# BIOE 4950: Biosystems Engineering Design 3

# Final Design Report

# Reliable Tire Recycling – Development of a Playground Tile Product

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## Executive Summary

The Reliable Tire Recycling (RTR) Playground Tile Project aims to develop an innovative, sustainable, and safe playground surfacing solution made from recycled rubber tires. This project was initiated to repurpose waste rubber into a functional, high-performance product. Playground tiles made of such material are not widely available in Canada which this project aims to address. The project was completed in collaboration with RTR, Manitoba's leading tire recycling company, to expand their product line. The playground tile is designed to meet ASTM F1292 impact attenuation safety standards, contribute to environmental sustainability, and enhance product innovation in the recycled rubber industry specifically in Canada.

The design process involved extensive research and experimentation in several key areas: material composition, tile shape, connection method, aesthetics, and manufacturing. The final material formula was selected based on performance test results that met the expected safety rating but also ensured durability, impact resistance, and ease of production. The Team developed a unique base design with a channelled, grid structure to improve shock absorption and water drainage, further enhancing the product's safety and longevity. Additionally, a dowel pin connection system was implemented to facilitate secure and easy tile assembly, improving product usability in playground installations. The tile's visual appearance was improved with the integration of coloured rubber from recycled shoes to which added a potential avenue for future product development at RTR.

To ensure the tiles met the main design objectives and specifications, various verification procedures were conducted. The Triax Impact Test in accordance with ASTM F1292 confirmed that the material composition and design features achieved the critical fall height desired by the client for playground applications. Additional tests evaluated the tile's performance under different environmental conditions including extreme temperatures and moisture resistance. These evaluations demonstrated the tile's durability and suitability for outdoor use, confirming its potential as a marketable product for RTR.

By successfully developing a high-quality playground tile using recycled rubber, this project not only contributes to sustainable waste management but also provides RTR with a viable, eco-friendly addition to their product line. The results validate the potential for further research and commercialization.

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## Glossary of Terms

| Term | Definition |
|---|---|
| Head Injury Criterion | A measure of the likelihood of head injury arising from an impact. |
| G-max or peak-G | The maximum acceleration of a missile during an impact, expressed in units of g's. 1 g unit = 1 standard gravity. |
| Poisson's Ratio | The negative ratio of transverse strain to axial strain. When a material is stretched or compressed |
| Strain | The ratio of the change in dimension, which can be the length or area or volume of the given body, under the action of external force to the original dimension of the body. |
| Strain Energy | The potential energy stored in a material when it undergoes deformation. |
| Stress | A measure of the internal forces that act within a material because of an applied load. |
| Yield Strength | The yield strength is a measure of the stress at which a material begins to deform plastically, or permanently, under an applied load. |
| Modulus of Elasticity | A measure of the stress–strain relationship on the object. |
| Apparent Density | The bulk mass of the particles and pores of a material divided by the total bulk volume. |
| Hardness | A measure of the resistance of a material to localized plastic deformation, such as indentation or scratching, caused by mechanical forces. |
| R-squared | Also known as the coefficient of determination, is a statistical measure used in regression analysis to assess the goodness of fit of a model. |
| FEA | Computer simulation tool for modelling the performance of different designs. |

## Abbreviations

| Term | Definition |
|---|---|
| RTR | Reliable Tire Recycling |
| HIC | Head Injury Criterion |
| BOM | Bill of Materials |
| FEA | Finite Element Analysis |
| FSA | Force Sensing Array |
| ASTM | American Society for Testing and Materials |
| ISO | International Standards Organization |
| EPDM | Ethylene propylene diene monomer (type of rubber) |

# 1.0 Introduction

## 1.1 Project Context

This project will utilize recycled rubber tires that have been ground into different raw materials to product a playground tile that aligns with ASTM F1292 Standard Specification for Impact Attenuation. This standard governs the design of playground base materials by determining their critical fall height which describes the maximum height a child can fall from, and a life-threatening head injury would not be expected to occur [1]. The main design considerations for this project include a material formula that maximizes critical fall height, a connection method for assembling the playground tiles, a base shape for the tiles with the intent to increase performance, and lastly a manufacturing method for creating the tiles. Creating a high performing tile is significant to the client as it will give them insight to their market potential for playground base materials, additionally it will identify a new use case for the raw materials created from the recycling of rubber tires. Currently, whole tires are banned from landfills due to the harm they pose on our environment [2]. As such, reusing this material is required for improving sustainability in tire production.

### 1.1.1 Purpose

In their annual survey on tire disposal, the Canadian Association of Tire Recycling Agencies recorded that in 2023, over four hundred thousand tons of discarded tires were collected across Canada [2]. This volume of tire rubber leaves a tremendous amount of waste and uptake of space in Canadian landfills. In addition, disposal of tire rubber in landfills creates several complications to the surrounding environment. These complications were outlined in an article written by Tire Review Magazine and include fires, soil pollution and the spread of diseases [3]. Rubber tires can be highly flammable and emit dangerous smoke when burned. This smoke adds pollutants to the air and contributes to greenhouse gas emissions. As a result of these complications, Canada has banned the disposal of rubber tires in landfills for highly populated areas [4] and therefore the tires must be recycled or repurposed. Therefore, this project aims to make playground tiles using the rubber obtained from recycled tires. This will introduce a new use case for rubber tires which must be recycled and reused to avoid landfill disposal. The playground tiles are also not currently being developed by the client and will give them an additional product in the rubber material market.

Overall, this report will outline the design for a playground tile made from recycled tire rubber which will increase the recycling potential of rubber tires, improving sustainability in the industry.

### 1.1.2 The Client

Based in Winnipeg, Reliable Tire Recycling (RTR) is Manitoba's largest tire collection depot and producer of recycled rubber products. The tires are shredded into different grades of crumb rubber which can be molded into various shapes via compression and heat. Currently, RTR's main line of products manufactured from recycled rubber tires include blast mats, silage covers, landscaping pads and gym mats. To stay competitive in the rubber product market, RTR has engaged the University of Manitoba Biosystems Capstone program for advancement on their playground-specific products. Specifically, on the optimization of the existing rubber formula for playground tiles and to investigate waste-reducing alternatives to this formula. To ensure safety of the users, the resultant playground tile must meet the ASTM F1292 standard [1] which outlines the minimum performance for playground equipment as it pertains to impact stresses on a child's body. It is essential for RTR to consider ASTM standards when repurposing rubber tires as the products must align with the contents of their respective standards to be sold on the market.

## 1.2 Background

To develop a high performing playground tile, background information and knowledge on the types of rubber materials utilized will be essential. Tires are made up of several different ingredients, similarly the playground tiles will also be made up of derivatives of those ingredients. This section will discuss those ingredients but also how playground tiles are evaluated. The goal of this project is to develop a high performing tile for the client so knowledge of the evaluation procedures will be equally essential to the knowledge of rubber ingredients.

### 1.2.1 Tire Rubber Composition

The material composition of tire rubber is rather complex. In addition to natural and synthetic rubber, there are several types of additives including textiles such as polyester [5]. Textiles act as a reinforcement, assisting with dimensional stability and supporting the weight of the vehicle. A diagram of a typical passenger tire composition is shown in Figure 1 below.



***Figure 1.*** *The different material components of a car tire [6].*

As Figure 1 above demonstrates, there are various materials that make up a typical passenger tire, resulting in a difficult recycling process. The process of extracting the rubber from the additives to produce crumb rubber for manufacturing is an intricate task, involving separation, grinding, and further processing of these multi-material components. This process is described further in Section 1.2.2.

### 1.2.2 Crumb Rubber

The process of extracting crumb rubber from tires at RTR's facility begins with collecting waste vehicle tires and separating the rubber from the rim and inner tubing. The separated rubber is then cleaned and shredded into small, workable sized fragments that can be further processed. Through various mechanical steps like grinding and milling, the rubber is further separated from metal and fabric components. Finally, the remaining rubber fragments are ground into different grades of crumb rubber, which vary in size depending on the application. A flow chart of this process can be found in Appendix A. The grade of crumb rubber is dependent on the mesh screen size used to filter the rubber fragments. The two main grades of crumb rubber used by RTR include 3-20 and -20, which represent the size of mesh screen the rubber was passed through. These sizes are defined in Table 1 below [7].

***Table 1.*** *Mesh Sizes Used for Screening Rubber at RTR [7].*

| Mesh Number | Size of Mesh Hole | Size of Mesh Hole |
|---|---|---|
| (number of holes per inch) | (in) | (mm) |
| 3 | 0.265 | 6.73 |

| Mesh Number | Size of Mesh Hole | Size of Mesh Hole |
|---|---|---|
| 20 | 0.0331 | 0.841 |

Based on the information in Table 1, RTR's 3-20 crumb rubber is inclusive for sizes ranging from 0.0331 – 0.265 inches and -20 crumb rubber includes sizes smaller than 0.0331 inches. Therefore, 3-20 and -20 represent a coarse crumb rubber and a fine crumb rubber, respectively. This crumb rubber is used as the base material in several of RTR's product formulas.

### 1.2.3 Rubber Fiber

When tire fragments are further shredded into crumb rubber, a fiber by-product is generated from the grinding methods, mostly composed of the polyester textiles described in Section 1.2.1. These fibers are collected post-shredding and typically landfilled by RTR as they currently serve no benefit in any production stream or to other businesses. Figure 2 shows the fibers collected at RTR's facility.



***Figure 2.*** *Collection of rubber fiber at RTR's facility.*

As seen in Figure 2 above, the rubber fiber is very airy and light and therefore, could possess suitable material properties for a particular product. While RTR has previously investigated recycling these fibers into its production process, a suitable recycling stream has not yet been identified. Integrating these fibers into the crumb rubber playground tiles may provide an opportunity to reduce the waste generated in the tire recycling process. This would create a more environmentally friendly product, as a result.

### 1.2.4 Playground Safety Standards

The ASTM F1292 standard is a test that determines the maximum fall height of playground surfaces, which is defined as the safest height a user can fall onto the surface without significant injury [1]. This data is used to design safe playgrounds and ensure that recreation equipment with appropriate heights is used. Therefore, optimizing the playground tile to achieve an increased safe fall height compared to market alternatives will make for a successful product. The test procedure outlined in ASTM F1292 requires data collection of the maximum acceleration, or g-max, sustained on a missile during impact. Using this acceleration data, the head injury criterion (HIC) is calculated. The HIC is a measure of impact severity and describes the relationship between the duration of the impact and head trauma. These two values are critical to the safety rating of playground surfacing. The formula to calculate the HIC is given as,

$$HIC\ (t_1, t_2) = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t=t_1}^{t_2} a_t dt\right]^{2.5}$$

where $a_t$ is the acceleration at time t and ($t_1$, $t_2$) represents a time interval. The HIC score is determined as the maximum value of all the ($t_1$, $t_2$) scores [1]. To perform this test, a Triax Impact Testing device can be purchased. The test is performed by dropping the missile containing an accelerometer onto to the playground surface. The accelerometer records the time, acceleration, drop height, and angle of drop. Note that the Triax Impact Testing device automatically programmed to calculate the HIC. The methodology to run this test according to ASTM F1292 is explained in Section 3.2.1. To officially a certify a playground surface according to ASTM F1292, a third-party company must perform testing.

### 1.2.6 Playground Tiles on the Market

Within Canada, there are several companies that specialize in rubber playground tiles. To remain competitive in the rubber product market, it is important to acknowledge the existing safety and design features currently available. This will set a benchmark for the RTR playground tile. These features are described in Table 2 below.

***Table 2.*** *Canadian rubber companies and their respective playground tile product features.*

| Company | Safety Features | Design Features |
|---|---|---|
| Rymar [8] | - Safe fall height of 4 ft to 12 ft.<br>- 'Tile Edge Adhesive' to prevent slips and trips | - Interlocking pin system. |
| Perfect Solutions [9] | - Safe fall height of 3 ft alone.<br>- Safe fall heigh of 6 ft when paired with 'Play Pad Foam Padding'. | - 'X-Connector' interlocking design.<br>- Shock and sound absorption. |
| Canada Mats [10] | - Safe fall height up to 10 ft.<br>- Slip resistant material. | - Quick installation with plastic pins and minimal adhesive.<br>- Porous for effective drainage. |

From review of different playground tiles currently available in the Canadian market, Table 2 shows that safe fall heights vary from three feet to twelve feet. The listed companies have explored additional features that improve safety, installation, maintenance, and visual appearance of the tile. However, one limiting factor in all these products is that they are sourced from virgin rubber or synthetic materials, with little to no recycled resources.

## 1.3 Problem Definition

The scope of this project can be defined through several different specifications and objectives. This section will outline these specifications to provide clarity on the project scope. There are also many constraints that come along with those specifications to maintain the scope within the allotted timeline for this project. These will all be defined in detail to create a set of deliverables and achieve the goal of this project.

### 1.3.1 Project Scope

The overall goal of this project is to develop an innovative and sustainable playground surfacing solution using recycled rubber tiles. The project focused on designing a high-performance, impact-absorbing tile that meets ASTM F1292 standards. The scope of the project included extensive research and optimization of the material composition, exploring different crumb rubber formulas, binders, and additives to enhance durability and safety. Additionally, the Team engineered the

tile's shape and connection method, incorporating a base design to improve shock absorption and drainage, along with a dowel pin system for secure installation. The project also considered visual aesthetics to enhance the tile's appeal to customers and children. The manufacturing procedure was considered to ensure a seamless integration of playground tile production at RTR's facility. Verification testing, including impact attenuation and environmental durability assessments, was conducted to evaluate the tile's performance under different conditions. These design goals, along with our client's desired, result in a list of technical specifications and design constraints that must be met for the successful development of the playground tile. These are described in the following sections.

### 1.3.2 Target Specifications

The information in Table 3 outlines the Target Specifications that must be met with the design of the playground tile. These specifications were communicated by RTR.

***Table 3.*** *Target Specifications for the recycled rubber playground tile.*

| Specification | Description | Criteria | Verification |
|---|---|---|---|
| S1.1 | Final dimensions of the playground tile. | 24.5 x 24.5 ± 0.05 in and 2 ± 0.05 in thick | Section 3.1.2 |
| S1.2 | Critical fall height achieved on the playground tile. | ≥ 4 ft | Section 3.2.1 |
| S1.3 | Maximum acceleration produced by impact, or g-max, on the playground tile. | ≤ 200 g's | Section 3.2.1 |
| S1.4 | Impact severity on the playground tile based on the Head Injury Criterion (HIC). | ≤ 1000 HIC score | Section 3.2.1 |
| S1.5 | Temperature range for maintained durability of the playground tile. | -40 °C - 40 °C | Section 3.3.1 and 3.3.2 |

| Specification | Description | Criteria | Verification |
|---|---|---|---|
| S1.6 | UV index exposure for maintained durability of the playground tiles. | 9 | Section 3.3.3 |
| S1.7 | Moisture resistance for maintained durability of the playground tiles. | Volume does not vary more than 5% between pre- and post-saturation. | Section 3.3.4 |
| S1.8 | Final mass of the playground tile. | ≤ 34 lbs. | Section 3.1.1 |

### 1.3.3 Design Constraints

The information in Table 4 outlines the design constraints that must be considered throughout the development of the playground tile. These constraints were communicated by RTR.

***Table 4.*** *Constraints for the recycled rubber playground tile.*

| Constraint | Description | Criteria | Implication |
|---|---|---|---|
| C1.1 | Size constraint | 24.5 ± 0.05 in x 24.5 ± 0.05 x 2 ± 0.05 in (width x length x thickness) | - As requested by the client, the size of the playground tile is fixed.<br>- The tile mould therefore should also abide by similar sizing. |
| C1.2 | Usage of recycled raw materials | The rubber materials that are used to make the tiles will be sourced from recycled tires. | - Recycled rubber may cause changes in physical and mechanical properties, along with the quality of final product compared to virgin rubber. |
| C1.3 | Compliance of relevant standards | Playground equipment must abide by safety criteria outlined in ASTM | - The prototype must undergo safety testing using the appropriate apparatus outlined in the standard. |

| Constraint | Description | Criteria | Implication |
|---|---|---|---|
| | | F1292, as described in 1.2.4. | - Apparatus to be obtained by Prairie Rubber (RTR company partner) or made in house. |
| C1.4 | Temperature | Manitoba temperature ranges from –40 °C to 40 °C. | - The final prototype of the tile must be able to withstand the temperature range of –40 °C to 40 °C. |
| C1.5 | UV Index | Manitoba summer's experience a UV Index of up to 10. | - The tile must be able to maintain its integrity and physique in harsh Manitoba summers. |
| C1.6 | Budget availabilities | The budget available for this project is provided by the University of Manitoba, with an amount of $500. | - As the testing of prototypes begins, the budget will need to be reviewed by the client to determine if extra funding is needed. |
| C1.7 | Time | The project timeline is a seven-month period between September 2024 and April 2025. | - A project workplan and Gantt chart was required and closely followed to stay on schedule. |
| C1.8 | Tile Connections | Dowel pins are to be used to connect the tiles together to create an adjoined playground surface with multiple tiles. | - Firm request by the client.<br>- Increases the budget compared to using a 'built-in' connection method through moulding connectors. |

### 1.3.4 Project Deliverables

As requested by the client, Team 4 has several deliverables to both aid in the development of the project and ensure a successful final product. These are listed as follows:

- Prototype of the final playground tile.
- Completion of ASTM F1292 Impact Attenuation Standard to determine the safety rating of the final prototype.
- CAD models and drawings of the final tile and mould design, along with fabrication of the mould for proof of concept.
- A Bill of Materials detailing all the raw materials, components, and/or hardware required to create the prototype.
- Performance data from finite element analysis (FEA) simulations and physical testing according to ASTM F1292.
- A final report summarizing the design process, testing results, and recommendations for tile to market.

# 2.0 Design Solution

This section will outline the Team's solution for a rubber playground tile with the subsections organized to reflect the design process followed, comprised of several stages including testing different crumb rubber formulas, optimization of the tile shape, the connection method, visual aesthetics, and manufacturing. Firstly, the design process began with selecting a suitable material composition using crumb rubber, binder, and possibly the addition of rubber fibers, as well as creating an aesthetically pleasing surface. The latter stages involved fabricating a mould that can support the creation of the tile with the desired shape and material. Alongside this, an appropriate connection method was selected that was also integrated into the mould. Lastly, the manufacturing process to produce the product at RTR's facility is described.

## 2.1 Material Formula

The material composition is an important factor of the design that will affect the tile's mechanical performance in terms of user safety and long-term durability. As described in Section 1.2, vehicle tires are shredded by RTR to different sizes of crumb rubber. For the purposes of this project, fine crumb rubber (-20 mesh size) and coarse crumb rubber (3-20 mesh size) are used within the formula selection process. Section 1.2.2 discussed how the process of shredding rubber creates a fiber by-product that is landfilled. To divert waste from the landfill, the fiber is an additional material that is integrated into the formula selection process. Finally, to ensure the rubber material holds its shape after compression moulding, a liquid binder is added to the mixture. Altogether, there were four different materials explored in the formula selection process to create the tiles. By changing the ratios of coarse crumb rubber, fine crumb rubber, rubber fibers, and binder, differences in physical and mechanical properties were attained. These differences affect performance results when measured against the critical ASTM F1292 test and the other verification procedures explored in Section 3.0.

The key to a high-performance product will be the composition of different materials used in the formula. However, the optimal composition is unknown and is thus investigated as part of the scope of this design project and tested against ASTM F1292 (see Section 1.2.4). The benchmark for this process was the formula RTR uses to produce a 'Soft Tile' product. Note that this product is not specifically used for playground purposes but provides a softer feel than RTR's hardscaping

products. As such, the current Soft Tile formula will be used as a baseline for improvement. The formula has [redacted] fine crumb rubber, [redacted] coarse crumb rubber, [redacted] binder, and [redacted] rubber fiber. Using this formula as a benchmark, variations will be created with corresponding 'Method IDs' seen below. Note that the unit of pounds was used to remain consistent with RTR's formulas.

***Table 5.*** *The different changes made to the benchmark formula material composition with corresponding Method IDs and rationales (expected effect of modifications).*

| Method ID | Description of Modification | Rationale |
|---|---|---|
| 1 | Increasing the mass ratio of coarse crumb rubber (or, decreasing the mass ratio of fine crumb rubber) in the formula. | Creates more pores which decreases the bulk density. Pores aid in flexibility of the material. |
| 2 | Adding rubber fibers to the formula. | Improves the sustainability of the product by integrating a waste material into the formula. The fibers are very lightweight and will reduce the overall mass of the tile. |
| 3 | Coarse crumb rubber exclusive (i.e. eliminating fine crumb rubber from the formula). | Creates more pores which decreases the bulk density. Pores aid in flexibility of the material. Improves ease of manufacturing by only using one type of crumb rubber. |
| 4 | Increasing the mass ratio of liquid binder in the formula. | Improves the long-term durability of the product. |
| 5 | Decreasing the mass ratio of liquid binder in the formula. | Aids in flexibility of the material, as there will be less glue holding the particles together. Expected to lower the total density. |
| 6 | Half and half mixture. All fine crumb rubber on top half, all coarse crumb rubber on bottom half. | A top surface comprised of only fine crumb rubber will improve the visual aesthetics of the surface and create a 'softer' feel under feet. |

From the above table, there are a total of six different methods explored in reference to the benchmark formula. Several tiles will be created based on these changes and will provide a diverse set of formulas to test. The formula that performs the best under the Triax Impact Test in

accordance with ASTM F1292 will be selected as the final proposed formula to RTR. The exact compositions of modified formulas are described in the following sub-section.

### 2.1.1 Compilation of Modified Formulas

Modifications were made to RTR's existing Soft Tile product formula to attempt to optimize the material composition in terms of user safety. This Soft Tile formula served as the 'Original' formula, or benchmark, with adjustments made based on the methods in Table 5. Each variation received a unique Formula ID, resulting in ten different formulations as shown in Table 6 below.

***Table 6.*** *The different formulas with their respective Formula ID, Method ID, and material composition in weight percentage. Note that each formula contains enough material to make a set of three tiles.*

| | | **Material Percentages** | | | |
|---|---|---|---|---|---|
| **Formula ID** | **Method ID** | **Coarse (%wt.)** | **Fine (%wt.)** | **Fiber (%wt.)** | **Binder (%wt.)** |
| Original | N/A | [redacted] | [redacted] | [redacted] | [redacted] |
| A | 1 | [redacted] | [redacted] | [redacted] | [redacted] |
| B | 2 | [redacted] | [redacted] | [redacted] | [redacted] |
| C | 1, 2 | [redacted] | [redacted] | [redacted] | [redacted] |
| D | 3, 5 | [redacted] | [redacted] | [redacted] | [redacted] |
| E | 3, 4 | [redacted] | [redacted] | [redacted] | [redacted] |
| F | 2, 3 | [redacted] | [redacted] | [redacted] | [redacted] |
| G | 4 | [redacted] | [redacted] | [redacted] | [redacted] |
| H | 5 | [redacted] | [redacted] | [redacted] | [redacted] |
| I | 6 | [redacted] | [redacted] | [redacted] | [redacted] |

The Team made a sample tile from each formula in Table 6 to test against ASTM F1292 to determine which material composition is the most optimal for user safety. Appendix B contains the material composition for each different formula in pounds. The Team used the formulas in Appendix B to make the tiles at RTR's facility following the manufacturing procedure outlined in

Section 2.4. RTR's existing mould (pre-modification, shown in Appendix C) was used to make the sample tiles.

### 2.1.2 Formula Selection Process

A total of ten sample tiles were made, each with a different material composition according to Table 6. Recognizing that the most critical feature of the playground tile for this project is safety, the ASTM F1292 standard was used to critique the different formulas and select the best one. ASTM F1292 outlines the methods used to classify and quantify the safety rating of playground surfaces, during which a test device is allowed to free fall from a specific height on to the playground surface (in this case the rubber tile) to gather data on the g-max and HIC [1]. Refer to Section 1.2.4 for a description on ASTM F1292. The results from the Triax Impact Test yielded the following results. Note that a lower g-max and HIC value indicate a safer tile in terms of reduced head injury.

***Table 7.*** *Results from the Triax Impact Test at 4 ft fall height for the ten different formulas.*

| Formula ID | g-max | HIC |
|---|---|---|
| Original | 185 | 1125 |
| A | 185 | 1118 |
| B | 181 | 1085 |
| C | 185 | 1108 |
| D | 158 | 854 |
| E | 166 | 915 |
| F | 164 | 927 |
| G | 181 | 1107 |
| H | 184 | 1113 |
| I | 157 | 839 |

The results show that Formula I under Triax Impact had the lowest g-max and HIC values. Therefore, Formula I is said to have the best safety rating out of the ten different material

composition formulas created by the Team. Also recognizing that to pass the Target Specification S1.3 and S1.4, the g-max and HIC should have a value less than 200 and 1000 respectively, at a fall height of four feet. While this is further explored in Section 3.2.1 against the final prototype, the results in Table 7 confirmed that Formula I is the most optimal material composition in terms of user safety. To achieve an even greater safety rating, modifications to the shape of the tile are required as explored in the following subsection.

## 2.2 Mould Design

A mould is required to form the desired shape of the playground tile. The mould acts as an apparatus to contain any given formula while being compressed into a solid form with heat and pressure under a hydraulic press. To help save on expenses from manufacturing a new mould, the decision was made to use existing tile moulds available at RTR and modify them as needed to create a functioning playground tile. The moulds available at RTR are made of aluminum and support the formation of an open-face square tile with dimensions of 24.5 ± 0.05 inches by 24.5 ± 0.05 inches and a thickness of 2 ± 0.05 inches. This is shown in Figure 3 below along with Appendix C showing an engineering drawing of the original mould.



***Figure 3.*** *Existing aluminum mould at RTR.*

When the mould is filled with material, an aluminum sheet metal cover with dimensions of 25 inches by 25 inches and one-eighth inch thick is placed on top. This cover acts to protect the material being moulded from direct heat of the hydraulic press and create a smooth, flat surface. To achieve an innovative, functional playground tile with RTR's existing mould, two major modifications are required which are described in the following subsections.

### 2.2.1 Tile Shape

The first modification required of the mould is to achieve an optimized shape of the tile. Two aspects of the tile shape are considered: the geometric dimensions and the base of the tile. The geometric dimensions of the tile chosen by the Team match the dimensions of the existing mould at RTR, which is 24.5 inches by 24.5 inches and a thickness of 2 inches. While these dimensions grant the use of RTR's mould, the square shape also lends itself suitably to the connection method, discussed in following sub-section. As well, the size allows for a given surface area to be achieved with less tiles as compared to a smaller sized tile. However, it was also important not to oversize the tile to make lifting, carrying, or moving difficult. As such, a tile with the selected dimensions is suitable for the intended application of playground surfacing.

The bottom surface of the tile was altered with a channelled base which acts to improve drainage, increase impact absorption, and reduce its mass. The existing mould gave the tile a rigid, flat base, which offers minimal energy transfer upon impact. Playgrounds are generally constructed with a loose granular substrate like gravel or sand placed underneath the selected playground surfacing product. A flat base does not offer adequate buffer from the hard surface created by the substrate and thus, the new base shape design will aim to increase the buffer between the substrate and tile. Additionally, the flat base lacks drainage capabilities from rain fall or snow melt. This may cause water retention within the tile for long durations and impact performance over time. A saturated tile will also cause puddles to form on the surface, increasing the risk of falls. To address these issues, a design alteration to the tile base was required to improve shock absorption and prevent moisture-related deterioration. An example of such a base to aid in the flexibility and drainage capabilities of the tile is shown in Figure 4.

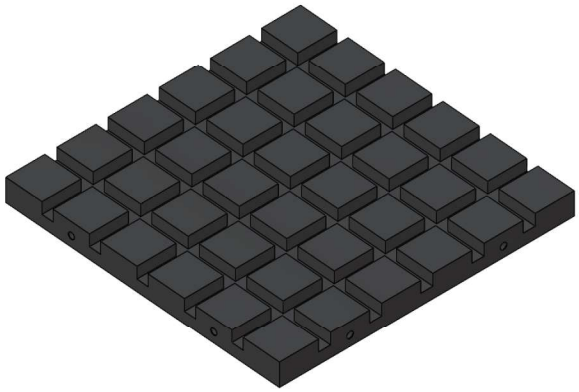


***Figure 4.*** *CAD model of playground tile showing the base design.*

To achieve the base shape shown in Figure 4 above, a grid-shaped aluminum insert is placed within the mould filled with material. This allows the material to be moulded in the shape of the aluminum grid when compressed in the hydraulic press. The insert can be seen in Figure 5 and Figure 6 below.

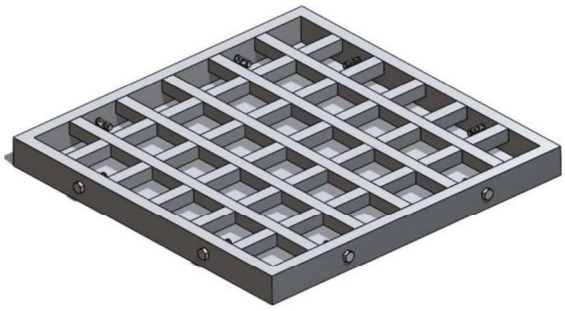


***Figure 5.*** *CAD model of the aluminum grid insert in the mould.*

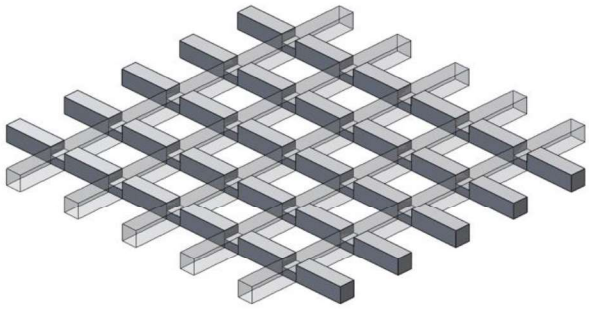


***Figure 6.*** *CAD model of the aluminum grid insert showing the slotted connections.*

As shown in Figure 5 and Figure 6 above, the aluminum insert is made with a series of aluminum bars. The grid insert was achieved by machining square aluminum bars sized appropriately with half-laps so the series of bars can connect to form the grid shape. See Appendix D for engineering drawings of the aluminum bars. The aluminum grid is placed on top of the rubber material after filling the mould, which allows for easy removal post-moulding. Aluminum metal is the required material due to the mould being made of aluminum and the temperature settings of the hydraulic press used.

To determine the most optimal base shape, Finite Element Analysis (FEA) in the SolidWorks Simulation v.2024 program was used. The number and the orientation of the aluminum bars was not chosen arbitrarily. Given that several different base shapes can be achieved by varying the number of aluminum bars, this will affect the total volume of the tile. The resulting displacement of rubber from the base will affect the tile's flexibility which consequently affects its mechanical performance. If too little rubber is displaced, there will be negligible effects in its performance improvement. Conversely, if too much rubber is displaced, the tile may become overly flexible and lose its rigidity and durability. Therefore, FEA was performed on various base shapes to determine the correlation between overall volume of the tile and mechanical performance.

A total of five different base shapes were investigated using orientations that could be achieved with square aluminum bar stock of 24.5 feet total length or less. This criterion was formed to limit the maximum possible material usage, due to the budget constraint given in C1.6. As such, with the given aluminum bar stock, the grid orientations listed in Table 8 were investigated.

***Table 8.*** *The different base shapes investigated, listing the orientation of the bars and the resultant total volume of the tile. Base IDs correspond to decreasing volume.*

| Base ID | Orientation (No. of bars x No. of bars – b x h x l) | Total Volume of Tile ($in^3$) |
|---|---|---|
| B0 | **No bars** | 1200.5 |
| B1 | **3x3** – 1” x 1” x 2’ | 1062.5 |
| B2 | **4x4** – 1” x 1” x 2’ | 1020.5 |
| B3 | **5x5** – 1” x 1” x 2’ | 980.5 |
| B4 | **3x3** – 2” x 2” x 2’ | 942.5 |
| B5 | **4x4** – 2” x 2” x 2’ | 872.5 |

As shown in Table 8, varying the orientation and size of the aluminum bars changes the total volume of the tile as compared to a tile with a flat base shape. Using this information, correlations between the base shape, volume, and mechanical performance as obtained in SolidWorks Simulation can be analyzed.

#### *2.2.1.1 Obtaining the FEA Results*

An applicable loading case must be defined to run an FEA within the SolidWorks Simulation program. The chosen loading case was the force exerted from a human foot, which matches the intended application of the playground tile. A device called a Force Sensing Array (FSA) was used to attain a pressure map of a volunteer’s foot as taken on a playground tile sample. This foot was approximately twelve inches in size, which allowed for an extreme case of human exertion of pressure to be assessed. An image of the pressure map is shown in Figure 7.

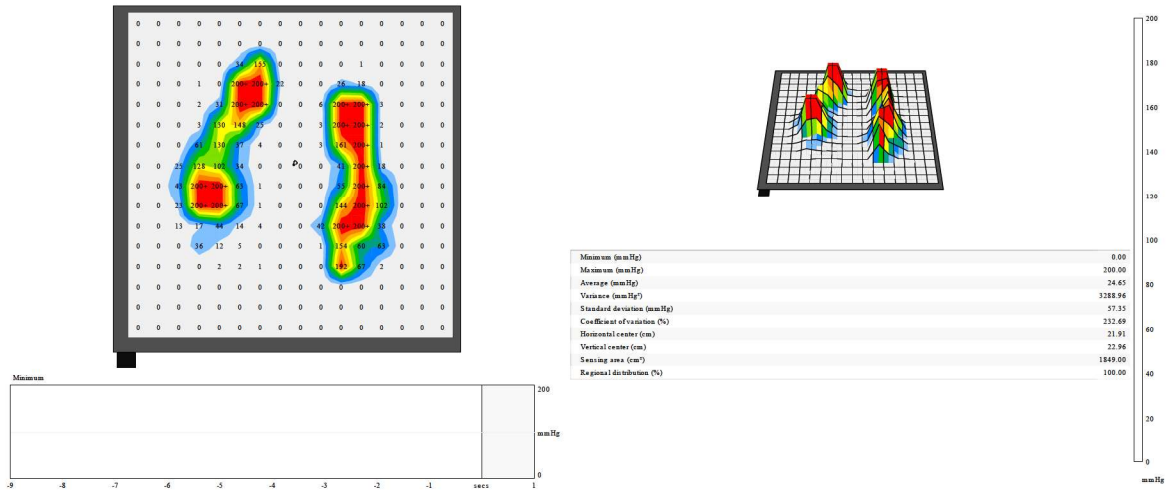



***Figure 7.*** *Force Sensing Array pressure map of bare human feet. Pressure readings are in mmHg.*

To transform the pressure map into workable data and apply it as a loading case within FEA, the .csv data was downloaded from the FSA program and translated into force (Newton units). This pressure and force data can be found in Appendix E. The pressure map contours of the volunteer's right foot in Figure 7 were converted to a .jpeg and imported into ImageJ (v1.53) to create a binary image, attached in Appendix F. The binary image was then converted to a .dxf CAD file to be imported and scaled onto the surface of the playground tile model in SolidWorks, as shown in Figure 8 below.



***Figure 8.*** *CAD model of a playground tile with the surface showing the scaled contoured sketch of the foot, representing the pressure map obtained from the FSA device.*

The imported contours on the surface of the playground tile were used as the loading boundaries. As seen in Figure 8, the separate contours represented a range on the pressure scale. Using the converted pressure to force data, the maximum force experienced on each contour, according to the given range, was applied at each contour boundary. The material properties obtained for Formula I (as found in Section 3.2.2) were applied to the material in the CAD model, as follows:

- Elastic Modulus: 118 270 $N/m^2$
- Poisson's Ratio: 0.3769
- Yield Strength: 14 000 $N/m^2$
- Mass Density: 686 $kg/m^3$

A diagram containing the complete list of material properties used within SolidWorks Simulation can be found in Appendix G. A static study was performed on each CAD model of the different base shapes being investigated with the results given in the following sub-section.

*2.2.1.2 Analyzing the FEA Results*

The results from the FEA study yielded the stress, deformation, and strain energy experienced within the tile. Appendix H contains the visual depictions of the results for stress as shown in SolidWorks Simulation. The data obtained for stress, deformation, and strain energy was exported and analyzed to determine the distributions for these properties and compare the results across the different base shapes. The distributions were plotted and are shown in Figure 9 and10 below, with a sample set showing the transformation to a distribution data set in Appendix I.

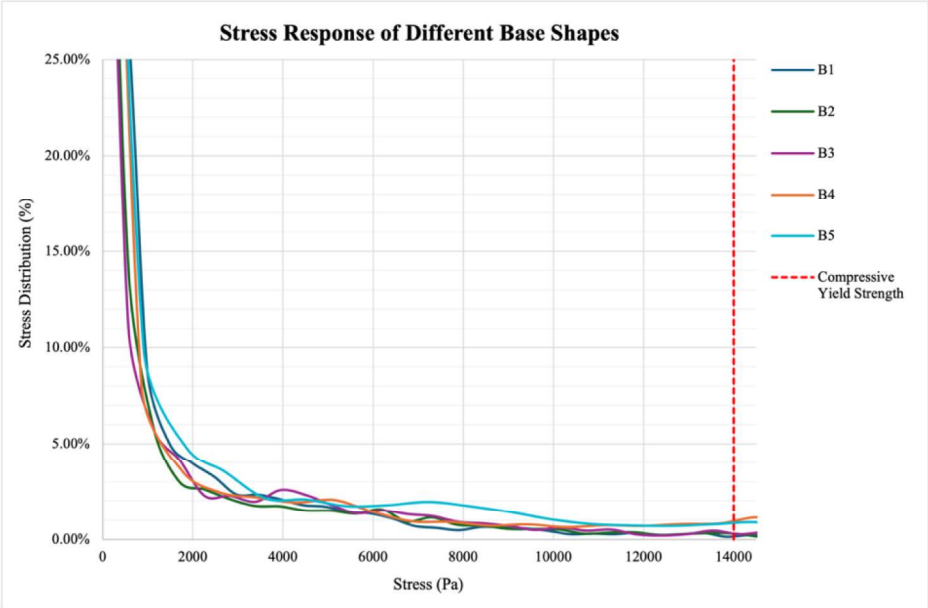



***Figure 9.*** *Stress distribution results for different base shapes obtained through FEA. The y-axis represents the percentage of values that fall within each stress range on the x-axis. A higher percentage indicates a greater concentration of stress at that value.*

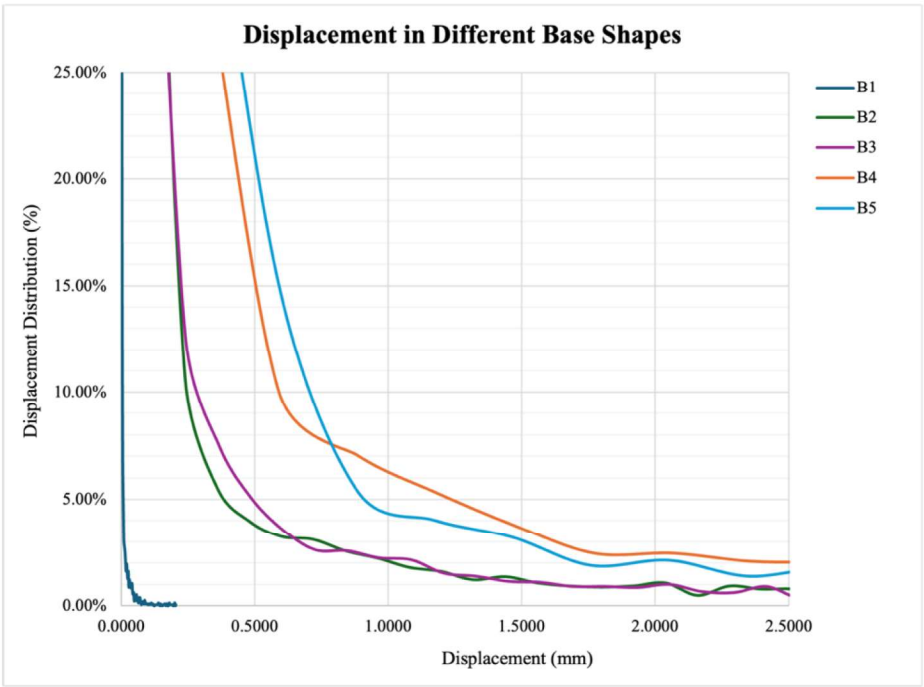



***Figure 10.*** *Displacement distribution results for different base shapes obtained through FEA. The y-axis represents the percentage of values that fall within each displacement range on the x-axis. A higher percentage indicates a greater concentration of displacement at that value.*

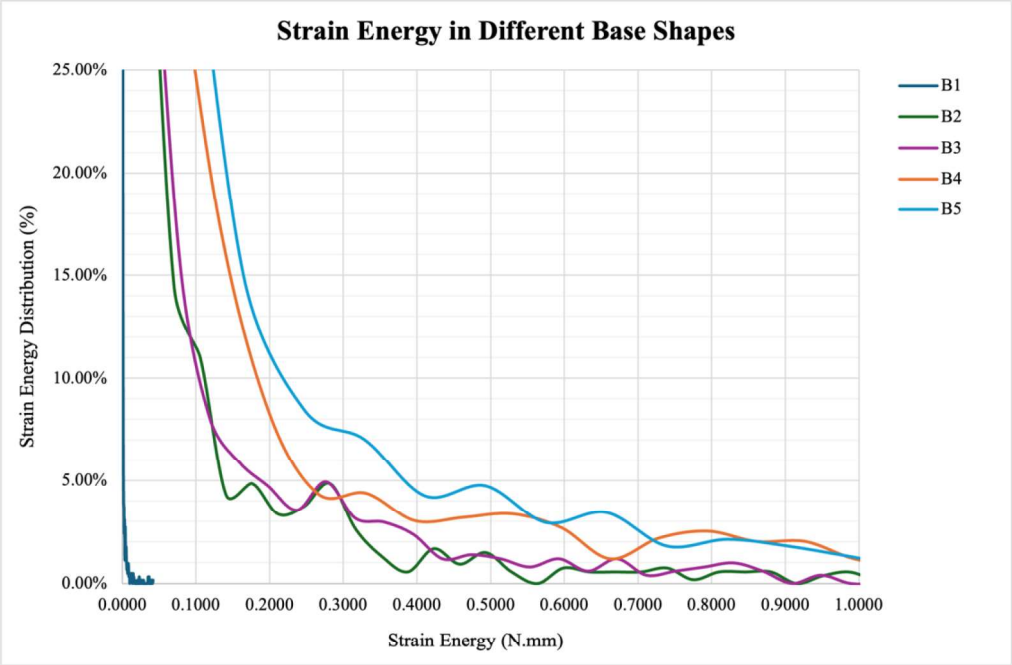



***Figure 11.*** *Strain energy distribution results for different base shapes obtained through FEA. The y-axis represents the percentage of values that fall within each strain energy range on the x-axis. A higher percentage indicates a greater concentration of strain energy at that value.*

The results for stress, displacement, and strain energy were obtained through FEA to evaluate the tile's response to the applied load and identify the base shape that best transmits the load. The results in Figure 9 show that there is minimal variance across the different base shapes in terms of stress distribution. The results in Figure 10 show that base shapes B4 and B5 experience greater displacement as compared to B1, B2, and B3. However, a larger displacement can correlate to greater stress within the material. The results in Figure 11 show that again, the base shapes B4 and B5 experience a greater strain energy, likely due to the greater displacement. A greater strain energy indicates more energy absorption in the tile which will translate to less energy experienced by the user during a fall. However, the overall differences seen between the results for stress, displacement, and strain energy are not significant. A closer look at the results obtained from the transformed stress distribution and strain energy data reveal the following in Table 9 and Table 10 below.

***Table 9.*** *The percentage of stress experienced in the tile that was below the compressive yield strength value (~14kPa) for different base shapes.*

| Base ID | Total Volume of Tile ($in^3$) | Stress Below Compressive Yield Strength (%) |
|---|---|---|
| B0 | 1200.5 | - |
| B1 | 1062.5 | 94.87 |
| B2 | 1020.5 | 91.46 |
| B3 | 980.5 | 90.08 |
| B4 | 942.5 | 73.23 |
| B5 | 872.5 | 80.63 |

***Table 10.*** *The total strain energy experienced in the tile for the different base shapes, relating to the total energy absorbed from the impact.*

| Base ID | Total Strain Energy (N.mm) |
|---|---|
| B1 | 1.9 |
| B2 | 117.1 |
| B3 | 122.5 |
| B4 | 249.7 |
| B5 | 284.7 |

The tabulated results show that in Table 9, as the volume of the tile decreases for B4 and B5, the percentage of stress that exceeds the yield strength increases. B4 and B5 do not transmit the load as effectively compared to B1, B2, or B3. If disregarding B4 and B5, the results in Table 10 reveal that B3 absorbs the most energy from impact, which correlates to less energy translated to a user during a fall. Given that safety is the most critical aspect of this project, B3 was selected as the best base shape for the final prototype. Considering that an additional goal of the base is to efficiently drain water, added grid space on the bottom surface will improve this function. Plus, B3 has the smallest volume compared to B1 and B2, which will also help reduce the total mass of

the tile, aiding in transportation and ease of assembly. The final prototype tile showing the B3 base shape as achieved from the 5x5 aluminum bar grid is shown in Figure 12 and Figure 13 below.

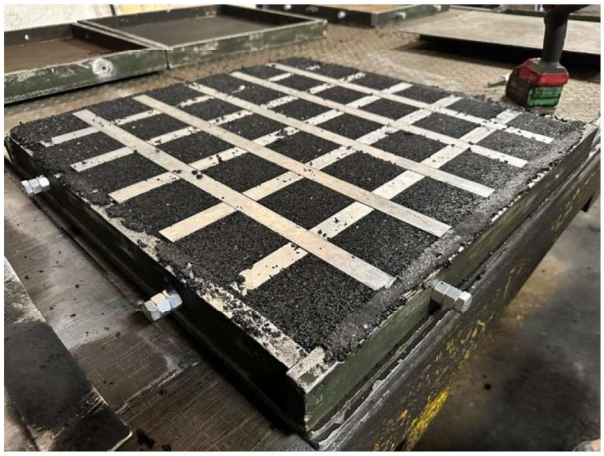


***Figure 12.*** *Post-moulding of tile showing the 5x5 aluminum bar grid to achieve the B3 base shape.*



***Figure 13.*** *Post-removal of tile from mould showing the B3 base shape achieved.*

### 2.2.2 Connection Method

The second modification made to the mould was to achieve a connection method within the production process of the tiles. The decision was made that dowel pins are the ideal connection method. This conclusion was drawn based on the results of a decision matrix that was presented to the client, which can be found in Appendix J. Dowel pins are cylindrical rods that are commonly made of either wood, metal, or plastic, used to align and strengthen adjacent parts. For playground tiles, dowel pins are the ideal solution for two important reasons: first being the ease of assembly and second being ease of manufacturing. Two tiles can be connected by placing one tile on the ground and inserting the dowel pins into holes on the sides of the tile. Then, the second tile would be placed over the opposite ends of the dowel pins, conjoining the two tiles. This creates a very simplistic assembly process with minimal steps involved. To comply with the dowel pins, holes on the walls of the tile were created. These holes could be drilled into the final tile after compression moulding. However, the aluminum mould itself streamlined this process by creating the holes parallel at the time of moulding. The existing moulds were altered by tapping two threaded holes on each wall to insert bolts, as seen in Figure 14 below.

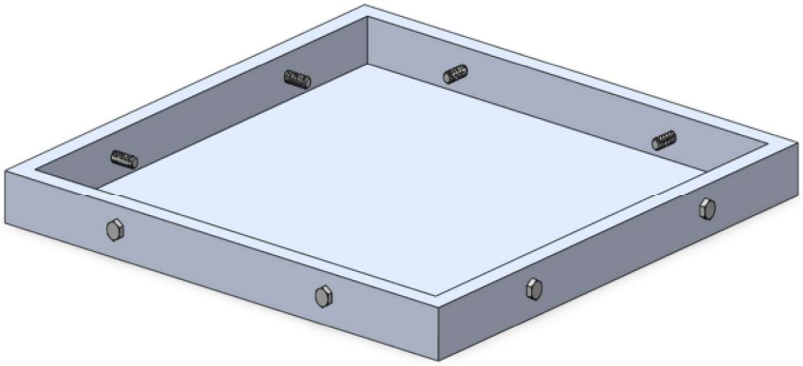


***Figure 14.*** *CAD model of the modified mould with the bolts inserted into the tapped threaded holes.*

As shown above, the addition of threaded holes on each wall of the mould allows a threaded bolt to be inserted prior to filling with rubber material. Then, when filling the mould, material will surround the bolt creating negative space. The bolt type and size can be found in the BOM in Appendix K. Compression moulding will solidify the material into the given shape with resultant holes for either a dowel pin insertion or dowel pin connection. Engineering drawings of the tiles and mould can be found in Appendix L and Appendix M and a demonstration of the dowel pin connections is shown in Figure X below.

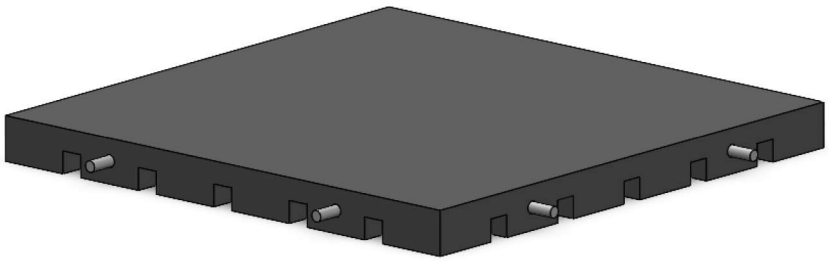


***Figure 15.*** *CAD model of the tile with the dowel pins inserted into the moulded holes.*

PVC plastic was selected as the ideal material for the dowel pins given that plastic is durable outdoors and relatively inexpensive. Bulk PVC rod stock was purchased according to the BOM in Appendix K and cut to appropriate size. A half inch diameter was selected for the dowel pins due to the availability of half inch PVC rod and to also fit within the two-inch-thick size constraint of the tile. For ease of assembly, the dowel pins will be pressed into the tile holes, which will also be half inch diameter from the selected bolts to ensure a contained fit. The dowel pins are cut to a two-inch length which allows for one inch per tile. Given that rubber can expand and contract in

different weather, an extra quarter inch is allotted to the hole, providing a buffer. Each tile will have a total eight holes, or two holes on each wall, for either a dowel pin insertion or connection.

### 2.3 Tile Aesthetics

Many of RTR's existing products remain black in color, matching the tires they are made from. To improve the visual appeal of the product to customers and children, the Team created a coloured surface on the tile with the addition of recycled running shoes. This was completed in accordance with the triple bottom framework to improve sustainability aspects of the design, as discussed further in Section 4.0. Rather than use paints or dyes which have the potential to leach into the environment, the Team took this opportunity to recycle a commonly landfilled waste [11] into value. The outer, bottom sole of a running or athletic shoe is made of high-performance rubber material such as EPDM (carbon) rubber or blown rubber [12]. EPDM rubber is a common alternative to recycled tire crumb rubber given its durability in varying weather conditions [13]. Blown rubber, while not used as an alternative to recycled tire crumb rubber, is very lightweight and flexible [14]. As such, the rubber material coming from running shoes is acceptable to add to the playground tile. The process flow for transforming recycled running shoes into a surfacing material for playground tiles is outlined below.

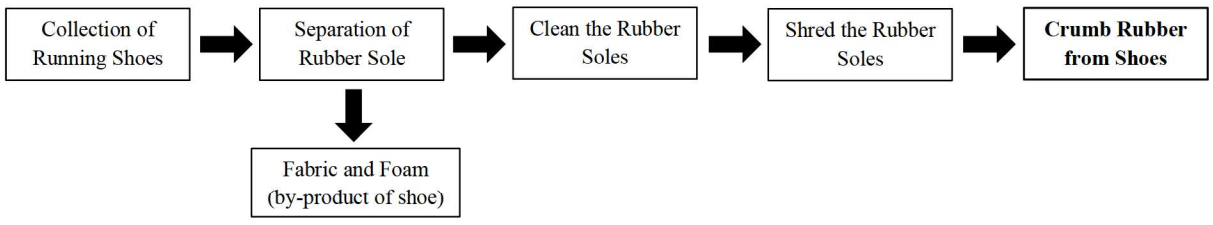



***Figure 16.*** *Flow chart showing the collection, separation, and production process of crumb rubber from recycled running shoes.*

A more detailed procedure for the separation of the rubber sole is described in Appendix N. The Team integrated the crumb rubber from the shoes into Formula I to obtain a sample for proof of concept. The shredded rubber is shown in Figure 17, and the resultant tile is shown in Figure 18.



***Figure 17.*** *The shredded rubber from recycled shoes combined into the Formula I crumb rubber mix.*



***Figure 18.*** *The sample tile created with a top surface composed of shredded recycled rubber from shoes.*

The logistics of integrating rubber from recycled shoes as a material input at RTR is discussed in Section 5.1.4.

## 2.4 Manufacturing Procedure

Following the correct manufacturing procedure is highly important to the resultant quality of the playground tiles. For example, the incorrect mass of crumb rubber poured into each mould will result in inconsistencies, likely causing the tiles to fail. To remain consistent with RTR's current work routines, the manufacturing procedure for the Team's final prototype follows closely with the current procedure for the Soft Tile product. The Soft Tile product is moulded at [redacted]. These settings remained consistent for the new formula, Formula I. The detailed manufacturing procedure to make a set of tiles is outlined in Appendix O, while a basic flow chart below in Figure 19 describes the main steps.

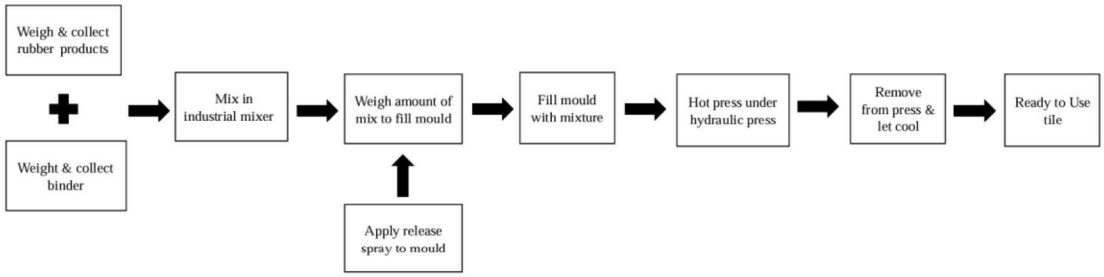



***Figure 19.*** *Flow chart of the tile manufacturing process.*

## 2.5 Summary

The design process for the playground tile explored various material compositions and modifications to the shape itself, optimizing shock absorption, durability, and functionality. After evaluating the formulations, Formula I was selected as the prototype material composition for verification testing. Note that the final prototype did not incorporate recycled shoe material in the surface layer. Due to time constraints, only one tile with the added aesthetic material was made for proof of concept. The following section details the verification testing used to assess the prototype's performance against the key design specifications and objectives. These tests ensure that the selected formula and mould modifications made to the tile allow the product to meet safety and durability requirements. A CAD model demonstrating the final prototype is shown below.



***Figure 20.*** *CAD model of the final prototype design showing the top surface and bottom surface along with the dowel pins and base feature.*

## 3.0 Verification and Evaluation

To ensure the final prototype described in Section 2.0 met the design objectives, various tests were completed. These tests are categorized into physical testing, mechanical testing, and environmental testing. The purpose of these tests is to verify the Target Specifications listed in Section 1.3.2 and evaluate the design's performance as a safe and durable playground surface for outdoor applications. A summary of the Target Specifications is found in Table 11 below.

***Table 11.*** *Summary of Target Specifications and their respective criteria and section.*

| Specification | Description | Criteria | Section |
|---|---|---|---|
| S1.1 | Final dimensions of the playground tile. | 24.5 x 24.5 ± 0.05 in and 2 ± 0.05 in thick | 3.1.2 (Physical Testing) |
| S1.2 | Critical fall height achieved on the playground tile. | Critical Fall Height ≥ 4 ft | 3.2.1 (Mechanical Testing) |
| S1.3 | Maximum acceleration produced by impact, or g-max, on the playground tile. | g-max < 200 g's for 4 ft fall height | 3.2.1 (Mechanical Testing) |
| S1.4 | Impact severity on the playground tile based on the Head Injury Criterion (HIC). | HIC < 1000 for 4 ft fall height | 3.2.1 (Mechanical Testing) |
| S1.5 | Temperature range for maintained durability of the playground tile. | Environmental Durability Range<br>-40 °C to 40 °C | 3.3.1, 3.3.2, 3.3.4 (Environmental Testing) |
| S1.6 | UV index exposure for maintained durability of the playground tiles. | UV Exposure Durability<br>UV index of 9 | 3.3.3 (Environmental Testing) |

| Specification | Description | Criteria | Section |
|---|---|---|---|
| S1.7 | Moisture resistance for maintained durability of the playground tiles. | Volume does not vary more than 5% between pre- and post-saturation. | 3.3.4 (Environmental Testing) |
| S1.8 | Final mass of the playground tile. | Final Mass of Playground Tile $\leq$ 34 lbs | 3.1.1 (Physical Testing) |

To provide supplementary information for the client, additional aspects of the final prototype were evaluated. These tests acted to support some of the verification tests but also provided useful insights to which areas of the design need improvements or modifications. Table 12 below summarize such tests explored.

***Table 12.*** *Summary of supplementary tests completed.*

| Test Name | Description | Section |
|---|---|---|
| Density | Determining the ratio of mass to volume of the prototype's material composition, as requested by the client. | 3.1.3 (Physical Testing) |
| Compression | Subjecting samples to a cyclical compression load to obtain and evaluate the stress-strain curve of the material. | 3.2.2 (Mechanical Testing |
| Hardness | Measuring the material's resistance to localized deformation using the Shore A hardness scale. | 3.2.3 (Mechanical Testing) |
| Drainage Efficiency | Determining the volumetric rate of water drainage through the material. | 3.3.5 (Environmental Testing) |

Recall that the results in Section 2.1.2 led the Team to select Formula I as the material composition for the final prototype tile. As such, the verification and evaluation of the design was completed with sample tiles containing the Formula I material composition.

## 3.1 Physical Testing

The physical material properties are important to the verification and evaluation of the resultant physical characteristics of the prototype. Within this section, the prototype undergoes verification and evaluation against a set of chosen material properties. These properties include its mass, dimensions, and density which describe the overall structure of the tile design.

### 3.1.1 Mass

The mass of the final prototype was obtained to verify S1.8 and confirm that the new product does not weigh more than the old product that it would replace. It is important to maintain a relatively light-weight product to help with ease of assembly and transportation related efforts. This verification was completed according to the methodology described in Table 13. However, due to time constraints, only one full size playground tile containing the modified base was ready at the time of testing. Therefore, an average between three replicates was not obtained which limits the accuracy of the results. In addition to testing the physical prototype, the theoretical mass of the prototype was found. This was completed by using the experimentally tested density of Formula I (see Section 3.1.3) and the expected volume of the tile with and without the selected modified base (see Table X in Section 2.2.1). From these calculations, the mass of the final prototype tile can be verified against the criteria and as well compared against the design with and without the base to see the effect on total mass. These results are tabulated in Table 14.

***Table 13.*** *Methodology for the Mass test.*

| Category | Details |
|---|---|
| Purpose | To verify the mass of the final prototype. |
| Criteria | Mass of the final prototype should not be more than 34 lb., i.e. the current mass of the Soft Tile product at RTR. |
| Materials | Three full size prototype tiles. |

| Category | Details |
|---|---|
| Equipment | Scale large enough to properly weigh the full-size prototype. |
| Procedure | Refer to Appendix P.1. |
| Results | Pass |

***Table 14.*** *Results of the Mass test for the prototype tile with and without the modified base.*

| Sample | Theoretical Mass (lb) | Experimental Mass (lb) |
|---|---|---|
| Modified Base | 24.5 | 30.0 |
| No Modified Base | 30.0 | 33.1 |

The results in Table 14 show that the mass of the final prototype with the modified base passes the given set of criteria with a total mass of 30.0 lbs. The results also confirm that the addition of the modified base successfully reduces the total mass. However, according to the theoretical mass, the final prototype weighs significantly more than expected. The potential reasonings for this are discussed in Section 5.0.

### 3.1.2 Dimensions

The dimensions of the final prototype were obtained to verify S1.1 and confirm the mould achieved the required size and consistency across a set of tiles. Especially given the context of this project, the verified dimensions will be useful to RTR when working with the base design and mix to either scale the tile or improve the manufacturing process. The tile dimensional consistency is essential information for quality control measures to keep the tile production consistent and supplying the customers with accurate product information. This verification was completed according to the methodology described in Table 15. Note that the three replicate prototype tiles tested did not contain the modified base, but its absence does not affect the dimensional readings. The results are tabulated in Table 16.

***Table 15.*** *Methodology for the Dimensions test.*

| Category | Details |
|---|---|
| Purpose | To verify the dimensions of the final prototype. |
| Criteria | Length and width of the tile can be 24.05 ± 0.5 in and the thickness can be 2 ± 0.05 in. |
| Materials | Three full size prototype tiles. |
| Equipment | Measuring tool (measuring tape and/or calipers). |
| Procedure | Refer to Appendix P.2. |
| Results | Pass |

***Table 16.*** *Results for the Dimensions test including the average and standard deviation for evaluation. Green indicates it meets the criteria.*

| Replicate | Length (in) | Width (in) | Thickness (in) |
|---|---|---|---|
| 1 | 24.47 | 24.55 | 1.965 |
| 2 | 24.55 | 24.55 | 1.950 |
| 3 | 24.55 | 24.55 | 1.972 |
| Average | 24.52 | 24.55 | 1.96 |
| Std. Dev. | 0.046 | 0.000 | 0.011 |

The results were averaged to give the average length, width and thickness across a set of three prototype samples. The average size of the final prototype is 24.52 in by 24.55 in and 1.96 in thick which falls within the accepted criteria. The standard deviation was also calculated to determine the deviation of size between the three replicate prototypes. As the results show, the standard deviation is minimal, and the moulds achieve a controlled set of dimensions across the set of tiles.

### 3.1.3 Density

Density is an important physical property of materials in terms of product design. Especially given the context of this project, the density of the selected formula will be useful to RTR when working

with the mix to either scale the tile or improve the manufacturing process. It also allows for the calculation of other important physical properties, as shown in Section 3.1.1, and is an important parameter to run FEA computer simulation of a specific material. So, while testing for the formula's density does not act to verify a Target Specification in Section 1.3.2, it acts as supplementary information for the client. For simplicity, the apparent density is tested rather than the true density. The methodology to complete this test is described in Table 17 along with the results in Table 18.

***Table 17.*** *Methodology for the Density test.*

| Category | Details |
|---|---|
| Purpose | To determine the density of the selected material composition formula, Formula I. |
| Criteria | N/A, test completed for evaluation purposes. |
| Materials | Three prototype tile samples with no modified base (to simplify volume calculation). |
| Equipment | Scale, measuring tool. |
| Procedure | Refer to Appendix P.3. |
| Results | Density obtained. |

***Table 18.*** *Results from the Density test.*

| Replicate | Density ($lb/ft^3$) |
|---|---|
| 1 | 40.09 |
| 2 | 42.11 |
| 3 | 46.33 |
| Average | 42.84 |

The results obtained from the Density test give three different readings which are then averaged to define the apparent density of Formula I. The average apparent density of Formula I is 42.84 $lb/ft^3$

or 0.025 lb/in$^3$. This value was utilized in the calculation of the theoretical mass of the prototype (Section 3.1.1) and the FEA for determining the best base shape (Section 2.2.1).

## 3.2 Mechanical Testing

The mechanical material properties of the final prototype are critical to the verification and evaluation of its performance in terms of safety and durability. Identifying the mechanical material properties will help in understanding how the material behaves under different types of loading which is important given the prototypes use case. Within this section, the prototype undergoes verification and evaluation testing against a set of chosen material properties. These properties include its critical fall height as obtained from ASTM F1292, Poisson's ratio, compressive yield strength, modulus of elasticity, and Shore A hardness.

### 3.2.1 Triax Impact Test

The Triax Impact Test is the most critical test to perform on a playground surfacing product to quantify it's standard of safety, as described in Section 1.2.4. The Triax device is designed to follow the ASTM F1292 standard [1] and obtain the necessary performance indicators of the playground surface to define its safety rating (i.e. critical fall height). This test was completed on the Team's final prototype tile and several Target Specifications were verified. These included S1.2, S1.3, and S1.4 which looks at the achieved critical fall height, the g-max value measured in g's, and the Head Injury Criterion value (HIC), respectively. The methodology used to complete the Triax Impact Test is adapted from ASTM F1292 and described in Table 19. The surface temperature of the prototype was taken before running the test, which was 18.9°C. The surface temperature is an important indicator of the environmental conditions the test was completed in. This test was completed in standard room temperature conditions. It was important to maintain room temperature conditions and not perform the test in an overtly hot or cold room as this would have skewed the results. The results are tabulated in Table 20.

***Table 19.*** *Test methodology for Triax Impact Test.*

| Category | Details |
|---|---|
| Purpose | To determine if the final prototype is in accordance with the ASTM F1292 standard at a 4 ft fall height. |

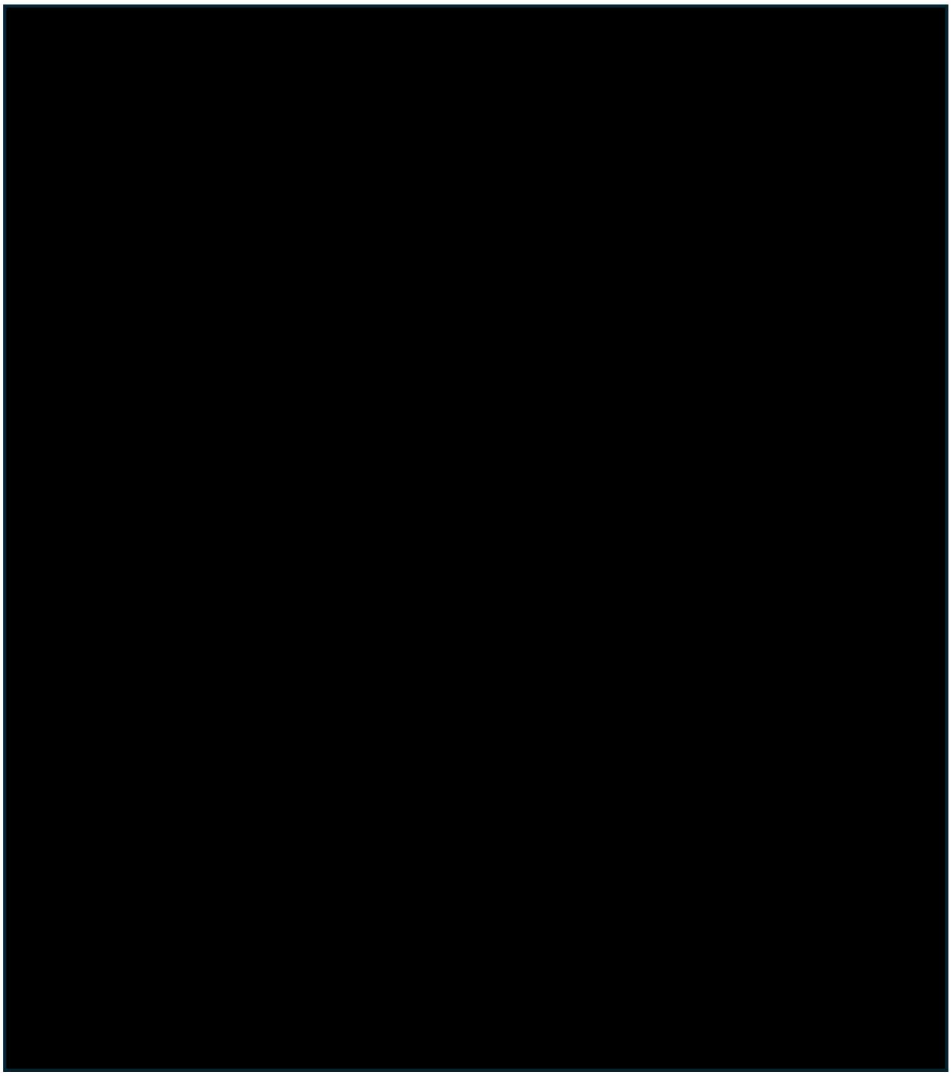
| Category | Details |
|---|---|
| Criteria | The readings obtained must give g-max score < 200, HIC < 1000, and critical fall height ≥ 4 ft. |
| Materials | Three full size prototype tiles. |
| Equipment | Triax impact test device missile and drop mechanism system, temperature measuring device.  ***Figure 21.*** *Triax Impact Test setup.* |
| Procedure | Refer to Appendix P.4. |
| Results | Pass |

***Table 20.*** *Results of the Triax Impact Test. Green indicates it meets the criteria.*

| Reading No. | g-max | HIC |
|---|---|---|
| 1 | 149 | 808 |
| 2 | 149 | 817 |
| 3 | 153 | 857 |
| *Average* | 150 | 827 |

As described in ASTM F1292, the critical fall height of the prototype is defined by determining the maximum drop height at which the test results meet the criteria, rounded to the nearest whole foot [1]. Table 20 demonstrates that the playground tile passes the Triax Impact Test at a drop height of 4 ft. Therefore, the critical fall height of the final prototype is 4 ft. The prototype was also tested at 5 ft but did not pass. These results are in Appendix Q.

As described in Section 1.3.2, when RTR officially certifies their product against ASTM F1292 with a reputable third-party company, the product will be tested against extreme weather conditions and additional heights. The purpose of these results is to provide the client with a baseline understanding of how the prototype performs against the Triax Impact Test and if additional modifications are needed before investing in official ASTM F1292 certification.

### 3.2.2 Compression

Compression testing is a valuable method for determining important material properties that help in understanding a material's mechanical behaviour. Through compression testing, several material properties of Formula I were identified including Poisson's ratio, yield strength, and elastic modulus. Note that while these properties are valuable for evaluating the performance of the formulas under a set of load conditions, they will not impact the pass or fail criteria outlined in Section 3.2.1. The critical fall height for this project is governed only by the outcomes of the Triax Impact Test. Further considerations regarding the safety performance of the tile from additional testing is at the discretion of the client. The methodology used for compression testing was adapted from ASTM D575 Rubber Properties in Compression and ASTM D1349 Rubber Properties in Compression. Additionally, the samples were compressed 12mm which is approximately half the

height of the sample. This aligns with ISO 7743 Rubber Determination of Compression Stress-Strain Properties. The complete methodology for the compression tests is outlined in Table 21.

***Table 21.*** *Methodology for the Compression test.*

| **Category** | **Details** |
|---|---|
| Purpose | To determine the material properties of the selected material composition, Formula I. |
| Criteria | N/A, test completed for evaluation purposes. |
| Materials | Three prototype samples, cut to 1" x 1" x 2" thick (l x b x h). |
| Equipment | Compression testing machine, data acquisition system, calipers. |
| Procedure | Refer to Appendix P.5. |
| Results | Force versus deformation data. |

The data obtained from the Compression test was transformed to plot the Stress versus Strain curve, which allows for material characterization of the Formula I sample. This was completed as follows.

Stress at any point can be evaluated using the following equation with the approximate cross section area (CSA) of the sample size [15] being approximately 25.4 mm x 25.4 mm.

$$\sigma = \frac{F_{applied}}{CSA}\ kPa \tag{1}$$

The Poisson's ratio is calculated as the negative ratio of transverse strain to axial strain and can be determined using the following formula [15].

$$\nu = \frac{d\varepsilon_{transverse}}{d\varepsilon_{axial}} \tag{2}$$

Strain at any point is evaluated as the change in length divided by the object's initial length [15]. Changes in length were measured using calipers during the point at which the sample was compressed 12 mm.

$$\varepsilon = \frac{L - L_0}{L_0} \tag{3}$$

Modulus of elasticity and yield strength are obtained directly from the resultant stress versus strain curve of the material.

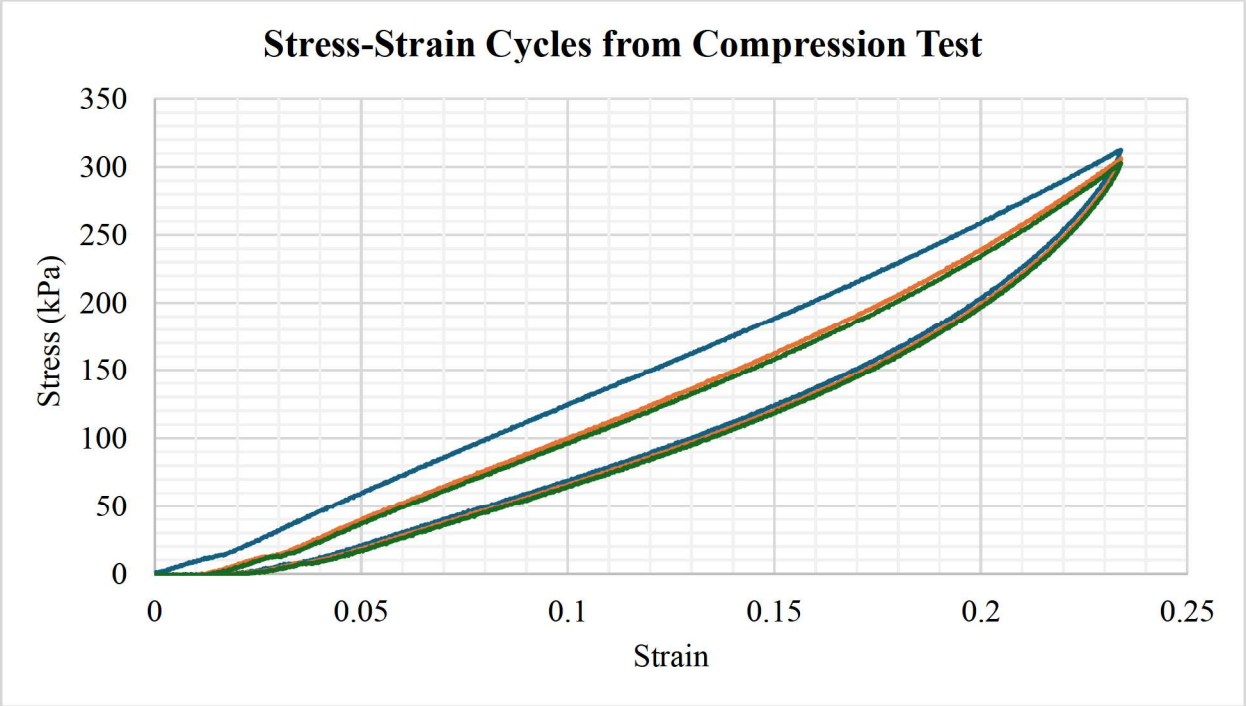



***Figure 22.*** *Stress vs Strain curve under three cyclical compression loadings for Formula I replicate one sample at room temperature (25$^{O}$C). Blue = Cycle 1, orange =Cycle 2, green = Cycle 3.*

Observations made in Figure 22 above show early yield at little strain, however complete fracturing was not experienced by the sample for the entire 12mm displacement. As such, a compressive ultimate strength value was not obtained. Additionally, successive yields did not have a large impact on the strength of the material. This is evident by succeeding cycles following the same trend as opposed to the initial cycle. Note that the area difference between successive cycles represents the percent energy recovered. The yield strength is identified at the section of the graph where initial linearity ends and the material transitions from elastic to plastic deformation. This is noted in the in figure 23 below. For the modulus of elasticity, the linear elastic region was extracted from the stress strain curve and Excel's trendline function was used to find the slope of that line. Additionally, an $R^2$ value was retrieved to ensure the line exhibited linear behaviour. This is seen in the following figure.

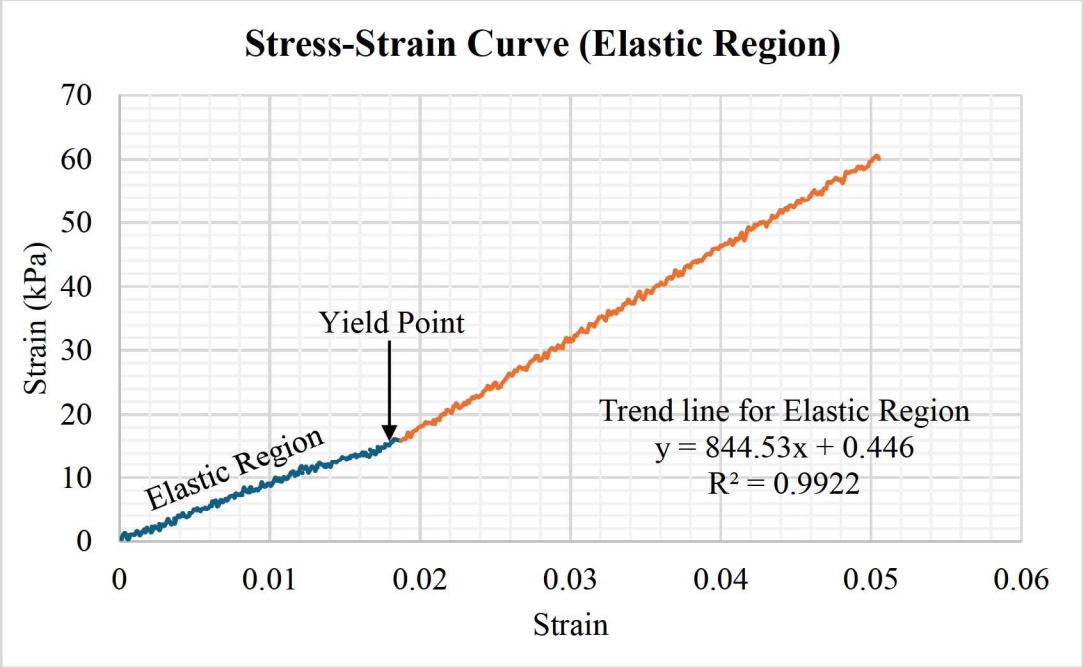



***Figure** 23. Stress vs Strain curve of Formula I replicate one sample at room temperature (25 °C), focused on the elastic region.*

***Table 22.** Averaged properties for Formula I identified from the Compression Test completed at room temperature for three replicates.*

| Avg. Poisson's ratio | Avg. Yield Strength (kPa) | Avg. Modulus of Elasticity (kPa) | Stress at 12 mm for initial loading (kPa) |
|---|---|---|---|
| 0.377 | 14 | 868.24 | 312 |

The properties in Table 22 were identified as valuable material properties as they can be used as comparative indicators of how the material behaves under different loading conditions. The stress to compress 12 millimeters will be used to compare with extreme temperature samples and from this understand how stiff the material becomes under different conditions. The Poisson's ratio, compressive yield strength, and modulus of elasticity assisted with performing FEA in Section 2.2.1.1, the environmental compression tests in Section 3.3.1 and Section 3.3.2, and provides general information about Formula I for the client.

### 3.2.3 Hardness

Hardness is a commonly used material property for rubber and is defined as the material's ability to withstand localized deformation. For rubber materials, the Shore A hardness scale is used. The scale has a range of one to one hundred, ranging from very soft to very hard. For the purposes of this project, a material with a low hardness reading is ideal. While the hardness test does not achieve a Target Specification, it is a useful indicator to evaluate the softness of the prototype. The methodology used to complete the Hardness test is adapted from the ASTM D2240 standard and is described in Table 23. The results are tabulated in Table 24.

***Table 23.*** *Methodology for the Hardness test.*

| Category | Details |
|---|---|
| Purpose | To determine the Shore A hardness of the selected material composition, Formula I. |
| Criteria | N/A, test completed for evaluation purposes. |
| Materials | Five prototype samples. |
| Equipment | Manual Shore A Scale Durometer |
| Procedure | Refer to Appendix P.6. |
| Results | Hardness readings obtained. |

***Table 24.*** *Results from the Hardness test.*

| Reading No. | Hardness (Shore A) |
|---|---|
| 1 | 28.3 |
| 2 | 26.2 |
| 3 | 34.1 |
| 4 | 36.3 |
| 5 | 26.3 |
| Average | 30.2 |

The results obtained from the Hardness test give five different readings which are then averaged to give an average hardness of 30.2 for Formula I. This is a rather low number on the Shore A Hardness Scale and indicates that the surface of the formula has a relatively low resistance to localized deformation. Again, while these results do not directly achieve a specific Target Specification, it provides useful information to RTR that they can communicate to potential customers. It as well gives another indicator of the 'softness' of Formula I versus the Triax Impact Test or Compression test.

## 3.3 Environmental Testing

The client has requested a playground tile product that is durable for outdoor use in Manitoba weather. Therefore, a set of tests were completed to evaluate the durability of the tile in different environmental conditions. Within this section, the prototype undergoes verification and evaluation testing for extreme cold, heat, UV, and moisture exposure. As well, the drainage efficiency of water through the prototype is determined.

### 3.3.1 Extreme Cold

The prototype was subjected to extreme cold environmental conditions to assess its durability for outdoor use according to S1.5. To perform this test, the prototype was conditioned at freezing temperatures for twelve days. Following this period, a visual inspection was performed to identify any signs of decay. Additionally, a Compression Test was completed to quantify the effects of cold exposure on the material's properties. The complete methodology for this test is described in Tables 25 and 21.

***Table 25.*** *Methodology for the Cold Compression test.*

| Category | Details |
|---|---|
| Purpose | To determine the effect of cold temperatures to the selected material composition formula, Formula I. |
| Criteria | No visual signs of disintegration or surface degradation. Material properties should not differ by 25% from the results in Section 3.2.2. |
| Materials | Three prototype samples, cut to 1" x 1" and 2" thick, exposed to freezing environmental conditions for a set duration. |

| Category | Details |
|---|---|
| Equipment | Compression testing machine, data acquisition system, calipers, freezer (if needed). |
| Procedure | Refer to Appendix P.7 (and Appendix P.5 for Compression Test). |
| Results | Visual inspection: Pass. Material properties: Fail. |

After exposure to freezing temperatures, visual inspection confirmed that the sample remained intact with no visible deterioration. However, the material property testing revealed deviations from room temperature results. Similar to Section 3.2.2, the stress versus strain curve (see Appendix R) was used to determine the Poisson's ratio, yield strength, modulus of elasticity, and stress at 12 mm displacement. The average values from three replicates were compared between cold and room temperature conditions, with percentage differences calculated. Results are summarized in Table 26.

***Table 26.*** *Material properties for Formula I identified from the Cold Compression Test versus the Compression Test under room temperature. Green indicates it meets criteria. Red indicates it does not meet the criteria.*

| Internal Temp. (°C) | Avg. Poisson's Ratio | Avg. Yield Strength (kPa) | Avg. Modulus of Elasticity (kPa) | Avg. Stress at 12 mm (kPa) |
|---|---|---|---|---|
| 25 | 0.379 | 10.6 | 1973.9 | 363.2 |
| -10 | 0.380 | 9.9 | 2766.2 | 471.1 |
| **Difference (%)** | **0.26** | **6.83** | **33.43** | **25.87** |

The results indicate that that the durability of the prototype in extreme cold conditions cannot be confirmed. Based on the test criteria, which requires material properties to not differ by more than 25%, the Poisson's ratio and modulus of elasticity do not meet this. The general trend observed from the data is that Formula I becomes more brittle and stiffer after being prolonged cold exposure, as reflected in the increased modulus of elasticity and stress at 12mm compression. These changes suggest that the behavior of the prototype in freezing temperatures is unpredictable. However, the yield strength remains within acceptable limits, indicating that some aspects of the material's integrity are maintained. While this test provided insight into how the prototype may

perform outdoors, further Triax Impact Testing on a frozen sample is required to confirm any conclusions.

### 3.3.2 Extreme Heat

The prototype was subjected to extreme heat conditions to assess its durability for outdoor use according to S1.5. To perform this test, the prototype was conditioned in a hot oven for twelve days. Following this period, a visual inspection was performed to identify any signs of decay. Additionally, a Compression Test was completed to quantify the effects of heat on the material's properties. The complete methodology for this test is described in Tables 27 and 21.

***Table 27.*** *Methodology for the Hot Compression Test.*

| Category | Details |
|---|---|
| Purpose | To determine the effect of hot temperatures to the selected material composition, Formula I. |
| Criteria | No visual signs of disintegration or surface degradation. Material properties should not differ by 25% from the results in Section 3.2.2. |
| Materials | Three prototype samples, cut to 1" x 1" and 2" thick, exposed to hot environmental conditions for a set period of days. |
| Equipment | Compression testing machine, data acquisition system, calipers, oven set to 60 °C. |
| Procedure | Refer to Appendix P.8 (and Appendix P.5 for Compression Test). |
| Results | Visual inspection: Pass. Material properties: Fail. |

After exposure to extreme heat, visual inspection confirmed that the sample remained intact with no visible deterioration. However, the material property testing revealed slight deviations from room temperature results. Similar to the Section 3.2.2, the stress versus strain curve (see Appendix Q) was used to determine the Poisson's ratio, yield strength, modulus of elasticity, and stress at 12 mm displacement. The average values from three replicates were compared between hot and room temperature conditions, with percentage differences calculated. Results are summarized in Table 28.

***Table 28.*** *The obtained material properties for Formula I sample from the Hot Compression Test. Green indicates it meets the criteria. Red indicates it does not meet the criteria.*

| Internal Temp. (° C) | Avg. Poisson's Ratio | Avg. Yield Strength (kPa) | Avg. Modulus of Elasticity (kPa) | Avg. Stress at 12mm (kPa) |
|---|---|---|---|---|
| 25 | 0.379 | 10.8 | 1973.9 | 363.2 |
| 51 | 0.428 | 10.1 | 1427.1 | 342.8 |
| **Difference (%)** | **12.14** | **6.70** | **32.16** | **5.80** |

The results show that the material properties do not fully meet the criterion and therefore, cannot be confirmed durable in extreme heat conditions. The general trend observed from the data is that Formula I becomes softer due to the thawing of the binder after exposure in convection ovens, as reflected in the decreased modulus of elasticity and stress required for 12 mm compression. However, it is worth noting that the Poisson's ratio, yield strength, and stress at 12 mm compression are within the acceptable limit indicating that most of the material's integrity is preserved. Again, further Triax Impact Testing is required to confirm the outcome of the material's behavior in extreme heat.

### 3.3.3 UV Exposure

This test acts to subject the prototype to bright daylight conditions and evaluated Formula I is suitable during harsh UV index days. Following exposure, the prototype is then inspected for UV-related deterioration and compared to tile samples kept indoors. The methodology for this test is outlined in Table 29.

***Table** 29. Methodology for the UV Exposure test.*

| Category | Details |
|---|---|
| Purpose | To determine the effect of UV exposure to the selected material composition, Formula I. |
| Criteria | No visible damage and no damage detected to the molecular structure on a microscope level. |
| Materials | Three prototype samples, cut to 1" x 1" and 2" thick. |

| Category | Details |
|---|---|
| Equipment | Inventronics LED UV lights. |
| Procedure | Refer to Appendix P.9. |
| Results | N/A |

Due to the unavailability of UV light equipment with the required intensity, the testing could not be completed during the duration of this project. However, it is recognized that rubber material generally has a high resistivity against UV light due to the microstructural properties and cross links within the material [16]. While the test could not conclude, it is not detrimental piece of information to the development of the prototype.

### 3.3.4 Moisture Exposure

The prototype was subjected to extreme moisture to assess its durability for outdoor use according to S1.5. To perform this test, the prototype was immersed in a bath of water for a period of 24 hours. Following this period, a visual inspection was performed to identify any signs of decay and the percentage change in volume between replicates was measured. Minimizing expansion is critical for playground tiles, as they are designed to fit seamlessly with little to no expansion buffer. Excessive volume increase could introduce stress, affecting the material's longevity. The methodology for this test is described in Table 30. The results for volume are listed in Table 31.

***Table 30.*** *Methodology for the Moisture Exposure test.*

| Category | Details |
|---|---|
| Purpose | To determine the effect of moisture on the selected material composition, Formula I. |
| Criteria | No visual signs of disintegration or surface degradation. Samples do not vary in volume by more than 5% between pre- and post-immersion. |
| Materials | Three prototype samples cut to 5" x 5" and 2" thick (to fit in bucket), room temperature water. |
| Equipment | Scale, bucket to hold water and submerged sample, measuring tool, thermohydrometer. |
| Procedure | Refer to Appendix P.10. |

| Category | Details |
|---|---|
| Results | Visual inspection: Pass. Saturated volume: Fail. |

***Table 31.*** *Volume of the samples pre- and post-immersion test. Green indicates it meets the criteria. Red indicates it does not meet the criteria.*

| Replicate No. | Volume Pre-Immersion ($in^3$) | Volume Post-Immersion ($in^3$) | Difference (%) |
|---|---|---|---|
| 1 | 53.8 | 58.3 | **8.03** |
| 2 | 52.8 | 56.2 | **6.24** |
| 3 | 54.9 | 59.0 | **7.19** |

After exposure to extreme moisture, visual inspection confirmed that the sample remained intact with no visible deterioration. However, the results in Table 30 demonstrate that the percent change in volume between the samples pre- and post-immersion fail to meet the criteria. After immersion in water, the volume of the samples expands notably.

### 3.3.5 Drainage Efficiency

To assess the drainage efficiency of the prototype, it was subjected to extreme moisture conditions. The test involved submerging the prototype in water for 24 hours. Following this period, its mass was recorded at hourly intervals to determine the rate of water loss. While this test does not act to verify a Target Specification, is important to understand how efficiently the playground tiles release water from its pores. Efficient drainage is crucial in preventing internal stress due to moisture expansion. The methodology for this test is described in Table 32 along with the results in Figure 24.

***Table 32.*** *Methodology for the Drainage Efficiency test.*

| Category | Details |
|---|---|
| Purpose | To determine the volumetric rate at which water drains through the selected material composition formula, Formula I. |
| Pass/Fail Criteria | N/A, test completed for evaluation purposes. |

| Category | Details |
|---|---|
| Materials | Three prototype samples cut to 5” x 5” and 2” thick (to fit in bucket), room temperature water. |
| Equipment | Scale, bucket to hold water and submerged sample, measuring tool, thermohydrometer. |
| Procedure | Refer to Appendix P.11. |
| Results | Volumetric rate found. |

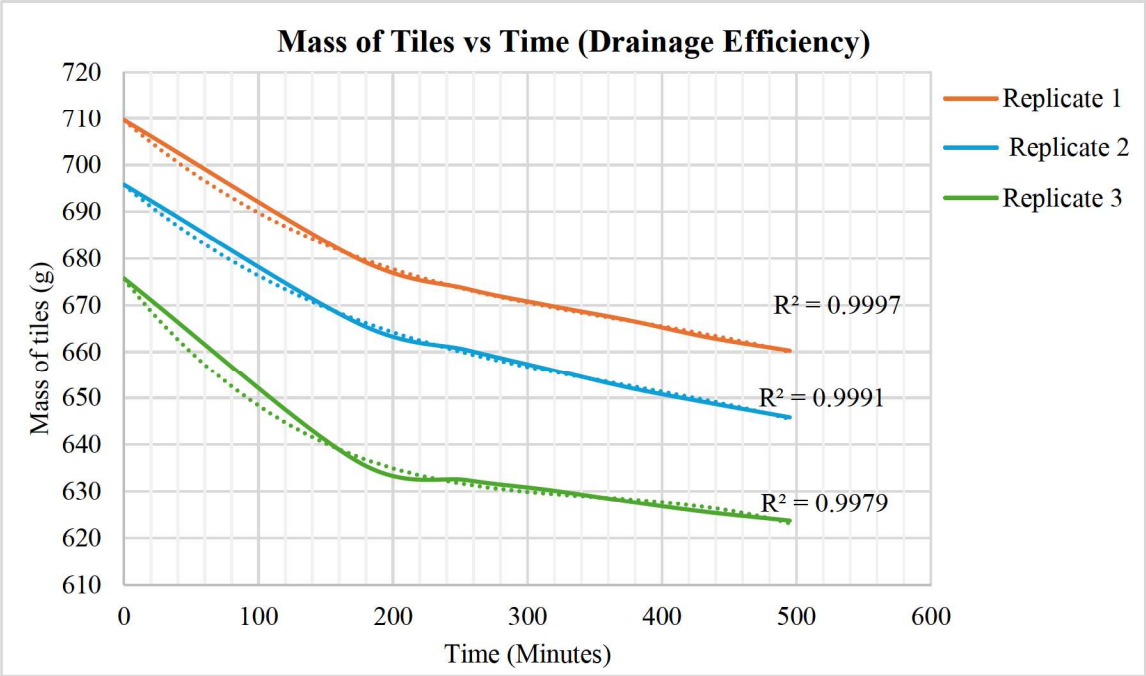



***Figure 24.*** *Graph showing drainage rate of water from the tiles.*

The raw data as measured during the test and the fitted trendline equations are given in Λppendix X. The time taken for the tiles to return to their initial mass was not recorded as the test was very time-consuming. However, using the trendline equations obtained from the plot for each sample, the theoretical time taken for all the water to be drained can be found. This is given in Table 33.

***Table 33.*** *Original mass of the tile replicates and the time it takes to return to the same mass.*

| Replicate No. | Initial Mass (g) | Time to Return to Initial Mass (hours) |
|---|---|---|
| 1 | 617.7 | 14.88 |
| 2 | 605.3 | 14.45 |
| 3 | 593.3 | 12.28 |
| Average | --- | 13.87 |

Therefore, the average time for the water to drain through Formula I samples is 13.87 hours or approximately half a day. Note that this test was conducted with solid 5" x 5" and 2" thick samples and the results will expectedly vary for a sample containing the modified base, designed to drain water more effectively.

### 3.4 Summary

The tests completed on the final prototype playground tile were done so to verify the Target Specifications in Section 1.3.2 or to provide informational support to evaluate the design. A summary of the specifications tested within this section is listed in Table 34 below, along with whether it was verified or not from the test results.

***Table 34.*** *Summary of Target Specifications tested and verification results.*

| Specification | Description | Results |
|---|---|---|
| S1.1 | Final dimensions of the playground tile. | Pass. The dimensions are within the requested size. |
| S1.2 | Critical fall height achieved on the playground tile. | Pass. The prototype achieved the minimum fall height of 4 ft. |
| S1.3 | Maximum acceleration produced by impact, or g-max, on the playground tile. | Pass. The prototype achieved g-max less than 200 g's. |
| S1.4 | Impact severity on the playground tile based on the Head Injury Criterion (HIC). | Pass. The prototype achieved a HIC less than 1000 at 4 ft. |

| Specification | Description | Results |
|---|---|---|
| S1.5 | Temperature range for maintained durability of the playground tile. | Fail. The prototype material properties did change beyond 25% after exposure to different environments. |
| S1.6 | UV index exposure for maintained durability of the playground tiles. | N/A |
| S1.7 | Moisture resistance for maintained durability of the playground tiles. | Fail. The change in volume exceeded 5% pre- and post-saturation. |
| S1.8 | Final mass of the playground tile. | Pass. The final prototype's total mass is less than 34 lb. |

## 4.0 Sustainability

Sustainability is an important consideration is engineering design that attempts to balance environmental, social, and economic needs and impacts. In the development of the rubber playground tile project, sustainability principles have been integrated to minimize waste, enhance product longevity, and promote circular economy practices as well as recognize the product's benefit to society at large. A focus on sustainability not only acts to reduce costs but also supports green innovation and improves efficiency in manufacturing and implementation. For this project, the Triple Bottom Line framework was employed, evaluating environment impact, social benefits, and economic feasibility through five key elements [17]. A detailed breakdown of this analysis is provided in Table 35.

***Table 35.*** *Assessment of project impacts using the Green Project Management guideline. Note: Orange = People Impacts, Green = Planet Impacts, Blue = Prosperity Impacts.*

| Element | Situation/Impact/Response |
|---|---|
| **Project Health and Safety** | **Situation**: RTR currently follows standard operating procedures for producing various products. However, training for different production processes is primarily constructed through verbal instruction.<br><br>**Impact**: Without documented procedures, personnel may encounter operational risks due to inconsistencies or gaps in training.<br><br>**Response**: To enhance safe work practices in regard to production of the playground tile, the Team proposes developing a written procedure that outlines the steps of the process, identifies potential hazards, outlines risk mitigation strategies, and provides essential information to ensure safe working conditions. Such a procedure can be adapted from Appendix O.<br><br>**Initial Score: 2 New Score = 3 Change = +1** |
| **Recycling and Reuse** | **Situation:** To achieve a colored product, RTR applies paint to the surface. However, due to the high costs associated with paint, most products at RTR remain black, the same color as the incoming rubber tires. While cost- |

| Element | Situation/Impact/Response |
|---|---|
| | effective, the black products are less aesthetically appealing to customers and children compared to color alternatives.<br><br>**Impact:** The use of paint to improve visual aesthetics of the design was not an environmentally sustainable solution. Additionally, customers seeking appealing options may turn to competitors offering a wider variety of colours, even if their products are not made from recycled materials such a tire rubber.<br><br>**Response:** To create a more sustainable and visually appealing product, the Team integrated recycled rubber soles from old shoes. Running shoe soles, typically made from high quality EPDM rubber [12], offer durability and softness, making them an ideal material. By incorporating coloured rubber soles into the top layer of the playground tile, RTR can produce a more attractive product, divert a common landfilled waste, and maintain its commitment to sustainability. Refer to Section 2.3 and Appendix N for more information on how the Team accomplished this.<br><br>**Initial Score: 2 New Score = 5 Change = +3** |
| **Waste Generation** | **Situation:** The process of shredding rubber tires into the different grades of crumb rubber produces a fiber by-product. This fiber, a synthetic polyester textile, is used in tire manufacturing to enhance mechanical properties [5]. While RTR collects this fiber, it is currently landfilled due to the lack of an internal use for it.<br><br>**Impact:** The diversion of this synthetic material to landfills contributes to environmental degradation. Landfills occupy immense land space, release methane through breakdown of various materials, and pose pollution risks if not properly managed. |

| Element | Situation/Impact/Response |
|---|---|
| | **Response:** To minimize waste and promote sustainability, the Team proposes integrating the discarded fiber into the production of playground tiles. As seen in the formula selection process for the playground tile design in Section 2.1.2, the addition of fibers did not correlate to a reduction in performance. As such, this approach would help reduce landfill contributions while adding a useful material input to the production stream.<br><br>**Initial Score: 1 New Score = 3 Change = +2** |
| **Social Return on Investment** | **Situation:** Playground surfacing options are typically limited to rubber tiles, poured rubber, or loose mulch, with rubber materials offering the best shock absorption capabilities for safety. While major cities have access to all three options, Northern communities often face limited availability.<br><br>**Impact:** Due to these limitations, Northern communities may resort to using non-recycled rubber tiles or loose mulch, which are less environmentally sustainable and may not provide the same level of safety as the recycled rubber playground tile the Team developed. This reduces opportunities for social wellbeing, waste reduction, long-tern durability in playground infrastructure up North.<br><br>**Response:** To enhance sustainability and social impact in Northern and remote communities, the Team recommends encouraging RTR to promote and distribute their recycled playground tiles to such regions. This initiative would provide children with safer play environments, support community wellbeing, and demonstrate the value of recycling.<br><br>**Initial Score: 1 New Score = 3 Change = +2** |
| **Indirect Benefits** | **Situation:** Playground equipment can pose safety risks to children and youth if the surrounding surface does not provide adequate shock absorption to cushion falls. Playgrounds play a vital role in communities, |

| Element | Situation/Impact/Response |
|---|---|
| | offering safe spaces for recreation in schools and neighborhoods. As such, it is important that playground surfacing is properly designed to reduce injury from potential falls.<br><br>**Impact:** If playground surfaces with low shock absorption, such as mulch, are used, the risk of injuries increases, negatively affecting the safety and wellbeing of children.<br><br>**Response:** The Team has identified and attempted to maximize the safe fall height of the developed playground tile through impact attenuation testing according to ASTM F1292 [1]. By incorporating a high-performance tile base as shown in Section 2.2.1, the design not only enhances safety but support the construction of more complex and engaging playground structures for children. This improvement encourages greater community use of playgrounds, providing children with safer spaces for active play. Additionally, increased playground accessibility will promote social interaction, helping children develop social skills outside of their home while remaining safe.<br><br>**Initial Score: 1 New Score = 4 Change = +3** |

***Table 36**. Summary of Triple Bottom Framework scores.*

| Element | Old Score | New Score | Change |
|---|---|---|---|
| Project Health and Safety | 2 | 3 | 1 |
| Recycling and Reuse | 2 | 5 | 3 |
| Waste Generation | 1 | 3 | 2 |

| Element | Old Score | New Score | Change |
|---|---|---|---|
| Social Return on Investment | 1 | 3 | 2 |
| Indirect Benefits | 1 | 4 | 3 |
| **Totals** | **7** | **18** | **+11** |

# 5.0 Limitations and Recommendations

## 5.1 Design Solution

The design of the recycled rubber playground tile has been developed with a strong emphasis on sustainability, durability, and safety. While the current prototype has shown promising results, certain aspects of the design still require refinement to ensure optimal performance. Factors such as material composition, manufacturing processes, and structural integrity need further evaluation to enhance the tile's overall functionality. Additional testing and adjustments will be necessary to improve properties like impact absorption over 5 ft, weather resistance, and longevity. The following sections outline specific limitations encountered during the design phase and provide recommendations for future improvements.

### 5.1.1 Tile Shape

The integrity of the shape of the tile plays an important role in both its structure and manufacturability. Throughout the testing and production process as shown in section 2.0 Design Solution, several challenges related to the mould design and tile formation were identified, highlighting key limitations that affect efficiency and quality. One major issue observed was the difficulty in removing the bars from the base of the mould after the tile had been pressed. Due to the high pressure and heat applied during moulding, the tile material adheres tightly to the bars, increasing friction and making removal challenging. This not only slows down the production process but also poses a risk of damaging either the mould or the tile itself during extraction.

Another significant limitation involved the alignment of the bars within the mould. It was observed that if the bars were not precisely positioned, the hydraulic press's extreme pressure and heat could cause the aluminium bars to deform or even melt. During one work session, the Team witnessed instances where misalignment led to the bars warping under the applied conditions. This suggests that the grade of aluminium used in the mould bars may not be sufficient to withstand repeated exposure to high temperatures and mechanical stress. Additionally, variations in cooling rates between the tile material and the mould components introduced shrinkage and warping, which could affect the final tile dimensions and consistency.

To address these challenges, several design modifications are recommended. Angling the bars at the base of the mould may help facilitate smoother removal after pressing, reducing the force needed for extraction and minimizing the risk of damage. Additionally, upgrading to a higher-grade aluminium alloy with better heat resistance would prevent the bars from deforming under extreme conditions. To further improve alignment and prevent shifting during the pressing process, the inclusion of a guiding or locking mechanism within the mould would ensure that the bars remain in their correct positions, eliminating the risk of misalignment. Another potential improvement is the application of non-stick coatings or lubricants to the bars, reducing adhesion and making the demoulding process more efficient.

By implementing these recommendations, the tile manufacturing process can be optimized to enhance efficiency, durability, and overall product quality. These modifications will not only reduce material wastage and production time but also contribute to a more consistent and reliable final product.

### 5.1.2 Material Formula

While Formula I was selected as the most optimal material tile formula based on the results of the Triax Impact Test, further refinements in the formula could enhance its performance. This combination of crumb rubber and binder consists of a gradient composition, with the top half made entirely of fine crumb rubber and the bottom half composed solely of coarse crumb rubber. Due to time constraints, only one variation of this gradient structure was tested. If additional time had been available, further investigations could have been conducted to evaluate different gradient compositions, such as altering the thickness ratio of the top and bottom layers. It is recommended that the client explore these modifications to optimize impact absorption and durability.

One of the primary limitations in determining the mass of the recycled rubber tile is the inconsistency in the composition of raw materials. Variations in the source, size, and density of rubber granules can lead to fluctuations in the overall weight of the tile. Additionally, differences in processing methods, such as the level of compaction and the curing process, may impact the final mass and structural integrity. Another challenge is scaling up production while maintaining

uniformity in mass distribution, as larger batches may introduce inconsistencies in material mixing and binding.

Additionally, results from the extreme moisture test (see Section 3.3.4) revealed that water absorption and retention cause tile expansion, which poses structural concerns for playground installations. Since the tiles are designed to fit tightly together with no allowance for swelling, the increased volume could lead to internal stress, potentially compromising their longevity. Without adequate room for expansion, the accumulated stress may degrade the material over time. To address this issue, further material modifications or the application of protective treatments should be considered to enhance moisture resistance and maintain structural integrity.

To address these limitations, it is recommended to standardize material processing techniques, ensuring that the rubber granules used have consistent size and density. Further testing should be conducted to explore different granule sizes and binding agents that optimize weight without compromising durability. Additionally, alternative lightweight fillers could be investigated to reduce the overall mass while maintaining strength and resilience. These measures will help improve the uniformity, quality, and performance of the recycled rubber tiles in practical applications.

### 5.1.3 Connection Method

The connection method of the tiles plays a crucial role in ensuring their structural stability, durability, and ease of assembly. The connection method selected for this project is 2-inch PVC Dowel pins. If the dowel pin connection points do not provide sufficient friction and grip, the tiles may shift under pressure or come apart over time, reducing the effectiveness and longevity of the final product. To address this, different strategies were explored, focusing on material selection and connection design modifications.

One key aspect of investigation was determining the most suitable plastic material for the connectors. While PVC was finalized, its coefficient of friction against the rubber formulation of the tiles may not be the best choice for preventing slippage and disassembly. PVC's relatively smooth surface could allow for slight movement underweight or impact, which might compromise the long-term interlocking stability of the tiles. To counteract this, alternative plastics with rougher

surface textures and inherently higher friction coefficients can be tested to assess whether they could provide stronger grip and better resistance to movement. Materials such as polyethylene (PE) and polypropylene (PP), which offer varying degrees of surface roughness and flexibility, can be considered. Increasing friction at the connection points is particularly important in high-traffic areas where repeated pressure could weaken the interlocking mechanism over time.

### 5.1.4 Aesthetics

The Team successfully integrated rubber from recycled shoes into the tile composition to add an aesthetically pleasing surface, as shown in Section 2.3. This was done for proof-of-concept purposes, recognizing that the logistics of a full-scale operation of collecting and shredding recycled shoes would be challenging with RTR's limited space and resources. However, the Team still recommends RTR to further investigate the potential of this idea that which creates another avenue for a waste-to-value product that makes up the principal of their company. This recommendation also stems from another set of Triax Impact Test results taken from the playground tile composed of the rubber from recycled shoes. Appendix Q reveals that this tile achieved the best safety rating, significantly outperforming the tiles with no added shredded soles. Note that these results were not expected and were only obtained one month prior to the project due data. As such, this tile was not pursued as the final prototype for this project. Rather, the Team presents these results to the client while strongly recommending further research into the integration of rubber from recycled shoes into recycled tire rubber composition formulas for product development. The Team also recognizes the by-product waste created from the separation of the sole from the shoe. It is recommended to investigate the possibility of shredding and granulizing the shoe fabric and foam to be used as the underlayment for playground surfacing assembly, as an alternative to sand, gravel, etc.

### 5.1.5 Manufacturing

Currently the entire manufacturing process as shown in Appendix O includes the mixing of crumb rubber, packing of crumb rubber, assembly of the mould with the base grid and dowel pins, press time, and extraction of tiles from the moulds. This process takes roughly one hour for a set of three tiles. This operates under the assumption that two more aluminum grids are made. At the time of this report being written, only one aluminum grid exists meaning only one tile can be made with a

patterned base at any time. If this remains, a major limitation to playground tile manufacturing would be total time as it will add forty minutes for pressing to achieve three tiles. As such, it is highly recommended that additional aluminum grids be created for procurement of these tiles and to streamline the total manufacturing time.

Additionally, the manufacturing process for the playground tiles is known by Team members and project advisors. To streamline this product for efficient manufacturing, a training session at RTR should be held in accordance with the procedure outline in Appendix O. Recognizing that employees at RTR are more familiar with the machinery and products involved in the creation of the tiles, they may have valuable insight on changes that can be made to the manufacturing process. For example, an impact driver was used to fasten and remove the bolts on the walls of the mould for creation of the dowel holes. This simple tool allowed for roughly twenty minutes saved on the manufacturing time as opposed to inserting the bolts by hand. Further considerations may be provided by RTR employees to reduce this manufacturing time.

## 5.2 Verification and Evaluation

To ensure the recycled rubber playground tile meets industry standards and safety requirements, thorough verification and evaluation testing as mentioned in the Design Verification Section 3.0 are necessary. While initial tests have provided valuable insights into the tile's performance, further assessments are required to validate its durability, impact resistance, and environmental sustainability. Additional testing will help refine the design by identifying potential weaknesses and optimizing material composition for long-term usability. This section outlines the key limitations in the current testing process and provides recommendations for future verification and evaluation methods.

### 5.2.1 Physical Testing

Due to the project time constraints, the recycled rubber from shoes was not tested for material properties. Physical testing of the shoe soles used on the top layer of the rubber tiles will be helpful for RTR to gain further insights into the viability of using this recycled material in their production process. After shredding the recycled rubber into usable crumb sizes such as 3-20 coarse and -20 fine, physical tests can be conducted to determine the densities and particle size distribution. It is unknown how well this rubber will shred in RTR's machines, given that for this project a small-

scale shredder on campus was used. As such, it would be helpful to trial the rubber through RTR's industrial shredders to see if it withstands the large-scale machines. Then, using the resultant crumb rubber, the suggested physical properties can be tested and evaluated as compared to RTR's original crumb rubber from tires. By determining the density and particle size distribution can provide insights into the surface texture achieved of the resulting tile made and the usability of the rubber into RTR products.

### 5.2.2 Mechanical Testing

Triax Impact Testing in accordance with ASTM F1292 found that the current design is acceptable for a fall height of four feet and up to five feet if recycled rubber soles are added to the top of the tile. Additional testing will be needed to obtain official certification of these tiles at those fall heights. For the purposes of this project, Triax Impact Testing was conducted only as a proof of concept. The results of said testing cannot be utilized to achieve certification for the product. A third party should be engaged to complete this certification in alignment with ASTM F1292. During such test, it is suggested that outdoor testing in extreme weather is also conducted to verify outdoor use of the playground tile. This is recommended due to the results found in Section 3.2 which showed that extreme cold caused the rubber to stiffen and would expectedly have an impact on the safety performance of the tiles.

Section 3.2.2 covered the behaviour of the material under cyclical compression to retrieve some mechanical properties of the tiles. Further mechanical testing such as tensile testing, fatigue testing, and puncture testing could be utilized to further classify this material. While the product is unlikely to be subject to high tension stresses, it may be valuable to have that information available. Fatigue testing and puncture testing should be conducted as these are likely scenarios the tiles will be subject to. The information gathered in these tests will aid in determining the lifetime of the tile and the predicted forces the tiles can withstand without significantly depreciating its performance and safety rating.

### 5.2.3 Environmental Testing

Our recommendation for RTR is to conduct a more sophisticated compression test of the tile exposed to different temperature conditions to better identify the weather durability of the rubber tiles. To verify the basic weather durability, Compression tests were performed on the tiles for

extreme cold and extreme heat conditions, as described in Section 3.3.1 and Section 3.3.2. However, the results of this test will need to follow further standard testing procedure to be verified. While the internal temperatures of the samples were maintained at hot/cold conditions, the surrounding ambient conditions were at room temperature. As such, these tests did not replicate the intended conditions to evaluate the tile's performance in variable outdoor environments. This was due to the Team not having access to the standardize equipment and operating procedures required to run such test. To achieve more accurate results, a testing machine equipped with a controlled temperature cell for long-term exposure to different weather conditions is desired. Then, the data acquired can be used to determine the longevity and resilience of the tiles in different environmental settings.

Another beneficial test that RTR can perform is a roughness test on the surface of the tile to determine the coefficient of friction to gain insights of how slippery the tile gets, especially in wet conditions. A higher coefficient of friction entails that there is more friction between the tile and say, a shoe and thus, the likelihood of slipping is low thereby, indicating a safer tile for use thereby reducing the risk of injuries. The coefficient of friction obtained from the test can also be compared to the acceptable range of coefficient of friction for rubber tiles so that the tiles made by RTR meet the necessary criteria for safety regarding how slippery a tile should be. We were unable to perform the roughness test due to time constraints.

## 6.0 Conclusion

The work completed in this project allowed for significant advancement in the application of recycled rubber materials for playground surfacing products. The final playground tile design successfully met ASTM F1292 standards at the desired fall height, providing a safe and impact-absorbing surface that minimizes injury to user. Through the optimized material formula, an innovative base design, and a secure connection method, the tile offers a durable and environmentally sustainable alternative to market competitors. By prioritizing safety, durability, and sustainability, the project not only produced a functional product but also aligns with RTR's goals of expanding their product line and improving their market competitiveness in the recycled rubber industry.

In addition to the technical achievements, the production of the playground tile contributes to environmental sustainability by repurposing waste tire rubber along with the option to integrate rubber from recycled shoes for colouring to improve aesthetics without relying on synthetic dyes. This reduces landfill waste while providing a quality solution for playground surfacing, benefiting both RTR and the broader community.

The Team deemed the results of this project successful. However, limitations still exist in both the design solution and verification testing. While the tile successfully met the ASTM F1292 safety standard in normal conditions, additional tests under extreme temperatures and moisture levels would provide a more complete understanding of durability in outdoor applications. Furthermore, the dowel pin connection system, while effective for assembly, may require additional reinforcement in high-traffic playgrounds to ensure long term success. These were some of the main limitations identified.

Overall, this project successfully demonstrated the potential of sustainable innovation in playground surfacing, which proved feasible and beneficial. The results of this project offer RTR an opportunity to expand their marketability with the eco-friendly playground solution. By recognizing the limitations and implementing the proposed recommendations, RTR can refine the design, optimize performance, and output a high-impact, sustainable product to market.

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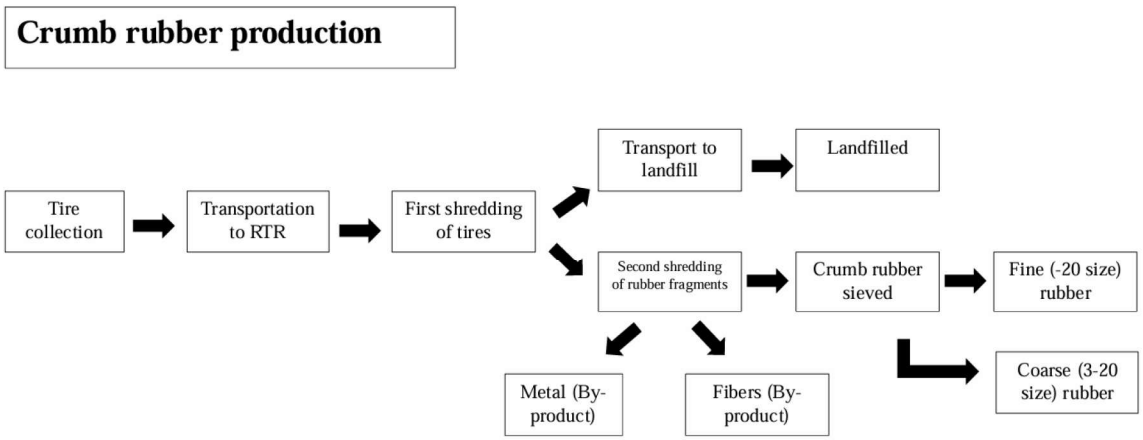
# Appendix A: Crumb Rubber Production Process



## Appendix B: Material Composition Formulas

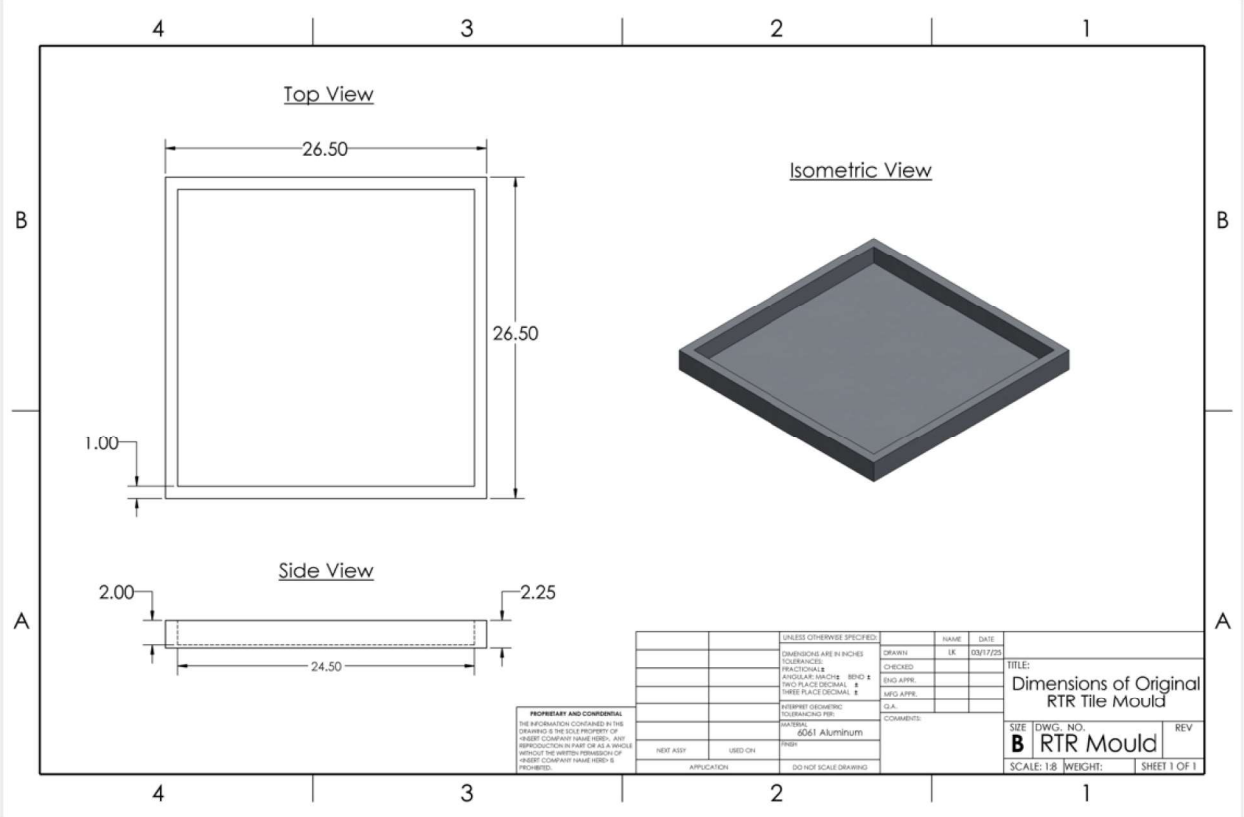
| Formula ID | Coarse (lbs) | Fine (lbs) | Recycled Fiber (lbs) | Recycled Soles (lbs) | Glue (lbs) |
|---|---|---|---|---|---|
| Original | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| A | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| B | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| C | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| D | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| E | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| F | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| G | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| II | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| I* | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| Modified I** | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |

*Selected formula for the playground tile.

**Modified Formula I contains the rubber from recycled shoes. The added material is mixed separately and added to the surface of the tile.

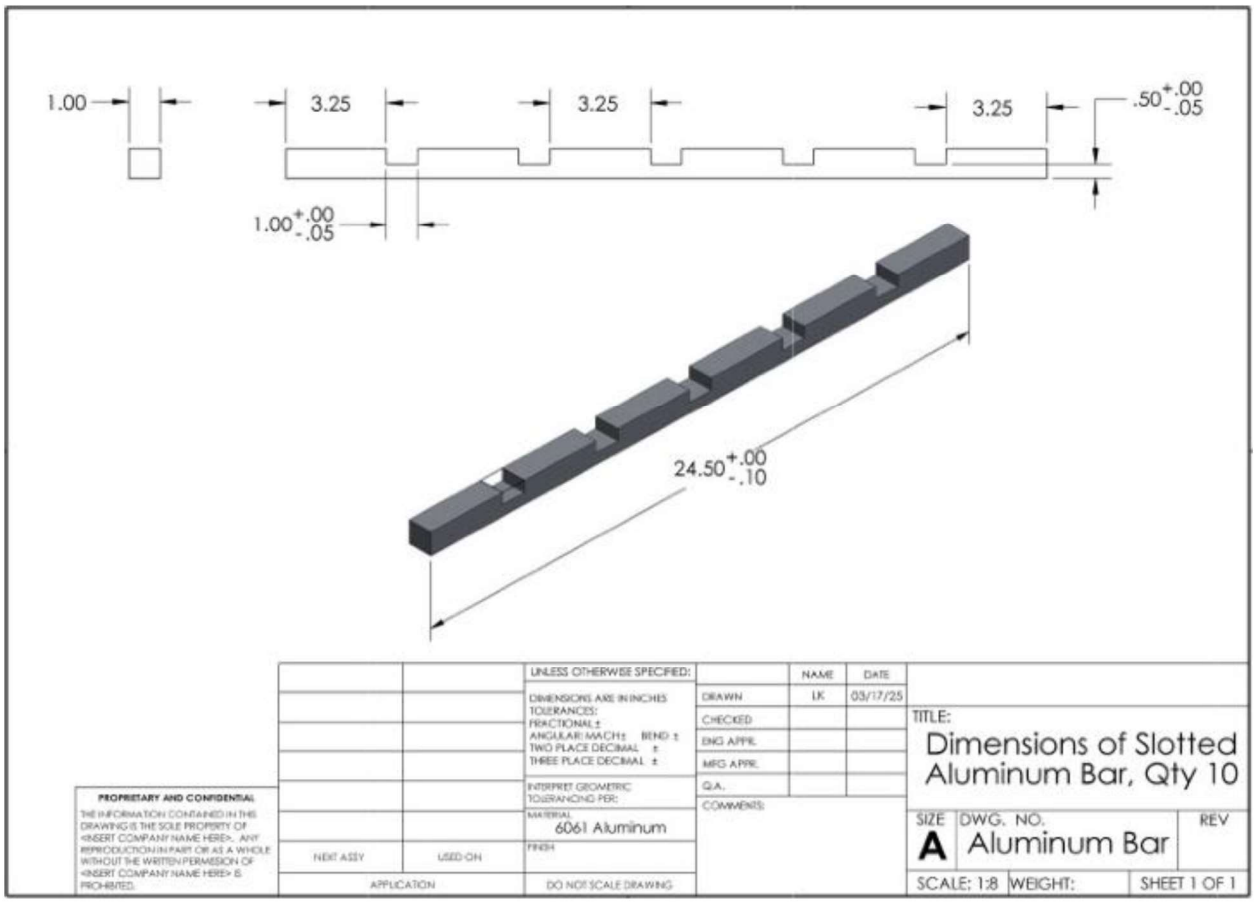
## Appendix C: Drawing of Original Mould

Note: Dimensions are in inches.



## Appendix D: Drawing of the Slotted Aluminum Bar

Note: Dimensions are in inches.

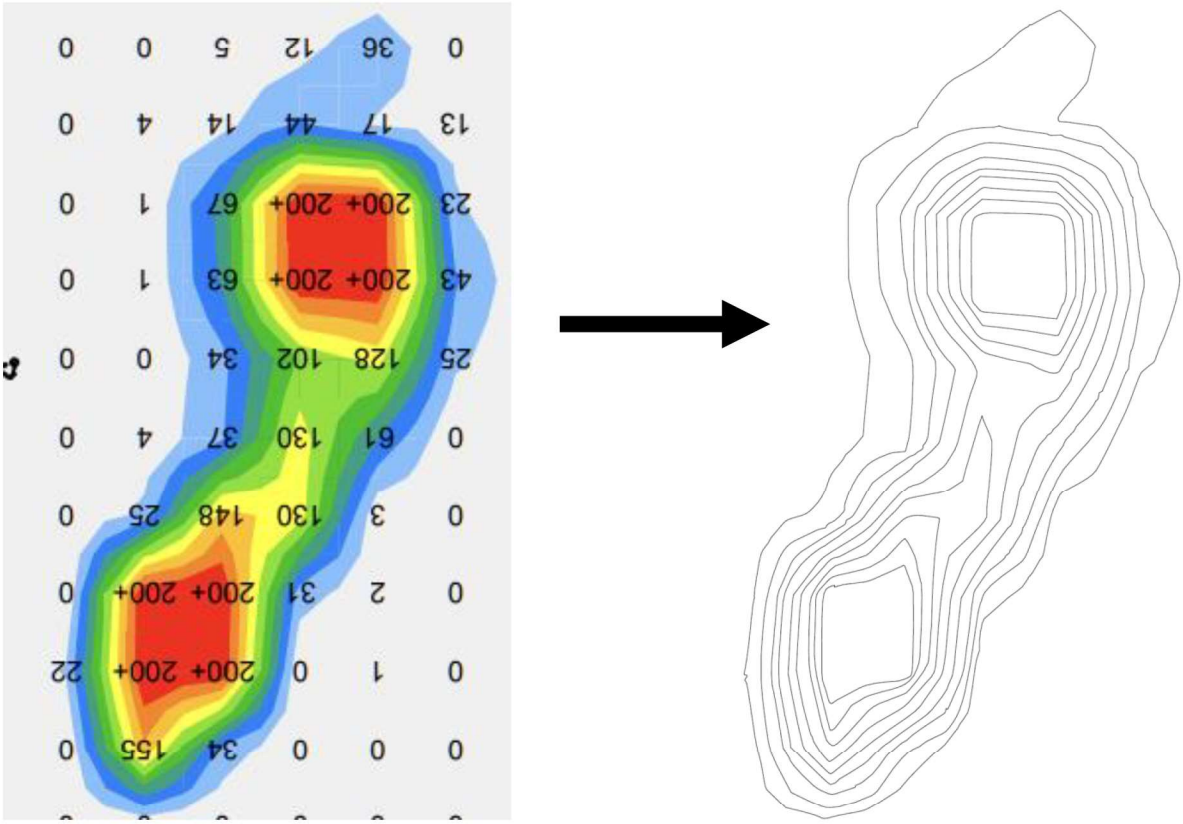


# Appendix E: FSA Transformed Data

| Sensor ID | Sensor Readings (mmHg) | Sensor Reading (Pa) | Sensor Reading (N) |
|---|---|---|---|
| K3 | 0.01 | 1.33 | 1.85 |
| G12 | 0.38 | 50.67 | 70.15 |
| G9 | 0.59 | 78.67 | 108.92 |
| G10 | 0.60 | 80.00 | 110.76 |
| L3 | 0.98 | 130.67 | 180.91 |
| D4 | 1.27 | 169.33 | 234.45 |
| G13 | 1.27 | 169.33 | 234.45 |
| J12 | 1.30 | 173.33 | 239.98 |
| M7 | 1.44 | 192.00 | 265.83 |
| E13 | 2.06 | 274.66 | 380.28 |
| F13 | 2.24 | 298.66 | 413.51 |
| M13 | 2.35 | 313.33 | 433.82 |
| D5 | 2.36 | 314.66 | 435.66 |
| M6 | 2.45 | 326.66 | 452.28 |
| J7 | 2.86 | 381.33 | 527.96 |
| D6 | 3.01 | 401.33 | 555.65 |
| M5 | 3.09 | 412.00 | 570.42 |
| J6 | 3.09 | 412.00 | 570.42 |
| G11 | 4.30 | 573.33 | 793.79 |
| G7 | 4.48 | 597.33 | 827.02 |
| F12 | 4.69 | 625.33 | 865.79 |
| J5 | 6.03 | 803.99 | 1113.15 |
| E12 | 12.06 | 1607.98 | 2226.31 |
| C11 | 12.91 | 1721.32 | 2383.22 |
| F11 | 14.06 | 1874.65 | 2595.51 |
| D11 | 17.48 | 2330.64 | 3226.85 |
| M8 | 17.92 | 2389.31 | 3308.08 |
| L4 | 17.94 | 2391.98 | 3311.77 |
| H4 | 21.94 | 2925.30 | 4050.18 |
| C10 | 22.81 | 3041.30 | 4210.78 |
| C8 | 25.13 | 3350.63 | 4639.06 |
| G6 | 25.31 | 3374.63 | 4672.29 |
| K4 | 26.48 | 3530.63 | 4888.27 |
| E5 | 30.83 | 4110.63 | 5691.29 |
| F8 | 33.79 | 4505.29 | 6237.72 |
| F3 | 34.00 | 4533.29 | 6276.48 |
| D12 | 36.28 | 4837.28 | 6697.38 |
| F7 | 36.73 | 4897.28 | 6780.45 |
| M11 | 38.27 | 5102.62 | 7064.74 |
| K8 | 40.85 | 5446.61 | 7541.01 |
| J11 | 42.14 | 5618.61 | 7779.15 |
| C9 | 42.81 | 5707.94 | 7902.83 |
| E11 | 43.57 | 5809.28 | 8043.13 |
| K9 | 54.71 | 7294.59 | 10099.60 |
| L12 | 60.45 | 8059.92 | 11159.22 |
| D7 | 61.03 | 8137.25 | 11266.29 |
| F9 | 62.98 | 8397.25 | 11626.26 |
| M12 | 63.22 | 8429.25 | 11670.57 |
| F10 | 66.56 | 8874.58 | 12287.14 |
| L13 | 67.04 | 8938.58 | 12375.75 |
| M9 | 83.74 | 11165.22 | 15458.61 |
| M10 | 101.52 | 13535.86 | 18740.84 |
| E8 | 101.94 | 13591.86 | 18818.37 |
| D8 | 128.15 | 17086.50 | 23656.80 |
| E6 | 129.88 | 17317.16 | 23976.17 |
| E7 | 130.36 | 17381.16 | 24064.77 |
| K10 | 143.82 | 19175.81 | 26549.52 |
| F6 | 148.15 | 19753.14 | 27348.85 |
| K12 | 153.94 | 20525.13 | 28417.70 |
| G3 | 154.70 | 20626.46 | 28558.00 |
| K7 | 160.97 | 21462.45 | 29715.46 |
| K13 | 192.07 | 25609.08 | 35456.59 |
| F4 | 200.00 | 26666.40 | 36920.49 |
| G4 | 200.00 | 26666.40 | 36920.49 |
| F5 | 200.00 | 26666.40 | 36920.49 |
| G5 | 200.00 | 26666.40 | 36920.49 |
| K5 | 200.00 | 26666.40 | 36920.49 |
| L5 | 200.00 | 26666.40 | 36920.49 |
| K6 | 200.00 | 26666.40 | 36920.49 |
| L6 | 200.00 | 26666.40 | 36920.49 |
| L7 | 200.00 | 26666.40 | 36920.49 |
| L8 | 200.00 | 26666.40 | 36920.49 |
| D9 | 200.00 | 26666.40 | 36920.49 |
| E9 | 200.00 | 26666.40 | 36920.49 |
| L9 | 200.00 | 26666.40 | 36920.49 |
| D10 | 200.00 | 26666.40 | 36920.49 |
| E10 | 200.00 | 26666.40 | 36920.49 |
| L10 | 200.00 | 26666.40 | 36920.49 |
| K11 | 200.00 | 26666.40 | 36920.49 |
| L11 | 200.00 | 26666.40 | 36920.49 |

## Appendix F: Binary Image of Foot Pressure Contours

The FSA pressure map image on the left was imported into ImageJ to extract the colored contours boundaries and export as a binary image, as seen on the right.



# Appendix G: SolidWorks Simulation Rubber Material Properties

Properties | Tables & Curves | Appearance | CrossHatch | Custom | Application Data

Material properties

Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic ☐ Save model type in library

Units: SI - N/m^2 (Pa)

Category: Rubber

Name: RTR Rubber Formula I

Default failure criterion: Max von Mises Stress

Description:

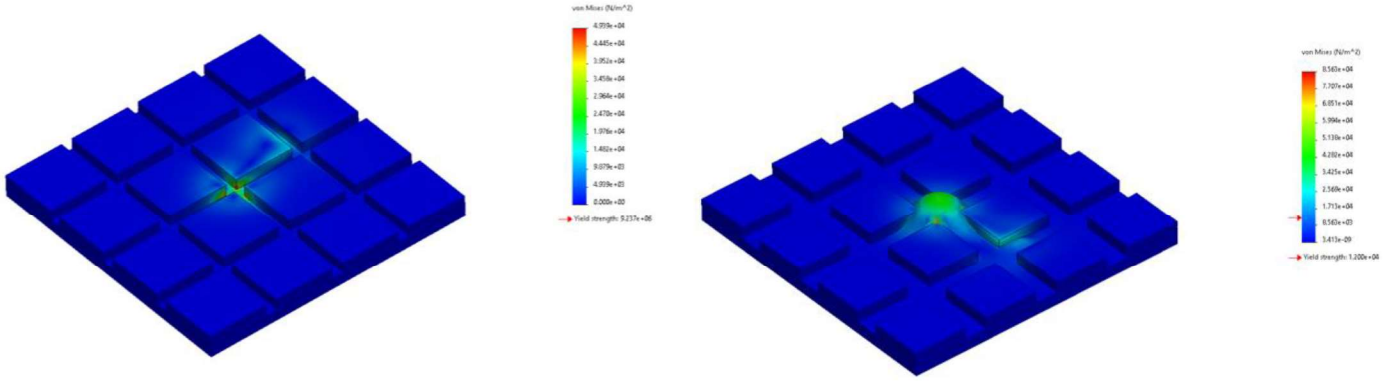
Source:

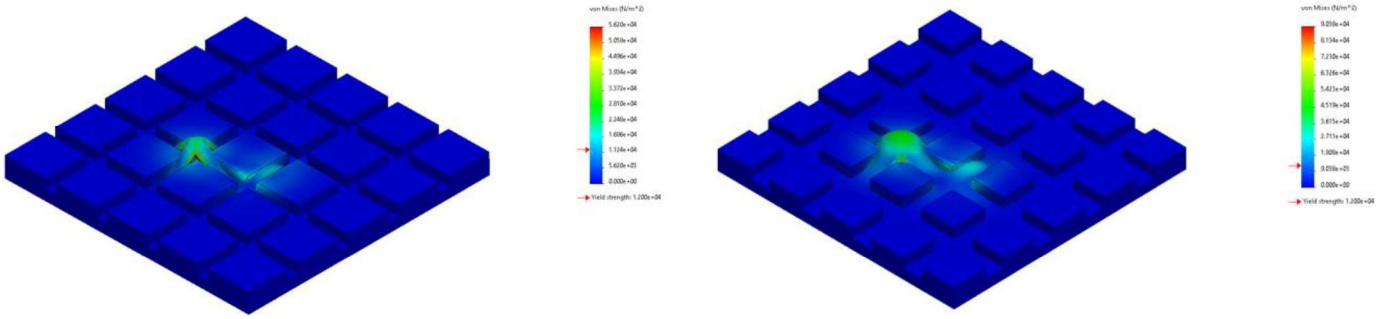
Sustainability: Undefined Select...

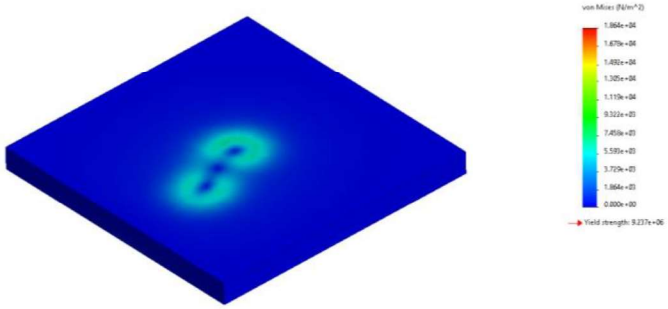
| Property | Value | Units |
|---|---|---|
| Elastic Modulus | 118270 | N/m^2 |
| Poisson's Ratio | 0.3769 | N/A |
| Shear Modulus | 2900000 | N/m^2 |
| Mass Density | 686 | kg/m^3 |
| Tensile Strength | 13787100 | N/m^2 |
| Compressive Strength | | N/m^2 |
| Yield Strength | 12000 | N/m^2 |
| Thermal Expansion Coefficient | 0.00067 | /K |
| Thermal Conductivity | 0.14 | W/(m·K) |
| Specific Heat | | J/(kg·K) |
| Material Damping Ratio | | N/A |

## Appendix H: SolidWorks Simulation Screenshots

Visual stress results of CAD models from FEA.







# Appendix I: FEA Transformed Data Set

Date: 13:50 Thursday March 13 2025
Model name: Tile Shape 3x3 bars
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Result Type: von Mises

| Node | Value (N/m^2) | value/max | sum | 14306.189 | step | stress step | count | Sum count | percent | cumulative |
|---|---|---|---|---|---|---|---|---|---|---|
| 1371 | 342.90 | 0.010 | average | 2350.67 | 0.00 | 0 | 1639 | 6086 | 26.93% | 26.93% |
| 1372 | 36530.00 | 0.740 | max | 49390.00 | 0.01 | 493.9 | 1750 | | 28.75% | 55.69% |
| 1373 | 85.28 | 0.000 | max/100 | 493.9 | 0.02 | 987.8 | 534 | | 8.77% | 64.46% |
| 1374 | 383.90 | 0.010 | count | 6086 | 0.03 | 1481.7 | 305 | | 5.01% | 69.47% |
| 1375 | 37260.00 | 0.750 | | | 0.04 | 1975.6 | 243 | | 3.99% | 73.46% |
| 1376 | 406.40 | 0.010 | | | 0.05 | 2469.5 | 199 | | 3.27% | 76.73% |
| 1377 | 391.80 | 0.010 | | | 0.06 | 2963.4 | 143 | | 2.35% | 79.08% |
| 1378 | 95.71 | 0.000 | | | 0.07 | 3457.3 | 142 | | 2.33% | 81.42% |
| 1379 | 210.90 | 0.000 | | | 0.08 | 3951.2 | 127 | | 2.09% | 83.50% |
| 1380 | 3389.00 | 0.070 | | | 0.09 | 4445.1 | 109 | | 1.79% | 85.29% |
| 1381 | 363.00 | 0.010 | | | 0.10 | 4939 | 104 | | 1.71% | 87.00% |
| 1382 | 37230.00 | 0.750 | | | 0.11 | 5432.9 | 87 | | 1.43% | 88.43% |
| 1383 | 3516.00 | 0.070 | | | 0.12 | 5926.8 | 82 | | 1.35% | 89.78% |
| 1384 | 1610.00 | 0.030 | | | 0.13 | 6420.7 | 66 | | 1.08% | 90.86% |
| 1385 | 38830.00 | 0.790 | | | 0.14 | 6914.6 | 42 | | 0.69% | 91.55% |
| 1386 | 432.40 | 0.010 | | | 0.15 | 7408.5 | 36 | | 0.59% | 92.15% |
| 1387 | 79.47 | 0.000 | | | 0.16 | 7902.4 | 29 | | 0.48% | 92.62% |
| 1388 | 167.40 | 0.000 | | | 0.17 | 8396.3 | 39 | | 0.64% | 93.26% |
| 1389 | 865.50 | 0.020 | | | 0.18 | 8890.2 | 37 | | 0.61% | 93.87% |
| 1390 | 28.25 | 0.000 | | | 0.19 | 9384.1 | 34 | | 0.56% | 94.43% |
| 1391 | 48.00 | 0.000 | | | 0.20 | 9878 | 27 | | 0.44% | 94.87% |
| 1392 | 789.90 | 0.020 | | | 0.21 | 10371.9 | 16 | | 0.26% | 95.14% |
| 1393 | 433.50 | 0.010 | | | 0.22 | 10865.8 | 18 | | 0.30% | 95.43% |
| 1394 | 46.58 | 0.000 | | | 0.23 | 11359.7 | 16 | | 0.26% | 95.70% |
| 1395 | 23.55 | 0.000 | | | 0.24 | 11853.6 | 21 | | 0.35% | 96.04% |
| 1396 | 551.10 | 0.010 | | | 0.25 | 12347.5 | 13 | | 0.21% | 96.25% |
| 1397 | 100.50 | 0.000 | | | 0.26 | 12841.4 | 16 | | 0.26% | 96.52% |
| 1398 | 27.76 | 0.000 | | | 0.27 | 13335.3 | 20 | | 0.33% | 96.85% |
| 1399 | 8.11 | 0.000 | | | 0.28 | 13829.2 | 8 | | 0.13% | 96.98% |
| 1400 | 173.80 | 0.000 | | | 0.29 | 14323.1 | 13 | | 0.21% | 97.19% |
| 1401 | 9.46 | 0.000 | | | 0.30 | 14817 | 10 | | 0.16% | 97.35% |
| 1402 | 20.09 | 0.000 | | | 0.31 | 15310.9 | 10 | | 0.16% | 97.52% |
| 1403 | 107.50 | 0.000 | | | 0.32 | 15804.8 | 6 | | 0.10% | 97.62% |
| 1404 | 374.70 | 0.010 | | | 0.33 | 16298.7 | 7 | | 0.12% | 97.73% |
| 1405 | 17.03 | 0.000 | | | 0.34 | 16792.6 | 7 | | 0.12% | 97.85% |
| 1406 | 14.70 | 0.000 | | | 0.35 | 17286.5 | 8 | | 0.13% | 97.98% |
| 1407 | 380.70 | 0.010 | | | 0.36 | 17780.4 | 7 | | 0.12% | 98.09% |
| 1408 | 88.16 | 0.000 | | | 0.37 | 18274.3 | 6 | | 0.10% | 98.19% |
| 1409 | 20.76 | 0.000 | | | 0.38 | 18768.2 | 12 | | 0.20% | 98.39% |
| 1410 | 6.90 | 0.000 | | | 0.39 | 19262.1 | 7 | | 0.12% | 98.50% |
| 1411 | 141.10 | 0.000 | | | 0.40 | 19756 | 6 | | 0.10% | 98.60% |
| 1412 | 8.77 | 0.000 | | | 0.41 | 20249.9 | 3 | | 0.05% | 98.65% |
| 1413 | 20.30 | 0.000 | | | 0.42 | 20743.8 | 4 | | 0.07% | 98.72% |
| 1414 | 92.47 | 0.000 | | | 0.43 | 21237.7 | 9 | | 0.15% | 98.87% |
| 1415 | 411.00 | 0.010 | | | 0.44 | 21731.6 | 1 | | 0.02% | 98.88% |
| 1416 | 13.60 | 0.000 | | | 0.45 | 22225.5 | 2 | | 0.03% | 98.92% |
| 1417 | 21.42 | 0.000 | | | 0.46 | 22719.4 | 4 | | 0.07% | 98.98% |
| 1418 | 378.70 | 0.010 | | | 0.47 | 23213.3 | 5 | | 0.08% | 99.06% |
| 1419 | 221.30 | 0.000 | | | 0.48 | 23707.2 | 2 | | 0.03% | 99.10% |
| 1420 | 24.52 | 0.000 | | | 0.49 | 24201.1 | 2 | | 0.03% | 99.13% |
| 1421 | 11.40 | 0.000 | | | 0.50 | 24695 | 2 | | 0.03% | 99.16% |
| 1422 | 330.10 | 0.010 | | | 0.51 | 25188.9 | 2 | | 0.03% | 99.19% |
| 1423 | 42.02 | 0.000 | | | 0.52 | 25682.8 | 2 | | 0.03% | 99.23% |
| 1424 | 92.36 | 0.000 | | | 0.53 | 26176.7 | 4 | | 0.07% | 99.29% |
| 1425 | 218.20 | 0.000 | | | 0.54 | 26670.6 | 4 | | 0.07% | 99.36% |
| 1426 | 4134.00 | 0.080 | | | 0.55 | 27164.5 | 2 | | 0.03% | 99.39% |
| 1427 | 104.80 | 0.000 | | | 0.56 | 27658.4 | 0 | | 0.00% | 99.39% |
| 1428 | 170.80 | 0.000 | | | 0.57 | 28152.3 | 2 | | 0.03% | 99.42% |
| 1429 | 3826.00 | 0.080 | | | 0.58 | 28646.2 | 2 | | 0.03% | 99.46% |
| 1430 | 1301.00 | 0.030 | | | 0.59 | 29140.1 | 2 | | 0.03% | 99.49% |
| 1454 | 0.00 | 0.000 | | | 0.60 | 29634 | 1 | | 0.02% | 99.51% |
| 1455 | 23.90 | 0.000 | | | 0.61 | 30127.9 | 0 | | 0.00% | 99.51% |
| 1456 | 19.17 | 0.000 | | | 0.62 | 30621.8 | 3 | | 0.05% | 99.56% |
| 1457 | 0.00 | 0.000 | | | 0.63 | 31115.7 | 1 | | 0.02% | 99.57% |
| 1467 | 563.90 | 0.010 | | | 0.64 | 31609.6 | 0 | | 0.00% | 99.57% |
| 1468 | 341.20 | 0.010 | | | 0.65 | 32103.5 | 2 | | 0.03% | 99.61% |
| 1469 | 11070.00 | 0.220 | | | 0.66 | 32597.4 | 1 | | 0.02% | 99.62% |
| 1470 | 618.50 | 0.010 | | | 0.67 | 33091.3 | 2 | | 0.03% | 99.65% |
| 1471 | 13840.00 | 0.280 | | | 0.68 | 33585.2 | 2 | | 0.03% | 99.69% |
| 1472 | 658.00 | 0.010 | | | 0.69 | 34079.1 | 2 | | 0.03% | 99.72% |
| 1473 | 572.50 | 0.010 | | | 0.70 | 34573 | 1 | | 0.02% | 99.74% |
| 1474 | 361.30 | 0.010 | | | 0.71 | 35066.9 | 1 | | 0.02% | 99.75% |
| 1479 | 643.00 | 0.010 | | | 0.72 | 35560.8 | 3 | | 0.05% | 99.80% |
| 1480 | 769.40 | 0.020 | | | 0.73 | 36054.7 | 2 | | 0.03% | 99.84% |
| 1481 | 1946.00 | 0.040 | | | 0.74 | 36548.6 | 2 | | 0.03% | 99.87% |
| 1482 | 14250.00 | 0.290 | | | 0.75 | 37042.5 | 2 | | 0.03% | 99.90% |
| 1483 | 17500.00 | 0.350 | | | 0.76 | 37536.4 | 1 | | 0.02% | 99.92% |
| 1484 | 17000.00 | 0.340 | | | 0.77 | 38030.3 | 0 | | 0.00% | 99.92% |
| 1485 | 3190.00 | 0.060 | | | 0.78 | 38524.2 | 0 | | 0.00% | 99.92% |
| 1486 | 1105.00 | 0.020 | | | 0.79 | 39018.1 | 1 | | 0.02% | 99.93% |
| 1490 | 319.50 | 0.010 | | | 0.80 | 39512 | 0 | | 0.00% | 99.93% |
| 1491 | 2093.00 | 0.040 | | | 0.81 | 40005.9 | 0 | | 0.00% | 99.93% |
| 1492 | 4401.00 | 0.090 | | | 0.82 | 40499.8 | 0 | | 0.00% | 99.93% |
| 1493 | 1227.00 | 0.020 | | | 0.83 | 40993.7 | 0 | | 0.00% | 99.93% |
| 3830 | 413.90 | 0.010 | | | 0.84 | 41487.6 | 0 | | 0.00% | 99.93% |
| 3831 | 731.80 | 0.010 | | | 0.85 | 41981.5 | 0 | | 0.00% | 99.93% |
| 3832 | 1172.00 | 0.020 | | | 0.86 | 42475.4 | 0 | | 0.00% | 99.93% |
| 3833 | 1899.00 | 0.040 | | | 0.87 | 42969.3 | 0 | | 0.00% | 99.93% |
| 3834 | 3244.00 | 0.070 | | | 0.88 | 43463.2 | 0 | | 0.00% | 99.93% |
| 3835 | 4863.00 | 0.100 | | | 0.89 | 43957.1 | 0 | | 0.00% | 99.93% |
| 3836 | 7349.00 | 0.150 | | | 0.90 | 44451 | 0 | | 0.00% | 99.93% |
| 3837 | 13150.00 | 0.270 | | | 0.91 | 44944.9 | 0 | | 0.00% | 99.93% |
| 3838 | 24120.00 | 0.490 | | | 0.92 | 45438.8 | 0 | | 0.00% | 99.93% |
| 3839 | 77.41 | 0.000 | | | 0.93 | 45932.7 | 0 | | 0.00% | 99.93% |
| 3840 | 84.68 | 0.000 | | | 0.94 | 46426.6 | 1 | | 0.02% | 99.95% |
| 3841 | 105.60 | 0.000 | | | 0.95 | 46920.5 | 0 | | 0.00% | 99.95% |
| 3842 | 126.00 | 0.000 | | | 0.96 | 47414.4 | 0 | | 0.00% | 99.95% |
| 3843 | 162.80 | 0.000 | | | 0.97 | 47908.3 | 1 | | 0.02% | 99.97% |
| 3844 | 186.20 | 0.000 | | | 0.98 | 48402.2 | 1 | | 0.02% | 99.98% |
| 3845 | 213.80 | 0.000 | | | 0.99 | 48896.1 | 0 | | 0.00% | 99.98% |
| 3846 | 253.70 | 0.010 | | | 1.00 | 49390 | 1 | | 0.02% | 100.00% |

# Appendix J: Decision Matrix for the Connection Method

| | | DOWEL PINS | | X-SPINE | | INTERLOCK | | TAB'n'LOOP | |
|---|---|---|---|---|---|---|---|---|---|
| CATEGORY | WEIGHT | Score | *Weighted* | Score | *Weighted* | Score | *Weighted* | Score | *Weighted* |
| Ease of Installation | 0.25 | 2 | 0.5 | 4 | 1 | 3 | 0.75 | 5 | 1.25 |
| Cost | 0.15 | 5 | 0.75 | 1 | 0.15 | 3 | 0.45 | 3 | 0.45 |
| Manufacturability | 0.15 | 4 | 0.6 | 2 | 0.3 | 4 | 0.6 | 3 | 0.45 |
| Maintenance | 0.10 | 1 | 0.1 | 3 | 0.3 | 4 | 0.4 | 1 | 0.1 |
| Safety | 0.35 | 5 | 1.75 | 2 | 0.7 | 1 | 0.35 | 1 | 0.35 |
| Total | 1.00 | **3.70** | | **2.45** | | **2.55** | | **2.60** | |

## Appendix K: Bill of Materials

Note: The following parts and materials are required to make *one* prototype tile.

**Raw Materials**

| Item | Mass (lbs) | Cost | Notes |
|---|---|---|---|
| [redacted] | 2.0 | $0.00 | Provided by RTR. |
| Crumb rubber | 31.3 | $0.00 | Provided by RTR. |
| Rubber fibers | 0.0 | $0.00 | Provided by RTR. |
| Mould release spray | --- | $0.00 | Provided by RTR. Mass used on one mould is negligible. |

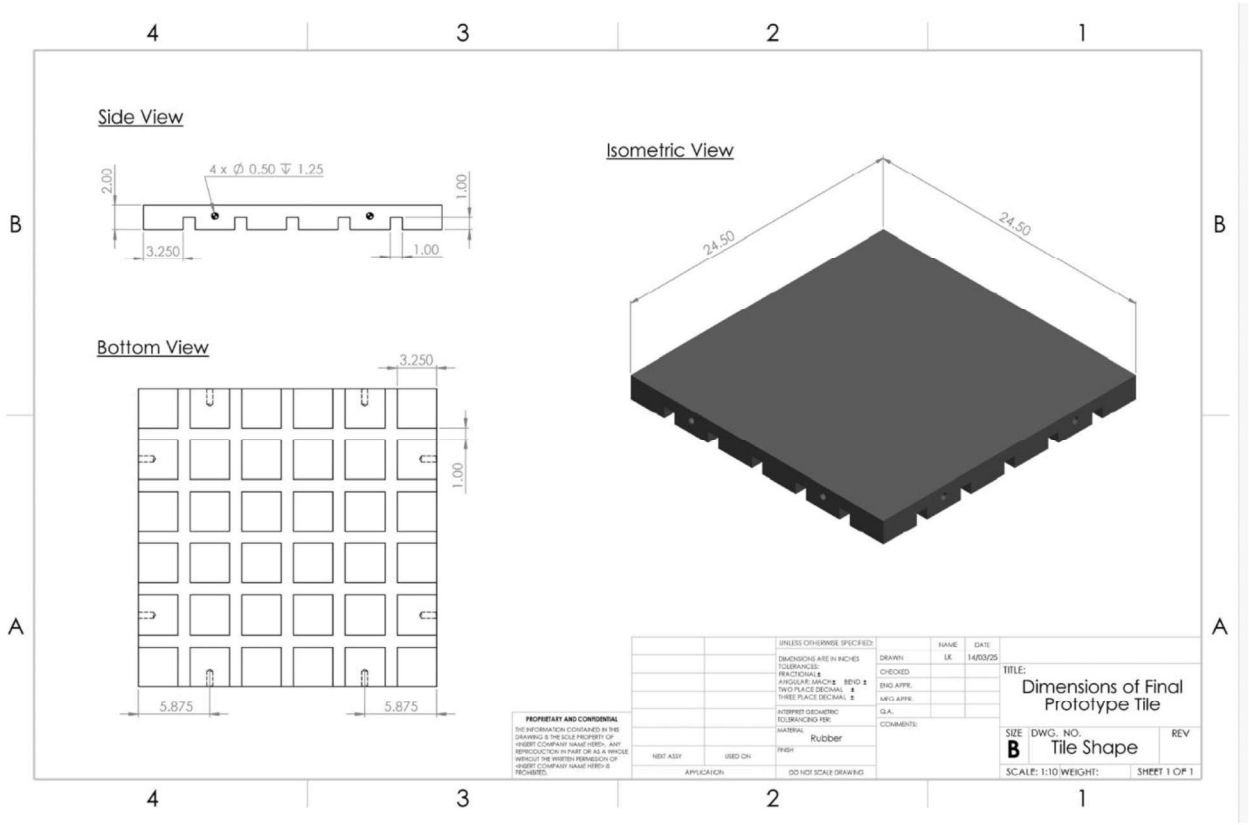
**Parts**

| Item | Quantity | Unit Cost | Total Cost | Notes |
|---|---|---|---|---|
| Aluminum tile mould | 1 | $0.00 | $0.00 | Provided by RTR. |
| Aluminum Hex Screw, 0.25" – 13 thread, 2.25" length McMaster-Carr Aluminum Hex Head Screw | 8 | $4.69 | $37.52 | 8 screws per mould to create the correct number of dowel pin holes. |
| PVC Rod, 0.5" diameter, 5 ft length McMaster-Carr PVC Rod | 1 | $6.12 | $6.12 | Cut into 2.5" long pieces, used as dowel pins. 5 ft stock returns 30 dowel pins. |
| 6061 Aluminum Square Bar, 1" x 1" x 50.5" Metal Supermarkets 6061 Aluminum Square Bar | 5 | $49.78 | $248.91 | The bars were cut to length and slotted to create the grid pattern. |

The total cost of the parts is **$292.55** before taxes. Additional aluminum bars and screws will be separately purchased by RTR to complete more moulds.

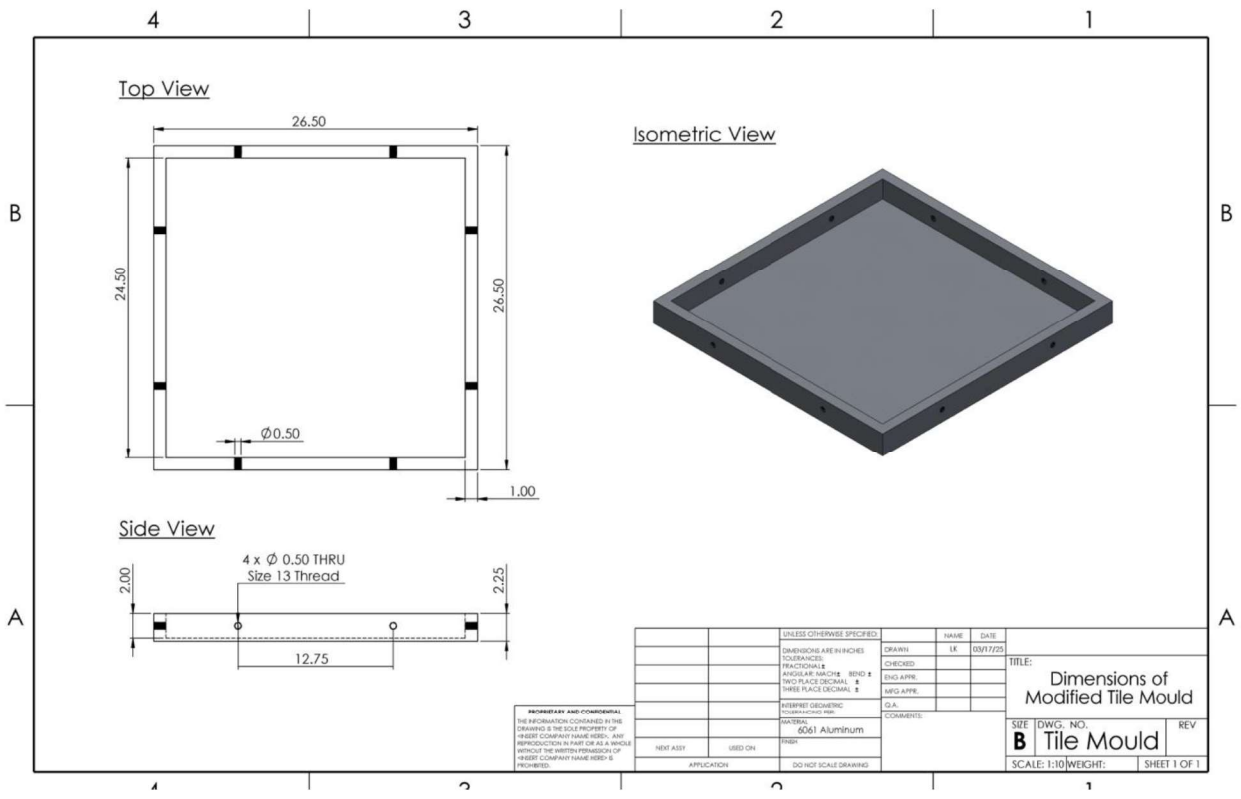
# Appendix L: Drawing of Final Prototype Tile

Note: Dimensions are in inches.



# Appendix M: Drawing of Modified Mould

Note: Dimensions are in inches.



## Appendix N: Recycled Rubber from Shoes - Separation Procedure

1. Collect inventory of athletic shoes or running shoes that were intended for the landfill.
2. Apply heat using a heat gun (set to maximum 500°C*) to the bottom area of the shoe focusing on the edges of the rubber sole. Apply heat directly for approximately one minute.
3. Use pliers to strip away and separate the rubber sole. If difficult to separate, continue applying heat until it becomes easier.
4. Collect the separated soles and wash with soap and hot water to eliminate unwanted debris.

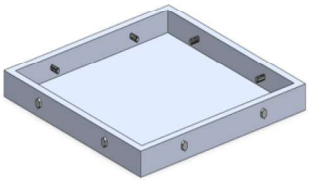
*Note: 500°C suggested as the maximum temperature due to observations made of melting materials at higher temperatures.

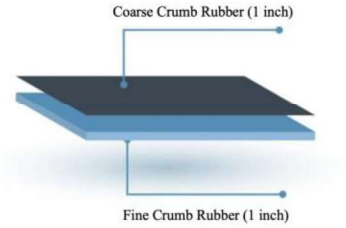


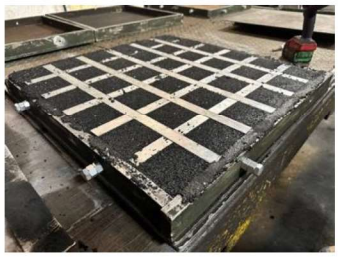
*Figure. Shoe soles*

## Appendix O: Tile Production Procedure (Modified)

| Step | Description | Picture |
|---|---|---|
| **1. Collect and weigh the fine ground rubber.** | - After accessing the rubber from the storage bag shown, access an empty barrel.<br>- Place the empty barrel underneath the automatic dispenser for fine ground rubber.<br>- Insert the weight of material needed into the machine.<br>- Press the dispense button.<br>- **Potential hazards:** Be aware of forklift moving the crumb rubber storage bags. |  |
| **2. Dispense and weigh the binder. Add to barrel containing fine ground rubber.** | - Using an empty bucket, tare the bucket on the scale beside the binder dispenser.<br>- Dispense the binder into the tared bucket to the desired amount.<br>- Add the binder into the barrel containing the fine ground rubber.<br>- **Potential hazards:** Ensure the binder dispenser is fully closed after use to prevent excess spillage. |  |
| **3. Collect and weigh the coarse ground rubber.** | - Using an empty bucket, tare the bucket on the large scale.<br>- Scoop the coarse ground rubber into the tared bucket to the desired amount.<br>- Add the material to a new empty barrel.<br>- **Potential hazards:** Be aware of forklift moving the crumb rubber storage bags. |  |

| Step | Description | Picture |
|---|---|---|
| **4. Dispense and weigh the binder. Add to barrel containing coarse ground rubber.** | - Using an empty bucket, tare the bucket on the scale beside the binder dispenser.<br>- Dispense the binder into the tared bucket to the desired amount.<br>- Add the binder into the barrel containing the fine ground rubber.<br>- **Potential hazards:** Ensure the binder dispenser is fully closed after use to prevent excess spillage. |  |
| **4. Mix the materials individually using the hydraulic mixer.** | - Lock the barrel into the hydraulic mixer machine using the two side handles and chains.<br>- Shut and lock the gate.<br>- Press 'start' on the control board.<br>- Run two mixes before removing the barrel.<br>- **Potential hazards:** Ensure the barrel is properly secured, the gate is locked and closed, and the worker stands a safe distance back in case of dismantle.<br>Note: It is advised to mix the fine rubber first as the fine rubber layer will go on the bottom of the tile mould. |  |
| **5. Prepare the mould.** | - Secure 8 bolts on all four sides using a drill.<br>- Spray the release agent thoroughly in the mould and all around the bolts.<br>- **Potential hazards:** Use caution when operating drill to fasten bolts. Be mindful of pinch points. |  |

| Step | Description | Picture |
|---|---|---|
| **6. Pour the crumb rubber mixture into the mould.** | - Fill each mould with 14 lbs of fine rubber mixture. Spread and level with hands. Make sure to pack under the bolts.<br>- Fill each mould with 16 lbs of coarse rubber mixture. Spread and level with hands.<br>- Place 5x5 aluminum grid covered in release agent. Press into rubber mixture.<br>- Place the sheet metal cover on top of the moulds.<br>- **Potential hazards:** Be mindful of pinch points when assembling 5x5 aluminum grid. | <br><br> |
| **7. Place the moulds into the hydraulic press.** | - Using the metal rod, hook the rod on the mould's side insert to push the moulds under the press.<br>- Press 'start' on the control board.<br>- Double the press time if completing first run of the day to allow the machine to heat up.<br>- **Potential hazards:** Use caution when pushing moulds under the press as the moulds with the mixture become very heavy. Be mindful of hot temperatures under the press.<br>- Note: Temperature and pressure should be set to [redacted], respectively. |  |

| Step | Description | Picture |
|---|---|---|
| **8. Remove the moulds from the hydraulic press.** | - Using the metal rod, hook the rod onto the mould's side insert to drag the mould out from under the press.<br>- Allow the moulds to cool for a couple minutes until warm to touch.<br>- Remove the bolts using a drill.<br>- Remove the 5x5 grid.<br>- Remove the cured tile from the mould using the metal scraper along the edge to 'lift' the tile.<br>- Clean surfaces with air gun.<br>- **Potential hazards:** Use caution when touching the moulds as they are hot after coming out of the hydraulic press. | <br> |

## Appendix P.1: Procedure for Mass Test

| Category | Details |
|---|---|
| Materials | Three full size prototype tiles. |
| Equipment | Scale |
| Procedure | 1. The tile is left in the test room a day in advance so that the tile is conditioned.<br>2. On the test day, the temperature and humidity of the test room is recorded to confirm normal and not extreme conditions are present.<br>3. Next, the tile is cleaned to make sure there is no debris on the tile.<br>4. The tile is then carefully placed on the balance and mass of the tile is recorded once the reading has stabilized.<br>5. Repeat for all three samples. Calculate the average mass for one sample. |

## Appendix P.2: Procedure for Dimensions Test

| Category | Details |
|---|---|
| Materials | Three full size prototype tiles. |
| Equipment | Measuring tool (measuring tape and/or calipers). |
| Procedure | 1. Tile samples were placed on a flat surface and were measured using a measuring tape.<br>2. The length, width, and thickness measurements were taken from three different spots on the tile and were averaged. |

## Appendix P.3: Procedure for Density Test

| Category | Details |
|---|---|
| Materials | Three prototype tile samples with no modified base (to simplify volume calculation). |
| Equipment | Scale, measuring tool. |
| Procedure | 1. Record the mass of the sample on a scale. Ensure the sample fully fits on the scale and does not hang off the edge.<br>2. Measure the length, width, and height of the sample using the calipers.<br>3. Calculate the apparent density of the sample.<br>$$\rho_{apparent} = \frac{m_{sample}}{V_{sample}} \quad g \cdot cm^{-3}$$<br>4. Repeat for all three samples.<br>5. Determine the average apparent density across all three samples. |

## Appendix P.4: Procedure for the Triax Impact Test

| Category | Details |
|---|---|
| Materials | Three full size prototype tiles. |
| Equipment | Triax test device missile and drop mechanism system, temperature measuring device. |
| Procedure | 1. Retrieve sample playground tile to be tested.<br>2. Place the sample to be tested on a flat, rigid concrete floor beneath the impact test system.<br>3. Align the center point of the sample's surface with the point of impact of the missile.<br>4. Before the first drop in any series, elevate the missile to the reference drop height. Measure and record this drop height (from the bottom of the missile to the top surface of the sample).<br>5. Before the first drop in any series, measure and record the surface temperature of the sample using a temperature measuring device.<br>6. Release the missile and record the outputs of the data collection and monitoring device.<br>7. Perform three impact tests for each sample, for each chosen reference fall height. Note: Drop height should differ by 1 ft.<br>8. Record the average g-max score and average HIC score at each combination of reference fall height. |

## Appendix P.5: Procedure for Compression Test

| Category | Details |
|---|---|
| Materials | Three prototype samples, cut to 3” x 3” and 2” thick. |
| Equipment | Compression testing machine, data acquisition system, calipers. |
| Procedure | 1. Cut three 1”x1” samples from the full-size tiles to fit the Instron test apparatus.<br>2. Fit the Instron Test Machine with a 3” x 3” probe.<br>3. Pre-compression test, measure and record the height and width of the samples using calipers.<br>4. Place one tile underneath the test probe.<br>5. Set the Instron test parameters to 2.5 cycles at 12 mm/min. and 12 mm of displacement.<br>6. After the 2.5 cycle, measure the new width of the samples. This will be used to determine Poisson’s ratio<br>7. Save the data as .csv file and export to Excel.<br>8. Test data is given in force and displacement, which can be converted to stress and strain.<br>9. Plot stress and strain for analysis.<br>10. Repeat for three replicate samples. |
| Results | Material properties obtained. |

## Appendix P.6: Procedure for Hardness Test

| Category | Details |
|---|---|
| Materials | Three prototype samples. |
| Equipment | Manual Shore A Scale Durometer |
| Procedure | 1. Place the sample on a flat, hard, horizontal surface.<br>2. Hold the durometer in a vertical position with the indenter tip towards the sample.<br>3. Apply the indenter tip to the sample, maintaining it in a vertical position keeping the presser foot parallel to the sample, with a firm smooth downward action that will avoid shock, rolling of the presser foot over the sample, or the application of lateral force. Apply sufficient pressure to assure firm contact between the presser foot and the specimen.<br>4. After the presser foot is in contact with the sample, the indicated reading shall be recorded within 1 +/- 0.1s, or as specified in the user manual of the instrument.<br>5. Make five readings in total at different position on the sample at least 6.0mm (0.24in) apart.<br>6. Calculate the arithmetic mean.<br>Note: Durometer readings below 20 or above 90 are not considered reliable. |

## Appendix P.7: Procedure for Cold Compression Test

| Category | Details |
|---|---|
| Materials | Three prototype samples, cut to 3” x 3” and 2” thick, exposed to freezing environmental conditions for a set period of days. |
| Equipment | Compression testing machine, data acquisition system, calipers, freezer if needed. |
| Procedure | 1. Cut three 1”x1” samples from Formula I tile.<br>2. Place all three samples outside in freezing weather to simulate the expected outdoor conditions in Winnipeg winters.<br>3. Leave the tiles outside for a set period, if temperatures are below zero freezing. Note that this test used twelve days.<br>4. If temperatures increase above zero, move the samples to the freezer until test day.<br>5. Once exposure time is expired, move the samples to the test area. If possible, place samples in insulated container to attempt to maintain it’s cold internal temperature.<br>6. Record the sample’s internal temperature before the test.<br>7. Refer to Appendix P.5 for compression test procedure. |

## Appendix P.8: Procedure for Hot Compression Test

| Category | Details |
|---|---|
| Materials | Three prototype samples, cut to 3” x 3” and 2” thick, exposed to hot environmental conditions for a set period of days. |
| Equipment | Compression testing machine, data acquisition system, calipers, oven set to 60°C. |
| Procedure | 1. 1”x1” samples placed inside a convection oven at 60°C temperature to simulate the application of tiles in Winnipeg heat.<br>2. The tiles were left in the convection oven for 12 days until test day to maintain the internal temperature.<br>3. Refer to Appendix P.5 for compression test procedure. |

## Appendix P.9: Procedure for UV Exposure Test

| Category | Details |
|---|---|
| Materials | Three prototype samples, cut to 1” x 1” and 2” thick. |
| Equipment | Inventronics LED UV lights. |
| Procedure | 1. Place 1”x1” samples 2 ft away from the UV lights for an even distribution of lights.<br>2. The tiles can be left exposed for 6 hours to mimic the realistic daylight exposure. |

## Appendix P.10: Procedure for Moisture Exposure Test

| Category | Details |
|---|---|
| Materials | Three prototype samples cut to 5” x 5” and 2” thick (to fit in bucket), room temperature water. |
| Equipment | Scale, bucket to hold water and submerged sample, measuring tool, thermohydrometer. |
| Procedure | 1. The dimensions of the 5” x 5” tile was measured using a measuring tape and recorded.<br>2. The mass of the tile was measured using an electronic scale and recorded.<br>3. The tile was completely immersed in a bucket of tap water using wooden planks as support.<br>4. The temperature of the water was recorded using a thermometer.<br>5. The tile remained immersed in the water for 24 hours.<br>6. At the end of 24 hours, the tile was removed from the water and any excess water was wiped off from the surface using a dry cloth.<br>7. The mass of the tile post-immersion was measured using an electronic scale and recorded.<br>8. The dimensions of the tile post-immersion were measured using a measuring tape and recorded.<br>9. The experiment was carried out for 3 different 5” x 5” tiles. |

## Appendix P.11: Procedure for Drainage Efficiency Test

| Category | Details |
|---|---|
| Materials | Three prototype samples cut to 5” x 5” and 2” thick (to fit in bucket), room temperature water. |
| Equipment | Scale, bucket to hold water and submerged sample, measuring tool, thermohydrometer. |
| Procedure | 1. The dimensions of the 5” x 5” tile was measured using a measuring tape and recorded.<br>2. The mass of the tile was measured using an electronic scale and recorded.<br>3. The tile was completely immersed in a bucket of tap water using wooden planks as support.<br>4. The temperature of the water was recorded using a thermometer.<br>5. The tile remained immersed in the water for 24 hours.<br>6. At the end of 24 hours, the tile was removed from the water and any excess water was wiped off from the surface using a dry cloth.<br>7. The mass of the tile post-immersion was measured using an electronic scale and recorded.<br>8. The tile was then placed on an open platform to allow water to continue draining through.<br>9. The mass of the tile was measured in 1-hour intervals until the tile reached its initial mass. |

## Appendix Q: Complete Triax Impact Test Results

Note: The average g-max and HIC was taken across three drops.

*Table. Triax Impact Test results for sample tiles (with no modified base) at a **4 ft fall height**.*

| Formula | Surface Temp. (°C) | Average g-max | Average HIC | Pass/Fail |
|---|---|---|---|---|
| Original | 18.7 | 185 | 1125 | FAIL |
| A | 17.6 | 185 | 1118 | FAIL |
| B | 17.8 | 181 | 1085 | FAIL |
| C | 17.2 | 185 | 1108 | FAIL |
| D | 18.0 | 158 | 853 | PASS |
| E | 19.9 | 166 | 948 | PASS |
| F | 17.4 | 164 | 927 | PASS |
| G | 19.8 | 181 | 1107 | FAIL |
| H | 17.8 | 184 | 1113 | FAIL |
| I | 11.6 | 157 | 839 | PASS |

*Table. Triax Impact Test results for sample tiles (with no modified base) at a **5 ft fall height**.*

| Formula | Surface Temp. (°C) | Average g-max | Average HIC | Pass/Fail |
|---|---|---|---|---|
| D | 15.1 | 189 | 1232 | FAIL |
| E | 19.1 | 200 | 939 | FAIL |
| F | 19.2 | 181 | 1322 | FAIL |
| I | 15.5 | 192 | 1271 | FAIL |

*Table. Triax Impact Test results for sample tiles (with modified base) at a **4 ft fall height**.*

| Formula | Surface Temp. (°C) | Average g-max | Average HIC | Pass/Fail |
|---|---|---|---|---|
| I | 18.9 | 150 | 827 | PASS |
| Modified I* | 15.6 | 130 | 635 | PASS |

*Table. Triax Impact Test results for sample tiles (with modified base) at a **5 ft fall height**.*

| Formula | Surface Temp. (°C) | Average g-max | Average HIC | Pass/Fail |
|---|---|---|---|---|
| I | 18.9 | 185 | 1272 | FAIL |
| Modified I* | 15.6 | 158 | 936 | PASS |

*Note: Modified Formula I contained the surface composed of rubber from recycled shoes.

# Appendix R: Compression Testing Results

## Room Temperature Compression Test

*Table. Material properties for Formula I identified from the Compression Test completed at 25 °C.*

| Replicate No. | Average Poisson's ratio | Average Yield Strength (kPa) | Average Modulus of Elasticity (kPa) | Average Stress at 12mm |
|---|---|---|---|---|
| 1 | 0.377 | 14.0 | 868.2 | 312.0 |
| 2 | 0.373 | 9.0 | 2172.7 | 388.3 |
| 3 | 0.387 | 9.4 | 2880.7 | 389.3 |

## Cold Compression Test

Please note that the third loading green is not a complete cycle due to final dimensional measurement constraints.

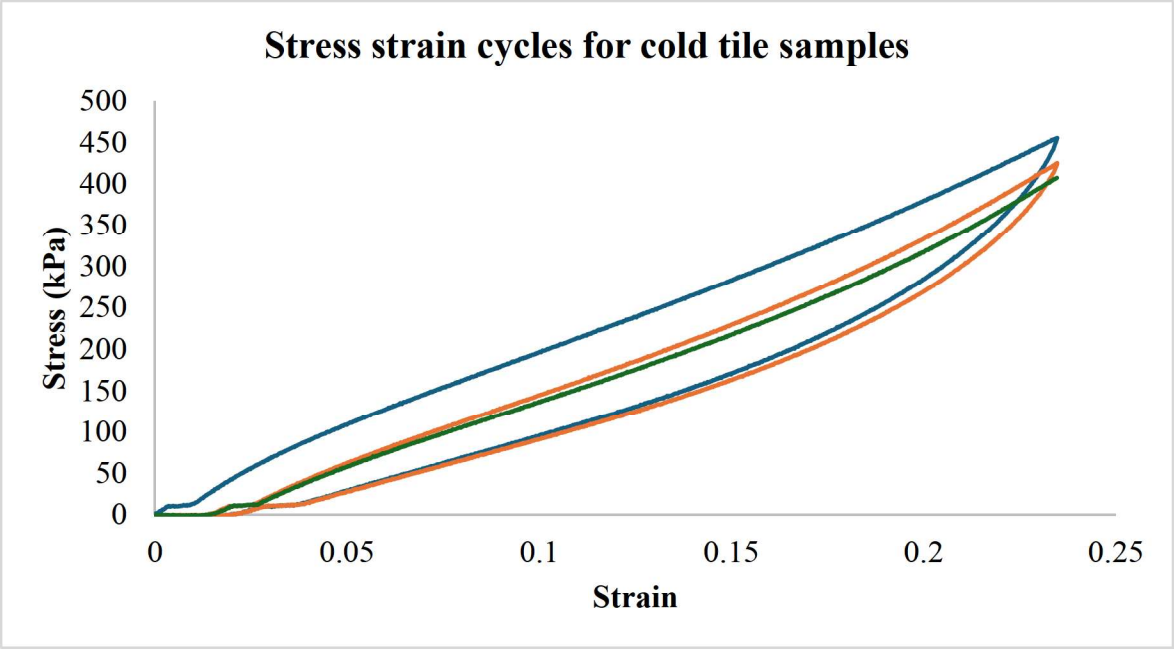



*Figure. Stress vs Strain cycles of Formula I sample at -10 °C temperature.*

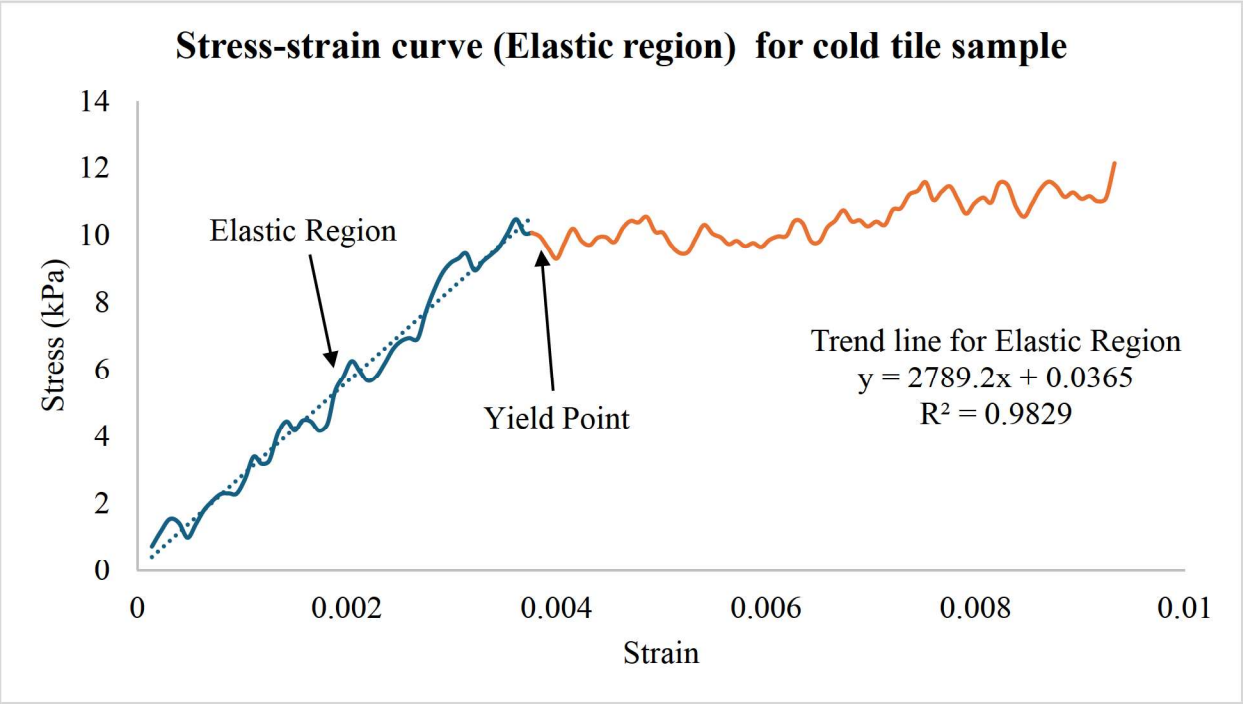



*Figure. Stress vs Strain curve of Formula I sample at 10 ℃, focused in on the elastic region.*

*Table. Material properties for Formula I identified from the Compression Test completed at -10 °C.*

| Formula | Average Poisson's ratio | Average Yield Strength (kPa) | Average Modulus of Elasticity (kPa) | Average Stress at 12mm |
|---|---|---|---|---|
| I (Replicate 1) | 0.471 | 9.0 | 2943.9 | 516.4 |
| I (Replicate 2) | 0.301 | 10.0 | 2721.1 | 454.9 |
| I (Replicate 3) | 0.367 | 10.6 | 2633.7 | 442.0 |

## Hot Compression Test Results

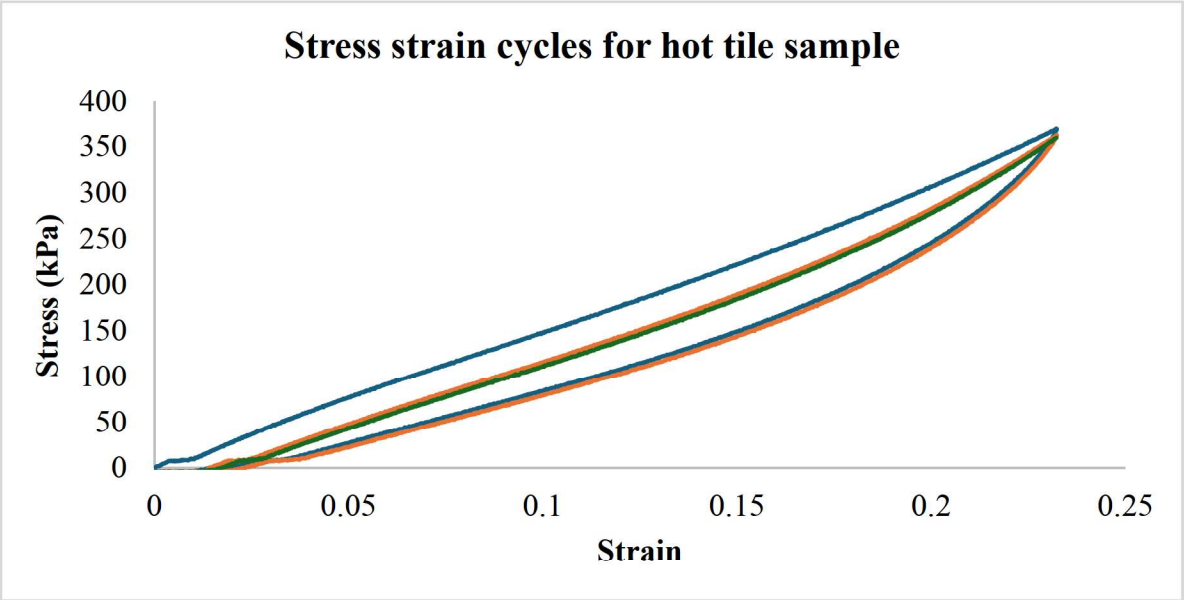



*Figure. Stress vs Strain cycles of Formula I sample at 51 ℃ temperature.*

Please note that the third loading green is not a complete cycle due to final dimensional measurement constraints.

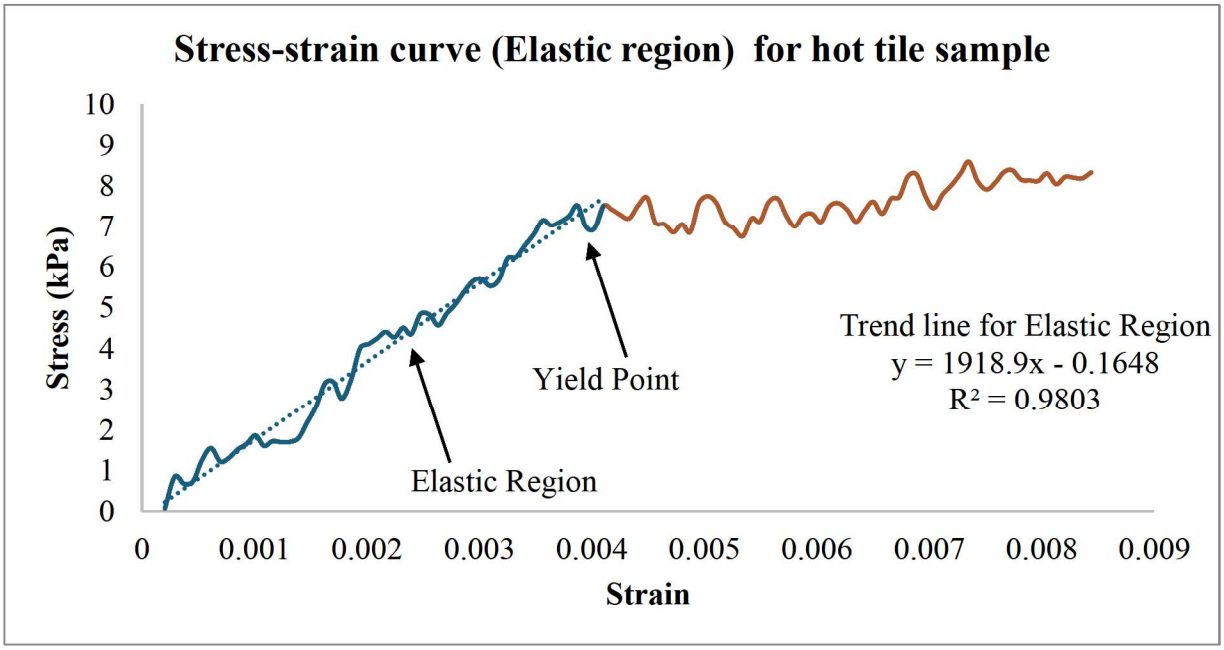



*Figure. Stress vs Strain curve of Formula I sample at 51 ℃ temperature, focused in on the elastic region.*

*Table. Material properties for Formula I identified from the Compression Test completed at 51 ℃.*

| Formula | Poisson's ratio | Yield Strength (kPa) | Modulus of Elasticity (kPa) | Maximum Stress (kPa) |
|---|---|---|---|---|
| I (Replicate 1) | 0.421 | 7.8 | 1916.3 | 359.2 |
| I (Replicate 2) | 0.443 | 10.4 | 1395.3 | 352.4 |
| I (Replicate 3) | 0.419 | 12.2 | 969.3 | 316.7 |

## Appendix X: Water Drainage Data

Drainage of water from the tiles in approximately 60-minute increments following the 24-hour moisture exposure test.

*Table. Drainage test results*

| | Time (minutes) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 173 | 255 | 315 | 375 | 435 | 495 |
| **Replicate No.** | **Mass (g)** | | | | | | |
| 1 | 709.6 | 680.1 | 673.5 | 670.0 | 666.8 | 663.1 | 660.3 |
| 2 | 695.8 | 666.3 | 660.4 | 656.3 | 652.2 | 648.9 | 645.8 |
| 3 | 675.7 | 636.5 | 632.4 | 630.3 | 627.8 | 625.5 | 623.7 |

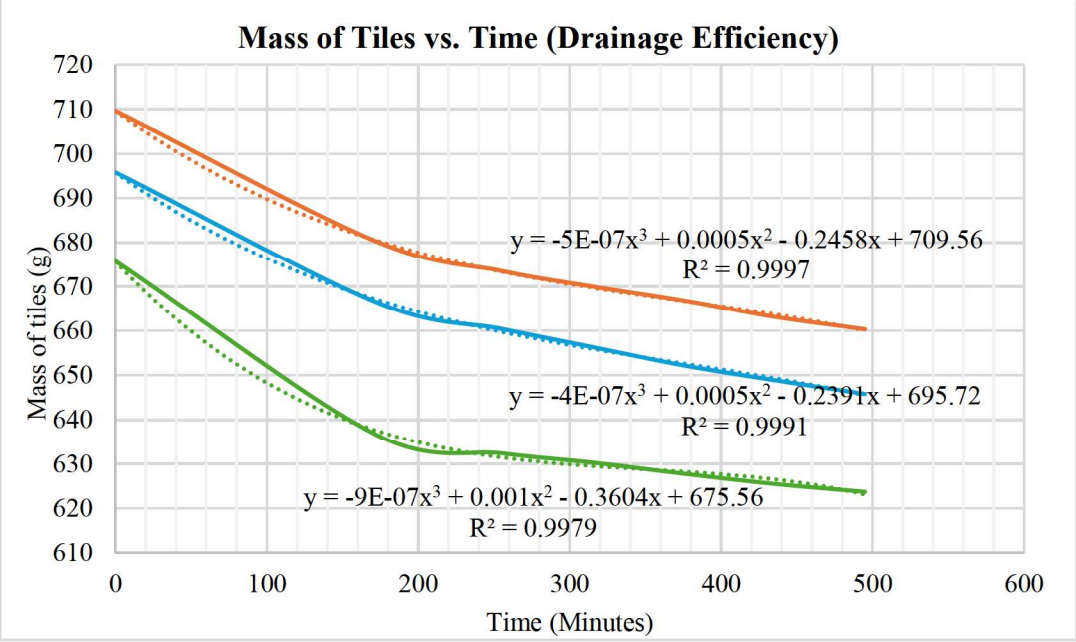



*Figure. Drainage test results*