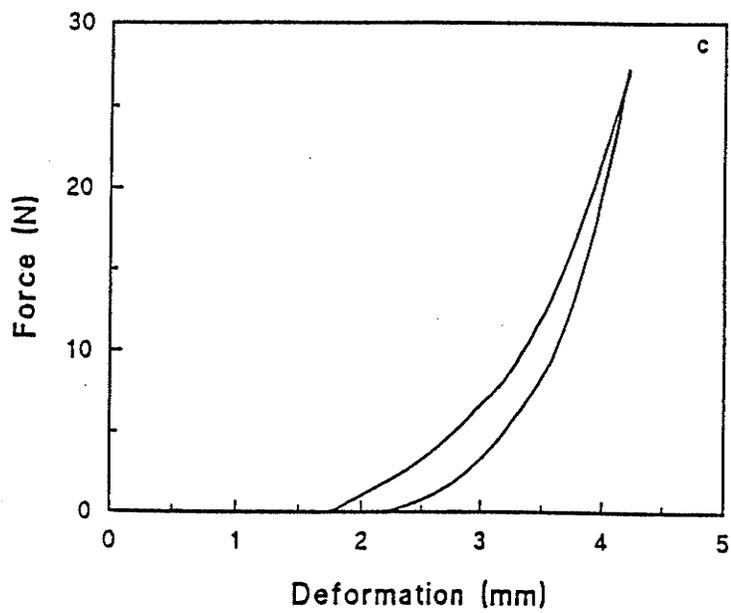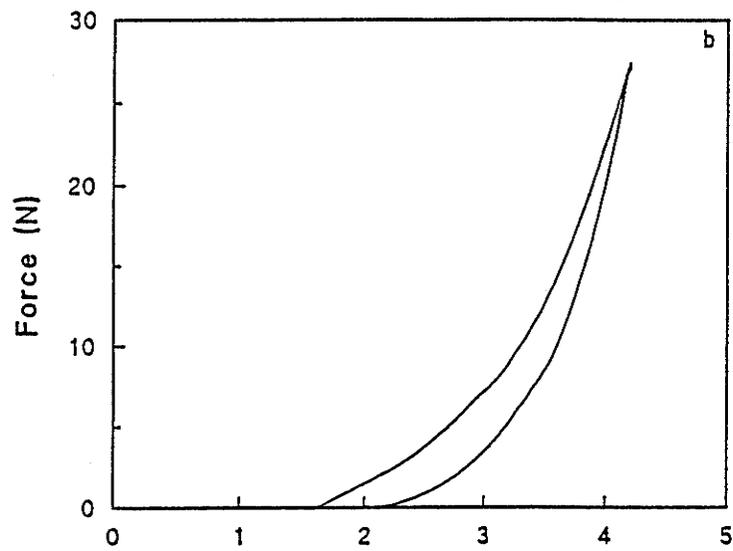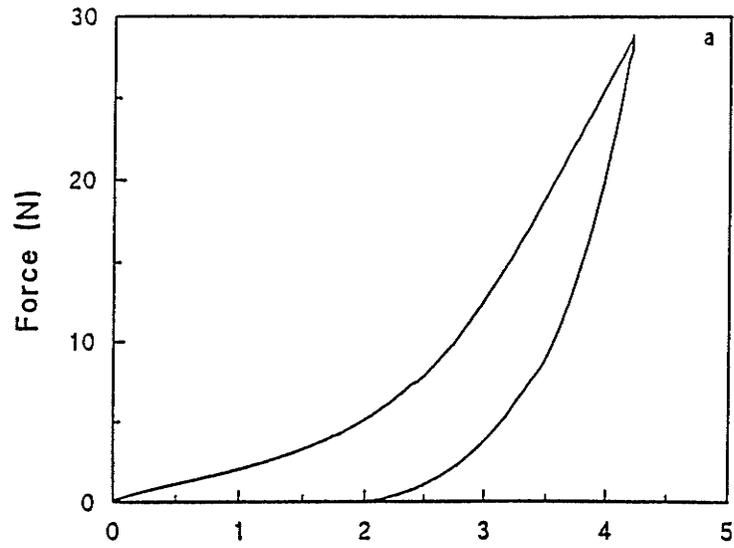
Figure 11.   Representative Curves for the New Crops under Uniaxial
Compression Test (Strain Rate at 2 cm min^{-1}); a. First
Cycle; b. Second Cycle; c. Third Cycle
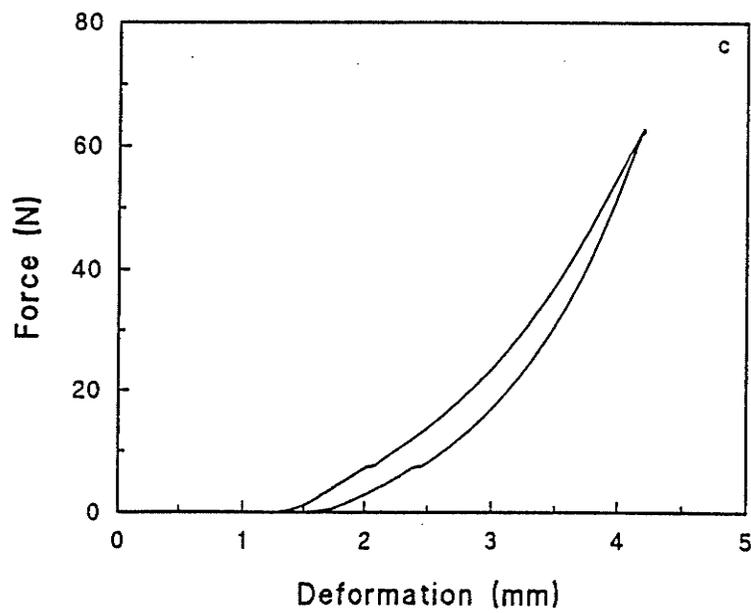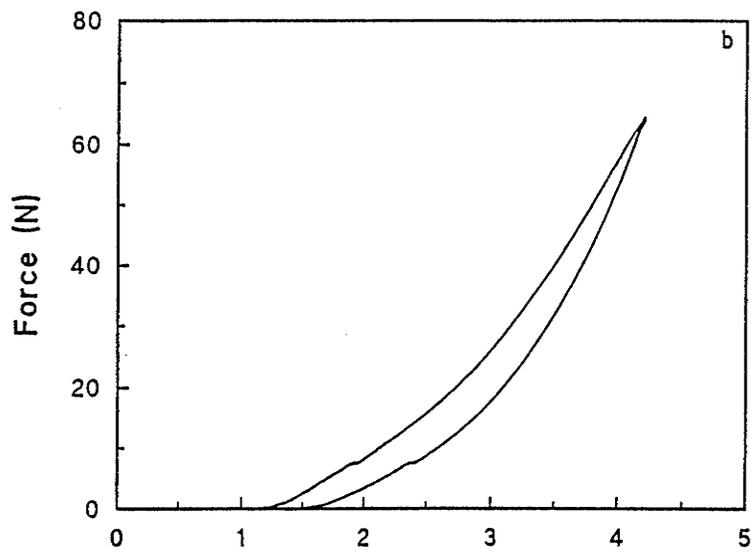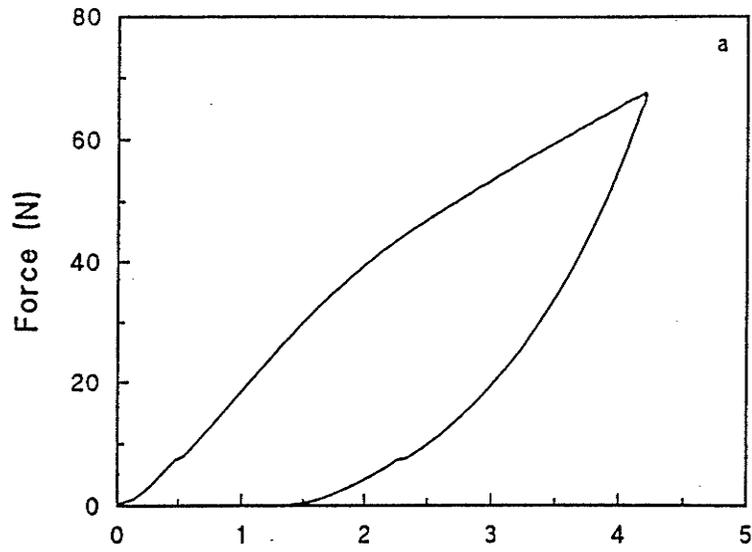
It can be seen from Figures 10a and 11a that the shape of the curve for the first cycle and the magnitude of deformation force attained at the pre-set final strain (10.5%) were different between old and new crops. Despite the difference in the magnitude of compression force, the shape of cycles 2 and 3 of the old crops were very similar to those of the new crops (Figure 10b,c & 11b,c).

4.6 Uniaxial Compression Results - Old and New Crops with 3 and 7% Mannitol Treatments

The c.v. for E_{in} and U_{tot} between replicates for the old and new crops at 2 mannitol concentrations are shown in Table 26 (see appendix 8.8 for the original c.v. at individual strain rates and cycles). Overall the c.v. values were lower at 3% than at 7% mannitol concentration. The c.v. values were also lower for the new crops than for the old crops.

Statistical analysis revealed that there were a number of interactions between mannitol concentration and axis, strain rate and cycle at the 0.05 level. As a result, mannitol concentration was separated in subsequent statistical analyses which revealed that interactions between axis, strain rate and cycle were not significant at the 0.05 level in most cases (see appendix 8.9 for significant interactions). Therefore, the main effects of axis, strain rate and cycle on the measured parameters for the old and new crops were reported at individual mannitol concentrations (Table 27 to Table 30).

In regards to the effect of axis on both the elastic modulus and energy terms at 3% mannitol concentration, the order was y-axis, followed by the x-axis and the z-axis

TABLE 26. Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) and Total Energy (U_{tot}) Values[1] for the Old and New Potato Crops at Two Mannitol Concentrations

Potato	Mannitol Concentration	C.V. of E_{in}	C.V. of U_{tot}
	(% w/v)	(%)	(%)
Old	3	23.55	16.91
	7	38.80	32.95
New	3	14.32	9.18
	7	19.48	23.37

1 Values were averaged over the 3 axes, 2 strain rates and 3 cycles measured.

TABLE 27. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the Old Potato Crops at 3% Mannitol Concentration[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} (10^3Jm^{-3})	U_{dis} (10^3Jm^{-3})	U_{rec} (10^3Jm^{-3})
Axis[2]					
X	1.29[a]	4.54[a]	8.36[a]	3.56[a]	4.80[a]
Y	1.43[b]	4.83[b]	9.01[b]	3.78[b]	5.23[b]
Z	1.13[c]	4.33[c]	7.75[c]	3.12[c]	4.64[c]
Strain Rate[3]					
2	1.18[a]	4.73[a]	8.05	3.54	4.50[a]
20	1.38[b]	4.41[b]	8.70	3.43	5.27[b]
Cycle[4]					
1	1.77[a]	2.47[a]	13.06[a]	8.00[a]	5.05
2	1.05[b]	5.51[b]	5.82[b]	1.39[b]	4.86
3	1.03[b]	5.72[b]	5.83[b]	1.07[b]	4.75

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

TABLE 28. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the New Potato Crops at 3% Mannitol Concentration[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} ($10^3 Jm^{-3}$)	U_{dis} ($10^3 Jm^{-3}$)	U_{rec} ($10^3 Jm^{-3}$)
Axis[2]					
X	3.44[a]	5.96[a]	13.76[a]	6.22[a]	7.54[a]
Y	3.64[a]	6.14[a]	14.21[a]	6.49[a]	7.72[a]
Z	2.98[b]	5.41[b]	12.49[b]	5.54[b]	6.95[b]
Strain Rate[3]					
2	3.06[a]	5.90	12.62[a]	5.99	6.63[a]
20	3.65[b]	5.77	14.35[b]	6.17	8.18[b]
Cycle[4]					
1	5.36[a]	2.36[a]	22.92[a]	15.19[a]	7.73[a]
2	2.40[b]	7.45[b]	9.14[b]	1.79[b]	7.35[b]
3	2.30[b]	7.69[b]	8.39[c]	1.27[c]	7.12[c]

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

TABLE 29. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the Old Potato Crops at 7% Mannitol Concentration[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} ($10^3 Jm^{-3}$)	U_{dis} ($10^3 Jm^{-3}$)	U_{rec} ($10^3 Jm^{-3}$)
Axis[2]					
X	0.09	0.53[a]	0.75	0.41	0.34
Y	0.09	0.72[b]	0.83	0.42	0.40
Z	0.10	0.57[a]	0.81	0.43	0.38
Strain Rate[3]					
2	0.09	0.63	0.67[a]	0.40	0.28[a]
20	0.10	0.59	0.92[b]	0.45	0.48[b]
Cycle[4]					
1	0.11	0.50[a]	1.03[a]	0.66[a]	0.38
2	0.09	0.64[b]	0.70[b]	0.32[b]	0.38
3	0.09	0.68[c]	0.66[b]	0.29[b]	0.37

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

TABLE 30. Effect of Axis, Strain Rate and Cycle on the Initial Elastic Modulus (E_{in}), End Elastic Modulus (E_{end}), Total Energy (U_{tot}), Energy Recovered (U_{rec}) and Energy Dissipated (U_{dis}) for the New Potato Crops at 7% Mannitol Concentration[1]

Main Effect	E_{in} (MPa)	E_{end} (MPa)	U_{tot} ($10^3 Jm^{-3}$)	U_{dis} ($10^3 Jm^{-3}$)	U_{rec} ($10^3 Jm^{-3}$)
Axis[2]					
X	0.63	4.09[a]	5.41	2.10	3.31
Y	0.68	4.17[b]	5.14	1.92	3.23
Z	0.69	3.84[c]	5.10	1.90	3.20
Strain Rate[3]					
2	0.61[a]	4.35[a]	5.01[a]	1.99	3.02[a]
20	0.72[b]	3.72[b]	5.43[b]	1.96	3.47[b]
Cycle[4]					
1	0.69	2.76[a]	7.56[a]	4.23[a]	3.33
2	0.65	4.61[b]	4.16[b]	0.92[b]	3.24
3	0.65	4.73[b]	3.94[b]	0.76[b]	3.18

1 Values followed by different letters are significantly different at 0.05 level.
2 Values were averaged over the 2 strain rates and 3 cycles measured.
3 Values were averaged over the 3 axes and 3 cycles measured.
4 Values were averaged over the 3 axes and 2 strain rates measured.

for the old crops (Table 27). The new crops (Table 28) followed the same pattern, but the x and y-axes were not significantly different from each other. The z-axis was significantly lower than the x and y-axes in both the elastic modulus and energy terms. The ratio of U_{dis}/U_{tot} in the x, y and z-axes for the old crops were slightly less than those of the new crops.

At 7% mannitol concentration, the x, y and z-axes were not significantly different from each other except for E_{end} (Table 29 and Table 30). However, the ratio of U_{dis}/U_{tot} at any particular axis were far lower in the new crops than in the old crops.

In general, higher strain rate resulted in higher E_{in} but lower E_{end} and U_{dis}/U_{tot} ratio for both the old and new crops at both mannitol concentrations. In terms of E_{in} cycle 1 was significantly different from cycles 2 and 3 at 3% mannitol (Table 27 & 28) but cycle 2 and 3 were not significantly different from each other at 3 and 7% mannitol (Table 29 & 30). The U_{dis}/U_{tot} ratio was highest in cycle 1, followed by cycle 2 and then cycle 3 for both the old and new crops at both mannitol concentrations. The representative compression curves for the old and new crops after 3 and 7% mannitol treatments are shown in Figures 12-15, respectively.

Generally speaking, under the same mannitol treatment the magnitude of the elastic modulus and energy terms were far higher in the new crops than the old crops.

Figure 12   Representative Curves for the Old Crops with 3% Mannitol Treatment under Uniaxial Compression Test (Strain Rate at 2 cm min^{-1}); a. First Cycle; b. Second Cycle; c. Third Cycle
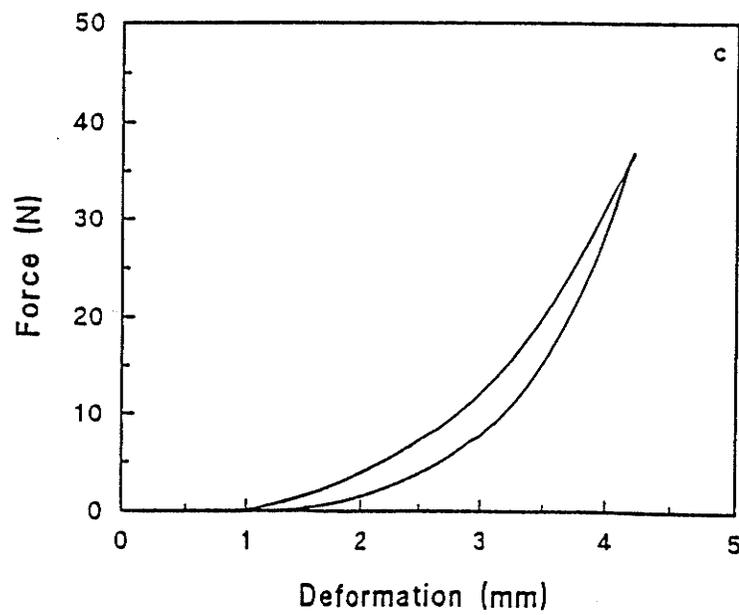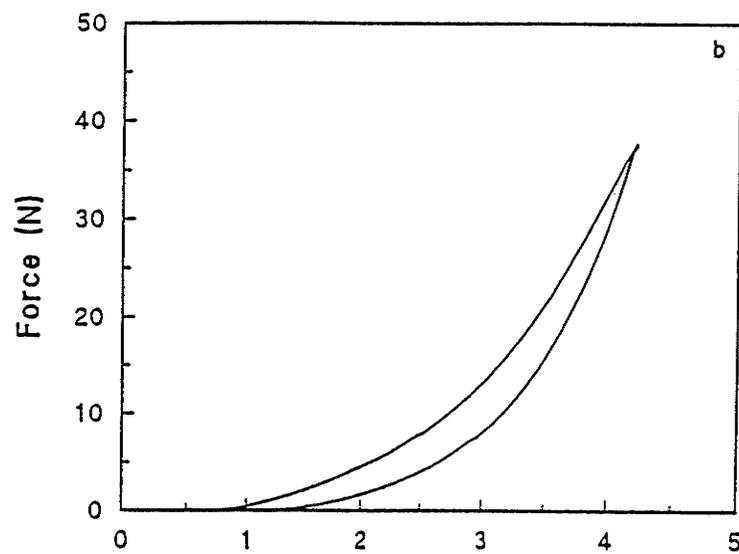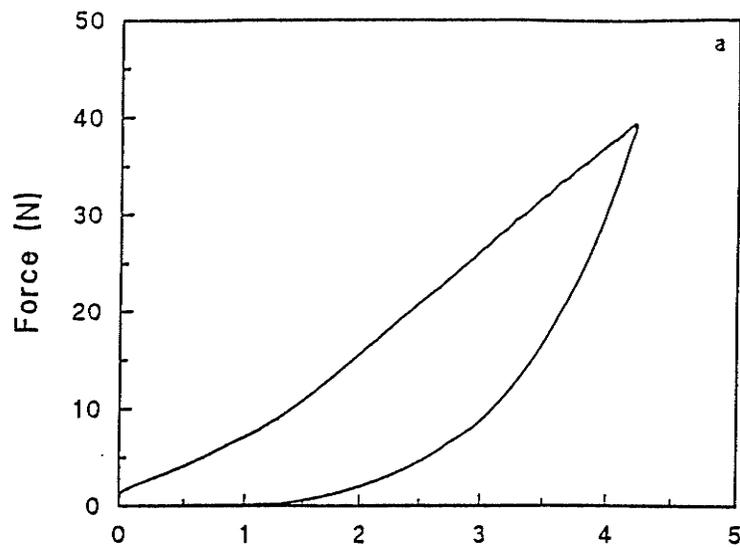
Figure 13   Representative Curves for the Old Crops with 7% Mannitol Treatment under Uniaxial Compression Test (Strain Rate at 2 cm min^{-1}); a. First Cycle; b. Second Cycle; c. Third Cycle
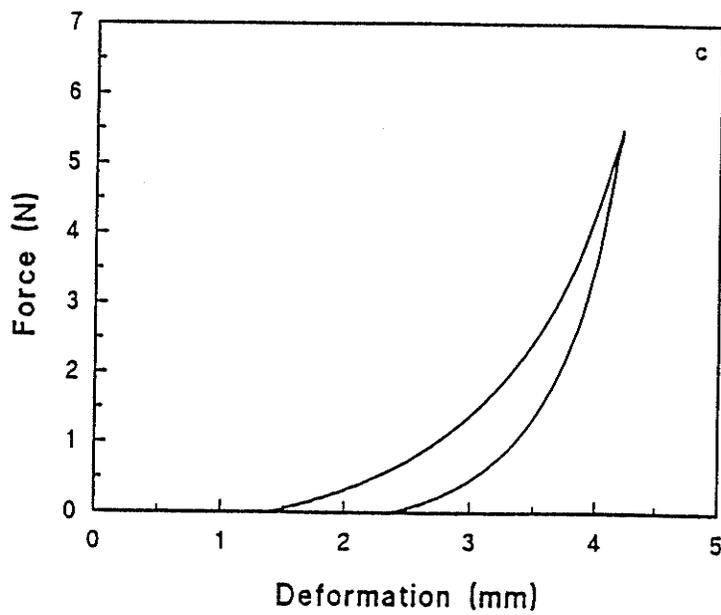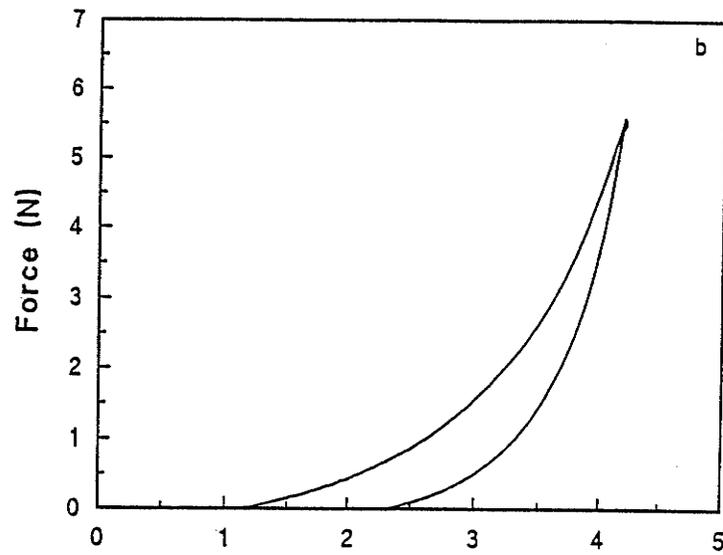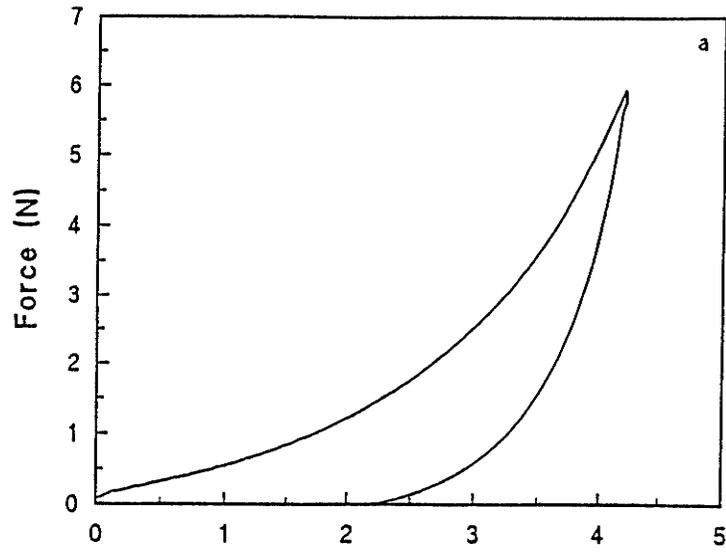
Figure 14.   Representative Curves for the New Crops with 3% Mannitol Treatment under Uniaxial Compression Test (Strain Rate at 2 cm min^{-1}); a. First Cycle; b. Second Cycle; c. Third Cycle

Deformation (mm)
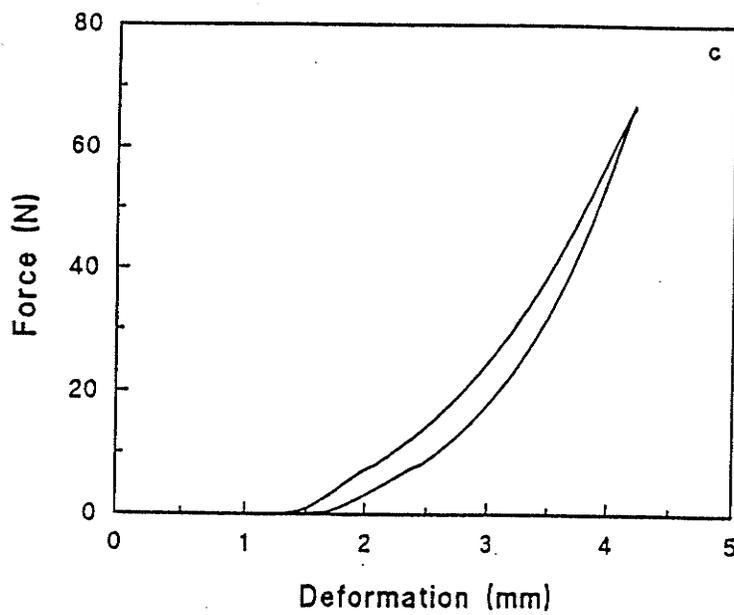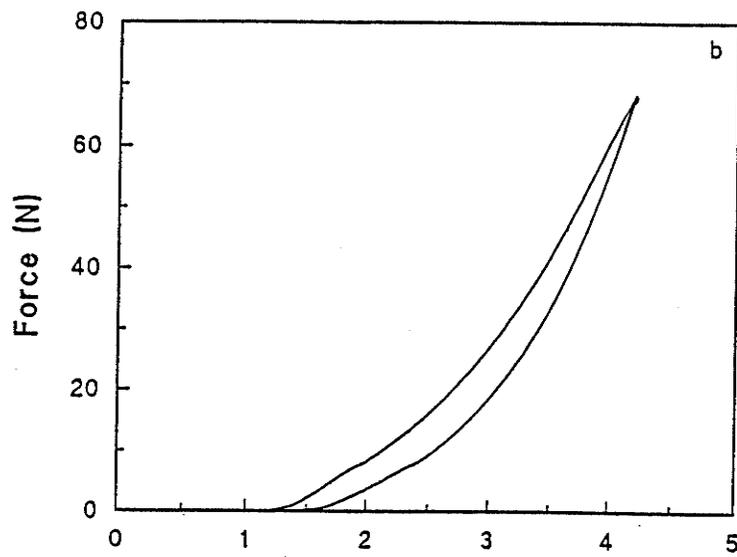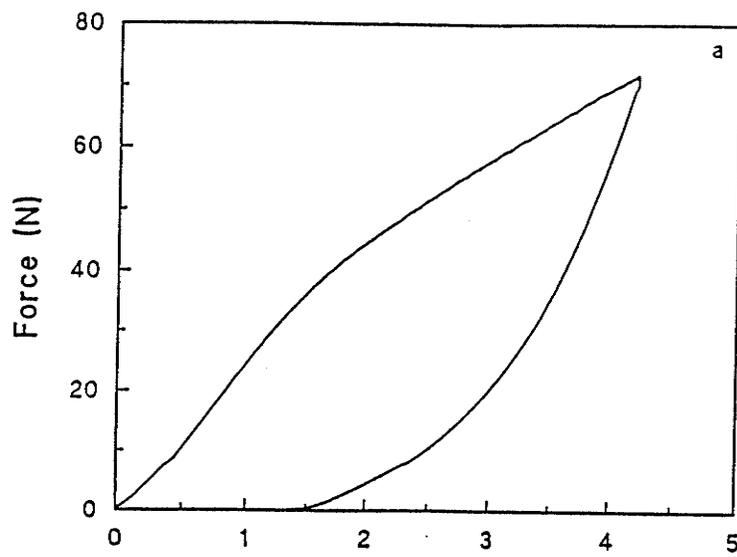
Figure 15. Representative Curves for the New Crops with 7% Mannitol Treatment under Uniaxial Compression Test (Strain Rate at 2 cm min^{-1}); a. First Cycle; b. Second Cycle; c. Third Cycle
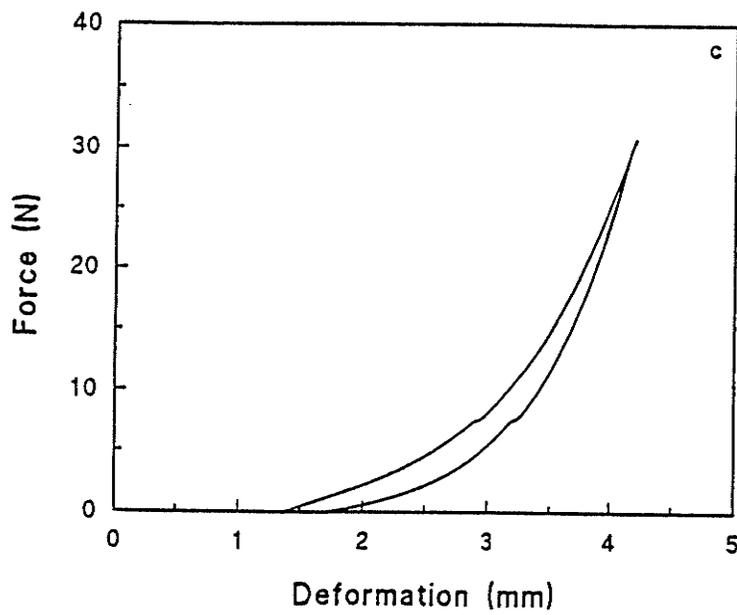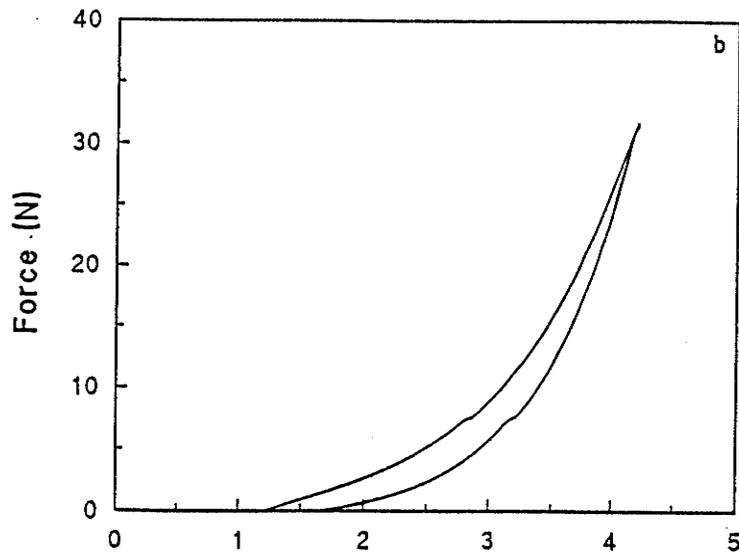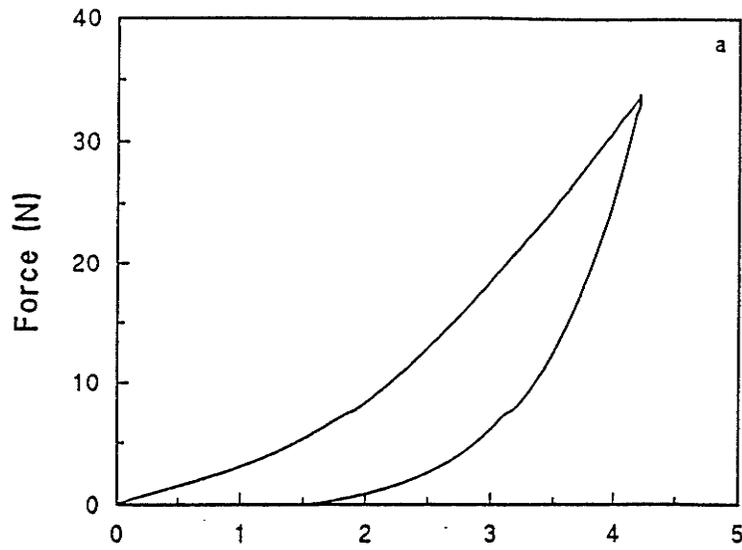
5. GENERAL DISCUSSION

5.1 Variability of Measurements

For the small strain oscillatory shear test, the coefficient of variation (c.v.) values were generally higher as measured by apparent G' than by apparent G". A possible explanation for this result is that the values of apparent G' were generally one order of magnitude higher than those of apparent G". The magnitude of the spreading of the apparent G' values was greater between sample measurements, and so higher standard deviations were observed, and thus contributed to higher c.v. values.

Examination of c.v. values between slices without mannitol treatment (Table 6) showed the x-axis to have the highest c.v. values, but not when the slices were subjected to mannitol treatment (Appendices 8.3.5 and 8.3.6). A possible explanation for this observation is that the inner slices of the x-axis were obtained along the pith which frequently radiates arms of medullary tissue outward along the longitudinal length of the pith (see Figures 2 & 3). The inner slices of the y and z-axes were obtained transversely to the pith. A change in the medullary arm pattern in the tubers would have more effect on the x-axis than on the y and z-axes at normal physiological turgor (without mannitol). The difference in measured parameters between two slices taken from the x-axis would be more pronounced than between two slices taken from either the y and z-axes.

However, under the mannitol treatments (3 and 7%), the moisture content of the inner slices obtained from the x, y and z-axes would more likely be approximately equal and the effect of tissue inhomogeneity would be diminished.

In contrast, for the uniaxial compression test higher c.v. values were found overall for the x-axis whether samples were not treated with mannitol (Table 23) or were treated with mannitol (Appendices 8.8). Since the cylindrical samples used in the compression test were 40 mm in length, they would be likely to include tissues from different histological regions along their length (see Figures 2, 3 & 6) (Burton, 1989; Reeve et al., 1973a; Smith, 1977). For the y-axis, the cylindrical samples would likely be composed of tissues from the pith (in the middle of the cylinder), the perimedullary zone (from both sides of the pith), and the vascular ring (on both ends of the cylinder). For the z-axis (the shortest axis of the tuber), the cylindrical samples would possibly comprise tissues from the pith, the perimedullary zone, the vascular ring (next to the perimedullary tissue on both sides of the cylinder), and the cortex (on both ends of the cylinder). For the x-axis (the longest axis), the cylindrical samples would likely comprise two tissues running longitudinally along the length of the cylinder; tissues from the pith on one side and perimedullary zone on the other side of the cylinder (see Figure 6). Therefore, samples from the y and z-axes were structurally more heterogeneous than x-axis samples and would have been expected to exhibit greater c.v. values. However, the results obtained discounted this consideration, and possible explanations for the higher c.v. observed for x-axis samples are: (1) the tissues from the perimedullary zone and the pith were oriented in a somewhat parallel fashion to each other along the length of the

cylinder in the x-axis samples, as opposed to tissues in the y and z-axes which were oriented in a sandwich fashion along the length of the cylinder, (2) x-axis samples would be affected more by differences in the degree to which arms of medullary tissue radiated along the pith, and (3) x-axis samples would be affected more by variation in the dry matter (starch) distribution, since it has been reported that the dry matter and cell size varied considerably from the stem end to the bud end (Reeve et al. 1973a,b).

In general, the c.v. values were higher at 7% than at 3% mannitol for both the small strain oscillatory shear and uniaxial compression tests (Tables 12 & 26). Overall, c.v. values were lower in the new crops than in the old crops for both the small strain oscillatory shear and the uniaxial compression tests. The higher c.v. observed for the old crops might be due to the imperfection of the samples after slicing (e.g. uneven thickness on the sides and loosening of the cells) and biological changes during storage which could change the cellular structure of the tubers (Aquilera and Stanley, 1990; Davis, 1962; Reeve, 1967; Van Buren, 1979). It was observed that the old crops became quite flaccid after eight months storage. In the same way that c.v. values were lowered by greater turgor at 3% mannitol compared to dehydration at 7% mannitol, changes in water relations in the tubers during eight months storage may account for the lower c.v. for the new crops.

5.2 Effect of Axis on Mechanical Properties

In the uniaxial compression test, y-axis samples were generally observed to be significantly stiffer than the other 2 axes. This was observed for both old and new crops

without mannitol (Tables 24 & 25), and at 3% mannitol treatment (Tables 27 & 28), but differences were not significantly different at 7% mannitol treatment (Table 29 & 30). Steudle et al. (1977) studied the volumetric elastic modulus, ϵ, of plant cells from a higher plant and giant algae. It was observed that ϵ was strongly dependent upon the size (volume) and turgor pressure of the cells; ϵ increased with cell volume at a given turgor pressure and the volume dependence was pronounced more at higher turgor pressures. The size of potato parenchyma cells varies; Reeve et al. (1973a) and Fedec et al. (1977) reported that the largest parenchyma cells were primarily located in the perimedullary zone, whereas the smallest cells were located primarily in the cortex. The size of the cells in the pith was intermediate. As discussed in section 5.1 the cylindrical samples obtained from the y-axis comprised mainly of perimedullary tissue, as compared to those of the x and y-axes which contained proportionally less perimedullary tissues. Therefore, at normal physiological turgor (without mannitol) and high turgor (with 3% mannitol), the y-axis samples would contain a larger amount of the larger cells and would likely exhibit a stronger stress-strain response. At the reduced turgor caused by plasmolysis (7% mannitol), it was likely that cell sizes would have been reduced and the effect of turgor pressure would be ameliorated, resulting in stress-strain responses that were indistinguishable among the axes.

In comparing the change in values of E_{in} and U_{tot} that occurred when the old crops were subjected to 3% mannitol treatment (Table 24 versus Table 27), it was noted that the relative changes were higher in the x-axis ($\approx$ 3 fold for the x-axis, versus $\approx$ 2.5 to 2 fold for the y and z-axes), This indicates that the x-axis cylinders were more sensitive

to 3% mannitol treatment. Since the x-axis cylindrical samples were composed of a larger portion of pith tissue than the y and z-axes, it is likely that the amount of water uptake at 3% mannitol was not equal for samples for different axes. The intermediate sized cells of the pith may have been influenced more by turgor changes.

In comparison to the old crops, the relative increase in the E_{in} and U_{tot} values were much less in the new crops (for any axis) when subjected to 3% mannitol treatment (Table 25 versus Table 28); the values of E_{in} and U_{tot} increased by only 30% and 3% on average, respectively. A similar trend was also observed between the old and new crops when subjected to 7% mannitol treatment (Table 24 & 25, versus Table 29 & 30); for any axis the relative reduction in the E_{in} and U_{tot} values after 7 % mannitol treatment were higher for the old crops than for the new crops. All of these observations suggested that under identical mannitol incubations (3 or 7%) the old crops were more permeable to water (uptake and withdrawal) than the new crops. In view of the work by Turnbull and Cobb (1992), in which structural disruption was found to take place in the cellular membrane and tonoplast of potato tuber cells after prolonged storage, and by Harker and Hallett (1994), in which cells from ripe kiwifruit were observed to withstand higher hypotonic stress than the cells from unripe kiwifruit during hypotonic mannitol incubation, it is likely that the parenchyma cell wall of the old crops underwent structural changes which resulted in a higher permeability to water. Further work would be necessary to verify this point.

In regards to energy recovery during compression, the highest overall U_{rec}/U_{tot} ratio was found for z-axis samples, followed by the y-axis and the lowest in the x-axis

(Tables 24, 25 & 27-30). It was likely that compositional differences accounted for the differences observed in the U_{dis}/U_{tot} ratios among the axes. The z-axis cylindrical samples are composed of the largest portion of xylem and phloem (as compared to the y and x-axis samples which are composed of mainly parenchyma cells with higher moisture contents). Since these conducting tissues are primarily cellulosic and thus, elastic in nature (Frey-Wyssling, 1952), greater recovery of strain energy would be expected in the z-axis samples.

For the small strain oscillatory shear tests, the x-axis was observed to be significantly stiffer than the other 2 axes in all cases except in the old crops without mannitol treatment (Table 7), and in this case the stiffness was greater than that of the other axes. In general, the y and z-axis samples were not significantly different from each other. The result obtained was contradictory to that obtained from the uniaxial compression test in which the y-axis was stiffer than the x and z-axes. For small strain oscillatory tests, the 4 inner slices were taken from the centre region of the tubers. The total thickness of the slices was approximately 16 mm. It was therefore unlikely that the slices from any axis contained tissues other than those from the pith and perimedullary zone. It was also unlikely that the size of the cells would vary among the slices as much as among the cylindrical samples used in uniaxial compression. For the x-axis, the inner slices were obtained along the pith. Therefore, they would likely be composed of the pith tissue located at the centre of the slices, with perimedullary tissue and possibly radiating arms of medullary tissue surrounding the pith tissue (see Figures 2 and 5). For the y and z-axes, slice numbers 5 and 6 would likely have similar cellular orientation to slices of

the x-axis, but slice numbers 4 and 7 would likely be composed of perimedullary tissue only (see Figures 3 and 5). It also can be seen in Figure 2 and 3 that numerous internal phloem tissues are scattered throughout the perimedullary zone. A more oriented pattern of internal phloem can be seen in Figure 2, particularly in the centre region of the tuber in which the internal phloem seemed to be oriented radially around the pith. This pattern of orientation was absent in Figure 3 and the internal phloem appeared to be randomly oriented. It is not known if these structural differences would have accounted for greater stiffness values for samples taken from the x-axis. Information available in the literature has presumed that potato parenchyma cells are isotropic in nature (Falk et al., 1958; Khan and Vincent, 1993), but information on the relationship between the cellular orientation of parenchyma cells and other conducting tissues (particularly in the pith region of potato tuber) and their mechanical properties has been scarce. The importance of cellular orientation in the mechanical properties of plant tissues has been emphasized by Ashby (1983). It is possible that the parenchyma cells and internal phloems found in the pith region of potato tuber are packed in a more symmetric and organized pattern along the longitudinal axis of the tuber than the transverse axes, contributing to a greater stress-strain response. Further work would be necessary to verify this hypothesis.

5.3 Mechanical Properties of Inner and Outer Slices

In comparing the inner and outer slices under small strain oscillatory testing, the old crops without mannitol treatment were not observed to be significantly different (Table 11). However, the outer slices were significantly stiffer than the inner slices after

both 3 and 7% mannitol treatments (Table 22). For the new crops the inner slices were significantly stiffer than the outer slices, but the reverse was true after 3 and 7% mannitol treatments (as for the old crops) (Tables 11 & 22). Differences in the mechanical properties between these two locations within the tuber have been reported recently. Huff (1967) reported that potato tissue obtained from the pith required higher tensile force at failure than tissues from the skin and perimedullary zone. In contrast, Anzaldúa-Morales et al. (1992) reported that tissue from the cortex required higher puncture force than the pith tissue in a puncture test.

It is noted that the inner and outer slices responded differently to mannitol treatments. For the old crops, the G' values of the inner slices decreased after the 3% mannitol treatment (Tables 7 & 14), whereas the G' values of the outer slices increased after the 3% mannitol treatment (Tables 8 & 18). After 7% mannitol treatment, the G' values of the inner slices decreased by more than 10 fold (Tables 7 & 16), whereas the G' values of the outer slices decreased by less than 8 fold (Tables 8 & 20). A similar trend was apparent for the new crops at both 3 and 7% mannitol treatments. It is known that the inner slices had over 7% more moisture than the outer slices on average (Table 4) and the structural composition, e.g. cell sizes, starch content and pectic substances concentration (Hoff and Castro, 1969; Reeve et al, 1973a,b) varied considerably between the inner and outer slices. It is also noted that the x-axis cylindrical samples behaved differently from samples from the y and z-axes in the uniaxial compression test when subjected to mannitol treatments (see section 5.2). Since the inner slices would have been expected to exhibit a greater stress-strain response because of larger cell sizes and

higher moisture content, as was observed in the new crops without mannitol treatment, it is therefore likely that the difference observed between the inner and outer slices after the mannitol treatments was caused by different responses of the outer and inner tissues to artificial turgor adjustment. Further work would be needed to investigate the effect of mannitol on potato tissues if it is to be used to induce artificial turgor in potato tissues.

5.4 Effect of Strain Rate and Frequency on Mechanical Properties

An increase in strain rate from 2 to 20 cm min^{-1} generally increased the values of E_{in}, U_{tot} and U_{rec}, but decreased those of E_{end}. E_{dis} did not appear to be affected by strain rate. Murase et al. (1980) reported that the Young's modulus of potato tissues at five different water potential levels increased as deformation rate increased from 2.1 x 10^{-3} to 4.2 x 10^{-3} m s^{-1}. In contrast, Jindal (1986) reported that the Young's modulus of potato tissue (as calculated at 3% compression) decreased as deformation rate increased from 50 to 100, 100 to 200, and 200 to 500 mm min^{-1}. The E_{in} value for the new crops was 3.76 MPa (Table 25, first cycle) which is higher than those reported by Jindal (1986) and Pitt (1984) but is in agreement with that reported by Lin and Pitt (1986), the values obtained were 2.93, 2.30 and 3.70 MPa, respectively. The difference between our value and those from Jindal (1986) and Pitt (1984) might be due to different experimental settings and potato storage time. For instance, the elastic modulus reported by Jindal (1986) was calculated at 3% compression, as compared to 1% used in our calculation. Pitt (1984) subjected cylindrical potato tissues to a pre-set final stress level of 1.4 MPa in compression, as compared to a pre-set final strain of 10.5% used in our

compression tests.

The increase in U_{tot} with increase in strain rate might be due to time differences in the loading process between different strain rates. At the lower strain rate (2 cm min^{-1}) more time was available for the potato tissue to dissipate the energy (Finney et al., 1964), while at higher strain rate (20 cm min^{-1}) greater internal pressure could build up in the tissues and give rise to higher U_{tot} values. Peleg and Calzada (1976) subjected potato tissues to stress relaxation and they observed that higher stress was obtained using a loading deformation rate of 10 cm min^{-1} compared to 1 cm min^{-1} at the end of 20% compression. In regards to the increase in U_{rec} with strain rate, the time of measurement at higher strain rate during the unloading cycle was shorter than at lower strain rate (1.2 s versus 12 s). At the lower strain rate, 10 times more time was available for the potato tissues to dissipate the energy than at higher strain rate. The energy which would otherwise be dissipated in the relaxation process at lower strain rate was being registered in the faster unloading cycle, resulting in a higher U_{rec} value.

The values of E_{end} in this experiment was determined at approximately 9% strain. Qiong et al. (1989) reported that lower stress-strain slope (modulus) was observed in potato tissue beyond 8% strain (induced by hypo/hypertonic mannitol treatments) and the author suggested that pectin matrix disruption was responsible for the fall in slope. Peleg and Calzada (1976) observed that the values of residual force within potato tissues deformed at a rate of 10 cm min^{-1} was smaller than the values of those deformed at 1 cm min^{-1} during 7 min stress relaxation measurement, implying that greater physical irreversible changes occurred at higher strain rate during the compression. In view of

the work above, it is likely that a higher strain rate would cause a greater disruption of the pectic matrix in the cell wall and/or middle lamella, resulting in the lower E_{end} values observed.

An increase in frequency from 0.02 to 2 Hz in the small strain oscillatory test generally increased the values of apparent G^*, G' and E_{st}, but decreased those of apparent G'', δ and E_{dis} for both inner and outer slices. Like the effect of strain rate in uniaxial compression, an increase in frequency reduced the time for the potato tissue to relax and the time of measurement in each cycle of oscillation, resulting in higher values in apparent G' and E_{st}, but lower values in apparent G'' and E_{dis}. Peterson and Hall (1974) reported that for potato tissue the complex dynamic modulus (E^*) and phase angle were linearly related to frequency from 50-300 Hz. Ramana and Taylor (1992a) reported that for potato tissue the apparent G' value was not altered between the two frequencies 0.2 and 0.03 Hz. For both inner and outer slices, the values of δ were lower for the new crops and the old and new crops at 3% mannitol treatment than the old crops and old and new crops at 7% mannitol, indicating that the new crops and crops after 3% mannitol treatment were more elastic than the old crops and crops after 7% mannitol treatment.

5.5. Effect of Cycling on Mechanical Properties

For the loading/unloading cycles performed in uniaxial compression, cycle 1 was significantly different from subsequent cycles in terms of the shape of the curves, the modulus and energy. For cycle 1, more energy was needed for the compression process than subsequent cycles and more than half of the input energy was dissipated during the

compression process (as indicated by the U_{dis}/U_{tot} ratios). In this respect the new crops and the new and old crops with 3% mannitol treatment required more deformation energy than the 7% mannitol treatments and the old crops. However, the ratio of U_{dis}/U_{tot} was comparable among them (60 ± 6%). In terms of E_{in}, cycle 1 generally showed higher values than subsequent cycles (though the values were not significantly different for the old crops without mannitol, and the old and new crops with 7% mannitol). For E_{end}, cycle 1 consistently showed significantly lower values than the subsequent cycles. Cycle 2 and 3 were not significantly different from each other except that the U_{dis}/U_{tot} ratio was lower in cycle 3. The value of E_{in} from the new crops after 3% mannitol treatment was comparable to the tensile modulus reported by Niklas (1988). In his work, the author subjected cylindrical potato tissues to various hypo- and hypertonic mannitol concentration solutions. The tensile modulus of hypotonically treated samples at -0.4 MPa water potential was reported to be between 4.58 and 5.23 MPa (as compared to 5.36 MPa in our work; Table 28, first cycle), whereas the tensile modulus of hypertonically treated samples at -0.8 MPa water potential was reported to be about 2 MPa (as compared to 0.69 MPa in our work; Table 30, first cycle).

The shape of the first compression curve was different for the new and old crops, and between the mannitol treatments. In general, 2 kinds of shape could be distinguished: the first group encompassed the new crops without mannitol treatment and the new and old crops with 3% mannitol (Figures 11a, 12a & 14a); the second group encompassed the old crops without mannitol treatment and the new and old crops with 7% mannitol treatment (Figures 10a, 13a & 15a). The first compression cycle of the

first group generally had the following shape: a rather short, flat initial slope at the beginning of the compression, then the slope rose sharply in a convex upward fashion and flattened slightly towards the end of the compression. An irrecoverable deformation of about 1 mm ($\approx$ 25% of the original strain) was observed after unloading. For the second group the general shape was as follows: a rather long, flat slope at the beginning of the compression, then the slope rose gradually in a concave upward fashion to the end of the compression. The irrecoverable deformation was about 2 mm ($\approx$ 50% of the original strain) after unloading.

The effect of 3% mannitol treatment on the old and new crops can be seen by comparing Figures 10a and 11a with 12a and 14a, respectively. For the new crops, no major change was observed in the overall shape after the 3% treatment except that the "bump" on the uprising convex slope was more apparent than that without mannitol treatment. For the old crops, the shape of the curve changed drastically after the 3% mannitol treatment and the resulting shape resembled that of the new crops without mannitol treatment. The effect of 7% mannitol treatment on the old and new crops can be seen by comparing Figures 10a and 11a with 13a and 15a. For the new crops, the shape changed drastically after the 7% mannitol treatment and the resulting shape closely resembled that of the old crops without mannitol. The magnitude of the force reading at a given amount of deformation (10.5%) dropped to about half that of the new crops without mannitol treatment. For the old crops, no apparent change was observed in the overall shape of the curves except that the magnitude of force reading at a given deformation dropped to a much lower level. Similar shape of curves have been reported

by Lin and Pitt (1986). In their work, potato samples subjected to hypertonic mannitol treatments were observed to exhibit a long, flat initial slope at the beginning of uniaxial compression, then follow by a concave upward slope until failure occurred. The flat initial slope was observed to be extended longer with increasing mannitol concentration. For potato samples subjected to hypotonic mannitol treatment, the initial slope was short and sharp, followed by a slightly flattened, convex, upward slope until failure occurred. A "bump" was observed at the inflection point and it became more apparent as mannitol concentration decreased. Despite the effect of the mannitol treatment and the difference in the physiological maturity of the new and old crops, the shape of the curves for cycle 2 and 3 were very similar (Figures 10b,c to 15b,c).

Our results are comparable to those reported by Pitt (1984) where cylindrical potato samples were subjected to cyclic loading to a pre-set final stress level (1.4 MPa). The author observed a large hysteresis loss and unrecoverable deformation after the first loading cycle. He attributed this deformation to plastic flow in the intercellular bonds, loss of cell fluid from the cells and plastic flow in the cell wall. During subsequent loading cycles the author observed a small initial stress-strain slope and large upward curvature which he attributed to the continuous loss of cell turgidity caused by fluid extrusion and cell wall plasticity.

6. CONCLUSIONS AND RECOMMENDATIONS

The present study was undertaken to characterize the mechanical properties of living potato tissues under small strain oscillatory shear and to compare the results with those obtained from uniaxial compression tests. With the above objectives in mind, the experiments were designed: (1) to map out the mechanical properties of potato tissues obtained from different histological regions of the potato tuber; (2) to examine the effect of strain rate on the mechanical properties of potato tuber tissues; (3) to study the difference in mechanical properties of potato tissues for crops from two crop years; and (4) to study the mechanical properties of potato tissues subjected to artificial osmotic adjustments.

With respect to the mapping of mechanical properties of potato tissues, both small strain oscillatory shear and uniaxial compression testing suggested that potato tissue was not isotropic in nature. In small strain oscillatory shear testing potato tissues obtained from the pith region exhibited different stress-strain responses, depending on the direction from which the tissue was obtained. Tissues obtained along the pith were found to be significantly stiffer than those obtained transversely to the pith. The observed phenomenon is thought to be related to differences in moisture content and size of parenchyma cells and orientation of parenchyma cells and internal phloems in the pith region. In addition, tissues obtained from the pith were found to exhibit a different

stress-strain response from tissues obtained from the vascular ring/cortex region. However, the results were complicated by the mannitol treatments. At normal physiological turgor (no mannitol treatment), tissues obtained from the pith were stiffer than tissues obtained from the vascular ring/cortex region. At hypotonic and hypertonic conditions, the reverse was observed to be true. Under uniaxial compression tissues obtained transverse to the pith were stiffer than tissues obtained along the pith. The result was contradictory to that obtained by small strain oscillatory shear testing, but it could be explained by the way the samples were sectioned. For the small strain oscillatory shear test the stress-strain response of tissues were measured for the pith and perimedullary regions. In uniaxial compression a combination of tissues from the pith, perimedullary, vascular ring and cortex regions was being measured. Further research is needed to fully quantify the mechanical properties of potato tissues with respect to their structural combination and orientation.

In uniaxial compression an increase in strain rate from 2 to 20 cm min^{-1} generally increased the Young's modulus as calculated at 1% strain, as well as the energy input and recovery, but it decreased the Young's modulus as calculated at 9% strain. In small strain oscillatory shear testing an increase in frequency from 0.02 to 2 Hz generally increased the apparent complex and storage moduli and the energy recovered, but decreased the value of the apparent loss modulus, the phase angle and the energy dissipated. Results obtained from cyclic uniaxial compression concur with literature findings.

With respect to the effect of a change in material from one harvest to another,

direct comparisons were not carried out due to different growing locations between old and new crops. Small strain oscillatory shear and uniaxial compression tests appeared to be equally capable of measuring the difference in the mechanical properties between old and new crops, regardless of whether they had been subjected to mannitol treatment or not. This is justified by the similar trends observed in the results from both techniques. For instance, the lower c.v. values for the new crops and in 3% mannitol treatments, and the different response of the old crops under mannitol treatment.

For the osmotic adjustment using 2 mannitol concentrations, it was found that long term storage had affected the permeability of potato tissues to water uptake and withdrawal. Potato tissues subjected to long term storage were found to be more permeable to water than tissues from tubers subjected to minimal storage. It was also found that potato tissues obtained from different histological regions responded differently to osmotic adjustments regardless of their physiological age. In this respect, tissue obtained from the pith region was found to be more permeable to water than tissues from the cortex and perimedullary zone. Future work is needed to investigate the effect of mannitol on the moisture sorption/desorption behaviour of potato tissues at different physiological stages and from different histological regions.

The use of small strain oscillatory shear test on living potato tissues is a relatively new application. It is the author's opinion that several points should be addressed before the technique's potential can be fully realized. Firstly, the preparation of plant tissue slices is critical in obtaining reproducible results. Any imperfection in the slice can lead to either slippage between sample and plates or excessive compression of the slice during

loading of the top plate. Secondly, a method should be developed to avoid desiccation of the sample during and between measurements, particularly if the testing is to be performed at low frequencies. Thirdly, the small strain oscillatory shear technique should be complemented with other measurements such as chemical, enzymic and microscopic analysis of the cell walls and cellular materials, in order to fully understand the contribution of cellular chemistry and component structure to the mechanical properties of potato tissues.

7. REFERENCES

Aguilera, J.M., and Stanley, D.W. 1990. Microstructure of food components. Pages 87-126 in: Microstructure Principles of Food Processing & Engineering. Elsevier Science Publishers Ltd., UK.

Anonymous. 1966. Sonic beams reveal inner texture of whole fruit. Food Technol. 20:1501-1502.

Anonymous. 1991. The Potato Industry of Manitoba - Final Report. Threshold Technologies Co. Manitoba

Anzaldúa-Morales, A., Bourne, M.C., and Somer, I. 1992. Cultivar, specific gravity and location in tuber affect puncture force of raw potatoes. J. Food Sci. 57:1353-1356.

AOAC. 1984. Official Methods of Analysis. 14th edition. Association of Official Analytical Chemists. Arlington, VG.

Artschwager, E. 1924. Studies on the potato tuber. J. Agric. Research. 27:809-835.

Ashby, M.F. 1983. The mechanical properties of cellular solids. Metallurgical Transaction A. 14A:1755-1769.

Bettelheim, F.A., and Sterling, C. 1955. Factors associated with potato texture. II. Pectic substances. Food Res. 20:118-129

Biliaderis, C.G. 1992. Characterization of starch networks by Small Strain Dynamic Rheometry. Pages 87-136 in: Developments in Carbohydrate Chemistry. R.J. Alexander and H.F. Zobel, ed. AACC, St.Paul, MN.

Biliaderis, C.G., and Zawistowski, J. 1990. Viscoelastic behaviour of aging starch gels:effect of concentration, temperature, and starch hydrolyzates on network properties. Cereal Chem. 67:240-245.

Bourne, M.C. 1976. Texture of fruits and vegetables. Pages 275-307 in: Rheology and Texture in Food Quality. J.M. deMan, P.W. Voisey, V.F. Rasper, and D.W. Stanley, ed. The AVI Publishing Co., Inc. Westport, CT.

Bourne, M.C. 1983. Physical properties and structure of horticultural crops. Pages 207-228 in: Physical Properties of Foods. M. Peleg, and E.B. Bagley, ed. The AVI Publishing Co., Inc. Westport, CT.

Brusewitz, G.H., Pitt, R.E., and Gao, Q. 1989. Effects of storage time and static pre-loading on the rheology of potato tissue. J. Text. Stud. 20:267-284.

Burton, W.G. 1989. The distribution and composition of the dry matter in the potato tuber. Pages 286-335 in: The Potato. 3rd edition. Longman Scientific & Technical, UK.

Burton, W.G., van Es, A., and Hartmans, K.J. 1992. The physics and physiology of storage. Pages 608-709 in: The Potato Crop. 2nd edition. P.M. Harris, ed. Chapman & Hall, London, UK.

Canet, W., and Sherman, P. 1988. Influence of friction, sample dimensions and deformation rate on the uniaxial compression of raw potato flesh. J. Text. Stud. 19:275-287.

Cutter, E.C. 1992. Structure and development of potato plant. Pages 65-146 in: The Potato Crop. 2nd edition. P.M. Harris, ed. Chapman & Hall, London, U.K.

Davis, Jr. R.M. 1962. Tissue air space in the potato; its estimation and relation to dry matter and specific gravity. Am. Potato J. 39:298-305.

Diefes, H.A., Rizvi, S.S.H., and Bartsch, J.A. 1993. Rheological behavior of frozen and thawed low-moisture, part-skim mozzarella cheese. J. Food Sci. 58:764-769.

Diehl, K.C., and Hamann, D.D. 1979. Structural failure in selected raw fruits and vegetables. J. Text. Stud. 10:371-400.

Dreese, P.C., Faubion, J.M., and Hoseney, R.C. 1988a. Dynamic rheological properties of flour, gluten, and gluten-starch doughs. I. temperature-dependent changes during heating. Cereal Chem. 65:348-353.

Dreese, P.C., Faubion, J.M., and Hoseney, R.C. 1988b. Dynamic rheological properties of flour, gluten, and gluten-starch doughs. II. effect of various processing and ingredient changes. Cereal Chem. 65:354-359.

Edwards, N.M., Izydorczyk, M.S., Dexter, J.E., and Biliaderis, C.G. 1993. Cooked pasta texture: comparison of dynamic viscoelastic properties to instrumental assessment of firmness. Cereal Chem. 70:122-126.

Fahn, A. 1974. Plant Anatomy. 2nd edition. Pergamon Press Ltd. Headington Hill Hall, Oxford.

Falk, S., Hertz, C.H., and Virgin, H.I. 1958. On the relation between turgor pressure and tissue rigidity. I. Experiments on resonance frequency and tissue rigidity. Physiol. Plant. 11:802-817.

Fedec, P. Ooraikul, B., and Hadziyev, D. 1977. Microstructure of raw and granulated potatoes. Can. Inst. Food Sci. Technol. J. 10:295-306.

Ferry, J.D. 1970. Viscoelastic Properties of Polymers. 2nd edition. John Wiley and Sons Inc, U.S.A.

Finney, E.E., and Hall, C.W. 1967. Elastic properties of potatoes. Trans. ASAE 10:4-8.

Finney, E.E., Hall, C.W., and Mase, G.E. 1964. Theory of linear viscoelasticity applied to the potato. J. Agric. Eng. Res. 9:307-312.

Finney, E.E., and Norris, K.H. 1968. Instrumentation for investigating dynamic mechanical properties of fruits and vegetables. Trans. ASAE 11:94-97.

Frey-Wyssling, R.A. 1952. Deformation and Flow in Biological Systems. Interscience Publishes Inc, New York, NY.

Harker, F.R., and Hallett, I.C. 1994. Physiological and mechanical properties of kiwifruit tissue associated with texture change during cool storage. J. Amer. Soc. Hort. Sci. 119:987-993.

Hoff, J.E., and Castro, M.D. 1969. Chemical composition of potato cell wall. J. Agric. Food Chem. 17:1328-1331.

Horton, D.E., and Anderson, J.L. 1992. Potato production in the context of the world and farm economy. Pages 794-815 in: The Potato Crop. 2nd edition. P.M. Harris, ed. Chapman & Hall, London, UK.

Hsieh, Y.L., Regenstein, J.M., and Rao, M.A. 1993a Gel point of whey and egg proteins using dynamic rheological data. J. Food Sci. 58:116-119.

Hsieh, Y.L., Yun, J.J., and Rao, M.A. 1993b. Rheological properties of mozzarella cheese filled with dairy, egg, soy proteins, and gelatin. J. Food Sci. 58:1001-1004.

Huang, J., Hess, W.M., Weber, D.J., Purcell, A.E., and Huber, C.S. 1990. Scanning electron microscopy: tissue characteristics and starch granule variations of potatoes after microwave and conductive heating. Food Struct. 9:113-122.

Huff, E.R. 1967. Tensile properties of Kennebec potatoes. Trans. ASAE 10:414-419.

Jackman, R.L., and Stanley, D.W. 1992. Failure mechanisms of tomato pericarp tissue suggested by large and small deformation tests. J. Text. Stud. 23:475-489.

Jadhav, S.J., Mazza, G., and Desai, U.T. 1991. Postharvest handling and storage. Pages 69-109 in: Potato: Production, Processing, and Products. D.K. Salunkhe, S.S. Kadam and S.J. Jadhav, ed. CRC Press Inc, Boca Raton, FL.

Jaswal, A.S. 1969. Pectic substances and the texture of french fried potatoes. Am. Potato J. 46:168-173.

Jindal, V.K. 1986. Compression tests for measuring the firmness of potatoes. Pages 52-76 in: Engineering for Potatoes. B.F. Cargill, ed. ASAE, St.Joseph, Mi.

Kadam, S.S., Dhumal, S.S., and Jambhale, N.D. 1991. Structure, nutritional composition and quality. Pages 9-35 in: Potato: Production, Processing, and Products. D.K. Salunkhe, S.S. Kadam and S.J. Jadhan, ed. CRC Press Inc, Boca Raton, FL.

Khan, A.A., and Vincent, J.F.V. 1993. Compressive stiffness and fracture properties of apples and potato parenchyma. J. Text. Stud. 24:423-435.

Kokini, J.L., and Plutchok, G.J. 1987. Viscoelastic properties of semisolid foods and their biopolymeric components. Food Technol. 41(3):89-95.

Lin, T.T. and Pitt, R.E. 1986. Rheology of apple and potato tissue as affected by cell turgor pressure. J. Text. Stud. 17:291-313.

Loh, J. 1992. The effect of shear rate and strain on the pasting behaviour of food starches. J. Food Engin. 16:75-89.

McLaughlin, N.B. 1987. Statistical models for failure of apple tissue under constant-strain-rate loading. J. Text. Stud. 18:173-186.

Mohsenin, N.N. 1977. Characterization and failure in solid foods with particular reference to fruits and vegetables. J. Text. Stud. 8:169-193.

Mohsenin, N.N. 1986. Physical Properties of Plant and Animal Materials. 2nd edition. Gordon and Breach Science Publishers, New York, NY.

Murase, H., Merva, G.E., and Segerlind, L.J. 1980. Variation of Young's modulus of potato as a function of water potential. Trans. ASAE 23:794-796, 800.

Navickis, L.L., Anderson, R.A., Bagley, E.B., and Jasberg, B.K. 1982. Viscoelastic properties of wheat flour doughs: variation of dynamic moduli with water and protein content. J. Text. Stud. 13:249-264.

Niklas, K.J. 1988. Dependency of the tensile modulus on transverse dimensions, water potential and cell number of pith parenchyma. Amer. J. Bot. 75:1286-1292.

Niklas, K.J. 1989. Mechanical behaviour of plant tissues as inferred from the theory of pressurized cellular solids. Amer. J. Bot. 76:929-937.

Nilsson, S.B., Hertz, G.H., and Falk, S. 1958. On the relation between turgor pressure and tissue rigidity. II. Theoretical calculations on model systems. Physiol. Plant. 11:818-837.

Nolan, E.J., Holsinger, V.H., and Shieh, J.J. 1989. Dynamic rheological properties of natural and imitation mozzarella cheese. J. Text. Stud. 20:179-189.

Peleg, M. 1977. The role of the specimen dimensions in uniaxial compression of food materials. J. Food Sci. 42:649-651, 659.

Peleg, M. 1987. The basics of solid foods rheology. Pages 3-33 in: Food Texture Instrumental and Sensory Measurement. H.R. Moskowitz, ed. Marcel Dekker, Inc. New York, NY.

Peleg, M., and Calzada, J.F. 1976. Stress relaxation of deformed fruits and vegetables. J. Food Sci. 41:1325-1329.

Peterson, C.L., and Hall, C.W. 1974. Thermorheological simple theory applied to the Russet Burbank potato. Trans. ASAE 17:546-552, 556.

Petrell, R.J., Mohsenin, N.N., and Wallner, S. 1980. Dynamic mechanical properties of the apple cortex in relation to sample location and ripening. J. Text. Stud. 10:217-229.

Pitt, R.E. 1982. Models for the rheology and statistical strength of uniformly stressed vegetative tissue. Trans. ASAE 25:1776-1784.

Pitt, R.E. 1984. Stress-strain and failure characteristic of potato tissue under cyclic loading. J. Text. Stud. 15:131-155.

Pitt, R.E. 1992. Viscoelastic properties of fruits and vegetables. Pages 49-76 in: Viscoelastic Properties of Foods. M.A. Rao and J.F. Steffe, ed. Elsevier Science Publishers Ltd., New York, NY.

Pitt, R.E., and Chen, H.L. 1983. Time-dependent aspects of the strength and rheology of vegetative tissue. Trans. ASAE 26:1275-1280.

Qiong, G., Pitt, R.E., and Bartsch, J.A. 1989. Elastic-plastic constitutive relations of the cell walls of apple and potato parenchyma. J. Rheol. 33:233-256.

Ramana, S.V., and Taylor, A.J. 1992a. Dynamic measurement of tissue rigidity during freezing and cooking of vegetables. J. Sci. Food Agric. 58:261-266.

Ramana, S.V., and Taylor, A.J. 1992b. Development of a method to measure rheological properties of carrot cell and cell wall materials. J. Sci. Food Agric. 60:39-45.

Ramana, S.V., Wright, C.J., and Taylor, A.J. 1992. Measurement of firmness in carrot tissue during cooking using dynamic, static and sensory tests. J. Sci. Food Agric. 60:369-375.

Rao, V.N.M. 1992. Classification, description and measurement of viscoelastic properties of solid foods. Pages 3-47 in: Viscoelastic Properties of Foods. M.A. Rao and J.F. Steffe, ed. Elsevier Science Publishers Ltd., New York, NY.

Reeve, R.M. 1967. A review of cellular structure, starch, and texture quality of processed potatoes. Econ. Bot. 21:294-308.

Reeve, R.M. 1970. Relationships of histological structure to texture of fresh and processed fruits and vegetables. J. Text. Stud. 1:247-284.

Reeve, R.M., Timm, H., and Weaver, M.L. 1973a. Parenchyma cell growth in potato tubers I. Different tuber regions. Am. Potato J. 50:49-57.

Reeve, R.M., Timm, H., and Weaver, M.L. 1973b. Parenchyma cell growth in potato tubers II. Cell divisions vs. cell enlargement. Am. Potato J. 50:71-78.

Rochefort, W.E., and Middleman, S. 1987. Rheology of xanthan gum: salt, temperature, and strain effects in oscillatory and steady shear experiments. J. Rheol. 31:337-369.

Rohm, H., and Weidinger, K.H. 1993. Rheological behavior of butter at small deformations. J. Text. Stud. 24:157-172.

Salunkhe, D.K., and Kadam, S.S. 1991. Introduction. Pages 1-7 in: Potato: Production, Processing, and Products. D.K. Salunkhe, S.S. Kadam, and S.J. Jadhav, ed. CRC Press Inc, Boca Raton, FL.

Shoemaker, C.F. 1992. Instrumentation for the measurement of viscoelasticity. Pages 233-246 in: Viscoelastic Properties of Foods. M.A. Rao and J.F. Steffe, ed. Elsevier Science Publishers Ltd., New York, NY.

Shomer, I., Rao, M.A., Bourne, M.C., and Levy, D. 1993. Impact of temperature and cellulase treatments on rheological behavior of potato tuber cell suspensions. J. Sci. Food Agric. 63:245-250.

Smith, O. 1977. Structure of potato plant. Pages 28-34 in: Potatoes: Production, Storing, Processing. 2nd ed. The AVI Publishing Co., Inc. Westport, CT.

Steudle, E., Zimmermann, U., and Lüttge, U. 1977. Effect of turgor pressure and cell size on the wall elasticity of plant cells. Plant Physiol. 59:285-289.

Steward, F.C., and Mühlethaler, K. 1953. The structure and development of the cell wall in Valoniaceae. Ann. Bot. 17:295-315.

Szczesniak, A.S. 1963. Classification of textural characteristics. J. Food Sci. 28:385-315.

Szczesniak, A.S. 1971. Consumer awareness of texture and of other food attributes, II. J. Text. Stud. 2:196-206

Szczesniak, A.S. 1972. Consumer awareness of texture and of other food attributes II. Children and teenagers. J. Text. Stud. 3:206-217.

Szczesniak, A.S. and Kahn, E.L. 1971. Consumer awareness of texture and of other food attributes I: Adults. J. Text. Stud. 2:280-295.

Szczesniak, A.S. 1977. An overview of recent advances in food texture research. Food Technol. 31(4):71-75, 90.

Thorton R.E., and Sieczka, J.B. 1980. Commercial Potato Production in North America. Potato Association of America Handbook. American Potato Journal Supplement (vol. 57). Potato Association of America, Maine, U.S.A.

Tijskens, L.M. 1979. Texture of golden delicious apples during storage. Lebensm-Wiss. U. Technol. 12:138-142.

Turnbull, N.D., and Cobb, A.H. 1992. A study of tuber cell integrity and ultrastructure during prolonged potato storage. Aspects App. Biol. 33:113-118.

Van Buren, J.P. 1979. The chemistry of texture in fruits and vegetables. J. Text. Stud. 10:1-23.

Vincent, J.F.V. 1989. Relationship between density and stiffness of apple flesh. J. Sci. Food Agric. 47:443-462.

Voisey, P.W. 1971. The Ottawa Texture Measuring System. Can. Inst. Food Sci. Technol. J. 4:91-103.

Voisey, P.W., and deMan, J.M. 1976. Application of instruments for measuring food texture. Pages 142-243 in: Rheology and Texture in Food Quality. J.M. deMan, P.W. Voisey, V.F. Rasper, and D.W. Stanley, ed. The AVI Publishing Co., Inc. Westport, CT.

Warren, D.S., and Woodman, J.S. 1973. Distribution of cell wall components in potato tubers: a new titrametric procedure for the estimation of total polyuronide (pectic substances) and its degree of esterification. J. Sci. Food. Agric. 24:769-777.

White, G.W. 1970. Rheology in food research. J. Food Technol. 5:1-32.

8. APPENDICES

Appendix 8.1.   Original Coefficient of Variation (C.V.) Values for Small Strain Oscillatory Shear Results - Old and New Crops without Mannitol Treatment

8.1.1 **Coefficient of Variation (C.V) between Replicates as Measured by G' for the Inner Slices at Three Frequencies**

Potato	Axis	C.V. Of G' (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	X	27.71	28.20	28.62
	Y	25.66	20.24	24.11
	Z	37.29	28.47	23.05
New	X	11.92	17.33	22.56
	Y	19.09	19.93	24.41
	Z	25.18	18.95	13.78

8.1.2 Coefficient of Variation (C.V) between Replicates as Measured by G" for the Inner Slices at Three Frequencies

Potato	Axis	C.V. of G" (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	X	24.34	29.68	39.68
	Y	15.63	14.60	12.88
	Z	21.50	27.20	17.79
New	X	14.25	14.07	25.49
	Y	15.58	24.31	24.19
	Z	16.4	16.57	15.99

8.1.3 Coefficient of Variation (C.V) between Replicates as Measured by G' for the Outer Slices at Three Frequencies

Potato	Axis	C.V. of G'(%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	Y	29.54	20.61	17.04
	Z	35.07	16.57	5.68
New	Y	18.33	15.52	13.39
	Z	15.51	14.26	11.47

8.1.4 Coefficient of Variation (C.V) between Replicates as Measured by G" for the Outer Slices at Three Frequencies

Potato	Axis	C.V. of G" (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	Y	35.17	26.43	5.39
	Z	12.82	11.99	6.72
New	Y	12.51	14.30	16.31
	Z	6.00	9.26	11.22

8.1.5 Coefficient of Variation (C.V) between Slices as Measured by G' for the Inner Slices at Three Frequencies

Potato	Axis	C.V. of G'(%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	X	40.11	29.15	22.72
	Y	26.05	31.06	24.49
	Z	21.87	28.95	30.23
New	X	23.16	19.15	17.28
	Y	18.64	14.55	7.43
	Z	15.62	16.75	18.59

8.1.6 Coefficient of Variation (C.V) between Slices as Measured by G" for the Inner Slices at Three Frequencies

Potato	Axis	C.V. of G" (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	X	29.91	19.80	23.78
	Y	9.84	20.63	27.34
	Z	15.47	18.71	17.01
New	X	20.04	14.83	34.63
	Y	11.36	16.82	8.21
	Z	12.32	8.60	11.24

8.1.7 Coefficient of Variation (C.V) between Slices as Measured by G' for the Outer Slices at Three Frequencies

Potato	Axis	C.V. of G' (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	Y	8.92	22.95	20.95
	Z	28.88	24.22	23.61
New	Y	13.55	13.67	16.85
	Z	17.08	13.95	14.12

8.1.8 Coefficient of Variation (C.V) between Slices as Measured by G" for the Outer Slices at Three Frequencies

Potato	Axis	C.V. of G" (%) At		
		0.02 Hz	0.2 Hz	2 Hz
Old	Y	17.72	35.00	24.06
	Z	19.94	16.65	6.89
New	Y	9.00	13.03	12.44
	Z	10.83	8.51	7.40

Appendix 8.2.   Summary of the Significant Interactions between the Main
Effects, Axis and Frequency, for the Outer and Inner Slices of
the Old and New Crops without Mannitol Treatment

8.2.1 **Significant Interactions between the Main Effects, Axis and Frequency, for the Outer and Inner Slices of the Old and New Crops without Mannitol Treatment**

Potato	Slice Position	Parameter[1]	Pr > F
Old	Outer	δ	0.0497
	Outer	U_{st}	0.0031
	Outer	U_{dis}	0.0014
New	Inner	δ	0.0136

1 δ = Phase Angle; U_{st} = Energy Stored per ¼ Oscillation Cycle; U_{dis} = Energy Dissipated per ¼ Oscillation Cycle.

Appendix 8.3.   Original Coefficient of Variation (C.V.) Values for Small Strain
Oscillatory Shear Results - Old and New Crops with 3 and 7%
Mannitol Treatments

8.3.1 Coefficient of Variation (C.V) between Replicates as Measured by G' for the Inner Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C.	C.V. of G' (%) At		
		(% w/v)	0.02 Hz	0.2 Hz	2 Hz
Old	X	3	10.28	13.39	15.71
		7	14.88	17.66	22.36
	Y	3	17.68	14.89	12.31
		7	37.25	23.80	12.80
	Z	3	28.92	35.62	42.49
		7	25.98	19.61	12.82
New	X	3	13.88	17.71	19.44
		7	17.75	13.88	11.01
	Y	3	10.27	14.72	18.96
		7	26.65	29.95	34.70
	Z	3	18.68	19.51	18.59
		7	16.62	23.90	29.89

8.3.2 Coefficient of Variation (C.V) between Replicates as Measured by G" for the Inner Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C.	C.V. of G" (%) At		
		(% w/v)	0.02 Hz	0.2 Hz	2 Hz
Old	X	3	17.71	11.35	30.89
		7	13.83	17.96	30.23
	Y	3	14.34	21.77	22.40
		7	33.11	27.12	24.57
	Z	3	13.40	14.85	15.41
		7	24.42	15.68	7.74
New	X	3	10.30	15.21	35.95
		7	12.71	8.53	5.93
	Y	3	12.48	7.81	13.26
		7	20.93	22.07	22.9
	Z	3	22.98	18.19	29.66
		7	15.98	18.67	18.68

8.3.3 Coefficient of Variation (C.V) between Replicates as Measured by G' for the Outer Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C.	C.V. of G' (%) At		
		(% w/v)	0.02 Hz	0.2 Hz	2 Hz
Old	Y	3	24.57	27.20	24.75
		7	31.63	43.92	57.31
	Z	3	18.42	32.21	42.21
		7	57.46	45.59	35.83
New	Y	3	34.87	27.62	21.77
		7	49.50	42.10	32.51
	Z	3	22.88	28.98	31.22
		7	30.58	37.05	36.73

8.3.4 Coefficient of Variation (C.V) between Replicates as Measured by G" for the Outer Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C.	C.V. of G" (%) At		
		(% w/v)	0.02 Hz	0.2 Hz	2 Hz
Old	Y	3	14.24	11.28	24.66
		7	26.89	31.98	42.31
	Z	3	16.81	19.15	38.87
		7	48.91	41.30	26.88
New	Y	3	15.37	16.82	25.80
		7	36.76	32.71	23.17
	Z	3	14.32	16.08	60.32
		7	32.38	32.63	29.56

8.3.5 Coefficient of Variation (C.V) between Sample Slices as Measured by G' for the Inner Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C. (% w/v)	C.V. of G' (%) At		
			0.02 Hz	0.2 Hz	2 Hz
Old	X	3	13.61	19.40	23.20
		7	14.39	22.73	28.05
	Y	3	30.70	22.95	20.87
		7	32.39	35.44	12.81
	Z	3	42.92	36.22	17.58
		7	22.37	30.03	26.35
New	X	3	26.39	19.51	13.57
		7	41.17	30.81	27.27
	Y	3	33.91	25.24	9.45
		7	32.87	30.26	27.37
	Z	3	39.28	26.12	12.05
		7	42.19	34.19	27.49

8.3.6 Coefficient of Variation (C.V) between Sample Slices as Measured by G" for the Inner Slices at Three Frequencies and Two Mannitol Concentrations (M.C.)

Potato	Axis	M.C.	C.V. of G" (%) At		
		(% w/v)	0.02 Hz	0.2 Hz	2 Hz
Old	X	3	23.45	15.12	48.73
		7	10.81	16.45	49.95
	Y	3	24.52	77.08	12.64
		7	28.56	30.25	11.23
	Z	3	23.27	14.55	17.63
		7	20.54	31.59	24.23
New	X	3	9.72	19.87	28.61
		7	30.75	21.47	21.64
	Y	3	18.37	14.49	7.45
		7	24.75	21.45	18.54
	Z	3	26.23	13.68	27.25
		7	30.74	22.49	10.29

Appendix 8.4.   Summary of the Significant Interactions between the Main
                  Effects, Axis and Frequency, for the Outer and Inner Slices of
                  the Old and New Crops with 3 and 7% Mannitol Treatments

8.4.1 Significant Interactions between the Main Effects, Axis and Frequency, of the Old and New Crops Analyzed Separately for Each Mannitol Concentration (M.C.)

Potato	Slice Position	Parameter[1]	M.C.	Significant Level
Old	Inner	G*	7	0.0373
	Inner	G'	7	0.0372
	Inner	U_{st}	7	0.0116
	Outer	U_{dis}	7	0.0162

1 G* = Complex Modulus; G' = Storage Modulus; U_{st} = Energy Stored per ¼ Oscillation Cycle; U_{dis} = Energy Dissipated per ¼ Oscillation Cycle.

Appendix 8.5.   Summary of the Significant Interactions between the Main Effects, Axis, Frequency and Slice Position, for the Outer and Inner Slices of the Old and New Crops with 3 and 7% Mannitol Treatments

8.5.1 Significant Interactions between the Main Effects, Axis, Frequency and Slice Position, of the Old and New Crops Analyzed Separately for Each Mannitol Concentration (M.C.)

Potato	M.C.	Parameter[1]	Interaction[2]	Pr > F
Old	7	G'	Axis*Freq	0.0049
	7	G"	Axis*Freq	0.0033
New	3	G"	Freq*Loc	0.0446
	3	G"	Axis*Freq*Loc	0.0169

1 G' = Storage Modulus; G" = Loss Modulus.
2 Freq = Frequency; Loc = Location.

Appendix 8.6.   Original Coefficient of Variation (C.V.) Values for Uniaxial Compression Results - Old and New Crops without Mannitol Treatment

8.6.1 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the Old Crops without Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	50.99
	2	2	61.08
	2	3	63.61
	20	1	35.73
	20	2	25.13
	20	3	26.59
Y	2	1	35.35
	2	2	43.70
	2	3	43.18
	20	1	32.87
	20	2	25.63
	20	3	25.40
Z	2	1	25.51
	2	2	25.55
	2	3	23.35
	20	1	26.29
	20	2	24.21
	20	3	23.69

8.6.2 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the Old Crops without Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	51.44
	2	2	48.27
	2	3	48.93
	20	1	45.13
	20	2	41.85
	20	3	42.08
Y	2	1	35.41
	2	2	32.84
	2	3	33.25
	20	1	34.08
	20	2	28.17
	20	3	27.72
Z	2	1	26.09
	2	2	25.17
	2	3	25.81
	20	1	31.80
	20	2	28.64
	20	3	29.34

8.6.3 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the New Crops without Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	26.10
	2	2	27.96
	2	3	33.97
	20	1	25.22
	20	2	20.76
	20	3	21.55
Y	2	1	31.01
	2	2	23.23
	2	3	24.08
	20	1	29.39
	20	2	19.46
	20	3	19.37
Z	2	1	20.88
	2	2	17.15
	2	3	18.15
	20	1	16.75
	20	2	10.28
	20	3	9.90

8.6.4 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the New Crops without Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	10.78
	2	2	7.80
	2	3	8.17
	20	1	9.71
	20	2	6.96
	20	3	6.44
Y	2	1	16.23
	2	2	13.92
	2	3	14.22
	20	1	16.39
	20	2	14.37
	20	3	14.85
Z	2	1	12.12
	2	2	9.45
	2	3	9.92
	20	1	9.90
	20	2	9.84
	20	3	11.11

Appendix 8.7.   Summary of the Significant Interactions between the Main
                 Effects, Axis, Strain rate and Cycle for the Old and New Crops
                 without Mannitol Treatment

8.7.1 Significant Interactions between the Main Effects, Axis, Strain Rate and Cycle for the Old and New Crops without Mannitol Treatment

Potato	Parameter[1]	Interaction[2]	Pr > F
Old	U_{dis}	Axis*Cycle	0.0022
New	E_{in}	Stra*Cycle	0.0030
	E_{end}	Axis*Cycle	0.0100
	E_{end}	Stra*Cycle	0.0001
	U_{dis}	Axis*Cycle	0.0005
	U_{dis}	Stra*Cycle	0.0001

1 U_{dis} = Energy Dissipated; E_{in} = Initial Elastic Modulus; E_{end} = End Elastic Modulus.

2 Stra = Strain Rate.

Appendix 8.8.   Original Coefficient of Variation (C.V.) Values for Uniaxial Compression Results - Old and New Crops with 3 and 7% Mannitol Treatments

8.8.1 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the Old Crops with 3% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	37.09
	2	2	28.74
	2	3	27.50
	20	1	11.63
	20	2	15.80
	20	3	18.63
Y	2	1	31.41
	2	2	31.59
	2	3	31.51
	20	1	19.51
	20	2	13.51
	20	3	13.34
Z	2	1	39.07
	2	2	31.82
	2	3	34.82
	20	1	13.87
	20	2	12.73
	20	3	11.37

8.8.2 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the Old Crops with 7% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	25.06
	2	2	43.24
	2	3	38.49
	20	1	48.80
	20	2	45.90
	20	3	52.47
Y	2	1	31.04
	2	2	38.70
	2	3	47.06
	20	1	38.16
	20	2	32.58
	20	3	31.91
Z	2	1	7.89
	2	2	34.86
	2	3	41.28
	20	1	45.74
	20	2	46.21
	20	3	48.99

8.8.3 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the Old Crops with 3% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	31.88
	2	2	25.97
	2	3	26.99
	20	1	10.16
	20	2	8.51
	20	3	8.71
Y	2	1	19.70
	2	2	14.95
	2	3	14.77
	20	1	11.80
	20	2	8.71
	20	3	7.87
Z	2	1	28.68
	2	2	24.07
	2	3	25.93
	20	1	14.59
	20	2	10.70
	20	3	10.43

8.8.4 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the Old Crops with 7% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	28.08
	2	2	26.00
	2	3	25.34
	20	1	42.49
	20	2	39.18
	20	3	37.65
Y	2	1	38.65
	2	2	36.36
	2	3	36.23
	20	1	38.89
	20	2	36.35
	20	3	36.20
Z	2	1	15.75
	2	2	12.90
	2	3	12.40
	20	1	47.37
	20	2	41.98
	20	3	41.34

8.8.5 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the New Crops with 3% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	30.88
	2	2	15.08
	2	3	16.27
	20	1	9.06
	20	2	13.76
	20	3	14.61
Y	2	1	16.46
	2	2	5.33
	2	3	7.89
	20	1	5.91
	20	2	12.83
	20	3	16.72
Z	2	1	18.54
	2	2	19.17
	2	3	21.77
	20	1	9.21
	20	2	11.33
	20	3	12.95

8.8.6 Coefficient of Variation (C.V.) between Replicates as Measured by Initial Elastic Modulus (E_{in}) for the New Crops with 7% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	31.75
	2	2	32.95
	2	3	33.20
	20	1	9.08
	20	2	9.53
	20	3	12.10
Y	2	1	7.16
	2	2	7.48
	2	3	8.41
	20	1	34.79
	20	2	21.95
	20	3	22.46
Z	2	1	29.86
	2	2	29.03
	2	3	28.51
	20	1	14.54
	20	2	9.43
	20	3	8.39

8.8.7 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the New Crops with 3% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	7.82
	2	2	8.86
	2	3	8.06
	20	1	7.84
	20	2	8.46
	20	3	10.46
Y	2	1	9.50
	2	2	13.63
	2	3	14.76
	20	1	9.15
	20	2	11.04
	20	3	13.88
Z	2	1	6.63
	2	2	6.91
	2	3	6.70
	20	1	6.09
	20	2	7.93
	20	3	7.48

8.8.8 Coefficient of Variation (C.V.) between Replicates as Measured by Total Energy Input (U_{tot}) for the New Crops with 7% Mannitol Treatment

Axis	Strain Rate (cm min^{-1})	Cycle	C.V. (%)
X	2	1	23.15
	2	2	18.76
	2	3	18.63
	20	1	9.55
	20	2	10.64
	20	3	9.60
Y	2	1	9.33
	2	2	12.04
	2	3	12.95
	20	1	27.47
	20	2	24.05
	20	3	23.49
Z	2	1	27.76
	2	2	24.11
	2	3	23.51
	20	1	12.70
	20	2	9.24
	20	3	9.31

Appendix 8.9.   Summary of the Significant Interactions between the Main
Effects, Axis, Strain Rate and Cycle for the Old and New Crops
with 3 and 7% Mannitol Treatments

8.9.1 Significant Interactions between the Main Effects, Axis, Strain Rate and Cycle for the Old and New Crops Analyzed Separately for Each Mannitol Concentration (M.C.)

Potato	M.C.	Parameter	Interaction	Pr > F
Old	7	E_{end}	Axis*Stra	0.0368
	3	E_{dis}	Stra*Cycle	0.0199
New	3	E_{in}	Stra*Cycle	0.0001
	7	E_{in}	Axis*Stra	0.0006
	3	E_{end}	Axis*Cycle	0.0196
	7	E_{end}	Axis*Stra	0.0351
	7	E_{end}	Stra*Cycle	0.0033
	3	U_{tot}	Axis*Cycle	0.0206
	3	U_{tot}	Stra*Cycle	0.0021
	7	U_{tot}	Axis*Stra	0.0018
	7	U_{rec}	Axis*Stra	0.0007
	3	U_{dis}	Axis*Cycle	0.0001
	3	U_{dis}	Stra*Cycle	0.0001
	7	U_{dis}	Axis*Stra	0.0364
	7	U_{dis}	Stra*Cycle	0.0189

1 E_{in} = Initial Elastic Modulus; E_{end} = End Elastic Modulus; U_{tot} = Total Energy Input; U_{rec} = Energy Recovered; U_{dis} = Energy Dissipated.

2 Stra = Strain Rate.