Final design report for roof shingle made from ground tire rubber (GTR) fibres to withstand Winnipeg weather.

BIOE 4900 Team 4

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Client:

Reliable Tire Recycling (RTR) | WOW Rubber

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Authors' Note

This capstone project is part of a larger research and incorporates some results from the PhD research performed by Jardel Nobrega dos Santos, EIT, funded by RTR. The guidance provided and the results shared by Jardel have been instrumental in planning and executing the research presented in this report.

We acknowledge the contributions of Jardel Santos and the support of RTR, and we affirm that this collaboration is aimed at fostering academic growth and innovation. This acknowledgment ensures transparency and avoids any conflict of interest, allowing for the continued use and publication of the information generated in this capstone project by both parties involved, when approved by RTR.

Executive Summary

The objective of this project was to design a shingle using recycled ground tire rubber capable of withstanding Winnipeg, MB weather conditions. Our team developed and tested various rubber and additive mixtures to assess their strength and durability under specific conditions. Of the mixtures that seemed promising during initial testing phases, they were then subjected to weather simulations representing 1 in 25-year storm conditions in Winnipeg.

The final stage involved creating full-scale prototypes using a mold designed by the team, which ultimately determined the project's success. Despite initial promising results, unexpected failures occurred during the full-scale production phase, resulting in inconclusive findings regarding shingle viability. Further testing and refinement are necessary to meet the client's requirements and to address the challenges that were encountered during this project.

Recommendations for future research and improvements include optimizing the materials used, enhancing the appearance of the shingles to better suit the aesthetic desires of the client, improve efficiency by manufacturing a different mold, process optimization such as incorporating an injection mold and exploring liquid mixture formulations, and researching the feasibility and economic factors in mass-producing shingles using the proposed materials.

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1. Introduction

1.1 Purpose

Tires are difficult to recycle due to the production of harmful chemicals, pollutants, and materials such as rubber and steel wires, all of which pose a significant impact on the environment. The global impact of tire waste is staggering, with one billion end-of-life tires generated annually and a cumulative total of four billion tires accumulating in landfills and stockpiles, as reported by the Tire Industry Project for the World Business Council for Sustainable Development (Tire Industry Project, 2018).

Understanding the complex composition of tires, which consist of rubber, steel, and fabrics, is essential when attempting to maneuver through the intricate process of tire recycling. The resource-intensive and costly separation of these components emphasizes the need for innovative solutions for recycling items such as this. The purpose of the design outlined in this report is to not only to address the environmental challenges posed by tire waste but also to create a sustainable and economically profitable product.

This project's efforts are centered on designing and fabricating roof shingles made from at least 95% recycled materials, primarily sourced from Ground Tire Rubber (GTR) fibres. By repurposing discarded tire materials, our project contributes to environmental conservation. Simultaneously, achieving economic viability aligns with the broader goal of creating a product that not only minimizes the environmental impacts from discarding old tires, but also introduces a market-value product. Our innovative roof shingle serves a dual purpose in promoting environmentally conscious recycling methods and offering economic benefits. With this project, we aim to reshape the realm of sustainable construction materials.

It is important to note that this report aims to provide a comprehensive analysis of the environmental challenges associated with tire waste and the potential solutions offered by the development of recycled tire roof shingles. By examining the intricate process of tire recycling and the innovative approaches taken in this project, readers can expect to gain insights into both the environmental impact of tire waste and the opportunities for sustainable construction materials.

1.2 Background

1.2.1 The Client: Reliable Tire Recycling

The client for this project is called Reliable Tire Recycling (RTR). RTR is a company based in Winnipeg, Manitoba that focuses on recycling used tires, that otherwise have no value, to make viable products. RTR's mission since 1992 has been to collect tires from all around Manitoba for processing (Reliable Tire Recycling, 2023). RTR was inspired by the Used Tire Management Program (UTMP), that focused on repurposing used tires. They began their product range with blasting mats and tire derived aggregate (shred) for civil engineering applications.

The company was able to expand in 2007, where they acquired the Tire Recycling Corporation of North America based in Winkler, Manitoba, which was a tire crumbing and molding operation that manufactured these products into rubber matting for sports and agricultural markets. In 2010 and 2011, RTR was able to move their crumbing and molding operations to Winnipeg, respectively. Acquiring OTR Recycling in Ashern, Manitoba, RTR was able to repurpose "off the road" tires (OTR) into cattle feeders, water troughs and mulch for the landscaping market.

According to RTR, as Manitoba's premier vertically integrated tire recycler, they have consistently provided efficient tire collection throughout the province. They transform tires into valuable products such as molded goods, rubber mulch, blast mats, sidewalls and traffic safety markers while continuing to develop new products to this day, which includes roofing shingles, as this product has to opportunity to become more profitable than items currently sold by RTR.

It should also be noted that for the purpose of this project, Jardel Santos, the main contact between this capstone group and RTR, has been an incredible resource for information due to the extensive research done in their Ph.D. candidacy at the University of Manitoba.

1.2.2 Recycling Process for Ground Tire Rubber

Tires are collected from their source and made into GTR through different degrees of decomposition, according to a review focused on GTR processing by Fazli and Rodrigue (Fazli and Rodrigue, 2020). The development of GTR involves shredding of the tires to reach the desired particle sizes.

This procedure, known as downsizing or down-cycling, involves fragmentation of tires into smaller particles. This fragmentation serves to increase the surface area of the particles, creating their distribution as fillers within matrices. Doing so improves the bonding between materials within the mixture. A filler distribution matrix involves arranging these small tire-derived particles in a way that enhances their even distribution within the composite material, ultimately strengthening the cohesion between different materials used in the mixture (Fazli and Rodrigue, 2020).

The tires further require the extraction of textile and steel reinforcements from the rubber particles which is done using pneumatic separators and electromagnets during the grinding phase. This ensures that the GTR does not include unwanted materials to make it suitable for a wider range of applications. The grinding processes described by Fazli and Rodrigue include cryogenic, ambient, wet and water jet methods. These different processes result in various particle sizes, including larger particle sizes of 50-300 mm to very fine powders of <500 mm. The choice for which method to use depends on the desired particle size to tailor the GTR for specific applications. In a study done by Al-Attar et. al., the larger crumb rubbers from waste tires are obtained using cryogenic grinding at a lower temperature than that of the glass transition and mechanical grinding at ambient temperature (Al-Attar et. al., 2022). Figure 1 shows large crumb rubber sample compared to fine powder crumb particles sized at approximately 0.36 mm in diameter.

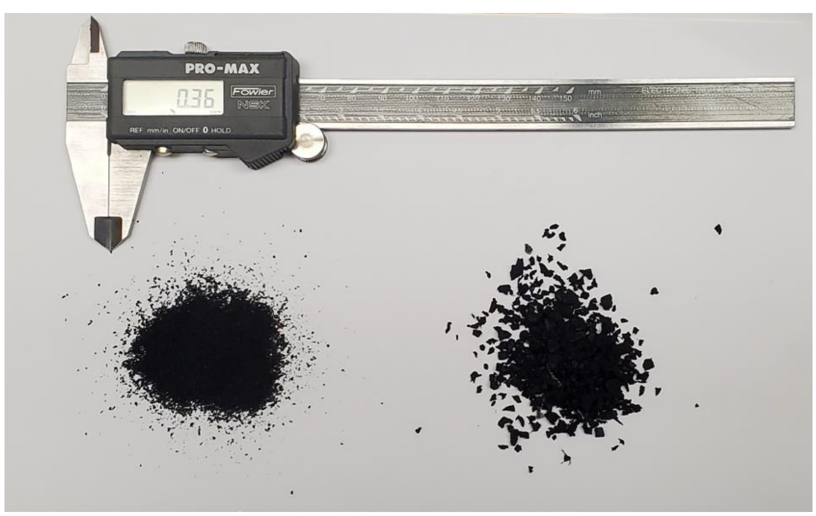


Figure 1. Ground tire rubber samples.

GTR serves as a versatile material with diverse applications. There are valuable properties in waste tires including natural and synthetic rubbers, which are useful reinforcing materials for composite production. According to Fazli and Rodrigue, blending waste tires with virgin matrices reduces the costs of the final product and decreases the consumption of virgin materials. This approach has been implemented in different applications such as improving road surfaces on highways and enhancing the resilience of concrete compositions in construction.

Integrating waste tires into polymer matrices, which includes thermosets, thermoplastic and rubbers, results in the creation of sustainable and environmentally friendly composite blends that have the potential to be commercialized (Fazli and Rodrigue, 2020). Products made from these blends often include mats, surfaces for playgrounds, athletic flooring, and automotive parts.

1.2.3 Roofing Shingles

Roofing shingles are a vital component of the home. They are designed to protect homes and buildings from the environment around them, serving as a durable, weather-resistant covering. Shingles have been historically made from many different materials, with the most common today being asphalt; however, wood, slate, and metal have also been used. Wooden shingles, often used in early construction, provided a rustic appearance, but were susceptible to rot and fire. Slate, known for its durability and elegant aesthetic, has also been a popular roofing option based on its durability. However, slate shingles tend to be relatively expensive and therefore are not a financially viable option for many homeowners in Winnipeg.

When testing these shingles in Canada, the Canadian Standards Association (CSA) oversees developing and testing the standards for which shingles can be certified. The common tests used for certification include tear strength, pull-through resistance, as well as class ratings for resistance to fire and impact damage tests. Tear strength and pull-through both measure the force required to either tear the shingle at a known location, or measure the force required to tear the head of a roofing nail through the shingle. Almost all asphalt shingles receive the highest rating (Class A), so the purpose of this test is to mainly compare specific products to one another. Impact testing operates on a Class 1 to Class 4 rating, with Class 4 displaying the most resistance (InterNACHI, 2024).

Advancements in technology and material science have expanded the options available for roofing shingles. Among these, asphalt shingles have emerged as a popular choice, providing a cost-effective solution for roofing needs. Despite their widespread use, asphalt shingles come with certain drawbacks. Their relatively shorter lifespan, typically around 15 years (GC Roofing Company Edmonton, 2022), compared to the lifespan of 75 years for slate shingles, stands out as a notable limitation. Moreover, concerns regarding their environmental impact during disposal have also been of concern.

Several factors contribute to these environmental concerns. Firstly, asphalt shingles derive from non-renewable resources, primarily petroleum, thereby raising questions about sustainability. Additionally, the manufacturing process for asphalt shingles is notably energy intensive (Dhar, 2023).

Further, according to a publication by researchers working with Innovative Waste Consulting Services, LLC, there are several health, environmental and sustainability concerns associated with asphalt shingles. The two main concerns include those related to asbestos and polycyclic aromatic hydrocarbons (PAHs) (Townsend et. al, 2007). Asphalt shingles contain a small number of PAHs which can leach into the environment causing health concerns due to carcinogens present, and environmental issues from bioaccumulation, air pollution, water pollution and they may disrupt sensitive ecosystems (Abdel-Shafy and Mansour, 2016).

As sustainability is an increasingly important issue today, creating a product that is both sustainable and economically viable is desirable. Recycled materials, such as GTR fibres, are gaining traction as components in innovative shingle designs. These materials not only repurpose waste but also contribute to a more sustainable and environmentally conscious approach to roofing.

In the context of this project, the focus is on utilizing GTR fibres from used vehicle tires to produce roofing shingles. The intent is to offer homeowners in Winnipeg, Manitoba, a sustainable roofing option that is both stylish and tailored to endure the city's unique weather cycles.

1.2.4 Tire Recycling Programs

Several existing tire recycling programs are implemented currently. Tire Stewardship Manitoba (TSM) is a not-for-profit corporation formed as a Producer Responsibility Organization (PRO) to represent tire stewards in Manitoba, according to their 2017 Program Plan (Tire Stewardship Manitoba, 2017). This organization collaborates with various stakeholders that include governments, industries, recyclers, and consumers. They exist to ensure that the collection, recycling, and disposal of used tires in Manitoba are done in an environmentally friendly manner. This organization plays a large role in the tire recycling processes and is involved in a collaboration with RTR. TSM acts as a middleman for RTR, facilitating the acquisition of used tires. While TSM itself does not currently manufacture products, they contribute to the existence of the products manufactured by RTR, which includes rubber mats, rain splash pads, steppingstones, eco borders, mulch tree rings, rubber mulch, playground tiles, and parking curbs (Tire Stewardship Manitoba, 2023).

[redacted]

1.3 Problem Definition

1.3.1 Problem Statement

RTR aims to utilize GTR fibres from the used vehicle tires they collect to make roofing shingles. These shingles, designed to appear like slate shingles, will uphold a warranty period of 25 years. This warranty period signifies the anticipated lifespan of the shingles to ensure long-lasting performance. The main goal of this project is to offer homeowners in Winnipeg, Manitoba a sustainable roofing option capable of withstanding the unique weather cycles this region experiences, such as extreme periods of cold weather, hot weather, snowfall, rainfall, and storms.

1.3.2 Target Specifications

The target specifications for the rubber roof shingles are listed in Table 1, below.

Table 1. Target specifications for roof shingles.

Spec.	Description	Criteria	Verification Approach	Verification Procedure
S1.1	Length	1.67 ft	Measure	3.1
S1.2	Width	1.67 ft	Measure	3.1
S1.3	Thickness	0.1176 in	Measure	3.1
S2.1	Weight	235 lb per 100 sq. ft	Measure	3.1
S3.1	Temperature Range	-60°C to 60°C	Test	3.2
S3.2	Hail Proof	1 in 25-year storm	Test	3.3
S3.3	Water/Rain Proof	1 in 25-year storm	Test	3.4
S3.4	Wind Resistance	4:12 ratio for roof slope	Test	3.5
S3.5	Ultraviolet (UV)	Extreme heat and summertime UV	Visual observation	3.6
S4.1	Recycled Material	95% rubber	Measure Test	3.7
S5.1	Installation	Uses roofing nailing method	Test	3.8

Spec.	Description	Criteria	Verification Approach	Verification Procedure
S6.1	Appearance	Resembles cedar or slate shingle	Visual observation	3.9

The technical specifications S1.1-1.3 detail the dimensions of the shingle. The length and width (S1.1 and 1.2 respectively) were provided from the initial project application form. The initial values of 40 x 20-in were then converted to International System of Units (SI) for the purpose of Table 1 above. Thickness (S1.3) was chosen based on in-person meetings and discussion with the client. All the specifications can be confirmed by measuring the prototype shingle.

Weight (S2.1) was another specification included in the original project application form. This was measured during the construction of the shingles, making sure to not exceed the specified number. This is important for the transportation and installation of the shingle as well as the load weighing on the home to which it will be installed.

S3 provides required details about the weather specifications of the shingle prototype. All four of the specifications can be verified by testing the shingle prototype and observing how it reacts. The ability of the shingle to work within a temperature range of –60^{o}C to 60^{o} C was tested by subjecting the shingle to each temperature for a period of 1 hour plus an additional hour at room temperature between each temperature extreme for a total of 25 cycles (S3.1). A temperature range of –40^{o}C to 40^{o} C was provided by the initial project application form and confirmed by the client, however, it was better to include a wider range due to the available testing equipment and due to the absorption of heat in shingles. It is also consistent with the climate that may occur in Winnipeg, Manitoba. Water/rain proof and hail proof specifications (S3.3 and S3.2 respectively), were chosen to withstand a 1 in 25-year Manitoba storm to coincide with the clients desired 25-year warranty period of the shingle. The prototype also needs to be able to withstand being blown away or damaged by wind while positioned at the 4:12 ratio for the slope of a roof, consistent with the average roof slope of Manitoba homes (S3.4). Additionally, ultraviolet (UV) testing should be completed to determine degradation due to heat and sunrays in the summertime.

The project application form specified that the shingle needs to be constructed using mostly recycled materials. Client meetings narrowed the percentage to at least 95% recycled rubber or greater (S4.1). The remaining 4% of this mixture will consist of binder and additives to add structure to the shingle.

Installation of the shingle is to utilize the roofing nailing method (S5.1), which is the typical industry standard method of installation, and will allow the team to gauge how the shingle withstands use by the main user. The verification of this can be tested and observed with the completed prototypes.

Lastly, the shingle needs to have a similar appearance to a cedar or slate shingle (S6.1). This specification is set for aesthetic purposes as the consumer would likely purchase a product that will look pleasing on their home.

These specifications are elaborated on in Section 3 of this report where the verification procedures are discussed.

1.3.3 Constraints and Limitations

The project has a few limitations in place affecting the workflow. Table 2 below provides descriptions of the project constraints and details the mitigation strategies being utilized should the issues occur. The main limitation of this project (C1) is the timeframe, with the team's scope of the project needing to be completed by April 2024.

Certain equipment is needed to construct and test the prototypes (C2), so progress will be constrained by the availability of the necessary equipment. This is also true for lab time and space. The conflicting schedules among the team members (C3) pose a challenge, leading to limited opportunities to collaborate on completing the project within the specified timeframe.

The previously described constraints are listed in a tabular form, shown in

Table 2, below.

Table 2. Constraints and mitigation strategies.

Constraint	Description	Mitigation Strategy
C1	Project limited to 8-month timeframe	The use of a Gantt chart to keep the team on track
C2	Access to equipment needed for construction and testing	The team's contact has emailed individuals with necessary equipment and lab space for this project
C3	Conflicting schedules limiting both online and in-person meeting availability	Discussions on weekends or Thursday mornings are being utilized to coordinate good online meeting times on a weekly basis

The next section of this report will discuss more detailed information about the design of the roofing shingles based on information covered in this section.

2. Design Solution

The design solution includes both material testing and creating a mold, so a prototype can be produced. A major portion of the design solution was to come up with a mixture of rubber and other recycled materials that meets the requirements of the project. At the request of the client, the mixture design needed to be 95% recycled materials or greater. A preliminary testing phase took place to determine which form of GTR (fine, coarse, or fibrous), along with what mixture of other materials would be good candidates for the next test stage. The test samples need to be rigid enough to pass testing, and not crumble or break apart due to surface agitation. There was a total of three test phases which will work to eliminate material options until the best material is determined. For most of the testing, a repurposed heat mold was used to create the samples. After the completion of tests which could be completed with a small sample disk, a full-sized prototype mold was created. Once all testing was complete, the result was an upscaled prototype of a two in one shingle. The outlined bill of materials can be seen in Appendix A, while the workplan the team followed can be seen in Appendix B. A flow chart outlining the design process steps can be seen in Figure 2.

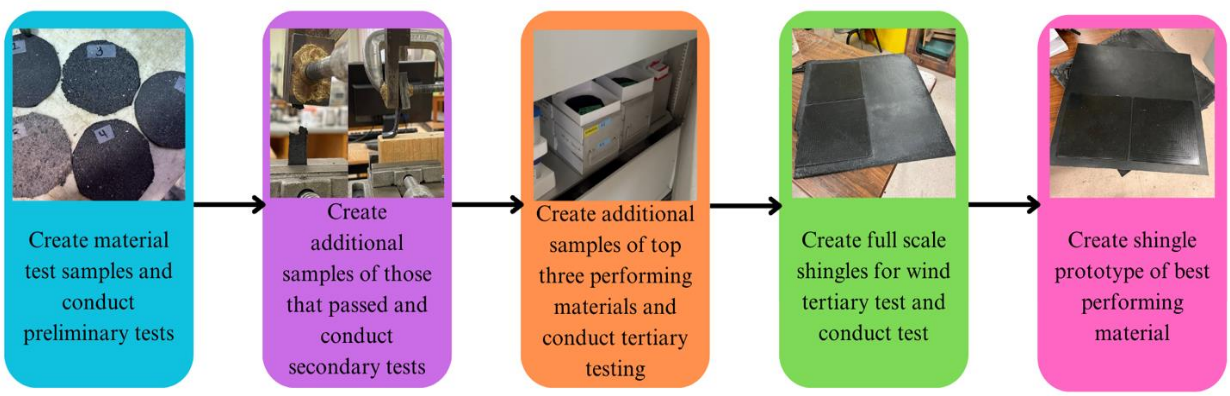


Figure 2. Flow chart outlining the general design process.

2.1 Mold Design

2.1.1 Test Mold

For most of the tests, a mold from a previous biosystems department project was repurposed to produce samples. Utilizing this mold saved on time and expenses associated with creating a new mold. Modifications have been applied to increase the gap between the two halves to achieve the required 3 mm thickness of the sample. The mold was calculated to have a volume of 12 cm^3. An image of the mold is depicted in Figure 3 below.

(a) Bottom half of mold (b) Top half of mold

Figure 3. Repurposed mold used to make samples.

The mold was previously used to make a plate like shape, so for the purposes of this project only enough material to form a circular disk was used, as depicted in Figure 3a by the flat bottom section of the mold. This mold was employed during the preliminary, secondary, and tertiary tests (excluding wind testing). A full-sized prototype mold will be designed and machined to complete the tertiary testing phase, as well as to provide the required prototype for the client.

The manufacturing procedure for creating the test pieces involves the following steps:

1) Attach the mold to the hydraulic hand press.
2) Electrically heat the mold by plugging in and turning on the control box.
3) Prepare the mixture based on weight.
4) Pour the mixture into the mold.

5) Utilize the hand press lever to apply approximately 85 psi to the rubber mixture for 8-10 minutes.
6) Remove the finished product from the mold.
7) Repeat the process for new samples.

2.1.2 Prototype Mold

A Prototype mold was designed and machined to create a full-scale shingle prototype. A prototype was a requirement of the client and is also needed for the wind test. The prototype mold was designed in AutoCAD and is 24 x 24 inches in size and can be seen in Figure 4 and Figure 5. The mold was manufactured by the University of Manitoba’s (U of M) Mechanical Engineering Machine Shop. The mold is a 2 in 1 shingle design that is 18 x 18 inches, and 0.118 inches (3mm) thick at most points, apart from the structural sections which are double the thickness.

The top half of the mold was machined from a 24 x 24-inch multipurpose 6061 aluminum sheet, 1 1/4-inch in thickness. The top of the mold features the structural grid design for the underside of the shingles. There is also a slightly lowered edge to indicate where to cut, as there is a 1-inch border surrounding the shingle to reduce imperfections that could be made by removing the shingle from the mold.

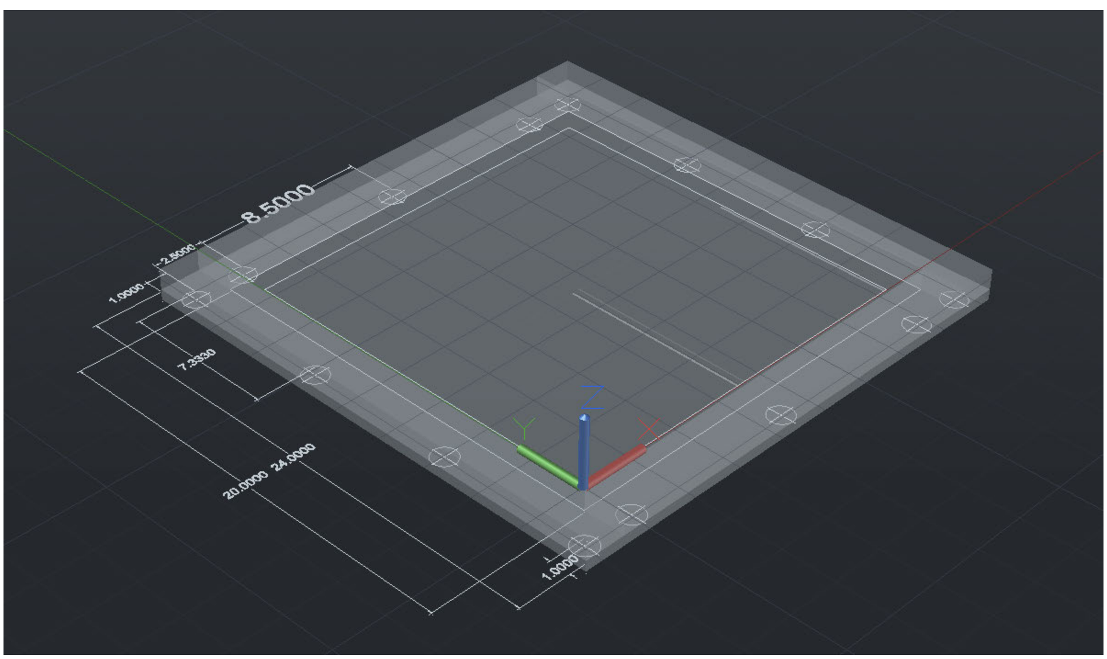


Figure 4. Inside view of top of prototype mold.

The bottom of the mold was made using a 24 x 24-inch multipurpose 6061 aluminum sheet, 1/2-inch in thickness, as well as four, 1 x 2-inch bars, 2-ft in length to make up the raised edge. Connecting the bars to the base plate are 14, 3/8" -16 black-oxide alloy steel hex drive, flat head screws, 1 1/4-inch in length. The screws are bolted up from the underside of the mold. The bottom half of the mold shows what the top face of the shingle will look like and features two, 9 x 8.75-inch rectangles 0.118 inches in depth with filleted edges. The team attempted a textured face resembling slate for the mold, by using a 3-D scan. Due to time constraints and computing requirements along with the complexity of the 3-D scan file, the team ended up continuing the mold with a smooth face. Along with the limitations of computing the file, the textural design would have taken extensive time to machine due to the detail, and it would not have been able to be completed at the U of M Machine Shop due to the tools and time required. Further details regarding the textural design process can be seen in Appendix D: Textural Design for Mold. There is, however, enough space remaining in the depth of the bottom plate to add texture to the design later, if the client wishes.

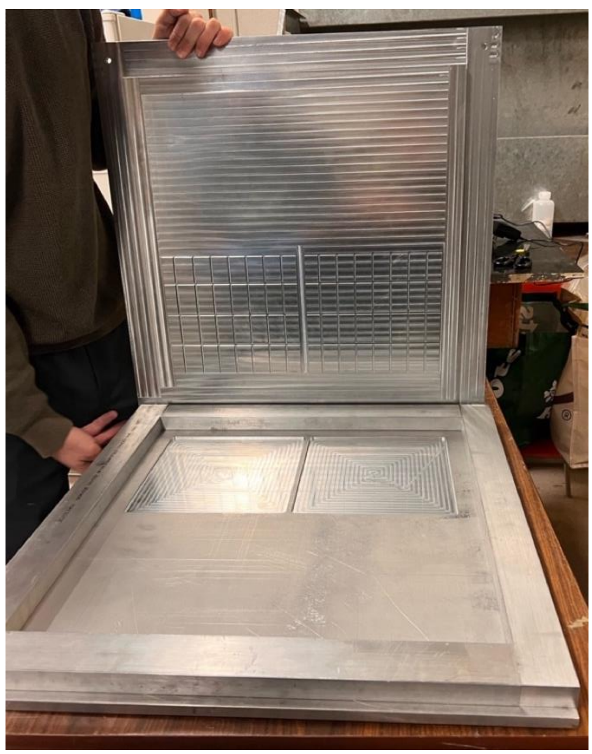
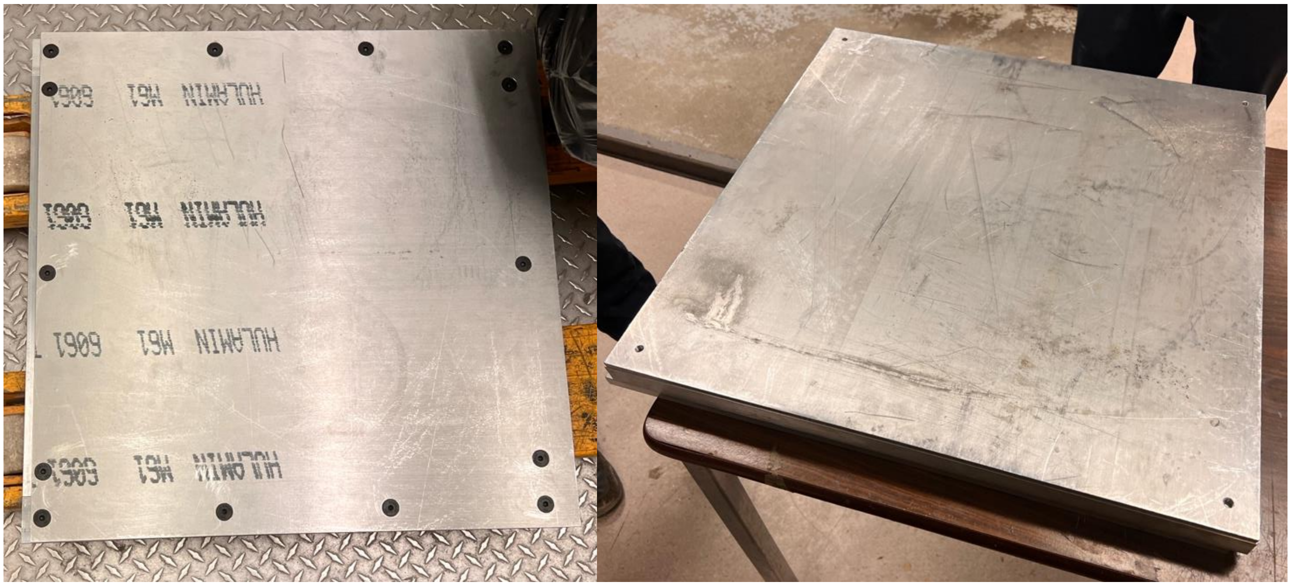


Figure 5. Inside of top and bottom mold.

Shown below in Figure 6 is the outside of the manufactured mold. The bottom of the mold features the previously discussed bolts, while the top features the threaded holes.



(a) Bottom of Mold (b) Top of Mold

Figure 6. Outside of manufactured mold.

A mistake was made during the construction of the mold, the bottom plate was shifted an inch over. The machine shop employees ensured that the internal portion of the mold still fit together as designed. As seen in Figure 7, the bottom plate is not flush with the rest of the mold. This error is indicated by an arrow shown in the figure.

Figure 7. Mistake made in manufacturing of mold.

A few changes were made to the design supplied to the machine shop to reflect the tools available. This included rounded corners, as well as a rounded design rather than a filleted design on the shingle on the bottom half of the mold. An additional 0.007-inch tolerance was added between the sides of the top and bottom halves of the mold, to aid with separating them during the prototype manufacturing process. Threaded holes were also a last-minute decision, not reflected in the CAD design, added to the top half of the mold on each corner to help release the mold if it sticks during the manufacturing process.

2.2 Material testing

The client provided four materials for material testing of our design: GTR produced by RTR, fibres extracted from the GTR as by-products of RTR's tire grinding process, and virgin High-Density Polyethylene (HDPE), a polymer derived from petroleum that, when combined with rubber through heating and compressed, enhances the resulting material's tensile strength (Xometry, 2022).

Due to natural rubber having a density of 1.34 g/cm³ (Suebel. 2023), a material weight of 16.08 g of material was initially determined to be used to make samples. This value was increased to an even 20.00 g for simplifying calculations, as the mixtures needed to consist of at least 95% rubber by weight. However, upon further inspection, this quantity was adjusted to 40.00 g due to the mold's size. With this final mixture weight, 38.00 g of rubber material was required to be combined with 2.00 g of HDPE for the testing mold samples. To prepare each mixture, the ingredients were individually measured, mixed in a beaker, and placed into the bottom section of the mold. Table 3 below provides details on the measured weights and the type of rubber used for the five preliminary test samples.

Table 3. Mixture Ratios for Preliminary Test Samples. (F: fine, Fb: fibre, C: coarse.)

	Sample #				
	1	**2**	**3**	**4**	**5**
Rubber (g, type)	37.79, F	38.05, Fb	38.01, C	19.00, F	26.60, F
				19.00, C	11.4, C
HDPE (g)	2.24	1.96	2.00	2.00	2.00
Total weight (g)	40.03	40.01	40.01	40.00	40.01

Samples 4 and 5, weighing 38.00 g (comprising 95% of the mixture's weight), were divided into a 50:50 and 70:30 ratio of fine to coarse GTR aggregate, respectively.

Additionally, the client supplied the team with sulphur and hydrogen peroxide to use as strengthening additives to use in combination with HDPE, or by itself. Table 4 below depicts the different mixtures that were created with these additives.

Table 4. Mixtures using additional additives provided by RTR.

Additive(s)	**Rubber (g)**	**Sulphur (g)**	**HDPE (g)**	**Hydrogen Peroxide (g)**
Sulphur	39.5	0.53	0	0
	39.59	0.46	0	0
Sulphur & HDPE	37.98	1.02	1.03	0

Additive(s)	Rubber (g)	Sulphur (g)	HDPE (g)	Hydrogen Peroxide (g)
	38.02	0.48	1.59	0
	38	0.86	1.27	0
	38	0.50	1.50	0
	38	0.75	1.25	0
	38	0.60	1.40	0
Hydrogen Peroxide	39.36	0	0	0.67

2.2.1 Preliminary Testing

The first sample mixtures using only HDPE and rubber were formed using a hand operated hydraulic press and compression mold plate, as detailed in Section 2.1.1. This procedure yielded five sample discs, each with an approximate 3 mm thickness and an approximate diameter of 106.1 mm, illustrated in Figure 8 below.

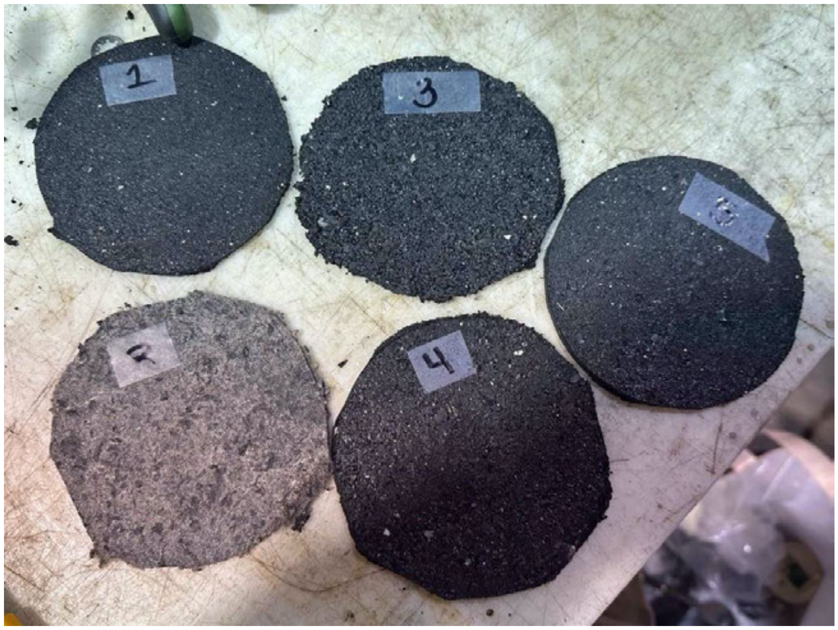


Figure 8. Material test samples for preliminary testing.

Following the cooling and removal of samples from the mold, preliminary tests were performed, which included stickiness tests, crumbling tests, flexibility/tensile tests, and aesthetic assessments.

The stickiness test involved feeling the flat surfaces of the sample discs to identify any areas that remained sticky after cooling. The sample passes the stickiness test if it does not feel sticky after cooling for some time. For the crumbling test, individuals ran their fingers across the disc faces to detect any flakes or pieces that may have been dislodged from the sample. A passing sample required that no pieces or flakes were removed from the sample. Assessing the flexibility was done by bending the discs at the centre, observing any cracks or deformations. If the sample remains uncracked or deformed, it is considered a pass. The aesthetic test, being subjective, relied on each team member's judgment to determine the best-looking samples in terms of their similarity to slate shingles and overall smoothness. The sample was considered a pass if it appeared to look smooth.

Each sample received a pass or fail grade, and the results are summarized in Table 5 below, with passing samples for all four preliminary tests outlined in black.

Table 5. Preliminary material test results.

Sample #	Stickiness	Crumbling	Flexibility/Tensile	Aesthetic
1	Pass	Pass	Pass	Pass
2	Pass	Fail	Fail	Fail
3	Pass	Fail	Pass	Fail
4	Pass	Pass	Pass	Pass
5	Pass	Pass	Pass	Pass

The test results revealed that the fine powder GTR exhibited the best performance. Samples 1, 4 and 5, each containing at least 50% fine powder GTR, passed all four preliminary tests.

It should be noted that the samples containing sulphur and hydrogen peroxide did not undergo formal preliminary testing. The sample containing hydrogen peroxide resulted in a somewhat aqueous sample and immediately did not meet the criteria of the preliminary tests. Combining these results with a general lack of knowledge by team members on how to properly mix the peroxide with the rubber, caused it to be dropped from further test mixtures. Further information on the chemistry of mixing peroxide and rubber can be read about in the link located in Appendix C: Project-specific Materials. Sulphur by itself and combined with HDPE performed similar to that of just HDPE and rubber samples across all preliminary tests. However, its strong scent poses a challenge to olfactory senses and may be off-putting to potential consumers. Secondary test results with the samples, outlined later in the report were used to help determine whether sulphur should be used or removed from the recipe entirely.

2.2.2 Secondary Testing

The mixtures of the samples that passed the preliminary tests were used to commence secondary testing. To determine the best samples for the later tertiary testing, each was subjected to a tensile loading test, and a pull-through tear test.

Tensile load testing required a testing setup of vice on top, a clamp below, a load cell (200lbs), and a motor that would pull upward to facilitate tensile force. Slices 10 mm wide and 30 mm long were cut from the samples and were fastened vertically into the vice on one end and the clamp on the other. The motor pulled the vice and load cell section until the sample slice had ripped into 2 pieces. The apparatus was connected to a computer program that recorded the force throughout the test runtime. After data interpolation the maximum tensile stress could be found.

The nail pull-through test is important for testing shingles, since they will be nailed into a roof, and must be able to withstand significant tear force concentrated around the head of the nail. For this test, a similar setup to the above-mentioned tensile load test was used, with slight modifications. 20 mm wide and 60 mm long slices were cut from each sample. A nail (1 ¼" roofing nail) was hammered through the sample; measured 10 mm inward, from the 20 mm wide edges, centered, and into a wooden block. The block was fastened into the bottom clamp with the nailed sample lying horizontal, while other end of the slice was gently angled upward to be attached into the top vice, holding that section vertical. The apparatus was then run in a similar manner as the tensile test, the difference being that the material had to tear through the nail head.

The sample mixtures that could withstand more than 350 lb/in² for their maximum tensile loading and above 450 lb/in² for their maximum tear stress were the top choices for moving onto verification tertiary testing, which will be discussed in Section 3 below. The top three mixtures are listed in Table 6.

Table 6. Top three samples with secondary test results.

Additive(s)	**Amount of Additive**	**Max Tensile Stress (lb/in²)**	**Max Tear Stress (lb/in²)**
HDPE	5 %	350.9	523.6
HDPE + Sulphur	1.25 % Sulphur 3.75% HDPE	362.7	513.7
HDPE + Sulphur	1.5% Sulphur	380.5	561.9

Additive(s)	Amount of Additive	Max Tensile Stress (lb/in^2)	Max Tear Stress (lb/in^2)
	3.5% HDPE		

These three mixtures produced the best secondary test results and were selected to be used for the verification (tertiary testing) procedures. Two of the three top performing mixtures were found to be ones containing sulphur. This result prompted the team to continue using sulphur regardless of the previously mentioned olfactory issues due to it seemingly improving the strength of the rubber.

2.3 Full-Scale Test Pieces

Full-scale test pieces were created to conduct the wind testing for the tertiary test phase. These were made using the prototype mold and Wabash hydraulic press. Further information about the hydraulic press used can be seen in Appendix C: Project-specific Materials. One of each of the top three samples to be used in the tertiary phase were made and could be cut in half to create two samples for the wind testing. The process for creating full-scale samples can be seen in Appendix E: Full-Scale Sample Procedure.

The amounts added by gram of each of the samples can be seen in Table 7. It should be noted that there is an additional sample that was not previously included in testing, this will be addressed later in the section. The first three samples were made using a temperature of [redacted] and a clamp force of [redacted] The clamp force was calculated using the standard [redacted] applied to the test mold and can be seen below.

$$Force = \ Pressure \times \ Area\ of\ Prototype\ Mold$$

$$Force = \text{[redacted]}\ (20\ in\ \times 20\ in) = \text{[redacted]}\ lbs = \text{[redacted]}\ tonnes$$

The fourth sample used a temperature of [redacted] and [redacted] of force. This was a recommendation made by the client.

Table 7. Mass used to make full-scale samples.

Sample	Additives	Mass Rubber (g)	Mass Sulphur (g)	Mass HDPE (g)	Total Mass (g)
1	5% HDPE	2213.46	0	116.50	2329.96
2	1.5% Sulphur 3.5% HDPE	1140.00	18.00	42.00	1200
3	1.25% Sulphur 3.75% HDPE	1045.16	13.73	41.25	1099.98
[redacted]	[redacted] [redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The amounts seen in Table 7 were linearly calculated based on the volume of the test mold and the mass used for test samples. The calculation for the mass of material used for sample one can be seen below.

$$\frac{Mass\ of\ Test\ Sample\ Material}{Volume\ of\ Test\ Mold} = \frac{Mass\ of\ Prototype\ Material}{Volume\ of\ Prototype\ Mold}$$

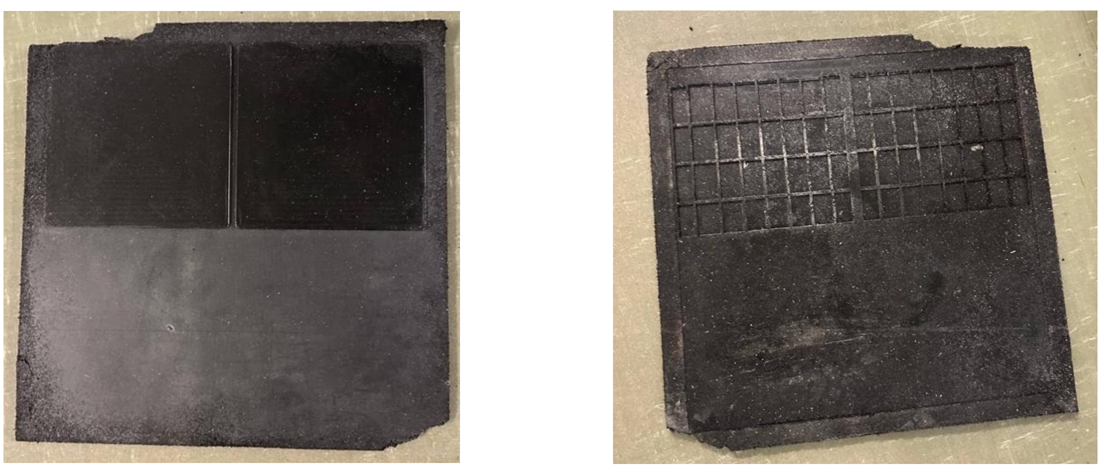
$$\frac{40g}{0.733in^2} = \frac{Mass\ of\ Prototype\ Material}{42.7in^2}$$

$$Mass\ of\ Prototype\ Material = \ 2330g$$

After the completion of the first full-scale sample, it was apparent that the mass of material added to the mold was too high, as the shingle was nearly double the thickness required. This is likely due to the extra space around the edges the test mold had for excess material to go, therefore, when upscaling the amount it created a large excess of material with nowhere to go. The decision was made to only use 1200 g of the material that was already mixed and ready for sample 2, as it was a little over half of the mass used for sample 1 and the sample was just under half as thick. The total mass was slightly altered again for sample 3 as the mold didn't fully close for sample 2. In sample 4 the team decided to return to 1200g as the thickness of sample 3 was inconsistent and some sections were very thin. The results of the full-scale test pieces are as follows.

Sample 1 (5% HDPE)

The images in Figure 9 show the material crumbling around the edges. This sample was nearly twice the required thickness. The material was easy to pull apart, especially around the edges, and there were inconsistencies in the material at different points. One of the inconsistencies of the material was the central regions of the structural components being ridged and strong while closer to the edges these ridges crumbled with ease. The faces of the individual shingles also appeared much shinier than the rest of the sample. This is due to that portion having been machined. That section of the bottom half of the mold is much smoother and shinier than the rest, as seen previously in Figure 5. This is causing better heat transfer and a smoother melt because of the surface finish, paired with this part of the shingle being in closer proximity to the heating element of the press. This could likely be remedied by lightly sand blasting the area to create a duller surface finish (KDMFAB, 2022). Sanding with a block or methods done by hand may create directional grain that would likely be visible on the shingle sample.



(a) Front of Sample 1 (b) Back of Sample 1

Figure 9. Full Scale Sample 1.

Sample 2 (1.5% Sulphur + 3.5% HDPE)

The images in Figure 10 show more crumbling than sample 1. This could be due to the shingle's thickness being close to the desired thickness when compared to sample 1. Mold release was not used on the bottom of this sample, which caused some additional tearing from the material sticking to the mold. The same inconsistencies of material mentioned in sample one, were seen with this sample. An issue that became apparent when the sample was the correct thickness was the lack of rigidity of the material once upscaled.

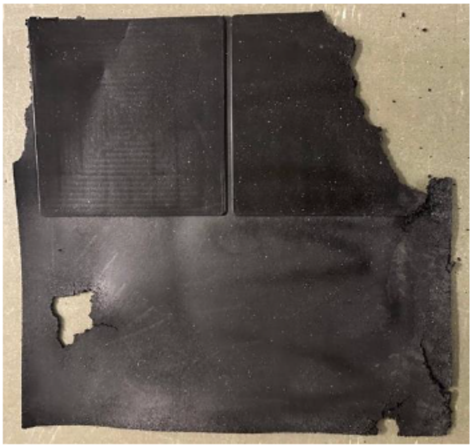
(a) Front of Sample 2

(b) Back of Sample 2

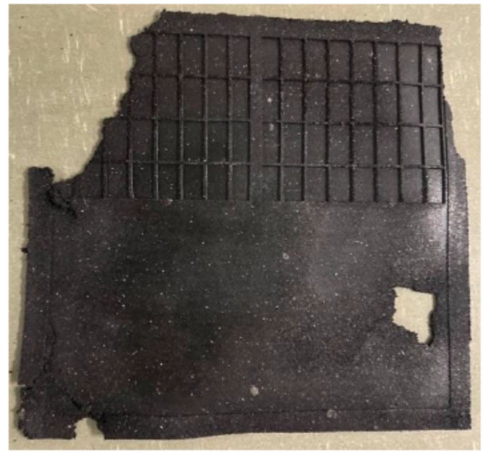
Figure 10. Full Scale Sample 2.

<u>Sample 3 (1.25% Sulphur + 3.75% HDPE)</u>

Sample 3 came out the least quality of the three samples, it was very easy to pull apart by hand and crumbly at a variety of sections even though mold release was used on both faces of the mold. Sample three held similar issues as samples 1 and 2. Sample 3 can be seen in Figure 11.



(a) Front of Sample 3

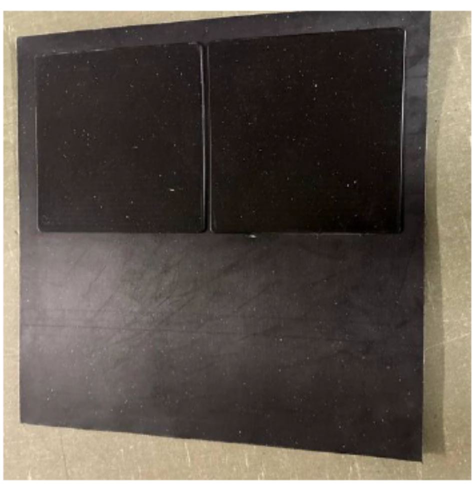


(b) Back of Sample 3

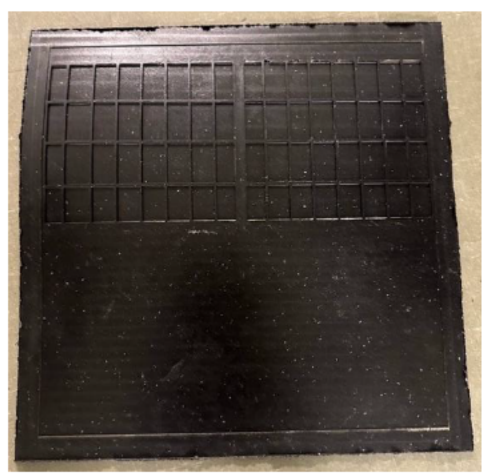
Figure 11. Full-scale Sample 3.

Sample 4 [redacted]

After the issues faced with upscaling the mixtures into a full-sized sample it became evident that none of the mixtures created by the team would create a quality shingle. Upon the client's recommendation, the team made a sample that was not previously sampled or tested. This sample contained [redacted] and seemed to perform much better than the previous samples. This sample was much more rigid and structurally sound, [redacted]



(a) Front of Sample 4



(b) Back of Sample 4

Figure 12. Full-scale Sample 4.

The full-scale test pieces did not go as the team anticipated. Once the material was upscaled, the structure lost rigidity. The material also crumbled more, near the edges and in other sections, which could be due to inconsistent mixing or could be due to inconsistencies in the heat distribution of the hydraulic press. It became apparent none of the samples would be suitable mixtures for a full-sized shingle. Upon the client's recommendations, [redacted]. Sample 4 is the only sample that will undergo the wind testing verification. One issue with Sample 4 is that it does not meet the required level of recycled material. This problem can likely be solved by using non-virgin HDPE, which is a recycled version of HDPE. Further testing should be completed using non-virgin HDPE to test performance. Other recycled materials such as plastics, polymers, or biomaterials could also be investigated further for impact on performance of material. The cost breakdown for each of the samples can be seen in Appendix A, Table 13.

2.4 Safety Considerations

To maintain a safe work environment over the course of this project, the team took precautions regarding the use of chemicals and the physical safety concerns during various processes of the project.

2.4.1 Chemical Handling

Over the course of the project, the team was in contact with chemicals. To gain an understanding of the precautions to take, material safety data sheets (MSDS) were printed and kept near the respective chemicals. [redacted]

For sulphur, the main concern was the fumes created at high temperatures. To maintain a safe working environment, the workshop fume vents were turned on so the air flow would reduce the accumulation of fumes. This helped to mitigate the negative effects of sulphur fumes and allowed the team to work on producing samples for longer periods of time without negative health effects.

While creating the sample for the peroxide mixture, the concern was the flash point, meaning there was a risk of the mixture exploding due to air bubbles being trapped under pressure. To protect the team members, an acrylic sheet was placed in front of the hand press while the mixture was under pressure, and the team was notified of the nearest fire extinguisher in case of emergency.

2.4.2 Physical Considerations

During the sample making process, the team was in close contact with the metal press, which [redacted] When exposed to extreme temperatures, the skin will immediately blister, and can cause permanent nerve damage wherever the skin was exposed. To reduce the risk of touching the heated mold, leather oven mitts were worn to provide a thick barrier between the team member and the hot metal of the press. These gloves were worn while moving the mold into position, as well as when removing the sample from the mold. The test mold was also only plugged into the outlet when a team member was in the room, and it was never left plugged in. This meant that someone would not come across the heated mold unexpectedly and reduced the potential exposure.

During the weather testing, the team placed the samples in a freezer set to –60° C, which can lead to frostbite if exposed directly to skin. To protect the hands of the team members while moving the samples in and out of the freezer, nitrile gloves were worn to keep the skin from freezing to the metal of the freezer. This prevented skin damage due to the extreme cold temperature.

While performing the impact test, there is a contact point between the hammer and the sample which could result in crushed fingers if performed improperly. To prevent injury, the team member would set up the sample so it would not need to be held for the impact and would only allow the hammer to fall when the hands were out of the test frame. This insured that the fingers of the team member were never at risk of being crushed by the force of the hammer.

The design for the mixtures and samples in this section went onto verification testing, which is detailed in the following section.

3. Verification Procedure

The prototype shingle needs to be verified for a 25-year period to ensure RTR can guarantee a 25-year warranty. Therefore, the verification (tertiary) testing aims to provide insight into the samples' ability to withstand weather conditions observed in Manitoba. In Table 8, the verification criteria for three different conditions are stated.

Table 8. Pass and fail criteria for weather simulating tests.

	Life Cycle	**Hail Protection**	**Extreme Wind**
Pass	No visible or structural damage observed during or after testing time	No damage to sample or surface underneath	Shingle stays intact after wind speed
Fail	Cracking, deformation, discolouration and/or other noticeable changes	Damage to surface underneath and/or sample	Nail rips through sample from wind speed

Each test involved creating a new sample of each mixture to limit the number of variables being tested during each individual test. The team acknowledges that some tests may impact the performance of others, but the limitation on time for this project means we cannot perform a cross-examination of these effects. The verification procedure served as an approximation of how the final prototype will do once it is formally tested for the 25-year warranty guarantee that RTR aims to achieve.

3.1 Dimensions and Physical Properties

The dimensions of the mold were designed to create shingles that are 18 x 18 inches, and 0.118 inches (3mm) thick. The criteria for the shingle dimensions were designated as 1.67ft x 1.67ft. although 18in is equivalent to 1.5ft, the shingle design was approved by the client, so this criterion is considered fulfilled. The weight of the shingles is equivalent to 117.58lb per $100ft^2$, which is below the 235lb per $100ft^2$ required. This means that the shingle fulfills this criterion as well.

3.2 Life Cycle

The following tests were chosen to give a general understanding of how the shingle will withstand normal weather patterns in Winnipeg, MB. Life cycle and sun exposure were specifically requested by the client to be included as part of our verification process. Our team also considered testing other factors like snow safety or freeze-thaw endurance, but due to the limited time of the project, the list was narrowed down to important parameters that could be performed within the time frame.

3.2.1 Extreme Temperature

Shingles are exposed to a wide range of temperatures and conditions throughout their lifespan. A Life Cycle test was performed to subject the smaller scale samples to extreme hot and cold environments, and to record any visible changes observed during the required life cycle of the product. This test involves subjecting samples to repeated exposure of 60°C and -60°C temperature conditions to simulate the summer and winter seasons for Winnipeg, Manitoba. The testing cycle can be visualized in Figure 13, below.

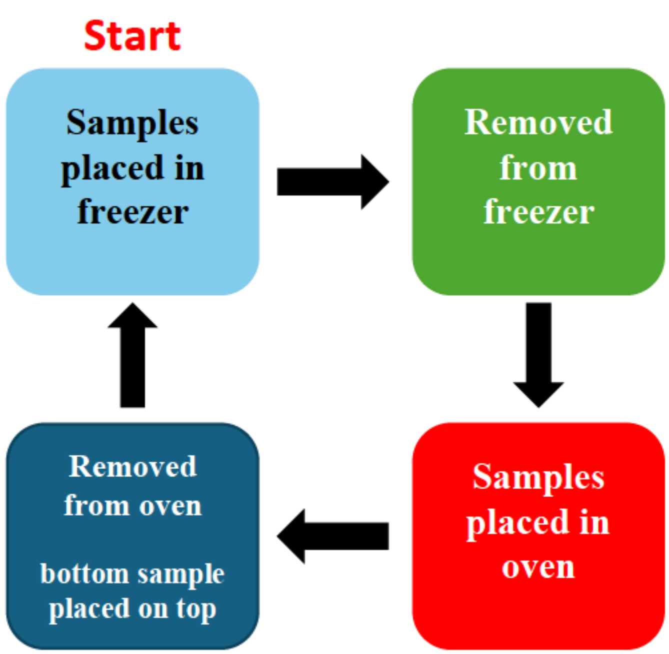


Figure 13. Life cycle test flow chart

In the graphic depicted in Figure 13, the cycle starts from the top-leftmost box. The life cycle tests were conducted by taking one sample disk of the top three mixtures, shown previously in Table 6, stacking them in a random order, and placing the stack inside a Forma –86C ULT Freezer set to -60°C. After 60 minutes elapsed the samples were removed and left to warm up to room temperature for 60 minutes. The samples would then be subsequently placed in a Fisher Scientific Oven set to 60°C for 60 minutes, removed, and left to cool to room temperature for another 60 minutes. Lastly the sample on the bottom of the stack was removed and placed on top of the stack; ready to be placed in the freezer. This entire process constituted one full cycle, with 25 total cycles being completed to simulate the products required 25-year warranty.

From March 1st, 2023, to March 1st, 2024, the monthly minimum and maximum temperatures of Winnipeg ranged from a mean of –12.2°C to 20.9°C (Weatherstats, 2024). The maximum and minimum temperatures observed during this time frame were 36.5°C and –30.2°C respectively. This means the samples were subjected to nearly double (60° vs. 36.5°, and –60° vs. -30.2°) the maximum and minimum temperatures recorded, but this still provided good temperature shock test results. A sample was considered to have passed this test if at the end of the 25th cycle, no visible discolouration, deformations, cracks, or other breakages were observed. Each of the three chosen mixtures had two samples being exposed to this life cycle testing to account for any unforeseen changes occurring throughout the exposure.

All six of the samples exposed to the test maintained same colouration from the first cycle through the 25th, and no visible breaks/tears were found. As a result, all the samples passed the extreme temperature test. These results suggest that all three of the tested mixtures would be able to survive for the required 25-year warranty if temperature was the only factor.

3.2.2 Secondary Testing after Exposure

Shingles need to be able to not only survive the extreme temperature ranges throughout the Winnipeg seasons, but they must also be able to function even at the end of the 25-year warranty. To calculate data on whether extreme temperature changes would deteriorate the strength of the shingles, the secondary tensile and pull-through tear tests as outlined in Section 2.2.1 and 2.2.2 were performed on a set of samples that had completed being exposed to the extreme temperature testing discussed in Section 3.1.1. Of the six samples discussed in the previous section, three of them (1 of each top mixture) were randomly chosen to undergo these tests. Shown below in Table 9 is the results for the tensile and pull through strength tests before and after temperature testing.

Table 9. Tensile and pull through strength comparisons before and after temperature testing.

Sample	**Tensile strength (lb/in^2)**	**Pull-through strength (lb/in^2)**	**% Strength change**
1.5 % Sulphur	Control: 358.75 Test: 276.45	Control: 564.93 Test: 355.99	Tensile: -22.9% Pull Through: -36.9%
1.25% Sulphur	Control: 302.02 Test: 267.06	Control: 408.24 Test: 384.52	Tensile: -11.5% Pull Through: -5.8%
5% HDPE	Control: 227.38 Test: 212.40	Control: 298.78 Test: 399.08	Tensile: -6.59% Pull Through: 33.6%

The samples had no visible changes after undergoing the temperature testing, but strength testing the samples shows that each developed a decrease in strength. The 5% HDPE had the lowest decrease in tensile strength, and the pull through strength surprisingly increased after temperature testing.

3.3 Hail Protection

Hail Protection tests are performed to determine the shingles ability to withstand the impact of hail. This test will involve placing the sample in a pendulum impact testing apparatus, shown in Figure 14 below.

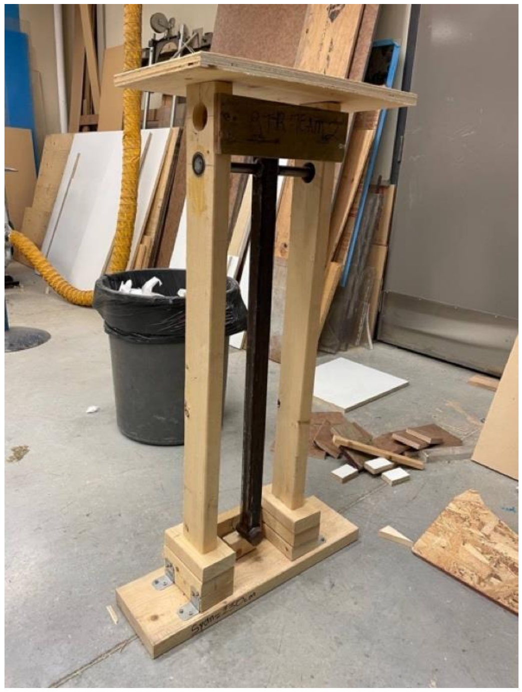


Figure 14. Impact testing apparatus

A 33-inch-long metal arm swings from a height chosen by the operator, impacting the surface of the sample at the bottom. Based on the mass of the hammer and height at which the arm is being dropped, the impact force can be calculated, and any damage to the samples can be observed and recorded. To find the appropriate force to use for this test, several calculations were done to find the height in which to release the hammer.

The volume of a hail sample can be calculated as follows using Equation (1).

$$V = \frac{4}{3}\pi r^3 \tag{1}$$

Where r is the radius of the hail in cm and V is the volume in cm^3. Using a radius of 5 cm (Government of Canada, 2022), the volume of a hail is calculated to be 523.6 cm^3.

The mass of the hail can be calculated via the following Equation (2).

$$m = \rho V \tag{2}$$

Where ρ is the density in g/cm^3 and V is the volume of the hail, as calculated, in cm^3. Using the density of ice of approximately 0.9168 g/cm^3 (Wikimedia Foundation, 2024), the mass of a hail is calculated to be 0.480 kg.

To find the force of the hail, the following Equation (3) was used.

$$F = mg \tag{3}$$

Where F is the force in Newtons, m is the mass of the hail in kilograms, and g is the acceleration due to gravity, which is known to be approximately 9.81 m/s^2. Using a mass of 0.480 kg, and the acceleration due to gravity, a force of 4.71 N was calculated. Therefore, hail with a diameter of 10 cm falling at terminal velocity, the force it would exert would be approximately 4.71 N.

To find the height at which to drop the hammer from the impact testing apparatus, we must conduct further calculations. Firstly, we calculate the potential energy of the hammer due to its height, shown in Equation (4).

$$P.E. = mgh \tag{4}$$

Where $P.E.$ is the potential energy in Joules, m is the mass of the hail in kilograms, g is the acceleration due to gravity, and h is the height at which the hammer is to be dropped at, in meters.

At the lowest point of the swing, the potential energy is converted into kinetic energy, shown in Equation (5).

$$mgh = \frac{1}{2}mv^2 \tag{5}$$

The velocity, v in m/s, can be expressed in terms of the length of the arm of the hammer and the force since this is what determines how high the hammer swings. The velocity of a pendulum, Equation (6), may be used.

$$v = \sqrt{2gh} \tag{6}$$

Substituting this expression for velocity into Equation (5) allows us to solve for h. This is shown in Equation (7)

$$h = \frac{FL}{2mg} \tag{7}$$

This equation gives us the height from which the hammer should be released to achieve the desired force at the lowest point of the swing, given a fixed arm length, L in m, and the mass of the hammer, m in kg. Solving using the calculated values and a given L of 33 inches (0.8382 m) gives a drop height of 0.202 m. Therefore, to simulate a 4.71 N force exerted by a 10 cm diameter hail, the hammer should be dropped 0.202 m from the sample.

This test can be used to simulate an impact force experienced in a typical hailstorm, and whether the samples are suitable for this type of environment. A sample is considered to have passed if there are no signs of damage like holes or thinned areas at the point of impact.

3.3.1 Results from the Impact Test

The results from this test can be found in Table 10. The test was performed by raising the hammer arm to 0.202m above the impact point and allowing gravity to move the hammer to strike the sample. Three samples were made of each mixture type, for a total of 9 samples. Within each mixture type, each sample was subjected to 1 hit, 3 hits, or 5 hits.

Table 10. Results from impact testing.

Sample Description	**Impact Test Results**		
	1 hit	3 hits	5 hits
1.25% Sulphur	No physical damage	No physical damage	No physical damage
1.5% Sulphur	No physical damage	No physical damage	No physical damage
5% HDPE	No physical damage	No physical damage	No physical damage

None of the samples resulted in any physical damage from the impacts performed. This test shows that the mixtures chosen would be able to withstand the force of a 10cm sized hail at terminal velocity.

3.4 Rain Resistance

Rain resistance test will determine the shingles ability to prevent water from seeping through the surface and wetting the area underneath. This test would involve placing a full-sized shingle on a surface with the standard roofing slope 4:12 ratio and pouring water on the shingle with a device that creates water droplets to mimic rain. Due to time constraints, the team was unable to complete this test, but recommends future teams to prioritize progress regarding this test.

3.5 Extreme Wind

Extreme Wind test will determine how the shingles perform under storm conditions. Since Manitoba is occasionally subjected to tornados, it is important to see how the shingles will withstand intense winds. This test involved placing a full-sized prototype shingle sample in a wind tunnel at the standard roofing slope 4:12 ratio. The sample is nailed at the specified slope and wind of a desired speed is blown across it, observing whether the shingle can survive without the head of the nail ripping through, and be rigid enough itself to survive the wind forces.

3.6 UV Protection

UV resistance test will determine the shingles ability to withstand the harsh conditions faced from the sun during the shingles expected lifetime. The sample should be subjected to conditions that mimic long-term exposure to the sun, including extreme heat, UV radiation, and infrared radiation. The team expected to perform a test for this requirement, but due to time constraints were unable to complete the test. The team also was unable to complete this test due to the weather conditions over the course of the project since the winter sun is not as harsh as the summer sun. To estimate the damage due to exposure over the course of the 25-year life expectancy, a test needs to be designed to accelerate the effects so the test can be done within the short time frame of the project.

3.7 Recycled Material

The verification of this constraint was satisfied during the mixture making process. The samples were made by calculating how many grams of additives should be combined with GTR to achieve specific percentages. Since the top three mixtures were made with 95% of their total mixture weight being recycled fine rubber aggregate, this satisfied the constraint of requiring at least 95% recycled material.

3.8 Installation Method

To satisfy this constraint, standard roofing nails must be capable of puncturing the sample shingles with a hammer. This was tested during the pull through strength testing (Section 2.2.2), where the samples were nailed to a piece of wood, and the team had no difficulty puncturing the sample material. While the team did not perform any specific tests to satisfy this constraint, the results during the pull through strength testing showed the team that this constraint was met.

3.9 Appearance

The appearance of the shingle was expected to resemble slate shingles, which have a smooth surface and organic edges to each shingle. During early iterations of sample making, the temperature of the press was [redacted] This resulted in samples that did not uniformly melt and gave a grainy texture to the samples. From the recommendation of the client, the temperature was thus [redacted] and the resulting samples were a more uniform texture that closer resembled slate shingles. The GTR that the team was provided with contained particulates of non-rubber material, resulting in shingles that had an appearance that was a mix of slate shingles and asphalt shingles. The particulates did not melt with the rubber, creating the appearance of asphalt shingles. The team recommends GTR that has been sorted so the non-rubber materials are not included in the raw material used for the shingle.

4. Limitations

As the project progressed, the team encountered a variety of limitations in categories such as materials, prototypes, time, testing, and product design. Many of the limitations overlap into multiple categories.

A major limitation the team faced was the issues encountered with upscaling the material to a full-scale sample. Due to the limitation of needing 95% recycled material, the team stuck rigidly within having 95% recycled rubber, which worked in a small sample, but did not perform well once upscaled. One factor that limited the team in testing larger samples earlier was the mold design completion and construction of the prototype mold. Decisions with the design changed frequently, and when the design was ready there were unforeseen delays with the machine shop. Had the team had access to a larger mold, earlier in the process, other material and recycled additive options could have been explored when the general formula didn't work well scaled up. Due to the limitation on time, the team was unable to further test the performance of the full-scale sample the client recommended (sample 4), with the testing and verification performed on the other three samples. Therefore, there are no results on the performance of sample 4's formula, or the effects of the higher HDPE content. The team also only had access to virgin HDPE, so it has not been tested if the recycled, non-virgin HDPE will perform as well.

There were also some limitations with the manufacturing of the small test samples, the repurposed heat mold used took a significant amount of time to heat up, this slowed down the efficiency of the sample creating process. It took the team too long to realize that the test pieces could be removed while hot. Even with the mold remaining hot, the process involved to make the samples, the time consumption of removing the test pieces and refilling the mold, was a limiting factor for the team. Access to the hydraulic press was limited to working hours, and due to conflicting schedules of the team members it was often difficult to find available times to produce samples.

Limitations were also seen while producing the prototype mold. As previously mentioned, the idea for the design of the mold changed frequently, it took until the 15th week of the project to settle on a design idea. The team hoped to do a stacking mold design, but due to time constraints and cost, it was decided that the stacking portion of the mold could be designed and constructed if the project continues. The team attempted a textured design for the shingle to mimic slate, but unfortunately due to the file size, there was a limitation with the amount of computing power needed to work with a file with so many points and surfaces. If the textured design were to have been completed, it would likely have been too complex to be completed at the U of M Machine shop in the required time frame.

The team was also limited in time available to do the verification and testing that was planned at the beginning of the project, so tests like the rain/weatherproof, UV, and hang tests ultimately had to be removed. Due to time as a limiting factor, the team was also unable to perform the wind resistance test, which the team had hoped to include in the report.

Additionally, there are some limitations the design has as a viable product at its current state. This mainly has to do with the mass production of the shingles, the process as is, is very time consuming, weighing and mixing the dry materials, pouring and leveling the material in the prototype mold, as well as moving the mold to and from the hydraulic press and waiting for the press to heat up and cool down in between are all time-consuming steps that would be costly in mass production.

Although the team faced challenging limitations throughout the project, there were many lessons learned during the process that will help progress this project.

5. Conclusion

5.1 Summary

Over the course of the project, the team has concluded that none of the decided top three mixtures is a viable design for a full-scale shingle. While the small-scale samples may have proven promising, these results did not translate into successful full-scale models. It is unclear as to what issues lead to the failures from full-scale prototyping, and due to time constraints, the team is unable to investigate further. The team believes that future progress should focus on adding stability to the mixture, either chemically with additives or physically with mechanical additions to the mold. Although we were able to achieve a successful attempt using a mixture of [redacted] weight, this does not fulfill the requirements of a shingle made of 95% recycled materials. It could be possible that using non-virgin HDPE could achieve the same results at full scale, while fulfilling the 95% recycled material requirement.

5.2 Recommendations

Recommendations the team would like to bring forth to the client or others continuing the project include possible solutions to limitations faced in materials, appearance, production, efficiency, and economics.

Due to the issues faced when upscaling the material into a full-sized sample, the team would recommend looking into other combinations of materials, specifically additives of recycled plastics, polymers, or biomaterials such as hemp or saw dust. This could be an interesting aspect to investigate if the project were to continue.

One of the additives used in the formula ss sulphur. Even though the amount of sulphur used in the shingles is only 1-2%, the team noticed a strong smell when manufacturing the samples, and when storing them afterwards. Having an entire roof full of these shingles is likely to cause an odour. For this reason, it is strongly recommended to investigate ways to mitigate the odour.

The appearance of the completed shingle is a limitation the team faced due to time constraints and computing power. The 3-D scan and file was too complex to be completed in AutoCAD. It is recommended to investigate methods to create a more simplified texture or file than the 3-D scan;

looking into programs that would help prepare the textured face design could also help with this process. Adding a texture to the mold would allow the shingle to have a more complete and slate-like appearance. Along with adding texture for the appearance, it is recommended that the portion of the mold that has been machined or will be machined for texture is lightly sand blasted to create a duller appearance to the shingle. Sand blasting is recommended due to directional grains that could be visible when adding texture by hand with other methods such as a sand block or toothbrush with grit. Sand blasting also ensures a more even look, when the textured design is added to the prototype mold it could be difficult to get a consistent look with a method completed by hand.

In addition to adjusting the mold to create an ideal appearance for the shingle, a limitation faced by the team was time when creating samples, as well as creating a more efficient procedure for manufacturing the shingles. The team recommends designing another section for the mold that could sit in the middle of the two current halves and be replicated multiple times to create a stacking effect. A stackable mold design would allow for 4 or 5 shingles to be manufactured at the same time, therefore accelerating the manufacturing process.

Limitations encountered such as time, cost, and inconsistent materials could be remedied by looking into creating a liquid mixture to enable the use injection molding rather than a heat press method. Injection molding is highly likely to increase efficiency and reduce costs associated with the manufacturing process of heat press molding. Having a liquid mixture could also reduce the possibility of having irregularities in the material due to inconsistent mixing of the materials. [redacted]

Due to the limiting factor of time and incomplete verification, it is recommended to consider testing verification procedures that were removed or incomplete due to lack of time such as the rain/water resistance, wind resistance, and UV tests. Methodology that could be used for these tests can be seen in sections 3.4, 3.5, and 3.6 respectively. These will help to prove if the shingle will be a viable product.

Lastly, it is recommended to further investigate the feasibility and economics of mass-producing shingles using the materials and methods mentioned in this report. The methods used are quite slow and time consuming, and therefore might benefit from some process/production engineering to create a process that can be replicated for mass production.

Overall, the project was a great learning opportunity for the team. The verification tests used and created would be a great addition for this project's next phase. In addition, the prototype mold will be useful when investigating if other additives and formulas will work when upscaled and can be easily adjusted to include the sought after textured slate design.

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7. Appendix A: Bill of Materials

The bill of materials is broken up into three categories; cost of materials to make mold and the hydraulic presses required to make samples can be seen in Table 11. Table 12 features the cost of materials used to make the preliminary test samples, while Table 13 shows the actual cost of creating each of the full-scale test samples, as well as what the cost would be to produce each sample with the correct quantity of material. It should be noted that the cost of the HDPE and Sulphur powder would decrease when bought directly though wholesale suppliers.

Table 11. Mold and manufacturing bill of materials (all costs in CAD and exclude taxes).

Project Materials	Manufacturer	Part/ Model #	Qty	Unit Cost	Total Cost
Test Mold	Repurposed from Biosystems Department	N/A*	1	N/A*	N/A*
Oversized Multipurpose 6061 Aluminum Sheet, 1/2" Thick – 24" x 24"	McMaster-Carr	89155K13	1	$360.75	$360.75
Oversized Multipurpose 6061 Aluminum Sheet, 1-1/4" Thick – 24" x 24"	McMaster-Carr	89155K17	1	$723.73	$723.73
Bar – Multipurpose 6061 Aluminum 1" x 2" -2ft Length	McMaster-Carr	8975K237	4	$51.67	$206.68
Black-Oxide Alloy Steel Hex Drive Flat Head Screw, 3/8"-16 Thread Size, 1-1/4" Long	McMaster-Carr	91253A626	14	$0.45	$6.25

Project Materials	Manufacturer	Part/ Model #	Qty	Unit Cost	Total Cost
High-Strength Grade 8 Steel Hex Head Screw, 3/8"-16 Thread Size, 1-1/2" Long	McMaster-Carr	91268A210	4	$1.72*	$6.86*
25-ton Hydraulic Hand press	Blackhawk MFG. CO.	BH8202 (Similar model still in production)	1	N/A*	N/A*
50-ton Heated Hydraulic Press	Wabash MPI	G50H-24-CLX	1	N/A*	N/A*
Mold and Manufacturing Total = $1,304.27					
Legend: * = No cost, supplied by University of Manitoba					

Table 12. Bill of materials for preliminary test sample materials (all costs in CAD and exclude taxes).

Project Materials	Manufacturer	Quantity	Unit Cost	Total Cost
Fine GTR	RTR	83.39 g	$0.26/kg	$0.02
Coarse GTR	RTR	68.41 g	$0.26/kg	$0.02
GTR Fibre	RTR	38.05 g	$0.26/kg	$0.01

Project Materials	Manufacturer	Quantity	Unit Cost	Total Cost
HDPE Powder	[redacted]	10.20 g	$0.05/g	$0.51
Sulphur Powder	BlackBookSupply	5.2 g	$0.23/g	$1.196
Hydrogen Peroxide	N/A	0.67 g	N/A	N/A
Total Preliminary Test Materials Cost = $1.76				
Legend: * = No cost, supplied by University of Manitoba ** = No cost, supplied by team member, lack of chemical knowledge for further use				

Table 13. Approximate cost to manufacture each type of shingle based on weight (all costs in CAD and exclude taxes).

Project Materials	**Manufacturer**	**Unit Cost**	**Cost of One Prototype Shingle Using 1200g Material**			
			Sample 1	Sample 2	Sample 3	Sample 4
Fine GTR	RTR	$0.26/ kg	$0.30	$0.30	$0.30	[redacted]

Project Materials	Manufacturer	Unit Cost	Cost of One Prototype Shingle Using 1200g Material			
			Sample 1	Sample 2	Sample 3	Sample 4
HDPE Powder	[redacted]	$0.05/g	$3.00	$2.10	$2.25	[redacted]
Sulphur Powder	BlackBook-Supply	$0.23/g	$0	$4.14	$3.45	[redacted]
Total Full-Scale Sample Cost = (Assuming 1200g material)			$3.30	$6.54	$6.00	[redacted]

Legend:

Sample 1 = 5% HDPE

Sample 2 = 1.5% Sulphur + 3.5% HDPE

Sample 3 = 1.25% Sulphur + 3.75% HDPE

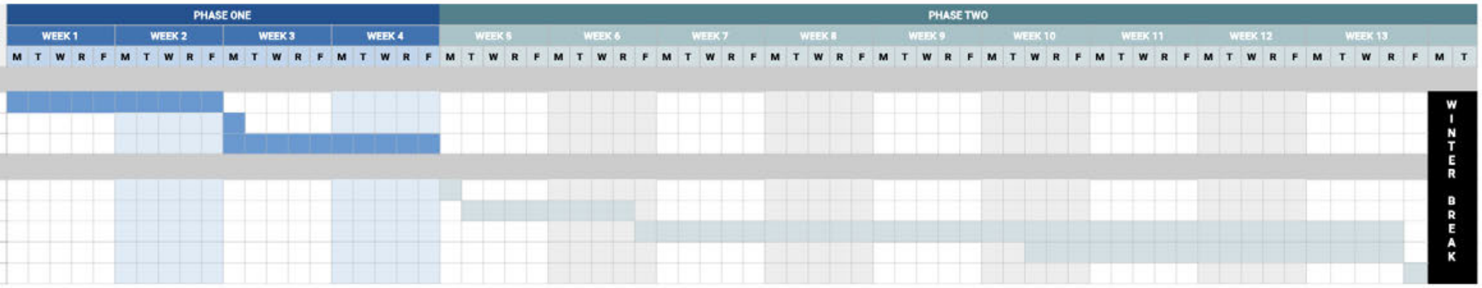
[redacted]

8. Appendix B: Workplan

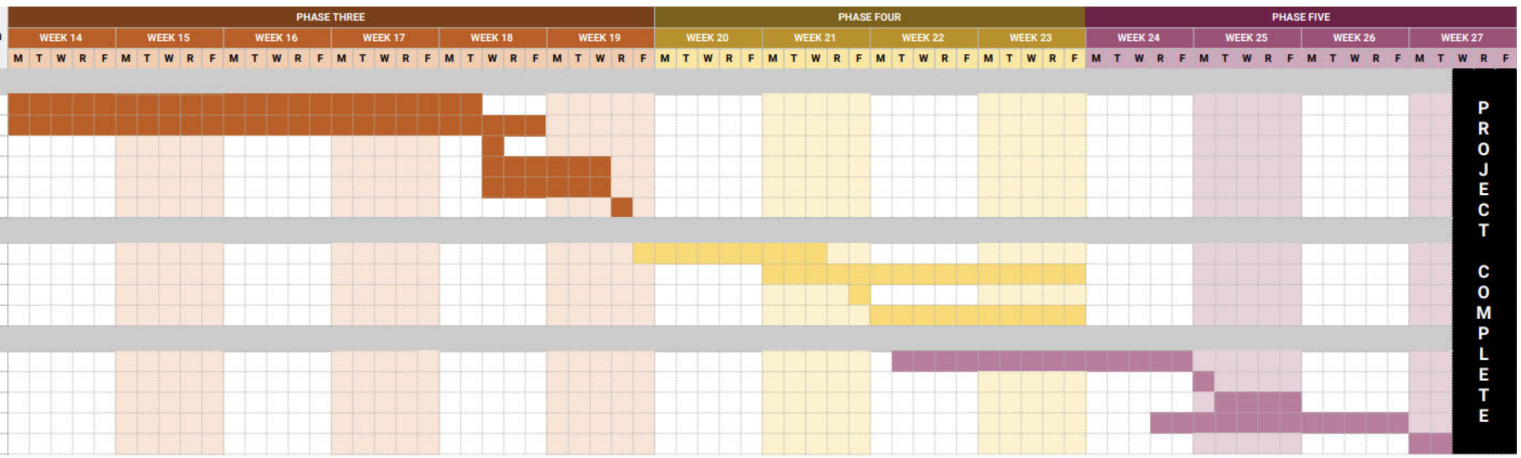
GANTT CHART

PROJECT TITLE	GTR SHINGLE	COMPANY NAME	RELIABLE TIRE RECYCLING
TEAM	4	DATE	9/11/23

WBS NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION
1	**Project Conception and Initiation**			
1.1	Project Research	9/11/23	9/22/23	11
1.2	Initial Client Meeting	9/25/23	9/25/23	0
1.3	Brainstorming	9/25/23	10/6/23	11
2	**Preliminary Testing**			
2.1	Tour Testing Lab	10/9/23	10/9/23	0
2.2	Create/Acquire Sample Mold	10/10/23	10/19/23	9
2.3	Create Samples	10/20/23	12/7/23	47
2.4	Conceptual Design Report	11/15/23	12/7/23	22
2.5	Analyze Data Collected	12/8/23	12/8/23	0



WBS NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION
3	**Secondary Testing**			
3.1	Create Samples with Additives	1/8/24	2/6/24	28
3.2	Design Final Mold	1/8/24	2/9/24	31
3.3	Tensile Testing	2/7/24	2/7/24	0
3.3.1	Pull Through Test	2/7/24	2/14/24	7
3.3.2	Hang Test	2/7/24	2/14/24	7
3.4	Analyze Data	2/15/24	2/15/24	0
4	**Tertiary Testing**			
4.1	Make Top 3 Samples	2/16/24	2/28/24	12
4.2	Weather Cycles Test	2/26/24	3/15/24	19
4.3	Impact Test	3/1/24	3/1/24	0
4.4	Wind Resistance Test	3/4/24	3/15/24	11
5	**Project Conclusion**			
2.1	Write Final Report	3/5/24	3/25/24	20
2.2	Hand-In Report	3/25/24	3/25/24	0
2.3	Create Prototype	3/26/24	3/29/24	3
2.4	Create Slides and Poster	3/21/24	4/5/24	11
2.5	Hand-In Slides and Present	4/8/24	4/9/24	1



9. Appendix C: Project-specific Materials

Materials specific to this project include [redacted] which was tested as one of the additives to the shingle mixture. This is a polymer that when mixed with the recycled tire rubber changes the physical properties of the mixture once heated [redacted] After heating above this temperature and subjecting the mixture to compression molding, the tensile, tear strength and rigidity of the mixture increases; resulting in stronger samples being produced. For more specific properties on HDPE, the following is a link to Xometry which has all the necessary information one would need:

Xometry: https://www.xometry.com/resources/materials/high-density-polyethylene-hdpe/

Another material the team tested as an additive was sulphur. The sulphur was supplied by the client as another additive to increase the strength of the mostly recycled rubber dry mixture. Small percentages of sulphur were chosen due to it having a flashpoint of 160°C (ILO), which is far lower than the required temperature (200°C +) the mixtures were being heated up to. Furthermore, the irritating smell meant that smaller percentages would limit the olfactory irritation while working with the substance. The following link provides the properties and necessary precautions while handling sulphur:

ILO:
https://www.ilo.org/dyn/icsc/showcard.display?p_version=2&p_card_id=1166&p_lang=en#:~:text=Flash%20point%3A%20160%C2%B0C%20c.c.&text=The%20substance%20can%20be%20absorbed,by%20inhalation%20and%20by%20ingestion.&text=The%20substance%20is%20irritating%20to,the%20nose%20and%20respiratory%20tract.

Hydrogen peroxide was provided by one of the team members. Peroxide was added to oxidize the rubber, allowing for it to create a stronger binding with the other additives in the mixtures during heating and compression.

Hydrogen Peroxide 2021. https://doi.org/10.3390/ma14030499

Wabash MPI is a company that manufactures hydraulic and pneumatic presses. These presses are standard or customizable for many uses including ASTM rubber and plastic testing. The model used for this project was a Genesis Series Hydraulic Press, which can supply 15 to 150 tonnes of force for compression molding. Heated platens with programmable heating and cooling systems allow for selectable temperatures for both the top and bottom sections that compress the samples. The machine used for this project is located on the University of Manitoba campus, can compress upwards of 50 tons, with a press surface of 23x23 inches. The cooling system in place has both water- and air-cooling components that work in tandem to cool the platens. Water flows through the inside along with compressed air to rapidly cool the material that is being compressed. Once the platens have been cooled, the water cooling can be shut off, but the air cooling automatically remains on until the platen is dry.

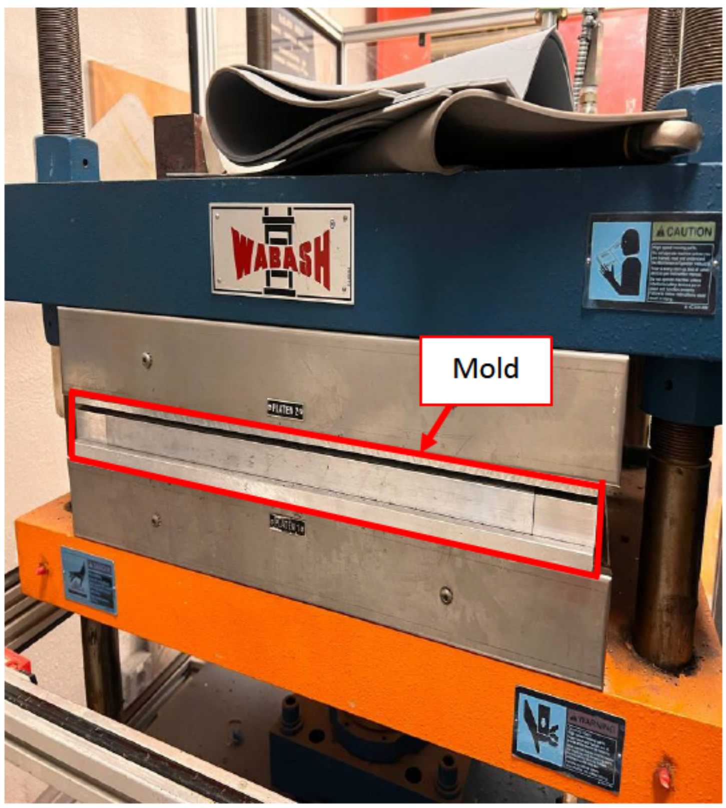


Figure 15. Wabash Hydraulic Press with Shingle mold inside being compressed

Figure 16. PanelView 550 of Wabash press showing the cooling controls

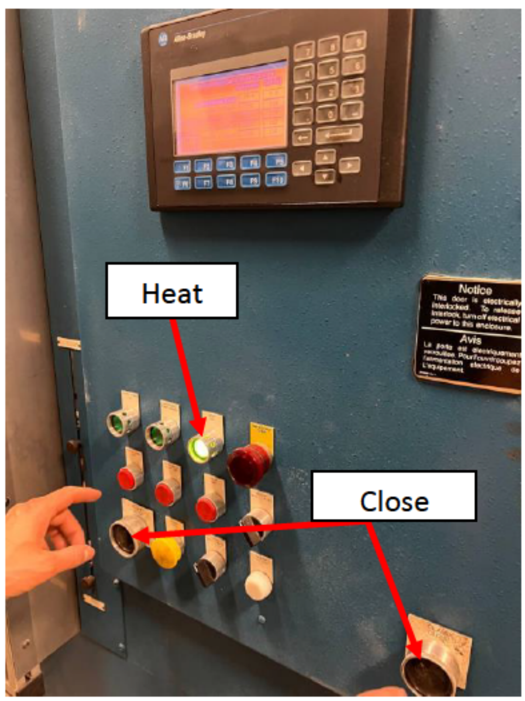


Figure 17. Front view of Wabash press with "lit" Heat On button and both Close Clamp buttons

10. Appendix D: Textural Design for Mold

Before beginning the mold in AutoCAD a slate design was 3D scanned using the Polycam app (https://poly.cam/). The scan was then downloaded as a point cloud DXF file. Once the file was loaded to the computer, Meshlab software was used to clean up the scan and turn it from point cloud into mesh. A YouTube video was used to learn the process (Siusiulala 2013). Once in mesh form, the DXF file can be loaded into AutoCAD. The 3D model then needed to be stretched to the correct dimensions. This was done by cutting the model and pasting it as a block, so all the points were combined to one piece. The scale feature can then be used to stretch the axis individually. Once the right scale is formed the model can then be exploded back into its original form. The final clean ups of any of the edges should then be completed. Next, the CONVTOSURFACE function can be used for the entire model. This will create a surface of each of the individual mesh pieces. The UNION tool can then be used to combine all the individual surfaces. This was as far as the team could get before facing limitations. The attempted texture can be seen in Figure 18.

Figure 18. Attempted texture for prototype mold in realistic view on AutoCAD.

Once the 3D model and the bottom mold design are ready, the next steps regarding the texture for the bottom plate would include completing the union, extruding the face as a solid, and lastly adding two copies into the bottom of the mold and subtracting the solids from each other.

11. Appendix E: Full-Scale Sample Procedure

1. Pre-heat the Wabash hydraulic press.
    a. From home menu select “machine set up”, then “manual mode”
    b. Set the temperature of all four platen to required temperature
    c. Set clamp force to required force
    d. Press “heat on” button (lights up when heating)
2. Collect and mix the correct masses of each material.
3. Spray mold release on all surfaces of the prototype mold the material will touch.
4. Pour mixture into the bottom half of mold.
5. Level out material.
6. Place top half of mold in bottom and ensure correct fit.
7. Insert mold into hydraulic press using heat resistant gloves or other PPE.
8. Press “hydraulic pump enable” button.
9. Press and hold both “clamp close” buttons until clamp force on screen reaches approximately 2 tonnes below required clamp force.
10. Start 10-minute timer once platen reach temperature.
11. After 10 minutes, cool the press and mold to 20°C.
    a. From the machine set up menu select “cooling control”
    b. Press “water on”, then “air on”
12. Once temperatures reach a level that can be handled (approximately 20 – 40°C), press “water off”.
13. Press and hold “clamp open” button until the hydraulic press is fully open.
14. Press “air off”.
15. Remove mold from hydraulic press.
16. Start pre-heat process from step 1 (if making another sample).
17. Insert bolts into threaded holes to release the mold (as seen in Figure 19).
18. Remove top half of mold.
19. If needed use knife to cut around the edges of the sample, then remove full-scale test sample.
20. Restart process from step 2 (if making another sample).

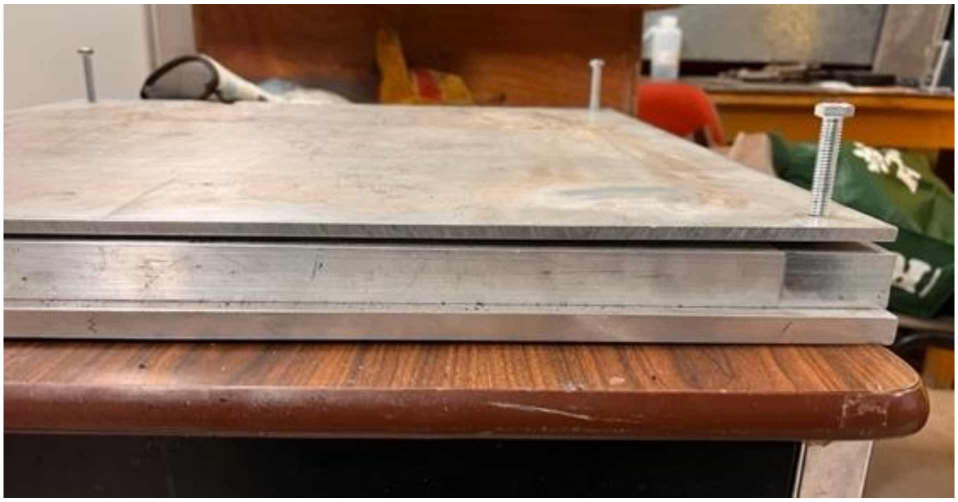


Figure 19. 3/8" - 16 thread bolts to release mold.