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FINAL REPORT

Investigation of Recycled Tire Chips for Use in GDOT Concrete Used to Construct Barrier Walls and Other Applications – Phase I

Georgia Department of Transportation

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16. Abstract

In 2013, GDOT constructed more than 42,000 LF of concrete barrier utilizing a Class A concrete mixture design (3000 psi). There may be potential for the beneficial utilization of recycled tire chips in concrete barrier applications which can possibly lead to improved safety for vehicle occupants as well as reduce disposed rubber from going to landfills or stockpiles, and potentially saving materials cost for GDOT. This study investigates the use of the recycled rubber tire chips as a replacement of natural aggregates in concrete mixtures. Fresh concrete properties in addition to concrete compressive strengths were investigated in this study. A coarse and fine aggregate size rubber particle were evaluated in this study: 3/4-in. tire chips and 30-mesh crumb rubber. The tire chips were used to replace coarse aggregates, while the crumb rubber was used to replace fine aggregate in the concrete mixtures in increments of 10% by volume. Results determined that concrete strength reduction was reduced with a fine aggregate replacement with crumb rubber as opposed to greater losses of strength exhibited by a coarse aggregate replacement with tire chips. Adequate strengths were achieved at replacement levels as high as 40% by volume with the crumb rubber. For the tire chips, satisfactory strengths were achieved with only a 10% replacement of coarse aggregates without surface pretreatement; however, higher strengths were realized by soaking the recycled tire chips in sodium hydroxide prior to batching. Slump and unit weight generally decreased with the addition of rubber pieces while air content increased slightly with higher rubber contents. Although, the indirect splitting tensile strength, modulus of rupture, and modulus of elasticity values were lower than the control mixture, results were all within typical ranges.. Concrete mixtures with rubber contents up to 20% exhibited superior impact resistance when compared to the control. Based on the results of this study, larger-scale barrier wall testing incorporating rubber contents up to 20% should be performance. In addition, other applications for which this material may prove useful include the concrete glare protection section on top of barrier walls, concrete curb and raised medians.

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Recycled materials, concrete, tire derived aggregates, tire chips, crumb rubber, rubberized concrete, rubber modified concrete

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1.0 | INTRODUCTION

1.1 | Use of Waste Materials in Concrete

The incorporation of waste-stream materials in concrete mixtures has been an important contributor to concrete production for several decades. Materials such as fly ash, which require specialized landfills if disposed, are repurposed in concrete production while providing additional benefits to concrete properties. The use of these materials in concrete has obvious benefits, and therefore, instead of discarding this waste, it is sold thereby providing an additional economic value. The use of recycled tires in concrete production can provide many of the same life-cycle benefits that more traditional supplementary concrete materials offer. The major benefits of using recycled tire aggregates in concrete are not found in the direct economics of the material, but rather in its effect on concrete properties and its life cycle analysis. One major benefit of the use of recycled tire aggregates is the proximity of the manufacturers. Tire recycling facilities are located in and near major metropolitan areas, resulting in reduced transportation costs when compared to natural aggregates that may be trucked or railed in for use in urban concrete construction.

Discarded tires are often disposed in landfills or large stockpiles, resulting in an environmental hazard. Stockpiled tires can harbor water, creating an environment conducive to mosquito breeding and other pests. In the past, tires were burned to avoid this accumulation in stockpiles. The tire fires were difficult to extinguish and would release harmful chemicals into the environment resulting in regulations making it illegal to do so in many countries. With approximately 4,038 thousand tons of tires generated in 2015 in the United States alone, it is critical to continue finding innovative ways to use this waste material [Rubber Manufacturers Association, 2016].

The use of waste tires in concrete mixtures has the potential to provide increased safety measures to drivers. Rubber modified concrete mixtures have long been discussed as having improved impact resistance and a heightened ability to absorb energy than ordinary portland cement concrete. This ideology could prove beneficial along highways and interstates travelled at high speeds, collisions with the concrete barrier could have fatal consequences. Construction of these walls or other applications involving impact could prove to be a more forgiving and ductile material thereby saving lives.

1.2 | Study Objectives

The objective of this research was to determine the impact resistance of rubber modified concrete mixtures for use in concrete barrier walls and other applications. In addition, chemical and mechanical methods to improve the bond between the rubber particles and the cement paste were studied. The toughness of the rubber modified concrete mixtures was a point of emphasis because of its relationship to impact resistance. Additionally, the relationship between the rubber quantity in a concrete mixture and its effect on various concrete properties was researched. The fresh concrete properties examined in this study were slump, air content, unit weight and temperature. The hardened concrete properties measured were compressive strength, split-tension strength, modulus of elasticity, modulus of rupture, absorption capacity, repeated drop-weight impact hammer test, and permeability.

The research was completed into two separate phases. In the first phase, mini-mixtures were designed and batched varying cement and rubber content to measure the influence increased rubber contents had concrete compressive strength. In addition, cement content coupled with higher rubber contents were examined as well. Furthermore, a series of mixtures batched with crumb rubber were used to compare the effects of rubber particle size on concrete properties. Two additional mixtures including tire chips and crumb rubber in combination as a replacement for sand and rock in the mixtures were investigated.

The second phase of the research aimed at comprehensively studying the effects of tire chip content on hardened concrete properties. The toughness of the rubber modified concrete was of particular interest because of its relationship with energy absorption. Additionally, methods of improving the bond between the recycled tire chips and the cement paste were studied. Recycled tire chips were used to replace coarse aggregates at 10 and 20% by volume. An optimum amount of rubber aggregates to meet current GDOT specifications was determined, as well as the most effective rubber surface treatment to improve the hardened concrete properties.

This study aims at developing a rubber modified concrete mixture that exhibits improved toughness when compared to ordinary portland cement concrete mixtures. The diversion of this waste-stream material is an ancillary benefit to the utilization of this material in practice. The goal was to find the maximum replacement of coarse aggregate with tire chips that displays the greatest impact resistance while satisfying other important concrete characteristics. The use of surface treatments on the rubber particles was aimed at improving the mechanical performance of the rubber-modified concrete, allowing for higher rubber contents to be used in the mixtures while still meeting the requirements for barrier wall construction.

2.0 | LITERATURE REVIEW

2.1 | Overview

This literature review examines the past studies of concrete mixtures utilizing recycled rubber aggregates and the effects rubber has on concrete material properties. The review notes the trends that researchers of past studies on rubberized concrete have investigated and how these results have impacted rubberized concrete mixture design and enabled the use of rubberized concrete in civil engineering applications.

2.2 | Applications

Organized recycling of scrap tires has existed for several decades, specifically between 1980 and 1990 when efforts were first made to mitigate the growing number of stockpiles. In 1990, an estimated 1 billion scrap tires were housed in stockpiles throughout the United States. While many states have reduced the number of tires stored in stockpiles below 1 million tires, Colorado and Texas far exceed the rest of the country, with more than 20 million and 10 million tires in stockpiles, respectively. Only 25 states have active stockpile cleanup programs working to actively resolve this issue. See Figure 2-1. With increasing numbers of disposed tires each year, new and innovative ways to repurpose this waste will serve the rubber industry well [Rubber Manufacturers Association, 2016].

In 2015, an estimated 4,038 thousand tons of tires were generated in the United States with about 67 million scrap tires remaining in stockpiles in the United States. These scrap tires are used in a variety of manners, including tire-derived fuel, ground rubber, and civil engineering applications. As shown in Figure 2-2, civil engineering applications utilized approximately 275 thousand tons of scrap tires in the United States in 2015, making up about 7% of the total tons of disposed tires. The usage is a 59.8% increase from 2013, where civil engineering applications represented only 172 thousand tons of the market. These recycled tires were used for road and landfill construction, septic tanks, and other construction applications [Rubber Manufacturers Association, 2016].

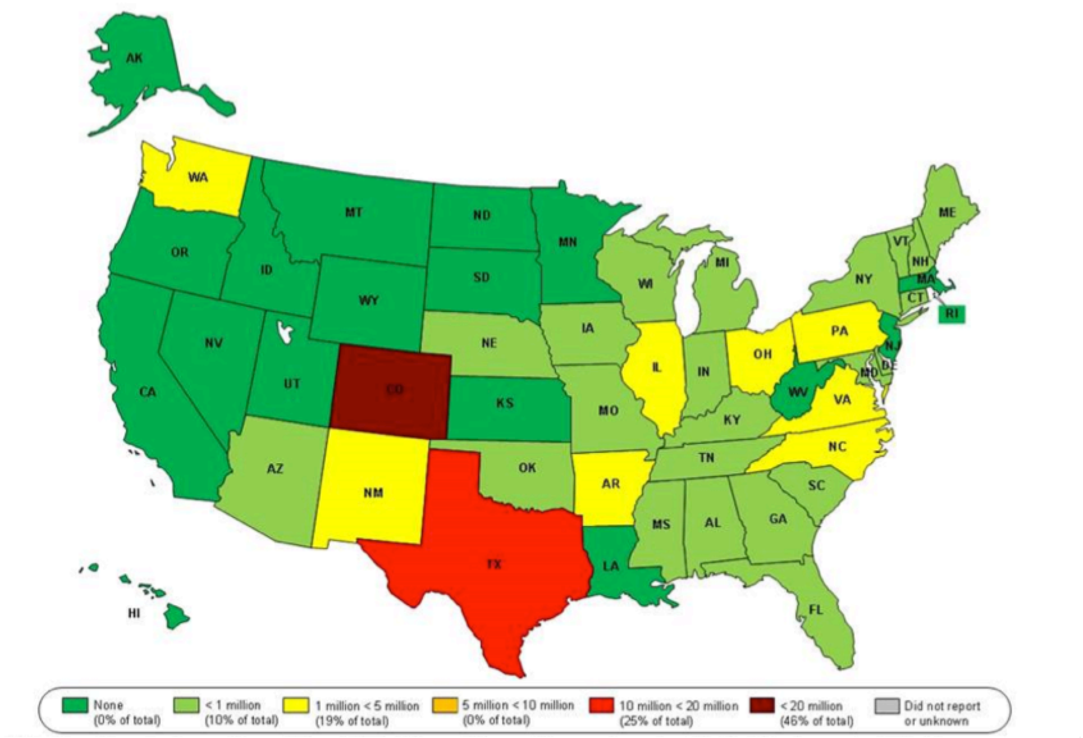


Figure 2-1 Waste tire stockpiles in the United States [Rubber Manufacturers Association, 2016]

2.3 | Materials

A comprehensive literature review was conducted prior to designing the concrete mixtures included in this study in order to determine the effects that utilizing recycled tire aggregates have on concrete fresh and hardened properties. Because of the varying applications for which recycled tires are used, the product is available in a number of different sizes. Research has been conducted on rubberized concrete mixtures using a variety of particle sizes, ranging from powdered rubber (<0.017in (0.425mm)) to rough shreds (1.97in (50mm)). The size and shape of the rubber particles have significant effects on the behavior of the concrete mixtures. The sizes of the rubber aggregates used in most studies are dictated by the availability of products within the regional markets. ASTM D 6270 *Standard Practice for Use of Scrap Tires in Civil Engineering Application* defined many of the different sizes of recycled tire particles. These definitions are displayed in Table 2-1.

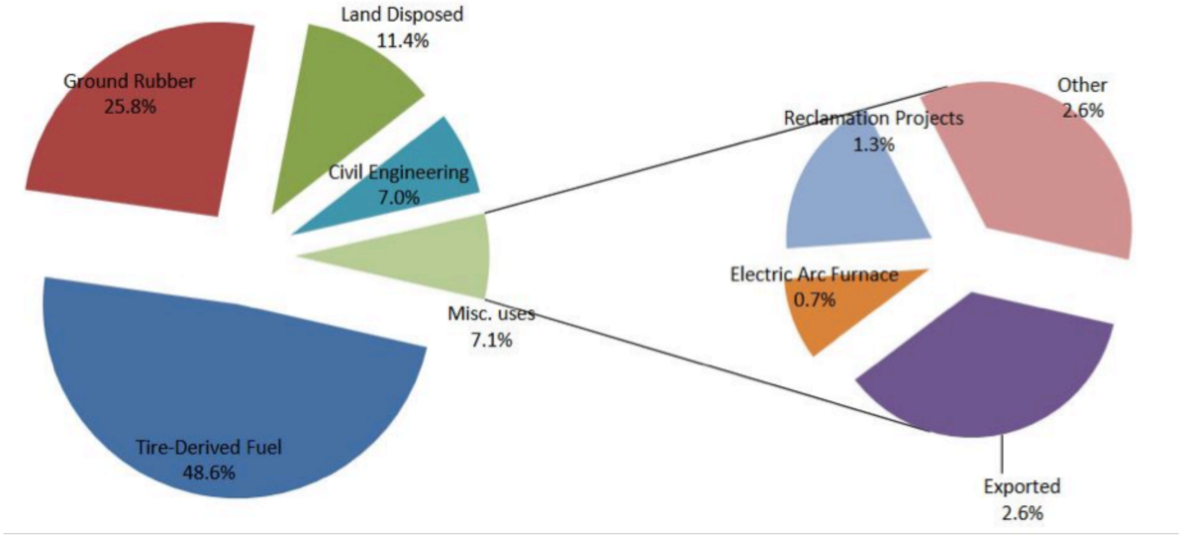


Figure 2-2 Waste tire uses in 2015 [Rubber Manufacturers Association, 2016]

Table 2-1 Terminology of Recycled Tire Prodcuts [ASTM Standard D 6270]

Tire Product	Size Upper Limit, in (mm)	Size Lower Limit, in (mm)
Chopped tire	relatively large pieces of unspecified dimensions	
Rough shred	30 x 1.97 x 3.94 (762 x 50 x 100)	1.97 x 1.97 x 1.97 (50 x 50 x 50)
Tire shreds	12 (305)	1.97 (50)
Tire derived aggregate (TDA)	12 (305)	0.47 (12)
Tire chip	1.96 (50)	0.47 (12)
Granulated rubber	0.47 (2)	less than 0.017 (0.425)
Ground rubber	0.079 (2)	less than 0.017 (0.425)
Powdered rubber	less than 0.017 (0.425)	-

Several factors affect the material properties of the recycled tires used in past studies. The waste tire source was a determining factor in its material properties. Gesoğlu et al. [2] noted that waste truck tires are more dense and stiff than tires from passenger vehicles, and therefore produced stronger and stiffer concrete. Another finding stated a difference in the unit weight of crumb rubber than that of tire chips. Crumb rubber was found to have a unit weight of 51.82 lb/ft^3 (830 kg/m^3), while tire chips had an increased unit weight of 63.68 lb/ft^3 (1020 kg/m^3) [Gesoglu and Guneyisi, 2007]. The density of tires is dependent on the age, manufacturer, and location of the tire.

The size and shape of the rubber particles dictates how the product was produced. Scrap tire rubber is primarily made of passenger car and truck tires, with a small percentage derived from off-road tires. Rubber properties such as strength and weight are affect by the original purpose of the tire and in return influence the manner in which the recycled tire particles are utilized. The production of crumb rubber particles is accomplished through numerous methods; however, the two most common are ambient grinding and cryogenic processing. Tires shredded using an ambient grinding method have a rough surface texture with a cut shape and similar dimensions. Smaller recycled tire products, such as crumb rubber, are often produced using cryogenic methods, which involve the use of liquid nitrogen or other chemicals to freeze the waste tires prior to reducing the material into smaller pieces [Scrap Tire News]. Another popular method used in the United States is a wet grind process, and it is used to produce crumb rubber with sizes ranging from 40 mesh to 200 mesh.

The ambient process, Figure 2-3, can be completed with the use of granulation or cracker mills. With this process, the material is stored at room temperature until they are processed. The granulation process usually requires three steps to separate the rubber, metal, and fabric from the waste tires. The first step shreds the tires into smaller tire chips, while the second machine removes the metal and fabric from the product. Large magnets are used to remove metals from the material, while air separators are used to remove the fabric from the rubber shreds. After each step is complete, the material is sent through a sifter to gather any large pieces of rubber to send them back through the grinding process once more in order to ensure uniform sizing.

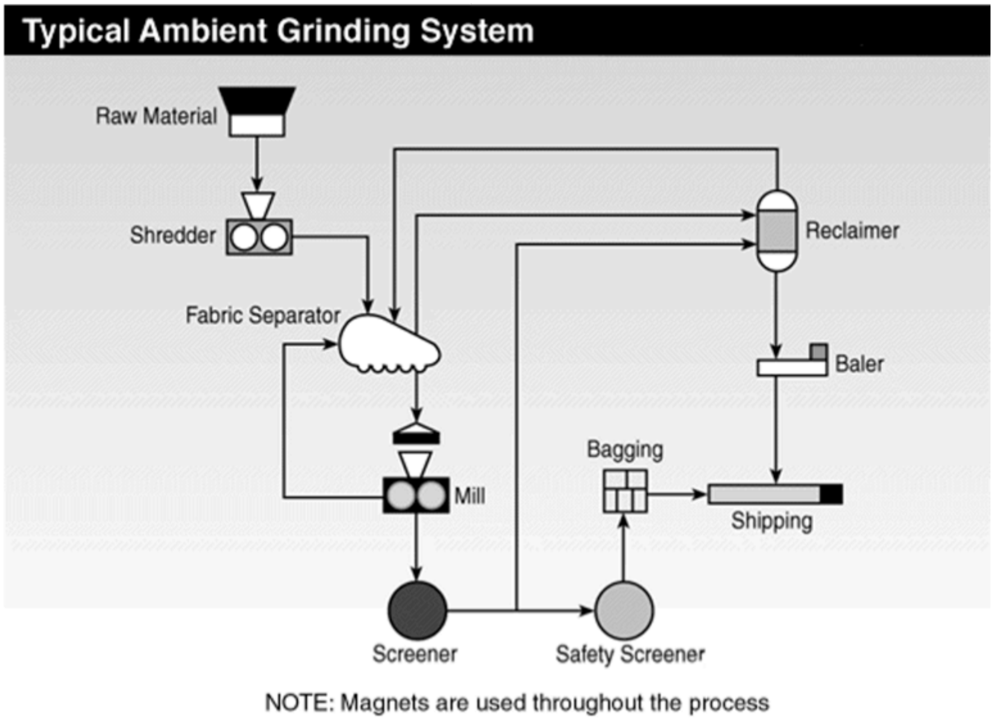


Figure 2-3 Diagram of the Typical Ambient Shredding Process [Scrap Tire News]

Once the rubber is grinded to an appropriate size and all of the extraneous materials are removed, the rubber is sent through a finishing mill to process the tire shreds into specified sizing. Cracker mills are very similar to this process. They usually involve two large rotating rollers with grooves cut in them to shred the tires. In this process, the size of the tire shreds is dictated by the distance between the rollers. The waste tires will pass through two or three of these cracker mills to attain the size necessary. Once this process is complete, the particles are sent through a screening system which sorts the tire pieces into different size categories. Particles that are deemed too large during this separate screening process are sent back through the cracker mills again. Shredded rubber products produced using the ambient method have rough surface texture with a cut shape and similar dimensions.

Methods of producing smaller rubber particle sizes usually involve a cryogenic process shown in Figure 2-4. This refers to the use of liquid nitrogen or other chemicals to freeze the waste tires prior to reducing the material into smaller pieces. The rubber is subjected to temperatures as low as -112°F (-80°C), at which the rubber material becomes glass-like. This process is generally used once the tires have been reduced to a 2 inch (5.08 cm) chip or smaller.

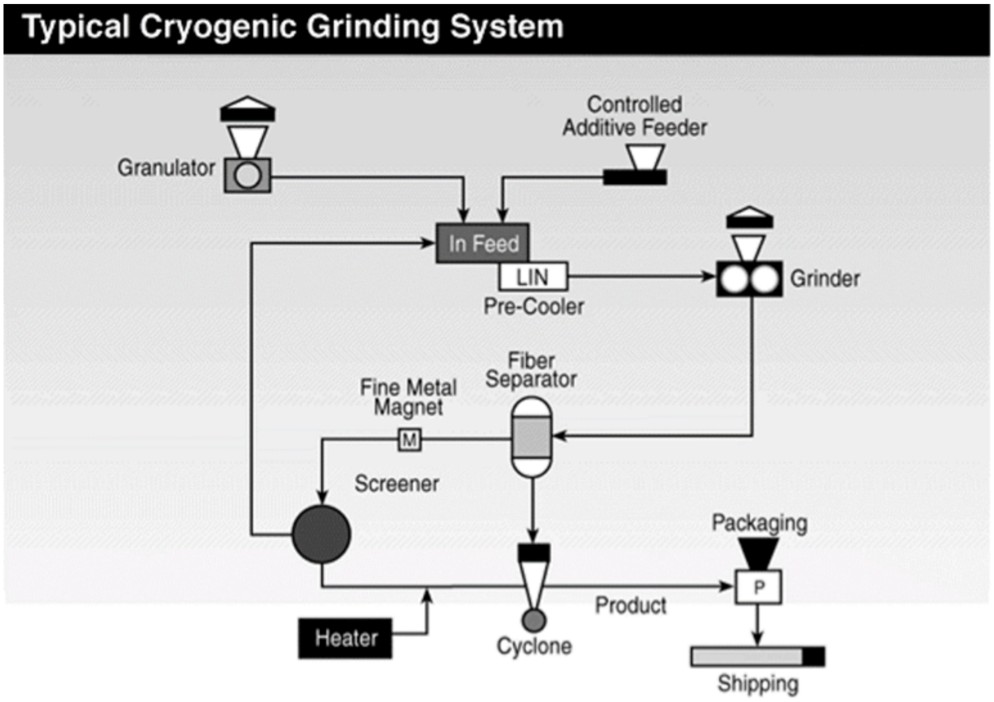


Figure 2-4 Diagram of the Typical Cryogenic Process of Crumb Rubber Production [Scrap Tire News]

The material is cooled by immersion in a bath of liquid nitrogen, or sprayed with the chemical. Then the product is essentially smashed with a hammer, shattering the frozen rubber into small grinds. This impact typically reduces the rubber to sizes ranging from 1/4 inch (0.635 cm) to 30 mesh. This process has the capability to produce anywhere between 4,000 to 6,000 pounds (1,814 to 2,722 kg) of crumb rubber per hour. The production of smaller crumb rubber particles requires an additional grinding stage. To produce crumb rubber finer than 40 mesh, micro milling, or wet grinding is used. Crumb rubber is added to water, creating a slurry, where it classified by size. When the correct sizes are separated, the slurry is dried, and the remaining rubber particles are ground in a process very similar to the ambient process. This process produces very clean rubber particles void of much debris that are mostly 60 mesh or finer [Scrap Tire News].

2.4 | Fresh Properties of Rubberized Concrete

Fresh concrete properties are an important indicator as to how the concrete mixture will ultimately behave in its hardened state. The initial properties impact the material's compressive strength, modulus of elasticity, durability, and likelihood of creep. The properties that are typically tested are slump, unit weight, temperature, and air content. The addition of other mixture constituents directly affects these properties, and ultimately, the long-term behavior of the material. In rubberized concrete, the size of the rubber particle added to the mixture also affects the concrete properties in different ways.

2.4.1 | Slump

Workability is an important measure of the concrete mixture that allows for it to be placed and finished without honeycombing or segregation. The slump test is a measure of concrete's workability and depends on the water-to-cementitious materials ratio (w/cm), water content, and air content of the concrete mixture. Rubberized concrete mixtures have been found to have lower slumps when compared to control mixtures. In one study, slump was reported to have decreased by more than 1/2 inch (1.27 cm) as compared to the control mixture when 25% of the coarse aggregate was replaced with rubber particles. The mixtures experienced even less slump as rubber content increased. This effect was mitigated with the use of plasticizer and air entraining admixture [Bing et. al., 2014]. Concrete mixtures that utilize silica fume as a cementitious material experienced even lower slump values [Antil, 2014]. Several studies have reported a slump of 0.0in (0.0mm) for mixtures which replaced 50% of the total aggregate volume with tire chips. Figure 2-5 shows the slump change for concrete mixtures with increasing rubber content by total aggregate volume.

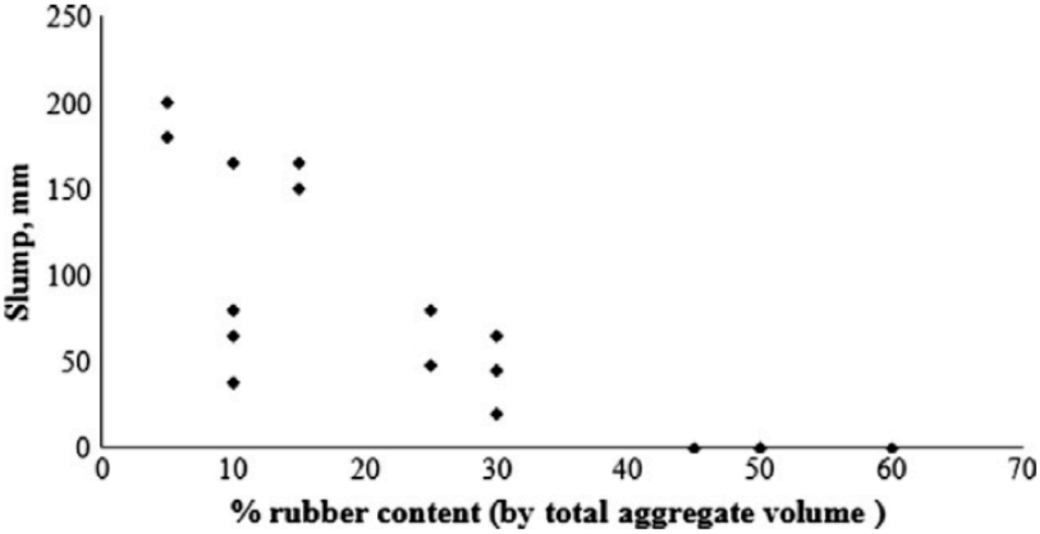


Figure 2-5 Effect of Percentage of Rubber Content on Slump Measurements [Najim et. al., 2010]

It is theorized that the decrease in slump with increasing rubber contents is due to friction created between the rubber and concrete mixture particles [Najim et. al., 2010]. In addition, the reduction in workability may be a result of the fact that rubber particles create “an interlocking structure that resists the normal flow of concrete under its own weight” [Bing et. al., 2014]. Despite the overwhelming majority of studies finding that slump decreases as rubber content increases in concrete mixtures, a few studies have reported the opposite effect. One study found that the maximum slump was more than 1.5 inches (3.81 cm) greater than the control mixture and occurred when 25% of both the coarse and fine aggregates were replaced with the same volume of rubber chips [Aiello et al., 2010]. Another study showing similar results found that tire derived aggregates increased the slump by an average of 1 inch when compared to the control mixture. In addition, the study found that silica fume in low quantities, 3 percent or less, further improved the workability of the mixture. Doses of silica fume greater than 5 percent, however, reduced the slump [Siringi et. al., 2015]. Another study showed that rubberized concrete mixtures that replaced 10% of the cement content with silica fume always had lower slump values than mixtures that were 100% cement [Gesoglu et. al., 2007].

The shape and size of the rubber particles impact the workability of the rubberized concrete mixtures. Khatib and Bayomy found that rubberized concrete mixtures that replaced fine aggregates with crumb rubber experienced lower slump values when compared to mixtures that replaced coarse aggregate with tire chips and mixtures that replaced both coarse and fine aggregates at equal percentages. All rubberized concrete mixtures produced slump values less than the control mixture [Khatib et. al., 1999].

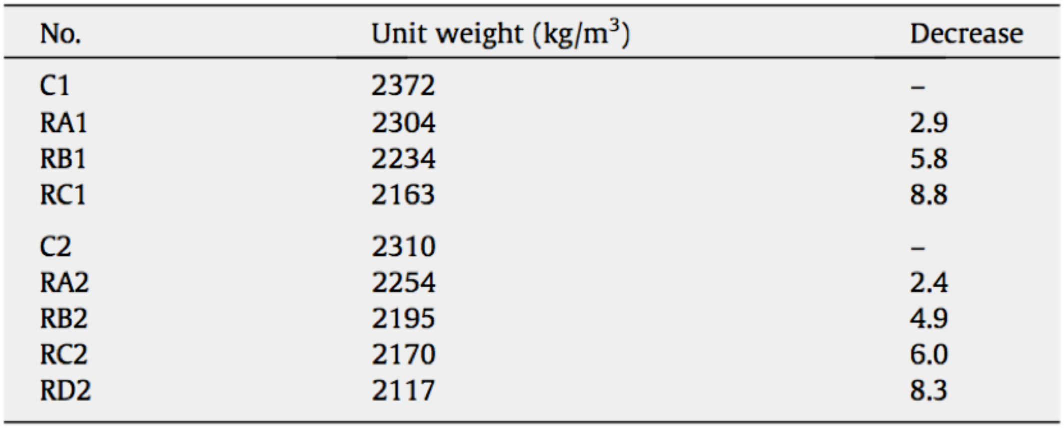
2.4.2 | Air Content

Agreement from several studies suggest the addition of rubber particles in concrete mixtures increases the air content of the sample even without the help of air entraining admixtures. One study found that increasing rubber aggregate content in 25% increments resulted in a quasi-linear relationship between the air content and rubber content of the mixture. The control mixture with a w/cm of 0.45 and no rubber aggregates had an air content of 2.5% while the rubberized concrete mixture consisting of a 100% replacement of coarse aggregates with tire chips had an air content of 6.0%. Similar to conventional concrete with only natural aggregates, the study showed an increase in air content with an increase in water content. The 100% aggregate replacement with tire chips mixture for the w/cm of 0.60 had an air content of 7.5% [4]. While this trend is evident in many studies, the size and shape of the rubber aggregates influences the air content of the rubberized concrete mixtures. Khatib and Bayomy found that concrete mixtures made with crumb rubber had greater air contents than those made with the same percent rubber content by total aggregate volume using tire chips [8]. It is believed the rough surface of the rubber aggregates is the cause of increased air contents in rubberized concrete mixtures. The non-polar nature of the rubber particles pushes away water molecules, while simultaneously trapping air on the surface of the rubber [Najim et. al., 2010].

2.4.3 | Unit Weight

Due to the increased air content of rubberized concrete samples and the replacement of dense aggregate with lighter rubber particles, the unit weight of rubberized concrete decreases as compared to conventional concrete as predicted. In one study, tests were completed replacing either coarse or fine aggregate by volume in 25% increments, with 75% replacement being the greatest. The unit weight decreased at approximately 2.9% for every 25% increase in coarse aggregate replacement. The results of this study are shown in Figure 2-6. The first grouping of mixtures in the figure include the control mixture, and mixtures replacing course aggregate with rubber particles at 25%, 50%, and 75%. The second grouping shows the unit weights and percent decrease for the control mixture and rubber replacing fine aggregate at 15%, 30%, 50%, and 75%

by volume [Aiello et. al., 2010]. Güneyisi et al. found that at a 50% rubber content, the unit weight was only 75% of the normal concrete [2004]. In addition, studies have shown unit weight to be affected by how the rubber is ground prior to its inclusion in concrete mixtures. Rubber ground using a mechanical process will likely produce rubberized concrete with a higher air content due to its angular shape and thus lead to a decreased unit weight [Pedro et. al., 2013].



No.	Unit weight (kg/m^3)	Decrease
C1	2372	–
RA1	2304	2.9
RB1	2234	5.8
RC1	2163	8.8
C2	2310	–
RA2	2254	2.4
RB2	2195	4.9
RC2	2170	6.0
RD2	2117	8.3

Figure 2-6 Effect of Increasing Rubber Content on Unit Weight [Aiello et. al., 2010]

One study determined the bulk density of cement to be 63.74 lb/ft^3 (1,021 kg/m^3), fine aggregate to be 90.58 lb/ft^3 (1,451 kg/m^3), and rubber to be only 28.16 lb/ft^3 (451 kg/m^3) [Pedro et. al., 2013]. These measurements differ greatly from those found in another study, which observed the gravel with a unit weight of 103 lb/ft^3 (1,650 kg/m^3), sand with a unit weight of 106.13 lb/ft^3 (1,700 kg/m^3), and rubber particles with a unit weight of 71.79 lb/ft^3 (1,150 kg/m^3) [Bing et. al., 2014].

2.4.4 | Temperature

While not widely reported in past research articles, temperature plays an important role in the strength development of concrete mixtures. Concrete temperature should range between 50 and 85°F (10 - 29°C) for proper cement hydration. Concrete with temperatures that exceed the 85°F

(29°C) are at risk for plastic shrinkage, and ultimately internal cracking resulting from these stresses. Studies have shown that the addition of rubber aggregates did not cause the temperatures to exceed the allowable range [Kardos et. al., 2015; Elchalakani, 2014].

It should be noted that it is important to utilize recycled rubber aggregates that have not been exposed to the sun for extensive periods of time. The black color of the tires will absorb heat, and could potentially speed up the hydration process of the rubberized concrete mixtures. The acceleration of the hydration process could make mixtures much less workable and much more difficult to place and finish.

2.4.5 | Fresh Concrete Properties Summary

In summary, past research on fresh rubberized concrete properties have shown the following trends:

- As rubber content increases, slump tends to decrease, becoming much less workable;
- At about 50% rubber content by total aggregate, slump nears 0 inches (0 cm);
- Air content of concrete increases as rubber content increases;
- Rubber particles are hydrophobic, allowing surface tension to trap air on its surface;
- Rubber does not affect concrete temperature; however, it is important to use rubber that has not been excessively exposed to the sun.

2.5 | Properties of Hardened Rubberized Concrete

Rubber aggregates have been shown to have a significant impact on concrete's hardened properties. Concrete's compressive strength, split tensile strength, flexural strength, impact resistance, and resistance to chloride ion penetration is a direct function of the amount of rubber present in the mixture. As discussed in the following, the rubber particles size affects the hardened concrete properties.

2.5.1 | Compressive Strength

Replacing aggregates with a more flexible, less dense material leads the concrete to have a reduced compressive strength. Rubber particle size and the material that is replaced has a strong influence on the effect of the replacement. In one study, coarse aggregates were replaced in increments of 25%, 50%, and 75% by total aggregate volume with recycled tire shreds. Cylinders were created and tested for each of these mixtures, and the compressive strength of each sample decreased by 47.8%, 54.4%, and 61.9% respectively compared to the control mixture. The other group in this study replaced fine aggregates with rubber particles by volume in increments of 15%, 30%, 50%, and 75%. While each of the mixtures experienced a decrease in compressive strength compared to the control mixture, the 75% fine aggregate replacement mixture only showed a 37.1% decrease [Aiello et. al., 2010]. This study suggests that replacing fine aggregates with crumb rubber particles has a less significant effect on the compressive strength than replacing coarse aggregates with tire chips. Another study agreed with this notion, noting that when all coarse aggregate was replaced with tire chips, the compressive strength experienced an 85% reduction, while only a 65% reduction in compressive strength was observed when 100% of the fine aggregates were replaced with crumb rubber particles [Siddique et. al., 2004]. Siringi et al. found that a 17% replacement of coarse aggregate with 2" tire derived aggregate produced compressive strengths that were 45% lower than the control after 7 days and 40% lower at 28 days. When only 10% of coarse aggregate was replaced with 2 inch (5.08 cm) tire chips, compressive strength reduction was only 28.6% and 33.8% at 7 and 28 days, respectively [2015]. One study showed more promising results, with a 25% replacement of coarse aggregate experiencing a 26.5% reduction in compressive strength as compared to the control mixture with a w/cm of 0.40 [Bing et al., 2014].

The use of silica fume as a cementitious material replacement has proven to increase compressive strengths in both plain portland cement concrete and rubberized concrete mixtures. Figure 2-7 shows the change in compressive strength through 90 days of age for rubberized concretes with increasing rubber aggregates.

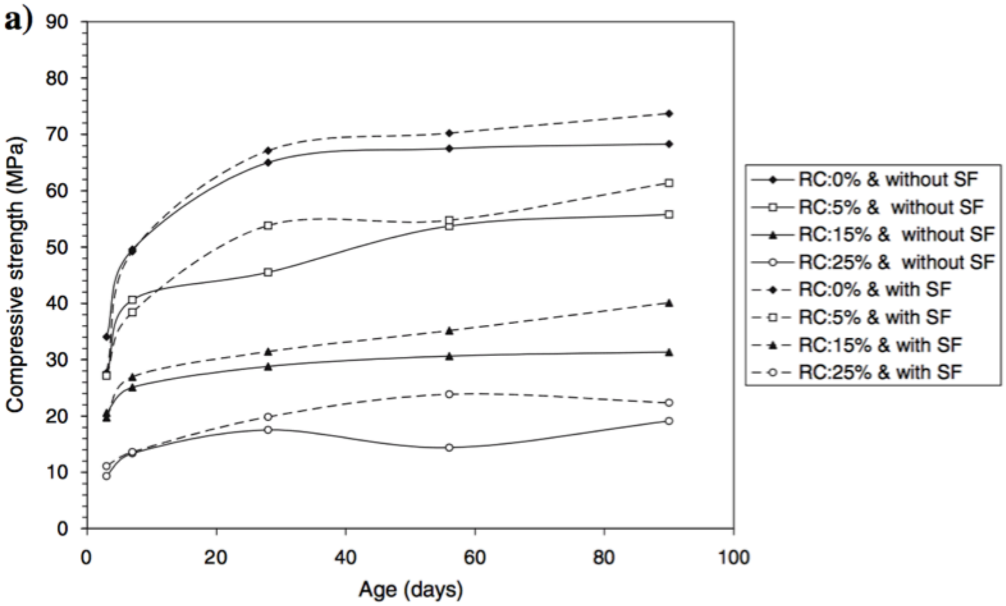


Figure 2-7 Compressive Strength of Rubberized Concrete Mixtures With and Without Silica Fume Over 90 Day Period [Gesoglu et al., 2007]

While there is still a systematic decrease in compressive strength as more rubber is present in the mixture, replacing just 10% of cement with an equal weight of silica fume improves compressive strength. Another observation is that rubberized concrete mixtures have a high rate of strength gain in the first seven days after mixing, with the rate slowing down over a

90-day period [Gesoglu et al., 2007]. Another study found that when fly ash made up 20% of the cementitious materials, the greatest compressive strengths occurred [Solanki et al., 2015].

Ganjian et al. attributes the loss in compressive strength to many contributing factors. One reason is that cement paste with rubber is softer than without, allowing for the development of cracks to form around rubber particles and expand during loading. In addition, poor bonding between cement and rubber particles leads to stresses being applied to the samples not uniformly. This causes cracks to occur between aggregates and the cement because they are responsible for a greater amount of the stress. Rubber aggregates are susceptible to movement toward the top of a sample when vibrated. This obviously leads to a non-uniform specimen with lower strength and stiffness toward the top, where failure is more likely to occur. Finally, Ganjian et al. states that rubber is a much less stiff material than natural aggregates. This results in rubberized concrete mixtures having a much lower modulus of elasticity than conventional concrete mixtures [2008].

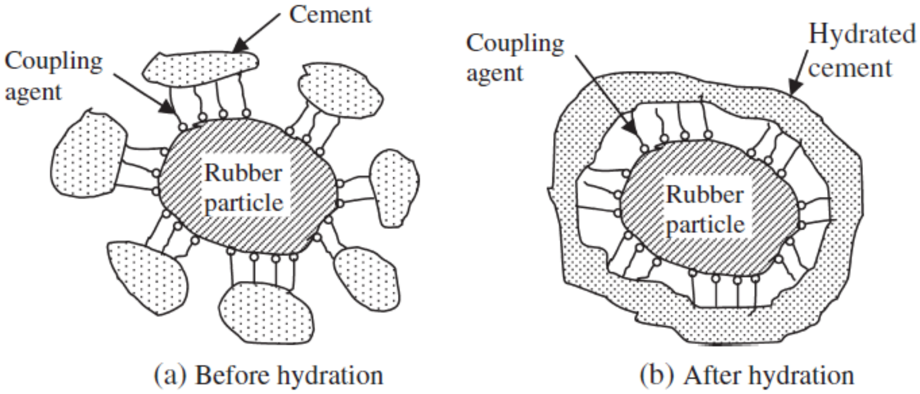
2.5.1.1 Surface Treatments of Recycled Rubber Particles

There are several methods that have been studied to help diminish the loss in compressive strength of rubberized concrete mixtures. Some techniques include washing the rubber surface with water, acid etching, plasma pretreatment, and coupling agents. The purpose behind performing these pretreatments is to increase the surface roughness of the rubber particles, allowing for a better bond to form between the rubber and cement. Among the most effective of the treatments that have been studied, immersion in sodium hydroxide (NaOH) was found to be one of the most effective solutions. Segre et al. used saturated NaOH aqueous solutions to soak rubber particles in for 20 minutes, while the mixture was continuously stirred. The rubber particles were then removed, rinsed with water and dried at room temperature. The interface between the rubber and cement paste was studied using a Scanning Electron Microscope (SEM) and it was observed that the adhesion was improved when NaOH was used [2000]. Segre et al. notes that pretreatments with higher NaOH concentrations improved the adhesion more effectively. Segre et al. also stated that it is hypothesized that the NaOH "hydrolyzes the acidic and/or carboxyl groups" on the surface of the tire [2000]. Siddique et al. states that the NaOH pretreatment increases the strength of the rubberized concrete by imposing microscopic grooves in the rubber particles, increasing the surface area of the aggregates and increasing the bond strength between the cement matrix and the rubber particles [2004].

Rostami et al. [1993] found that simply soaking rubber particles in water resulted in compressive strengths 16% higher than those which were untreated. When carbon tetrachloride and water were used to pretreat rubber aggregates, the mixtures saw a 57% increase in compressive strength [Siddique et. al., 2004].

Dong et al. performed a pretreatment in which the rubber particles used in the study were coated with a silane coupling agent. It was determined that the rubberized concrete mixtures that used silane coated particles performed much better under compression than the uncoated rubber modified concrete did. At the 28-day sample, the 30% coated rubber mix exhibited strengths that were 25% greater than the 30% uncoated rubberized did. The coating also prevented the concretes from losing as much strength when compared to the control mixture. At 28-days, the 15% coated rubber mixture lost only 10% of the compressive strength when compared to the control mixture, while the 30% coated rubber mixture lost only 23%. In comparison, the uncoated rubber mixtures lost 32% and 38% of the compressive strength, respectively [2013].

Dong et al. chemically bonded cement particles to the surface of rubber particles. The procedure to coat the rubber particles first began with creating an ethyl alcohol aqueous solution at a predetermined concentration and adding silane and stirring for a duration of 10 minutes with the use of a magnetic stirrer. Once this was complete, the rubber particles were added and stirred for 20 minutes. The rubber-silane-ethyl alcohol concoction was then heated to 80°C and refluxed for 30 minutes and cooled to room temperature. Once this was complete, the rubber was rinsed with alcohol by filtration and dried in an oven at 110°C for 12 hours. The result is an improved rubber particle that will bond with cement particles as displayed in Figure 2-8. The use of this method produced compressive and split tensile strengths that were 10-20% higher than the untreated rubberized concrete mixtures. Another notable finding was that the silane coated rubber particle mixtures experienced an improvement in energy absorptivity when compared to the untreated rubberized concrete mixtures.



(a) Before hydration

(b) After hydration

Figure 2-8 Silane pretreated and cement coated rubber particles [Dong et al., 2013].

Huang et al. studied a two-staged pretreatment of rubber particles for bond improvement. In the first stage, a silane coupling agent was used to coat the particles. This method was used because of ability of the silane solution to attach to organic materials like rubber, allowing the surface of the rubber particles to better attach to the cement paste. The particles were then treated with cement to coat the silane layer. This provided a hard shell around the rubber and improved the bond to the rest of the concrete matrix. The compressive strengths of the concrete mixes made with this two-stage method saw substantial improvements when compared to as-received rubber modified concretes. Rubber contents of 5, 10, 15, 20, and 25% were tested, and saw 24, 9, 18, 14, and 22% increases in strengths between the two groups [Huang et al., 2012].

2.5.2 | Flexural Strength and Modulus of Rupture

Much like the compressive strength results, as more rubber aggregates are incorporated into concrete mixtures, flexural strength decreases. This result is expected, because flexural strength is a function of a material's compressive strength. One study replaced coarse aggregate with rubber chips having a maximum nominal size of 0.79 inch (20 mm) by volume in 3% increments. The control mixture had an average flexural strength of 707.78 psi (4.88 MPa), while the mixture with just 12% rubber aggregates was only 362.59 psi (2.50 MPa). The mixture with 3% rubber aggregate lost 6.76% of its flexural strength after 28 days [Shah et al., 2014]. Similarly, a study which used a combination of crumb rubber and fine rubber powder to replace fine aggregates found that when 40% of the aggregate was replaced, the rubberized concrete lost 72% of its flexural strength. When only 10% of rubber was added, the rubberized concrete lost 37.9% of its flexural strength as compared to the control mixture. The study compared the results of these mixtures to similar mixtures containing 10% silica fume and found that the mixture containing 40% fine rubber aggregates lost 68.9% of its flexural strength. The mixture containing silica fume only lost 23.7% of its flexural strength with 10% rubber aggregates [Elchalakani, 2014].

One observation worth noting is the failure behavior of rubberized concrete when subjected to flexural loadings. Kardos et al. notes that control mixtures with no rubber particles failed suddenly after the initiation of crack. The rubberized concrete specimens using crumb rubber particles were able to withstand one-quarter of its ultimate load after failure. This is explained by the crumb rubber pieces bridging the cracks in the concrete, much like how steel fiber reinforcement behaves [2015]. This ability to withstand residual loading is shown in Figure 2-8.

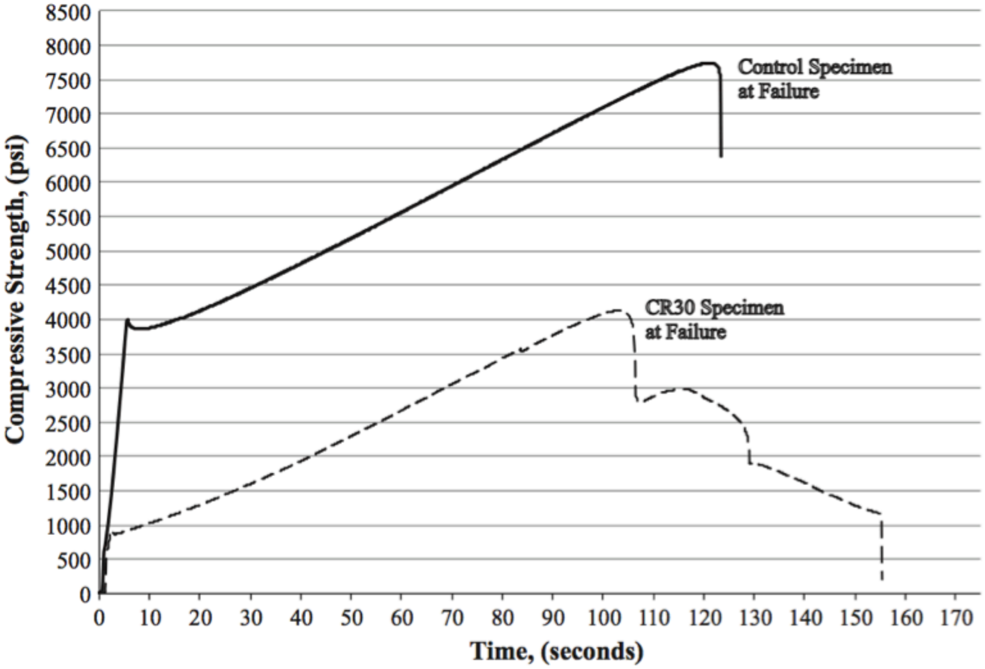


Figure 2-9 Modulus of Rupture of Control Mixture Versus 30% Crumb Rubber Concrete [Kardos et al., 2015]

2.5.3 | Split Tension Strength

Split tension strength has been shown in many studies to decrease with the addition of rubber into the concrete matrix. One study tested the indirect tensile strength of cylinders with varying amounts of tire screenings, tire chips, and fly ash. When no tire screenings were added to the mixture, the sample that had 40% fly ash had the greatest tensile strength, measuring at 831 psi (5.73 MPa). However, when the mixture had 40% tire aggregates replacing the fine aggregates, and 40% fly ash, the mixture had the least amount of tensile strength, at only 22 psi (0.15 MPa). With increasing amounts of tire screenings, the tensile strength decreased, with no apparent relationship to the amount of fly ash. When coarse aggregates were replaced with tire chips, the same trends occurred, except the tensile strengths were noticeably greater for the samples with tire chips [Solanki et al., 2015]. Another study found an interesting trend. While all mixtures showed tensile strengths less than the control mixture, Ganjian et al. found that ground rubber particles substituted for cement had greater tensile strength than chipped rubber replacing coarse aggregates for all replacement percentages by weight [2009].

Studies have shown that the interesting and noteworthy observation discovered while performing the split tension test is the manner by which the specimens failed. While the study found that the tensile strength decreased with increasing rubber content, cylinders that contained crumb rubber particles showed a crushing effect before failure. Cylinders with no rubber aggregates simply crack suddenly in half. The rubberized concrete cylinders showed flattened out bearing surfaces from where the load was applied, and crumbled under the stress [Kardos et al., 2015].

2.5.4 | Modulus of Elasticity

The modulus of elasticity is a measure of a material's stiffness and is a ratio of stress to strain. One study found that samples with a 7.5% replacement of course aggregates with tire chips saw a 20% decrease in the modulus of elasticity [Siringi et al., 2015]. Guneyisi et al. also found that increasing the rubber content decreased the modulus of elasticity of the rubberized concrete sample. For a w/cm of 0.60, the control mixture had a modulus of elasticity of 4,786 ksi (33 GPa), while the sample with a w/cm of 0.40 had a modulus of elasticity of 6,672 ksi (46 GPa). A sample with a 50% rubber content of the total aggregate volume experienced a modulus of elasticity of 943 and 1160 ksi (6.5 and 8.0 GPa) for w/cm of 0.60 and 0.40 respectively. For this study, the concrete experienced an 83% decrease in the modulus of elasticity for all rubberized concretes. The addition of silica fume improved the modulus of elasticity slightly, increasing the value up to 15% [2004]. One journal explains that the modulus of elasticity of the rubberized concrete experiences the decrease compared to the control mixture because it is directly dependent on the stiffness of the constituents in the mixture. In their experiment, they saw the effect that the w/cm had on the modulus of elasticity as well. In Series I, a w/cm content of 0.40 was used while Series II used 0.60. For replacement percentages of 25, 50, 75 and 100% of coarse aggregate with rubber particles, the mixtures for Series I saw a decrease in the modulus of elasticity of 13, 36, 44, and 57% respectively. The same percent replacements for Series II saw decreases in the modulus of elasticity of 30, 40, 54.6 and 69.5% respectively [Bing et al., 2014]. A study completed by Ganjian et al. compared the effect of crumb rubber versus rubber chips on the reduction in the modulus of elasticity. With a 5-10% replacement of aggregate with rubber, chipped rubber saw a 17-25% reduction in the modulus of elasticity while powdered rubber experienced an 18-36% reduction [Thomas et al., 2015].

2.5.5 | Energy Absorption

Rubberized concrete is often considered a quality option for lightweight concrete where strength is not the most important defining characteristic. Studies have shown that rubber aggregates provide concrete with increased toughness and the ability to sustain loading after failure. Pedro et al. performed an impact test where a 1 kg (2.20 lb) mass was dropped at increasing heights onto rubberized concrete samples. The results showed that the rubberized samples had between 2 and 2.5 cm (0.79 and 0.98 in) diameter dents, while the control mixture had dents ranging from 1 and 1.5 cm (0.39 and 0.59 in). In addition, the authors found that mixtures with higher rubber contents were able to sustain drops from greater heights without cracking compared to the control mixture. Crack widths also decreased with the inclusion of rubber particles. It was concluded that introducing rubber into the concrete matrix improved the concrete's response to impact and could withstand "higher energy without rupture" [2013]. Najim et al. found that rubberized concrete's toughness increased up to a rubber content of 25% volumetric replacement. Further, it was found that rubberized concrete exhibits improved fracture toughness, where a 75% replacement had a 350% improvement over the control mixture. While the introduction of rubber chips improves the impact resistance, it was found that "crack width and propagation is greater in comparison with natural aggregate content." This phenomenon is thought to be due to the higher strain rate rubberized concrete experience. Because of this fact, rubberized concrete is able to absorb more energy when compared to traditional concrete mixtures [2010].

Tantala et al. found that the toughness of concrete mixtures with 5% and 10% rubber by volume of the coarse aggregate content was greater than that of the control mixture. The mixture with only 5% rubber content had greater toughness than the 10% mixture as a result of a more substantial decrease in compressive strength for the mixture with the greater rubber content. Raghvan et al. found that rubberized concrete mixtures made with rubber shreds were able to withstand additional loading after the peak load. This was due to the rubber particles bridging the cracks in the concrete. Rubberized concrete mixtures made with shredded rubber pieces were not broken entirely in half during this experiment, while mixtures made with crumb rubber pieces broke into halves after peak load. It was concluded that post-cracking strength was "enhanced when rubber shreds are used instead of granular rubber" [Siddique et al., 2004].

Elchalakani notes that not much previous work has been done on the use of rubberized concrete in barrier wall construction. Rubber modified concrete mixtures are generally regarded as useful in situations where strength is not important. Many suggested uses of the composite material is for sound barriers or vibration absorptive infrastructure for use in agriculture. Previous studies on the use of rubberized concrete in barrier walls found that increased rubber content reduced vehicular deceleration forces significantly. The drop tests for this study found that rubberized concretes are more resilient, and able to endure high impact load "without inducing a stress more than the plastic limit" [2014].

2.5.6 | Resistance to Chloride Ion Penetration (Permeability)

A concrete's resistance to chloride ion penetration is an indication of the concrete's permeability. Less permeable concrete is more likely to have a longer life, because water is not allowed to seep into the concrete and form internal stresses. In a study conducted by Gesoglu et al., it was observed that the depth of chloride penetration increases with the increase in rubber content. This effect was magnified with a higher w/cm. The effects varied with increased moist curing times. Longer moist curing times decreased the chloride penetration depth in all samples [2007]. These effects are evident in the Figure 2-9. The first graph shows the chloride penetration depth for concrete with a w/cm of 0.40 while the second is a ratio of 0.60. For the concrete with a 0.40 w/cm, the chloride penetration depth varied 27-59% from the control mixture, while the 0.60 w/cm concrete varied about 6-40%. The chloride penetration depth significantly decreases with 28 days of moist curing. In addition, the inclusion of silica fume, at dosages of 10% by mass, greatly improves the resistance to chloride penetration.

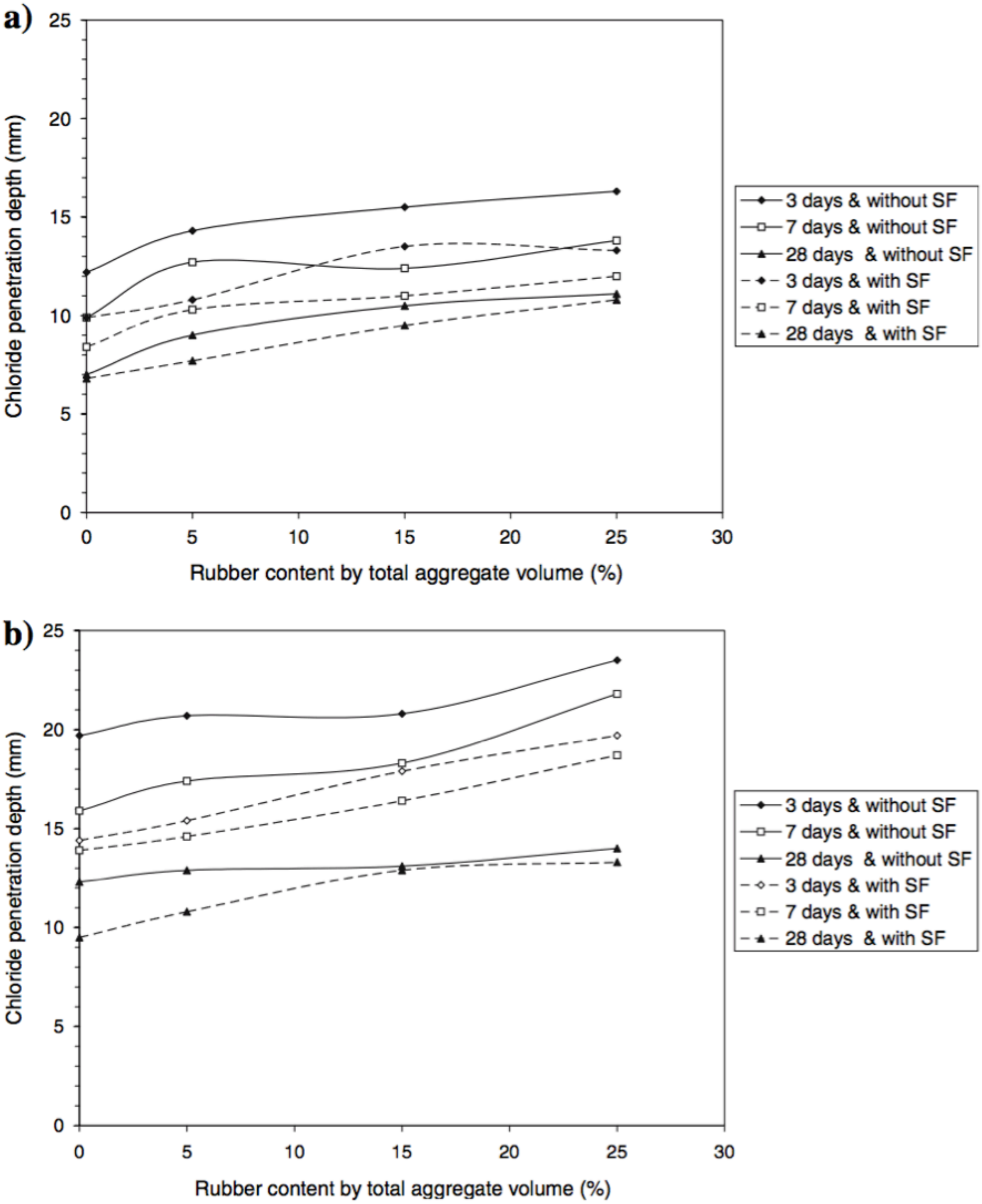


Figure 2-10 Effects of Rubber Content on Chloride Ion Penetration [Gesoglu et al., 2007]

2.5.7 | Hardened Concrete Properties Summary

In summary, past research on hardened rubberized concrete properties have shown the following trends:

- As rubber is added to concrete mixtures, compressive strength decreases significantly;
- When cement is replaced with 10% silica fume in rubberized concrete mixtures, better compressive strengths are reported;
- Flexural strength decreases with increased rubber content; however, rubberized concretes are able to withstand residual loads after failure;
- Rubberized concretes show improved resistance to impact loads, often cracking less than the control mixtures;
- Concrete is more permeable with increased rubber contents;
- Permeability decreases when silica fume is present in the mixture at equal rubber contents;
- Rubberized concrete mixtures show a less brittle, more elastic failure mechanism than traditional concrete cylinders.

3.0 | PROBLEM STATEMENT

In recent decades, tires have been recycled in numerous ways across the United States. However, as the population continues to grow, it is important to continue investigating new and innovative ways to repurpose this waste material. Georgia lawmakers passed legislation in the early 1990s which outlined specific guidelines to follow for disposing of waste tires throughout the state. The Department of Natural Resources Environmental Protection Division is responsible for overseeing the proper disposal of these waste tires. This agency requires that all scrap tires receive an identification number and be tracked to its final end user or disposal facility. Permits are assigned to approved disposal facilities as well as any individual transporting the scrap tires. Additionally, there exists strict requirements for processing plants intended to recycle these waste tires.

In 2013, GDOT constructed more than 42,000 LF of concrete barrier utilizing a Class A concrete mixture design (3000 psi). There may be potential for the beneficial utilization of recycled tire chips in concrete barrier applications which can possibly lead to improved safety for vehicle occupants as well as reduce disposed rubber from going to landfills or stockpiles, and potentially saving materials cost for GDOT. Additionally, there may be other applications requiring less compressive strength, Class B – 2200 psi, where rubberized concrete could be advantageous. Concrete safety barriers are one of the widely used impact attenuators that are intended to either decelerate vehicles to a safe stop or redirect them away from a fixed object. However, concrete exhibits little plastic deformation when impacted by a vehicle and thus an undesirable trait for safety barriers. GDOT has not studied recycled rubber tires for concrete barriers or other concrete related applications despite the potential for safety, environmental, and economic benefits.

The overall objective of this study was to create rubber-modified concrete that exhibits improved toughness for impact resistance when compared to concrete mixtures without rubber aggregates. More ductile barrier walls and other concrete infrastructure will provide a safer, more durable and energy absorptive surface in the case of car collisions. An ancillary benefit of the use of this waste material is that it provides another destination for recycled tire chips. The use of this material in concrete barrier walls will aid in the management of waste produced by increasing urbanization. To accomplish this, GDOT Class A (3,000 psi, 20.68 MPa) concrete design requirements will be abided by for the rubberized concrete mixtures developed in this study. Additional recommendations will be made for use in GDOT Class B concrete (2,200 psi, 15.17 MPa).

Ultimately, the study purpose is to assess the potential for recycled tire particles for use as a virgin aggregate replacement in concrete production in Georgia. In particular, the effect of the replacement of coarse aggregate with recycled tire chips and fine aggregate with crumb rubber particles on various fresh and hardened concrete properties were determined. In each instance, the virgin aggregates were replaced volumetrically in 10% increments up to the maximum of 50%. In the first phase of the project, the effects of the replacement with rubber on the concrete’s compressive strength along with slump, air content, temperature, and unit weight was determined. In the second phase of the project, additional tests to determine more extensive hardened concrete properties were explored. These tests include: split-tension strength, modulus of elasticity, modulus of rupture, energy absorption, repeated drop-weight impact hammer test, and resistance to chloride ion penetration (permeability). The primary objective of this study was to determine an optimized rubber content and surface treatment for concrete mixtures exhibiting improved toughness and resistance to impact. Recommendations for inclusion of rubber tire chips for concrete applications are included within this report.

4.0 | CONCRETE MATERIALS

4.1 | Research Study Purpose

This study aimed at designing and testing modified concrete incorporating recycled waste tires to improve the toughness and energy absorption when subjected to impact. To ensure the fresh and hardened concrete material properties are deemed correct, the individual material constituents and properties must first be gathered or determined. These properties include the physical and chemical properties of the cement, the gradation, specific gravity, and absorption capacity of the fine aggregates, and correct dosage rates for chemical admixtures. Details of each are presented in the following sections of this report.

4.2 | Cementitious Materials

A Type I-II cement was used for this study. No additional cementitious materials were used in place of cement. The cement used had a specific gravity of 3.16. The complete chemical and physical properties analysis of the cement is shown in Table 4-1.

4.3 | Virgin and Recycled Tire Aggregate Materials

Both the virgin coarse and fine aggregates used in this study were obtained from quarries local to Athens, Georgia. The aggregate properties as well as the sieve analyses were provided by the supplier and confirmed through laboratory testing. The coarse aggregate used in the study was an ASTM C33 size #57 stone. In addition, the fine aggregate satisfied the requirements of ASTM C33. The material properties of the natural coarse and fine aggregates were verified using the test procedures described in ASTM C127 and ASTM C128, respectively.

Table 4-1. Chemical and Physical Test Data for Type I/II Cement

Chemical and Physical Properties		Test Results	ASTM C 150 Specifications
SiO_2	*(%)*	19.7	--------
Al_2O_3	*(%)*	4.7	6.0 max
Fe_2O_3	*(%)*	3	6.0 max
CaO	*(%)*	63.3	--------
MgO	*(%)*	3.1	6.0 max
SO_3	*(%)*	3.2	3.0 max
CO_2	*(%)*	1.7	--------
Limestone	*(%)*	4	5.0 max
$CaCO_3$ in Limestone	*(%)*	98	70 min
C_3S	*(%)*	54	--------
C_2S	*(%)*	15	--------
C_3A	*(%)*	7	8 max
C_4AF	*(%)*	9	--------
$C_3S + 4.75\ C_3A$	*(%)*	89	100 max
Loss of Ignition	*(%)*	2.7	3.0 max
Blaine Fineness	cm^2/g	387	260 - 430
Air Content of PC Mortar	*(%)*	8	12 max
Specific Gravity		3.16	--------

This project aimed to replace coarse aggregate with tire chips ranging in between 3/4" and 1-1/2” in size and a crumb rubber similar to ASTM C33 fine aggregate. Figure 4-1 shows the tire chips utilized for this study along with the virgin coarse aggregate. While some of the tire chips are longer than the coarse aggregate, the materials are very similar in size. Figure 4-2 shows the crumb rubber selected for the study in comparison to the standard concrete sand. Material properties tests were conducted on the tire chip and crumb rubber aggregates used in this study. It was important to obtain tire chip and crumb rubber products that were similar in size to the virgin aggregates that were being replaced. A sieve analysis was performed using ASTM C136 on each recycled aggregate. The gradation results of the sieve analyses of both the tire chip and crumb rubber combined with the natural aggregates, and ASTM C33 upper and lower limits are shown in Figure 4-3.

Figure 4-1. Tire Chip and Virgin Coarse Aggregate Comparison

Figure 4-2. Crumb Rubber and Virgin Fine Aggregate Comparison

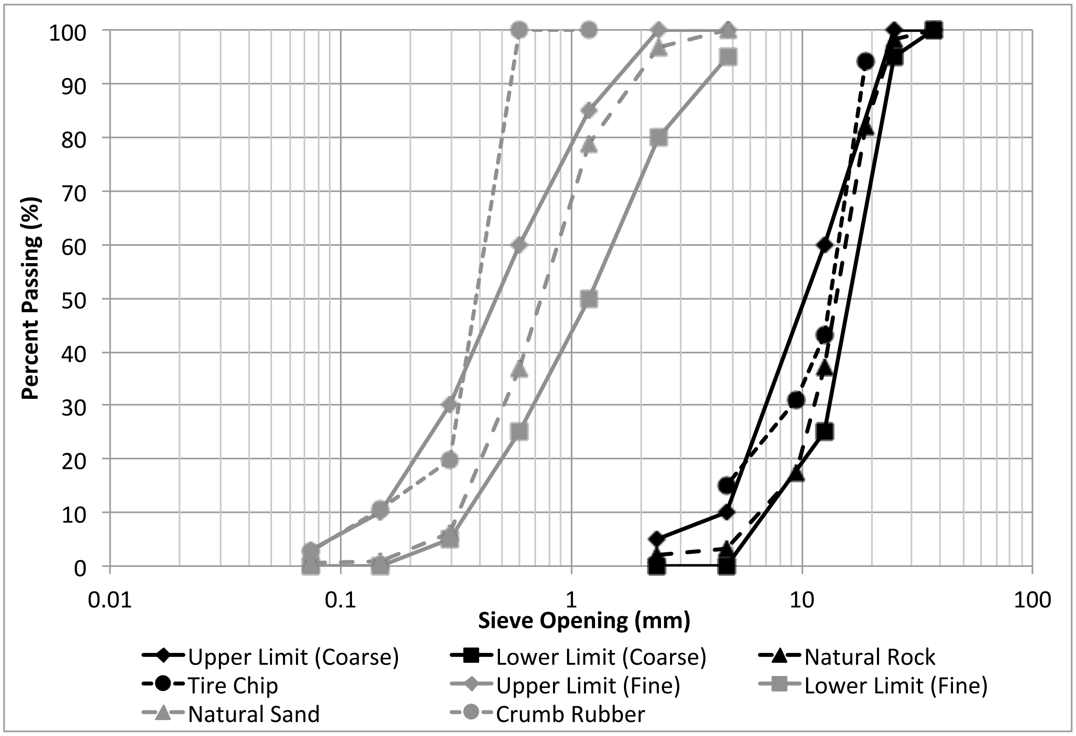


Figure 4-3. Sieve Analysis for Natural and Recycled Rubber Coarse and Fine Aggregates

While the gradation curve of the tire chip falls outside of the ASTM limits for a No. 57 aggregate, it is clear that the rubber coarse aggregate is similar in size to the virgin rock. Similarly, the crumb rubber is comparable in size to the fine aggregate, but falls outside the limits because of its more uniform size. Although the recycled rubber aggregates fell outside the upper and lower limits of ASTM C33, the authors felt they were acceptable for inclusion in the study mixtures as a result of the blended natural/recycled aggregate composites satisfying the graduation requirements. The blended aggregate gradations are illustrated for the coarse and fine aggregates in Figures 4-4 and 4-5, respectively. As shown, the blended coarse aggregate satisfies the ASTM C33 requirements for Size #57 stone at coarse aggregate replacement with tire chip up to 50%. However, the blended fine aggregate only satisfied ASTM C33 grading requirements up to 30% of fine aggregate replacement with crumb rubber.

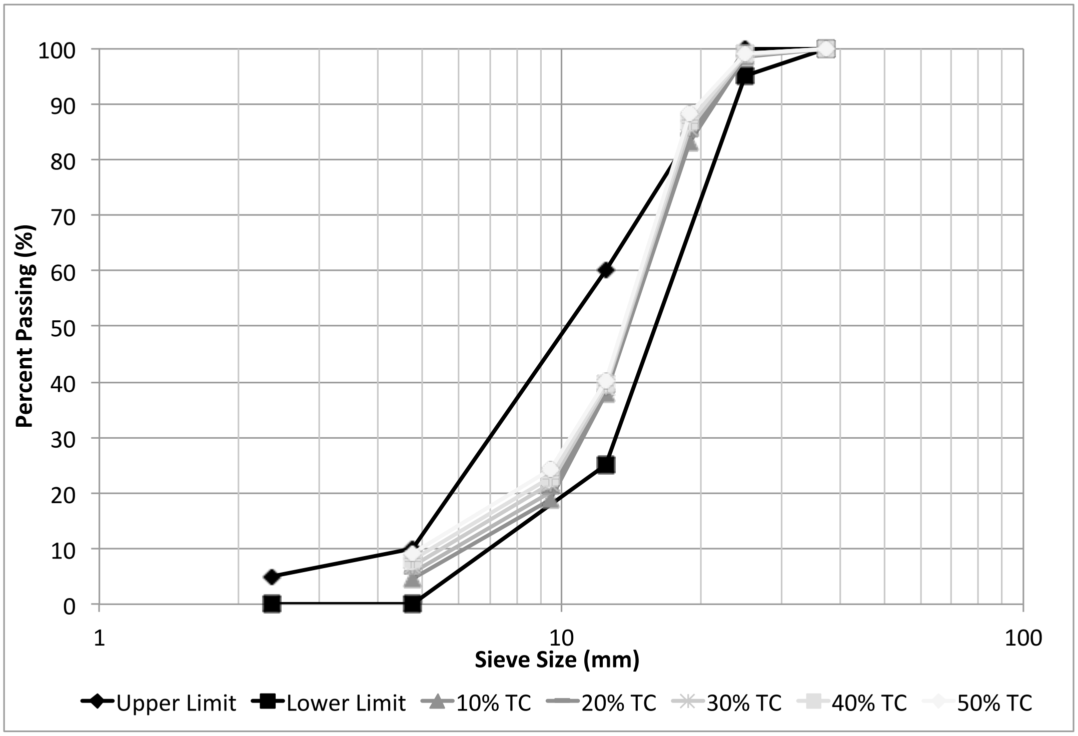


Figure 4-4. Gradations of Natural Rock and Tire Chip Aggregates at Various Replacement Levels

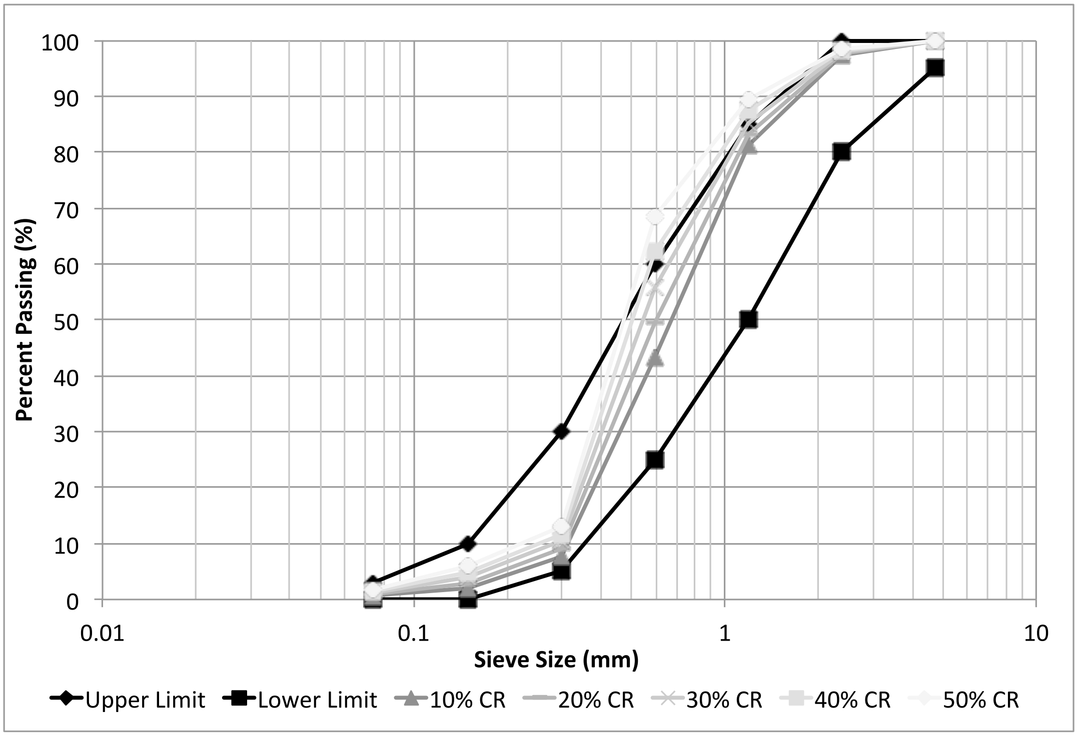


Figure 4-5. Gradations of Natural Sand and Crumb Rubber Aggregates at Various Replacement Levels

Depending on the type of tire and what it was used for during its service life, the physical properties of the rubber can differentiate. In many research articles that were reviewed, the specific gravity of the tire particles reported were in a large range of values. Determining the specific gravity of the rubber aggregates was a key step in the initial stages of the study. Because the absolute volume method was used to replace the virgin aggregates with tire chip and crumb rubber, it was important to determine an accurate ratio of the specific gravities between the materials in order to property proportion the mixtures. *ASTM C-127 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate* was adapted and used to determine these properties of the rubber aggregates for this study. Because some of the tire chips floated during the test, the tire chips were manually agitated until the rubber particles sunk to the bottom of water. The tire chip and crumb rubber aggregates were found to have a SG of 1.12, which is less than half the virgin coarse and fine aggregates reported as both being 2.65. The absorption capacity of the rubber particles was found to be 0.3%

4.4 | Chemical Admixtures

In this study, an air-entraining admixture (AEA) was used to maintain adequate air contents as defined by GDOT. Additionally, a high-range water-reducing admixture (HRWRA) and a viscosity modifying admixture (VMA) were used to ensure good consistency of the fresh concrete. The VMA was introduced during the 705 lb/yd^3 series due to some of the tire chips floating to the surface of the concrete cylinders after finishing. The VMA was able to suspend the rubber particles within the concrete matrix more effectively.

The typical dosages for these admixtures was 5-8 fl oz/cwt (326-522 mL/100 kg), 3-6 fl oz/cwt (196-391 mL/100 kg), and 0.5-5 fl oz/cwt (33-326 mL/100 kg) for the VMA, HRWRA, and AEA, respectively. This study served as a preliminary investigation into a larger study, thus the admixture dosages were altered throughout the process to ensure consistent fresh properties later on. Typically, 1.25 fl oz/cwt (81 mL/100 kg) of AEA, 8 fl oz/cwt (522 mL/100 kg) of VMA, and 4-6 fl oz/cwt (261-391 mL/100kg) of HRWRA was used in these mixtures. More HRWRA was used for mixtures with greater rubber contents because rubber reduces the workability of the concrete.

5.0 | EXPERIMENTAL DESIGN

5.1 | Design Plan

The primary objective of this research study was to find an optimized mixture utilizing recycled rubber aggregates from waste tires as a substitute for coarse aggregates in the construction of concrete barrier walls and other applications. The addition of rubber was intended to create a concrete mixture capable of absorbing greater impact loading than traditional concretes. The optimized concrete mixture satisfies the requirements of GDOT Class A fresh and hardened concrete properties. In addition, concrete mixtures will be compared with the GDOT Class B specification as to allow for other potential uses for the rubber-modified concrete. Previous research studies examining similar concepts uncovered the potential applications of this study where energy absorptivity would be advantageous. Though there is limited literature on the use of rubber modified concrete in barrier wall construction, the increase in toughness of the composite material is well documented. These studies assisted in the development of trial concrete mixtures and ultimately a recommended optimized mixture design.

5.2 | Batching of Concrete Mixtures

Rubberized concrete mixtures using tire chips and crumb rubber particles were batched and completed through trial mixture design and testing. The same mixture design process was used for all mixtures that were produced through this study. The procedures specified by ASTM C-192 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* dictated the processes followed for the mixtures batched during this study with few variations. The procedures were deviated from the standard when treatments were applied to the surface of the rubber particles in order to improve the bond between the rubber particles and the concrete paste.

5.2.1 | Batching Procedure for Each Mixture

The materials used for each mixture were weighed and stored in five gallon buckets sealed with lids prior to batching. These materials remained sealed in storage until mixing commenced. The cement was set aside in the laboratory along with the mixing water and stored to maintain temperatures in accordance with ASTM C-511. Extra water was set aside to account for fluctuations in moisture contents of the coarse and fine aggregates. Storing the aggregates beforehand in this manner was performed to ensure moisture contents of the materials would remain constant before mixing could take place.

5.2.2 | Preparation the Day before Batching Concrete Mixtures

Approximately 24 hours before batching of the mixtures, samples of both coarse and fine aggregate were weighed and oven dried in order to calculate the moisture content of the constituents. The samples were taken from the center of the aggregate buckets in order to measure an average aggregate moisture content. The drying process followed the procedures required by ASTM C-566 *Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying*. Once the moisture content was calculated, the oven-dried aggregates were returned to their respective buckets for use in the mixing process.

All of the necessary tools and equipment required to test the fresh concrete properties were gathered and prepared for testing the concrete mixtures. Additionally, any molds needed to prepare specimens for hardened concrete property tests at later ages were gathered and placed with the materials for the following day.

5.2.3 | Mixture Process

The procedures followed during the mixing process for this study met the guidelines set by ASTM C-192 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. Instead of “buttering” the mixer, the mixer was simply rinsed with water prior to batching. Once the water was drained from the mixer, the coarse and fine aggregates along with any recycled rubber aggregates were added to the mixer and allowed to blend for a total of ten minutes prior to the addition of any other components. The rubber was added with the virgin aggregates and allowed to mix in order to mechanically roughen the surface of the particles in an attempt to improve the adhesion between the rubber and the concrete materials. Before adding the mixing water to the mixture, admixtures were combined into the water and stirred. Upon completing the initial ten minutes of aggregate mixing, the cement was added to the mixer and allowed to blend with the aggregates. The purpose of this was to separate any large pieces of cement present in the bucket and prevent additional clumping of the mixture. This practice helped to prevent the cementitious materials from clumping and sticking to the sides of the mixer during the mixing process. Finally, the mixing water containing the admixtures used for the experiment was added to the other constituents. The concrete was allowed to mix for an additional five minutes. The total mixing time for each mixture was approximately fifteen minutes.

Once the mixing process was completed, the batch was discharged from the mixer into a dampened wheelbarrow to begin performing fresh properties tests on the concrete. Additionally, the concrete was cast into molds for hardened properties tests at later ages.

5.3 | Curing Concrete Specimens

Water tanks located in the materials testing laboratory include heaters and circulating pumps. The temperature in the water tanks is controlled and maintained within the limits of *ASTM C-511 Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes*. The storage tanks used for curing the concrete samples were maintained at a temperature ranging between 69.8°F and 77°F (21°C and 25°C). The tanks were not equipped with temperature recording or sensing devices; however, were checked manually on a daily basis to ensure compliance. The heating elements were managed manually to ensure that the temperature of the baths were within proper limits. Additionally, the water in the storage tanks were saturated with calcium hydroxide. The purpose of this is to prevent leaching of this chemical from the concrete specimens during the curing period. The water in the baths was constantly circulated using a pump, and the water stirred at least once a month to ensure that the lime was still effective. The specimens were added to the water tanks 24 hours after mixing, and remained in the tank until time of testing.

5.4 | Testing for Concrete Properties

The testing of the concrete specimens took place at two different times. The fresh concrete properties were tested and recorded in the concrete's fresh, or plastic state, while the hardened properties were measured after the concrete specimens solidified and gained strength. The hardened concrete properties were measured at time intervals specified by ASTM.

5.4.1 | Fresh Concrete Property Tests

Notable fresh concrete properties were tested and recorded for each mixture. The properties tested after mixing each sample included slump, air content, unit weight, and temperature. Fresh concrete properties are important because they are often indicators for concrete workability, fluidity, durability, and density. Table 5-1 provides the testing standard procedure followed for the testing of each fresh concrete property.

Table 5-1 Fresh Concrete Properties Tests

Fresh Concrete Tests	**Standard Identification**	**Testing Day**
Slump	*ASTM C-143*, AASHTO T 119	Batching Day
Temperature	*ASTM C-1064*, AASHTO T 309	Batching Day
Pressure Meter Air Content	*ASTM C-231*, AASHTO T 152	Batching Day
Unit Weight	*ASTM C-138*, AASHTO T 121	Batching Day

5.4.2 | Hardened Concrete Property Tests

The hardened concrete properties tests were completed in accordance with ASTM standards. In the first phase of the study, only concrete compressive strength tests were completed on the specimens. During the second phase of the research, additional tests were conducted to measure the mechanical and impact performance of each mixture. The tests completed during the second phase of the study include: compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, rapid chloride ion permeability, force-displacement (static energy dissipation capacity), and repeated drop-weight impact hammer test. Table 5-2 shows the standard identification and testing time for each hardened concrete test.

5.5 | Mixture Design Proportioning

The GDOT specifies minimum and maximum quantities and values for its Class A concrete. The minimum amount of cement was listed as 611 lb/yd^3, while the maximum water/cement ratio was 0.49. In addition, GDOT requires the use of either Size No. 56, 57, or 67 coarse aggregates. Furthermore, the minimum compressive strength for Class A concrete is listed as 3,000 psi

(20.7MPa), which served as the baseline strength for all mixtures. GDOT provides a range of 2 to 4 inches (50.8mm to 101.6mm) for slump and an entrained air content between 2.5 and 6%.

Table 5-2 Hardened Concrete Tests

Hardened Concrete Tests	**Standard Identification**	**Testing Day**
Compressive Strength	*ASTM C-39*, AASHTO T 22	1, 7, 28, 56 Days
Flexural Strength	*ASTM C-78*, AASHTO T 97	28, 56 Days
Splitting Tensile Strength	*ASTM C-494*, AASHTO T 198	28, 56 Days
Modulus of Elasticity	*ASTM C-469*	28, 56 Days
Permeability	*ASTM C-1202*, AASHTO T 227	28, 56 Days
Coefficient of Thermal Expansion	*ASTM E-831*	28 Days
Force-Displacement	None	28 Days
Impact Hammer Test	None	28 Days

The strategy for proportioning the mixture designs for this study was to maintain consistent batch sizes when the virgin aggregates were replaced with the recycled rubber aggregates. In order to accomplish this, the absolute volume method was utilized. Because of the use of the rubber aggregates, it was difficult to predict the hardened characteristics of the concrete mixtures. Mini-mixtures were designed, batched, and tested in order to establish a baseline for concrete strength characteristics as a function of cement and rubber content. The study began with twenty-four concrete mixture designs followed by seven additional mixtures that were analyzed and tested extensively. From the second phase of the study, adequate knowledge was gained such that recommendations regarding the use of recycled rubber in concrete mixtures for barrier wall and other concrete applications.

5.5.1 | Phase I - Trial Proportioned Research Mixtures

The first phase of the study began with a total of twenty-four trial mixtures. This phase included varying cement content as well as increasing the rubber content. Additionally, one series was used to examine the differences in concrete performance when using crumb rubber as compared to tire chips. Two additional mixtures were completed combining the use of crumb rubber and tire chips. Table 5-3 outlines the mixtures completed in the first phase of this study.

Table 5-3 First Phase Trial Mixture Design Matrix

Mixture ID	w/cm	Cementitious Content, lbs (kg)	% Sand Volume	% Crumb Rubber Volume	% Tire Chip Volume	% Coarse Aggregate
.42/611/100CA/0TC	0.42	611 (277)	100	0	0	100
.42/611/90CA/10TC	0.42	611 (277)	100	0	10	90
.42/611/80CA/20TC	0.42	611 (277)	100	0	20	80
.42/611/70CA/30TC	0.42	611 (277)	100	0	30	70
.42/611/60CA/40TC	0.42	611 (277)	100	0	40	60
.42/611/50CA/50TC	0.42	611 (277)	100	0	50	50
.42/660/100CA/0TC	0.42	660 (299)	100	0	0	100
.42/660/90CA/10TC	0.42	660 (299)	100	0	10	90
.42/660/80CA/20TC	0.42	660 (299)	100	0	20	80
.42/660/70CA/30TC	0.42	660 (299)	100	0	30	70
.42/660/60CA/40TC	0.42	660 (299)	100	0	40	60
.42/660/50CA/50TC	0.42	660 (299)	100	0	50	50
.42/705/100CA/0TC	0.42	705 (320)	100	0	0	100
.42/705/90CA/10TC	0.42	705 (320)	100	0	10	90
.42/705/80CA/20TC	0.42	705 (320)	100	0	20	80
.42/705/70CA/30TC	0.42	705 (320)	100	0	30	70
.42/705/60CA/40TC	0.42	705 (320)	100	0	40	60
.42/705/50CA/50TC	0.42	705 (320)	100	0	50	50
.42/660/90FA/10CR	0.42	660 (299)	90	10	0	100
.42/660/80FA/20CR	0.42	660 (299)	80	20	0	100
.42/660/70FA/30CR	0.42	660 (299)	70	30	0	100
.42/660/60FA/40CR	0.42	660 (299)	60	40	0	100
.42/660/90FA/10CR/95CA/5TC	0.42	660 (299)	90	10	5	95
.42/660/80FA/20CR/90CA/10TC	0.42	660 (299)	80	20	10	90

Key: w-cm/cement content/coarse aggregate content/tire chip content

The effect of cementitious content was evaluated by selecting three different quantities of cement when using recycled tire chip as the coarse aggregate replacement for this study: 611, 660, and 705 lb/yd^3 (362, 392, and 418 kg/m^3). The series of mixtures that investigated the use of crumb rubber as a sand replacement used only 660 lb/yd^3 (392 kg/m^3) of cement. Additionally, the mixtures that included a combination of crumb rubber and tire chips contained 660 lb/yd^3 (392 kg/m^3) of cement. Each mixture in the study maintained a constant w/c of 0.42. The target air content for each mixture was 5%, while the target slump was 3 inches (76.2mm). Chemical admixtures were utilized in attempt to achieve the ranges specified by GDOT. The quantities of each constituent is provided in Table 5-4

The knowledge and experience gained from producing these trial mixtures guided the design and batching for the second phase. The second phase included an extensive examination into the hardened concrete properties through the testing of seven rubberized concrete mixtures. Tire chips were solely utilized as a coarse aggregate replacement in percentages up to 20% in 10% increments using three different surface treatments designed to improve bonding between the rubber particle and cement paste.

5.5.2 | Mixture Design Identification

The mixture identification numbers for each of the specimens represents all of the relevant information regarding each mixture. For example, the first number (.42/611/100CA/0TC) represents the w/cm of the mixture. For the purposes of this study, the w/cm for all of the mixtures remained constant at 0.42. The second number in the identification number represents the cement content. For the example mixture, this number incorporates 611 lb/yd^3 (362.5 kg/m^3) of cement. The third number indicates the percentage of coarse aggregate or fine aggregate present in the sample. The letters "CA" indicate the number is referring to coarse aggregate, while the letters "FA" refer to the amount of fine aggregate in the mixture. Finally, the last number in the identification number refers to the percentage of tire chips or crumb rubber in the mixture.

Table 5-4. Trial Mixture Quantities

Mixture Identification	w/c	*Cement	*Coarse Aggregate	*Fine Aggregate	*Tire Chips	*Crumb Rubber	**AEA	**HRWRA	**VMA
.42/611/100CA/0TC	0.42	611 (362)	1800 (816)	952 (432)	0	0	0	3 (196)	0
.42/611/90CA/10TC	0.42	611 (362)	1620 (735)	952 (432)	76 (34)	0	0	3.5 (228)	0
.42/611/80CA/20TC	0.42	611 (362)	1440 (653)	952 (432)	152 (69)	0	0	3.5 (228)	0
.42/611/70CA/30TC	0.42	611 (362)	1260 (572)	952 (432)	228 (103)	0	0	5.5 (359)	0
.42/611/60CA/40TC	0.42	611 (362)	1080 (490)	952 (432)	304 (138)	0	0	7 (756)	0
.42/611/50CA/50TC	0.42	611 (362)	900 (408)	952 (432)	380 (172)	0	0	7 (756)	0
.42/660/100CA/0TC	0.42	660 (392)	1800 (816)	952 (432)	0	0	0	7 (756)	0
.42/660/90CA/10TC	0.42	660 (392)	1620 (735)	952 (432)	76 (34)	0	0	7 (756)	0
.42/660/80CA/20TC	0.42	660 (392)	1440 (653)	952 (432)	152 (69)	0	0	7 (756)	0
.42/660/70CA/30TC	0.42	660 (392)	1260 (572)	952 (432)	228 (103)	0	0	7 (756)	0
.42/660/60CA/40TC	0.42	660 (392)	1080 (490)	952 (432)	304 (138)	0	0	7 (756)	0
.42/660/50CA/50TC	0.42	660 (392)	900 (408)	952 (432)	380 (172)	0	0	7 (756)	0
.42/705/100CA/0TC	0.42	705 (418)	1800 (816)	952 (432)	0	0	1 (65)	8 (522)	8 (522)
.42/705/90CA/10TC	0.42	705 (418)	1620 (735)	952 (432)	76 (34)	0	1 (65)	7 (756)	8 (522)
.42/705/80CA/20TC	0.42	705 (418)	1440 (653)	952 (432)	152 (69)	0	1.25 (81)	4.5 (293)	8 (522)
.42/705/70CA/30TC	0.42	705 (418)	1260 (572)	952 (432)	228 (103)	0	1.25 (81)	4 (261)	8 (522)
.42/705/60CA/40TC	0.42	705 (418)	1080 (490)	952 (432)	304 (138)	0	1.25 (81)	5 (326)	8 (522)
.42/705/50CA/50TC	0.42	705 (418)	900 (408)	952 (432)	380 (172)	0	1.25 (81)	5.5 (359)	8 (522)
.42/660/90FA/10CR	0.42	660 (392)	1800 (816)	936 (425)	0	44 (20)	1.25 (81)	4 (261)	8 (522)
.42/660/80FA/20CR	0.42	660 (392)	1800 (816)	832 (378)	0	88 (40)	1.25 (81)	4 (261)	8 (522)
.42/660/70FA/30CR	0.42	660 (392)	1800 (816)	728 (330)	0	132 (60)	1.25 (81)	4 (261)	8 (522)
.42/660/60FA/40CR	0.42	660 (392)	1800 (816)	624 (283)	0	176 (80)	1.25 (81)	4 (261)	8 (522)
.42/660/90FA/10CR/95CA/5TC	0.42	660 (392)	1710 (776)	936 (425)	38 (17)	44 (20)	1.25 (81)	4 (261)	8 (522)
.42/660/80FA/20CR/90CA/10TC	0.42	660 (392)	1620 (735)	832 (378)	76 (34)	88 (40)	1.25 (81)	4 (261)	8 (522)

* lb/yd^3 (kg/m3)

** fl. oz/cwt (mL/100 kg)

The letters “TC” refers to tire chips while “CR” indicates that crumb rubber is used in the mixture. The final two mixtures in the trial mixture list have longer identification numbers resulting from the mixtures including rubber aggregates for both coarse and fine aggregate.

5.5.3 | Phase II – Research Mixture Designs

Because of environmental and economic factors, it was proposed that a cement content of 611 lb/yd^3 (362.5 kg/m^3) be used for the second phase large-scale mixtures. Cement is the most economically and environmentally taxing ingredient in concrete, thus it was important to limit these factors as much as possible. In addition, tire chips were selected as the only rubber aggregate used in the second phase of this study as a result of the tire chips being more cost effective to produce and purchase when compared to crumb rubber. Based on the first phase results, up to 20% replacement of coarse aggregate with tire chips was studied during the second phase of the project. Additionally, three surface treatments were utilized to study the bond between the rubber aggregates and the cement paste. The surface treatments that were examined included a mechanical roughening, sodium hydroxide and silane coupling agent to treat the surface of the rubber. The mixture design matrix is shown in Table 5-5.

Table 5-5 Second Phase Research Mixtures

Surface Treatment	Mixture ID	w/cm	Cementitious Content, lbs (kg)	% Tire Chip Volume	% Coarse Aggregate
None	.42/611/100CA/0TC	0.42	611 (277)	0	100
Mechanical	.42/611/90CA/10TC/M	0.42	611 (277)	10	90
Mechanical	.42/611/80CA/20TC/M	0.42	611 (277)	20	80
Sodium Hydroxide	.42/611/90CA/10TC/NaOH	0.42	611 (277)	10	90
Sodium Hydroxide	.42/611/80CA/20TC/NaOH	0.42	611 (277)	20	80
Silane Coating	.42/611/90CA/10TC/S	0.42	611 (277)	10	90
Silane Coating	.42/611/80CA/20TC/S	0.42	611 (277)	20	80

To perform the NaOH surface treatment, the tire chips were placed in a saturated bath of the chemical, and allowed to rest there for 20 minutes. After this duration, the tire chips were removed from the bath and rinsed with water and dried to room temperature. A similar procedure was used with the silane coupling agent; however, drying was performed through the use of a standard laboratory oven. Appropriate laboratory personal protection equipment was used when handling the solvents. The surface treatments were used on the rubber-modified concrete mixtures for replacement levels of 10% and 20% in order to determine the effect of the treatment on the bond between the rubber and concrete. The mixture proportions are presented in Table 5-6.

5.5.3.1 | Mechanical Abrasion Surface Treatment

The mechanical abrasion surface treatment of the recycled tire chips was completed at the time of mixing. Once all of the materials were weighed out and the mixing process was ongoing, the coarse and fine aggregates along with the recycled tire chips were added to the concrete mixer. All of the materials were mixed continuously for ten minutes before the addition of any other materials. The idea behind this surface treatment was that the friction between the natural aggregates and the tire chips would roughen the surface of the recycled tire chips, giving the rubber more surface area for the concrete mixture to bond to. Past research has indicated that the Interfacial Transition Zone (ITZ) between the cement matrix and the tire chips is the main point of weakness for rubberized concrete mixtures, so theoretically increasing the surface area of the ITZ will give the cement more area to bond to, improving the strength of the bond between the rubber and the concrete matrix.

Table 5-6. Research Mixture Quantities

Mixture Identification	w/c	*Cement	*Coarse Aggregate	*Fine Aggregate	*Tire Chips	**AEA	**HRWRA	**VMA	Rubber Treatment
.42/611/100CA/0TC	0.42	611 (362)	1800 (816)	952 (432)	0	1.25 (81)	7 (756)	8 (522)	None
.42/611/90CA/10TC/M	0.42	611 (362)	1620 (735)	952 (432)	76 (34)	1.25 (81)	7 (756)	8 (522)	Mechanical
.42/611/80CA/20TC/M	0.42	611 (362)	1440 (653)	952 (432)	152 (69)	1.25 (81)	7 (756)	8 (522)	Mechanical
.42/611/90CA/10TC/NaOH	0.42	611 (362)	1620 (735)	952 (432)	76 (34)	1.25 (81)	7 (756)	8 (522)	Sodium Hydroxide
.42/611/80CA/20TC/NaOH	0.42	611 (362)	1440 (653)	952 (432)	152 (69)	1.25 (81)	7 (756)	8 (522)	Sodium Hydroxide
.42/611/90CA/10TC/S	0.42	611 (362)	1620 (735)	952 (432)	76 (34)	1.25 (81)	7 (756)	8 (522)	Silane Coating
.42/611/80CA/20TC/S	0.42	611 (362)	1440 (653)	952 (432)	152 (69)	1.25 (81)	7 (756)	8 (522)	Silane Coating

* lb/yd^3 (kg/m3)

** fl. oz/cwt (mL/100 kg)

5.5.3.2 | Sodium Hydroxide Surface Treatment

The sodium hydroxide used in this research was a 98% pure sodium hydroxide provided by Pro Supply Outlet. While this chemical is listed as a food grade product, it showed to be as effective as lab grade sodium hydroxide products that were used earlier in this research. Saturated sodium hydroxide solution surface treatments have shown to eat away at the surface of the rubber aggregates, providing a rougher surface texture. Similar to the mechanical abrasion surface treatment, the use of a sodium hydroxide soak increases the surface area of the ITZ, helping to bond the rubber particles to the cement paste.

To apply this treatment, a saturated sodium hydroxide solution was first prepared. To create this, 111 grams of NaOH for every 100 milliliters of water was mixed together. For each mixture, about 10 liters of saturated sodium hydroxide solution was prepared. Once the solution was created, the tire chips to be used in the concrete mixture were added to the NaOH solution and stirred continuously for 20 minutes. Once the treatment was applied to the rubber, the tire chips were removed from the solution, and the surface was rinsed with water. The tire chips were then completely dried prior to adding them to the concrete mixtures.

While applying this treatment, it is important to wear appropriate laboratory personal protection equipment. Saturated sodium hydroxide is a highly caustic base, and can leave chemical burns when exposed to skin. For this research, long sleeves, gloves, and eye protection were worn when handling this chemical.

5.5.3.3 | Silane Coupling Agent Surface Treatment

Silane coupling agents are used to bond inorganic and organic materials together through strong chemical bonds. They are silicon-based chemicals that contain inorganic and organic reactivity within the same molecule. The agent acts as an interface between an inorganic substrate, like glass or metal, and an organic material such as an organic polymer, coating, or adhesive. The general structure of the silane coupling agent molecule is $(RO)_3SiCH_2CH_2CH_2$-X where “RO is a hydrolyzable group, such as methoxy, ethoxy, or acetoxy, and X is an organofunction group, such as amino, methacryloxy, epoxy, etc.” [A Guide to Silane Solutions, 2009]. A silane can be a very diverse molecule, but the common denominator is the existence of a central silicon atom with four attachments. The combinations of these attachments give the chemical its defining characteristics, making the groups nonreactive, inorganically reactive, or organically reactive. Silanes are small molecules, which allows for the chemical to penetrate the substrates and create strong bonds [Limitless Silanes, 2017].

The silane coupling agents that were used in this study were XIAMETER OFS-6020 Silane and XIAMETER OFS-6040 Silane. The material properties of each are presented in Tables 5-7 and 5-8, respectively. Both of these solutions can be used as either a primer or an additive to promote adhesion. It is recommended that when these substances are used as a primer, that they be diluted down to a concentration of 1.0%. If they are being used as an additive, the typical concentration should be 0.5-2.0% for the OFS-6020 and 0.05-3.0% for the OFS-6040. Both of the solutions can be diluted in alcohols and water [Coatings & Inks Additive Selection Guide, 2017]. The benefits of using these products are that they improve adhesion, and compressive, tensile, and flexural strengths [msds for 6040 and 6020, 2017].

To apply the silane coupling agent surface treatments, both products were completely mixed together at a 1:1 ratio by weight. This solution was then diluted in an aqueous solution by adjusting the pH of water to 4.5 using acetic acid and adding the silane at a concentration of 1.0%. This new aqueous solution was then mixed for a duration of 15 minutes to ensure a homogenous substance. It is imperative that this diluted solution be used within 24 hours of being prepared because the XIAMETER OFS-6040 is not indefinitely stable in water and older solutions will begin to show a slight haze.

Table 5-7. Material Properties of XIAMETER OFS-6040 Silane

Test	Unit	Value
Appearance		Clear liquid
Color	APHA	50
Viscosity	cst	3
Specific gravity at 25°C (77°F)		1.07
Refractive index		1.428
Flash point-closed cup	°C (°F)	>101 (>213)
Purity by GC	%	>98.5
Chloride	ppm	<10
Molecular weight	g/mol	236.34
CAS #		2530-83-8

Table 5-8. Material Properties of XIAMETER OFS-6020 Silane

Test	Unit	Value
Appearance		Clear liquid
Flash point-closed cup	°C (°F)	85 (185)
Specific gravity at 25°C (77°F)	°C (°F)	1.03
Refractive index		1.445
Neutral equivalents	g/eq	115
Color		Light straw
Viscosity	mm2/s	5

Once this diluted silane solution was created, the previously weighed tire chips for the mixture were added to the solution and stirred for 20 minutes to completely coat the surface of the tire chips. Once this was completed, the tire chips were removed from the solution and dried in a standard laboratory oven heated to a temperature between 221° and 248°F (105° and 120°C) for 12 hours. This drying process completes the condensation of the silanol groups at the surface of the rubber while also removing any moisture that may be present on the rubber aggregates. After the drying is completed, the tire chips are added to the mixer at time of batching and the mixing process continues using normal procedures.

Similar to when performing the NaOH surface treatment, it is important to adhere to proper safety precautions when handling both of these silane coupling agents. When using both of these products, it is necessary to wear eye and face protection, because the products have the danger of causing serious eye damage. Additionally, XIAMETER OFS-6020 Silane is a combustible liquid, can potentially cause skin irritation, and could be harmful to inhale. While performing this surface treatment, long sleeves, gloves, safety glasses, and a face shield were always used. Additionally, it was important to either handle these chemicals outside, or in a well ventilated area. If these conditions are not possible, respiratory protection should be used. Additionally, these chemicals should be kept away from any sort of fire hazard.

5.6 | Data Analysis and Design Summary

The experimental design for this study allowed for the researchers to investigate the effect of cement content and rubber particle size on the fresh concrete properties and compressive strength of rubber-modified concrete mixtures. Further investigation was performed to more comprehensively understand the mechanical performance of the rubberized concrete when subjected to other forms of loading, specifically impact. The test results from the first phase of this study were compared to previous work performed on this topic to see if trends were predominantly similar. Ultimately, results from the second phase of the study are used to provide recommendations to GDOT regarding the use of rubberized concrete mixtures for barrier wall construction in Georgia. Additionally, the results from this study may be used to provide recommendations regarding the use of tire chips and/or crumb rubber for use in alternative concrete construction.

6.0 | EXPERIEMNTAL RESULTS

6.1 | Trial Mixtures

6.1.1 | Batching of Trial Mixtures

The batching of trial mixtures with rubber contents ranging up to 50% were completed as the initial investigation of this study. This process was completed for mixtures with 611, 660, and 705 lb/yd^3 (362, 392, and 418 kg/m^3) of cement. Additionally, a series of mixtures with 660 lb/yd^3 (391.6 kg/m^3) of cement was completed that included a fine aggregate replacement with crumb rubber. Further, two mixtures with a combination of crumb rubber and tire chips were batched in the preliminary investigation. Because the w/cm remained constant throughout the study, the mixtures will be referred to as its shorthand mixture identification name throughout the remainder of the report. For instance, 660TC20 will be used to refer to the mixture with 660 lb/yd^3 (391.6 kg/m^3) of cement and 20% tire chip replacement.

6.1.2 | Fresh Concrete Properties of Trial Mixtures

The primary objectives of designing and testing the trial batches was to determine the appropriate dosages needed for the design of the larger scale rubberized concrete mixtures as well as to establish the limits of aggregate replacement with rubber and meet the GDOT specifications. The concrete properties measured included slump, air content, unit weight, and temperature. Table 6-1 provides the fresh concrete properties results from the trail mixtures.

A Viscosity Modifying Admixture (VMA) was used during later mixtures included in the trail batching sequence as a result of the tire chips floating to the top of the concrete specimens after fabrication. This phenomenon resulted in the cylinder tops being uneven and creating a level of difficulty when testing specimens for compressive strength. The VMA improved the mixtures by helping to suspend the rubber particles within the specimens and prevented the tire chips from floating to the tops of the cylinders. Further, the HRWRA dosages increased with the increased amounts of rubber particles because of the recycled aggregate's effect on the workability. As the literature suggested, increasing rubber content reduces the workability of concrete mixtures. This was accounted for when specifying dosages for HRWRA in the second phase of the study. Additionally, the brand of HRWRA that was used for early trial mixing was switched for later mixtures because of a consequential effect of entraining air without the use of an AEA.

Table 6-1 Fresh Concrete Properties in Trial Mixtures

Mix Name	Slump, in (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %
611TC0	2.50 (63.5)	144.6 (2,316)	4.9
611TC10	0.00 (0.0)	140.0 (2,242)	3.8
611TC20	0.50(12.7)	137.6 (2,204)	4.2
611TC30	0.25 (6.4)	134.0 (2,147)	4.9
611TC40	1.00 (25.4)	129.8 (2,079)	4.5
611TC50	0.50 (12.7)	125.6 (2,012)	4.1
660TC0	5.50 (139.7)	149.2 (2,390)	2.5
660TC10	3.50 (88.9)	145.0 (2,323)	3.8
660TC20	1.00 (25.4)	138.8 (2,224)	4.5
660TC30	2.50 (63.5)	133.4 (2,137)	4.5
660TC40	3.50 (88.9)	126.4 (2,025)	5.0
660TC50	1.50 (38.1)	124.2(1990)	4.5
705TC0	5.50 (139.7)	144.3 (2,312)	5.5
705TC10	6.50 (165.1)	143.0 (2,291)	6.5
705TC20	7 .00 (177.8)	129.2 (2,070)	8.5
705TC30	1.00 (25.4)	132.0 (2,115)	4.8
705TC40	0.50 (12.7)	129 .0 (2,067)	4.5
705TC50	2.50 (63.5)	120.2 (1,930)	6.5
660CR10	0.50 (12.7)	141.2 (2,262)	5.3
660CR20	2.00 (50.8)	139.2 (2,230)	4.5
660CR30	1.50 (38.1)	138.6 (2,220)	5.0
660CR40	1.00 (25.4)	136.2 (2,182)	5.5
660CR50	0.00 (0.0)	124.2 (1,990)	7.0
660CR10TC5	0.00 (0.0)	137.0 (2,1950	5.0
660CR20TC10	0.00 (0.0)	133.0 (2,131)	4.5

6.1.2.1 | Slump

The target slump for all mixtures was between 2 and 4 inches (50.8mm to 101.6mm), per GDOT requirements. Because these mixtures were used as small-scale trial batches for the large-scale study, the admixture dosages were adjusted accordingly to approach the acceptable range per the standards. Previous literature indicated that higher rubber contents resulted in lower workability, thus HRWRA dosages were adjusted in order to combat this issue. Figure 6-1 shows the slump results for each of the mixtures performed for this study.

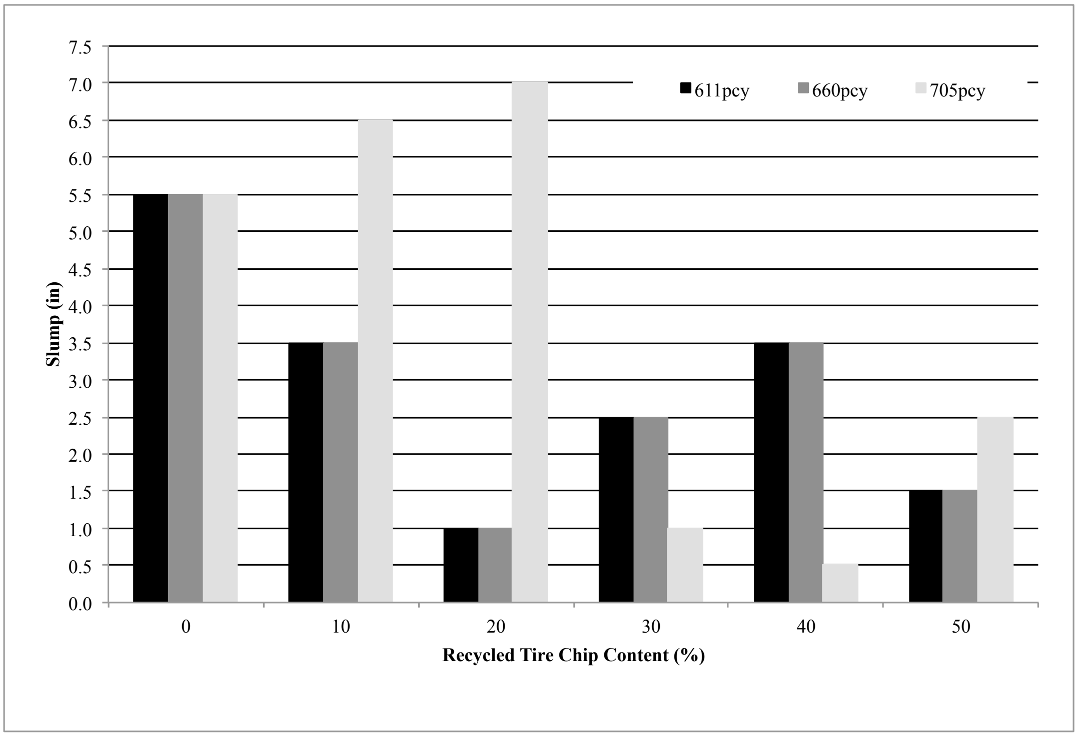


Figure 6-1. Slump Results for Trial Tire Chip Mixtures

While the slump results were outside the target slump range for some mixtures, the more important concern was a consistent and consolidated concrete mixture that could be placed with relative ease. Even though the slump measurement was low for several mixtures, especially mixtures with 20% replacement of coarse aggregate with tire chips, the problem could be easily overcome with a higher HRWRA dosage.

The study results show a decrease in slump for both the 611 lb/yd^3 and 660 lb/yd^3 (362 and 392 kg/m^3) mixtures up to a 20% replacement of coarse aggregate for tire chips. This was mitigated using a higher dosage of HRWRA going forward ultimately improving the workability of the future mixtures. Additionally, for the 705 lb/yd^3 (418 kg/m^3) cement mixtures, a VMA was added to improve the consistency of the concrete and reduce the rubber particles from floating to the surface of the specimens once they were fabricated. After the high initial slumps experienced by the 705TC10 and 705TC20 mixtures, the HRWRA dosages were adjusted and thereby reducing the workability.

Crumb rubberized concrete mixtures exhibited similar erratic slump results to that of the tire chip. The same dosage of HRWRA was used for all crumb rubber mixtures. The 10% replacement produced the lowest slump at 0.5 in (12.7mm). The remaining mixtures decreased linearly from 2 in. (50.8mm). Two mixtures using a combination of tire chips and crumb rubber as a replacement for coarse and fine aggregate, respectively, produced a slump of 0 in. The slump results for the CR and combination mixtures are shown in Figure 6-2.

6.1.2.2 | Air Content

No AEA was utilized for the 611 and 660 lb/yd^3 (362 and 392 kg/m^3) series mixtures due to appropriate air contents being attained with only the use of a HRWRA. The HRWRA was changed for the 660TC and 705TC mixture series requiring small AEA dosages in order to achieve the desired air content of 2.5-6%, as required by GDOT for Class A concrete mixtures. Previous literature indicated that concrete mixtures with higher rubber contents typically produced higher air contents, thus small AEA dosages were used to ensure that the air contents would not to exceed the required maximum.

The air contents of the concrete mixtures utilizing tire chips as a replacement for coarse aggregates saw air contents generally ranging between 2 and 5%, though two mixtures had higher air contents, with 705TC20 reaching as high as 8.5%. See Figure 6-3.

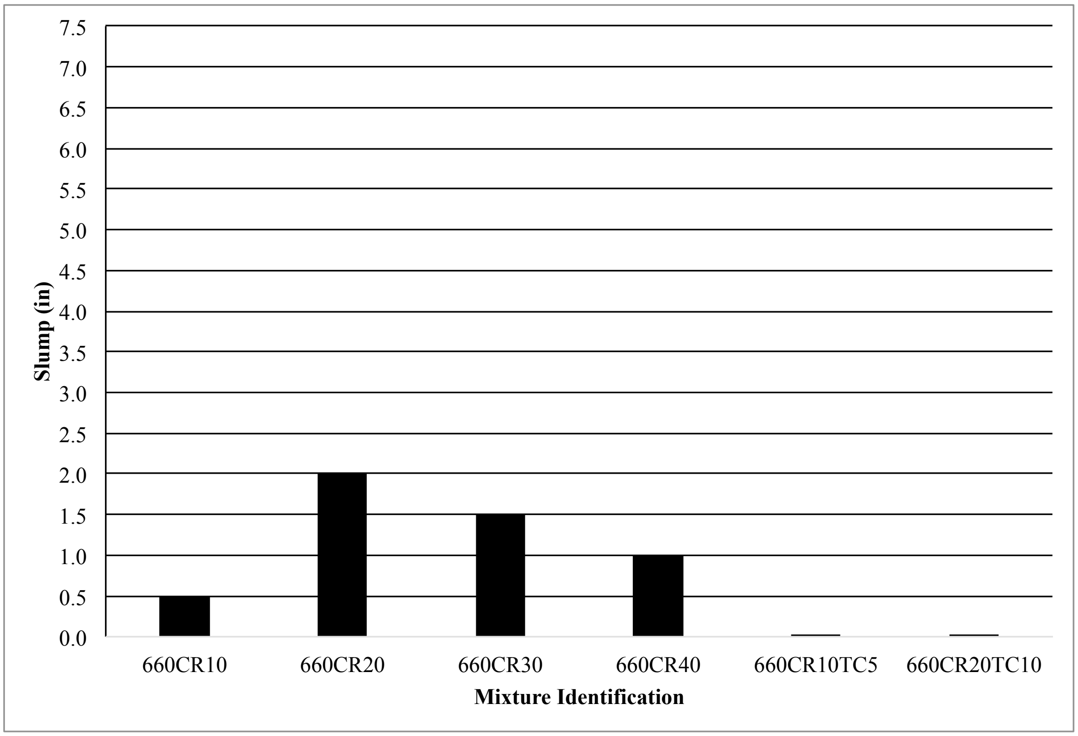


Figure 6-2. Slump Results for Trial Crumb Rubber and Combination Mixtures

An AEA was not used until the 705 lb/yd^3 (418 kg/m^3) series began. The 705TC0 and 705TC10 used a low AEA dosage of 1 fl oz/cwt and had air contents below the GDOT requirement; however, this was accounted for by increasing the dosage slightly to 1.25 fl oz/cwt for the remaining 705 lb/yd^3 mixtures. The air contents for the CR and combination mixtures remained consistent between 4.5% and 5.5% regardless of rubber content. In general, the results of the air content tests showed higher air contents being produced with greater amounts of tire chips and crumb rubber.

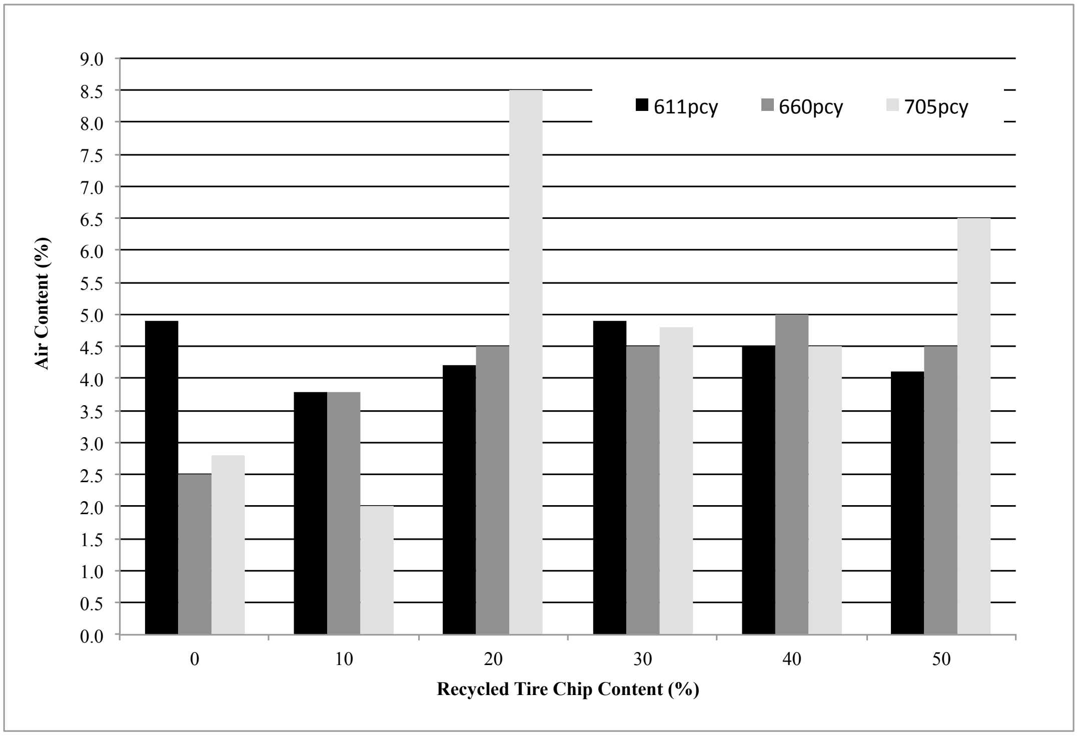


Figure 6-3. Air Content Results for Trial Tire Chip Mixtures

6.1.2.3 | Unit Weight

The unit weight was measured while the concrete was fresh by the methods defined in ASTM C138. The design unit weights for the mixtures replacing coarse aggregates with tire chips ranged between 119.8 lb/ft^3 and 140.9 lb/ft^3 (1,919 kg/m^3 and 2,257 kg/m^3) while the design unit weights for the crumb rubber mixtures ranged between 131 lb/ft^3 and 137.7 lb/ft^3 (2,098 kg/m^3 and 2,205 kg/m^3). The design unit weights for the combination mixtures 660CR10TC5 and 660CR20TC10 were 135.7 lb/ft^3 and 131.6 lb/ft^3 (2,174 kg/m^3 and 2,108 kg/m^3), respectively. The rubberized concrete mixtures' had lower than normal unit weights as a result of the property's dependency on the mixture constituent's specific gravities as well as air content. The study mixtures produced a 3.85 lb/ft^3 (61.7 kg/m^3) decrease in unit weight for each 10% increase in tire chips. The crumb rubber mixtures decreased by 2.25 lb/ft^3 (36.0 kg/m^3) for each 10% increase in crumb rubber replacement. The measured unit weights decreased nearly linearly with increased rubber contents. The experimental unit weight results are shown in Figures 6-4 and 6-5 for the tire chips and crumb rubber mixtures, respectively.

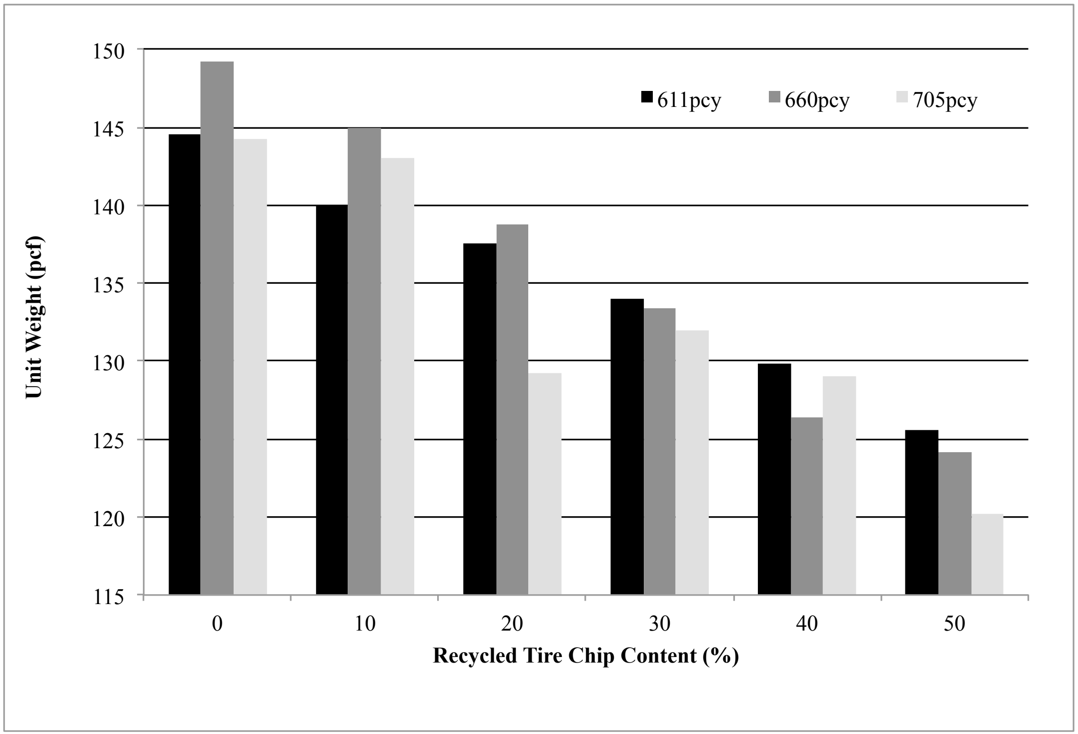


Figure 6-4. Unit Weight Results for Trial Tire Chip Mixtures

6.1.2.4 | Temperature

Concrete temperature is an important characteristic to consider when placing concrete because it is highly dependent on the environment during its plastic state. Previous studies have found that the ideal temperature to batch and place concrete ranges between 50 and 60°F and should not exceed 85°F. This is important because greater temperatures can speed up the cement hydration process as well as lead to the evaporation of water within the concrete mixtures. All of the temperatures recorded during the production of the mixtures for this study were below this maximum temperature.

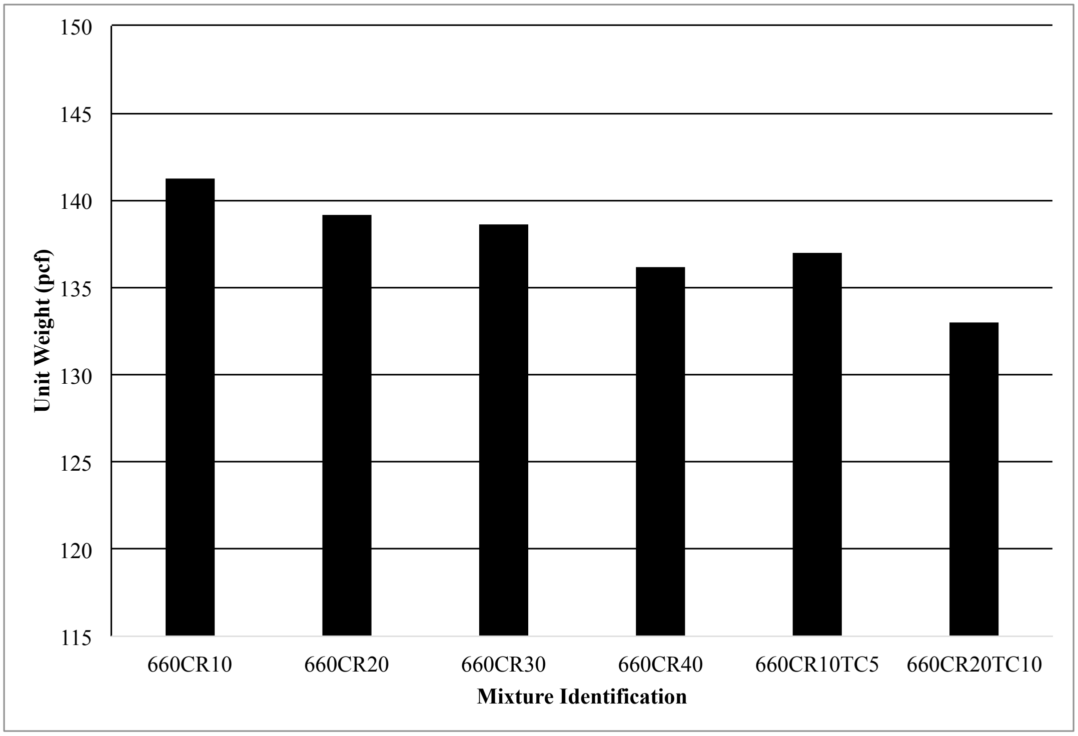


Figure 6-5. Unit Weight Results for Trial Crumb Rubber and Combination Mixtures

6.1.3 | Hardened Concrete Properties of Trial Mixtures

6.1.3.1 | Compressive Strength

Ultimately, the compressive strength of the rubberized concrete mixtures was the deciding factor as to its acceptability as a GDOT Class A concrete. Each mixture's compressive strengths were recorded at 1, 7, and 28 days of age in accordance with ASTM C39. Nine cylinders measuring 4 in by 8 in (100 mm by 200 mm) were fabricated for each mixture. Requirements specified by GDOT state that Class A concretes must reach an average 28-day compressive strength of 3,000 psi (20.7MPa). In addition, the compressive strengths were compared to the GDOT Class B concrete mixture requirements to determine whether the mixtures could be used for other applications where compressive strength was not as critical. GDOT Class B concrete fresh property requirements are identical to those of the Class A specification; however, the acceptable compressive strength minimum is only 2,200 psi (15.2 MPa) at 28 days.

The compressive strengths for the rubberized concrete mixtures were compared against the control mixture for each cement content as well as the benchmark value for GDOT Class A and B concrete. The average compressive strengths for tire chip, crumb rubber, and combination mixtures at 1, 7, and 28 days of age are listed in Table 6-2.

Table 6-2. Average Compressive Strength of Trial Rubberized Concrete Mixtures

Mixture Identification	1 Day	7 Day	28 Day	Average Percent of 28 Day Strength by 7 Days of Age
	psi (Mpa)	psi (Mpa)	psi (Mpa)	%
611TC0	1837 (13)	5295 (37)	6613 (46)	80
611TC10	1367 (9)	3179 (22)	3226 (22)	75
611TC20	438 (3)	1696 (12)	1835 (13)	
611TC30	385 (3)	820 (6)	1773 (12)	
611TC40	225 (2)	523 (4)	758 (5)	
611TC50	101 (0.7)	343 (2)	497 (3)	
660TC0	2095 (14)	2908 (20)	5109 (35)	57
660TC10	1425 (10)	2361 (16)	3585 (25)	67
660TC20	731 (5)	2471 (17)	2629 (18)	
660TC30	934 (6)	1345 (9)	1755 (12)	
660TC40	643 (4)	634 (4)	1279 (9)	
660TC50	542 (4)	333 (2)	660 (5)	
705TC0	3351 (23)	6184 (43)	7505 (52)	82
705TC10	2488 (17)	4271 (29)	4852 (33)	106
705TC20	463 (3)	1682 (12)	1792 (12)	
705TC30	565 (4)	1810 (12)	2050 (14)	
705TC40	414 (3)	1590 (11)	1196 (8)	
705TC50	158 (1)	811 (6)	628 (4)	
660CR10	2239 (15)	5194 (36)	6490 (45)	80*
660CR20	1821 (13)	4364 (30)	5191 (36)	
660CR30	1189 (8)	3313 (23)	4088 (28)	
660CR40	937 (6)	2653 (18)	3456 (24)	
660TC5CR10	1560 (11)	3968 (27)	5229 (36)	85*
660TC10CR20	688 (5)	2922 (20)	3136 (22)	

* Compared to the 660TC0 mixture

On average, concrete mixtures including rubber of any type and combination proved to gain a higher percentage of the 28 day strength within 7 days of age when compared to mixtures without rubber. The average rate of 7 day strength gain is listed in Table 6-2 and compared to the control for each mixture series (i.e., 611, 660, and 705 lb/yd^3 (362, 392, and 418 kg/m^3)). With the exception of the 611 lb/yd^3 (362 kg/m^3) mixture series, the average rate of strength gain by 7 days of age was approximately 10-20% higher than the control. The 611TC30 mixture exhibited a much lower rate of strength gain when compared to other tire chip mixtures resulting in a change from this trend.

Figure 6-6 and 6-7 shows the composite results for the compressive strength of tire chip and crumb rubber concrete mixtures, respectively. In addition, Figures 6-8, 6-9, 6-10, and 6-11 show the compressive strength vs. age for the 611, 660, and 705 lb/yd^3 (362, 392, and 418 kg/m^3) tire chip and 660 lb/yd^3 (392 kg/m^3) crumb rubber and combination mixtures, respectively. Regardless of cement content, a maximum of 10% coarse aggregate replacement with TC could be used in order to satisfy the required 28-day compressive strength of 3,000 psi. However, replacing up to 40% of the sand volume with crumb rubber met the appropriate specifications. Further, it was determined that adequate strengths could be reached with a 20% replacement of fine aggregate with crumb rubber in conjunction with a 10% replacement of coarse aggregate with tire chip. Overall, the compressive strengths generally decreased with higher rubber contents. The increased cementitious content did improve the compressive strength of the tire chip mixtures up to 30% replacement; however, had little influence in mixtures with higher rubber contents. While improvement was made with increasing cement content and lower tire chip content, similar to the GDOT Class A, the lesser GDOT Class B requirement was not satisfied for mixtures with greater than 10% tire chips.

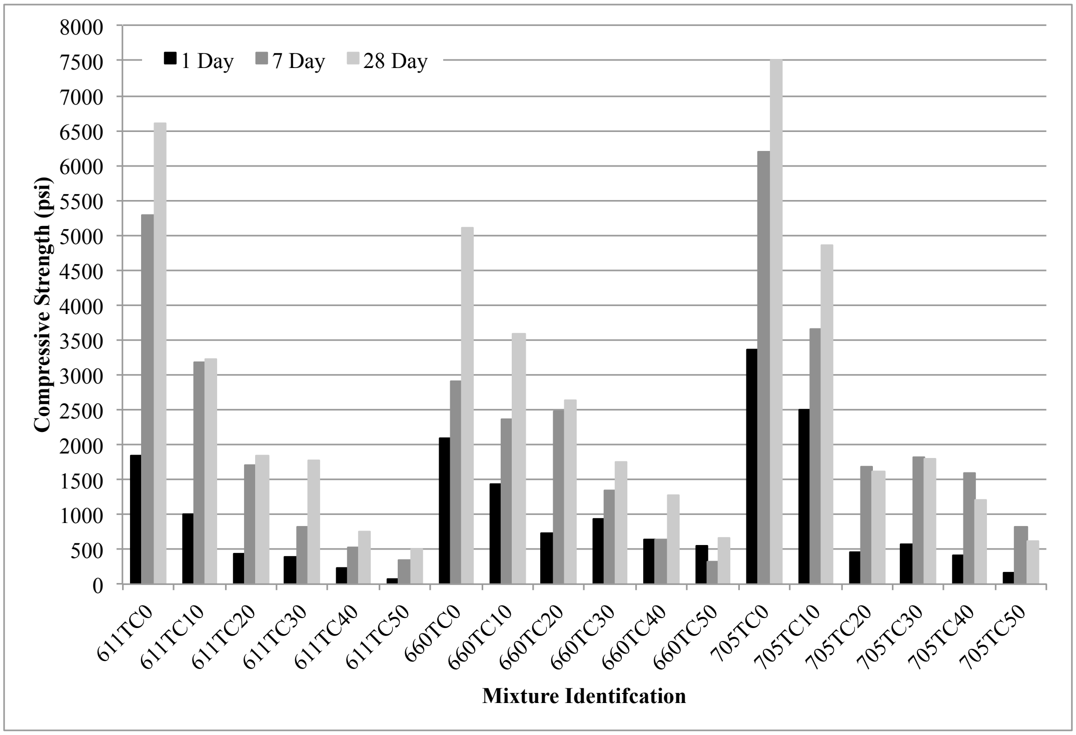


Figure 6-6. Compressive Strength Results for Trial Tire Chip Mixtures.

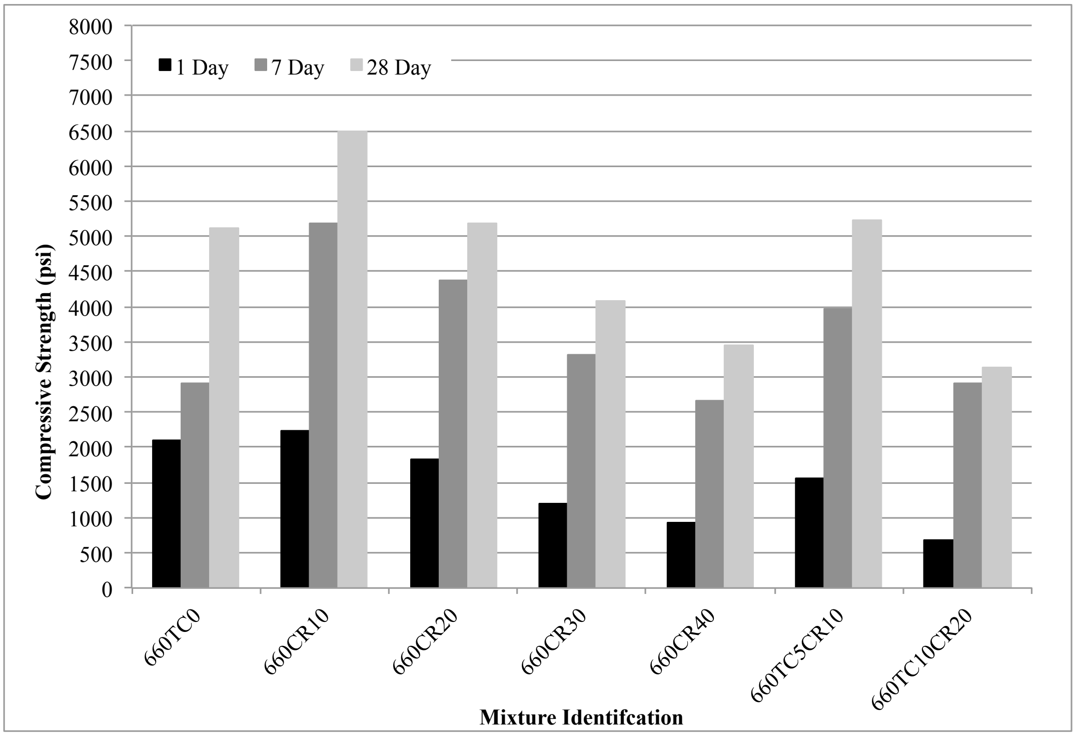


Figure 6-7. Compressive Strength Results for Trial Crumb Rubber and Combination Mixtures.

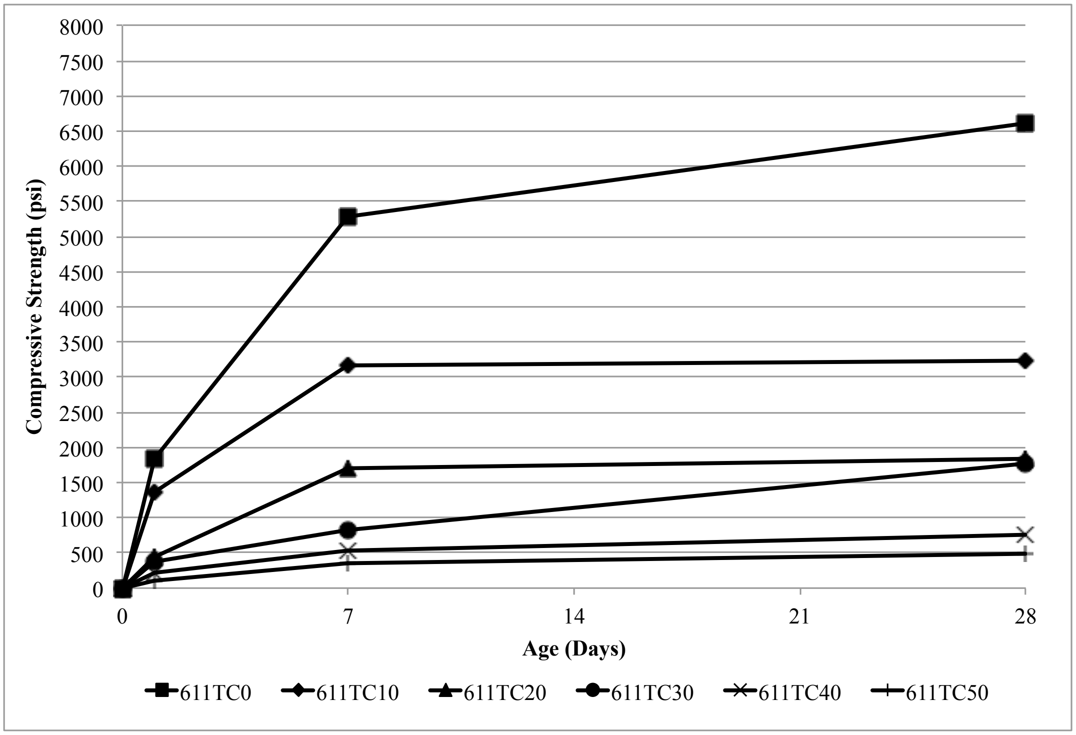


Figure 6-8. Compressive Strength vs. Age for 611 lb/yd^3 (362 kg/m^3) Trial Series

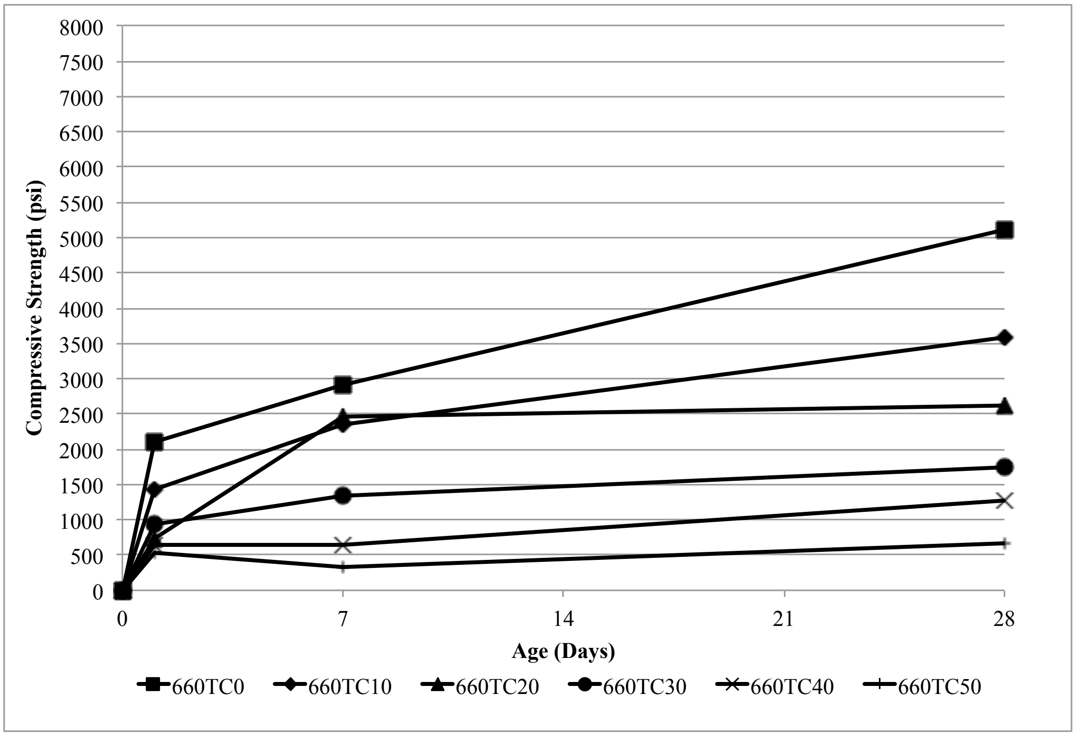


Figure 6-9. Compressive Strength vs. Age for 660 lb/yd^3 (392 kg/m^3) Trial Series

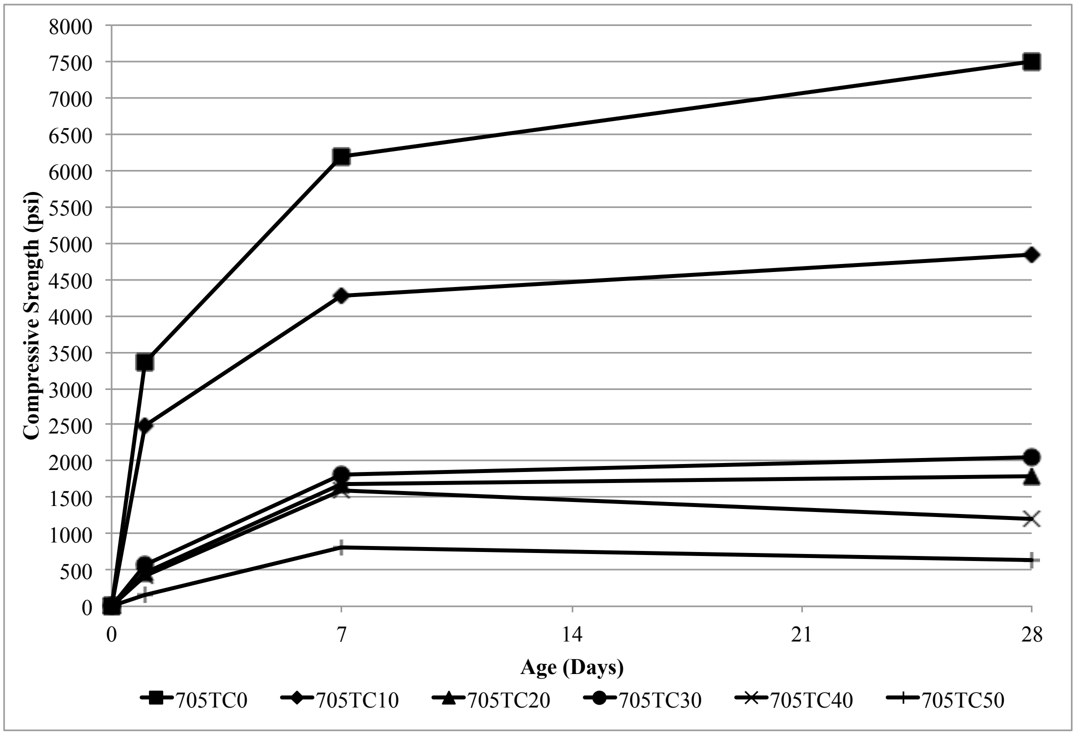


Figure 6-10. Compressive Strength vs. Age for 705lb/yd^3 (418kg/m^3) Trial Series

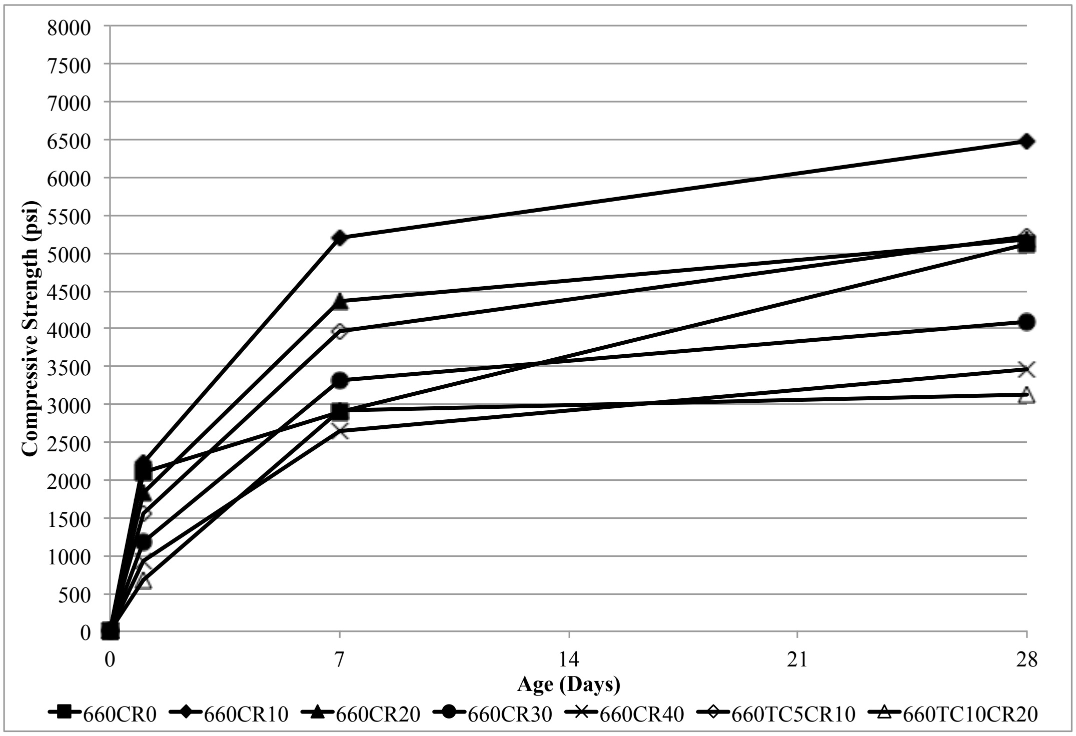
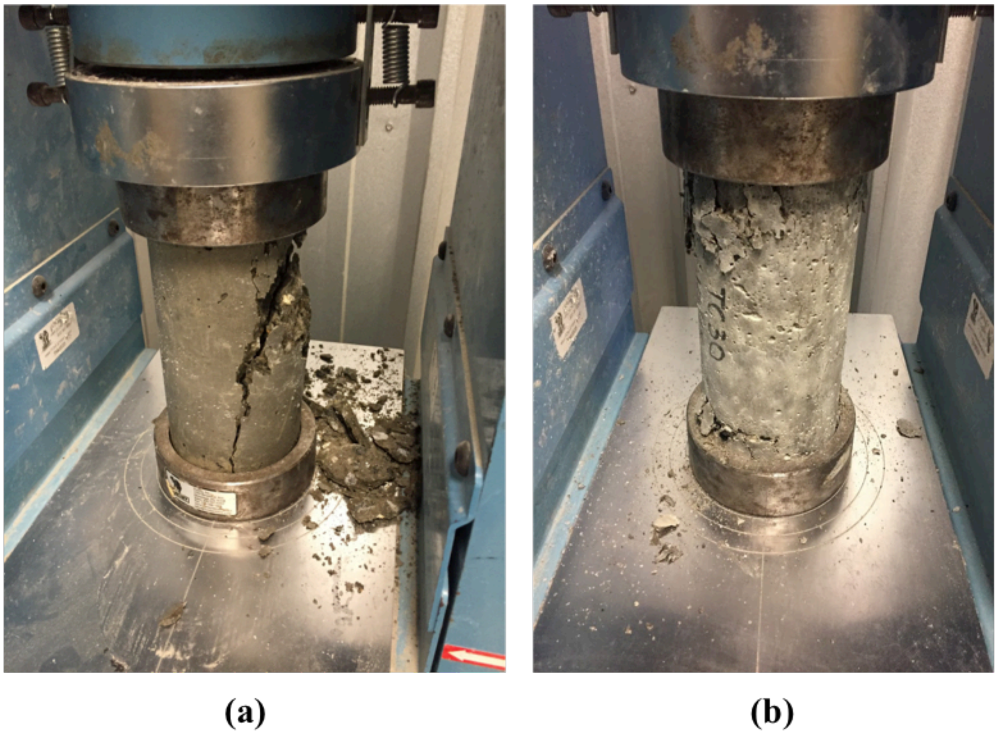


Figure 6-11. Compressive Strength vs. Age for 660 lb/yd^3 (392 kg/m^3) Trial Crumb Rubber and Combination Mixtures

The failure mechanism of the rubber modified concrete was very different than that of the control mixtures. Ordinary concrete mixtures failed abruptly, often splitting down the center of the cylinder; however, the rubberized concrete mixtures crushed during failure. The cylinders containing tire chip in particular typically remained almost entirely intact, with the pieces of rubber bridging the cracks and holding the broken concrete pieces together. Figure 6-12 shows a failed conventional and rubberized concrete cylinders to illustrate this behavior.



(a) (b)

Figure 6-12. Failed (a) Control and (b) 30%TC Concrete Specimens

6.1.3.2 | Effect of Cement Content on Rubberized Concrete

Illustrated in this study, the volume of rubber included as an aggregate replacement will significantly affect the concrete's compressive strength. However, this phenomenon is not a linear relationship. As shown in Figure 6-13, the compressive strength differential at higher rubber volumes (i.e., 25-30% of total aggregate volume) becomes much smaller compared to lower rubber contents (5-10% of total aggregate volume). Additionally, increased cement content will provide higher compressive strengths for the same rubber volume at low replacement levels, but becomes less of a factor at higher rubber contents. This is best illustrated by the trend lines shown in Figure 6-14.

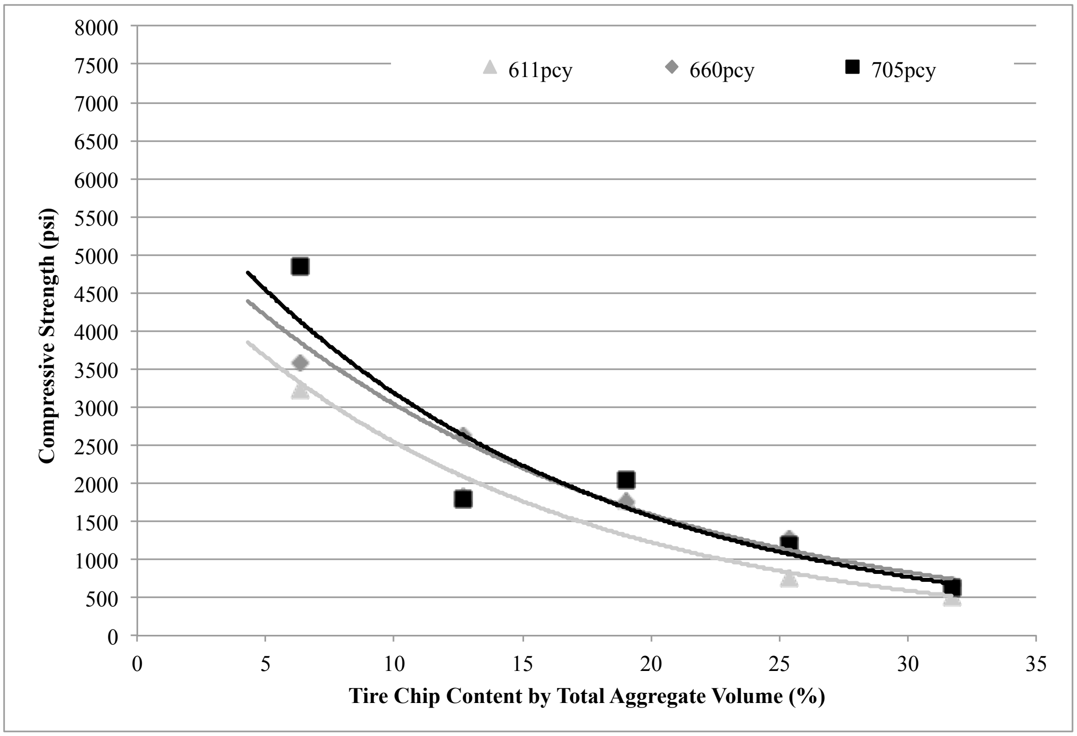


Figure 6-13. Effect of Cement Content on Rubberized Concrete Compressive Strength

6.1.3.3 | Rubber Particle Size on Concrete Strength

While cement content influences the overall compressive strength of rubberized concrete mixtures, the rubber particle size will have a more influential effect the concrete's performance. This study produced concrete mixtures that incorporated a coarse aggregate replacement with tire chip of a similar size, a fine aggregate replacement of a similar size, and a combination of the two recycled products. At a constant cement content, the compressive strength increased when the same replacement percentage of aggregate (coarse vs. fine) was used in the concrete mixture. Figure 6-14 shows the 28 day compressive strength for the 660pcf (392 kg/m^3) tire chip and crumb rubber, mixtures for all recycled aggregate replacement levels. Further, the combination of coarse and fine aggregate replacement aligned with this trend of increasing compressive strength with the incorporation of the finer crumb rubber when tire chips were used in the mixture.

It should be noted, however, that the same percentage of fine aggregate replacement with crumb rubber does not possess the same rubber volume as that of an equal percent replacement of coarse aggregate with tire chip. This is because the fine aggregate volume of the concrete mixtures is typically less than that of the coarse aggregate, thus replacement volumes will yield higher values for the tire chip. When comparing tire chip and crumb rubber mixtures with similar rubber aggregate volumes (i.e., 660TC20 and 660CR40), crumb rubber mixtures had an approximately 24-30% increase in compressive strength over the tire chip mixture. Ultimately, a higher percentage of finer rubber particles can be used in concrete mixtures without significantly sacrificing compressive strength.

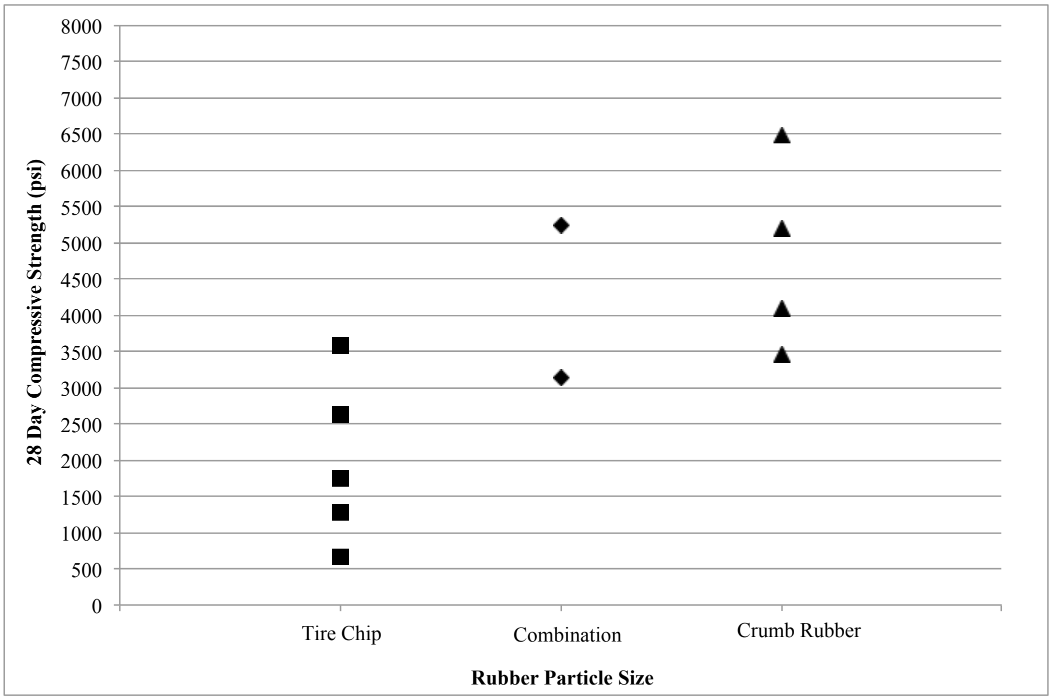


Figure 6-14. Rubber Particle Size on Concrete Compressive Strength

6.2 | Research Mixtures

6.2.1 | Batching of Research Mixtures

The batching of research mixtures including tire chips at 10% and 20% replacement levels of coarse aggregate were subjected to further evaluation in the second phase of the study. The phase maintained a constant w/cm (0.42) and cement content (611 lb/yd^3 (362 kg/m^3)) and evaluated three rubber surface treatments in an effort to improve the adhesion between the rubber particles and the cement paste. Specifically, mechanical roughening of the rubber surface, soaking in a sodium hydroxide solution, and application of a silane coating were utilized to increase bond. Similar to the first phase of the study, mixtures will be referred to as its shorthand mixture identification name throughout the remainder of the section with the addition of the surface treatment variables: M – mechanical roughening, NaOH – sodium hydroxide solution, and S – silane coating. For instance, 611TC20/S will be used to refer to the mixture with 611 lb/yd^3 (362 kg/m^3) of cement and 20% tire chip replacement with a silane coating.

Each of the seven design mixtures were batched and tested for fresh and hardened concrete properties. Additionally, two mixtures, the control and 611TC10/NaOH, were batched in replicate to demonstrate mixture consistency and repeatability. A total of nine mixtures were produced as a part of this phase. At the time of batching each mixture was evaluated for slump, air content, unit weight, and temperature. Specimens were fabricated for testing the mechanical and durability properties of the concrete mixtures at 1, 7, 28, and 56 days of age. Per ASTM C39, all specimens were broken within the permissible tolerances prescribed in Table 6-3.

Table 6-3. Tolerance Times for Hardened Concrete Tests, ASTM C39

Test Age	Permissible Tolerance
24 h	±0.5hr
7 days	6hr
28 days	20hr

6.2.2 | Fresh Concrete Properties of Research Mixtures

Tests for slump, air content, unit weight and temperature were performed on each research mixture at the time of batching. Table 6-4 provides the fresh concrete properties results of the research mixtures with the appropriate discussion for each in the following sections.

Table 6-4 Fresh Concrete Properties in Research Mixtures

Mix Name	Slump, in (mm)	Unit Weight, lb/ft^3 (kg/m^3)	Air Content, %	Temperature, °F (°C)
611TC0 - Control	3.00 (76.2)	142.8 (2,288)	6.0	59 (15)
611TC0 - Replicate	3.75 (95.3)	146.0 (2,339)	4.2	77 (25)
611TC10/M	5.00 (127.0)	138.0 (2,211)	6.0	62 (17)
611TC20/M	0.25 (6.4)	136.0 (2,179)	5.3	63 (17)
611TC10/NaOH	3.00 (76.2)	141.0 (2,259)	5.5	68 (20)
611TC10/NaOH Replicate	5.00 (127.0)	135.4 (2,169)	3.0	-
611TC20/NaOH	7.00 (177.8)	137.6 (2,204)	4.9	80 (27)
611TC10/S	2.00 (50.8)	142.8 (2,288)	3.3	70 (21)
611TC20/S	0.25 (6.4)	134.4 (2,153)	4.0	89 (32)

6.2.2.1 | Slump

The slump results were consistent in terms of the cohesiveness and flow consistency of the mixtures. See Figure 6-15. While the slump varied from as low as 0.25in (6..35mm) for the 611TC20/M mixture to as high as 7.00in (177.8mm) for the 611TC20/NaOH mixture, all mixtures produced quality consistency required for placing concrete and the fabrication of test specimens. A constant HRWRA and VMA were used for all mixtures, thus the fluctuation in slump is likely the result of moisture condition of the coarse and fine aggregates at the time of batching. Although the mixtures are adjusted for aggregate moisture, free water on the surface of the aggregate could change the fluidity of the mixture during the batching operation.

6.2.2.2 | Air Content

ASTM C173 states that in concrete mixtures containing lightweight aggregates shall use the volumetric method for air content testing. However, it is unknown as to whether recycled waste tire particles are considered a lightweight particle. Most literature consider lightweight aggregate as highly porous with a significant void content. Because the absorption capacity on the tire chips was very small (0.3%), it is concluded that the tire chip does not qualify as a lightweight aggregate as it relates to the terminology of ASTM C173. Currently, there is limited research related to the type of air content test performed on rubberized concrete mixtures. Kardos and Durham performed both the Roll-a-Meter and Pressure Meter air content tests and determined a slight reduction in air content values; however, the difference was not significant. The Pressure Meter method was utilized for this study.

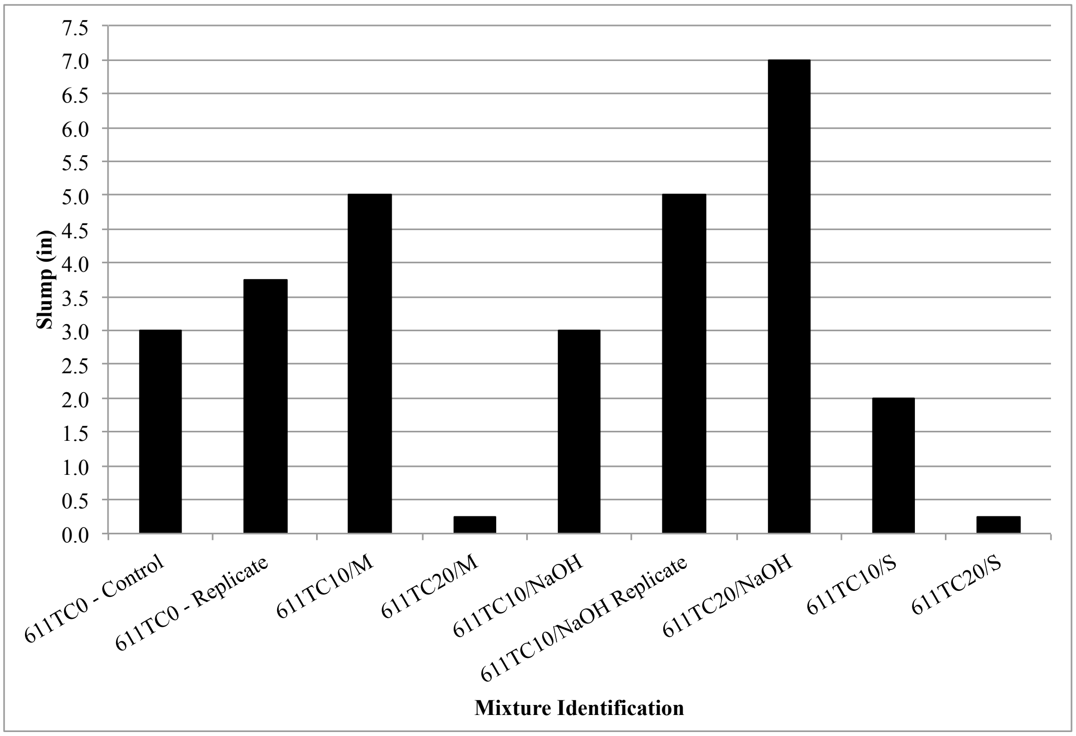


Figure 6-15. Slump Results for Research Mixtures

The air content results are presented in Figure 6-16. An AEA was utilized in order to achieve the desired air content of 2.5-6%, as required by GDOT for Class A concrete mixtures. Adjustment of AEA dosage within the trial mixture analysis led to the successful implementation of the correct dosage rate providing satisfactory air contents for all research mixtures. Air contents remained fairly consistent between 3.0-6.0% with no noticeable change as a result of tire chip inclusion.

6.2.2.3 | Unit Weight

The unit weight of the research mixtures was determined using ASTM C138. The unit weight was calculated as the weight of fresh concrete per unit volume. The design unit weight for the mixtures ranged from 145.0 to 137.3 lb/ft^3 (2,323 to 2,200 kg/m^3) depending on the replacement quantity of coarse aggregate with recycled tire chips.

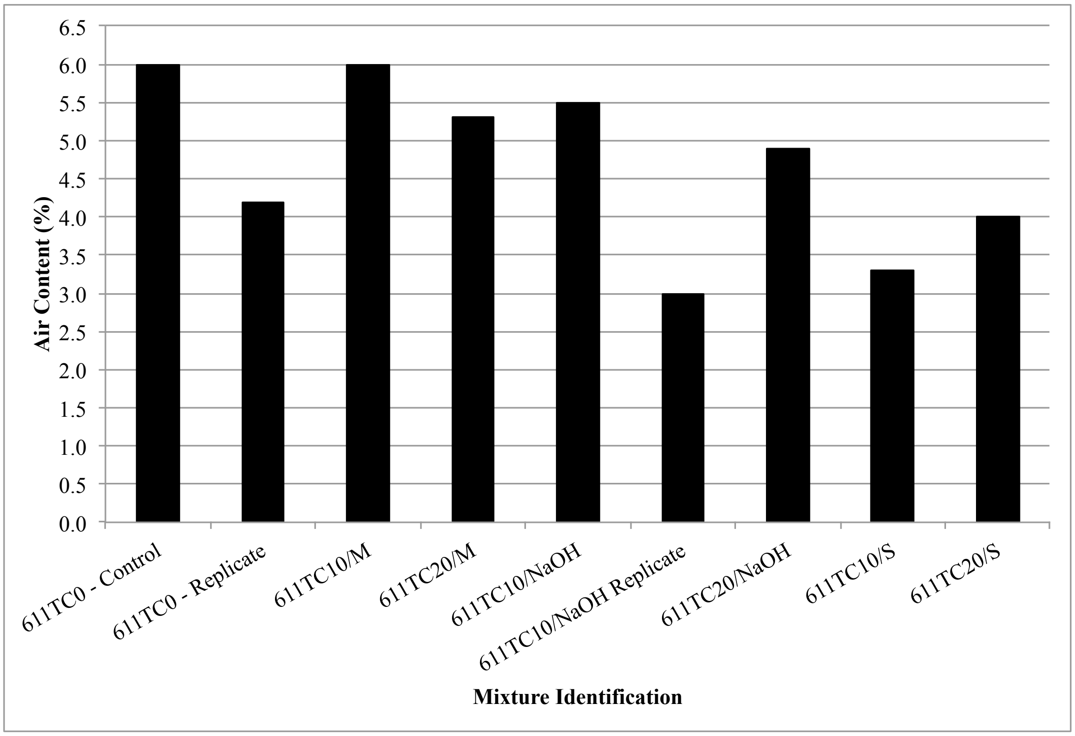


Figure 6-16. Air Content Results for Research Mixtures

Similar to the trial mixture phase, the measured unit weight decreased with increasing percentage of tire chips. As shown in Figure 6-17, the measured unit weight values did fluctuate from the design due to changes in the air content where by lower than design air contents produced higher unit weights. However, measured unit weight values were all considered within the acceptable range for rubberized concrete ranging from 142.8 to 134.4 lb/ft^3 (2,275 to 2,153 kg/m^3). The measured unit weight values were unaffected by the rubber surface treatment with all

6.2.2.4 | Temperature

Concrete temperature is an important characteristic to consider when placing concrete because it is highly dependent on the environment during its plastic state. Previous studies have found that the ideal temperature to batch and place concrete ranges between 50 and 60°F and should not exceed 85°F. This is important because greater temperatures can speed up the cement hydration process as well as lead to the evaporation of water within the concrete mixtures.

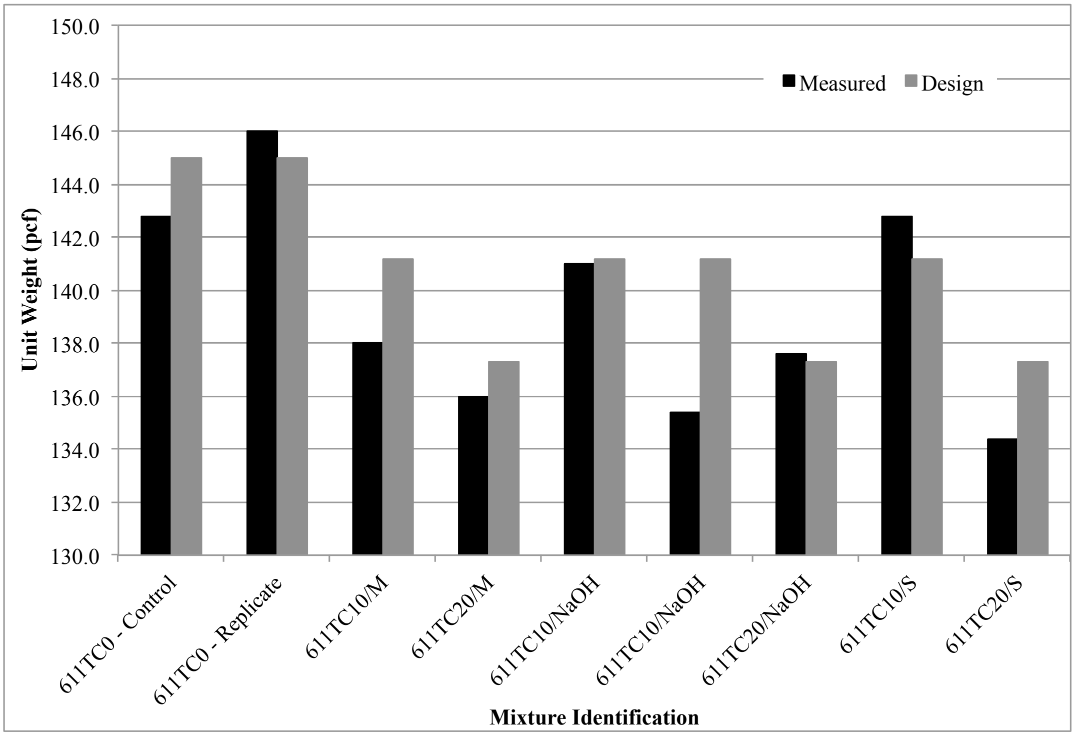


Figure 6-17. Unit Weight Results for Research Mixtures

With the exception of the 611TC20/S mixture, all recorded concrete temperatures were below this maximum. It is believed the high ambient temperature on the day of batching the 611TC20/S mixture was the cause of higher than normal temperature. In addition, a temperature was inadvertently not recorded for the 611TC10/NaOH replicate mixture. The research mixtures' measured temperatures are presented in Figure 6-18.

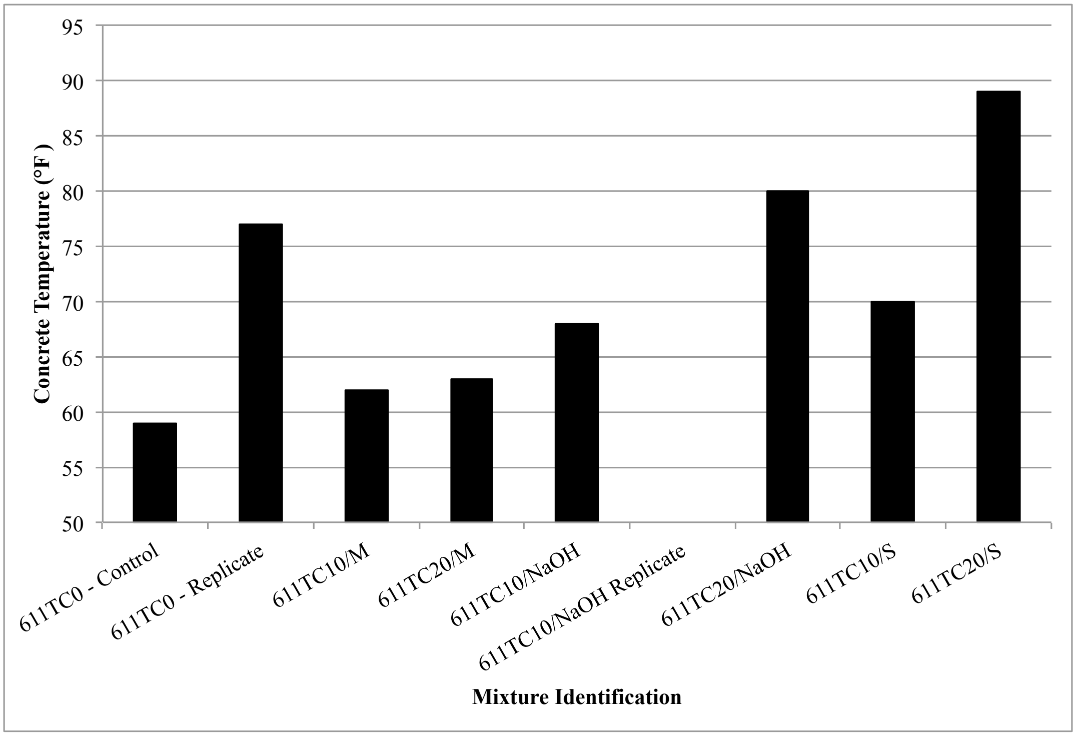


Figure 6-18. Temperature Results for Research Mixtures

6.2.3 | Hardened Concrete Properties of Trial Mixtures

Hardened concrete properties were performed on the control and rubber-modified concrete mixtures in accordance to the appropriate ASTM standard. Each mixture produced a total of 34 – 4in x 8inx (100mm x 200mm) cylinder specimens, 4 – 3in x 4in x 16in prismatic beams, 2 – 6in x 6in x 18in prismatic beams, and 3 – 6in (diameter) x 2in (height) pucks. The hardened concrete properties were measured in the following manner:

- Compressive strength – average of 3 cylinders at 1, 7, 28, and 56 days of age
- Indirect splitting tensile strength – average of 3 cylinders at 28 and 56 days of age
- Modulus of rupture strength – average of 2 beams at 28 and 56 days of age

- Dynamic modulus of elasticity – average of 3 cylinders at 28 and 56 days of age
- Static modulus of elasticity – average of 3 cylinders at 28 and 56 days of age
- Rapid chloride ion penetrability – average of 2 cylinders at 28 and 56 days of age
- Impact drop hammer testing – average of 3 pucks at 28 days of age
- Load-deflection testing – 2 beams at 28 days of age.

6.2.3.1 | Compressive Strength

Per Section 500 of the GDOT Supplemental Specification, the concrete classified as Class A and Class B shall have a minimum specified compressive strength, f'c, of 3,000 psi (21 MPa) and 2,200 psi (15 MPa), respectively. The minimum compressive strength desired for this study was selected to be 3,000psi (21 MPa) in order to satisfy concrete typically used in concrete barrier walls.

The compressive strength is an important component in the concrete design and generally the most specified property. The compressive strength was tested in accordance to ASTM C39. Three cylinders were tested for each mixture on the respective day of age. The cylinders were of the dimensions 4in by 8in (100mm by 200mm). Strength development trends were compared against the control mixtures and among the three rubber surface treatments. The trend was established by calculating the percent change between mixtures.

Table 6-5 lists the average compressive strength, $f_c^{'}$, for the nine mixtures examined this phase. These values are plotted versus concrete age in Figure 6-19. All of the mixtures designed and produced during the second phase of the study met the minimum specified compressive strength of 3,000psi (21 MPa) at 28 days of age with the exception of the 611TC20/M (20% tire chip with mechanical roughening of the surface) and 611TC20/S (20% tire chip with silane coupling agent). However, all mixtures did satisfy the GDOT Class B specified minimum strength of 2,200psi (15 MPa) at 28 days of age.

Table 6-5. Average Compressive Strength of Research Mixtures

Mixture Identification	1 Day, psi (Mpa)	7 Day, psi (Mpa)	28 Day, psi (Mpa)	56 Day, psi (Mpa)
611TC0 - Control	1082 (7)	5348 (37)	6783 (47)	7063 (49)
611TC0 - Replicate	3753 (26)	5805 (40)	7128 (49)	8737 (60)
611TC10/M	997 (7)	3349 (23)	3867 (27)	4659 (32)
611TC20/M	1171(8)	2663 (18)	2642 (18)	2909 (20)
611TC10/NaOH	1677 (12)	3408 (23)	4864 (34)	4294 (30)
611TC10/NaOH Replicate	2030 (14)	3346 (23)	4448 (31)	5468 (38)
611TC20/NaOH	1623 (11)	2607 (18)	3136 (22)	3390 (23)
611TC10/S	1041 (7)	3731 (26)	4350 (30)	5512 (38)
611TC20/S	1359 (9)	2041 (14)	2328 (16)	2896 (20)

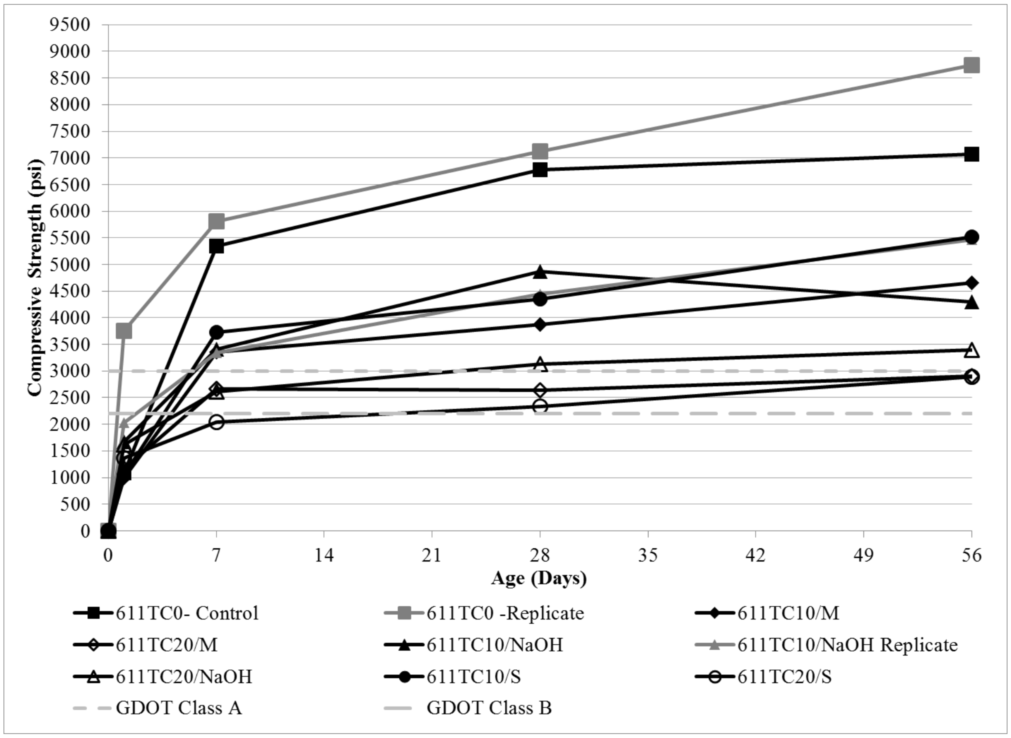


Figure 6-19. Compressive Strength Results for Research Mixtures

As shown in Figure 6-16, the air content for the mixtures varied from the design of 5.0%. Compressive strength is inversely affected by air content. As the air content of a concrete mixture increases, compressive strength decreases. Specifically, a standard relationship considered within the concrete industry is a 5% decrease in compressive strength for each 1% increase in air content (Mindess, Young, and Darwin, 2003). To allow for a better comparison of mixtures without the affect of air content, the 28 day compressive strengths were normalized using this relationship. The results of this compressive strength adjustment are illustrated in Figure 6-20. Normalizing the compressive strength results at 28 days had little effect on the overall trend of decreasing strength with increasing rubber content. Additionally, all mixtures satisfied the GDOT Class A specification with the exception of 611TC20/M and 611TC20/S and all mixtures satisfied GDOT Class B requirements.

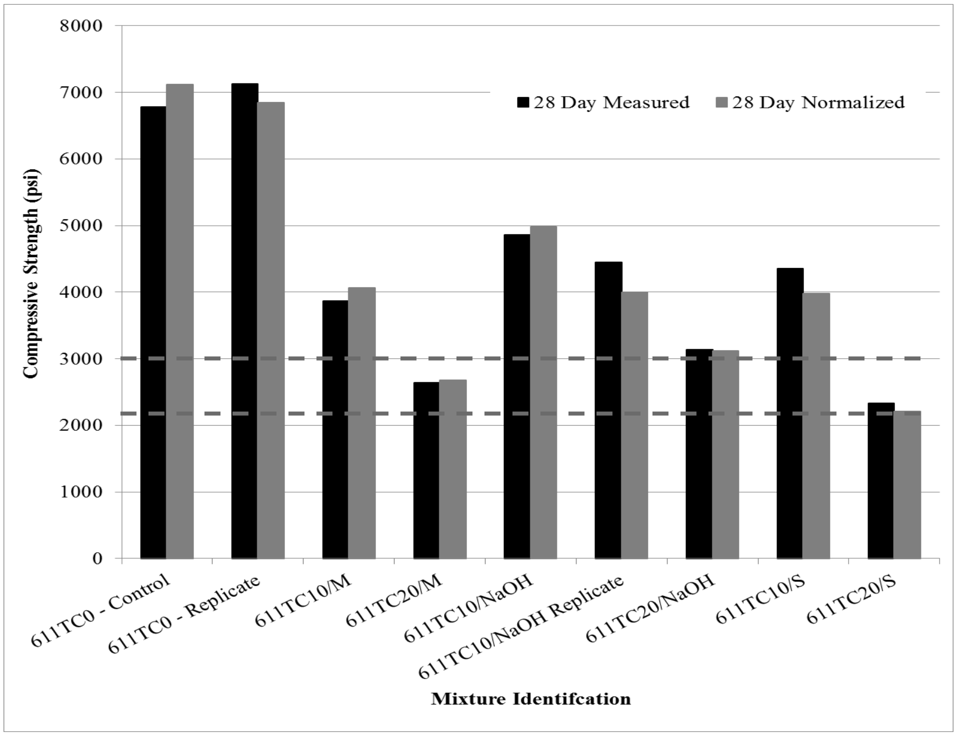


Figure 6-20. Compressive Strength Results Normalized for 5% Air Content

The rubberized concrete mixtures illustrated a 49% decrease in compressive strength when compared to the control without rubber aggregates. The second phase of the research investigation examined surface treatments on the rubber in an effort to improve adhesion between the tire chips and cement past and reduce the strength loss as a result of rubber inclusion. Specifically, the compressive strength for the rubberized mixtures was determined when NaOH and silane coupling agent treatments were performed and compared to the mechanical roughening pretreatment. The NaOH surface treatment proved to be the most beneficial and consistent in improving the strength of rubberized concrete mixtures. Table 6-6 provides the percent increase in strength for the NaOH and silane coupling agent surface treatments when compared to the mechanical roughening treatment.

Table 6-6. Percent Increase in Compressive Strength When Compared to Mechanical Roughening Surface Treatment

Replacement Level	NaOH	Silane Coupling Agent
10% Tire Chips	17%	11%
20% Tire Chips	16%	-13%

The results indicate an average 16.5% increase in compressive strength across the 10% and 20% tire chip replacement levels. While the silane coupling agent treatment produced a 15% percent increase in strength for the 10% tire chip replacement level, the 20% tire chip silane couple treated mixture experienced a decrease in strength when compared to the mechanical roughening mixture. In addition, it should be recognized that the NaOH surface treatment mixtures were the only concrete mixtures to satisfy the GDOT Class A minimum strength requirement of 3,000 psi at both 10% and 20% replacement levels.

6.2.3.2 | Indirect Splitting Tensile Strength

The control and rubber-modified concrete mixtures were subjected to indirect splitting tensile strength testing per ASTM C496. Figure 6-21 shows the indirect splitting tensile test configuration with typical failures of the (a) control mixture and (b) tire chip mixtures. The results of the indirect splitting tensile strength test illustrate a similar trend to that of the compressive strength with decreased tensile strength with increasing rubber contents. See Figure 6-22. When comparing the effect of surface treatments on the splitting tensile performance, the NaOH surface treatment specimens performed similarly or slightly better than the mechanical roughing treatment. However, the silane coupling agent appears to provide better performance in tension when compared to the other two surface treatments producing a tensile strength greater than that of the control specimen without rubber aggregate. Similar to the mode of failure observed in the trial mixture phase of the study, the split cylinder specimens experienced a crushing without complete separation along the cylinder length. The control mixtures without rubber particles did not exhibit this behavior.

(a) (b)

Figure 6-21. Indirect Splitting Tensile Test Configuration and Test Samples (a) Control and (b) 10% Tire Chip

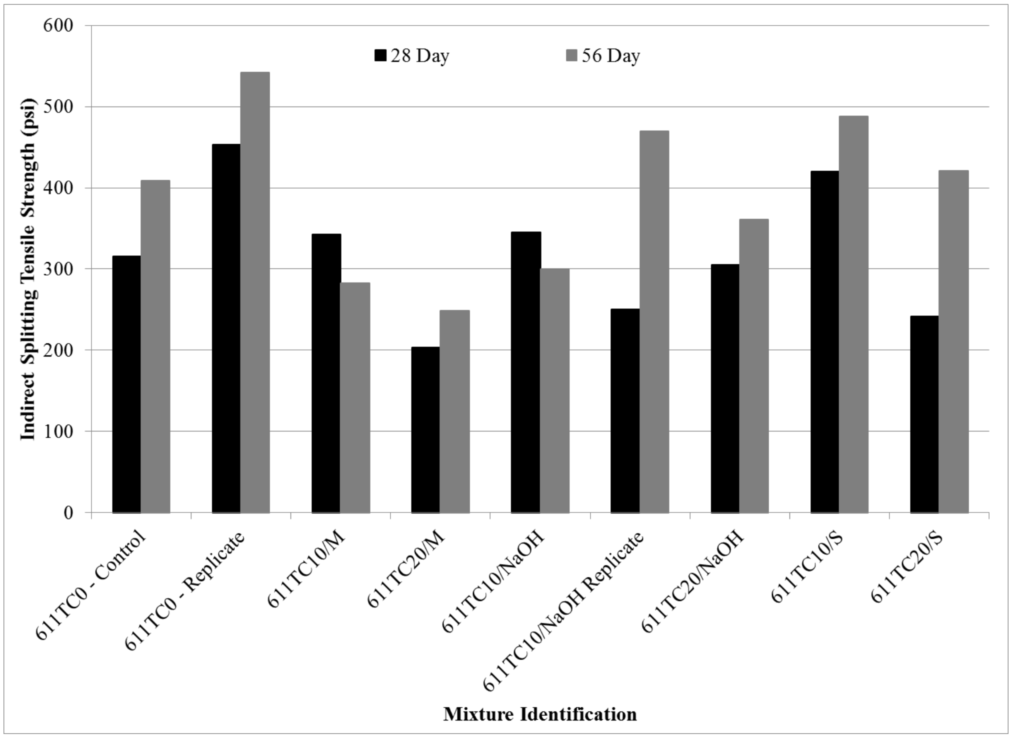


Figure 6-22. Indirect Splitting Tensile Test Results

6.2.3.3 | Modulus of Rupture Strength

Flexural strength was evaluated for the research mixtures in accordance to ASTM C78. See Figure 6-23. There is not a minimum MOR specified by the GDOT Class A or Class B standards. The results obtained for the nine mixtures are shown in Figure 6-24. The nine mixtures produced MOR values ranging from 409 psi to 738 psi (3 MPa to 5 MPa) at 28 days of age and 395psi – 687psi (3MPa to 5MPa) at 56 days of age.

(a) (b) (c)

Figure 6-23. Modulus of Rupture Test Configuration and Test Samples (a) Configuration, (b) Control Mixture, and (c) 20% Tire Chip Mixture

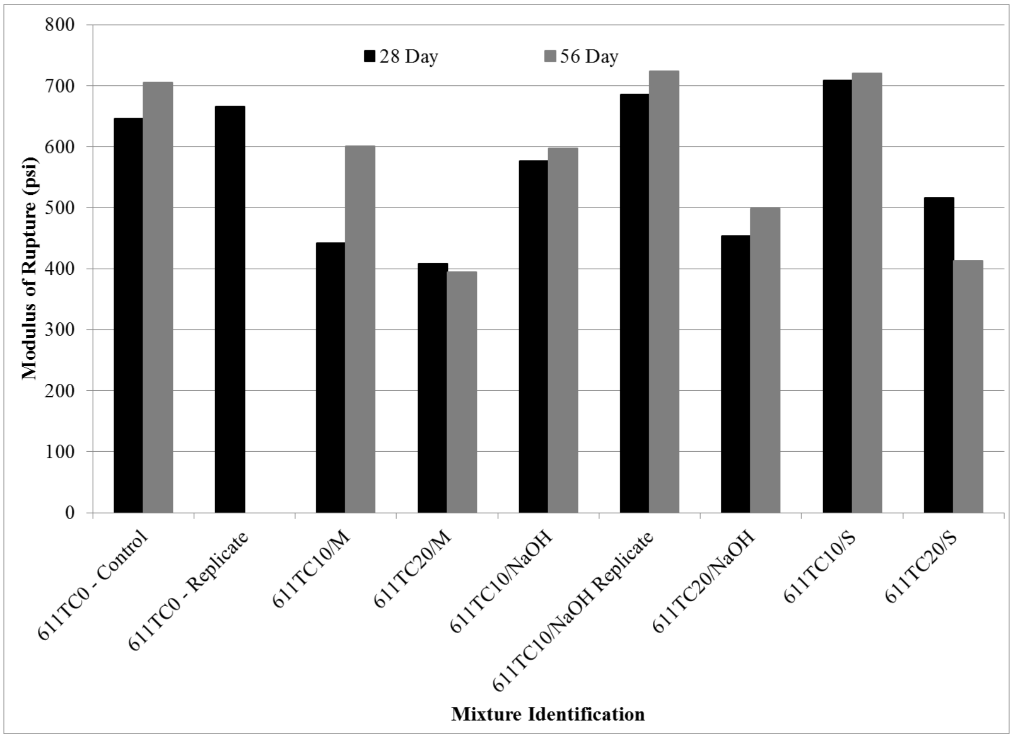


Figure 6-24. Modulus of Rupture Flexural Test Results

Similar to other literature, the modulus of rupture values collectively were higher than the measure of tensile capacity via the indirect splitting tension test. On average across all specimens tested, the modulus of rupture test results were approximately 43% higher than the indirect splitting tensile strength. When compared to the modulus of rupture empirical prediction equation $7.5\sqrt{f'c}$, the measured strength produces higher values. Even though rubber aggregates were used in the concrete mixtures evaluated in this study, the prediction equation remains a conservative estimation of the modulus of rupture. This is a similar trend for conventional concrete mixtures. Analogous to the indirect splitting tensile test, the trend of decreasing modulus of rupture strength with increasing tire chips was observed fro the rubberized concrete mixtures. However, contrary to the indirect tensile strength results, the rubber-modified concrete mixtures incorporating a NaOH treated rubber performed better than mixtures incorporating a silane coupling agent treatment.

Most notable with the modulus of rupture testing was the behavior of the prismatic beams at and immediately following failure. When the ultimate load was reached for the control mixtures, the beam would crack in the maximum tensile region of the beam resulting in complete failure with no ability for additional load. However, the concrete prismatic beams incorporating the tire chip aggregate demonstrated a behavior such that additional load was carried by the beam immediately following the formation of a tensile crack. This alternate behavior is the result of the tire chip aggregate bridging the crack upon formation. Ultimately, failure is the result of the tire chip pulling out of the cement paste or rupturing of the rubber particle. While the modulus of rupture values for the rubber-modified mixtures were at or below that for the control specimens, the ability of the rubber particles to act as internal reinforcement (ie. rubber fibers) may prove beneficial for certain concrete applications where fracturing of the concrete is likely.

6.2.3.4 | Static Modulus of Elasticity

The static modulus of elasticity test was used to examine the concrete response to load. Specifically, this test was used to measure the concrete stiffness. It was expected that the static modulus of elasticity would decrease with an increased tire chip content. This is the result of an elastic material (tire chip) replacing a more rigid material (coarse aggregate). The test configuration utilized for this phase of testing is shown in Figure 6-25. As expected, the static modulus of elasticity decreased with increased tire chip content. The static modulus of elasticity results are presented in Figure 6-26. With the exception of mixture 611TC20/M, the 28 day and 56 day modulus of elasticity values are similar. Thus, little increase in modulus of elasticity is experienced beyond 28 days of age. Similar to other mechanical properties a decrease in the static modulus of elasticity was observed with increasing tire chip contents. The modulus of elasticity values measured are within the normal range of concrete mixtures (ie. 3,000 – 5,000 ksi (21 – 34 GPa)).


(a) (b)

Figure 6-25. Static Modulus of Elasticity Test Configuration (a) Motion capture camera (b) Detection sensors.

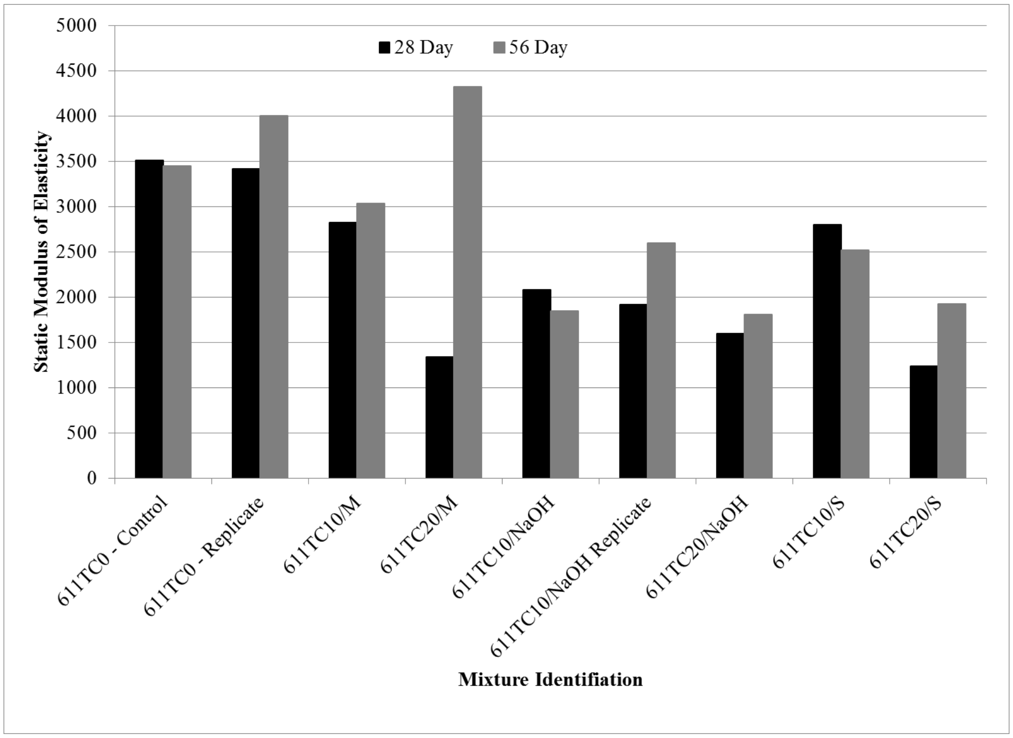


Figure 6-26. Static Modulus of Elasticity Test Results

6.2.3.5 | Dynamic Modulus of Elasticity

The dynamic Young's modulus of elasticity is the ratio of stress to strain under vibratory conditions. The dynamic modulus of elasticity in this study was tested in accordance to ASTM C215 – *Standard Test Method for Fundamental Transvers, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens.* The impact resonance method of the standard was utilized during the testing of 4in x 8in (100mm x 200mm) cylinders in the transvers mode. The test set up shown in Figure 6-27 shows the cylinder properly supported with the impactor and accelerometer. From this configuration, the transvers resonance frequency was determined for each mixture. The average of two specimens was recorded. They dynamic modulus of elasticity is calculated by multiplying the square of the transvers frequency (Hz), the mass of the specimen, and a coefficient (C) equal to 1.6067(L^3T/bt^3) where L is the specimen length, d is the cylinder diameter, and T is a correction factor specified by ASTM C215.

Figure 6-27. Dynamic Modulus of Elasticity Test Configuration

The results of the dynamic modulus of elasticity test for the research mixtures is presented in Figure 6-28. Observations with the data include little change in the dynamic modulus of elasticity between 28 and 56 days of age. In addition, when comparing the control mixtures without tire chips and the rubberized concrete mixtures, the test results indicate that the dynamic modulus of elasticity is not as sensitive to the tire chips as other mechanical properties such as compressive strength. While nearly all of the rubberized mixtures produced dynamic modulus of elasticity values were less than the control, the percent difference (16% reduction) was not as great when compared to that of the compressive strength (49% reduction). Thus, the tire chips have less influence on the dynamic modulus of elasticity than other test methods. While all dynamic modulus of elasticity measured results are within the typical range of values for concrete specimens, the dynamic modulus of elasticity results were on average 45% higher than the static modulus of elasticity values. This significant difference in moduli is similar to that experienced by other researchers since the dynamic modulus is more representative of the initial tangent modulus than the secant modulus determined in the static method.

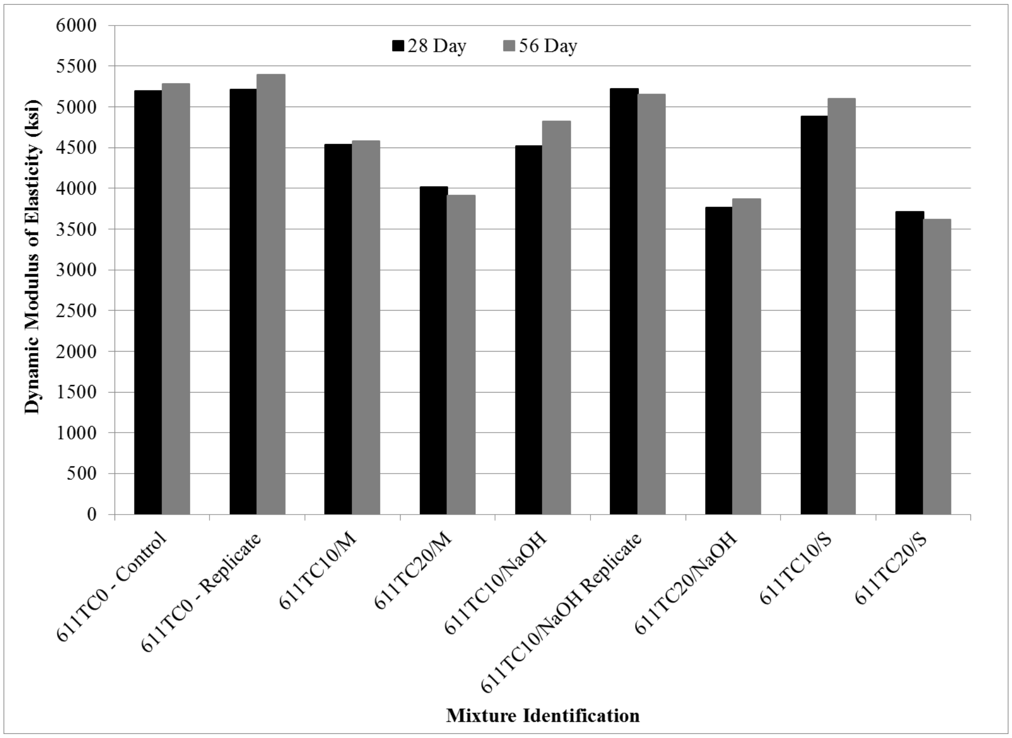


Figure 6-28. Dynamic Modulus of Elasticity Test Results

6.2.3.6 | Rapid Chloride Ion Penetrability Test

The durability of concrete mixtures can often be predicted based upon its permeability. As the permeability of the concrete mixtures increases, aggressive chemicals such as sulfates and chlorides can more easily penetrate the concrete resulting in sulfate attack and reinforcement corrosion. ASTM C1202, rapid chloride ion penetrability test (RCIP), was performed at 28 and 56-days of age for each research mixture. This test procedure involves the monitoring of electrical current passing through a 2 in (51mm) thick by 4 in (102mm) nominal diameter cylinder section of concrete for a 6 hour duration.

Samples were first prepared by wet-saw cutting the top finished surface of a 4 in x 8 in (100 mm x 200 mm) concrete cylinder specimen. The samples were placed under a dry vacuum (approximately 25 inches (63.5 cm) of mercury) in a desiccator for 3 hours. Water was then introduced to the desiccator and the samples completely submerged. A wet vacuum was held for 1 hour prior to release. Next the samples were continued to soak in the desiccator for 24 hours. The specimens were then removed from the water and dried. The cylinder was then placed into the test cell as shown in Figure 6-29.

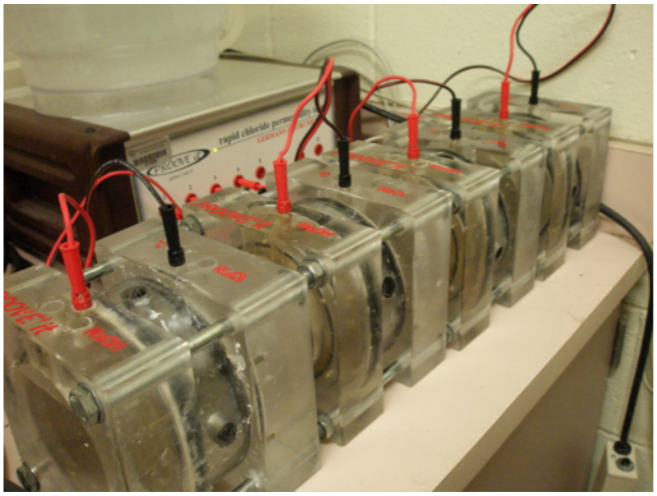


Figure 6-29. Rapid Chloride Ion Penetrability Test Configuration

A potential difference of 60-volts (direct-current) is maintained across the ends of the specimen. One side of the specimen cell includes sodium chloride solution (NaCl) while the other specimen includes sodium hydroxide solution (NaOH). ASTM C1202 provides a correlation between the total charge passed (coulombs) through the concrete sample and its ability to resist chloride ion penetration. Table 6-7 provides the permeability designations based upon the coulombs passed during the test.

Table 6-7. Permeability Classification per ASTM C1202

Charge Passed (Coulombs)	Permeability Classification
> 4000	High
2,000 – 4000	Moderate
1,000 - 2,000	Low
100 - 1,000	Very Low
<100	Negligible

Even though the GDOT Class A and Class B requirements do not specify a permeability classification, lower ion penetrability will ultimately result in more durable and longer lasting concrete when exposed to aggressive environments. The results of the permeability testing for the research mixtures is presented in Table 6-8 and graphically illustrated in Figure 6-30. The control and rubberized concrete mixtures all produced charges between 2,000 and 4,000 coulombs resulting in the classification of "moderate" permeability.

Table 6-8. Rapid Chloride Ion Penetrability Results

Mixture Identification	28 Day (coulombs)	Chloride Ion Penetrability	56 Day (coulombs)	Chloride Ion Penetrability
611TC0 - Control	3245	Moderate	3173	Moderate
611TC0 - Replicate	2576	Moderate	2300	Moderate
611TC10/M	3457	Moderate	3239	Moderate
611TC20/M	2622	Moderate	2443	Moderate
611TC10/NaOH	3092	Moderate	2217	Moderate
611TC10/NaOH Replicate	3607	Moderate	2650	Moderate
611TC20/NaOH	4457	High	3215	Moderate
611TC10/S	2425	Moderate	2022	Moderate
611TC20/S	3455	Moderate	3508	Moderate

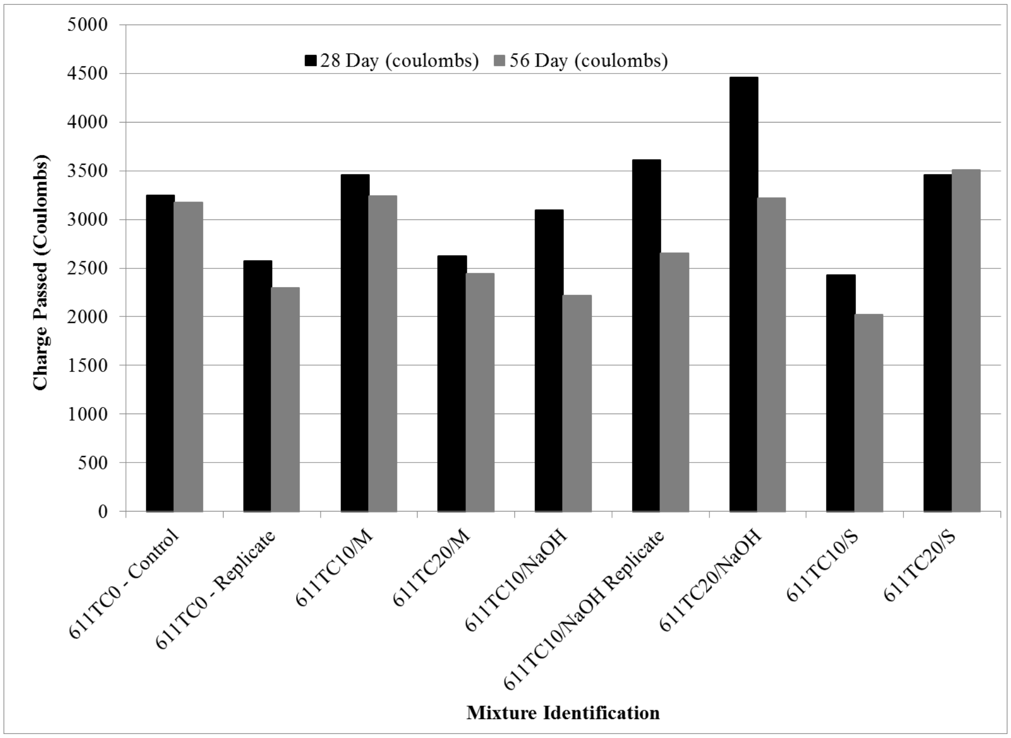


Figure 6-30. Rapid Chloride Ion Penetrability Test Results

6.2.3.7 | Coefficient of Thermal Expansion Test

A material's coefficient of thermal expansion describes the elongation that a material will undergo when exposed to temperature differentials. This characteristic is particularly important when discussing concrete pavements because of the potential for stresses to be exerted on the concrete pavement as it expands and contracts. The coefficient of thermal expansion test was conducted on each concrete mixture at 28 days after mixing. The test uses an LVDT to measure the length of concrete specimens as they cycle three times in a water bath between 10°C and 50°C (50°F and 122°F). The results from these tests are displayed in Figure 6-32. The coefficient of thermal expansion increases for concretes incorporating recycled tire chips. Rubberized concrete mixtures experienced a coefficient of thermal expansion value between 6.0 – 7. 0 x 10^{-6} in/in/ °F which is higher than the control mixture (conventional concrete) at 5.25 x 10^{-6} in/in/ °F.

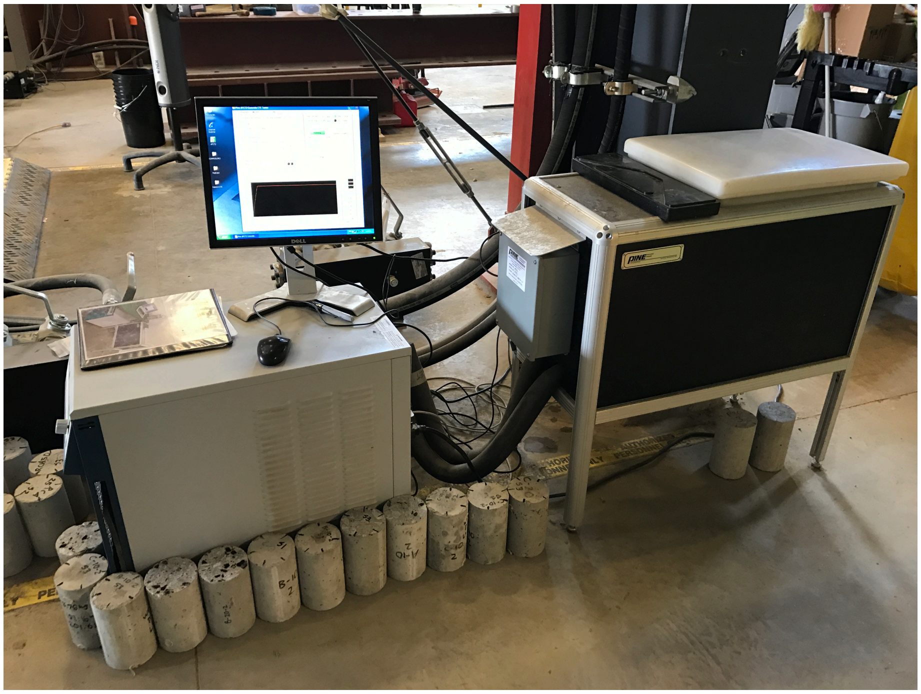


Figure 6-31. Coefficient of Thermal Expansion Test Equipment.

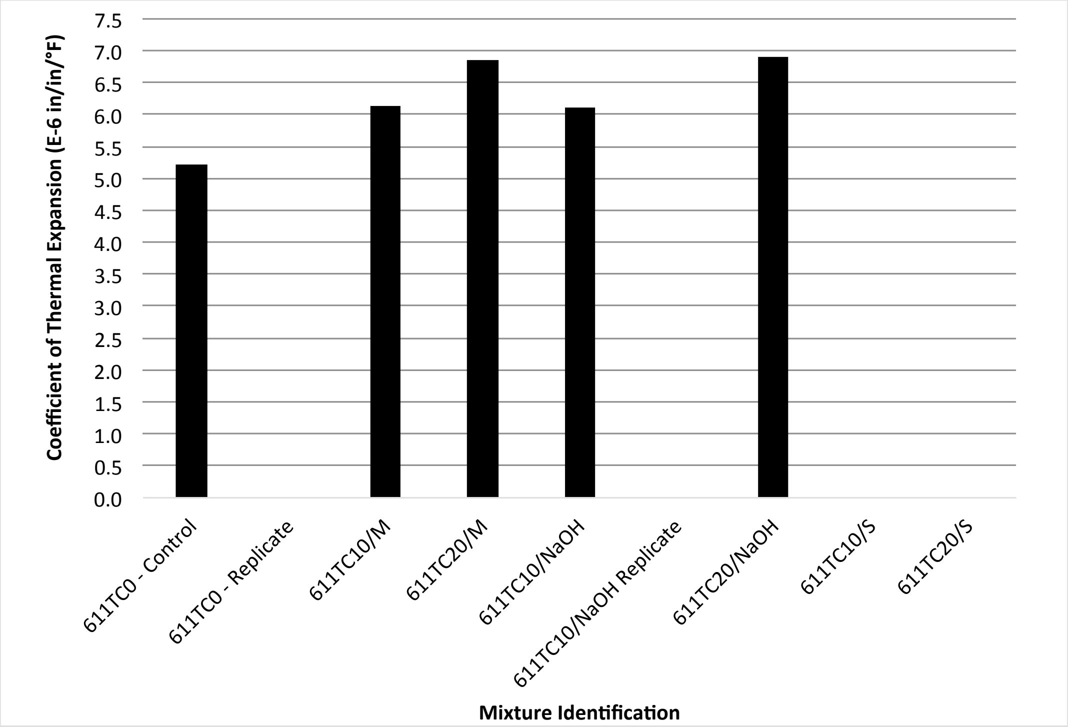


Figure 6-32. Coefficient of Thermal Expansion Test Results

6.2.3.8 | Drop Weight Impact Test

The primary objective of this research study was to evaluate the use of tire chips as a coarse aggregate replacement in an effort to improve the impact resistance and toughness of concrete. Specifically, because GDOT Class A requirements governs concrete mixtures used in the construction of barrier walls, the fresh and hardened concrete properties herein have been compared to the design standard. While the desire was to produce concrete mixtures that remained in compliance with the standard, the hope was to produce rubber-modified mixtures with the potential to absorb impact and remain intact after impact.

Currently, no standard test method is available to measure such property, thus the research team developed a procedure for evaluating concrete's cracking performance when subjected to repeated impact. Specimens measuring 2in (51mm) height by 6in (152mm) diameter were placed in a metal ring as to secure the sample from movement during testing. A metal sphere was placed on the top of the metal ring such that impact loading would be transmitted to the specimen via a direct point load. A standard proctor compaction hammer weight 5.5 lb was used to produce the repeated impact loadings. The hammer consisted of a 2in (51mm) diameter face and a drop height of 12in (305 mm). The testing apparatus is shown in Figure 6-33.

Throughout the test, the technician observes the condition of the specimen following each drop. The number of drops to first crack (the initiation of a crack), control failure (equivalent failure as though no rubber was included), and complete failure (complete separation of the concrete specimen) were recorded for each specimen. The drop hammer impact test results are listed in Table 6-9 and illustrated in Figure 6-34.


(a) **(b)** **(c)**

Figure 6-33. Impact Drop Hammer Test Configuration and Test Sample: (a) Sample in Test Ring, (b) Compaction Hammer, and (c) Sample After Complete Failure

Table 6-9. Drop Hammer Impact Test Results

Mixture Identification	First Crack	Control Failure	Complete Failure
611TC0 - Control	52	55	55
611TC0 - Replicate	36	43	43
611TC10/M	47	59	64
611TC20/M	53	103	126
611TC10/NaOH	76	100	119
611TC10/NaOH Replicate	28	38	53
611TC20/NaOH	41	51	68
611TC10/S	72	80	94
611TC20/S	32	52	91

As expected, the tire chip concrete mixtures increased the number of repeated impacts when compared to the control mixture. The most notable improvement is the number of drops the rubberized concrete mixtures absorbed prior to complete failure. The control was only capable of withstanding 3 additional drops following the formation of an initial crack. However, the rubberized concrete mixtures averaged an additional 19 drops following the formation of the crack before the control failure condition was reached and an additional 38 drops after the initial crack prior to complete failure.

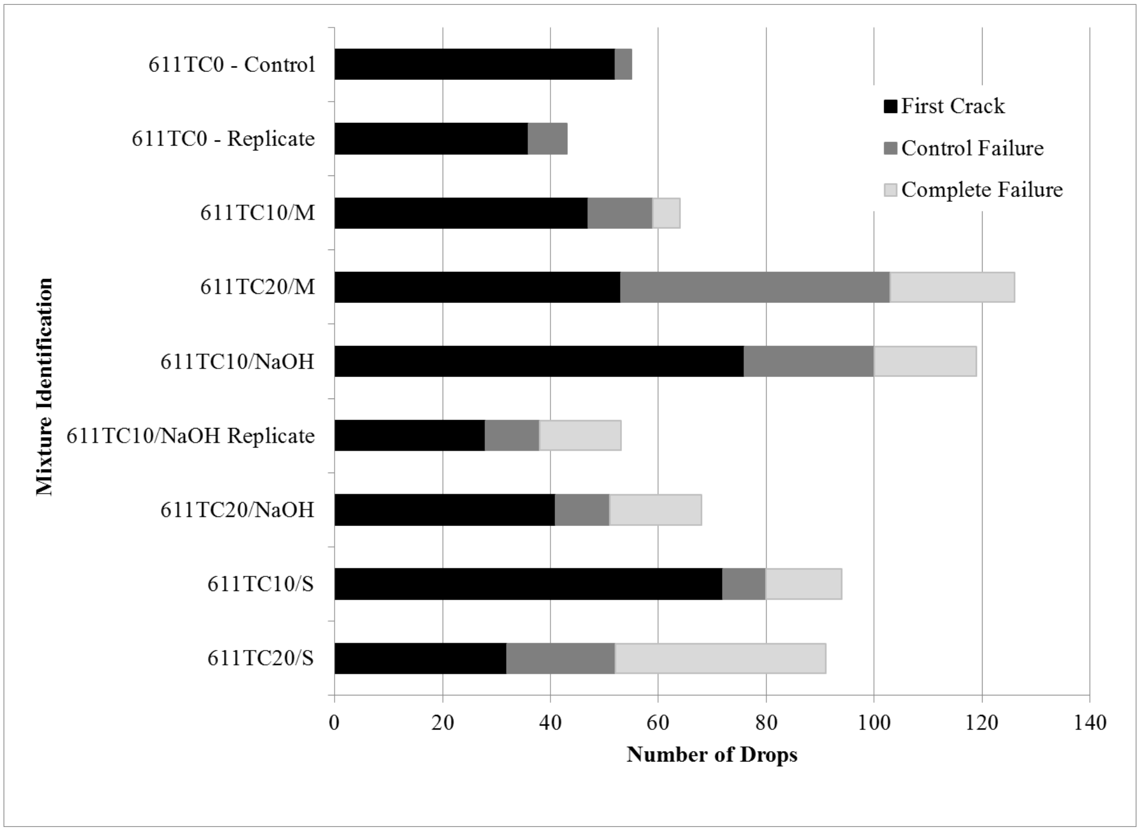


Figure 6-34. Drop Hammer Impact Test Results

In nearly all cases, the concrete mixtures incorporating the highest tire chip content (20%) were capable of withstanding the largest number of drop hammer impacts. There was variation in the results between the surface treatments making it difficult to conclude one surface treatment performing better than another. The major conclusion from this test was the improved behavior of the concrete when subjected to repeated impact making rubberized concrete mixtures ideal for applications that may experience regular and instantaneous impact loadings.

6.2.3.9 | Load-Deflection

The primary objective of this research was to optimize concrete mixtures to improve the impact resistance of the material while maintaining characteristics required by GDOT concrete specifications. A primary measure of this quality is the ability of the concrete to deflect when subjected to loading. The area beneath a load-displacement curve indicates the energy that the concrete can absorb prior to failure.

There currently exists no standard test procedure to measure the load-deflection of concrete beams. The research team developed two methods of producing the results for this property. The first method included the use of a TE connectivity (TE) string potentiometer, commonly referred to as a string pot, that was connected to the middle of each concrete beam to measure the deflection of each specimen. Beams sized 6 in x 6in x 22 in (15.24 cm x 15.24 cm x 55.88 cm) were subjected to a standard MOR test while the deflection data was being simultaneously captured. The string pot records electrical signals that are proportional to the length of the cable that extends from the mechanism. The deflection data was then converted to a displacement in inches and matched to the corresponding load data from the MOR test.

The second method of performing this test used a high-speed motion capture camera and sensors attached to concrete beams to collect the deflection data points. The motion capture sensors were attached to the sides of the 6 in x 6in x 22 in (15.24 cm x 15.24 cm x 55.88 cm) concrete beams faced toward the motion capture camera. Similar to the previous method, concrete beam was subjected to an MOR test. While the MOR test is running, the motion capture camera recorded the location of the sensor at the side of the beam. Once complete, the load data was matched to the corresponding displacement data. The toughness of each concrete beam was calculated from the load-deflection plot generated from conducting these tests and presented in

Table 6-10. The load deflection curves for the mechanical abrasion, sodium hydroxide, and silane coupling agent pretreatments are shown in Figures 6-35, 6-36, and 6-37. From the load-deflection curves, it is observed that the rubber modified concrete beams deflected much more than the control mixtures while still approaching or obtaining similar MOR values when compared to the control mixtures. This provided more substantial calculated toughness values for the rubber modified concrete beams than the control mixtures due to the residual load capacity experienced by the rubberized concrete mixtures. In addition, the toughness calculations demonstrate that higher percentages of rubber contents produce greater toughness values. The average toughness for each mixture is provided in Table 6-10.

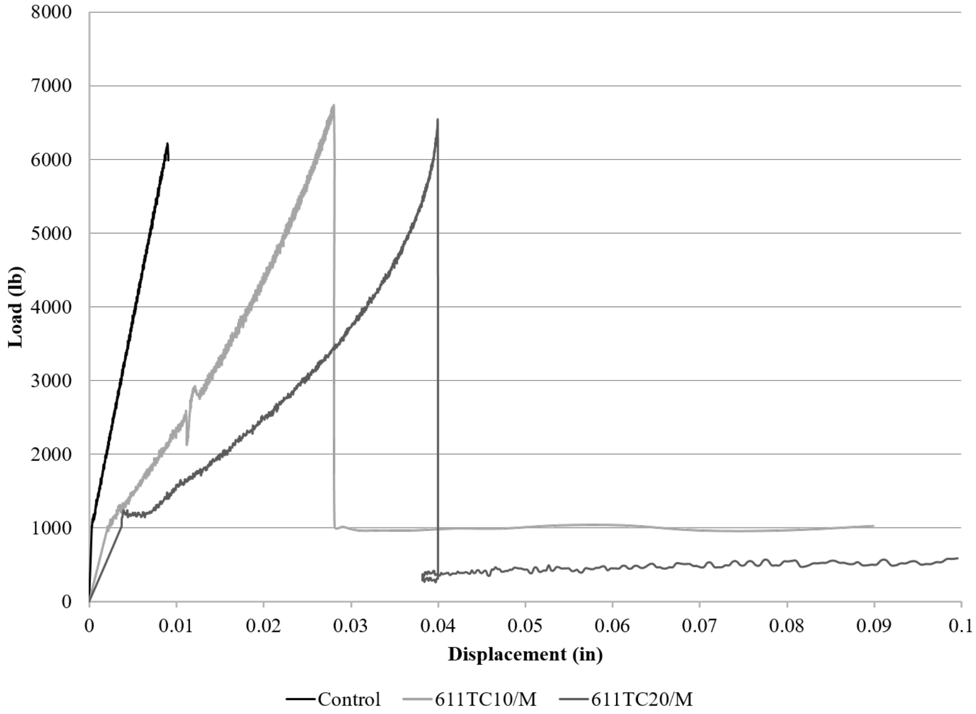


Figure 6-35. Load Displacement of Mechanical Abrasion Pretreatment Concrete Mixtures

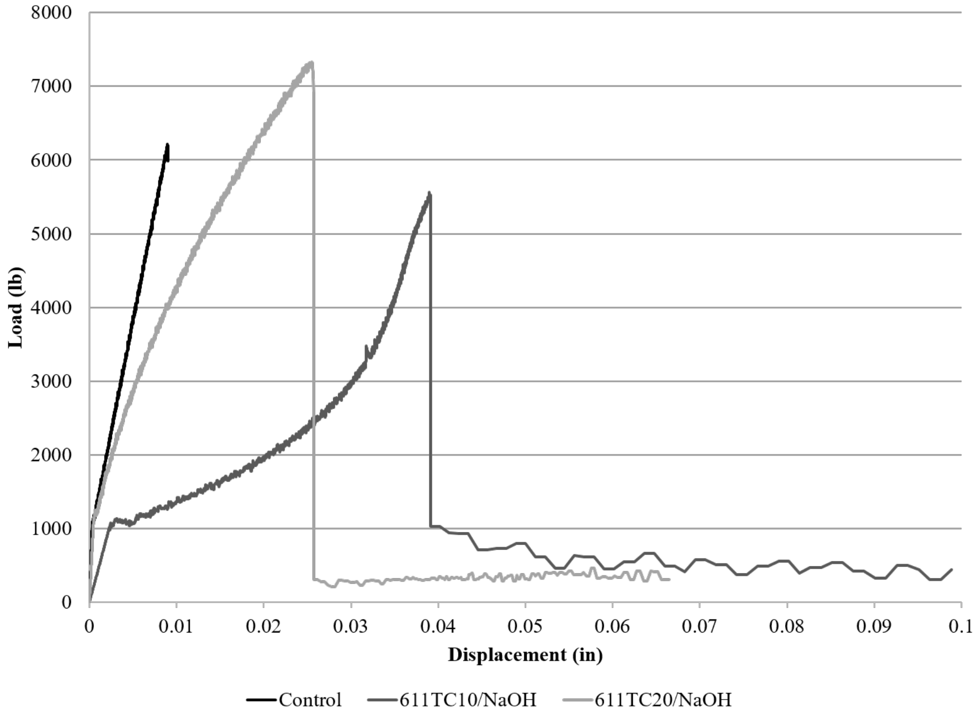


Figure 6-36. Load Displacement of Sodium Hydroxide Pretreatment Concrete Mixtures

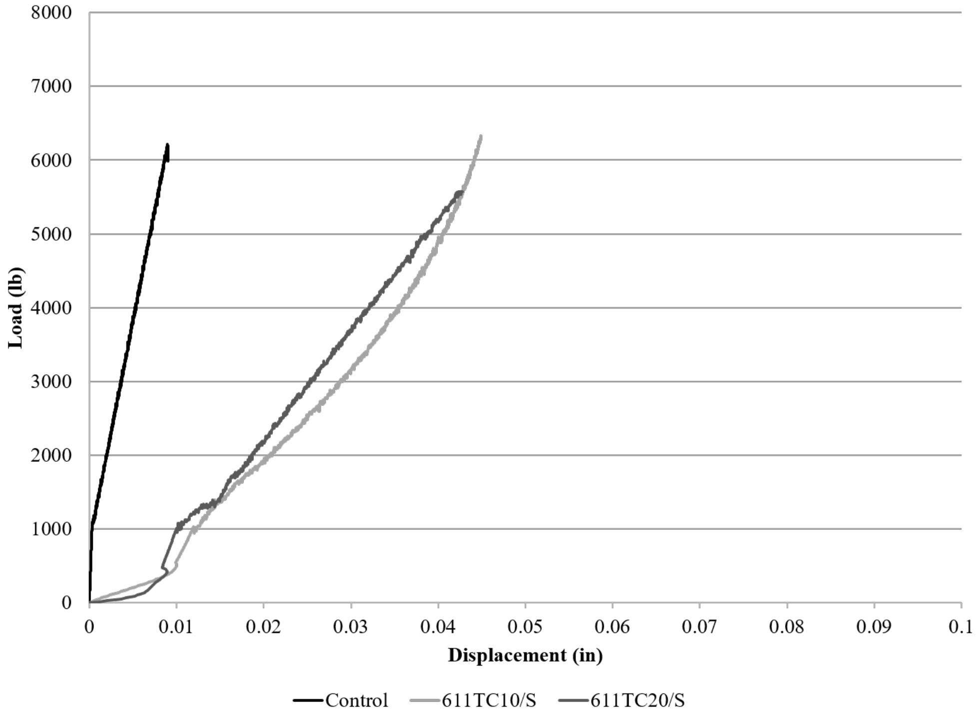


Figure 6-37. Load Displacement of Silane Coupling Agent Pretreatment Concrete Mixtures

Table 6-10. Area Under the Load-Deflection Curve

Mixture Identification	Toughness, lb-in
611TC0 - Control	45.131
611TC0 - Replicate	70.319
611TC10/M	120.714
611TC20/M	168.949
611TC10/NaOH	177.218
611TC10/NaOH Replicate	64.525
611TC20/NaOH	121.312
611TC10/S	121.934
611TC20/S	193.405

7.0 | ECONOMIC CONSIDERATIONS

Construction materials are often evaluated not only on their mechanical performance but on economic value. While the rubber tire chips and crumb rubber in this study were recycled products, there is a cost associated with the recycling and processing of the rubber from a waste tire to rubber particles. Material unit costs were gathered in an effort to compare the cost of the control mixture (611TC0) to the rubberized concrete mixtures incorporating 10% (611TC10) and 20% (611TC20) tire chips. In addition, the cost of the 20% crumb rubber mixture was determined. The local producer and distributor of the product, Liberty Tire Recycling, provided the unit costs for the tire chip and crumb rubber. The cost for both products was \$350 per ton (0.91 metric ton). Table 7-1 provides the materials unit costs and total cost of the control, 10% and 20% tire chip and 20% crumb rubber mixtures. It should be noted that the costs included in the table are only material costs and does not include costs associated with concrete delivery and indirect costs required by a ready-mixed concrete producer.

Table 7-1. Economic Comparison of Control and Rubberized Concrete Mixtures

Material	Unit Costs	Mixture Identification			
		611TC0	611TC10	611TC20	660CR20
Cement	\$140/ton	\$36.66	\$36.66	\$36.66	\$39.60
Water	\$5/1000 gal	\$0.08	\$0.08	\$0.08	\$0.08
Coarse Aggregate	\$24/ton	\$16.20	\$14.58	\$12.96	\$16.20
Tire Chip	\$350/ton	-	\$13.31	\$30.43	-
Fine Aggregate	\$18/ton	\$8.57	\$8.57	\$8.57	\$7.49
Crumb Rubber	\$350/ton	-	-	-	\$17.58
AEA	\$3.50/gal	\$0.48	\$0.48	\$0.48	\$0.48
HRWRA	\$8/gal	\$2.64	\$2.64	\$2.64	\$2.64
VMA	\$15/gal	\$3.04	\$3.04	\$3.04	\$3.04
Total Cost =		\$67.67	\$79.36	\$94.86	\$87.11

A noticeable difference is observed in the cost between the control and rubberized concrete mixtures. A cost increase of approximately 15% for each 10% increase in tire chip content was determined for the rubberized concrete mixtures. This equates to a cost increase of \$1.17 per percent addition of tire chip. The crumb rubber had a slightly less increase in cost resulting in a cost increase or 11% for each 10% increase in crumb rubber or \$1.12 per percent addition of the product. Although the addition of the tire particles result in an increased cost of the concrete mixture, the benefit of adding rubber to the concrete mixtures for applications subjected to impact may outweigh this additional costs. In order to compare the improved impact resistance with the increased costs, Figure 7-1 was produced relating the number of drop impacts to mixture cost. For the purposes of this analysis, all of the 611TC10 mixtures regardless of surface treatment were averaged. Similarly, all of the 611TC20 mixtures were averaged.

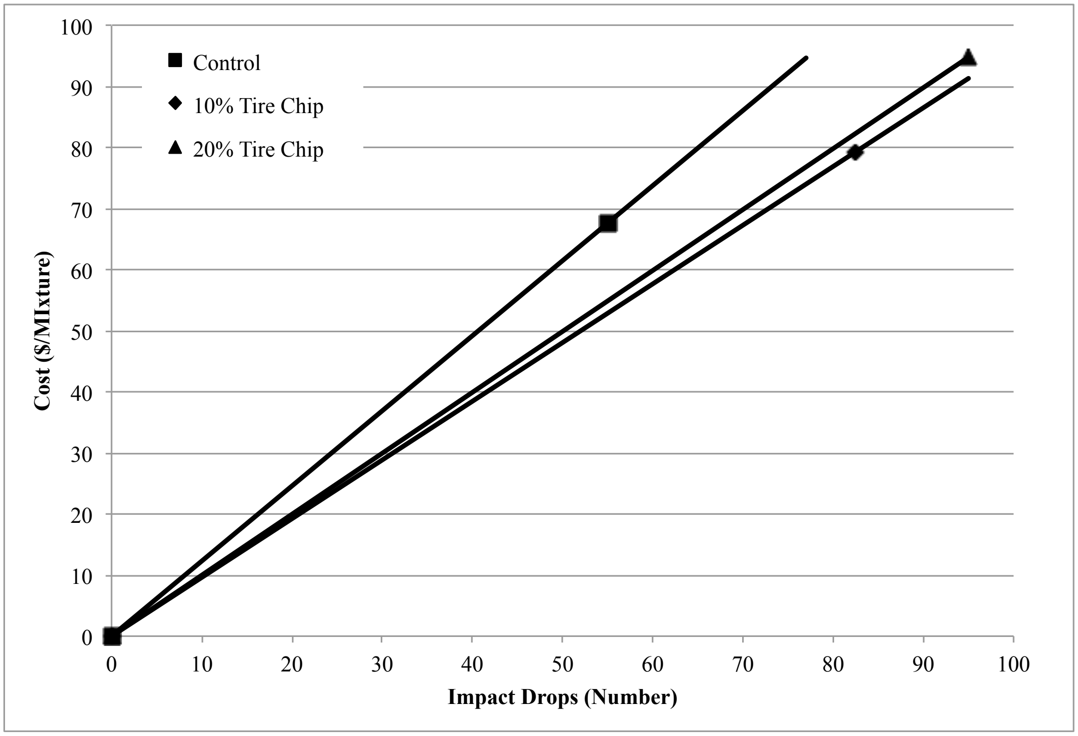


Figure 7-1. Cost Vs. Impact Performance Relationship

Because the slope of the lines for the 10% and 20% tire chip are smaller than that of the control, the rubberized concrete mixtures considered to be more economical with regards to impact resistance. Ultimately, the 10% and 20% rubberized mixtures produced similar slopes with the 10% tire chip mixture being slightly lower. In summary, the economic analysis demonstrates that while the rubberized concrete mixtures have an added cost when compared to a conventional concrete mixture, the additional expense may be warranted for concrete structures subjected to impact where added resistance and toughness prove beneficial.

8.0 | FUTURE WORK

The work completed in this study determined the optimal levels of recycled tire chips to improve impact resistance and energy absorption while still satisfying the GDOT Class A concrete specification for potential use in concrete barrier walls and other applications. In addition, mechanical roughening, sodium hydroxide soaking, and a silane coupling agent were evaluated to improve adhesion between cementitious materials and the rubber particle surface.

The results of this study demonstrated the successful inclusion of rubber tire chips in concrete mixtures up to 20% replacement of coarse aggregate. Additionally, the rubberized mixtures may prove to be advantageous in application subject to repeated impact as a result of its toughness. In order to optimize concrete barrier wall designs incorporating tire chips, a performance-based evaluation must be accompanied. However, testing truck impacts is often unrealistic to evaluate the effect of rubberized concrete designs on the barrier performance. To study the impact performance, it is essential to develop a computer simulation model. In addition, the simulation model must be validated by reasonably predicting the results of a small-scale impact test or a component test. Once the analytical approach and material models are validated, a full-scale crash simulation conducted in the absence of a full-scale test may be considered reliable for design optimization.

Future work should involve developing a nonlinear finite element analysis model for crash simulation of vehicle impacts and to assess the likely impact and full potential of the concrete barrier design utilizing the experimental results from this study coupled with a new examination of fiber reinforced concrete. In addition, the analytical model must be validated through the construction of scaled concrete barrier walls incorporating the recycled tire chips and/or fibers utilizing drop-weight impact tests.

The development of a computer simulation model will provide a more detailed understanding of the three-dimensional impact response and energy absorption capacity of the current, rubber-modified and fiber reinforced concrete barrier designs, assist in enhancing the cementitious composite designs used in GDOT concrete barriers and better inform for future full-scale safety testing at a certified vehicle-barrier testing facility, if deemed necessary.

9.0 | CONCLUSIONS AND RECOMMENDATIONS

This study researched the effect of using recycled rubber aggregates on the fresh properties and compressive strength of concrete mixtures. A total of twenty-four mixtures were evaluated in the preliminary phase and nine mixtures in the more comprehensive research phase. Initially, three series of mixtures with varying cement contents of 611, 660, and 705 lb/yd^3 (362, 392, and 418 kg/m^3) were evaluated with tire chip replacement levels for coarse aggregate in increments of 10% by volume, up to a maximum of 50%. In addition, one series of mixtures with a cement content of 660 lb/yd^3 replaced fine aggregate with crumb rubber in 10% increments up to a 40% replacement. Lastly, two mixtures within the preliminary phase were evaluated which replaced percentages of both coarse and fine aggregates for their rubber counterparts. Three rubber surface treatments were investigated in the research phase to improve the adhesion between the rubber particles and cement paste. Ultimately, the objective was to recover a portion of the strength lose as a result of the elastic rubber materials replacing the more rigid virgin aggregate. The treatments evaluated in the study included: roughening through mechanical abrasion, soaking in a sodium hydroxide solution, and application of a silane coupling agent. A comprehensive suite of tests were conducted on the research mixtures that evaluated the rubberized concrete mixtures for fresh concrete properties, compressive strength, indirect splitting tensile strength, flexural modulus of rupture, static modulus of elasticity, dynamic modulus of elasticity, rapid chloride ion penetrability, drop hammer impact resistance, and load-deflection area. The major findings and conclusions as a result of this work are summarized in the following.

9.1 | Fresh Concrete Properties Summary

Overall, it was determined that rubber aggregates have a significant effect on fresh concrete properties. Generally, when HRWRA dosages remained constant, slump values tended to decrease with increased rubber contents. Even though the slump values were low for some rubberized concrete mixtures, the mixtures remained cohesive and easy to place. Concrete air contents were shown to increase slightly with increased rubber replacement levels; however, the appropriate air contents were maintained with low AEA addition rates. As was expected, the unit weight decreased nearly linearly with increased rubber contents. Ultimately, the fresh concrete properties were able to be maintained to within the GDOT Class A and Class B specification.

9.2 | Hardened Concrete Properties Summary

The compressive strengths of the concrete mixtures decreased with increased rubber aggregate contents. Cement contents were observed to have greater influence on rubberized concrete compressive strength at lower rubber contents than higher levels. In addition, the replacement of fine aggregate with crumb rubber produced higher compressive strengths when compared to an equal percent replacement of coarse aggregate with tire chip. Ultimately, concrete mixtures containing 10% tire chip were able to attain adequate compressive strengths for GDOT Class A concrete at all cement levels tested without a rubber surface treatment and 20% when a sodium hydroxide treatment was performed. Concrete mixtures utilizing crumb as a fine aggregate replacement were able to gain adequate strengths up to a 40% replacement level. Additionally, adequate strengths were attained with up to a 20% crumb rubber and 10% tire chip replacement.

The results of the indirect splitting tensile strength test showed a decrease in tensile strength with increasing rubber contents. The NaOH surface treatment performed similarly or slightly better than the mechanical roughing treatment; however, the silane coupling agent appeared to provide better performance in tension when compared to the other two surface treatments. Similar to the indirect splitting tensile strength results, a decrease in modulus of rupture was experienced with increasing rubber contents. Most notable observation with the modulus of rupture testing was the behavior of the prismatic beams at and immediately following failure where additional load below the peak was carried by the specimen for an appreciable amount of time after cracking. The static and dynamic modulus of elasticity tests produced results within the typical range of concrete. Similar to trends found in the literature, the dynamic modulus of elasticity values were considerably higher than that of the static method. Rubber inclusion appeared to have less impact on the dynamic modulus of elasticity test when compared to other mechanical properties. Rubberized concrete mixtures were categorized as having moderate permeability per the rapid chloride ion penetrability test. This was comparable to the control mixture.

The most influential outcome was the performance of the rubberized concrete mixtures during the drop hammer impact test. The rubberized mixtures at 10% and 20% replacement levels and all surface treatments out performed the control mixture by remaining intact after initial crack formation and the ability to absorb additional impact loads without fracturing.

9.3 | Recommendation

Based upon the results from this study, the recommended use of rubber aggregates in concrete mixtures include:

- The use of recycled tire chips or crumb rubber may be used in the proportioning of concrete mixtures so long as the blended aggregate gradation remains in satisfactory compliance with ASTM C33.
- Rubberized concrete mixtures shall be proportioned using the absolute volume method where the replacement of coarse and fine aggregate is made on a volume basis.

- The use of chemical admixtures are necessary to ensure rubberized concrete mixtures entrain the appropriate quantity of air voids while maintaining adequate workability and consistency. A VMA was necessary to suspend the rubber particles and prevent them from floating to the top of the concrete surface.
- The inclusion of 10% replacement of coarse aggregate with tire chip without a rubber pretreatement and up to 20% replacement with a sodium hydroxide treatment may be used and satisfy the GDOT Class A and Class B compressive strength requirements.
- The impact resistance of the concrete was significantly improved through the incorporation of tire chips.

9.3.1 | Applications for Rubberized Concrete

Although compressive strength may be sacrificed to a reduced level, the impact resistance of rubberized concrete may prove beneficial in certain applications. The results of this study demonstrated satisfactory mechanical performance (compressive strength, tensile capacity, modulus of elasticity, and permeability) for mixtures incorporating a maximum of 20% tire chips. The improved resistance of the rubber-modified concrete to impact will benefit concrete structures subject to repeated and instantaneous loadings. This section discusses a few applications for which rubberized concrete in structural applications should be explored.

9.3.1.1 | Concrete Barrier Walls

Concrete barrier walls are a necessary part of GDOT's interstate system and are frequently impacted by vehicles. Figure 9-1 shows impacted and damaged barrier walls along I-20 near Conyers, GA. The results of this study signify the utilization of recycled tire chips for concrete mixtures designated for barrier walls may result in better performance, yielding greater plastic deformation on impact and smaller deceleration forces during vehicle-wall collisions, and ultimately creating a safer barrier for the motoring public and saving lives from vehicle impact. Section 8.0, Future Work, discusses the need to extend this investigation into the development of a nonlinear finite element analysis model for crash simulation on concrete barrier walls incorporating tire chips as well as testing on scaled concrete barriers to confirm the analytical model. Further, the addition of fibers should be evaluated for improved performance.

Figure 9-1. Impacted and Damaged Concrete Barrier Walls on I-20

9.3.1.2 | Concrete Barrier Glare Protection Section

Conventional concrete is often used in the construction of the concrete glare protection section that extends from the top of the standard concrete barrier walls. These sections cast on top of the barrier wall may not require the same stringent requirements as that of the barrier wall itself. However, the glare protection section will often be damaged during vehicular impact resulting in section loss. Incorporating a concrete such as the rubberized concrete mixtures produced in this study that exhibited improved impact resistance and remained intact through repeted loadings may prove beneficial for this type of section. Figure 9-2 shows damaged glare protection concrete sections along EB I-20. Figure 9-3 shows a recently repaired section.

Figure 9-2. Damaged Glare Protection Concrete Sections on EB I-20

Figure 9-3. Repaired Glare Protection Concrete Sections on EB I-20

9.3.1.3 | Concrete Curb and Raised Medians

Other applications for which the rubberized concrete mixtures could be used include concrete curbs and raised concrete medians. These structures are often subjected to repeated loading when drivers veer out of the roadway lane impacting the curb. Over time, these structures experience severe cracking resulting in complete section loss. See Figure 9-4. In addition, raised concrete medians, Figure 9-5, have become a popular addition to highways located within urban areas. These may see repeated impact loading as a result of turning semi-trucks with wide turning radii. The improved toughness and ability to remain intact through significant impact loadings make rubberized concrete an ideal material for construction of curb and raised concrete medians.

Figure 9-4. Concrete Curb Section Loss

Figure 9-5. Raised Concrete Medians

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