Development of a New Product Using Fibres from Recycled Tires: Design Project Report

BIOE 4950 Biosystems Engineering Design 4
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Executive Summary

Reliable Tire Recycling (RTR) tasked Team 2 to develop a recycling method for a synthetic fibre by-product produced by their tire recycling process. This by-product is made from a heterogenous mixture of short fibres such as polyester and nylon and contains significant amounts of impurities like dirt and crumb rubber. RTR expressed interest in using the by-product to create a new parking curb that would supersede their current model. They requested that the new design be light enough for a single person to carry, be able to withstand all-year Winnipeg weather, and can hold up during interactions with vehicles (i.e., collisions, rollovers, etc.).

Team 2 proposed a new parking curb that incorporates the fibre by-product into RTR's existing rubber mixture, paired with a redesigned form that meets the specified design objectives. The redesign includes underside cavities as well as reduced length for weight and material reduction. The proposed curb would be composed of 22% fibre by-product by mass, which was mixed directly into the rest of the ingredients (70% crumb rubber, 7.5% hydraulic binder, 0.5% water) to create test specimens for material evaluation. The mixture was formed by compressing it with 1700 psi of pressure and baking it at 100 °C. Other compositions were tested as well, including a control composition, 5% fibre by-product, 12% fibre by-product, RTR's existing curb and two existing market options.

The density of each test specimen was calculated first, and that density was used to determine the weight a proposed curb would be if it was made using each composition. All compositions containing fibre would result in a curb weight under the 35 lb design objective. The test specimens were evaluated by uniaxially compressing them according to ASTM standards. This test showed that the addition of fibre by-product, as well as applying higher pressure in the material creation process made the material deform less under load. All specimens containing fibre deformed less than 50% under the design load of 100 psi, passing the design objective. All specimens were then subjected to thermal testing, where they were exposed to extreme hot and cold temperatures (+75 °C and -80 °C respectively). After exposure, each was inspected for deformation and then hit with a metal rod at 21.7 km/hr to evaluate how it responded to impact force. All specimens passed, as none degraded noticeably post temperature exposure and all withstood the impact. A digital curb was then constructed using the 22% fibre by-product mixture, which was then subjected to 100 psi of pressure on the top face. The digital curb deformed a maximum of 8%, passing the deformation design objective.

After analyzing the test results Team 2 recommended that RTR make several changes to their current mode of production. It was recommended that RTR increase the pressure used to manufacture curbs and begin introducing the fibre by-product into their curb mixture, starting with 22% replacement of crumb rubber for increased strength and reduced waste to landfill. It was also recommended that RTR adopt a curb design similar to the one proposed by Team 2 for weight, material, and cost savings.

1.0 INTRODUCTION

1.1 Purpose

The purpose of the project is to discover a way to recycle a fibre by-product generated by RTR's recycling process line. At RTR, there is currently no use for these fibres, and they are sent to landfills. An option to divert this waste is to create a fibre-composite parking curb that utilizes as much fibre as possible, while retaining structural integrity. This project would improve upon current curb designs at RTR and generate revenue for the company from something that would otherwise be thrown away.

1.2 Background

RTR is a tire recycling company in Winnipeg, Manitoba that repurposes used and degraded tires into products such as mulch, blast mats, rubber parking-lot curbs, and crumb rubber. RTR's manufacturing processes utilizes a continuous production line that iteratively shreds the rubber from the tires into different sizes. Impurities are removed via a combination of magnets, shaker tables, and vacuums.

Once the rubber is shredded to the size of 3/16" pellets, fibre by-products are separated from the rubber using a rotational shaker. Due to the lack of a single dedicated tire supplier to RTR, the fibres vary greatly in material and percentage composition. However, common fibres found in rubber tires consist of synthetic, semi-synthetic, and/or natural materials such as rayon, nylon, polyester, and aramid. RTR has no immediate use or consumer for these fibres and, as a result, they are sent to landfill.

RTR has proposed that a parking lot curb (also commonly known as wheel stops or stop blocks) be developed that contains as much of the tire fibres as possible in order to divert the fibres from the landfill and create an alternate revenue stream for the company. Note that RTR already creates anchorable rubber curbs that are made of recycled rubber, Ryvec M-480 binder and water. They are molded at a length of no more than 8 feet, baked at 100° C, and designed to be used in parking lots. However, these curbs contain none of the fibre by-product.

Figure 1. Recycled tire fibres. Impurities like crumb rubber can be seen in the clumped fibres.

Figure 2. Rubber curb currently manufactured by RTR.

The exact mechanical properties of the tire fibres are difficult to determine. Fibres form the internal plies in passenger tires, which serve to provide structure, maintain inflation pressure, and help it keep its shape in different road conditions (U.S. Tire Manufacturers Association, 2020).

Parking lot curbs ensure that vehicles park in the appropriate spot to prevent damage to buildings or walkways. Commercially available parking lot curbs are typically made of concrete, rubber, or plastic composites. However, recycled rubber curbs are steadily replacing traditional concrete parking curbs because they are durable, elastic and much lighter than concrete. They are also hardwearing because they provide resistance against cracking corrosion and crumbling. Furthermore, they are cheaper and easier to anchor than the traditional, hefty cement curbs.

There are studies that research the effects of fibre-reinforced versions of these curbs and their respective matrixes. For example, when mixed with concrete, rubber fibres were found to increase the flexural strength of concrete (Gupta et al., 2014). Also, Abdullah et al. (2016) found that replacing as little as 3% of the aggregate in concrete with rubber particles decreases the compressive strength of the concrete. This shows that adding recycled rubber to concrete can decrease its compressive strength. This research will give us a roadmap of how recycled tire fibres from RTR will behave if added to concrete composites. Existing standards for rubber, plastic or fibre-composite curbs are highly limited, however, several exist for concrete.

Parking curb manufactures often do not publish the mechanical properties of their curbs, so the team tested the uniaxial compressive strength in the vertical direction of the following curbs: Go Plus Rubber Parking Curb, and Pyle Rubber Parking Curb. The results from these curbs were compared against the experimental compositions described in Section 3.1.

1.2.1 Go Plus Rubber Parking Curb

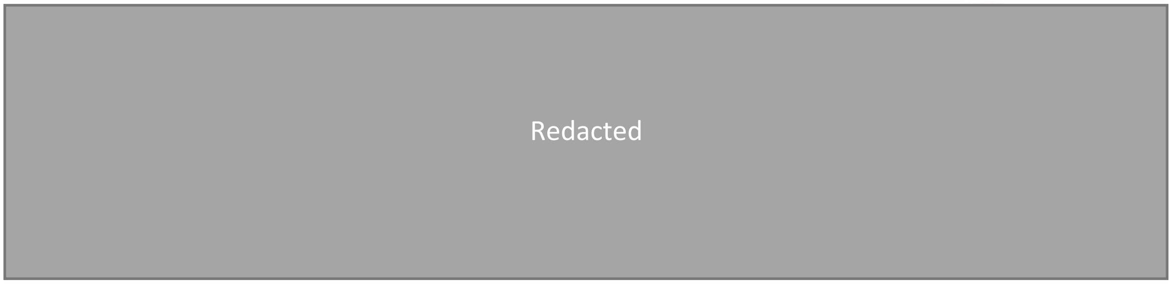

Figure 3. Go Plus Rubber Plus Curb image with dimensions (Via Go Plus, 2022)

This parking curb is 72” x 6” x 4” (L x W x H) and weighs 31 lbs. The underside of the curb has a hollow design and uses high resilience rubber. The hollow bottom grants the curb flexibility, which enables it to be used on uneven ground. It has a rated weight capacity of 4400 lbs., or roughly the weight of a 2023 Toyota Tacoma single cab. The pressure that the curb can withstand is of larger concern than its rated weight capacity (Amazon.ca, 2022).

1.2.2 Rubber Parking Curb by Pyle

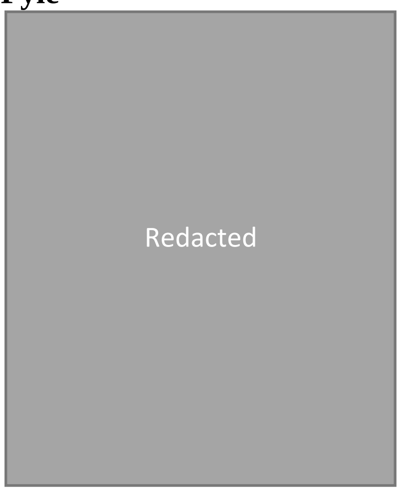

Figure 4. Promotional image of Pyle rubber parking curb (Via Pyle, 2022.)

This parking curb is 72” x 6” x 4” (L x W x H). This model is made from rubber and weighs 38.6 lbs. The curb claims to have a 44 000-pound capacity, ten times that of the Go Plus model, although failure conditions are not described.

Samples were taken from each of these curbs and subjected to uniaxial compression according to ASTM D575-91: Standard Test Methods for Rubber Properties in Compression. This was done so a benchmark could be obtained for Team 2’s custom samples. The team estimated a desired yield strength for the prototype fibre curb using the curb weight of a typical pickup truck, which was assumed to be 4705 lbs. based on the weight of the 2023 Ford F150 Super crew (AutoBlog, 2022) and the dimensions of existing curbs:

$$P = \frac{F}{A} = \frac{\frac{1}{2} the\ curb\ weight\ of\ a\ dual\ cab\ F150}{contact\ area} = \frac{\frac{4705\ lbs}{2}}{2 \times 2\ in \times 10.4\ in} = 56.6\ psi$$

In order to select an adequate location for installing a parking curb stop, one needs to consider convenience, safety, the surrounding landscape, climate, and more. Winnipeg weather is one of the important aspects of consideration for our design because of heavy precipitation and freezing weather. “The average daily temperature in Winnipeg in summers is above 19 °C and the average daily temperature in winters range is below -3 °C. The hottest month of the year in Winnipeg is July, with an average high of 26 °C and low of 16 °C. The coldest month of the year in Winnipeg is January, with an average low of -18 °C and high of -10 °C” (Weather Spark, 2022). The average annual UV index in Winnipeg ranges from 1 to 5. The annual average precipitation in Winnipeg ranges from 10 mm to 70 mm (Weather Atlas, 2022).

The fibre samples collected from RTR, are in fact a combination of semi-synthetic and synthetic fibres, shredded rubber, dust, and miscellaneous. The team attempted to identify the fibres by conducting preliminary burn tests (where a sample was held against a flame and left to burn). The burn test indicated that the fibres are synthetic due to the lack of ash, presence of hardened and blackened surface that was exposed to the flame, and thick gray smoke. Cotton was burned as well to compare the results from burning a natural fibre. A pungent smell of “tar” was also observed but this may be due to the presence of micro rubber impurities in the sample. The main synthetic fibres used in tire production in North America include nylon or polymers such as polyester, polypropylene, polyethene, or polyethylene. The burn test provided Team 2 with confirmation that the fibre by-product was synthetic.

The team also attempted to use Fourier-Transform Infrared Spectroscopy (FTIR) on the fibres. FTIR is a method of identifying and classifying the nature of a material that works by measuring the amount of radiation absorbed and emitted by that material (Thermo Fisher Scientific, n.d.). Due to its common application in tire fibres in North America, the fibre by-product was initially suspected to be mostly, if not all nylon. Therefore, FTIR was conducted on nylon-6 and nylon-66 samples to compare the results between pure nylon and the fibre by-product. 1500-1600 cm^{-1} are literature wavelength values of nylon (Fayemi et al., 2016). Figure 5 displays an initial FTIR test performed on the fibre by-product where the large peak on the right at 1637.86 cm^{-1} replicates peak values of pure nylon. However, FTIR tests were deemed inconclusive after performing multiple FTIR tests provided peak wavelength values $\approx$ 720 to 3400 cm^{-1} (see Appendix). Chemical processing was used to identify the fibres as well, by completely immersing the fibre by-product in hydrochloric acid (HCl). This too, proved inconclusive as the fibre by-product did not disintegrate at all as opposed to the nylon-6 and nylon-66 samples that did.

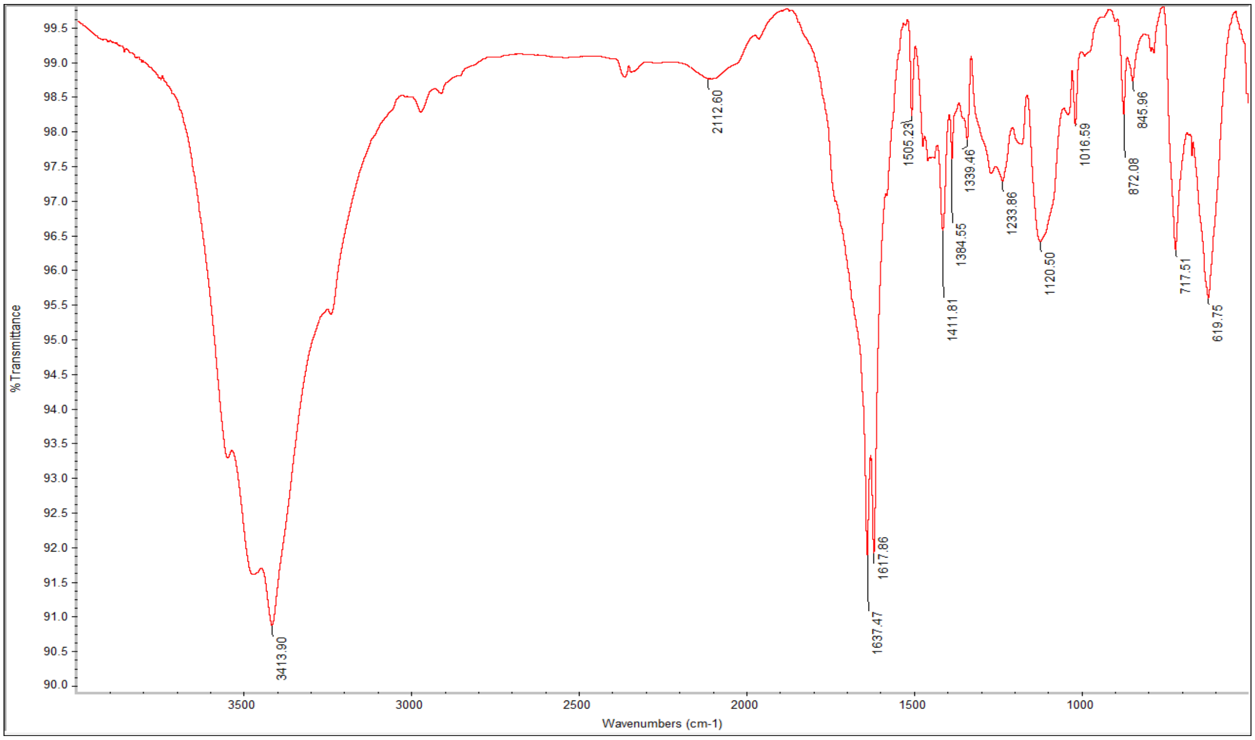

Figure 5. Results of the FTIR test on fibre by-product.

1.3 Problem Definition

RTR requires a new, lightweight curb made with synthetic fibre by-products generated by their recycling process, to redirect the fibres from landfill and provide a new revenue stream. The curb must be lightweight enough to be carried by one person, must not crack when anchoring hardware is installed, and it must withstand –50°C to 38°C. Furthermore, this curb will be deployed in parking lots in the city of Winnipeg by business owners and should have a lifespan of at least two years.

TABLE 1. Design Functions, Objectives and Constraints

Design Functions	Design Objectives	Design Constraints
Redirect fibre by-product from landfills	Fibres compose 30% of the total mass of component materials.	Fibres compose 10% of the total mass of component materials.
Contain ½” face-to-face holes for anchoring hardware	Contain ½” countersunk face-to-face holes for anchoring hardware.	Must not crack when anchoring hardware is installed and tightened.
Does not significantly deform (burst, crack or break) in extreme high or low temperatures	Withstand –50°C to 65° C. Black objects outdoors can frequently reach 15° C above air temperature (Berens, 1970).	Withstand –50° C to 38° C[1] Testing was conducted using an air oven and a deep freezer.
Light enough for a single person to carry	Have a total weight under 35 lbs.	Have a total weight under 45 lbs. Density of material was calculated and multiplied by curb volume to calculate hypothetical weight.
Fulfills other design functions during a time period based on warranty lifespans of existing rubber curbs	Product lifespan exceeds 5 years.	Product lifespan of at least 2 years. This matches warranties of available products.
Be able to withstand being parked on by vehicles	Does not fracture or deform more than 50% under 100 psi of vertical compressive load.	Does not fracture or deform more than 50% under 60 psi of vertical compressive load. Administered according to ASTM D575-91: Standard Test Methods for Rubber Properties in Compression. Limited impact resistance testing was also conducted.
Can tolerate high UV levels without noticeable degradation	Does not show visible physical degradation after experiencing high UV level 10 throughout the year.	Does not show visible physical degradation after experiencing UV level 10 for one simulated week, according to ASTM D1148-13.

[1] Average annual temperature values for Winnipeg obtained from Current Results 2022

2.0 PROPOSED SOLUTION

The solution can be viewed as two interconnected parts; a 3D design with reductions in material volume and therefore weight, and the novel mixture that is used to create the physical product. A 3D model of the proposed solution is represented in Figure 6. The solution is a three-foot long, six-inch-tall parking curb composed of a novel mixture of crumb rubber, binder, water, and RTR's fibre by-product. This proposed design allows for weight reduction while still meeting the strength, elasticity, and durability requirements imposed by parking lot environments.

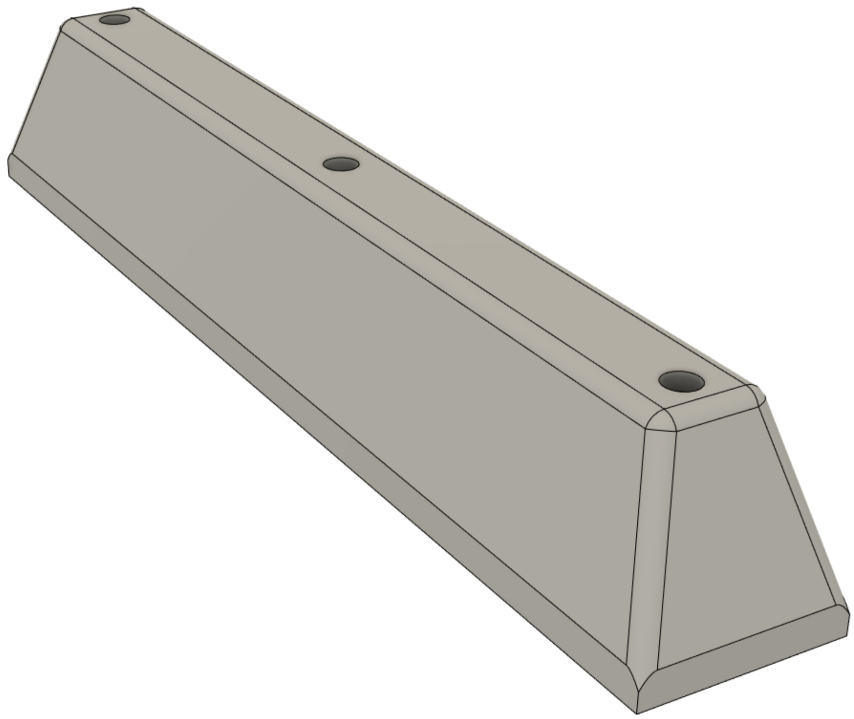

Figure 6. Isometric view of conceptual curb design.

2.1 Curb Design

Each design choice in the proposed curb was made to meet the design objectives defined in Section 1.3. The largest departure from typical parking lot curbs is the three-foot length of the proposed curb. Most curbs on the market are six to eight feet long, which contributes to the high weight of most parking curbs. Parking spots in North America are typically 7.5 to 9 feet long (Parking Industry Insights, 2020), which would require two of the proposed curbs to fill. The curbs can be spaced apart by any amount to reach the owner's desired effect. Legal requirements on parking spot minimum dimensions are trending downward in many jurisdictions, positioning the proposed curb at the front of the market for increasingly narrow spots. This also makes it applicable to many European countries, which may have significantly narrower spots because of the smaller average vehicle size and issues around density. Figure 7 depicts a mock-up of two proposed curbs replacing an eight-foot curb.

Figure 7. Mock-up depicting two proposed curbs replacing a single eight-foot curb in an 8' 6" parking spot. Not to scale.

The three-foot length facilitated the accomplishment of a major design objective, keeping curb weight under 35 pounds. The density of the chosen material is discussed in Section 3.1 and 3.4. Other benefits from the reduced length of the proposed curb include reduced material costs per unit, ability to fit inside of small vehicles for transport, and easier installation and handleability for a single operator when compared to a six or eight-foot curb.

The proposed curb features cavities on its underside. The cavities are 12 inches long, 4.5 inches deep and feature a 105-degree taper as shown in Figure 6. These serve to reduce the amount of material used per curb, and therefore decrease the weight of each curb. The cavities can also be viewed in the curb cross-section shown in Figure 8. The effect that these cavities have on the load bearing capacity of the curb is discussed in Section 3.5.

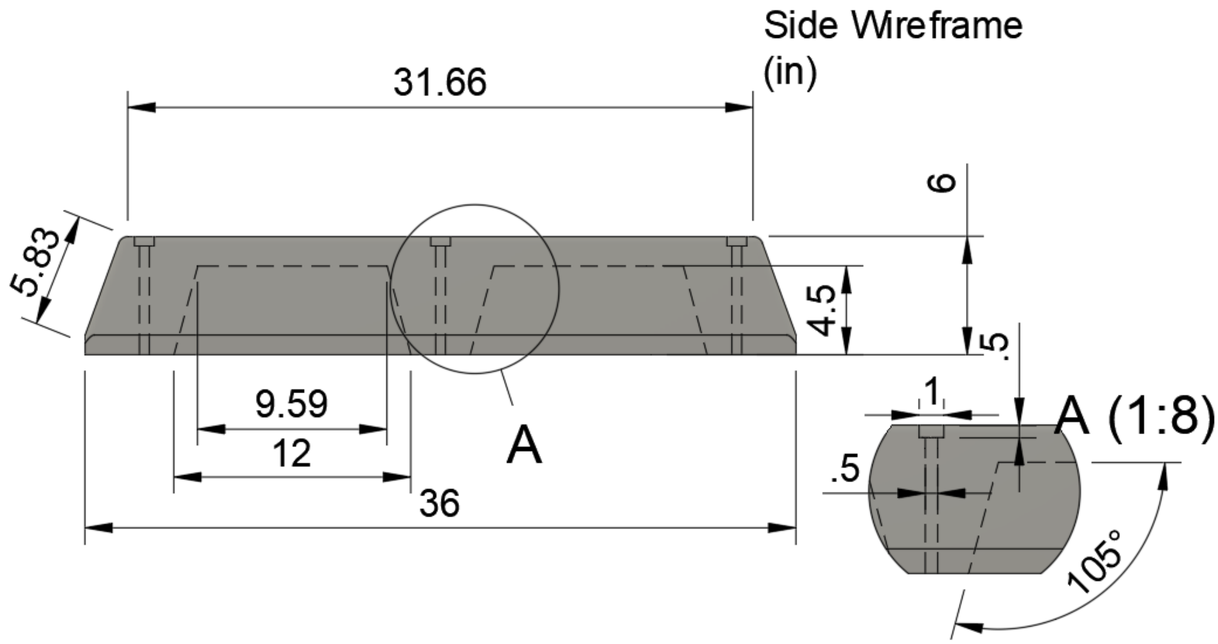

Figure 8. Side wireframe view of proposed curb design.

In addition to the cavities, counterbore bolt/anchor holes are visible in Figure 6. These holes are used to secure the curb to pavement during installation. Three bolt holes were designed to ensure the curb b stayed fixed if one bolt was rendered non-functional via shear, removal, or other means. The lighter weight of the curb necessitates that anchoring hardware be present, compared to heavier concrete curbs which are significantly more difficult to move.

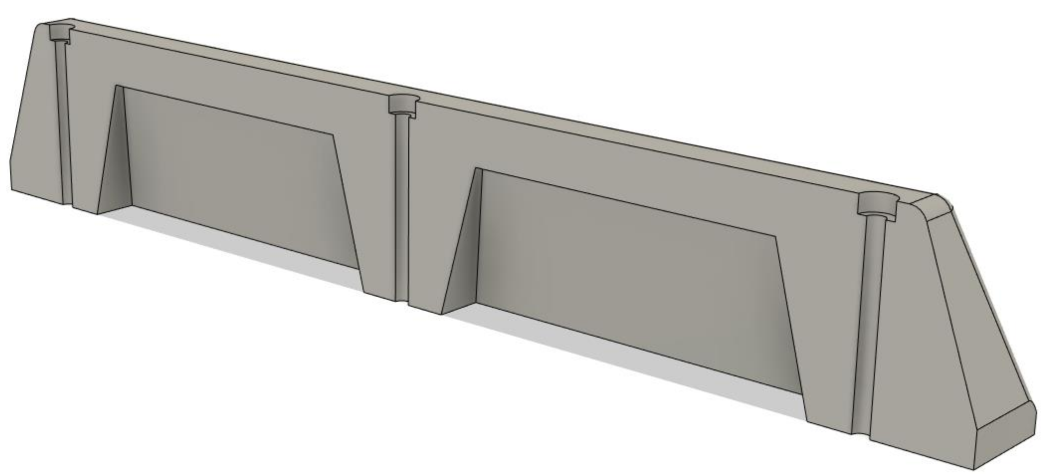

Figure 9. Cross-section render of the conceptual curb.

The proposed curb can be anchored to the pavement using one of two methods: rebar anchoring spikes or lag bolts. The bolt holes in the curb are unthreaded, as threads are difficult to create in rubber and may impede the use of anchoring spikes. It is common for curbs secured with lag bolts to be unthreaded, and a lag anchor is inserted into the ground below each hole instead.

A bolt size of ½” was chosen because it was identified as the industry standard. This will ensure that customers can purchase hardware separately if RTR chooses not to bundle hardware with the purchase of a curb, or they need replacement hardware. A counterbore is present on each anchor hole to prevent bolt heads or anchor heads from protruding from the curb surface. This could cause risks to tire integrity and pedestrian safety.

With pedestrian safety in mind, sharp corners present on the top and side faces of the curb were rounded to decrease the risk of severe injury if a pedestrian were to fall on the curb. A table summarizing the decisions made while designing the model of the proposed curb is available below.

TABLE 2. Summary of Design Decisions for 3D Model

Decision	Rationale
Reduce the length of the curb from 8 ft or 6 ft to 3 ft.	• Reduced weight compared to full length curb. • Easier for single operator to carry and install.
Rounded top corners instead of industry standard sharp corners.	• Reduced risk of severe injury to pedestrians.
Cavities on the bottom of the curb instead of solid material.	• Reduced materials cost per unit. • Reduced weight via removal of material that would otherwise fill the space.
½” Counterbore holes for anchoring hardware.	• Matches industry standard. • The counterbore hole allows for bolts to sit flush with curb surface, preventing damage to tires or pedestrians.
Three holes for anchoring hardware.	• The curb is still secured to the ground in the event one bolt/anchor fails.

2.2 Curb Mixture

The experiments conducted on the fibre by-product (detailed in Section 1) resulted in three general conclusions:

1. It was not viable to process the by-product in some fashion to improve its mechanical properties. Solutions that did process it required large-scale changes to RTR’s tire recycling line. Processes such as separation or extrusion were deemed to be not viable due to the short fibre length, heterogeneous composition, and high presence of impurities.
2. The composition of the fibre by-product would vary at any given time, meaning that density measurements and chemical analyses would have to be performed over a large sample size on a regular basis, or they should be omitted.
3. As the composition varied, so would the mechanical properties of the fibre by-product. Detailed tests on the fibre were deemed to be out of scope, however observations indicate that it has a significantly lower compressive strength, tensile strength, and impact resistance than the crumb rubber mixture currently produced by RTR.

A matrix material was chosen with these conclusions and the design objectives in mind. Thus, concrete, plastic, and rubber were considered for matrix materials due to their accessibility, existing research on the use of these materials, and wide use in industry for making curbs.

TABLE 3. Mechanical properties of possible matrix materials.

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Density (kg/m^3)
Concrete[2]	20 - 50	2 – 5	~2402.8
Polyethylene (HDPE)[3]	4 – 23 (avg 12.6)	11 – 43 (avg 26.2)	924 – 995 (avg 954)
Synthetic Rubber (E-SBR)[4]	14.4 – 25.2	12 – 21	940 - 950

[2] Values for concrete retrieved from Heisler, 1998
[3] Values for HDPE (High Density Polyethylene) retrieved from MatWeb, 2022.
[4] Values for synthetic rubber retrieved from AZO Materials, 2003.

RTR's recycled crumb rubber was selected as the matrix. By using recycled rubber as the matrix, the proposed solution addresses several design objectives:

- Rubber's superior tensile strength and elastic properties lead to improved impact resistance and reduced damage to vehicles which strike the curb.
- The low density of rubber ensures that the curb is significantly lighter than a counterpart made of concrete.
- Materials costs for RTR are reduced by using their in-house product.

RTR's in-house recipe for making compressed recycled rubber products was used as a base for the proposed curb material. Several material compositions were tested with varying ratios of replacement of crumb rubber with the fibre by-product. The material composition containing fibre by-product that performed best when evaluated is displayed in Table 4.

TABLE 4. Ratio of materials in proposed curb composition.

Material	Percentage by mass (%)
Crumb rubber	70
Hydraulic binder	7.5
Water	0.5
Fibre by-product	22

2.3 Manufacturing Procedure

The proposed solution could be manufactured by RTR with minimal adjustment to existing processes. A new aluminum mold based on the proposed curb design will be required. The steps in the manufacturing process are listed in Figure 10. This is a recommendation; the team did not manufacture a full-scale prototype due to the costs associated with the production of a new mold.

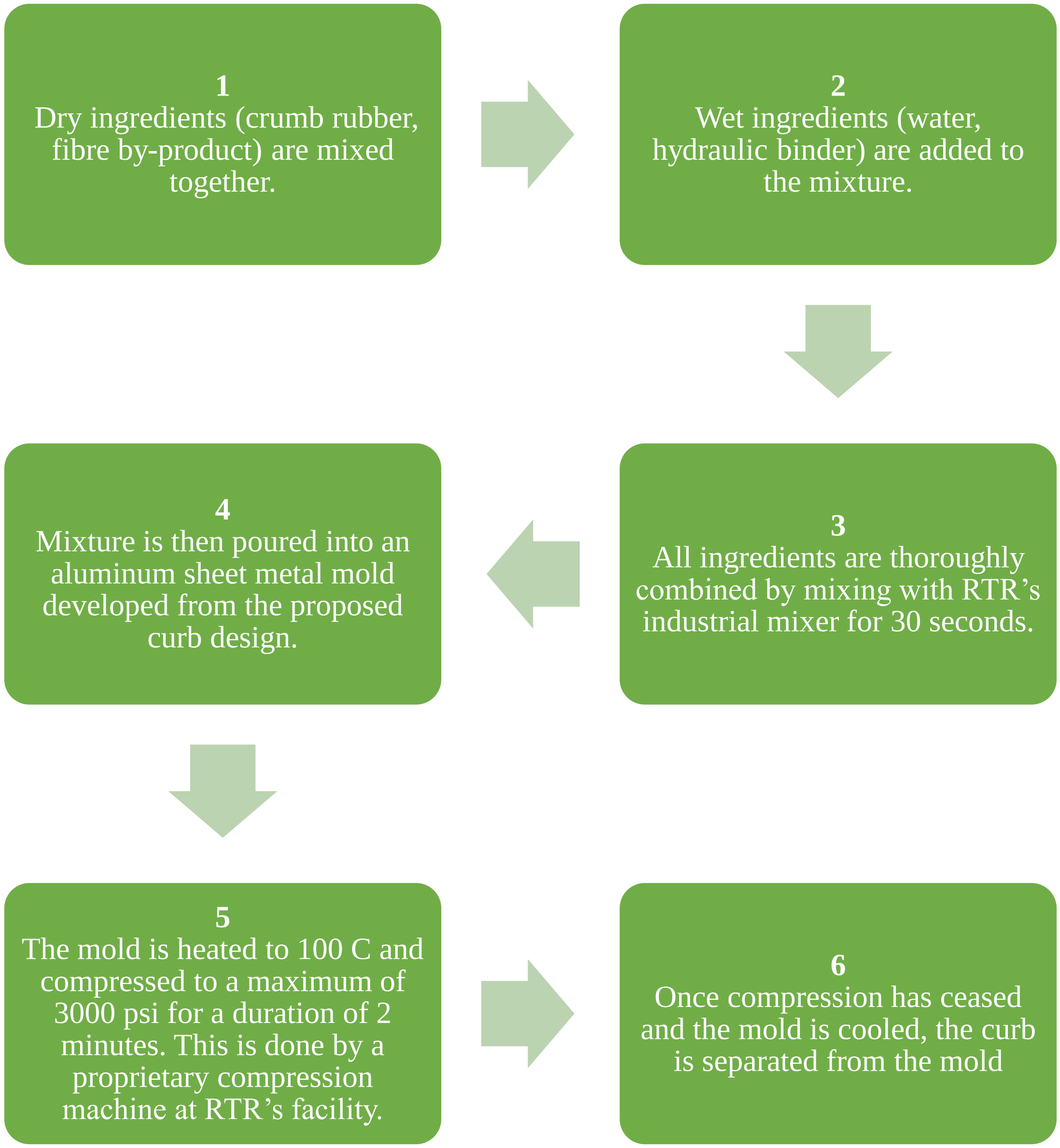

Figure 10. Process diagram detailing how curbs could be developed at RTR, including the incorporation of fibre by-product.

2.4 Proposed Solution Summary

The three-foot length of the curb was chosen to meet the design objective of keeping the curb weight under 35 pounds. The reduced length of the curb as compared to the typical parking lot curbs (6 to 8 feet) resulted in ease of transportation and installation. The fibre by-product used for curb manufacturing serves to reduce the amount of material used and the weight of each curb. The bolt/anchor holes were designed to secure the curb in place during installation. The curb can be anchored using rebar anchoring spikes or lag bolts, with a ½’’ bolt size chosen as industry standards.

The experiments conducted on the fibre by-product showed that processing it to improve its mechanical properties was not viable, and the composition of the by-product would vary, leading to varying mechanical properties. The proposed curb design uses un-processed fibre by-product in its raw form, taking advantage of its fibrous structure and low density to reach design objectives. The proposed curb design takes into consideration the requirements for a parking lot environment, including strength, elasticity, and durability. It is an innovative solution that utilizes waste fibre by-product, Ryvec binder, and water, which will meet the needs imposed by a parking lot environment, create a new revenue stream and divert waste fibres from landfills.

3.0 DESIGN EVALUATION

To ensure compliance with the design objectives, experimental testing was necessary. Small scale samples were created with varying compositions of crumb rubber and fibre by-product, which were then subjected to uniaxial compression tests, thermal exposure tests, and impact tests. The results were used to inform the development of a digital material in Fusion 360 (2023 ed.), which was used to model the deflection that may be observed in a full-scale curb under load. A summary of the design requirements that were evaluated, and the tests conducted to do so can be found in Table 5. Section 4.0 addresses several design requirements that were not able to be evaluated and recommends further testing.

TABLE 5. Design requirements and evaluation criteria.

Requirement	Evaluation Method	Acceptance Criteria
Can withstand being parked on by a vehicle	• Tested the compressive characteristics of the prototype. The compression test was based on ASTM D575-91: Standard Test Methods for Rubber Properties in Compression. • Instron 3382A in Agricultural Engineering was used to conduct tests. • Prototype test results were compared to results produced by existing parking curbs.	• Pass = Curb does not fracture or exceed 50% deflection when placed under 60 psi • Fail = Curb fractures or deflects more than 50% of its total height when loaded under 60 psi.
Can be carried by a single person	• Measure density, then use volume of proposed curb design to determine the mass weight of a hypothetical curb made from each composition.	• Pass = under 45 lbs. for design constraint, under 35 lbs. for design objective. • Fail = over 45 lbs.
Does not significantly degrade (burst, crack, or break) in extreme low temperatures	• Expose the test specimen to -80 ºC for 24 hours. • Observe any visible changes that occur to the prototype surface. • Conduct impact test after exposure and compare to pre-exposure.	• Pass = Prototype does not display any visible wear and elasticity and impact resistance does not degrade by more than 30%. • Fail = Prototype displays visible signs of wear, and elasticity or impact resistance appears to degrade by more than 30%.
Does not significantly degrade (burst, crack, or break) in extreme high temperatures	• Expose the prototype curb to high temperatures (75 ºC) using an air oven for 24 hours. • Observe any visible changes that occur to the prototype surface. • Conduct impact test after exposure and compare to pre-exposure.	• Pass = Prototype does not display any visible wear and elasticity and impact resistance does not degrade by more than 30%. • Fail = Prototype displays visible signs of wear, and elasticity or impact resistance appears to degrade by more than 30%.

3.1 Sample Composition and Creation Process

All samples were created from the same materials: water, hydraulic binder, crumb rubber and fibre by-product. However, the amounts of each material varied by composition. A gradient in fibre by-product inclusion was developed to explore the relationship between fibre by-product content and material properties. These compositions are listed on a percentage by mass basis in Table 6.

TABLE 6. Percentage by mass of each material in four experimental compositions.

Percentage By Mass (%)				
Material	**Control**	**Composition 1**	**Composition 2**	**Composition 3**
Water	0.5	0.5	0.5	0.5
Hydraulic Binder	7.5	7.5	7.5	7.5
Crumb Rubber	92	87	80	70
Fibre By-Product	0	5	12	22
Total	100	100	100	100

The control sample is roughly equivalent to the recipe currently used by RTR; [redacted]. The other compositions were chosen at intervals that RTR may deem useful. The total percentage of fibre by-product was kept relatively low in the investigation due to the desire to find a viable material mixture in the allotted time. The team recommends that RTR explore options with a higher percentage of fibre by-product given the satisfactory results discussed in Sections 3.2-3.5.

To create small-scale samples, it was first necessary to create a casting die. The casting die was composed of several major elements, as depicted and outlined in Figure 11.

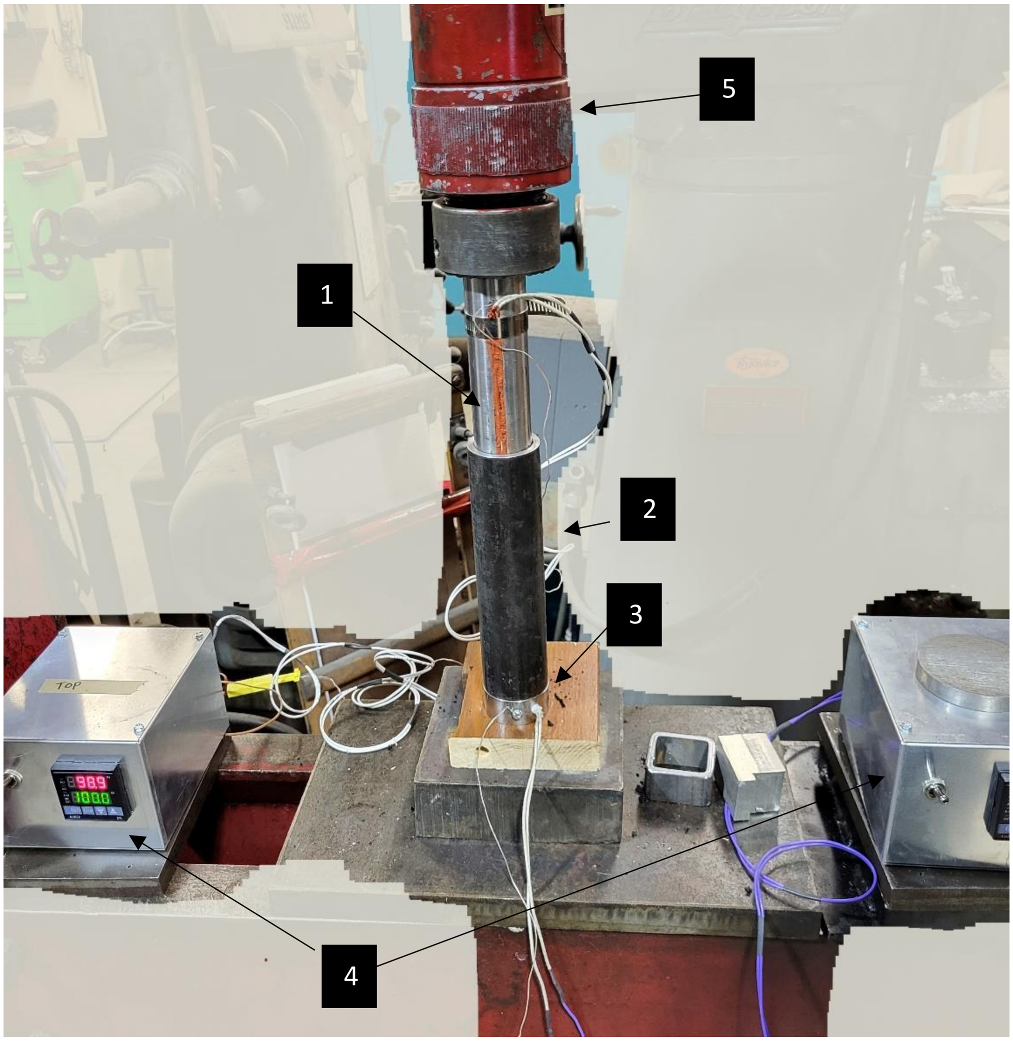

Figure 11. Casting die for creating specimens.

1. 1.5-inch diameter mild steel plunger to transfer force from a hydraulic cylinder into the sample mixture. An electrical heater was embedded near the bottom of the plunger.
2. 1.5-inch inner diameter mild steel tube to contain the sample mixture.
3. Removable mild steel bottom plate with an embedded electrical heater. A machined fillet in the bottom plate allows for tight interlocking with the steel tube, but also for easy removal when the sample is set.
4. 2 Proportional-Integral-Derivative (PID) units to control the temperature of the electric heaters.
5. Hydraulic cylinder that applied force to the steel plunger.

The team took guidance from RTR's current manufacturing process when developing a sample creation method. Samples were mixed until combined, heated to 100°C and compressed to a pressure of roughly 1700 psi. The hydraulic cylinders in RTR's compression machine exert an unknown amount of pressure on the products they generate but are limited to a maximum of 3000 psi. 1700 psi was chosen as the pressure for sample creation because it produced samples with more elasticity that were significantly easier to remove from the die, as opposed to samples that were subjected to 3000 psi. The temperature and “cook time” of the samples matches those currently used by RTR.

In addition to the design compositions, samples were created from existing market curbs. This included an older model of RTR’s recycled rubber curb, and curbs from Go Plus and Pyle. The density of each composition was measured prior to any testing and can be found in Table 7.

TABLE 7. Density of each tested material in kg/m3

	Control	Composition 1	Composition 2	Composition 3	RTR	Go Plus	Pyle
Density (kg/m^3)	1118.7	1065.9	1049.6	1066.6	730.73	1441.6	1658.2

Figures 12 and 13 depict specimens from Control and Composition 3, respectively. Additional images of compositions can be found in the appendix. The specimens with higher fibre content demonstrated similar texture, color, odor, and deformability to control when observed prior to any empirical testing. The singular noticeable difference between the control and the compositions containing fibre by-product was the occasional presence of the by-product on the outer surfaces of the specimens.

Figure 12. A specimen made from the control composition.

Figure 13. A specimen made from Composition 3 (22% fibre by-product by mass). Fibres are visible in the mixture.

3.2 Compression Tests

To ensure that the proposed curb met the design requirement of being able to withstand the weight of a vehicle, all specimens were evaluated on their deformation under load.

3.2.1 Compression Methodology

The specimens detailed in Section 3.1 were subjected to a uniaxial compression test according to ASTM D575-91: Standard Test Methods for Rubber Properties in Compression (ASTM International, 2018c). This was to ensure that the curb could be parked on by a large vehicle (i.e., per tire curb pressure of 60 psi) without deflecting more than 50%. To facilitate testing, an Instron 3382A Universal Testing System (Figure 14) was used. A spring was fixed in series with specimens in compression for two reasons. Firstly, to prevent possible damage to the Instron due to shock from applied load and secondly, to prevent load spiking from the samples under compression. The spring was calibrated, and its rate of deflection was determined before any compression testing begun. The following is a summary of the compression testing methodology. For a more detail description, see ASTM D575-91.

1. The specimen was placed on the metal spring plate and the crosshead of the Instron was brought into light contact with the specimen.
2. Two consecutive uniaxial compressive loading cycles of 5 kN at a rate of 12 mm/min were applied to the specimen to condition it for readings.
3. A third loading cycle of 5 kN was applied to the specimen at the same rate. Data analysis was focused on the results obtained during the third cycle.
4. With the specimen unloaded, the crosshead was moved to the starting position and the specimen was removed from the Instron.

3.2.2 Compression Results

The principal observation made during the compression tests was the vertical deflection and horizontal expansion of nearly all specimens. Specimens sourced from RTR's pre-existing curb failed to withstand the test; falling apart and failing to regain shape after the load was removed. This significantly impacted their deflection results.

Figure 14. Spring setup on the Instron 3382A. The top of the spring is covered by a metal plate to ensure even contact with the sample. The crosshead of the Instron is contacting the metal plate.

Figure 15. Compression of a control specimen. The vertical and horizontal deflection are substantial.

The load-deflection curves generated during the third cycle of compression are displayed in Figure 15. Curves were created using the average of three specimens, and the deflection of the spring was calibrated for and removed.

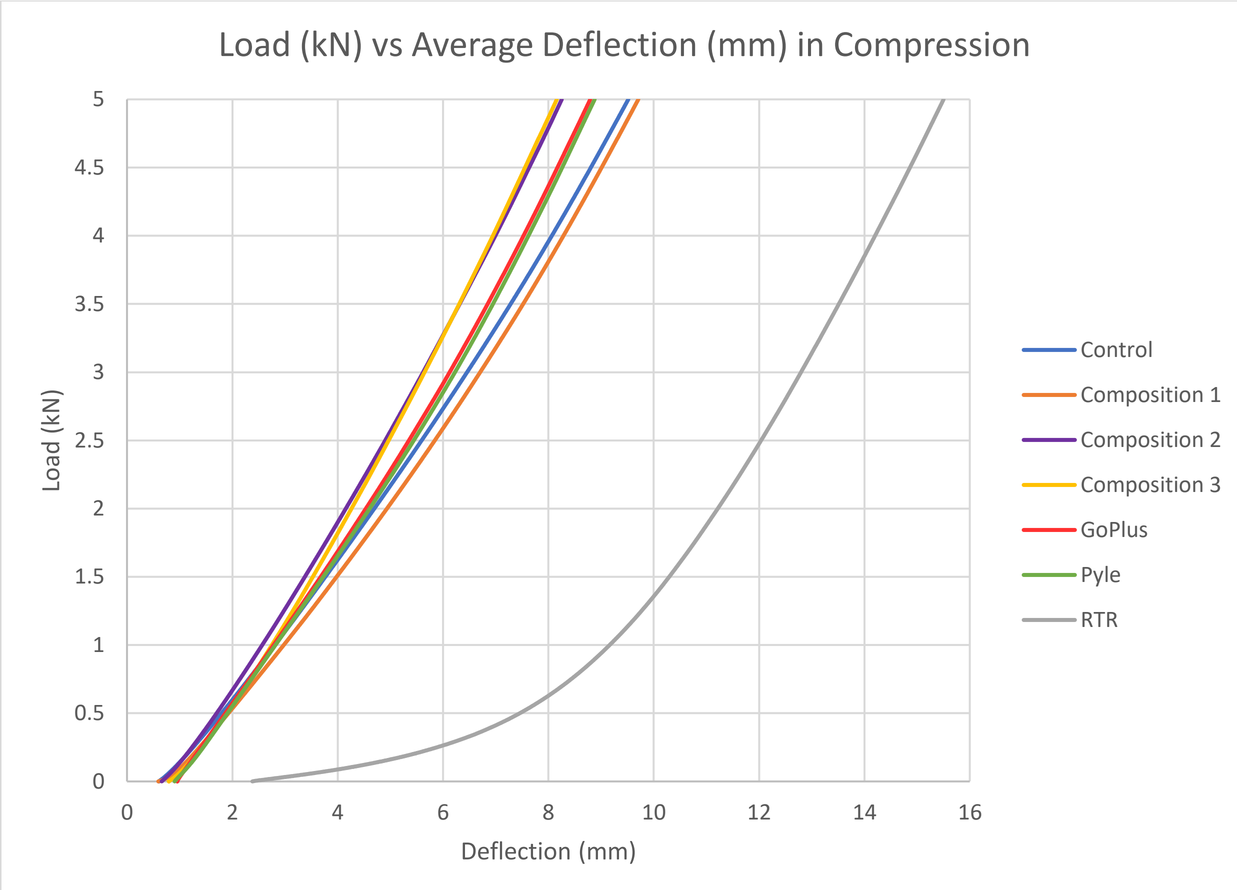

Figure 16. Load vs average deflection graph for all compositions tested in compression.

Many of the materials held a tight group, while RTR's existing curb material deflected significantly more than any other. The maximum observed deflection of 15.501 mm experienced by the RTR specimen is higher than its initial height of 14.43 mm. This discrepancy is due to the specimens crumbing apart during the conditioning cycles, as well as potential errors in spring calibration due to the crumbling. Compositions 2 and 3 deformed the least overall, as demonstrated by the Figure 16.

Each specimen was evaluated on its deflection when under the design constraint load of 60 psi. This translated to a force of 0.472 kN based on the area of the specimens. The design objective load (100 psi) was also evaluated, which equated to a force of 0.786 kN on the specimens. The results of the evaluation are summarised in Figures 17 and 18.

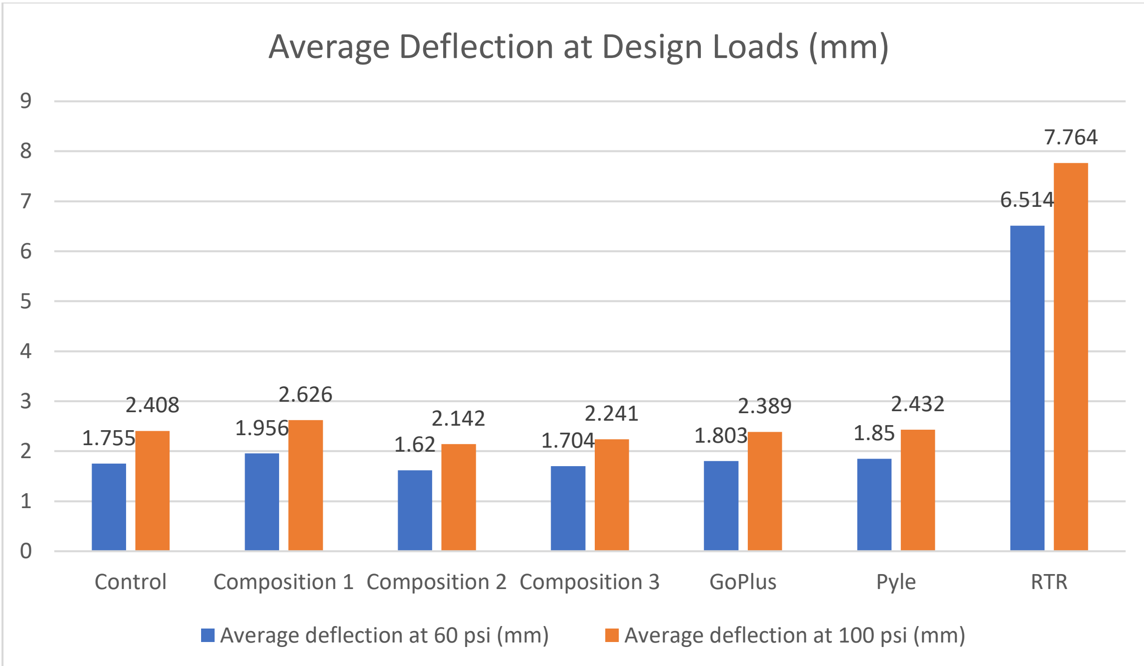

Figure 17. Average deflection at design loads (60 psi & 100 psi) in millimeters.

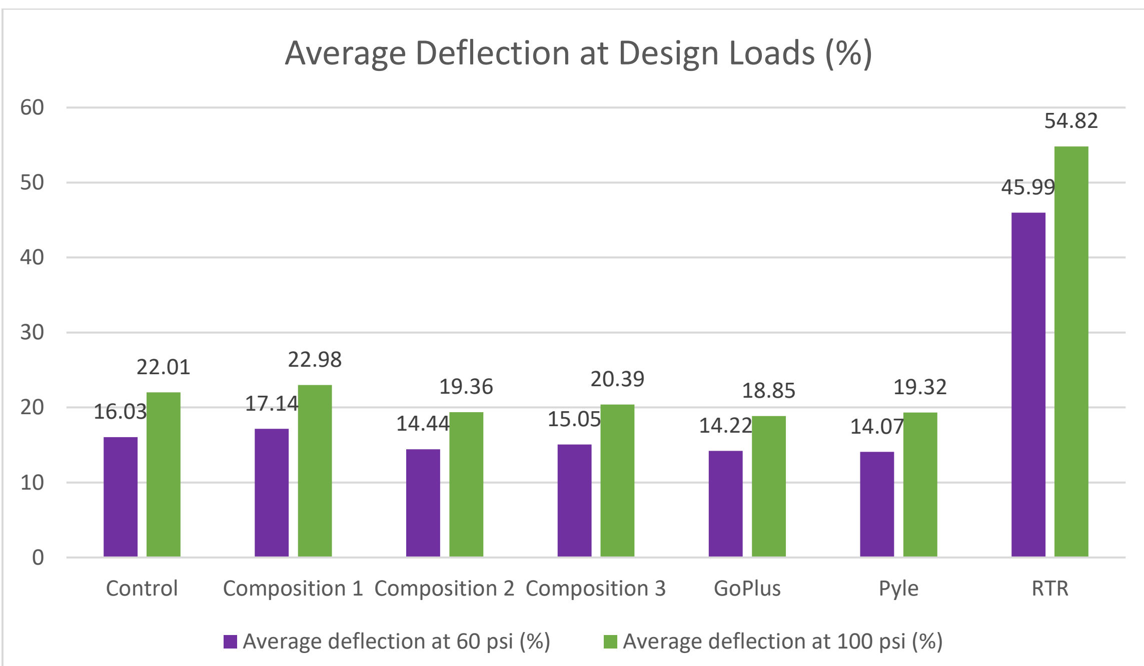

Figure 18. Average deflection at design loads (60 psi & 100 psi) as a percentage.

The results of the compression test show that any of the compositions containing fibre by-product are able to withstand both specified design loads without deforming more than 50%. Composition 2 nearly achieved parity with the material used by Pyle, making it the strongest composition that contained fibre, with Composition 3 being a close second.

3.3 Thermal Tests

The samples detailed in Section 3.1 were subjected to hot and cold testing to ensure that they did not display any visible defects when exposed to extreme hot or cold temperatures.

3.3.1 Thermal Methodology

A summary of the methodology is as follows:

1. The specimens were placed inside of an air oven or deep freezer, depending on the nature of evaluation. For the heat exposure tests, specimens were inserted into an air oven heated to 75° C, while for cold exposure tests specimens were placed into a deep freezer set to -80° C.
2. The specimens were exposed to the test temperature for 24 hours.
3. After 24 hours had passed, the specimens were removed from the temperature chamber and allowed to return to ambient temperature (21° C) over the course of one hour.
4. Observations were made on the state of specimens post-exposure. Qualitative evaluations were made on properties like elasticity and cohesion.
5. Each specimen was then placed into the impact testing apparatus, where it was subjected to impact loading. The impact was observed and recorded with a camera phone.
6. The specimen was evaluated after impact for any signs of degradation or wear. The video recording was reviewed.

The results of the thermal tests led the team to conclude that all material compositions possess adequate thermal performance. Further testing on the long-term effects of heat exposure is discussed in Section 4.0.

3.3.2 Thermal Test results

The impact testing apparatus consists of two vertically oriented 2x4" SPF members, a wooden baseplate, and a metal impact rod. The impact rod has a 1.5" circular face attached to the lower end to ensure full contact with the specimen. The constructed impact testing apparatus shown in Figure 16.

The impact rod was released from rest after being rotated to a 90° angle from the towers. It struck the specimens at a velocity of 6.017 m/s (21.7 km/hr). The acceptance criteria states that the specimens must not show visible wear or tear and they must not degrade more than 30%. Specimens were impact tested at ambient temperature after extreme heat and cold exposure, and then impact tested again while at a temperature of -80° Celsius. Neither test showed visible deformation, deflection or denting on any samples.

Figure 19. Impact Testing Apparatus

3.4 Density Measurement

Each specimen was weighed on a scale. Calipers were used to determine the height and diameter of each specimen. This data was used to compute the average density of each composition, which is displayed in Table 8. Density measurement was conducted prior to uniaxial compression testing and thermal testing.

TABLE 8. Density of each tested composition.

	Control	Composition 1	Composition 2	Composition 3	RTR	Go Plus	Pyle
Density (kg/m^3)	1118.7	1065.9	1049.6	1066.6	730.73	1441.6	1658.2

Using the density of each composition and the volume of the proposed curb design, the estimated weight of a proposed curb made from each composition was determined. The results of the evaluation are displayed in Table 9.

TABLE 9. Weight of proposed curb if constructed.

	Control	Composition 1	Composition 2	Composition 3	RTR	Go Plus	Pyle
Curb Weight (lbs.)	32.48	30.95	30.47	30.96	21.21	41.86	48.15

Interestingly, despite the existing full curb weighing 100 lbs, RTR's existing curb has the lowest observed density. This likely relates to the pressure used during their manufacturing process, which is suspected to be lower than the pressure used to create the other specimens employed in this design evaluation. The weight of RTR's curb combined with the low density of their present material indicates that there is excess material in their existing design.

All compositions containing RTR's synthetic fibre by-product are under the 35 lb design objective, meaning that they pass.

3.5 Digital Stress Analysis

The results detailed in Sections 3.2 to 3.4 were used to create a digital material in Autodesk Fusion 360 (2023 ed.). This material was designed to replicate composition 3 used in testing. Composition 3 was chosen over Composition 2 despite being slightly weaker. It was chosen because of its high fibre by-product content, which advances the goal of repurposing the waste product. A built-in butyl rubber material was used as a base, and the values of the following properties were changed to align with the estimated characteristics of material composition 3:

- Density – 1056.6 kg/m^3
- Young's Modulus – 6.683 MPa
- Poisson's Ratio – 0.35

All other material properties remained as their default values for butyl rubber material. The decision was based on the inability to gather information on the other properties, and the perceived similarities between Composition 3 and traditional butyl rubber. A diagram containing a breakdown of the digital material properties can be found in the appendix.

A digital simulation was selected over the manufacturing of a physical prototype. The rationale for the decision was the price, time and expertise associated with the production of a full-scale mold were too great for the scale of this project. Additionally, had an issue been discovered, the mold would no longer be useful to RTR. The ease of modification of the digital model proved to be a crucial asset during the development of the proposed solution, and the evaluation of Composition 3.

The digital composition 3 was applied to the proposed curb model and was simulated under two load cases. A uniform load of 60 psi was applied to the top surface of the model for the first loading scenario. This represents the design constraint of being able to withstand 60 psi without deflecting more than 50%. The deflection data is depicted in Figure 20. The maximum observed deflection was 0.2887 inches (0.773 mm) centered on the top surface which bridges the underside cut-outs. This value represents a 4.81 % deflection, significantly less than the constraint.

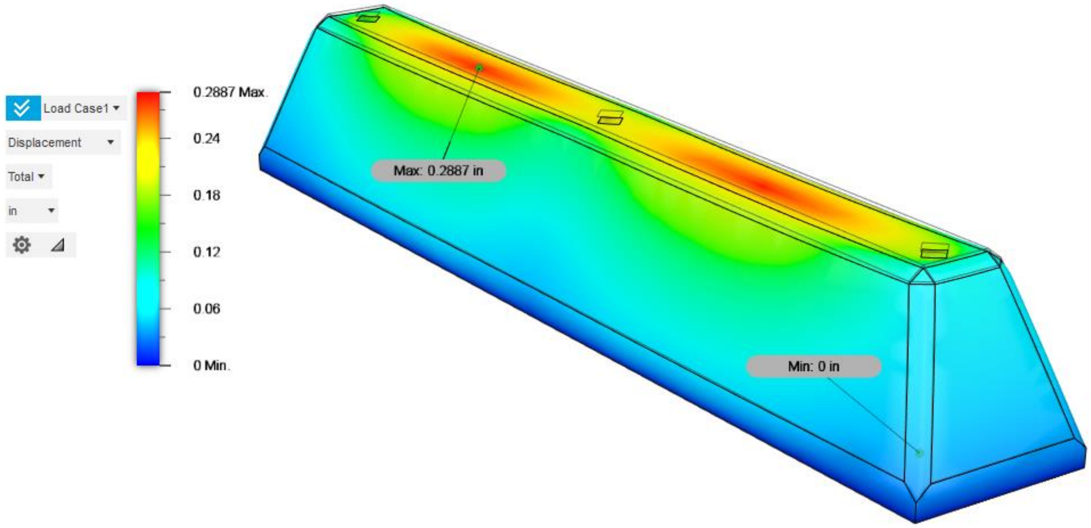

Figure 20. Screen capture depicting Fusion 360 deflection simulation results with a load of 60 psi applied to the top face of the model.

The design objective load of 100 psi was then applied to the model for the second scenario. The load was applied on the entire top surface. The maximum observed deformation was 0.4812 inches (1.22 mm) in the same location as the previous loading scenario, as depicted in Figure 18. This represents a deflection of 8.02 %, significantly less than the objective of under 50% deformation.

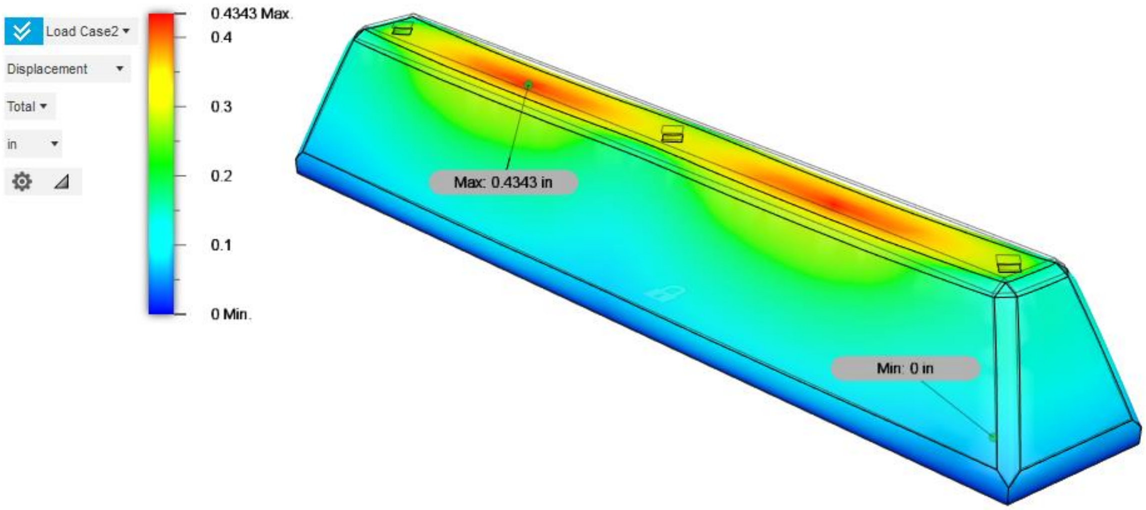

Figure 21. Screen capture depicting Fusion 360 deflection simulation results with a load of 100 psi applied to the top face of the model.

The results from the digital model simulations indicate that a physical curb based on the proposed solution, using material Composition 3 (22% fibre by-product) would be more than able to withstand the design loads.

3.6 Evaluation Summary

The tests conducted to evaluate the proposed curb design, and the three different compositions containing RTR's fibre by-product yielded promising results. Uniaxial compression tests indicated that all three compositions could withstand the design loads of 60 psi and 100 psi, with Compositions 2 & 3 outperforming the control material. Thermal tests using both an air oven set to 75° C and a deep freezer set to -80° C showed that the compositions did not noticeably degrade when exposed to extreme temperatures, and that they could survive minor impacts at -80° Celsius.

All compositions containing fibre by-product had a density lower than the control, and if used to construct a curb following the proposed design would have a total weight under 35 lbs, passing the design objective.

Composition 3 was made into a digital material for use in Fusion 360 simulations due to its high strength and high fibre by-product content. Two load cases were then simulated, wherein the proposed curb design constructed with the digital Composition 3 was put under stress by an application of 60 psi and 100 psi respectively to the top surface. The deformation observed in both load cases was well within the design objective. The results of the design evaluation indicate that the proposed solution, using Composition 3, is able to fulfil its desired role in parking lot environments.

4.0 LIMITATIONS

While Team 2 is confident in the proposed solution, and evaluation of said solution, there are several limitations of our analysis.

4.1 Limitations of the Proposed Design

The proposed design was constructed using Fusion 360 (2023 ed.) and was not made into a physical prototype. This impacts the confidence that Team 2 has in several properties of the design, mainly the ability to manufacture the design at scale. The 3D design would need to be translated to a series of metal sheet molds, which may necessitate alteration of the design.

Additionally, things like overflow channels or uniformity of heating were not considered, which may significantly impact the production of a physical curb. It is recommended that RTR iterate on the design to ensure that it makes sense from a molding and manufacturing perspective. RTR has expressed interest in employing a second capstone team to continue research on the synthetic fibre by-product. Iterating on the proposed design could serve as a major cornerstone of the following team's work.

4.2 Limitations of the Evaluation

Several design requirements introduced in Section 1.3 were not evaluated. This is because they were determined to be out of scope for the scale of this investigation. The requirement which states that the product should have a lifespan exceeding two years was one of these out of scope requirements. Testing for product lifespan is a long and arduous process which spawns frequent debates over its accuracy. Li Kunheng et al. (2022) discusses optimizing this process. We recommend that testing for the lifespan of the product is undertaken using the standard ASTM D573-04: Standard Test Method for Rubber—Deterioration in an Air Oven (ASTM International, 2019) and information from Kunheng et al., 2022.

In addition to lifespan, UV testing was also deemed to be out of scope. Access to testing equipment and the expertise to use them was not available, and UV tests are frequently performed on timescales exceeding those that would be acceptable for this project. We recommend that RTR contracts a firm to conduct UV testing for them. Testing can use ASTM D1148-13: Standard Test Method for Rubber Deterioration—Discoloration from Ultraviolet (UV) or UV/Visible Radiation and Heat Exposure of Light-Colored Surfaces (ASTM International, 2018a) as guidance.

While some impact testing was performed via the thermal experiments, it did not adequately evaluate the material's impact resistance. The team was unable to source an Izod, Gardner or Charpy impact testing machine accurately simulate parking lot collisions. Accessible standards on impact testing focus primarily on plastics, however documents including the following may be helpful as a guide:

- ASTM D8160-20: Standard Test Method for Un-notched Cantilever Beam Impact Resistance (Izod Impact) Testing of Thermoplastic Pavement Marking Materials (ASTM International, 2018b).

- ASTM D5420-21: Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact)(ASTM International, 2018d).

Alternatively, firms such as Qualitest Canada, Cambridge Materials Testing, and others can provide impact testing for a fee.

The thermal testing was limited to short-term exposures, as the team was restricted to borrowing equipment for short periods of time. In reality, a curb could be exposed to the temperature extremes for days or weeks at a time and would often cycle between more extreme temperatures and less extreme temperatures (i.e., daytime solar radiation to nighttime cool air). These scenarios could be evaluated by a firm such as Cambridge Materials Testing if RTR desires to determine performance under real-world thermal cases.

5.0 RECOMMENDATIONS

With the limitations of our evaluation known, Team 2 is confident in the proposed solution. The recommendations that Team 2 has for RTR are included in Subsections 5.1-5.4.

5.1 Increase Manufacturing Pressure

The first recommendation that Team 2 has for RTR is for RTR to consider raising the pressure applied during their curb manufacturing process. The current pressure used by RTR when manufacturing rubber curbs is unknown and should be determined first. Given the results of the evaluation and the content of conversations with RTR, it is assumed that the pressure used is significantly lower than the pressure that Team 2 used to create the test specimens for the control and compositions 1 through 3.

Team 2 used 1700 psi to create the test specimens. All specimens created by Team 2 were significantly denser and stronger in compression when compared to RTR's existing material. This is partly due to the higher pressure used when creating the specimens. RTR should consider raising the pressure used when manufacturing curbs to achieve higher compressive strength and reduced deformation under load, however they may find that 1700 psi creates a material that is too dense and does not deform enough under load. RTR should experiment with manufacturing pressures between their current value and 1700 psi to see what produces an ideal result.

5.2 Adopt Elements of Proposed Curb Design

Team 2 recommends that RTR uses a curb design similar to the proposed design outlined in Section 2. The reduction in material and weight that is facilitated by the 3-foot length and underside cavities are strong benefits. This will drastically impact ease of installation and transport.

As mentioned in Section 4.2, the proposed curb design may need to be iterated on to ensure that it makes sense from a molding and manufacturing perspective, however the benefits from general design features such as the reduction in length and underside cavities are clear.

5.3 Incorporate Fibre By-Product

Given the stellar performance of the compositions containing fibre by-product in all evaluation methods, Team 2 recommends that RTR begin incorporating fibre by-product into their parking curbs, and potentially into some of their other offerings as well. The addition of the fibre by-product should result in decreased deformation under load, increased compressive strength, decreased materials costs, and decreased waste to landfill.

The highest amount of fibre used in any composition was 22% by mass in Composition 3. Team 2 recommends that RTR continues to explore the impact of higher fibre by-product content exceeding 22%. Such compositions may have to contend with decreased elasticity, however the degree to which elasticity is reduced at higher fibre by-product content is unclear.

5.4 Further Evaluate Materials

As described in Section 4.2, there are several areas such as UV, lifespan, impact, and thermal testing where Team 2 feels additional evaluation of the proposed solution would be beneficial.

RTR should consider the recommendations made in Section 4.2 and further evaluate the materials where required.

6.0 SUMMARY

Reliable Tire Recycling requested that Team 2 investigate the synthetic fibre by-product resulting from their process line and detail a method of recycling the material. RTR expressed interest in using the by-product to create a new offering, a parking curb that would supersede their current model.

Team 2 developed a proposed solution; a parking curb composed of 22% fibre by-product by mass, while RTR's existing materials composed the rest (7.5% hydraulic binder, 0.5% water, 70% crumb rubber). The proposed solution meets all design constraints. It would weigh just under 31 lbs, meeting the design objective weight of 35 lbs. This was achieved through a reduction in total curb length and the intentional reduction of material in other areas such as the underside cavities.

It would deflect a maximum of 8.02% under the design objective load of 100 psi, well under the maximum of 50% deflection set by the design objective. This was achieved through increased pressure while forming the material, and the addition of fibre by-product. Additionally, the proposed curb would not degrade following short term extreme temperature exposure.

RTR should continue to explore this concept and consider implementing the recommendations outlined in Section 5. They have the potential to drastically improve the product, reduce materials costs and the amount of waste entering landfills, and help contribute to a more circular economy.

APPENDIX

A1. Bill of Materials

TABLE A1. Bill of materials for project.

Component	Qty	Description	Unit Cost	Total	Distributor	Distributor P/N	Manufacturer	Manufacturer P/N
Goplus Rubber Parking Curb	1	Rubber curb acting as baseline for prototype curbs	160	160	Amazon Canada	B07X3BRGHH	Goplus	SU-35140-LT
Pyle Parking Curb	1	Rubber curb acting as baseline for prototype curbs	103	103	Amazon Canada	B07RCCTVCZ	Pyle	PCRSTP14
Liquid Adhesive Binder	N/A	M-480	Free	Free	Ryvec	N/A	Ryvec	N/A
Crumb Rubber	N/A	Recycled rubber particles from various tires	Free	Free	RTR	N/A	RTR	N/A
Fibre By-product	N/A	Polyester / Nylon	Free	Free	RTR	N/A	RTR	N/A
Ball Bearing	2	Ball bearing of ¾” outer diameter	5.50	11.0	Princess Auto	N/A	N/A	SKU-3850674
Stainless Steel Rod	1	Stainless steel rod 1.5” long for impact testing apparatus	Free	Free	N/A	N/A	N/A	N/A
SPF Wood	3	2” by 4” SPF wood for tower and base plate	Free	Free	N/A	N/A	N/A	N /A
Table Cloth	1	Solid color table cloth used on design day when presenting posters	4.25	4.25	Dollarama	3080103	N/A	N/A
Glass Jars	3	Glass jars to display our ingredients i.e., rubber, binder, and fibre by-products on design day	1.33	4.00	Dollarama	3023487	N/A	N/A
Serving Tray	1	Serving tray to display our produced specimens	3.75	3.75	Dollarama	N/A	N/A	N/A

A2. Stakeholders

TABLE A2. Stakeholders and members involved in the project.

Name	Role	Organization	Responsibilities
Caitlyn Yim	Team Member	University of Manitoba	Design
Dryden Lanoway	Team Member	University of Manitoba	Design
Chiamaka Nwadike	Team Member	University of Manitoba	Design, Communication
Shehroze Baig	Team Member	University of Manitoba	Design
Jardel Santos	Client	Reliable Tire Recycling	Provides project scope
Dr. Natasha Jacobson	Instructor	University of Manitoba	Course Instructor
James White	Instructor	University of Manitoba	Industry Support
Dr. Jillian Seniuk - Cicek	Instructor	University of Manitoba	Communications Support
Dr. Mashiur Rahman	Consulting professor	University of Manitoba	Advises fibre research
Dale Bournes	Technician	University of Manitoba	Design Support

A3. Revision History

TABLE A3. Document revision history.

Date	Section/Subsection	Page	Change/Addition	Comments
03/02/2023	2.0	6	Reformatted the paragraph to make it look more organize.	Suggestions made by NJ.
03/02/2023	2.0	7	Proposed Solution chapter created. Introduction copied over from Project Plan R2.	Prepared for peer review
20/02/2023	2.1	7	Renamed the section name from “3-D model” to “Curb Design.”	Suggestions made by NJ.
20/02/2023	2.1	10	Resolved spacing issues.	Suggestions made by NJ.
20/02/2023	2.2	10	Resolved formatting issues and numbered the conclusion sentences.	Suggestions made by NJ.
20/02/2023	2.3	12	Replaced an image of the process with a flowchart.	Suggestions made by NJ.
25/02/2023	3.0	14	Design Evaluation chapter created.	Prepared for Peer Review
15/03/2023	All	N/A	Modifications made to ensure that text directly followed all headers.	Suggestions made by NJ.
15/03/2023	3.0	14	Spacing, reader direction, formatting and clarity issues resolved in Evaluation chapter.	Suggestions made by NJ.
08/04/2023	4.2	26	Sub section “Recommendation for further evaluation” has been moved to limitation as “Limitation of the Evaluation”.	Suggestions made by NJ and better aligned with rubric.
09/04/2023	Executive Summary	vi	Added executive summary	Aligned with rubric.
12/04/2023	All	All	Made formatting consistent, adjusted figure references and made pass for grammar and conciseness.	Prepared for submission.

A4. Project-Specific Materials

A4.1 Sample Compositions

Figure A1. Sample of Control 1.

Figure A2. Sample of Pyle curb.

Figure A3. Sample of GoPlus curb.

Figure A4. Sample of RTR rubber curb.

A4.2 Fourier-Transform Infrared Test Results

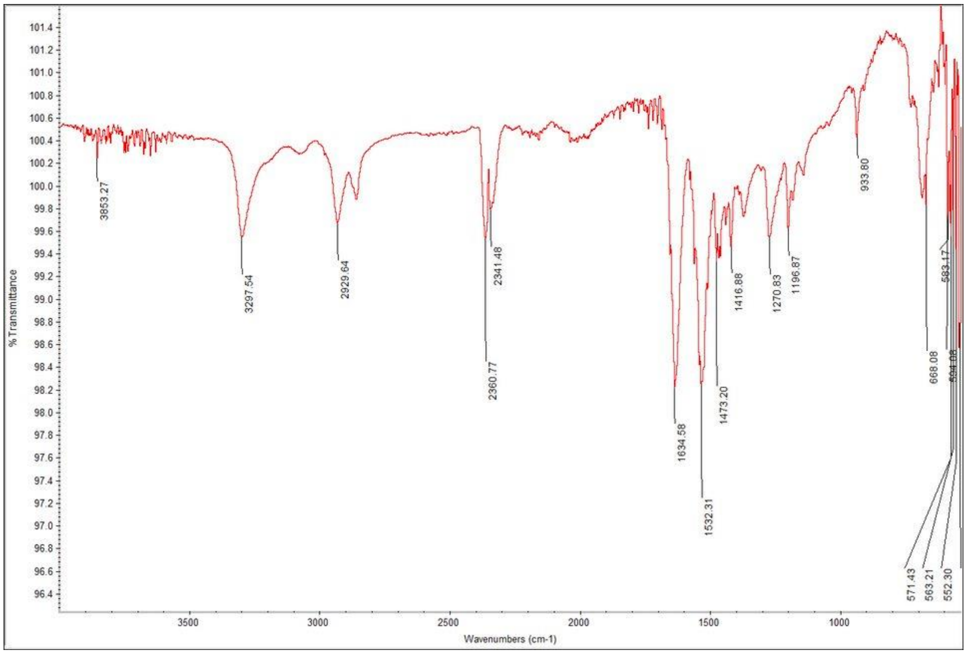

Figure A5. FTIR of Nylon 66 to compare fiber by-product against. Highest peak is 1532.31 mm.

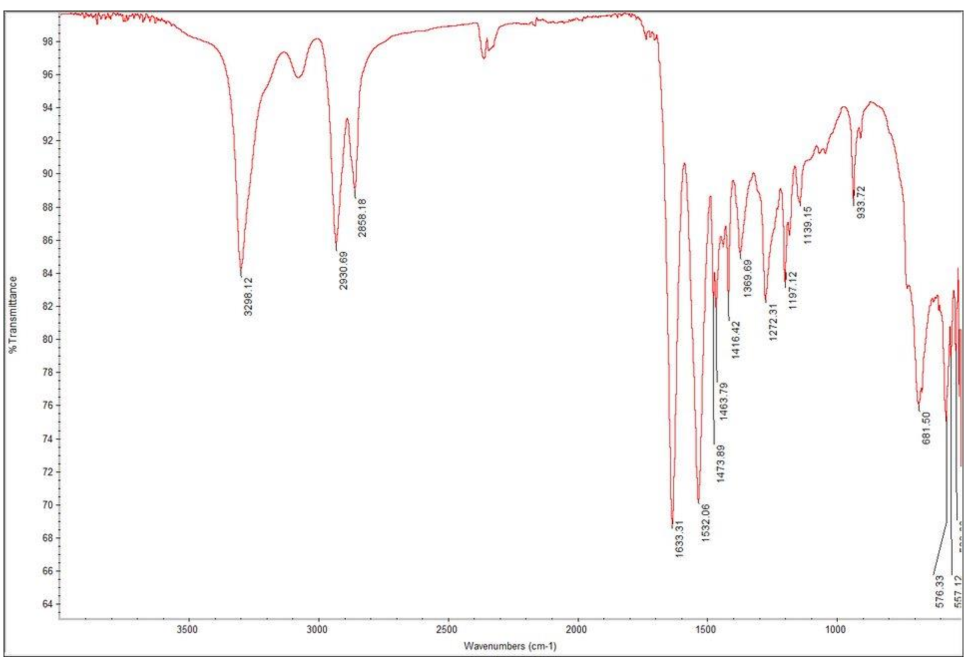

Figure A6. FTIR of Nylon 6 for to compare fiber by-product against. Highest peak is 1633.31 cm^{-1}.

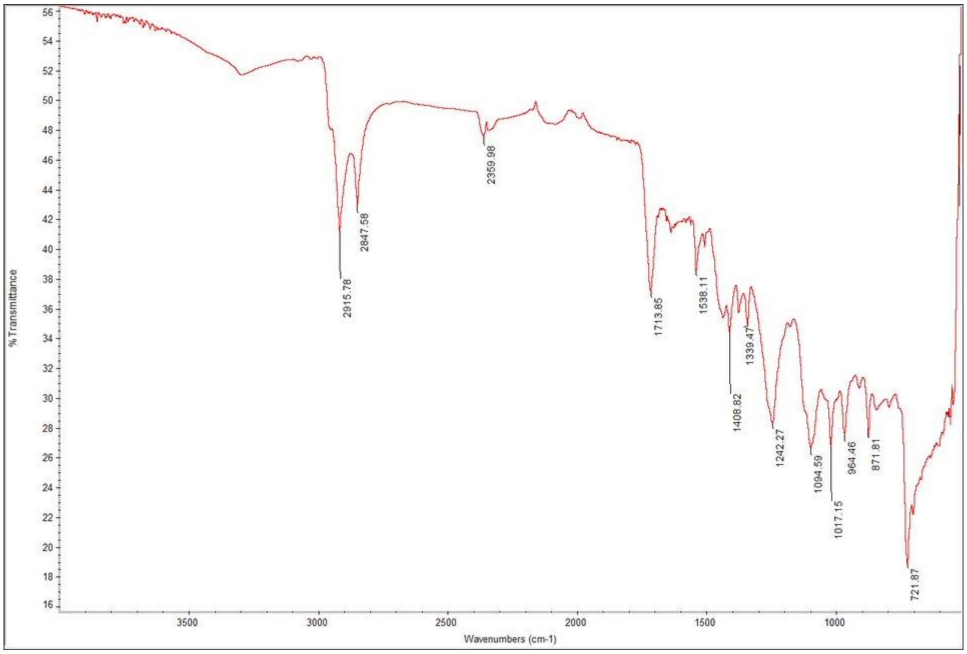

Figure A7. FTIR of fiber by-product. Highest peak is 721.91 cm^{-1}.

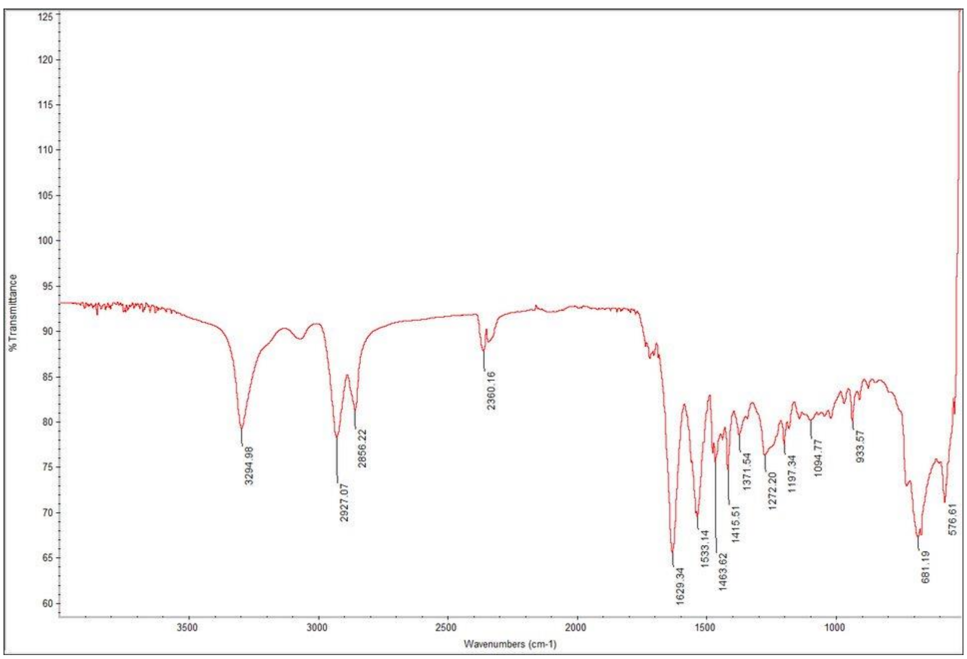

Figure A8. Second FTIR of fiber by-product. Highest peak is 1629.34 cm^{-1}.

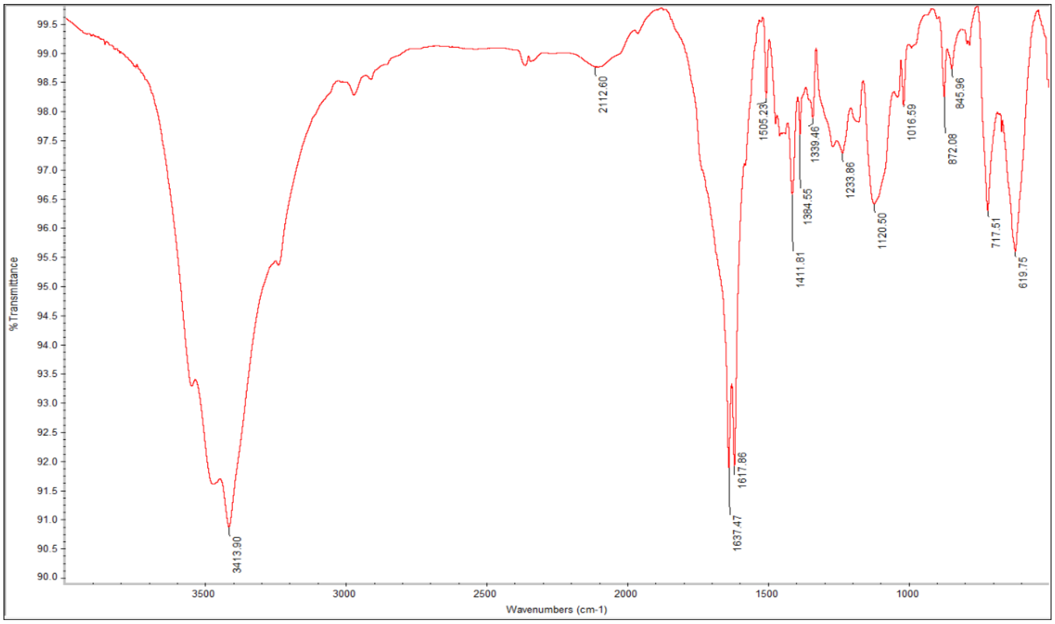

Figure A9. Second FTIR of fiber by-product. Highest peak is 3413.33 cm^{-1}. FTIR results are considered inconclusive and fibre composition is deemed inconsistent.

A4.3 Curb Schematic

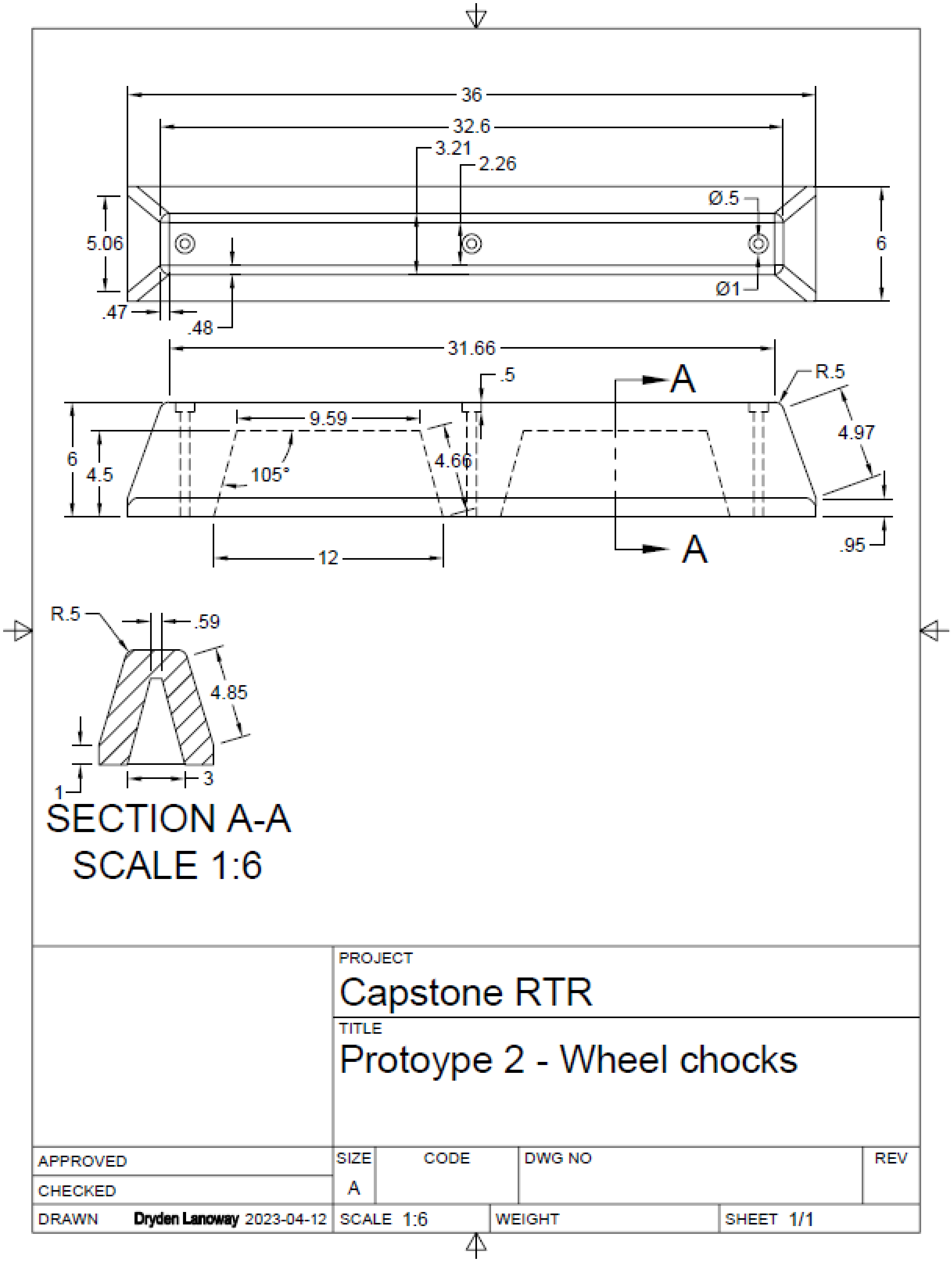

Figure A10. Engineering drawing of proposed curb design.

A4.4 Digital Material Properties

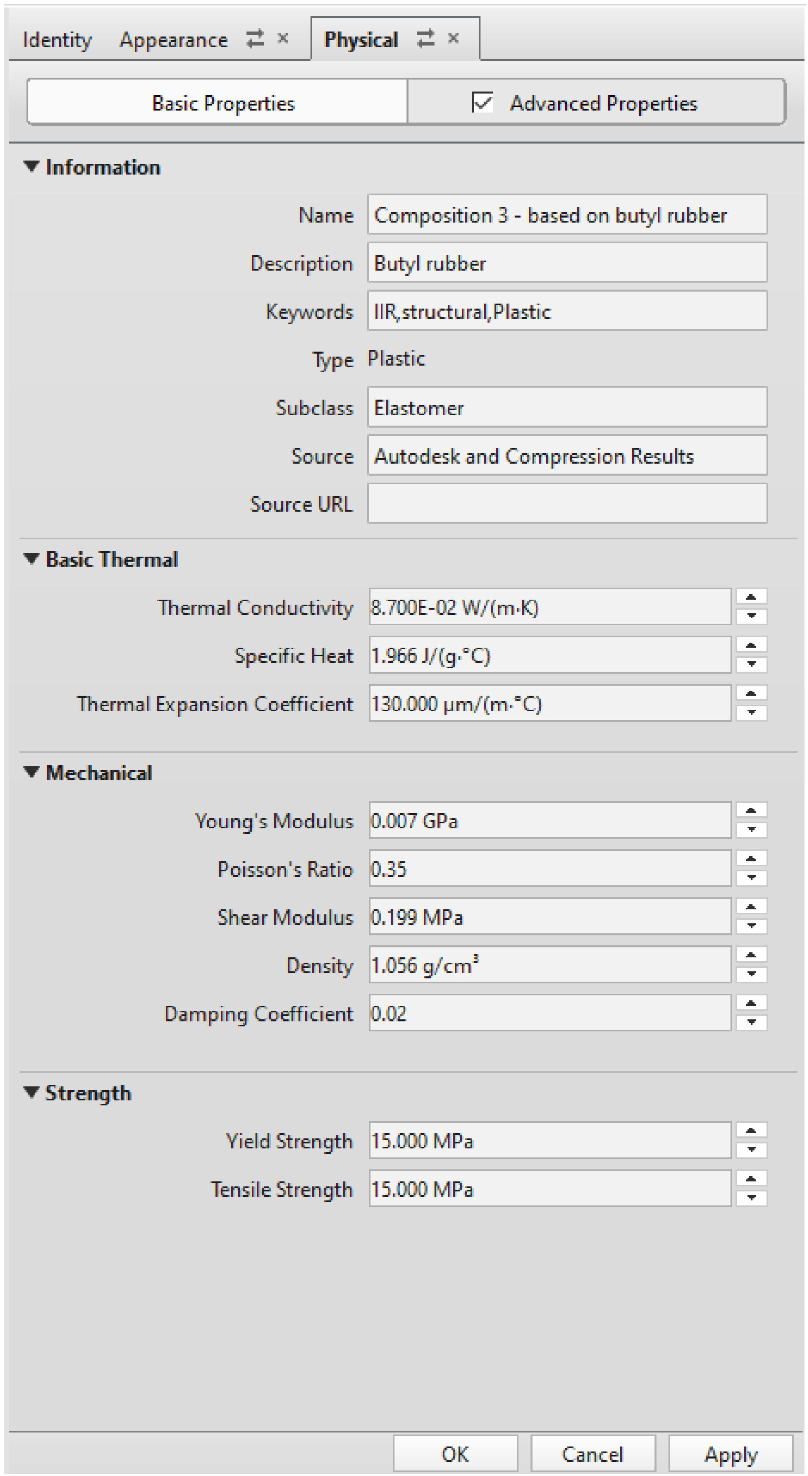

Figure A11. Fusion 360 (2023 ed.) material properties window for Composition 3.

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