FINAL REPORT

Ground Tire Rubber (GTR) as a Component Material in Concrete Mixtures for Paving Concrete

Contract No. BDV30 977-08

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DISCLAIMER

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
yd	Yards	0.914	meters	m
mi	Miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		AREA		
in^2	Square inches	645.2	square millimeters	mm^2
ft^2	Square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003).

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	Grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric	1.103	short tons (2000	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per	lbf/in^2

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16. Abstract
This research was done to investigate if the problems associated with flexibility and temperature sensitivity (expansion and contraction) in roadway concrete pavements can be addressed by replacing some of the fine or coarse aggregate component with crumb rubber, specifically, Ground Tire Rubber (GTR). The research also intended to find out the general effects of adding the GTR to the conventional pavement concrete, in terms of the mechanical properties and workability, requiring several laboratory tests to be conducted as part of the study. Finally, the research was required to evaluate the practical implementation at a ready mix plant, of the proposed use of GTR as a component in the concrete. It was found from the study that the modulus of elasticity of concrete is reduced when GTR is used in concrete, thus the pavement concrete becomes more flexible. Based on the results of the tests for the coefficient of thermal expansion (CTE), it was not conclusive from this study, that adding GTR will significantly affect the expansion and contraction in the concrete pavement.

Many valuable findings from this study include the following: the optimal content for GTR for use as a component in the paving concrete mixture is 15% by weight of the fine aggregate; at a water/cementitious ratio of 0.44, concrete with GTR of 15% by weight of the fine aggregate, using water-reducing admixtures, can achieve a 28-Day compressive strength of about 3000 psi as well as reasonable values of the flexural strength and split tensile strength; slump was observed to typically decrease with addition of GTR but use of the water-reducer will eliminate this problem; the unit weight of the GTR concrete is less than that of the conventional concrete; air content will always increase with addition of GTR to the concrete but the use of a defoaming agent will reduce the foam and air content; GTR concrete has a non-brittle mode of failure in compression and flexure; examining GTR concrete under the Scanning Electron Microscope (SEM) indicated that there is good bonding between the rubber particles and the cement matrix in the concrete; pretreatment of GTR by simple washing and drying may improve the compressive strength of the GTR concrete; GTR concrete has very good plastic and dry shrinkage attributes, with the ability to resist shrinkage cracking; the ready mix plant operations will require dry-safe storage of the GTR, customized packaging (bag sizes or bag material) of the GTR for convenient batching, and a less duration for mixing before placement (when compared to the 90 minutes mixing duration allowed for conventional concrete); the GTR concrete can be used in the following applications: Class I pavement; sidewalks; curbs and inlets; or applications where the compressive strength of 3000 psi or less is adequate and also where shrinkage may be a problem.

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EXECUTIVE SUMMARY

FDOT has identified some issues related to inadequate flexibility in its roadway concrete pavements. These issues include the use of high strength mixtures with limited flexibility, as well as induced expansion and contraction in the pavement due to temperature changes. This research investigated whether these problems can be addressed by replacing some of the fine or coarse aggregate component with crumb rubber, specifically, Ground Tire Rubber (GTR). The study sought to discover whether GTR will increase flexibility in concrete pavement and address the temperature sensitivity issues. The research also intended to explore the general effects of adding GTR to conventional pavement concrete, in terms of its mechanical properties and workability. Finally, the research was required to evaluate the practical implementation of GTR as a component in the concrete at a ready mix plant.

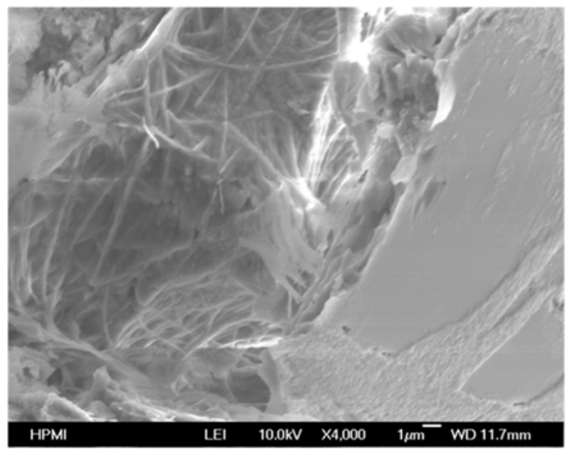
The first primary conclusion from this study is that, yes, because the modulus of elasticity is reduced, the pavement concrete is made more flexible by partially replacing fine aggregate with GTR. However, the coefficient of thermal expansion (CTE) tests did not conclusively show that adding GTR will significantly affect the CTE of the concrete. Thus, GTR cannot be confirmed to have an effect on the expansion and contraction of concrete pavement.

Many valuable findings resulted from this study of the effects of adding GTR to concrete in terms of the following concrete properties: air content; workability; unit weight; compressive strength; flexural strength; tensile strength; modulus of elasticity and Poisson’s ratio; impact resistance or toughness; interface bonding evaluated through use of the Scanning Electron Microscope (SEM); plastic shrinkage; and dry free shrinkage.

Although the primary focus was on GTR, it should also be noted that the research involved some preliminary tests using tire rubber chips in concrete (as partial coarse aggregate replacement) to evaluate their effects on the concrete’s mechanical properties. The final task of the study (ready mix plant implementation, including the casting and monitoring of the test slabs on grade) was also successfully done, resulting in some useful observations.

While the detailed explanations are given later in this summary, the following conclusions can be made:

- The optimal content for GTR as a component in paving concrete is 15% by weight of the fine aggregate;
- At a water/cementitious ratio of 0.44, concrete with GTR of 15% by weight of the fine aggregate can, using water-reducing admixtures, achieve a 28-Day compressive strength of about 3000 psi;
- Slump was observed to typically decrease with the addition of GTR, but use of the water-reducer will eliminate this problem;
- Temperature trends relative to time in a fresh mix of GTR concrete are the same as conventional concrete (studied using thermocouples);
- Unit weight of GTR concrete is less than conventional concrete, making it useful for lightweight applications and for reducing dead loads from self-weight;
- Air content will always increase with addition of GTR to concrete, as well as foam formation on the surface of washout water. Use of a defoaming agent will reduce the foam and air content, but will make the concrete denser;
- Because they are directly related to compressive strength, the flexural strength, split tensile strength, and modulus of elasticity of GTR concrete mixes are lower than those of conventional concrete. However, with use of the water-reducer, their values can be increased;
- GTR concrete appears to be tougher and have a higher impact resistance than conventional concrete, but based on the stress strain curves; this cannot be proven to be necessarily true at this time. However, GTR concrete has a non-brittle mode of failure in compression and flexure;



- Examining GTR concrete under the Scanning Electron Microscope (SEM) indicated that there is good bonding between the rubber particles and the cement matrix in the concrete;
- Pretreatment of GTR by simple washing and drying may improve the compressive strength of the GTR concrete, but the GTR drying process may be demanding in order to avoid unwanted moisture in the concrete;
- The coefficient of thermal expansion (CTE) results did not support a strong correlation of CTEs with the addition of GTR to the concrete mixture;
- GTR concrete has very good plastic and dry shrinkage attributes, with a higher resistance to shrinkage crack formations than conventional concrete. This was demonstrated through controlled laboratory tests and also through long-term monitoring of concrete slabs cast on grade;
- The ready mix plant operations will require dry-safe storage of the GTR, customized packaging (bag sizes or bag material) of the GTR for convenient batching, and a shorter duration for mixing before placement (when compared to the 90 minutes allowed for conventional concrete).The compressive, flexural, and split tensile strengths were higher for samples taken at 15% of the dispatch than for those sampled at 85% of the entire mix, while the slump was also observed to increase with the time spent in the mixer.
- The GTR concrete can be used in the following applications: Class I pavement; sidewalks; curbs and inlets; or applications where the compressive strength of 3000 psi or less is adequate and also where shrinkage may be a problem.

Some preliminary tests were done on concrete mixes without the use of admixtures, using specimens cast by adding 0% to 40% GTR (by weight of fine aggregate) at 10% increments and 0% to 30% Rubber Chips at 10% increments. Final tests were conducted using concrete with admixtures (i.e., water reducer, air-entraining agent, and fly ash) and adding 0% to 20% GTR at 5% increments. The range in the amount of GTR added in the final tests was refined based on the preliminary tests, particularly by considering the ease of handling (workability) and the strength values of the samples. Other tests were also done towards the end of the study, including an evaluation of the pretreatment of GTR, a reduction in the water/cement ratio, and the addition of a de-foaming agent to reduce foam formation and air voids.

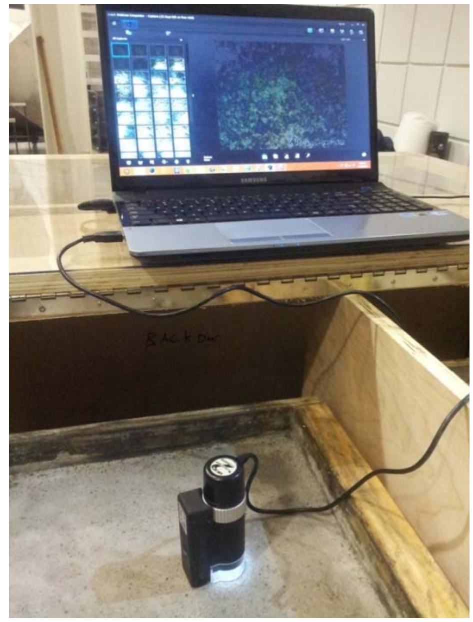
In the preliminary tests done without admixtures, the properties of fresh rubber concrete after adding rubber chips or GTR included a reduction in the slump and unit weight, and an increase in the air content. For instance, 20% GTR concrete had a slump of 0.5 in. and air content of about 6%. In comparison, the control concrete had a slump and air content of 2.5 in. and 2% respectively. In terms of the mechanical properties of the hardened concrete, adding rubber to the concrete decreased all the strength values and the modulus of elasticity. The rubber chips concrete were observed at comparable concrete contents to be slightly stronger than the GTR concrete. The 28-Day modulus of elasticity (x10^6 psi) for 20% GTR and 20% Rubber Chips were 1.85 and 2.60 respectively, compared to 3.70 for the control concrete.

In the final tests, use of a water-reducer enabled the slump to be maintained at about 1.5 in. for all the GTR mixes, compared to 2 in. for the control concrete mix. Air content was still high at about 6%. The unit weight dropped from 145 lb/ft^3 for the control concrete to about 130 lb/ft^3 for 15% GTR concrete. Despite the overall reduction in the mechanical properties, it was possible to achieve with 10% GTR and 15% GTR concrete with admixtures the compressive strength values of about 1800 psi and 1100 psi respectively at 28 days. The strength at 90 days for 10% GTR and 15% GTR concrete were about 2400 psi and 1400 psi respectively. The flexural strength and split tensile strength at 28 days were about 450 psi and 160 psi respectively for 15% GTR, compared to about 725 psi and 360 psi respectively for the control concrete.

The 28 day modulus of elasticity (x10^6 psi) and Poisson's ratio for 15% GTR were 1.6 and 4.1 respectively, compared to 4.1 and 0.21 respectively for the control concrete. For the coefficient of thermal expansion tests, the CTE values obtained were 10.1 x10^{-6} (in/in)/°C for 15% GTR compared to 9.86 x10^{-6} (in/in)/°C for the control concrete. The CTE results were within the range for normal concrete, that is, 8 to 12 x10^{-6} (in/in)/°C, but the trend of the results was not strong in supporting that adding GTR to concrete increases or decreases the CTE values of the concrete.

The results described above were based on a water/cement ratio of 0.50. By reducing the water/cement ratio to 0.44, the compressive strength values of 15% GTR concrete was increased to about 3000 psi and 3800 psi at 28 days and 90 days respectively, compared to 5700 psi and 6800 psi respectively for the control concrete.

To investigate the interactions among internal components, thermocouples were inserted in the fresh mixes of 15% GTR concrete and conventional concrete. Because the hydration process is exothermic, the stability in temperature trends of both specimens indicates that GTR does not interfere in the hydration process. Another effort to study the GTR at a detailed level involved using the Scanning Electron Microscope (SEM) to examine the bonding between rubber particles and other components of the cement matrix within concrete. Observation of needle-like ettringites on the interface of the cement matrix with the rubber indicated that there is good bonding.



For plastic shrinkage tests, which also include setting time tests, a modification of the ASTM C1579 specifications was adopted. This modification required the construction of an environmental chamber (described as a fan box in ASTM C1579), as well as the fabrication of two specified molds for the testing. The concrete mix design for the plastic shrinkage tests was revised according to specification requirements of the maximum size aggregate, with no admixtures. Results obtained from setting time tests showed that GTR delays the setting in concrete. For 15% GTR concrete, the initial and final setting times were 360 min. and 850 min. respectively, compared to 215 min. and 410 min. respectively for the control concrete. In terms of plastic shrinkage cracks observed on the samples, the control concrete had continuous cracks identified at 70 locations, with an average crack width of 0.44 mm. The 15% GTR concrete had discontinuous cracks at 35 locations and an average crack width of 0.34 mm. Results from plastic shrinkage crack measurements showed including GTR in concrete decreases and slows down the formation and propagation of plastic shrinkage cracks. When compared to the control concrete, the crack frequency decreased generally with addition of GTR. However, while the crack widths remained fairly constant, incremental increases in rubber content also caused a slight increase in frequency of crack positions. The 20% GTR concrete had more cracks than 15% GTR concrete, which also had more than 10% GTR concrete.

A limited drying (free) shrinkage test was conducted using control concrete and 10% GTR concrete. It was observed that the GTR concrete exhibited less shrinkage strain. It should be noted that this was a limited test and further research is needed. GTR concrete in free shrinkage performed favorably during the ready mix plant tests when two 4 in. thick 30 ft. sidewalk concrete slabs were cast on grade, one with 15% GTR concrete and the other as the control with conventional concrete. Both slabs were continuously monitored for several weeks and it was observed on Day 54 that while the GTR concrete slab had not cracked anywhere, the control concrete slab had a continuous crack across the entire width about 12 ft. from the top edge of the slab. Both slabs were also observed continuously for temperature at the surface relative to the ambient temperature, which estimates the concrete's contribution to the heat island effect, a very important factor in sustainability (energy conservation). No significant difference occurred in the surface temperatures for both slabs.

Lessons from the ready mix plant operations suggest that the GTR packaging is very important, as they cannot be introduced into the mixers like the other conventional components of concrete. Customizing packaging to allow ease of introduction is recommended, e.g., when say 135 lbs is needed, two 50 lb. standard bags (manufacturer's size) will be used along with a customized bag of 35 lbs GTR. Storage is very important as the GTR may absorb moisture if not kept dry. For the fresh concrete, it was observed that extended mixing time for the GTR concrete may lead to increase in the slump and reduction in eventual strength of the hardened concrete.

Finally, there is a great deal of interest in the sustainability of concrete, both in its production and its applications, including its use as pavement slabs. The GTR is a recycled material that improves some properties of concrete, which makes GTR concrete more sustainable, both environmentally and economically. GTR serves as a partial replacement for sand in concrete. Because sand is a mined or quarried product, GTR replacing sand may reduce the negative effects associated with producing and transporting the fine aggregates (energy consumption, global warming, fossil fuel depletion, etc.). By reusing waste rubber tires, GTR reduces the unhealthy stockpiling of waste rubber tires that constitute fire hazards and locations for breeding mosquitoes, etc. Economically, use of GTR will lower the overall life-cycle cost of the concrete member when compared to conventional concrete: lighter unit weight implies smaller member size and cost; lower modulus and reduced cracking from plastic and dry shrinkage strains imply lower maintenance cost and reduction or elimination of construction joints on concrete pavement slabs.

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1. Introduction

Disposal of waste tire rubber in landfills has been an environmental concern worldwide, and particularly in the United States, because the rubber is not biodegradable. These environmental concerns have led to considerable rubber-recycling uses, mainly in the form of ground rubber, also referred to as sized-reduced rubber or crumb rubber. There are two classes of particle sizes: “ground” rubber (passing No. 10 sieve) and “coarse” rubber (larger than No. 10 sieve, with a maximum size of one-half inch) (EPA 2012). In California, Arizona, and Florida, the most popular users in highway construction, the largest application for ground rubber is as asphalt binder. Through 2011, these states have consumed an estimated 220 million pounds, or approximately 12 million tires (EPA 2012).

With similar motivation, many studies have investigated using ground rubber as a construction material component in mortar (Huynh et al. 1996) and in Portland cement concrete (Li et al. 1998, Nehdi and Khan 2001, Kaloush et al. 2005, Savas et al. 1997, and Fedroff et al. 1996). The Florida Department of Transportation (FDOT) has funded some studies on the use of rubber in asphalt binders (FDOT 2012a), resulting in the development of specifications for its applications.

1.1 Background and motivation for study

The Florida Department of Transportation (FDOT) has currently identified some problems with its roadway concrete pavements being of high-strength mixtures that are not flexible enough.as well as induced expansion and contraction in the pavement due to temperature changes. To address these problems, it was suggested that replacing some of the fine or coarse aggregate component with crumb rubber would provide temperature-adaptable flexibility in the concrete pavement.

Naik and Siddique (2002) described tire rubbers, in terms of its reuse, as being identified by whether they are from automobiles or trucks, and can be classified as whole tire, slit tire, shredded or chopped tire, ground rubber or, as a crumb rubber product. The typical materials used in the manufacture of tires are Synthetic Rubber; Natural Rubber; Sulfur and sulfur compounds; Phenolic resin; Oil (Aromatic, Naphtthenic, and Paraffinic); Fabric (Polyester, Nylon etc.); Petroleum waxes; Pigments (Zinc oxide, Titanium dioxide etc.); Carbon black; Fatty acids; Inert materials; and Steel wires. Tire chips are typically sized from ½ inch to 3 inch while ground rubber may range in size from 0.15 mm (No. 100 sieve) to 19 mm (3/4 inch). Repeated magnetic separation processes as well as screenings produce the ground rubber particles. Crumb rubber has particles with sizes ranging from 4.75 mm (No. 4 Sieve) to less than 0.075 mm (No. 200 Sieve).

Documents revealed that FDOT has already been using GTR in improving asphalt applications based on developed standard specifications (Item 919), test methods, and research projects (FDOT 2012a, 2012b, and West et al. 1996). The Department also sponsored research investigating potential application of GTR in the stabilization of subgrade soils (Cosentino and Bleakley 2012). Though the specifications of Item 919 were intended for asphalt-related applications, a review of the general requirements of GTR as well as the physical requirements were very helpful in understanding the FDOT’s experience in using this material. The Department’s Qualified Products List (QPL) indicated potential vendors of the GTR. The test method FM 5-559 was identified for GTR, as well as GTR’s requirements for specific gravity, moisture content, metal contaminants, and gradation (Types B and C). Other useful information from this specification includes the chemical composition and packaging of the GTR.

1.2 Literature review

The initial search of literature involves finding any established ASTM standard for GTR or rubber particles used in production of concrete or similar materials for pavement construction. The only applicable one was the ASTM Standard D6270. With focus on application in civil engineering facilities, the ASTM D6270 is primarily a standard for using recycled tire rubber as tire derived aggregate (TDA) in soil mixtures and other geotechnical applications such as in roadway bases, retaining wall backfills, embankment fills, etc. (ASTM 2012). This standard does not address using tire rubber in Portland cement concrete or cementitious composites.

One of the early studies on using recycled rubber in cementitious composites involved application in mortars, when Huynh et al. (1996) evaluated the mechanical properties of the mixture. This study explored two types of samples, one with granular rubber and the other with rubber shreds. The rubber granules decreased the compressive and flexural strengths of the mortar, while the rubber shreds reduced the mortar's cracking associated with plastic shrinkage.

Li et al. (1998) determined that incorporating rubber tire particles into Portland cement concrete, lowered compressive and flexural strengths. However, it was observed that toughness of the concrete was improved, as well as its capacity to absorb vibration. Fedroff et al. (1996) examined the feasibility of using finely ground rubber in Portland cement concrete, studying the effects on workability of the fresh mix, compressive strength, flexural strength, tensile strength, and the stress-strain relationship. The research included estimates of the modulus of elasticity. It was observed that the workability was slightly affected but that the strength and stiffness characteristics were reduced, when compared with conventional Portland cement concrete.

Most of the pertinent previous research efforts have identified common findings that the mechanical strength of the rubber concrete will decrease relative to that of conventional concrete, while shrinkage crack is reduced and impact resistance is improved. Some of the studies such as Kaloush et al. (2005) further identified that in crumb rubber (1 mm size rubber as fine aggregate) entrapped air may have contributed to the reduction in compressive strength. The same study also found that crumb rubber concrete has better thermal properties.

Eldin and Senourci (1993) reported from some of the early studies that substitution of coarse aggregates with tire rubber chips and crumb rubber led to considerable loss of compressive and split-tensile strength. Substitution for coarse aggregates caused up to 80% reduction in compressive strength while fine aggregate substitution produced up to a 65% reduction. Also substitution of both aggregate types led to a 50% reduction in split-tensile strength. Tountaji (1996) indicated that substitution of coarse aggregates led to 75% reduction in compressive strength and 35% reduction in flexural strength. Li et al. (1998) experimented with crumb rubber with diameter up to 2.5 mm as fine aggregate substitute. The study also observed that coating the ground rubber particles with cement improved the compressive strength of the rubber concrete, but not much effective in terms of improving the flexural strength.

Both studies by Li et al. (1998) and Fedroff (1996) noticed reduction in the rubber concrete's unit weight as more rubber is added. This acquired characteristic will enhance the rubber concrete's use as a lightweight component, with a lower dead load. Kaloush et al. (2005) performed some of the tests described above, in addition to thermal expansion tests, involving heating and cooling cycles. It was observed that adding crumb rubber reduced the coefficient of thermal expansion, when compared to the conventional concrete.

The challenges to using GTR in concrete generally would therefore primarily include the following: obtaining the adequate mechanical strength (compressive, flexural and tensile); assessing the benefits accrued in terms of impeding shrinkage crack propagation, improved impact resistance, or toughness; and estimating the extent of the improvement in thermal expansion capabilities. Other issues include evaluating which size of rubber to use (superfine size, fine aggregate size, or coarse aggregate size), and also ensuring workability during preparation and placement of the fresh mix.

1.2.1 Mechanism of strength development/reduction

Behavior of conventional concrete under compression is well understood, in terms of the stress-strain curve and the initiation and propagation of cracks within the matrix. But this behavior is not the same in the case of rubber concrete. Khatib and Bayomy (1999), in their study of the 28-day compressive strengths of rubber concrete mixtures, explained that the reduction may be due to rubber being a "soft" component in the concrete, thus becoming an elastic mismatch with its surrounding cement paste. This mismatch allowed cracks to develop quickly around the rubber particles when the concrete is loaded, leading to the failure of the rubber-cement matrix.

Eldin and Senouci (1993) observed that under compression loading, specimens of rubber concrete exhibited a gradual failure instead of the brittle mode in conventional concrete. They argued that when microcracks rapidly propagate in the cement paste, they encounter a rubber aggregate. Because of their ability to withstand large tensile deformations, the aggregate will act as tiny springs (Figure 1.1), delaying the widening of cracks and preventing full disintegration of the concrete mass.

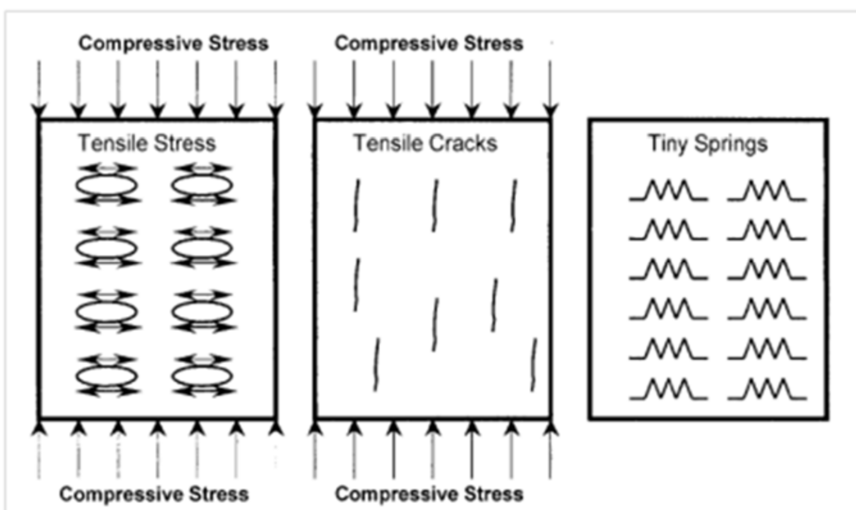


Figure 1.1. Behavior of rubber concrete specimens under compression (Eldin and Senouci 1993).

Strength development in freshly mixed Portland cement concrete is basically the result of a chemical reaction (the hydration process). The cement compounds, i.e., Tricalcium silicate, Dicalcium silicate, Tricalcium aluminate, Tetracalcium aluminoferrite, and Gypsum, undergo various reactions with water to produce calcium silicate hydrates (C-S-H) and other secondary byproducts such as calcium hydroxide. The C-S-H constitutes the primary component responsible for strength generation in concrete. Rubber is supposed to be a relatively inert material, not expected to seriously interfere in the chemical reaction, but the real chemical influence has not been studied. It is not impossible that the some of the cement chemical compounds are having slight reactions with the rubber particles in the transition zone, or perhaps slowing down the exothermic hydration process. These processes warrant further investigation. Scanning electron micrographs (SEM) will show, at highly magnified levels, the components of the hydrated concrete sections. Figures 1.2 and 1.3 reveal samples of SEMs, illustrating the formation of the various chemical components. Such SEMs will identify the rubber particles, the extent of bonding with other cement paste components, and any presence of trapped air.

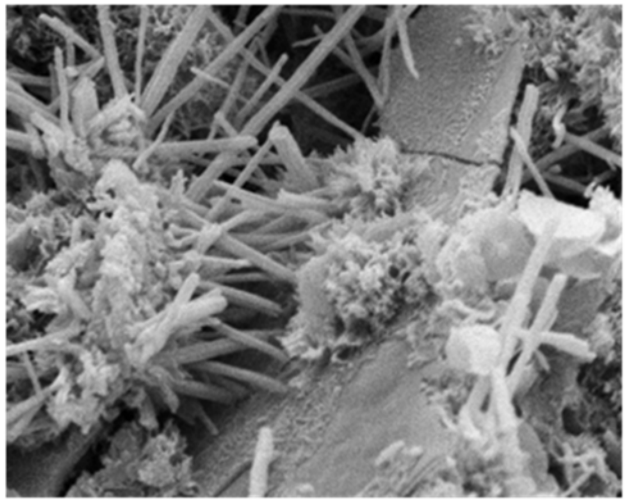


Figure 1.2. SEM of hydrated cement paste showing C-S-H, calcium hydroxide and ettringite (CementLab 2012)

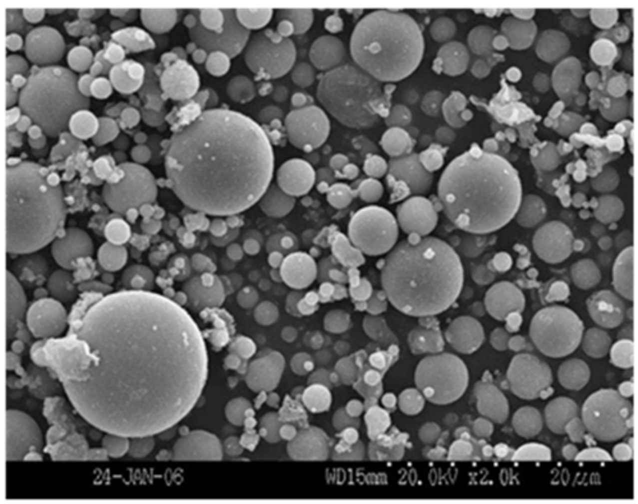


Figure 1.3. SEM of flyash in hydrated cement paste (UK 2012)

1.2.2 Shrinkage and impact resistance

While many studies have not examined shrinkage in rubber concrete, Hunyn et al. (1996) and Ravhavan et al. (1998) both reported that the addition of rubber shreds to mortar reduced plastic shrinkage cracking. Shrinkage in concrete is typically attributed to the cement paste rather than the aggregates. The contributions of rubber particles in the improvement of shrinkage crack resistance can be explained in the same way that fiber reduce shrinkage effects in concrete -- impeding the crack propagation. The impact resistance and toughness are due to the extended strain capability when rubber particles are mixed into the concrete.

1.2.3 Unit weight, workability, and air content

The addition of rubber lowers the unit weight of the concrete, because the rubber has a lower specific gravity than the other typical solid components. It has been reported that by adding rubber particles, the workability of concrete is reduced (Fedroff et al. 1996, and Khatib and Bayomy 1999), while the air content is increased (Fedroff et al. 1996, Khatib and Bayomy 1999, and Kaloush 2005). The concrete mixtures with finely ground rubber particles were found to be more workable than the coarse aggregate-sized rubber chips. To properly evaluate the influence of the rubber content on the workability requires performing the slump tests and studying the gradation (size distribution) of the rubber particles and its effect on the rheology of fresh concrete.

Furthermore, researchers have shown that pre-treating the rubber particles has improved its bonding with the cement paste. Treatments have included washing rubber particles with water, acid etching, plasma pretreatment, and coating with cellulose ethers solution (Eldin and Senouci 1993, Rostami et al. 1993, Tantala et al. 1996, and Li et al. 1998). These measures remove contaminants, increase the surface roughness of the rubber, and improve the internal bonding. Moreover, the compressive strengths obtained after the pretreatment of rubber were higher than those cases where common rubber particles were used.

1.2.4 Thermal properties

A previous study by Kalousha et al. (2005) observed that rubber concrete has favorable coefficient of thermal expansion (CTE) values, while reducing the thermal effects of heating and cooling on the concrete. For concrete pavements, the CTE is considered an important factor in the design of joints, calculating stresses, joint sealant design, and selecting sealant materials (USDOT 2012). There are three suggested levels for determining the CTEs for concrete pavements. Level 1 involves direct measurement of the change in length of laboratory specimens subjected to changes in temperatures, using AASHTO TP60, "Standard Test Method for CTE of Hydraulic Cement Concrete." Level 2 uses a weighted average of the constituent values based on the relative volumes of the constituents, while Level 3 is based on historical data. Level 1 testing is typically adequate, with an acceptable CTE range of $7.4 \times 10^{-6}/^{o}C$ to $13.0 \times 10^{-6}/^{o}C$ or $4.1 \times 10^{-6}/^{o}F$ to $7.3 \times 10^{-6}/^{o}F$ for the concrete material (USDOT 2012). The range of CTE values reflects the variation in CTE of concrete's component materials. The aggregate type has the greatest effect on the CTE of concrete. For instance, concrete containing limestone aggregate has a lower CTE than concrete containing siliceous aggregate. Also affecting the CTE of the concrete is the CTE of hardened cement paste, which is influenced by factors such as the water/cement ratio, cement fineness, cement composition, and age.

Thermal expansion was also a major interest in an FDOT-sponsored study evaluating the properties of concrete towards implementation of the AASHTO recommended mechanistic-empirical rigid pavement design (Ping and Kampmann 2008). This study by Ping and Kampmann (2008) measured the coefficient of thermal expansion (CTE) of Portland cement concrete. Their experience is crucial to this ongoing GTR concrete study, especially with the experimental aspects of the research.

1.3 Research objectives and tasks

Based on a review of what has been done in this field of research, and considering innovative techniques to handle the challenges, the proposed project involves the following components:

- Develop a revised formal mix design of the GTR paving concrete, with optimal selection of components based on established criteria of strength, workability, and sustainability;
- Design an experiment (considering factors such as air content, water cement ratio, etc.) for varying the amount of superfine or fine aggregate size GTR in trial mixes of rubber concrete;
- Establish pretreatment procedures for the GTR particles and any other component of the rubber concrete;
- Conduct laboratory tests, with the conventional pavement concrete mix as a control, to study within the rubber concrete mix the following: workability, air content, compressive strength, flexural strength, stress-strain relationships, Young's modulus of elasticity, shrinkage crack, impact resistance, and the coefficient of thermal expansion;
- Select the GTR best percentage content of the mix;
- Document experience and observations regarding mixing rubber concrete in the laboratory, in terms of air content, water cement ratio, and the GTR's moisture content;

- Work with a ready-mix plant as research partner, execute the implementation of results from the laboratory experiments, in terms of the mix design and actually mixing at the ready plant;
- Identify and recommend methods for storing GTR at the ready mix plant and also methods for introducing the GTR into the ready-mix trucks;
- Perform a sustainability analysis of the GTR concrete, including a comparison with the conventional concrete mix, in terms of lifecycle costs; and
- Prepare a final comprehensive report documenting all results and recommendations in the form of specifications indicating range of mix parameters, strengths, shrinkage crack requirements, and coefficients of expansion.

1.4 Summary and report organization

The society has recognized the environmental problems associated with disposal of waste rubber tires, and FDOT, along with some other organizations have already taken steps to use recycled tire rubber in construction materials. A familiar example is using asphalt binders in roadway construction. Technical literature review has revealed prior efforts by researchers to study the use of recycled rubber in mortar and concrete mixtures. Findings and recommendations from these previous studies serve as a background for the research conducted and presented in this report.

This report begins with a brief introduction and description of research objectives and tasks as already presented in this section. Next, Section 2 presents the experimental program in terms of the proposed laboratory tests, including selection of materials, the relevant specifications in terms of methods and procedures for the tests, and the development of a formal mix design for incorporating the GTR as a component of the concrete. The results from the laboratory tests are presented in Section 3, including findings first on preliminary tests performed on both rubber chips and GTR types of rubber mixed into concrete. With focus on GTR, more detailed tests are conducted on the concrete's mechanical and other pertinent properties; the results appear in this section. Section 4 discusses how the findings from the laboratory tests were implemented at a local ready mix concrete plant, documenting the benefits and challenges of implementing the proposed use of GTR concrete on a large scale. With GTR in concrete, the use of waste tire rubber is recognized as a sustainable measure and discussed in Section 5. Finally, the overall discussion and recommendations are presented in Section 6. Appendixes A and B show sample detailed data from various tests conducted in the study.

2. Experimental program

This section of the report describes the preparation for the experiments conducted as part of this research. A major focus of the research was on conducting laboratory experiments. Following the literature review, initial efforts were made to identify sources and specifications for the materials needed for the experiments. As part of the experimental program, a formal mix design was required for incorporating the GTR as a component of the concrete. The standard specifications for all the tests to be conducted were also reviewed and plans established for the test procedures, including documenting each test, the required methods, data collection, and analyses.

2.1 Materials

The materials used in the tests include coarse aggregates, fine aggregates, rubber (tire) chips and ground tire rubber (GTR). Admixtures were also obtained, including fly ash, water reducers, and air-entraining agents. The primary material being evaluated as a component in concrete is the GTR. Described in the following paragraphs, are the research team's experience and findings from a field trip to a GTR plant. The basic properties of all the materials were obtained from both manufacturer data and laboratory experiment procedures.

2.1.1 Field trip to GTR plant

The potential vendors for the GTR for this study were identified from the FDOT Quality Products List (QPL) as shown below in Table 2.1. Based on review of the product specifications at the supplier's plants, and also the proximity to Tallahassee, the research base, the Global Tire Recycling (GTR) Company located in Wildwood, Florida, was selected as the supplier of GTR for this study. The research team made a visit to the GTR plant to learn more about the material production.

Table 2.1. FDOT List of suppliers for Standard Item No. 919 Ground Tire Rubber Type B

QPL Number	Product ID	Manufacturer	Approval Date
S919-0005	PaveFlex Type B	Liberty Tire Recycling9675 Range Line Road Port Saint Lucie FL 34987	8/27/2002
S919-0006	Microgrind Ground Tire Rubber	Global Tire Recycling1201 Industrial Drive Wildwood FL 34785	10/1/2002
S919-0008	MicroDyne 400-AM-D	Lehigh Technologies120 Royal Woods Ct. SW Tucker GA 30084	8/3/2012

Global Tire Recycling is a manufacturer of fine mesh crumb rubber serving all of Florida and the United States. The plant also produces custom-ground sizes and ships products to various destinations. The purpose of the field trip to the Global Tire Recycling was to observe the overall processes and the grinding technology involved in producing different sizes of crumb rubber. The trip was also intended to facilitate purchase of the needed materials for the research. Upon arrival at the plant office, the team was given an overview of the sample sizes of crumb rubber mostly produced at the plant for various customers. Some sizes and their corresponding uses are listed below:

- 1 inch chip – these are mostly used as landscaping material, as it offers a beautiful background to highlight shrubs and flowers. It can be used in any decorative scheme to contrast with other materials like gravel, marble, woodchips and mulch. It provides excellent drainage since it does not absorb water but helps to hold moisture in the soil and reduce evaporation by providing a barrier.

- 3/8 – 1/8 inch chip - these are commonly used in playgrounds. This granular product, primarily between 3/8 inch & 1/8 inch in size, is 100% steel free and contains naturally occurring white accent color from small amounts of cushion fiber and white granular rubber. They meet the maximum safety standard for fall height. At 6" deep, the critical fall height of shredded tires ranges from 10-12 feet. This product is tested to ASTM specification and meets the maximum 12 foot (or greater) critical fall height criteria. This means that it has greater shock absorbing characteristics, which should result in fewer injuries from falling compared to sand, mulch, or pour-in-place surfaces.
- 40 mesh (1/16 inch) – these are primarily used in asphalt mix. All F.D.O.T. asphalt highway projects require D.O.T. 40 mesh crumb rubber in a 12% mixture in the liquid asphalt for the top friction course and D.O.T. 20 mesh crumb rubber in a 5% mixture as a membrane inter-layer. These mixtures provide an extended life for the highways, a quieter ride for all passengers, and a useful recycling outlet for some of Florida's waste tires.

The research team was given a tour of the tire processing plant and observed the process of recycling tires, cutting tires into various sizes, screening, processing, and bagging of the various tire sizes. Recycled tires of various sizes are collected and passed through a primary shredder where they are cut into 2 inch chips as an initial process. This similar process goes on with chips going through series of shredders with each shredder cutting the tire chips into increasingly smaller sizes, and the repeated process of screening to remove all the steel and unwanted fibers. For each stage of shredding, particles that do not meet the requisite size are returned to the shredder through a repeated process of cutting/shredding.

The 40-mesh (1/16 inch) crumb rubber which was of particular interest to the research team is produced by a power grinder (1800 rpm). These sizes are obtained at a temperature of 153^{o}F. In order to prevent the crumb rubber from hardening (due to the excessively high temperature) during the bagging process, Calcium carbonate ($CaCO_3$) is added to speed up cooling. Crumb rubber is usually bagged as 50 lbs or super sizes of 2000 lbs. Waste steel strands are cleaned and taken to the steel mill, while tire fibers with fair amounts of rubber particles are taken to the furnaces. It is known that 1 ton of tire fiber burns as much as 1 ton of coal with tire fiber costing half the price of coal. In essence, nothing goes to waste. The research team was also briefed on the costs of GTR products. The following photographs were taken during the trip.


Figure 2.1. Initial pile and shreds of tire rubber being transported into the processing plant

Figure 2.2. Packaging of ground tire rubber and close-up view

2.1.2 Properties of materials

The list of the basic materials used on the research project is summarized in Table 2.2, showing the basic properties and sources of the materials.

Table 2.2 Basic materials and their properties

	[illegible]	ne Aggregate	Rubber chips	Ground Tire Rubber (GTR)
Type	**Crushed Limestone**	**Silica sand**	**3/8 in.**	**40 mesh**
Grade	57			
Supplier	Roberts Sand Co., Tallahassee, FL	Roberts Sand Co., Tallahassee, FL	Global Tire Recycl., Wildwood, FL	Global Tire Recycl., Wildwood, FL
Specific Gravity (SSD)	2.52	2.66	1.11	0.95
Absorption (%)	3.68	0.60	4.66	0.20
Dry-rodded unit weight (lb/ft^3)	93.80			
Fineness modulus		2.31		

NOTE: Admixtures (water reducer, fly ash, and air-entraining agent) obtained from Vulcan Materials, Tallahassee, FL.

The gradation of the aggregates and rubber components are shown in Figure 2.3, relative to the respective FDOT specifications, with the GTR shown relative to the FDOT Type B requirements.

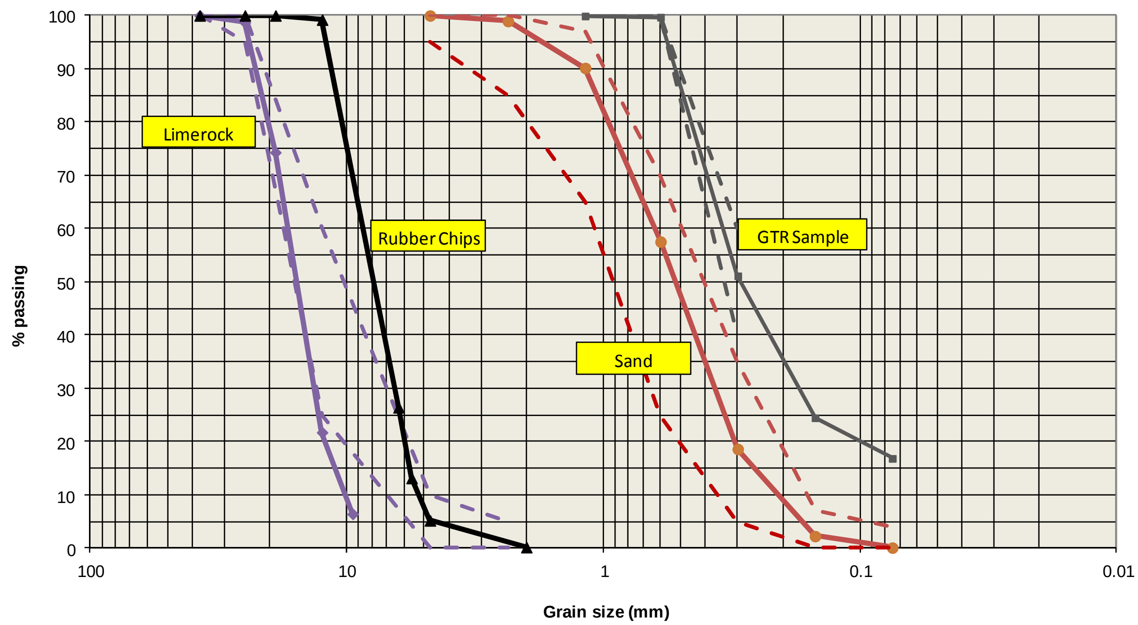


Figure 2.3. Gradation of rubber components and aggregates relative to FDOT Specification limits

2.2 Overview of laboratory tests

Various samples were prepared and tested. Using the conventional pavement concrete mix as a control the relevant ASTM, AASHTO, and FDOT standards, summarized in Tables 2.3 and 2.4, were utilized to perform the following tasks and tests:.

- Mixing concrete and preparing samples
- Workability (slump), air content, and unit weight tests
- Compressive strength, Modulus of Elasticity, and Poisson's Ratio
- Flexural strength test
- Split tensile strength test
- Coefficient of expansion test
- Plastic shrinkage test, and
- Drying shrinkage test

In addition to these listed standard tests, the Scanning Electron Microscope (SEM) examined the hardened concrete samples at very high magnification levels. The tests were conducted in stages. In the first stage, aggregates and rubber components (rubber chips and ground rubber) were tested for their individual properties. Also at this stage, considering both rubber chips and GTR, all the tests (except the shrinkage tests) were conducted on Portland cement concrete mixtures, including varied amount of rubber components. The rubber chips' contents were defined by percentage of the coarse aggregate, while GTR content was defined by percentage of fine aggregates.

The second stage of tests involved considering only the ground tire rubber, using admixtures in the concrete mixtures, and repeating the tests conducted earlier. The final stage of the tests included focus on the shrinkage tests and using concrete mixtures without admixtures, considering only the ground rubber. In the first stage tests on concrete mixtures, amounts of rubber components varied from 0% to up to 40%, in 10% increments, based on the limits of the ease of handling the concrete specimens. The results of the initial tests led to a refinement of the varied amount of rubber in the subsequent tests in the later stages, with the use of 0%, 5%, 10%, 15%, and 20% GTR contents.

Table 2.3 Test standards for aggregates and GTR

Test Type	**ASTM Designation**
Sieve analysis	FM 5-559: Florida Method of Test for Testing of Ground Tire Rubber
Moisture content	FM 5-559: Florida Method of Test for Testing of Ground Tire Rubber
Specific gravity	FM 5-559: Florida Method of Test for Testing of Ground Tire Rubber
Sieve analysis	ASTM C136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
Specific gravity and absorption	ASTM C127 Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
Unit weight	ASTM C29 / C29M Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate

Table 2.4 Test standards for concrete mixtures

Test Type	**ASTM Designation**
Slump	ASTM C1430 Standard Test Method for Slump of Hydraulic Cement
Air Content	ASTM C231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
Unit Weight	ASTM C138 Standard Test Method for Unit Weight, Yield and Air Content (Gravimetric) of Concrete
Compressive Strength	ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Modulus of Elasticity and Poisson Ratio	ASTM C469 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Flexural Strength	ASTM C78 Standard Test method for Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)
Split Tensile Strength	ASTM C496 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
Plastic Shrinkage	ASTM C1579 Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)
Hardened Shrinkage	ASTM C157 / C157M Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
Thermal Expansion	AASHTO TP60 Standard Test Method for CTE of Hydraulic Cement Concrete.

2.3 Mix design procedures

This section presents the development of a formal mix design method for proportioning constituents of a Portland cement concrete mixture incorporating the GTR as a component in pavement concrete. The mix design procedures are presented, as well as some preliminary data collected from FDOT sources. The design is implemented in a Microsoft excel spreadsheet template.

Due to the different specific gravities of the constituting materials, the concrete mix design approach adopted in this study is the Absolute Volume Method, also known as the American Concrete Institute (ACI) method. Fully described in the ACI 211.1 Specification (ACI 2012), and exemplified in its application by the Virginia Department of Transportation (VDOT 2012), this method is well explained in many reports. The overall concept is to consider unit cubic yard or 27 ft^3 of Portland cement concrete and determine the solid volumes occupied by the constituent materials, including the entrapped air. The coarse aggregate properties such as maximum nominal size, specific gravity, and absorption are utilized as well as the fineness modulus, specific gravity, and absorption of fine aggregates. In this study, the specific gravity of GTR is considered, with a desired percentage of the GTR-Fine aggregate mix, in the final stages of the mix design to estimate the amount of GTR needed. The mix design will result in the amount (weight) of each material needed to produce 27 ft^3 of concrete. A Microsoft Excel Spreadsheet was developed to implement this mix design procedures, but the steps are explained in the following paragraphs.

The first step in the design is to enter the total amount of cementitious materials before estimating the required amount of Portland cement and fly ash based on the specifications. The solid volumes occupied by these two materials, as well as other constituent materials, are then estimated based on equation 2.1 below.

$$v_s = \frac{W}{G_s \gamma_w} \tag{2.1}$$

Where

v_s = solid volume of material, say in ft^3
W = weight of material, say in lb.
G_s = specific gravity of solids
γ_w = density of water, 62.4 lb/ft^3.

The amount of water can be estimated based on the permitted water/cement ratio, and the weight computed is converted to the solid volume. Entrapped air can be read from ACI Tables using the nominal maximum size of coarse aggregates, and the corresponding volume is estimated for the 27 ft^3 of concrete.

The next procedure involves estimating the solid volume of coarse aggregates. The dry-rodded unit weight of the coarse aggregate and its specific gravity are used to compute the solid volume (b_o) in unit dry-rodded volume. Based on the nominal size of coarse aggregate and fineness modulus of the fine aggregate, the dry-rodded volume (b/b_o) of coarse aggregate per unit of volume of concrete is read from pertinent ACI tables on coarse aggregates. This information is finally used to estimate the solid volume (b) of coarse aggregates in 27 ft^3 of concrete.

The remaining solid volume to complete the mix will be that of the GTR and the fine aggregate. This is estimated by simply subtracting the solid volume sum of all materials considered so far from the total volume of 27 ft^3. The resulting solid volume is then proportioned between GTR and fine aggregate using the desired proportions by weight in the GTR-fine aggregate mix. It is also necessary to convert the ratio by weight of GTR and Fine aggregate (FA) to respective ratios by volume.

Let the ratios by weights of GTR and FA be r_{GTR} and r_{FA} respectively, with the corresponding specific gravities G_{GTR} and G_{FA}, and the density of water represented as γ_w. Considering 1 lb amount of the GTR and FA mix, the ratio by volume of GTR, or v_{GTR} is given as

$$v_{GTR} = \frac{\left(\frac{r_{GTR}}{G_{GTR}\gamma_w}\right)}{\left(\frac{r_{GTR}}{G_{GTR}\gamma_w}\right)+\left(\frac{1-r_{GTR}}{G_{FA}\gamma_w}\right)} \tag{2.2}$$

Simplified, the ratios by volume becomes

$$v_{GTR} = \frac{1}{1+\left(\frac{G_{GTR}}{G_{FA}}\right)\left(\frac{1}{r_{GTR}}-1\right)} \tag{2.3}$$

And the ratio by volume of fine aggregate is estimated as

$$v_{FA} = 1 - v_{GTR} \tag{2.4}$$

The ratios by volume are then used, along with the specific gravities, to estimate the respective solid volumes of the GTR and fine aggregate in the mix. Finally using the information on specific gravities and density of water, the required amount of GTR, fine aggregate, and other component materials are estimated in terms of weight (lbs) for a cubic yard of the concrete mix.

2.3.1 Preliminary data gathering on mix design

A thorough review of the pertinent FDOT specifications on Portland cement concrete pavement and its materials was conducted to ascertain requirements relevant to the mix design. Also, FDOT District 2 was contacted and samples of mix design for concrete pavement were obtained.

The identified sections/items in the Standard FDOT specifications include Section 350 Cement Concrete Pavement, which has a material-related reference to "Concrete, Class I (Pavement)" in the FDOT Specifications Section 346 (FDOT 2012). Under Section 346, the following information was determined as relevant to mix design of concrete for pavements:

- 346-2.2 Types of Cement: Portland Type I or III.
- 346-2.3 Pozzolans and Slag, part (d) *Class I and Class II concrete, excluding Class II (Bridge Deck), are not required to meet the minimum fly ash or slag requirements. The fly ash content shall be less than or equal to 25% by weight of cement and the slag content shall be less than or equal to 70% by weight of cement.*
- 346-2.4 Coarse Aggregate Gradation: *Produce all concrete using Size No. 57, 67 or 78 coarse aggregate…For Class I and Class II, excluding Class II (Bridge Deck), the coarse and fine aggregate gradation requirements set forth in Sections 901 and 902 are not applicable and the aggregates may be blended..*
- 346-2.5 Admixtures: *Use admixtures in accordance with the requirements of this subarticle. Chemical admixtures not covered in this sub-article may be approved by the Department…*
- 346-3 Classification, Strength, Slump, and Air Content.

	Table 2		
	Specified Minimum Strength (28-day) (psi)	Target Slump (inches) (c)	Air Content Range (%)
Class 1 Concrete (Pavement)	3000	2	1 to 6
(c) The Engineer may approve a reduction in the target slump for slip-form operations.			

- 346-4.1 Master Proportion Table: Proportion the materials used to produce the various classes of concrete in accordance with Table 3:

-

	Table 3	
	Minimum Total Cementitious Materials Content lb/yd3	*Maximum Water to Cementitious Materials Ratio lb/lb
Class 1 Concrete (Pavement)	470	0.5
*The calculation of the water to cementitious materials ratio (w/cm) is based on the total cementitious material including cement and any supplemental cementitious materials that are used in the mix.		

- Although the specification for Class I concrete (Pavement) is not very restrictive on the aggregates, Sections 901 and 902 of the Standard Specifications are shown in the following paragraphs to portray the relevant information used in this study, with examples for Size Nos 57 and 67 Coarse aggregates and silica sand as the fine aggregate.
- 901-1.4 Gradation: *Coarse aggregates shall conform to the gradation requirements of Table 1, when the stone size is specified.*

	TABLE 1 Standard Sizes of Coarse Aggregate							
		Amounts Finer than Each Laboratory Sieve (Square Openings), weight percent						
Size No.	Nominal Size Square Openings	1 1/2 inches	1 inch	3/4 inch	1/2 inch	3/8 inch	No. 4	No. 8
57	1 inch to No. 4	100	95 to 100	-	25 to 60	-	0 to 10	0 to 5
67	3/4 inch to No. 4	-	100	90 to 100	-	20 to 55	0 to 10	0 to 5

- 902-2.1 Composition: *Silica sand shall be composed only of naturally occurring hard, strong, durable, uncoated grains of quartz, reasonably graded from coarse to fine, meeting the following requirements, in percent total weight.*

Sieve Opening Size	Percent Retained	Percent Passing
No. 4	0 to 5	95 to 100
No. 8	0 to 15	85 to 100
No. 16	3 to 35	65 to 97
No. 30	30 to 75	25 to 70
No. 50	65 to 95	5 to 35
No. 100	93 to 100	0 to 7
No. 200	minimum 96	maximum 4

As mentioned earlier, the next step in data gathering was to request sample of actual mix designs used on previous FDOT pavement concrete construction projects. Two of such samples were obtained from District 2 as shown in Figures 2.4 and 2.5 (Ivery 2012). In these mix designs, important information were obtained, for example, the types of coarse and fine aggregates used and their respective properties, as well as the specific admixtures used in the mixes.

CLASS CONCRETE: I PAVEMENT (3000 PSI)

SOURCE OF MATERIALS

COARSE AGGREGATE	: RINKER MATERIALS		GRADE: 57 S.G.(SSD):2.430
FINE AGGREGATE	: FLA ROCK IND.		F.M.: 2.21 S.G.(SSD):2.630
PIT NO.(COARSE)	: 87-090		TYPE: CRUSHED LIMESTONE
PIT NO.(FINE)	: 76-349		TYPE: SILICA SAND
CEMENT	: SUWANEE AMERICAN	BRANFORD	SPEC: AASHTO M-85 TYPE II
AIR ENTR.ADMIX	: DARAVAIR 1000	W.R. GRACE	SPEC: AASHTO M-154
1ST ADMIX	: WRDA 60	W. R. GRACE	SPEC: AASHTO M-194 TYPE D
2ND ADMIX	: ----		SPEC: ----
3RD ADMIX	: ----		SPEC: ----
FLY ASH	: STI PROASH	JACKSONVILLE	SPEC: ASTM C-618 CLASS F

HOT WEATHER MIX DESIGN
AGGREGATE CORRECTION FACTOR=0.8%

CEMENT (Kg) LBS	406	SLUMP RANGE	: 0.50 TO 3.50	(mm) IN
COARSE AGG (Kg) LBS	1780	AIR CONTENT	: 1.0 % TO 6.0 %	
FINE AGG (Kg) LBS	1275	UNIT WEIGHT (WET)	: 141.1	(Kg/M3) PCF
AIR ENT ADMX (mL) OZ	1.2	W/C RATIO(PLANT)	: 0.48	(Kg/Kg) LBS/LB
1ST ADMIXTURE (mL) OZ	25.4	W/C RATIO (FIELD)	: 0.48	(Kg/Kg) LBS/LB
2ND ADMIX (mL) OZ	0.0	THEO YIELD	: 27.00	(M3) CU FT
3RD ADMIX (mL) OZ	0.0			
WATER (ML) GAL	29.40			
WATER (Kg) LBS	245.0			
FLY ASH (Kg) LBS	102			

PRODUCER TEST DATA

CHLORIDE CONT	: 0.148	(Kg/M3) LB/CY
SLUMP	: 2.75	(MM) IN
AIR CONTENT	: 2.00	%
TEMPERATURE	: 99	DEG (C) F

COMPRESSIVE STRENGTH (MPA) PSI
7 -DAY- 3560 21 -DAY- 4420
-DAY- -DAY-

CC:
D.M.E. 2

Figure 2.4. Sample I of FDOT pavement concrete mix designs (Ivery 2012)

CONCRETE SUPPLIER: [redacted]
ADDRESS: [redacted]
PLANT LOCATION: [redacted] TELEPHONE NO: [redacted]
FDOT ASS[redacted]T NO. [redacted] PROJECT NO: [redacted]
DATE: [redacted]

CLASS CONCRETE: I PAVT. (3000 PSI)

SOURCE OF MATERIALS

COARSE AGGREGATE:	TARMAC	GRADE:	57 S.G.(SSD):2.440
FINE AGGREGATE :	FLORIDA ROCK	F.M.:	2.21 S.G.(SSD):2.630
PIT NO.(COARSE) :	87-145	TYPE:	CRUSHED LIMESTONE
PIT NO.(FINE) :	76-349	TYPE:	SILICA SAND
CEMENT :	PENNSUCO	SPEC:	AASHTO M-85 TYPE II
AIR ENTR.ADMIX :	MBAE 90 MASTER BUILDERS	SPEC:	AASHTO M-154
1ST ADMIX :	POZZ 200N MASTER BUILDERS	SPEC:	AASHTO M-194 TYPE D
2ND ADMIX :	----	SPEC:	----
3RD ADMIX :	----	SPEC:	----
FLY ASH :	SEPARATION TECH.	SPEC:	ASTM C-618 CLASS F

HOT WEATHER MIX DESIGN

CEMENT (Kg) LBS	406	SLUMP RANGE :	0.50 TO 3.50	(mm)IN
COARSE AGG (Kg) LBS	1710	AIR CONTENT :	1.0 % TO 6.0 %	
FINE AGG (Kg) LBS	1334	UNIT WEIGHT (WET):	141.0	(Kg/M3)PCF
AIR ENT ADMX (mL) OZ	4.0	W/C RATIO(PLANT) :	0.50	(Kg/Kg)LBS/LB
1ST ADMIXTURE (mL) OZ	20.3	W/C RATIO (FIELD):	0.50	(Kg/Kg)LBS/LB
2ND ADMIX (mL) OZ	0.0	THEO YIELD :	27.00	(M3)CU FT
3RD ADMIX (mL) OZ	0.0			
WATER (ML) GAL	30.50			
WATER (Kg) LBS	254.1			
FLY ASH (Kg) LBS	102			

PRODUCER TEST DATA

CHLORIDE CONT :	0.121	(Kg/M3)LB/CY
SLUMP :	2.50	(MM)IN
AIR CONTENT :	2.70	%
TEMPERATURE :	99	DEG (C)F

COMPRESSIVE STRENGTH (MPA)PSI
28 -DAY- 4830 -DAY-
-DAY- -DAY-

CC:
D. M. E. 2
TEST FILE

Figure 2.5. Sample II of past FDOT pavement concrete mix designs (Ivery 2012)

2.3.2 Example calculations on the mix design

In a Microsoft Excel Spreadsheet developed to implement this mix design, the procedures are those shown in Figures 2.6 and 2.7. An example of the mix design calculations is presented as follows. Looking at the sample mix designs from FDOT District 2 and also reviewing the FDOT Standard Specifications, the total amount of cementitious materials is taken as 500 lbs., which can be split into 400 lbs of Portland cement and 100 lbs of fly ash, based on the specifications (20% fly ash). The solid volumes occupied by Portland cement and fly ash are then estimated based on equation 2.1 to be 2.035 ft^3 and 0.712 ft^3 respectively. Next the amount of water is estimated based on the permitted water/cement ratio of 0.5, which is half of 500 lbs or 250 lbs. This is equivalent to 4.006 ft^3 "solid" volume. The assumed coarse aggregate here is the ½ in. maximum nominal size since the specifications is not really restrictive or specific on aggregate type. Entrapped air can be read from ACI Tables (Table 2.5) as 2.5% resulting in 0.675 ft^3 of "solid" volume in the designed 27 ft^3 concrete.

Table 2.5. Concrete mix design data

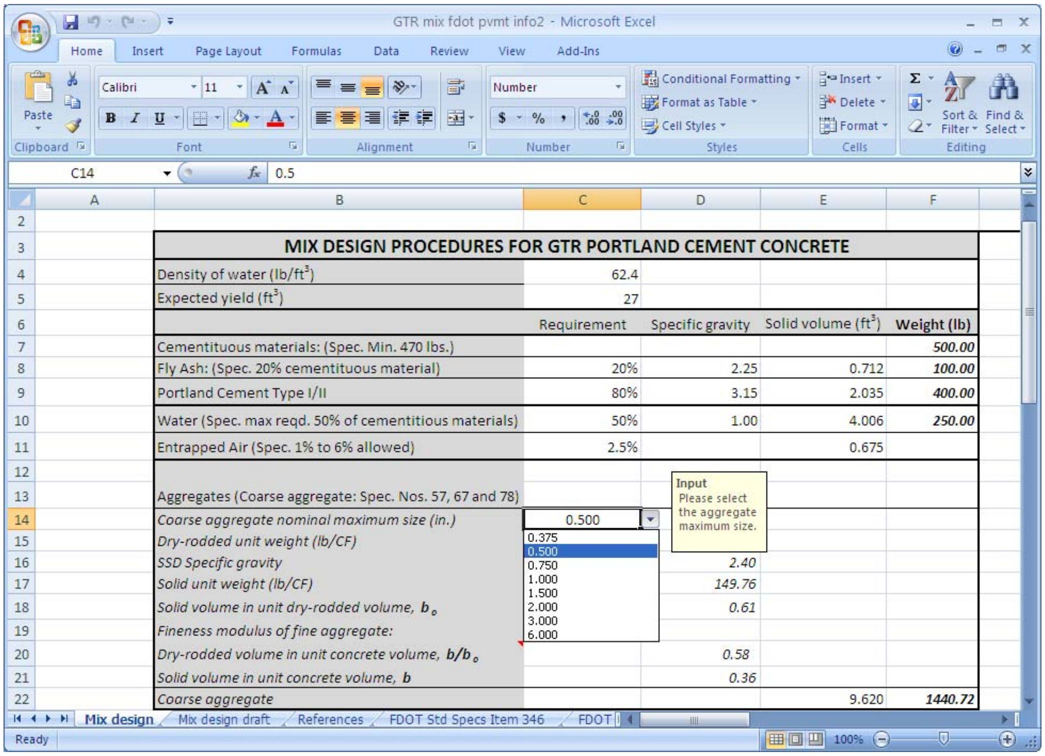
ACI TABLE A1.5.3.6 VOLUME OF COARSE AGGREGATE PER UNIT OF VOLUME OF CONCRETE								
Nom. Max. Size of Coarse Aggregate	Fineness Modulus of Sand							Entrapped air (%)
	2.40	**2.50**	**2.60**	**2.70**	**2.80**	**2.90**	**3.00**	
$^3/_8$ in.	**0.50**	**0.49**	**0.48**	**0.47**	**0.46**	**0.45**	**0.44**	2.5
$^1/_2$ in.	**0.59**	**0.58**	**0.57**	**0.56**	**0.55**	**0.54**	**0.53**	2.5
$^3/_4$ in.	**0.66**	**0.65**	**0.64**	**0.63**	**0.62**	**0.61**	**0.60**	2
1 in.	**0.71**	**0.70**	**0.69**	**0.68**	**0.67**	**0.66**	**0.65**	1.5
$1^1/_2$ in.	**0.75**	**0.74**	**0.73**	**0.72**	**0.71**	**0.70**	**0.69**	1
2 in.	**0.78**	**0.77**	**0.76**	**0.75**	**0.74**	**0.73**	**0.72**	1
3 in.	**0.82**	**0.81**	**0.80**	**0.79**	**0.78**	**0.77**	**0.76**	1
6 in.	**0.87**	**0.86**	**0.85**	**0.84**	**0.83**	**0.82**	**0.81**	

Next, the procedure requires estimating the solid volume of coarse aggregates. Assuming the specific gravity of 2.4, the solid unit weight of the aggregates is estimated as 2.4*62.4 or 149.76 lb/ft^3. With a dry-rodded unit weight of the coarse aggregate of 92 lb/ft^3, the solid volume (b_o) in unit dry-rodded volume is computed as a ratio 92 to 149.76 or 0.61. Based on the nominal size of coarse aggregate and fineness modulus of the fine aggregate (assumed as 2.50), the dry-rodded volume (b/b_o) of coarse aggregate per unit of volume of concrete is read from ACI Tables (Table 2.5) as 0.58. The product (b_o)*(b/b_o) is finally used to estimate the solid volume (b) of coarse aggregates, as 0.36 per ft^3 or 9.620 ft^3 in 27 ft^3 of concrete.

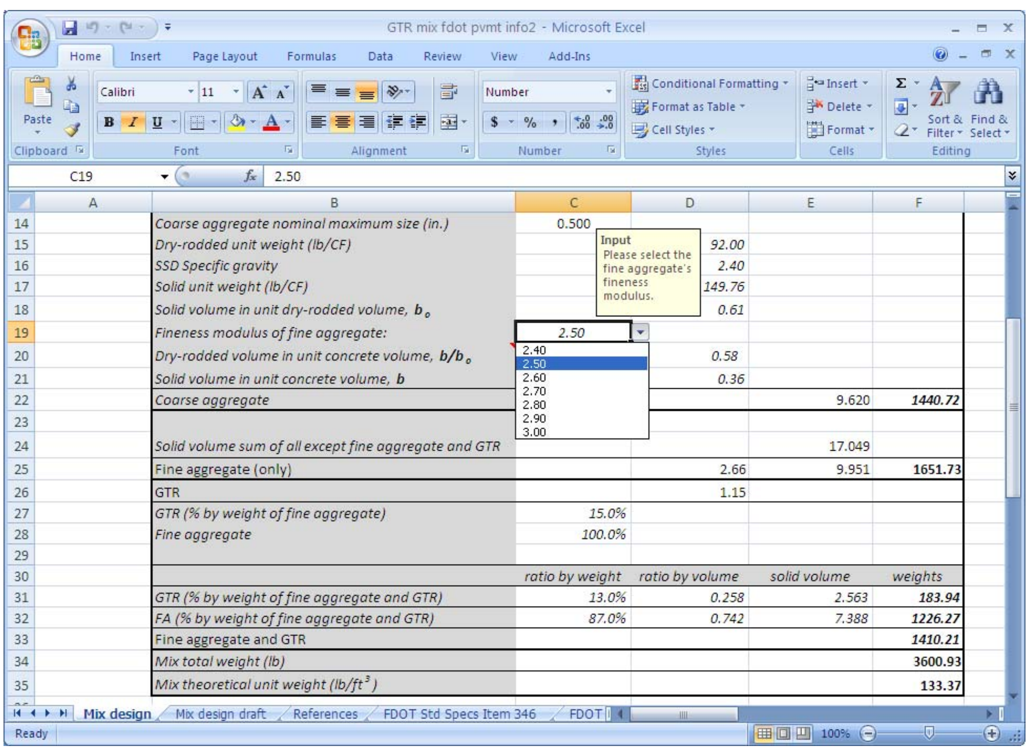
The remaining solid volume to complete the mix, i.e., that of the GTR and the fine aggregate, is 27 minus sum of all materials considered so far or 27 – 17.049, which is 9.951 ft^3. If the desired proportion of GTR is 15% by weight of FA or estimated 18% by weight of the GTR-FA mix, the equivalent volume proportions are computed using equations 2.2 and 2.3 as 25.8% of the GTR-FA mix. The resulting solid volumes for GTR and FA are then calculated using the materials' specific gravities to be 2.563 ft^3 and 7.388 ft^3 respectively. The required amount of each material, in lbs, with that of cement, fly ash, and water already known, is finally computed using the specific gravities and density of water. So for 1 cubic yard of concrete, the required amount (weights) for Portland cement, fly ash, water, coarse aggregate, fine aggregate, fine aggregate, and GTR are estimated to be, respectively, 400 lbs., 100 lbs, 250 lbs, 1440.72 lbs, 1226.27 lbs, and 183.94 lbs. The needed amount of admixtures (air-entraining and water-reducing agents) is not indicated in the mix design but can be reasonably assumed to be the same as in the sample FDOT mix designs.

MIX DESIGN PROCEDURES FOR GTR PORTLAND CEMENT CONCRETE				
Density of water (lb/ft^3)	62.4			
Expected yield (ft^3)	27			
	Requirement	Specific gravity	Solid volume (ft^3)	**Weight (lb)**
Cementituous materials: (Spec. Min. 470 lbs.)				***500.00***
Fly Ash: (Spec. 20% cementituous material)	20%	2.25	0.712	***100.00***
Portland Cement Type I/II	80%	3.15	2.035	***400.00***
Water (Spec. max reqd. 50% of cementitious materials)	50%	1.00	4.006	***250.00***
Entrapped Air (Spec. 1% to 6% allowed)	2.5%		0.675	
Aggregates (Coarse aggregate: Spec. Nos. 57, 67 and 78)				
Coarse aggregate nominal maximum size (in.)	0.500			
Dry-rodded unit weight (lb/CF)		*92.00*		
SSD Specific gravity		*2.40*		
Solid unit weight (lb/CF)		*149.76*		
Solid volume in unit dry-rodded volume, ***b_o***		*0.61*		
Fineness modulus of fine aggregate:	*2.50*			
Dry-rodded volume in unit concrete volume, ***b/b_o***		*0.58*		
Solid volume in unit concrete volume, ***b***		*0.36*		
Coarse aggregate			9.620	***1440.72***
Solid volume sum of all except fine aggregate and GTR			17.049	
Fine aggregate (only)		2.66	9.951	**1651.73**
GTR		1.15		
GTR (% by weight of fine aggregate)	*15.0%*			
Fine aggregate	*100.0%*			
	ratio by weight	*ratio by volume*	*solid volume*	*weights*
GTR (% by weight of fine aggregate and GTR)	*13.0%*	*0.258*	*2.563*	***183.94***
FA (% by weight of fine aggregate and GTR)	*87.0%*	*0.742*	*7.388*	***1226.27***
Fine aggregate and GTR				***1410.21***
Mix total weight (lb)				**3600.93**
Mix theoretical unit weight (lb/ft^3)				**133.37**

Figure 2.6. MS Excel Concrete Mix Design Template



a. Top section of mix design template



b. Bottom section of template

Figure 2.7. MS Excel Screen plots for concrete mix design template

2.3.3 Concrete mix proportions for laboratory tests

Using the mix design spreadsheet described above, the volume and weight requirements of the various components of the mixes were determined and utilized in the different types of tests conducted on the study. Table 2.6 shows a sample mix design for the first stage tests while tests under stage 2 were done using the mix design shown in Table 2.7. Table 2.8 shows the mix design for the shrinkage tests which required use of a smaller size coarse aggregate, changing it from the 1 inch to a ¾ in. max size.

Table 2.6 Sample mix design for stage 1 tests (1 in. max. size coarse aggregate) without admixtures

Rubber chips RBCHIP (% by weight of coarse aggregate); GTR (% by weight of fine aggregate)	0.0%	10.0%	20.0%	30.0%	10.0%	20.0%	30.0%	40.0%
Mix label	**PCC CONTROL**	**RBCHIP10**	**RBCHIP20**	**RBCHIP30**	**GTR10**	**GTR20**	**GTR30**	**GTR40**
Expected yield (ft^3)	2.7	2.1	2.1	2.1	2.7	2.7	2.7	2.7
Material	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**
Cementitious materials: (Spec. Min. 470 lb/CY)	**50.00**	**38.89**	**38.89**	**38.89**	**50.00**	**50.00**	**50.00**	**50.00**
Fly Ash: (Spec. 20% cementitious material)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Portland Cement Type I/II	**50.00**	**38.89**	**38.89**	**38.89**	**50.00**	**50.00**	**50.00**	**50.00**
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing only	**25.00**	**19.44**	**19.44**	**19.44**	**25.00**	**25.00**	**25.00**	**25.00**
Additional water for aggregate absorption	**7.25**	**5.22**	**4.94**	**4.73**	**7.08**	**6.97**	**6.89**	**6.83**
Entrapped Air (Spec. 1% to 6% allowed)	**1.5%**	**1.5%**	**1.5%**	**1.5%**	**101.5%**	**1.5%**	**1.5%**	**1.5%**
Coarse aggregate: Spec. No. 57	**172.53**	**0.00**	**0.00**	**0.00**	**172.53**	**172.53**	**172.53**	**172.53**
Fine aggregate	**150.60**	**117.13**	**117.13**	**117.13**	**117.65**	**96.54**	**81.85**	**71.04**
Rubber chips	**0.00**	**10.92**	**18.41**	**23.86**	**11.77**	**19.31**	**24.55**	**28.41**
Mix total weight (lb)	**405.38**	**300.78**	**290.83**	**283.58**	**384.03**	**370.34**	**360.82**	**353.81**
Mix theoretical unit weight (lb/ft^3)	**150.14**	**143.23**	**138.49**	**135.04**	**142.23**	**137.16**	**133.64**	**131.04**

Table 2.7 Sample mix design for stage 2 tests (1 in. max. size coarse aggregate) with admixtures

GTR (% by weight of fine aggregate)	0.0%	0.0%	5.0%	10.0%	15.0%	20.0%
Mix label	**PCC CONTROL1**	**PCC CONTROL2**	**GTR5**	**GTR10**	**GTR15**	**GTR20**
Expected yield (ft^3)	4.0	4.0	4.0	4.0	4.0	4.0
Material	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**
Cementitious materials: (Spec. Min. 470 lb/CY)	**74.07**	**74.07**	**74.07**	**74.07**	**74.07**	**74.07**
Fly Ash: (Spec. 20% cementitious material)	**0.00**	**14.81**	**14.81**	**14.81**	**14.81**	**14.81**
Portland Cement Type I/II	**74.07**	**59.26**	**59.26**	**59.26**	**59.26**	**59.26**
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing only	**37.04**	**37.04**	**37.04**	**37.04**	**37.04**	**37.04**
Additional water for aggregate absorption	**10.74**	**10.71**	**10.57**	**10.46**	**10.37**	**10.30**
Entrapped Air (Spec. 1% to 6% allowed)	**1.5%**	**1.5%**	**1.5%**	**1.5%**	**1.5%**	**1.5%**
Coarse aggregate: Spec. No. 57	**255.60**	**255.60**	**255.60**	**255.60**	**255.60**	**255.60**
Fine aggregate	**223.11**	**218.10**	**191.32**	**170.39**	**153.59**	**139.81**
GTR	**0.00**	**0.00**	**9.57**	**17.04**	**23.04**	**27.96**
Mix total weight (lb)	**589.82**	**584.81**	**567.60**	**554.14**	**543.34**	**534.48**
Mix theoretical unit weight (lb/ft^3)	**147.45**	**146.20**	**141.90**	**138.54**	**135.84**	**133.62**
Water reducer (oz.)	**0.00**	**3.00**	**3.00**	**3.00**	**3.00**	**3.00**
Air entraining agent (oz.)	**0.00**	**0.60**	**0.60**	**0.60**	**0.60**	**0.60**

Table 2.8 Sample mix design for stage 3 tests (¾ in. max. size coarse aggregate) without admixtures

GTR (% by weight of fine aggregate)	5.00%
Expected yield (ft^3)	1.4
Material	Weight (lb)
Cementitious materials: (Spec. Min. 470 lb/CY)	25.93
Fly Ash: (Spec. 20% cementitious material)	0
Portland Cement Type I/II	25.93
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing only	12.96
Additional water for aggregate absorption	3.51
Entrapped Air (Spec. 1% to 6% allowed)	2.00%
Coarse aggregate: Spec. No. 57	83.16
Fine aggregate	73.31
GTR	3.67
Mix total weight (lb)	199.03
Mix theoretical unit weight (lb/ft^3)	142.16
Water reducer (oz.)	0
Air entraining agent (oz.)	0

2.4 Preparation of concrete mixtures

Concrete batches were mixed with the aid of two 6-cubic-foot rotary drum mixers with the capability of mixing an expected yield of up to 4.5 cubic feet. Mixing was done in accordance with ASTM C192 (Section 7.1.2). This section provides directions for laboratory mixing and precautions to adhere to. In summary, concrete was mixed after all ingredients were in the mixer for three minutes followed by a three-minute rest and a two-minute final mixing sequence.

Below is a more detailed procedure used for mixing concrete batches:

1. All component materials were weighed according to the mix-design specifications.
2. Coarse aggregates, ground tire rubber, and half of the mixing water were placed in the mixer and allowed to mix for 1 minute in order to allow all lump formation in GTR to break.
3. Fine aggregates, cement, and the rest of the mixing water were added in that order and allowed to mix for another two minutes, after which the mixer was stopped.
4. The mixer was made to rest for three minutes, while concrete attached to the inner surface of the mixer was scraped off.
5. The mixing procedure continued for two minutes after which the fresh concrete was poured into a wheel burrow.
6. Temperature, slump, air content, and unit weight tests were then performed on the freshly poured concrete.

2.4.1 Specimens for compressive, modulus and split tensile tests

In evaluating the mechanical properties, the following steps were taken in making concrete specimens:

1. Cylindrical molds of dimension 6x12-in were filled in three equal layers with portion of freshly poured concrete.
2. Each layer was compacted with a 5/8-in diameter tamping rod with 25 times for each filling.

3. The third (final) layer was made to exceed the top of the mold prior to rodding in order to prevent filling the mold with more concrete following the third layer.
4. Excess concrete was scraped off the molds and the concrete surface was finished with the aid of a trowel.
5. Specimens were covered and placed in a cool environment for 24 hours.
6. Specimens were demolded after 24 hours and placed in curing tanks until specified times for testing.

2.4.2 Specimens for flexural tests

1. Beam molds of dimension 6x6x21-in were filled in three equal layers with portions of freshly poured concrete.
2. Each layer was compacted with a 5/8-in diameter tamping rod, 25 times for each filling, making sure the blows were evenly spread along the mold surface.
3. Similar to the cylindrical specimens, the third (final) layer was made to exceed the top of the mold prior to rodding in order to prevent filling the mold with more concrete after the third layer.
4. Excess concrete was scraped off the molds and the concrete surface was finished with the aid of a trowel after which specimens were covered and placed in a cool environment for 24 hours.
5. Specimens were demolded after 24 hours and placed in curing tanks with lime water (to avoid any length/volumetric change) until specified times for testing.

2.4.3 Specimens for coefficient of thermal expansion (CTE) tests

1. Cylindrical molds of dimension 4x8-in were filled in two equal layers with portion of freshly poured concrete.
2. Each layer was compacted with a tamping rod - 25 times for each filling.
3. The second (final) layer was made to exceed the top of the mold prior to rodding in order to prevent filling the mold with more concrete after the third layer.
4. Excess concrete was scraped off the molds and the concrete surface was finished with the aid of a trowel. Specimens were then covered and placed in a cool environment for 24 hours after which the specimens were demolded and placed in curing tanks until specified time for testing (28 days).

2.4.4 Specimens for plastic and free shrinkage tests

This will be covered comprehensively in the next major section of this report as part of the laboratory testing program.

2.4.5 Further processing of concrete specimens

Cylindrical Specimens for compressive strength, modulus of elasticity and coefficient of thermal expansion tests were end-grounded to ensure a uniform or flat surface for testing. The method of grinding the ends of cylindrical specimens is in accordance with ASTM C 617 as one of the methods of cylinder end treatment prior to testing. This process was done especially to attain uniform loading during compressive strength tests (Figure 2.8).

Figure 2.8. End-ground concrete specimens.

2.5 Tests on fresh concrete mixtures

Air Content tests were conducted on freshly poured concrete in accordance with ASTM C 173 volumetric method. This test was conducted for each batch or mix type of freshly poured concrete. At least one pint of 70 percent isopropyl alcohol was used for each mix. However, for mixes containing Ground Tire Rubber (GTR), at least three (3) pints of alcohol were used and requisite adjustments made at the end of the test as stipulated by ASTM C 173. Unit weight tests for freshly poured concrete were conducted in accordance with ASTM C 138 on each mix type. For our testing purposes, a 0.5 cubic foot steel container (bucket) was used. Slump tests were conducted to ascertain the workability of freshly poured concrete for each batch or mix type. These tests were carried out in accordance with ASTM C 143 immediately after pouring concrete from the concrete mixer.

2.6 Test for compressive, split tensile and flexural strengths

The procedure is described here for the stage 2 tests, where compressive strength test specimens were cast for 7, 28, and 90 day tests. Three 6-inch by 12-inch cylinders were cast for each mix type for each of the three testing dates. With the aid of a cylinder-end-grinder, the ends of the cylindrical specimens were ground for the desired flat and smooth end condition. The *TestMark* compression test machine was used on all samples with a gradual loading increment and stabilized loading rate between 565 and 1414 pounds per second.

The compressive strengths were computed as:

$$\sigma = P/A \tag{2.5}$$

where:

P = ultimate load (load at failure) during testing (lbs)
A = load area (computed using the average diameter of test specimen) (square-inch)

Compression tests were conducted on concrete specimen cast with variations on use of admixtures and the addition of GTR. There were control samples with and without admixtures, while samples were also made with admixtures and varied GTR contents of 5%, 10%, 15%, and 20% by weight of the fine aggregates. Figure 2.9 shows a sample test setup for compressive strength test

Figure 2.9. Setup for compressive strength tests.

The splitting tensile strength test was conducted in accordance with ASTM C 496M test method. In this test, a compressive force was applied at a loading rate from 100 psi/min to 200 psi/min along the length of the cylindrical specimen of dimensions 6 inches by 12 inches. As a result of the applied load, tensile stresses are induced on the plane along which the load is applied and corresponding compressive forces around the area of load application. This loading results in tensile failure since the area at which load is applied is in triaxial compression enabling the specimen to withstand much higher compressive stresses. As part of the setup for this test, thin plywood bearing strips were used to distribute the applied load along the entire length of the cylinder as seen in Figure 2.10 below.

The split tensile strength of each specimen was calculated as follows:

$$T = \frac{2P}{\pi l d} \tag{2.6}$$

where:

T = splitting tensile strength, psi
P = maximum applied load displayed by testing machine, lb
l = measured specimen length, in
d = measured specimen diameter, in

Figure 2.10. Setup for splitting tensile strength tests.

For flexural strength test, the cast beams were tested with the three point load setup, as illustrated in Figure 2.11.

Figure 2.11. Third point loading setup for flexural strength tests

At final loading (failure), the distances from the end of specimen to the crack position was taken to verify if failure was within the middle third.

2.7 Test for modulus of elasticity

Modulus of Elasticity tests were run on cylindrical concrete specimens in accordance with ASTM C 469. In this testing procedure, three (3) cast cylindrical concrete specimens (6-inch by 12-inch) for all mix types were positioned in a compressometer set-up with linear variable differential transducers connected to the compressometer frame. These LVDTs were two (2) in number and were used to measure longitudinal and transverse displacement of the test specimen under loading. The LVDTs were connected to an ADMET data acquisition system (DAS) which was connected to a laptop computer (Figures 2.12 and 2.13). The TestMark compression machine was also connected to the DAS. The DAS was used to collect readings from the connected LVDTs and testing machine in order to display live readings and the final test results were retrieved with the help of installed ADMET software on the laptop computer. Testing was done for each specimen by loading and unloading the test specimen up to 40% of determined strength at failure of similar samples of the same mix type. The loading and unloading process was carried out three (3) times and the results for modulus of elasticity were determined from the second and thirds loadings. Results from the initial loading were ignored since it was for the seating of the gauges (LVDTs).

Figure 2.12. Laboratory set-up for modulus of elasticity tests

Figure 2.13. Compressometer with LVDTs on concrete specimen, and computer output

Modulus of Elasticity results were computed, to the nearest 50 000 psi (344.74 MPa) as follows:

$$E = \frac{(S_2 - S_1)}{(\epsilon_2 - 0.000050)} \tag{2.7}$$

where:

E = chord modulus of elasticity, psi,

S_2 = stress corresponding to 40 % of ultimate load,

S_1 = stress corresponding to a longitudinal strain, ϵ_1, of 50 millionths, psi, and

ϵ_2 = longitudinal strain produced by stress *S2*.

For Poisson's ratio, to the nearest 0.01:

$$\mu = \frac{(\epsilon_{t2} - \epsilon_{t1})}{(\epsilon_2 - 0.000050)} \tag{2.8}$$

where:

μ = Poisson's ratio,

ϵ_{t2} = transverse strain at mid-height of the specimen produced by stress S_2, and

ϵ_{t1} = transverse strain at mid-height of the specimen produced by stress S_1.

2.8 Test for coefficient of thermal expansion (CTE)

First, some discussions are presented on the methodology behind the CTE. The ratio of the degree of expansion to the change in temperature is called a material's coefficient of thermal expansion (CTE) and generally varies with temperature. Specifically, this is a measure of the material's fractional change in size per degree change in temperature at a constant pressure. Whereas several types of coefficients have been developed--volumetric, area, and linear--in most cases for solids, there may only be a concern with the change along a length, or over some area.

During the hydration process in concrete, heat is generated; this is a function of several factors such as temperature during placement, the type and fineness of the cement, the quantity of other cementitious materials (e.g. fly ash), type and quantity of aggregates as well as water content. After concrete setting, even though all the component materials have an effect on the thermal expansion behavior, the aggregate type has the most influence on the extent to which concrete expands and contracts during temperature changes.

Upon the increase in temperature, concrete expands and contrarily concrete contracts when temperature decreases. Coefficient of thermal expansion (CTE) of concrete is defined as the volumetric changes in concrete produced by temperature changes. It can also be defined as the alteration in the unit length per degree change in temperature. The types of aggregates as well as the degree of saturation are factors which tend to determine the CTE of a concrete mixture. Coarse aggregates, which form most of the concrete volume, are considered the most influential component material in determining the CTE of concrete. Among the various coarse aggregate types mostly used in concrete pavements, quartz is considered to have the highest CTE. As a result, most coarse aggregates have their CTE being largely dependent on their quartz content. Fine aggregates also contribute to the CTE of concrete. Silica contained in natural sands has high CTE while fine aggregates from crushed limestone have lower CTE values. Table 2.9 below shows typical CTE values for concrete depending on aggregate type used.

Table 2.9. CTE of Concrete by Aggregate Type (LTPP Standard Date Release 25.0)

Primary Aggregate Class	Average CTE (/°F x 10^{-6})	Standard Deviation (/°F x 10^{-6})	Average CTE (/°C x10^{-6})	Standard Deviation (/°C x 10^{-6})	Sample Count
Andesite	4.32	0.42	7.78	0.75	52
Basalt	4.33	0.43	7.80	0.77	141
Chert	6.01	0.42	10.83	0.75	106
Diabase	4.64	0.52	8.35	0.94	91
Dolomite	4.95	0.40	8.92	0.73	433
Gabbro	4.44	0.42	8.00	0.75	8
Gneiss	4.87	0.08	8.77	0.15	3
Granite	4.72	0.40	8.50	0.71	331
Limestone	4.34	0.52	7.80	0.94	813
Quartzite	5.19	0.50	9.34	0.90	131
Rhyolite	3.84	0.82	6.91	1.47	7
Sandstone	5.32	0.52	9.58	0.94	84
Schist	4.43	0.39	7.98	0.70	30
Siltstone	5.02	0.31	9.03	0.56	21

Pavement concrete behavior is largely affected by changes in temperature of the concrete member. Joints and cracks open and close frequently as a result of daily as well as seasonal phases of temperature changes. During the day (in the afternoon), when the surface of a concrete slab becomes warmer than the base of the slab, concrete expands on the surface of the slab exceeding the expansion at the base, which can cause the slab to bend downwards if it is not restrained. Restraints along the slab's edges, however, result in high bearing stresses between the concrete and the dowels. Similarly, during the night when the concrete surface becomes colder than the base of the slab, the concrete will undergo more contraction on the surface than the base and this could cause the slab to curl upward if it has no restraint. Also, in this case, restraints along the slab's edges result in high bearing stresses between the concrete and the dowels (USDOT, 2012).

This test was conducted in accordance with AASHTO T 336 at the Florida Department of Transportation (FDOT) Materials Laboratory in Gainesville. The test involved the measurement of the change in length of a 4-in diameter cylindrical concrete specimen under temperature variations. As described earlier in this report, three specimens were cast for each mix type, and then end-ground and transported to FDOT's laboratory at Gainesville for testing. Specimens are cured for 28 days after which they were end-ground to approximately 7 inches for testing.

Concrete specimens were fixed in a steel frame and LVDT's were fixed at the top of each frame to make contact with the surface of the specimens. The concrete specimens and frame/test apparatus were submerged in a water bath to ensure that the specimens had a maintained saturation state during testing. Measurements are then taken for cooling and heating cycles as the temperature is increased from 50°F to 122°F (10°C – 50°C) and reduction in the temperature is made back to 50°F/10°C. Measurements taken during the cycle of expansion and contraction are adjusted to cater to the effects of temperature changes on the test apparatus. The test is repeated until results show that the CTE values between the expansion and contraction sections of the test are 0.2 x 10-6 per °F (0.3 x 10-6 per °C) from each other. The CTE is found by computing the average of two consecutive CTE readings, one from each sections of the test--that is, one from the expansion section and the other from the contraction section.

2.9 Test for plastic shrinkage

The tests were conducted using a modification of the ASTM C1579, with the required test facility configuration shown in Figures 2.14 and 2.15 below. An environmental chamber described as a fan box in ASTM C1579 was constructed according to specification to seat two plastic shrinkage molds for testing. This chamber was constructed of plywood and made air-tight to prevent outflow of air during testing (Figure 8). The top of the chamber was built as a see-through door frame that can be opened upwards to make it easier when placing concrete filled molds in the chamber. The see-through design of the top also helped observe the propagation of plastic shrinkage cracks on the test specimens. The back of the chamber was constructed as an air tight door in order to provide access to the fan and heaters used in conditioning the chamber to specification.

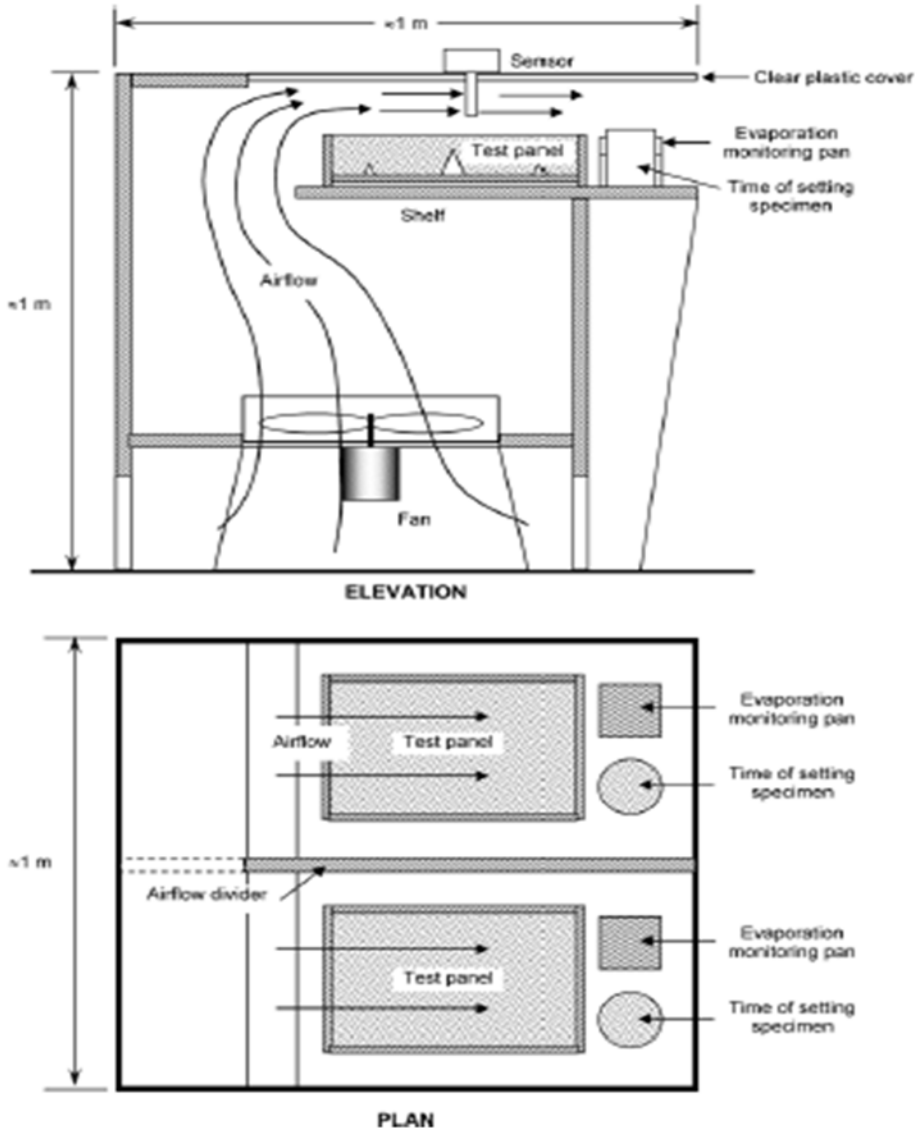


Figure 2.14. Test facility configuration for plastic shrinkage tests (ASTM C1579)

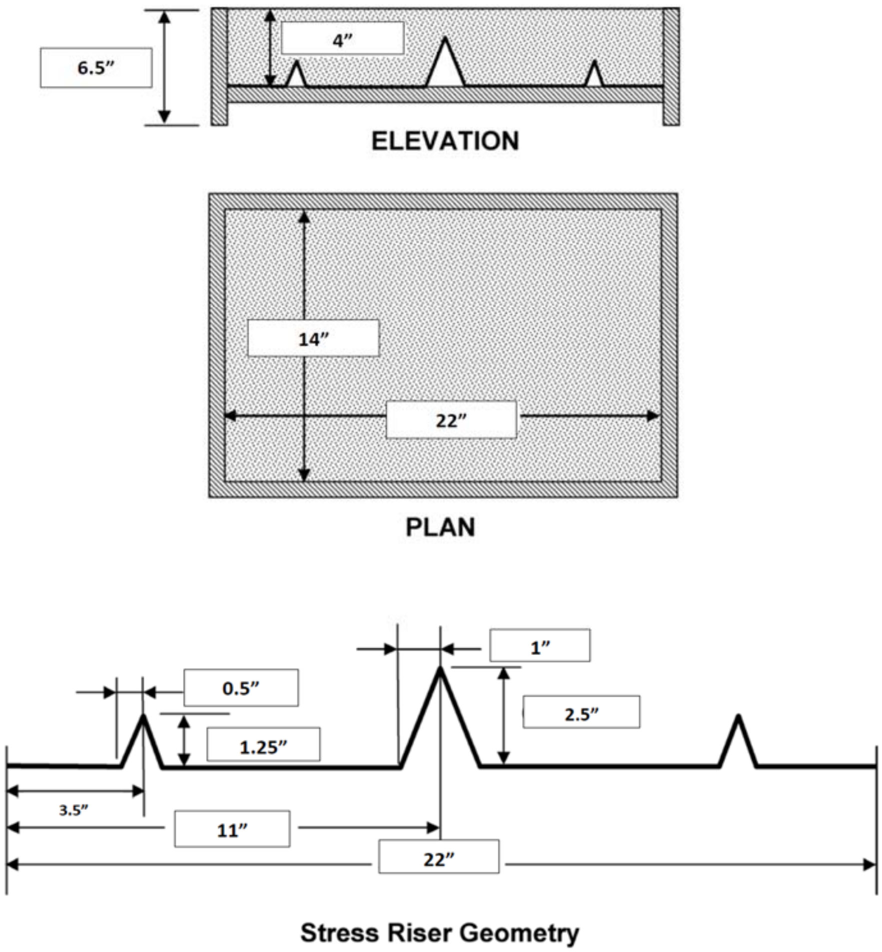


Figure 2.15. Test mold requirement for plastic shrinkage tests (ASTM C1579)

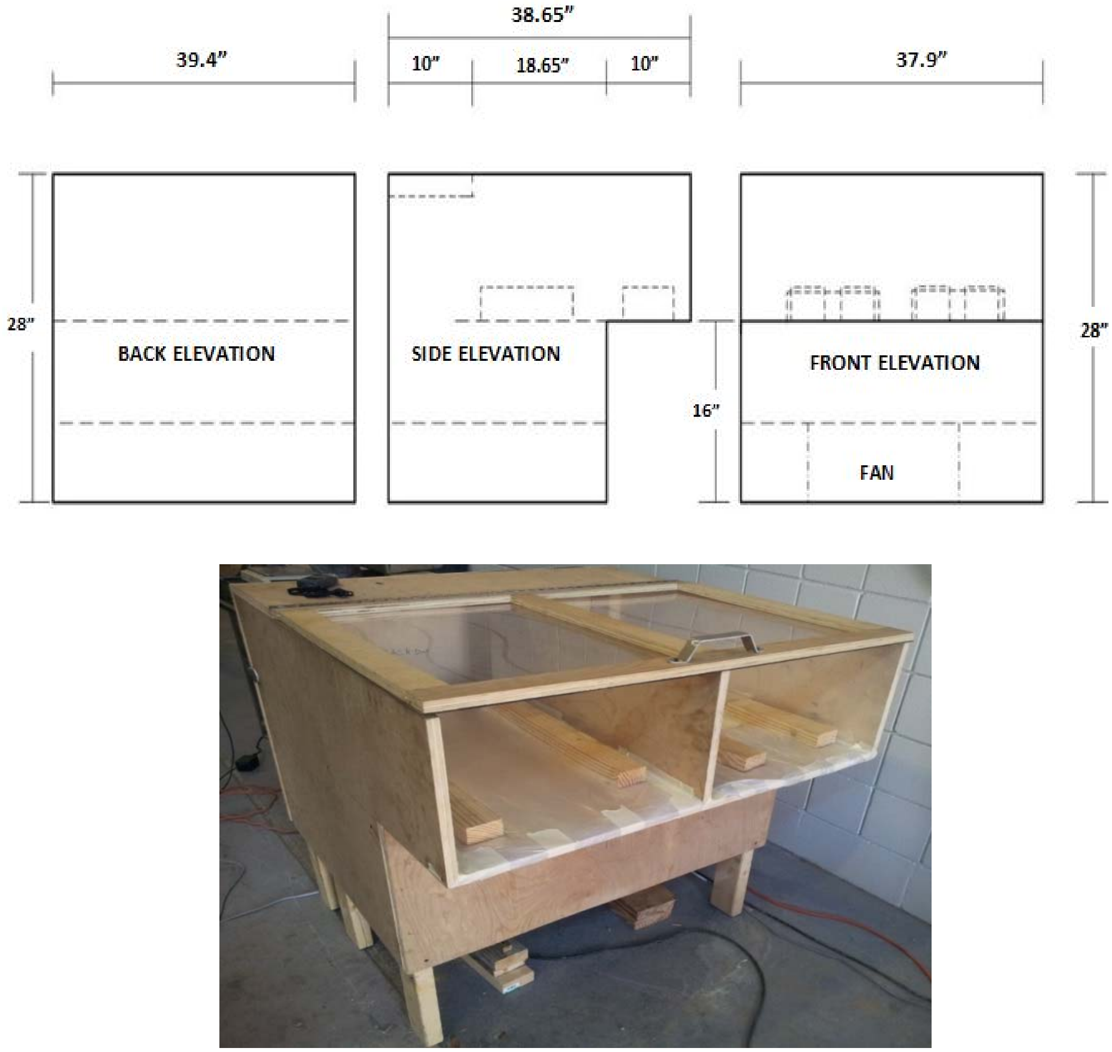


Figure 2.16. Construction of environmental chamber for plastic shrinkage tests

As part of this testing method, two (2) plastic shrinkage molds of dimensions seen in the Figure 2.17 below were constructed out of plywood. Steel risers were also fabricated out of 18-gauge steel and dimensioned according to ASTM specifications. The overall depth of the mold was increased by 0.5 inches to suit ASTM standards which stipulate a minimum depth of 2.6 inches plus at least twice the maximum coarse aggregate size being used. The final overall depth for the mold was built as 4.5 inches to satisfy the coarse aggregate size of 1 inch for No. 57 stone obtained from gradation. However, during testing procedures and in order to observe cracks, the overall depth of the mold used for testing was 3.25 inches, that is, 0.75 inches above the middle riser.

Figure 2.17. Construction of molds for plastic shrinkage tests

Plastic shrinkage tests were performed on both control and GTR concrete specimens. This test was performed in two sequences (Figure 2.18). The first sequence involved having one control specimen and one GTR specimen in each compartment of the environmental chamber. However in the second sequence, each of the compartments had GTR concrete specimens of the same mix.

(a) First Sequence

(b) Second Sequence

Figure 2.18. Conducting the plastic shrinkage tests in two sequences

2.9.1 Fabrication and test procedures

During batching, coarse aggregates were sieved to obtain a maximum size of ¾ inch aggregates. This configuration was used because the effective depth of the plastic shrinkage molds were reduced to 3.25 inches in order to better observe propagation of shrinkage cracks. Mixing was done using "3, 3, 2" method described earlier in this memo as the standard method for laboratory scale mixing. For each test batch, the slump as well the temperature of freshly poured concrete was taken.

Before pouring concrete into the plastic shrinkage molds, the molds were oiled lightly with grease (Figure 2.19) to aid in easy removal of concrete after testing, without damaging the mold.

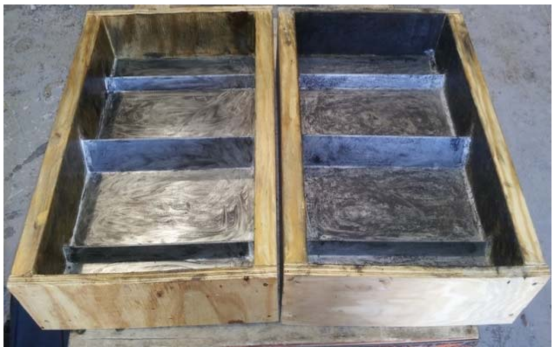


Figure 2.19. Lubricated molds before pouring concrete and vibrated concrete sample

A small portion of the concrete was also sieved in the No.4 sieve as required by specifications, to obtain the sample for the time of setting test. The environmental chamber was then set to meet the requirements at a temperature of 85 ^{o}F, humidity of 39.4%, and wind speed of 10.5 mph. Plastic shrinkage molds were filled in a single layer and vibrated for approximately one (1) minute on a vibrating table after which the surface was finished.

Both plastic shrinkage and setting time specimens were placed in the conditioned chamber; a pan filled with water monitored the evaporation rate (Figure 2.20).

Figure 2.20. Test set-up in environmental chamber

2.9.1.1 Setting time

Time for specimen setting was conducted for both control specimens and GTR concrete specimens. This tests employed vicat needles and penetration equipment seen in the Figure 2.21 below.

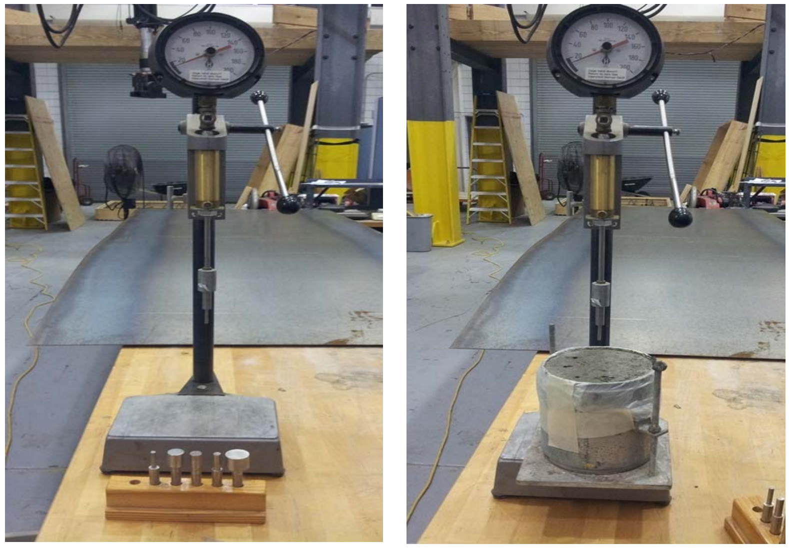


Figure 2.21. Use of vicat needles for determining setting times

During the first sequence of testing, the plastic shrinkage (control specimens) and setting time specimens were placed in the environmental chamber, two (2) hours prior to starting the setting time tests. However, penetration tests for GTR concrete specimens were run three (3) hours after placing the specimens in the chamber. This time interval was necessary because the specimens took longer to set as GTR increased, and also the initial setting time for control specimens was not observed until after the third reading. As a result, during the second testing sequence, the initial setting time reading was taken 3 hrs after placing the control specimens in the environmental chamber at 30-min intervals (4 - 5hrs for GTR specimens).

The vicat needle sizes used for this test were 1/10 sq. in, 1/20 sq. in, and 1/40 sq. in. These sizes cover a smaller area on the setting time specimen and allow for more penetrations on a single specimen. The pressure equipment indicates the load which is then divided by the area of the vicat needle to get the stress in pounds per square inch (psi). After the first penetration test for each specimen, subsequent penetrations were made at 30-minute intervals till the final set (4000 psi) was reached. The control specimens took approximately 6 hours to set; however, as the percent of GTR increased, the setting time also increased with 15 percent GTR concrete taking as long as 12 hours for final setting to be reached. ASTM C1579 stipulates that the test should be halted at 6 hours; but because the setting times for GTR specimens were longer, our testing procedure included an extension of this time to 9 hours after which the final setting was extrapolated. The researchers used the following regression analysis as stipulated by ASTM C403 Standard test method for time of setting of concrete mixtures by penetration resistance:

$$\mathrm{Log}\,(PR) = \mathrm{a} + \mathrm{b}\,\mathrm{Log(t)} \qquad (2.9)$$

where:

PR = penetration resistance, and
t = elapsed time.

From the above equation,

$$\mathrm{Log(t)} = \frac{\mathrm{Log}\,(PR) - a}{b}, \qquad (2.10)$$

$$t = 10^{\left(\frac{Log\,(PR)-a}{b}\right)} \tag{2.11}$$

After the final setting time readings (or 9 hours for GTR specimes), the heaters and fan in the environmental chamber were shut off, and the specimens were covered with nylon sheeting until 24 hours after the starting time for mixing the concrete.

2.9.1.2 Crack measurement and quantification

An image acquisition and processing method were used in quantifying crack widths (Figures 2.22 and 2.23), width distributions, and crack patterns for control and GTR samples. Automated image capturing software was used to view cracks on a laptop after which the images were captured. A magnifying lens was used to locate all positions and distributions of cracks along the risers. A calibrated microscope was then employed to read the values of crack widths on the specimen.

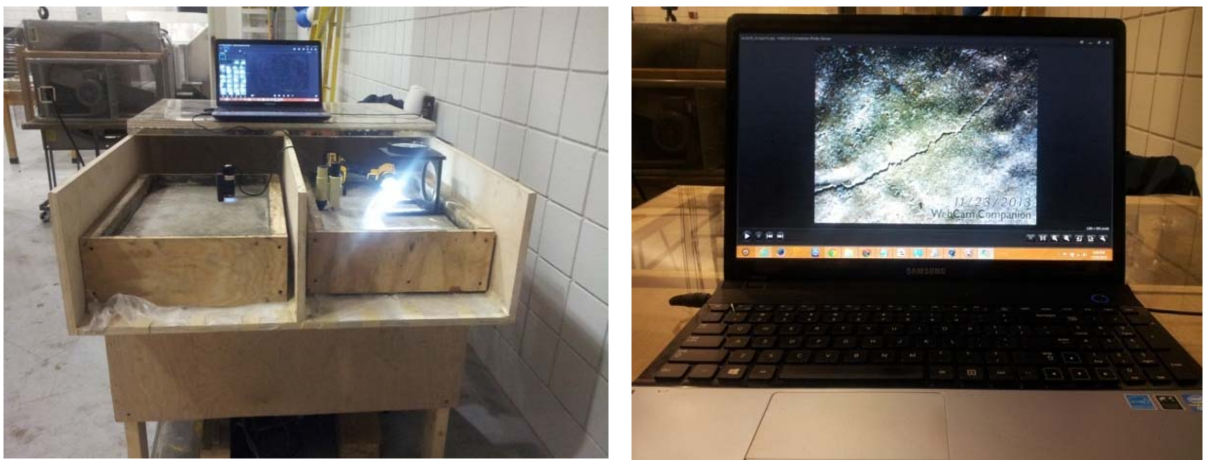


Figure 2.22. Image acquisition and processing of plastic shrinkage cracks

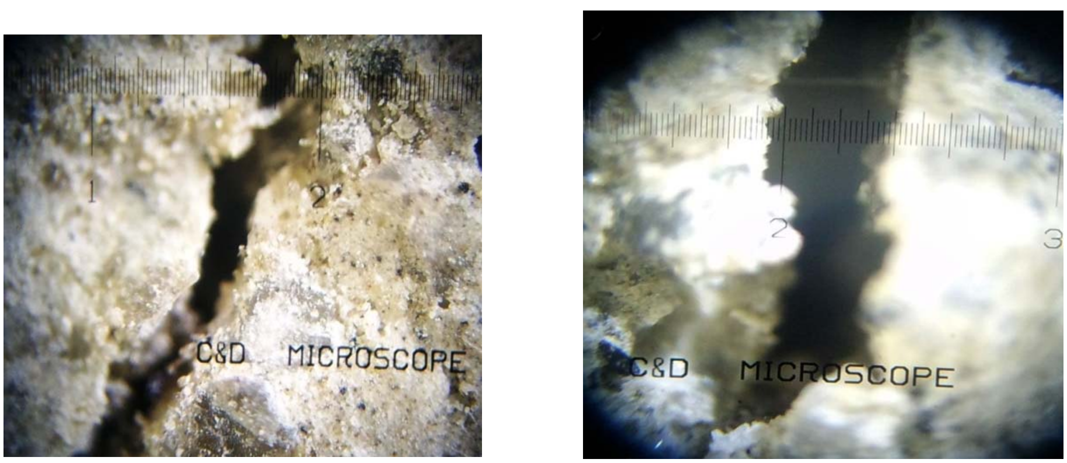


Figure 2.23. Sample images of plastic shrinkage cracks

2.10 Test for drying shrinkage

This test was conducted in accordance with ASTM C 157 and modified based on prior FDOT research on the evaluation of shrinkage cracking potential of concrete used in Florida bridge decks (Mang et. al, 2005), using LVDT's on specimens from 24 hours to 21 days. This test was primarily conducted to compare free shrinkage in plain concrete specimens to that of GTR concrete specimens. The object was to determine whether the inclusion of GTR in concrete would help reduce free shrinkage in concrete and hence the resultant cracks. The procedures for this test were the following:

- Free Shrinkage molds (prisms) dimensioned 3 in. x 3 in. x 11.25 in. were cleaned and oiled with grease to facilitate easy demolding of concrete after setting.
- Metal studs were inserted into the removable plates at both ends of the molds such that the gauge length for strain measurements would be 10 inches.
- Concrete was mixed with the specified mix design for both plain concrete specimens and specimens with 10% GTR replacing fine aggregates by weight.
- Free shrinkage molds were filled in two (2) equal layers with each layer vibrated for 30 seconds after which the surface was finished. During mold filling, the freshly mixed concrete surrounded the metal studs properly to ensure efficient bonding.
- Vibrated and finished specimens were then covered with polyethylene sheeting and allowed to set for 24 hours (Figure 2.24).
- After 24 hrs, specimens were removed from the molds by carefully unwinding the end plates from the studs at both ends.
- Demolded specimens were then placed in lime water for at least 30 minutes.
- Samples were then surface dried and setup on steel frames that were well aligned with the aid of a spirit level. Mounting the specimens on the frames was done by fitting one end with a metal stud into the base of the frame.

Figure 2.24.Vibrated and covered sample for drying shrinkage

The LVDT's were mounted on top of the frame and the tip touched the metal stud on top of the specimen (Figure 2.25). The LVDT's were in a compressed state as the specimens were expected to shrink over time. The LVDT's were connected to their corresponding read out boxes which were all connected to an uninterruptible power supply (UPS) as a safety measure in case of power fluctuations (Figure 2.26). Read-out boxes were all set to zero. Free Shrinkage readings were taken three (3) times a day at 8-hour intervals continuously for 21 days.

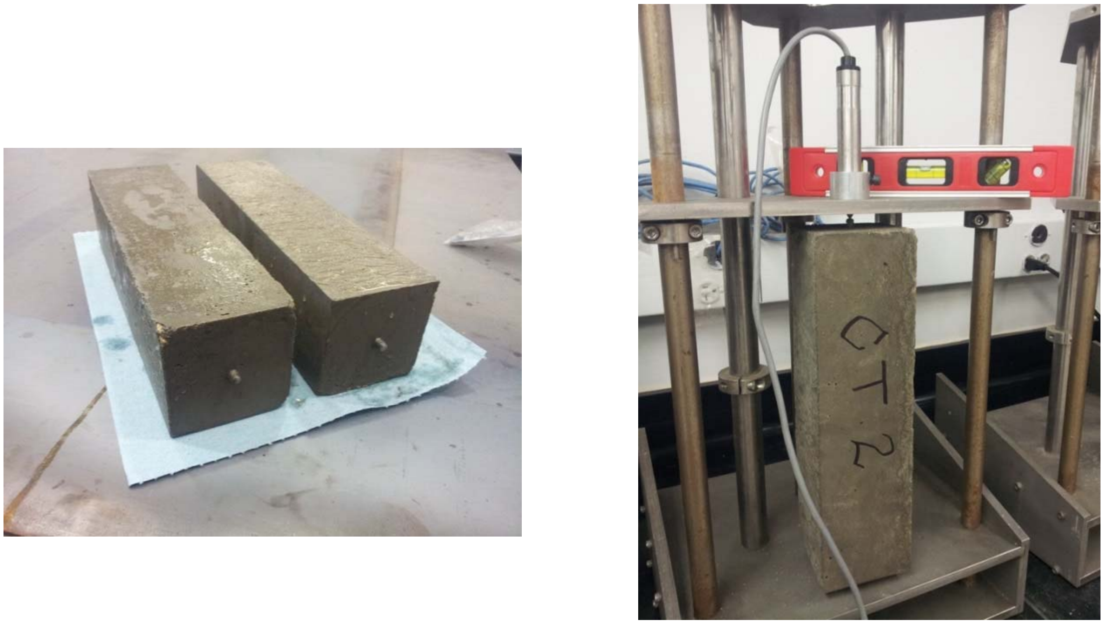


Figure 2.25. Dried sample and mounting on test frame for measurement of drying shrinkage

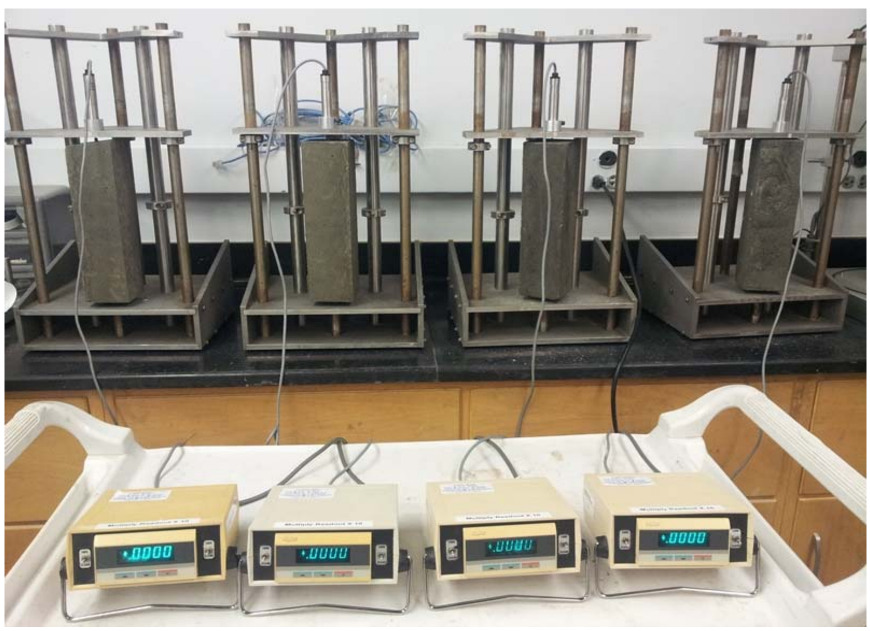


Figure 2.26. Assembled frame with samples for measuring drying shrinkage

2.11 Scanning Electron Microscope (SEM) Analysis

A scanning electron microscope (SEM) can scan a material sample with a focused beam of electrons to produce images at very high magnification levels. The interaction between the electrons and the atoms in the sample produces various signals that can be detected with information produced about the sample's surface topography and composition. Dry samples of GTR sample as well as that of hardened concrete with 20% GTR were examined using the SEM. With the aid of a magnetic tape, samples were attached to cylindrical stainless steel plate and placed on a specially designed seat that held the cylindrical plate. Samples placed into a coating chamber were coated with gold to clarify the SEM image. As illustrated in Figures 2.27 and 2.28, samples were then placed in the SEM machine which was then vacuumed to eliminate air. The samples were examined at various magnification levels (between 100X and 4500X) in order to help identify them in the GTR concrete and analyze the interfacial bonding with cement mortar.

Figure 2.27. Placing the sample into the SEM

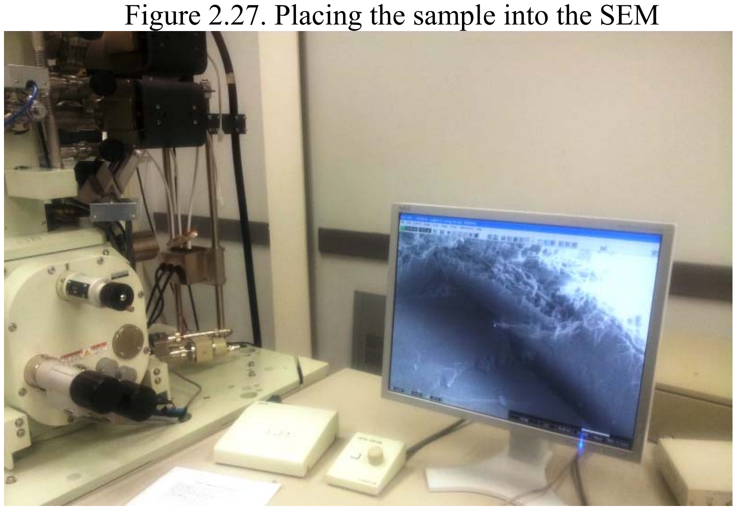


Figure 2.28. Display unit showing the microscopic view of specimen under SEM analysis

2.12 Modified test procedures

During the research, the test methods described above were revised slightly based on some observations. This includes the following modifications: pretreating the GTR before use in the concrete; reducing water-to-cement ratio and increasing cementitious material content; and adding a defoaming agent to the GTR concrete during mixing.

2.12.1 Pretreatment of GTR

Previous studies have indicated that if the rubber particles have rougher surfaces or when the rubber particles are pretreated, improved bonding with the surrounding matrix may occur, which may also produce higher compressive strength. From previous studies, rubber pretreatments may vary from washing rubber particles with water to acid etching, plasma pretreatment, and various coupling agents (Tantala et. al, 1996). (Eldin and Senouci, 1993) in their research soaked and thoroughly washed rubber aggregates with water to remove contaminants. (Rostami, et al., 1993) used water, water and carbon tetrachloride solvent, and water and a latex admixture cleaner to pre-treat rubber. The results were that concrete containing washed rubber particles achieved about 16% higher compressive strength than concrete containing untreated rubber aggregates, whereas this improvement in compressive strength was 57% when rubber aggregates were treated with carbon tetrachloride. In view of the aforementioned results reported by various researchers, laboratory tests involving pretreated GTR were conducted to determine whether any increase in compressive strength of GTR concrete occurred.

A dry sample of GTR was weighed and then washed thoroughly with water on a No. 200 sieve. The washed GTR sample was then spread evenly on a wide pan and air dried for 2 to 3 days (Figures 2.29 and 2.30).


Figure 2.29. Washing of GTR sample as a pretreatment method


Figure 2.30. Drying prewashed GTR sample

Moisture content of the dried GTR sample was then measured in accordance with FDOT specification FM 5-559 prior to concrete mixing. Cylindrical concrete samples (6-inch by 12-inch) were cast and tested for 7 and 28 days compressive strength. Pretreatment was done on GTR mixes where 15% and 20% GTR was used to replace fine aggregates by weight. For each GTR concrete mix, control specimens were also cast. As seen in Table 2.10, the mix design used did not include admixtures, while the amount of cement used was 500 pounds per cubic yard of concrete and the water-to-cement ratio was 0.5.

Table 2.10. Sample Mix design for 15% GTR Concrete (Pretreated)

GTR (% by weight of fine aggregate)	15.0%
GTR (% by weight of coarse aggregate)	9.2%
Expected yield (ft^3)	1.4
Material	**Weight (lb)**
Cementitious materials: (Spec. Min. 470 lb/CY)	**25.93**
Fly Ash: (Spec. 20% cementitious material)	**0.00**
Portland Cement Type I/II	**25.93**
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing only	**12.96**
Additional water for aggregate absorption	**3.64**
Entrapped Air (Spec. 1% to 6% allowed)	**1.5%**
Coarse aggregate: Spec. No. 57	**89.46**
Fine aggregate	**54.99**
GTR	**8.25**
Mix total weight (lb)	**191.59**
Mix theoretical unit weight (lb/ft³)	**136.85**

2.12.2 Reduced water/cement ratio

Results from previous laboratory tests on mechanical properties of GTR concrete have indicated that the strength properties of concrete decrease with increases in GTR content in the concrete mix. It is also a common knowledge that the compressive strength of concrete increases as the water/cement ratio is reduced. It is expected that with a lower water/cement ratio and more cementitious material, mechanical properties of GTR concrete will be improved. In this mixing stage, fly ash and admixtures (water-reducer and air-entrainer) were included in the concrete mix design, which improved the strength properties of GTR concrete.

Thus, to help improve the strength properties of GTR concrete, a mix design was adopted that involves increasing the amount of cement used. This design roughly follows the minimum cementitious materials and maximum water-to-cement ratio requirements for FDOT bridge deck design. Increasing the amount of cement and reducing the water-to-cement ratio also aids in increasing the other strength characteristics of concrete.

The hydration process in concrete only requires a certain amount of water usually satisfied by the designed water-to-cement ratio. The rest of the water contributes to the porosity of the concrete sample by creating capillary pores which may lead to loss of strength in concrete.

Also, because experiments confirmed in literature demonstrate that the pretreatment of GTR helps to improve the mechanical properties of GTR concrete, a mix containing pretreated GTR particles was included as part of these laboratory tests.

Kaloush et. al (2005) in their research on the properties of crumb rubber concrete also used 525 lbs//yd^3 of cement and 125 lbs/yd^3 of fly ash in their mix design. This finding implied that a total cementitious material of 650 lbs/yd^3 was used for concrete mixtures. An increase t in the amount of cementitious material used in rubber concrete in order to improve upon its mechanical properties has also been adopted by Fedroff et. al (1996) and Rangaraju et. al (2012), who used 600 lbs/cy and 809 lbs/cy of cementitious material respectively.

From the FDOT requirements for bridge decks, the minimum amount of cementitious materials is 611 lbs/yd^3, and the maximum water-to-cement (cementitious material) ratio is 0.44 lb/lb. For this study as shown in Table 2.11, the mix design was based on using GTR 15% of fine aggregate by weight. T he total amount of cementitious materials was 625 lb/yd^3 with fly ash taking 20% of this amount and the rest being Portland cement.

The following batches were used for final laboratory tests: Control Concrete (with fly ash and admixtures); 15% GTR (Pretreated) Concrete with fly ash and admixtures; and 15% GTR (Not Pretreated) Concrete (with fly ash and admixtures)

Table 2.11. Mix Proportions Used for Reduced w/c ratio Concrete Tests

MIX TYPE	**Control with fly ash and admix**	**15% GTR (Pretreated) with fly ash and admix**	**15% GTR (Not Pretreated) with fly ash and admix**
GTR (% by weight of fine aggregate)	0.0%	15.0%	15.0%
Expected yield (ft3)	3.5	3.5	3.5
Material	**Weight (lb)**	**Weight (lb)**	**Weight (lb)**
Cementitious materials: (Spec. Min. 470 lb/CY)	**81.02**	**81.02**	**81.02**
Fly Ash: (Spec. 20% cementitious material)	**16.20**	**16.20**	**16.20**
Portland Cement Type I/II	**64.81**	**64.81**	**64.81**
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing only – **40% USED**	**32.41**	**32.41**	**32.41**
Additional water for aggregate absorption	***9.44***	***9.17***	***9.17***
Entrapped Air (Spec. 1% to 6% allowed)	**1.5%**	**1.5%**	**1.5%**
Coarse aggregate: Spec. No. 57	**228.62**	**228.62**	**228.62**
Fine aggregate	**170.82**	**120.29**	**120.29**
GTR (lb)	**0.00**	**18.04**	**18.04**
Mix total weight (lb)	**512.86**	**480.38**	**480.38**
Mix theoretical unit weight (lb/ft3)	**146.53**	**137.25**	**137.25**
Water reducer (oz.)	**2.63**	**2.63**	**2.63**
Air entraining agent (oz.)	**0.53**	**0.53**	**0.53**

Slump tests, unit weight, concrete temperature, and air content tests were performed on freshly poured concrete for all mix types. In addition, compressive strength tests were conducted on 6-inch by 12-inch cylindrical specimens at 3, 7, 28, and 90 days. Concrete mixes with fly ash were tested for 90-day compressive strength as well. Moisture content analysis was also performed on aggregates to determine the actual water-to-cement ratio of the concrete mix.

2.12.3 GTR Concrete with Defoaming Agent

Previous literature has indicated the inclusion of defoaming agents in ready-mix trucks in order to improve upon the quality and strength properties of rubber concrete. Kaloush et. al 2005 included a defoaming agent in their crumb rubber concrete mix in ready-mix trucks. There is limited literature on the use of this admixture in rubber concrete. However, defoaming agents, or defoamers as they are generally called, are known to reduce concrete air voids and help densify concrete, leading to improved mechanical properties.

This research project used the C-64 concrete defoamer and densifying admixture produced by Fishstone (Figure 2.31). The producer describes C-64 as a highly concentrated defoamer and densifying admixture specially designed for self-consolidating type concrete. One quart of C- 64 is marketed to produce over 200 cu. ft. of concrete. The following are the attributes of this defoaming agent:

- Reduces trapped air in concrete
- Reduces bug holes greatly reducing need to slurry surface
- Improves densification of concrete
- Increases compressive strength
- Develops stronger/denser concrete
- Works with a dosage of 5-20ml per gal of mix water

Figure 2.31. C-64 concrete defoamer and densifying admixture

In this research, two trials of 15% GTR concrete mixtures were made. Defoamer dosages of 2.5 ml per gallon of water and 10 ml per gallon of water were used for the first and second concrete mixtures respectively (Table 2.12). Tests on freshly poured concrete were then performed to investigate the influence of the defoaming agent on the air content, unit weight, and the slump of 15% GTR concrete.

Table 2.12 Mix Design Used for 15% GTR Concrete Mixtures with Defoaming Agent

	15% GTR Concrete with 2.5 ml of Defoaming agent	15% GTR Concrete with 10 ml of Defoaming agent
GTR (% by weight of fine aggregate)	15.0%	15.0%
GTR (% by weight of coarse aggregate)	7.4%	7.4%
Expected yield (ft3)	1.5	1.5
Material	Weight (lb)	Weight (lb)
Cementitious materials: (Spec. Min. 470 lb/CY)	34.72	34.72
Fly Ash: (Spec. 20% cementitious material)	6.94	6.94
Portland Cement Type I/II	27.78	27.78
Water (Spec. max reqd. 50% of cementitious materials) reqd for mixing --- 45% USED	15.63	15.63
Additional water for aggregate absorption	*3.91*	*3.91*
Entrapped Air (Spec. 1% to 6% allowed)	1.5%	1.5%
Coarse aggregate: Spec. No. 57	97.98	97.98
Fine aggregate	48.30	48.30
GTR	7.25	7.25
Mix total weight (lb)	203.87	203.87
Mix theoretical unit weight (lb/ft3)	135.92	135.92
Water reducer (oz.)	1.13	1.13
Air entraining agent (oz.)	0.00	0.00
Defoaming agent (oz.)	0.15	0.64

2.13 Summary

As a major task in this study, laboratory tests involved selection of materials, developing mix design, and following the necessary specifications. Visit by the research team to a Florida GTR plant aided in evaluating and selecting the GTR to be used in the laboratory experiments. Standard FDOT and ASTM specifications were adopted, including an elaborate fabrication of an environmental chamber and molds for conducting the plastic shrinkage tests. Some modified procedures are also presented in terms of pre-treating the GTR before use in the concrete, lowering the water/cement ratio, and using a defoaming agent to help reduce air content in the GTR concrete.

3. Results

Based on the experimental setup previously described, extensive testing evaluated the properties of GTR concrete. This section presents the results from the laboratory experiments, including preliminary tests, final tests, and tests done with modified procedures.
.

3.1 Preliminary tests

Preliminary tests were used to determine the characteristics of concrete when adding GTR in varying proportions to the aggregates. In this testing stage, four mix types were used. GTR replaced some of the fine aggregate in each of the mix types by either 10, 20, 30, or 40 percent by weight. Also, Rubber Chips (3/8-in) replaced a proportion of coarse aggregates by weight, either 10, 20, or 30 percent. Admixtures were excluded from this testing stage because the preliminary tests' purpose was to ascertain the actual influence GTR has on plain concrete mix.

3.1.1 GTR concrete: mechanical properties

The preliminary tests on GTR concrete included compressive, flexural, and split tensile strength tests, as well as the modulus of elasticity test. The results are summarized in Table 3.1. Compressive strength tests were conducted on each of the four GTR mix types and compared with plain concrete (Portland cement concrete) which served as control specimens. Three cylindrical specimens of 6-inch by 12-inch were cast for two testing periods (7 days and 28 days) for each mix type. All specimens showed a considerable increase in compressive strength between 7 days and 28 days. But as Figure 3.1 demonstrates, the mixes with higher percentages of GTR have a much lower compressive strength than the control. Overall, a decrease occurred of approximately 56-76% in compressive strength for GTR specimens when compared to control specimens, with 30% and 40% GTR specimens showing the lowest compressive strength results.

Table 3.1. Preliminary results on 7-Day and 28-Day strengths and modulus of GTR concrete

	7-Day strength			28-Day strength			
Mix Type	Compressive	Flexural	Split Tensile	Compressive	Flexural	Split Tensile	Modulus of Elasticity (10^6 psi)
Control	2020	480	250	2610	490	260	3.70
10% GTR	530	260	120	870	340	140	1.85
20% GTR	770	220	110	1090	210	130	1.85
30% GTR	560	210	110	870	200	120	1.60
40% GTR	460	140	90	610	210	90	1.05

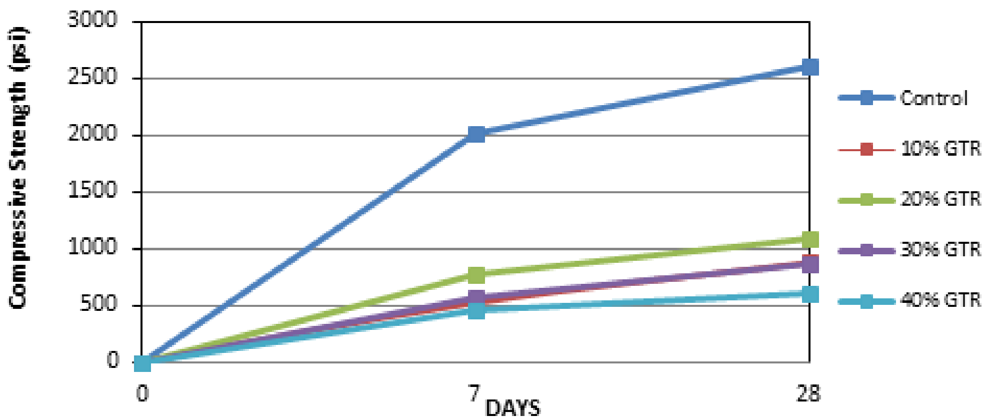


Figure 3.1. Preliminary test results for GTR concrete compressive strength

Flexural strength tests were conducted on three specimens (6-inch by 6-inch by 21-inch beams) of each mix type for both 7 days and 28 days. The results showed a decrease in flexural strength as rubber content increased. The difference between the results for 20% and 40% GTR concrete were minor, but similar to the compressive strength tests, 30% and 40% GTR specimens displayed the least flexural strength (Figure 3.2).

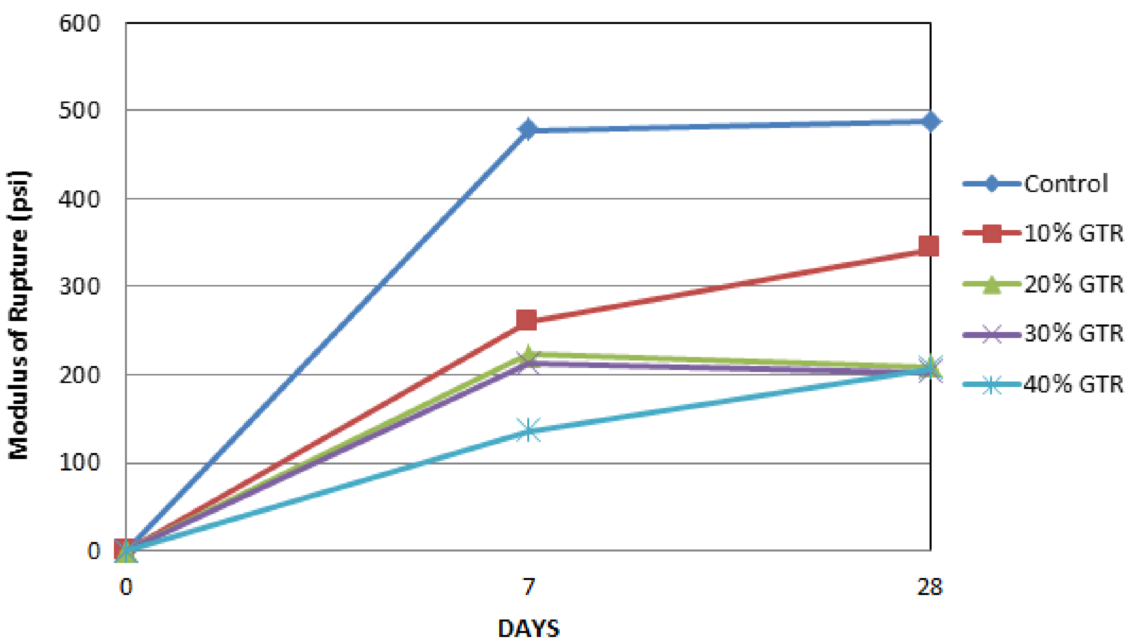


Figure 3.2. Preliminary test results for GTR concrete flexural strength

Split tensile strength tests were conducted on three specimens (6-inch by 12-inch) of each mix type for both 7 days and 28 days. Split tensile strength was reduced by about 46% to 64% compared to the control specimens, with the lowest split tensile strength in the 30% and 40% GTR mixes (Figure 3.3).

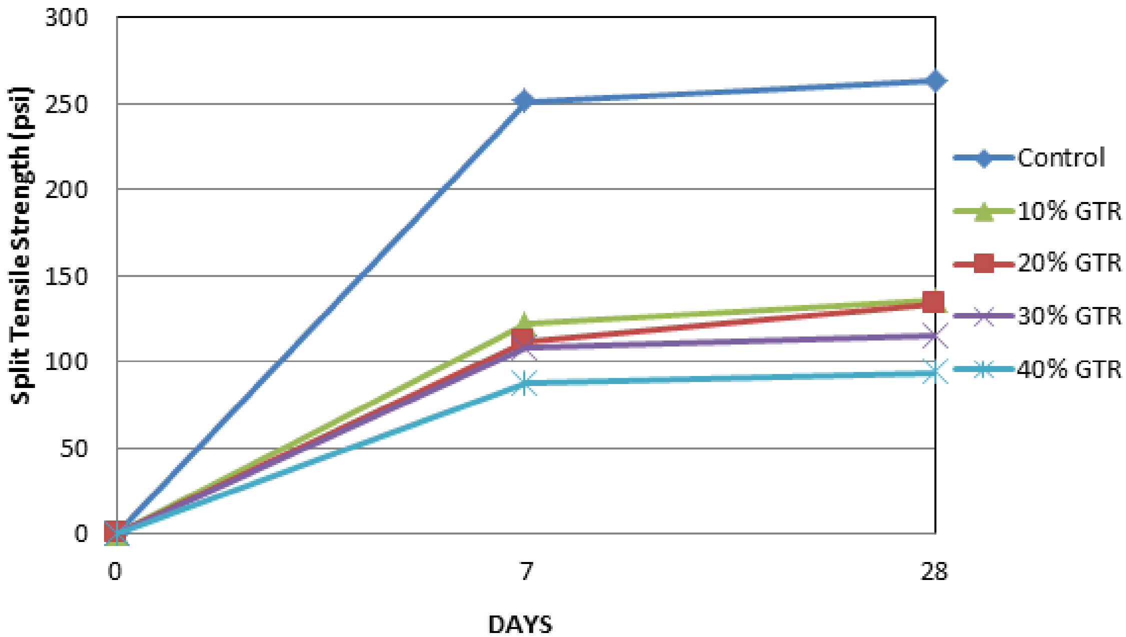


Figure 3.3. Preliminary test results for GTR concrete split tensile strength

Modulus of elasticity tests were conducted on three specimens of each mix type after curing for 28 days. Tests were conducted with the aid of a Humboldt data acquisition system (DAS) with linear variable differential transformers (LVDT) connected to a compressometer and the DAS connected to a laptop computer. Results showed that an increase in GTR content generally led to a decrease in the modulus of elasticity. While control specimens were stiff, with a modulus of 3.7×10^6 psi, results for GTR concrete samples ranged from 1.05×10^6 to 1.85×10^6 psi. The 40% GTR mix displayed the lowest modulus of elasticity (Figure 3.4).

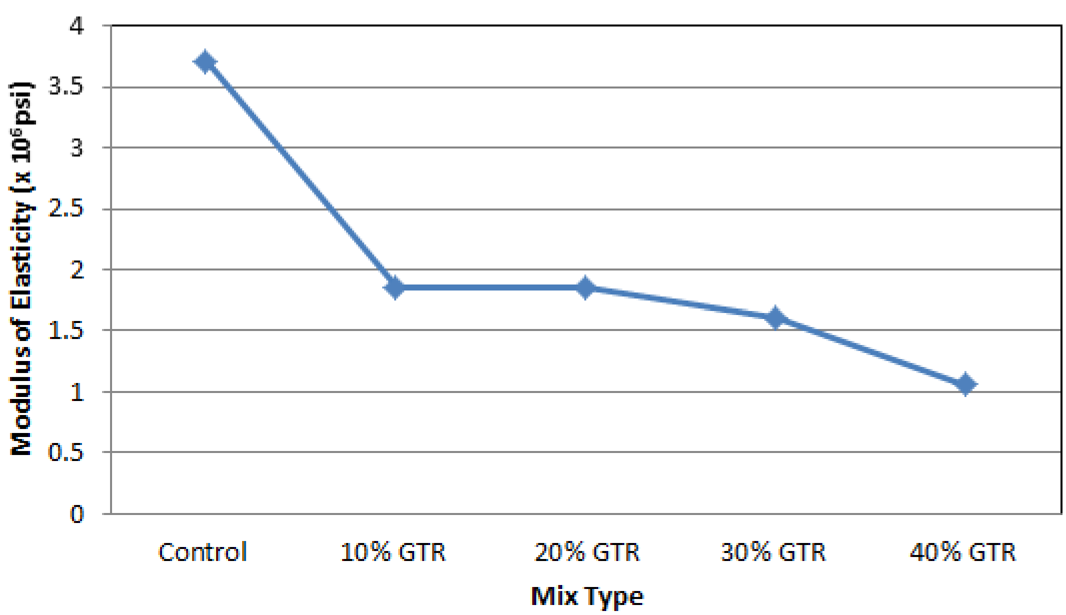


Figure 3.4. First laboratory testing stage with GTR, modulus of elasticity results

3.1.2 Rubber chip (RC) concrete: mechanical properties

The preliminary tests also measured the characteristics of concrete mixed with tire rubber chips via the modulus of elasticity test and the compressive, flexural, and split tensile strength tests. The results are summarized in Table 3.2. Compressive strength tests revealed that compressive strength was reduced as the percentage of rubber chips increased. The 10% rubber chips (RC) specimens showed the highest compressive strength, with the 28 days compressive strength significantly exceeding that of 20% and 30% RC concrete specimens (Figure 3.5).

Table 3.2. Preliminary results on 7-Day, 28-Day strengths and modulus of Rubber chip concrete

Mix Type	7-Day strength			28-Day strength			Modulus of Elasticity (10^6 psi)
	Compressive	Flexural	Split Tensile	Compressive	Flexural	Split Tensile	
Control	2020	480	250	2610	490	260	3.70
10% RC	950	320	160	1680	350	220	3.10
20% RC	840	260	110	980	350	120	2.60
30% RC	680	210	80	800	290	120	2.05

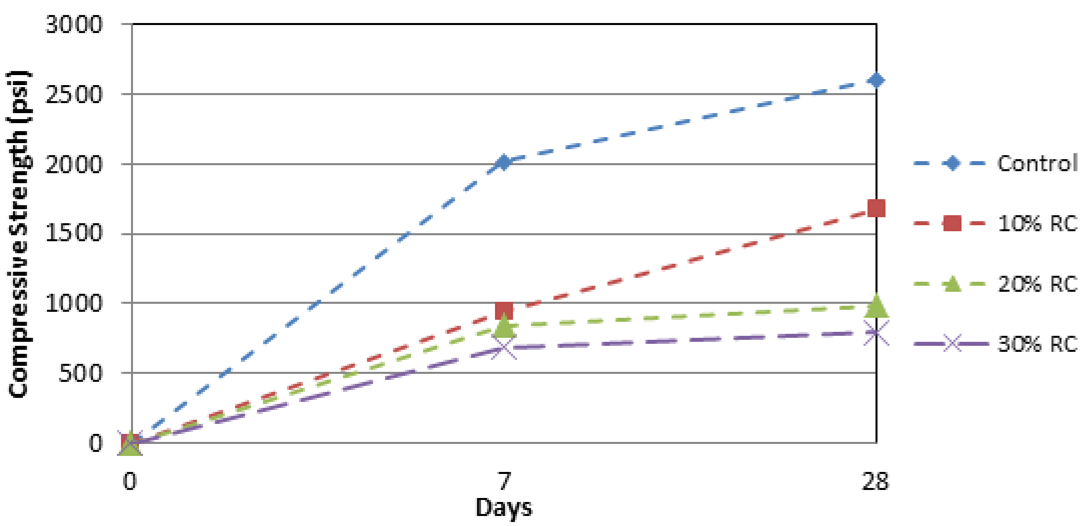


Figure 3.5. Preliminary test results for Rubber chips concrete compressive strength

Flexural tests on RC concrete showed that its flexural strength decreased as the percentage of rubber chips increased. However, RC specimens displayed higher flexural strength than GTR specimens (Figure 3.6). Also, RC concrete specimens appear to display higher toughness because the samples would not break apart even after failure. A closer look showed that a few strands of rubber were holding the concrete together at the failure zone, preventing them from splitting apart. This was even more evident in 30% RC specimens.

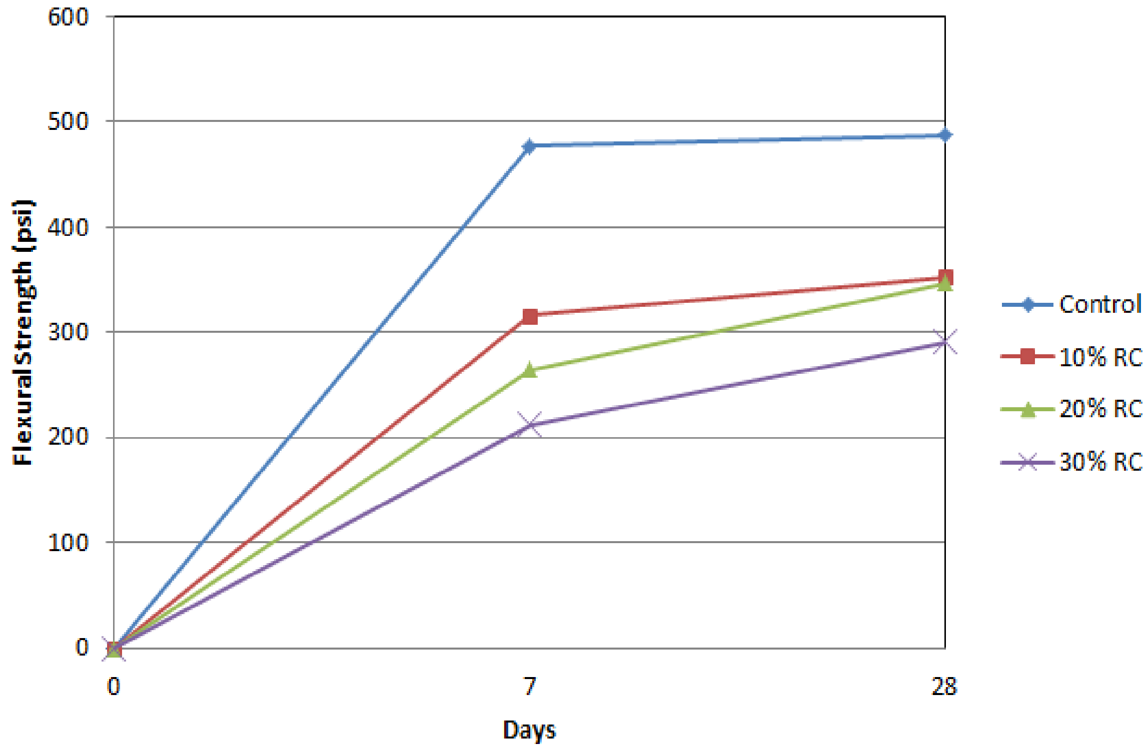


Figure 3.6. Preliminary test results for Rubber chips concrete flexural strength

Split Tensile Strength Test results on RC concrete showed a decrease in strength as the percentage of rubber chips increased in the mix. The 30% RC concrete showed a slightly higher split tensile strength than that of 20% RC. The 10% RC concrete showed high strength compared to GTR concrete specimens (Figure 3.7).

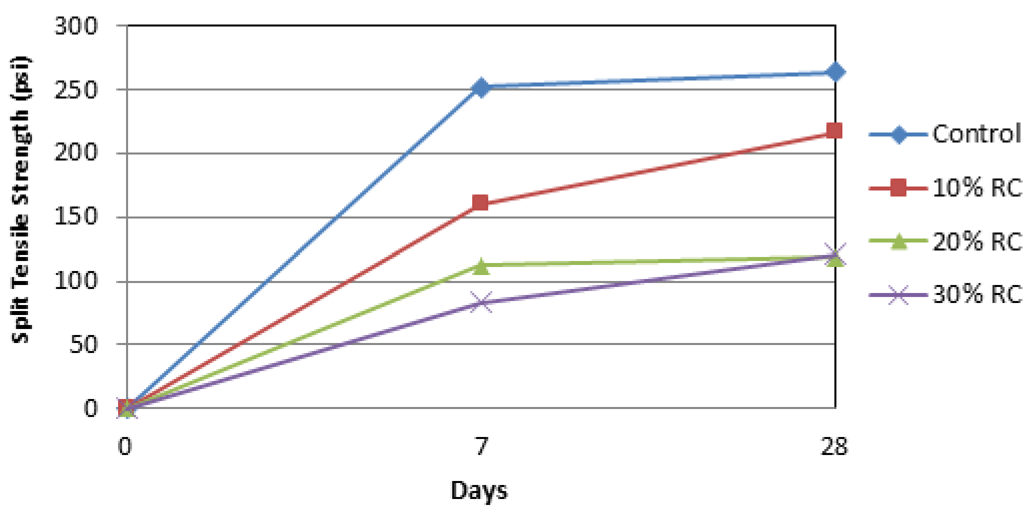


Figure 3.7. Preliminary test results for Rubber chips concrete split tensile strength

Modulus of elasticity of concrete decreased as the percentage of rubber chips increased in the concrete mix. However, the modulus of elasticity in GTR concrete mixes was much lower than in mixes with rubber chips. Results generally proved that including rubber in concrete reduces stiffness by lowering its modulus of elasticity. Summary of results are in Figure 3.8.

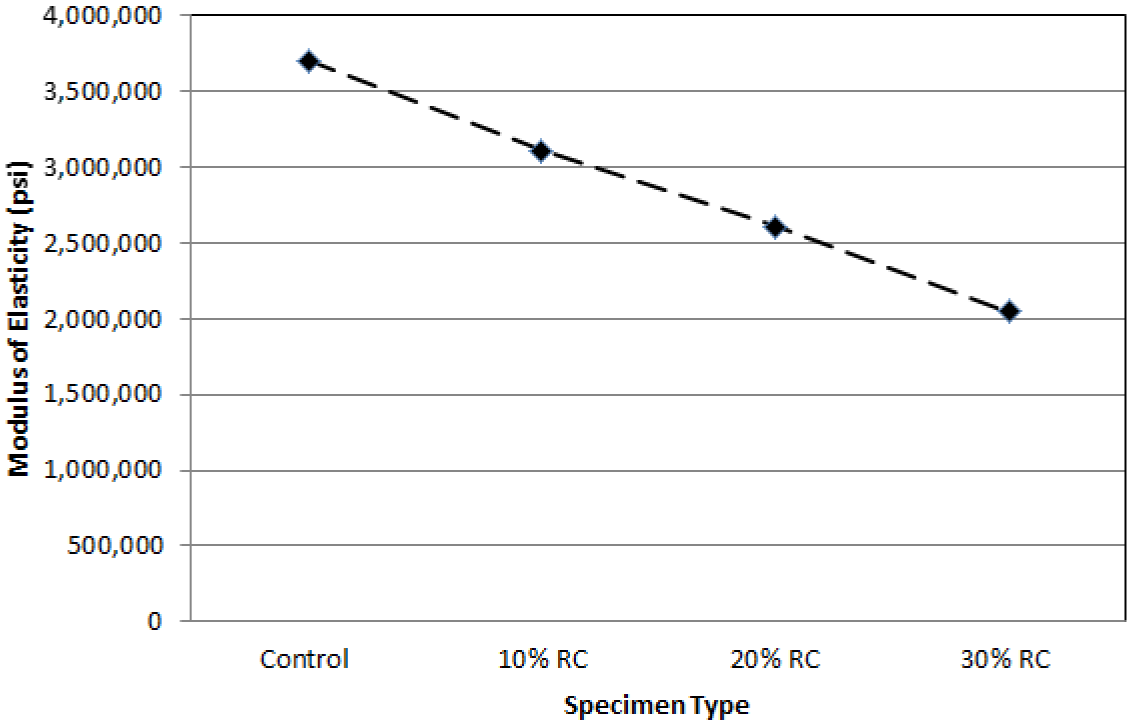


Figure 3.8. Preliminary test results for Rubber chips concrete modulus of elasticity

3.1.3 Summary from preliminary tests

Preliminary tests demonstrate that mechanical properties (e.g. compressive, flexural and split tensile strength) tend to decrease as rubber content increases in the concrete mix. However, adding rubber to concrete appears to enhance its toughness, because GTR and RC concrete specimens did not break into pieces at failure for all strength tests. A higher display of toughness was seen in RC concrete specimens, which did not split apart during flexural strength tests. Results also showed that 30% and 40% GTR concrete specimens had very low strength characteristics. Modulus of elasticity decreased as the percentage of rubber increased. GTR concrete specimens showed lower modulus values than RC concrete specimens. The reduction in modulus indicates that including rubber in concrete reduces its stiffness and hence may prove vital in introducing flexibility in paving concrete.

3.2 Final tests

Based on the results from the preliminary tests, the final tests were conducted; the results are described in the following sections. The major differences between the preliminary and final tests include the following: using only GTR as the rubber content; using concrete admixtures; and restricting the amount of GTR to 0%, 5%, 10%, 15%, and 20% of the fine aggregate content.

The decision to only use GTR reflected the primary focus of the FDOT on GTR rather than rubber chips. The use of admixtures was intended to improve detrimental properties observed during the preliminary tests, especially the lower slump. Addition of water reducer and air entraining agent is supposed to improve some of these properties. Lastly, the proportion of GTR used was limited to no more than 20% because the 28 day compressive strengths of the samples were significantly lower in mixes above 20% GTR. Moreover, mixing and handling fresh GTR concrete was more difficult above 20% GTR.

3.2.1 Unit weight

Unit weight tests were conducted on each mix type immediately after batching. The unit weight of the mix decreased as the amount of GTR increased (Figure 3.9). This is because the specific gravity of GTR (0.95) is slightly lower than water (1.00) and much lower than the sand it replaces (2.79). Additionally, GTR increases air voids in concrete, which further reduces the unit weight of GTR concrete. Similarly, Kaloush et al. (2004) found that the unit weight of crumb rubber concrete (about 1 mm particle size) decreased approximately 6 pcf for every 50 lbs per cubic yard of crumb rubber added.

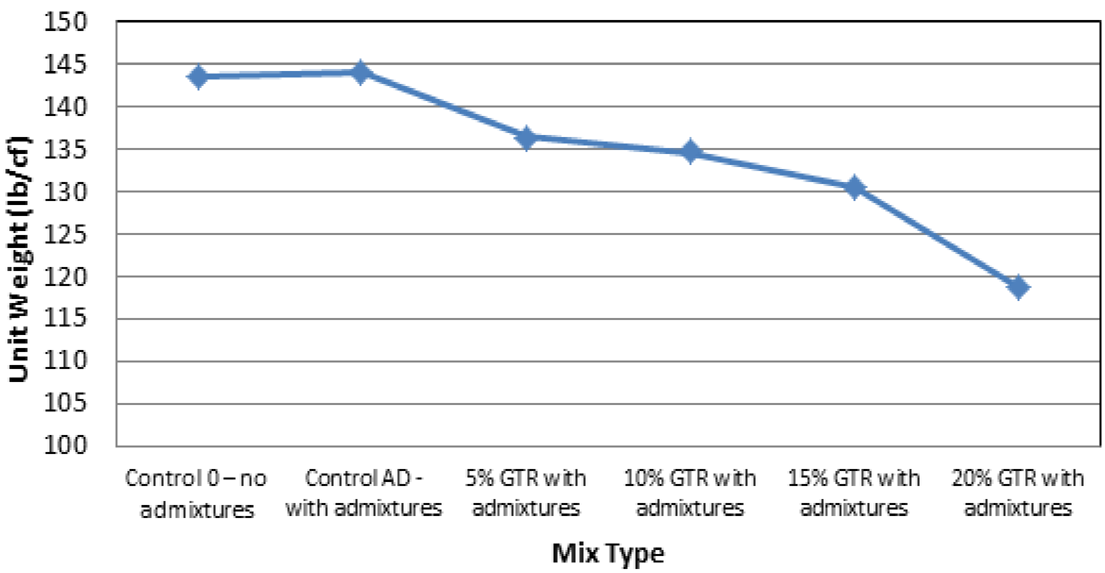


Figure 3.9. Unit weight of various concrete mix types

3.2.2 Air Content

Air content tests on freshly poured concrete showed a general increase in air content as the amount of GTR increased in the mix. These results can be seen in Figure 3.10 below. Fedroff et al. (1996) and Khatib and Bayomy (1999) also observed higher air content in rubberized concrete mixtures than in plain concrete.

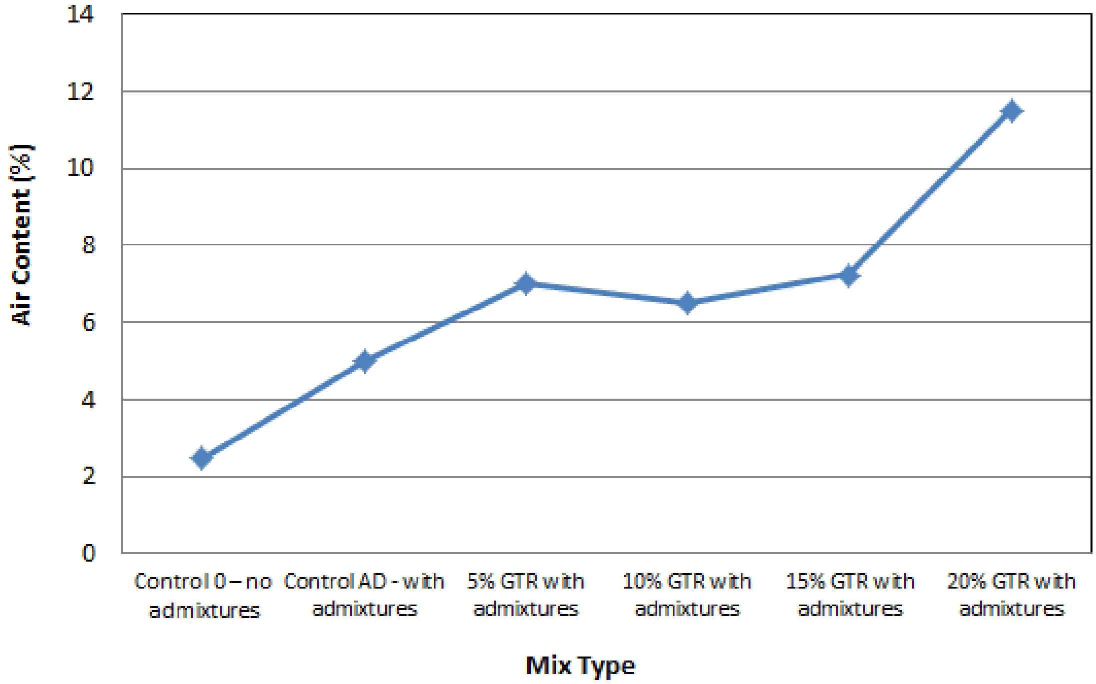


Figure 3.10. Air content of various concrete mix types

3.2.3 Compressive strength

Compressive strength decreased as GTR increased per mix-type, which is shown in Table 3.3 and Figure 3.11. Similarly, Eldin and Senouci (1993) noted that replacing both fine aggregates and coarse aggregates with rubber reduced the compressive strength of rubberized concrete. However, in our study there was a higher gain in compressive strength for GTR samples between 7 days and 28 days than in the control samples. At 28 days, GTR samples demonstrated a compressive strength increase of 60 - 100%, whereas control samples increased in compressive strength between 30 - 40%.

Table 3.3. Final test results for GTR concrete compressive strength

Mix Type	7-Day Compressive Strength (psi)	28-Day Compressive Strength (psi)	90-Day Compressive Strength (psi)
Control 0 – no admixtures	3320	4390	5100
Control AD - with admixtures	2930	4050	5090
5% GTR (GTR 5) with admixtures	1410	2350	3140
10% GTR (GTR 10) with admixtures	890	1750	2420
15% GTR (GTR 15) with admixtures	680	1110	1450
20% GTR (GTR 20) with admixtures	360	760	850

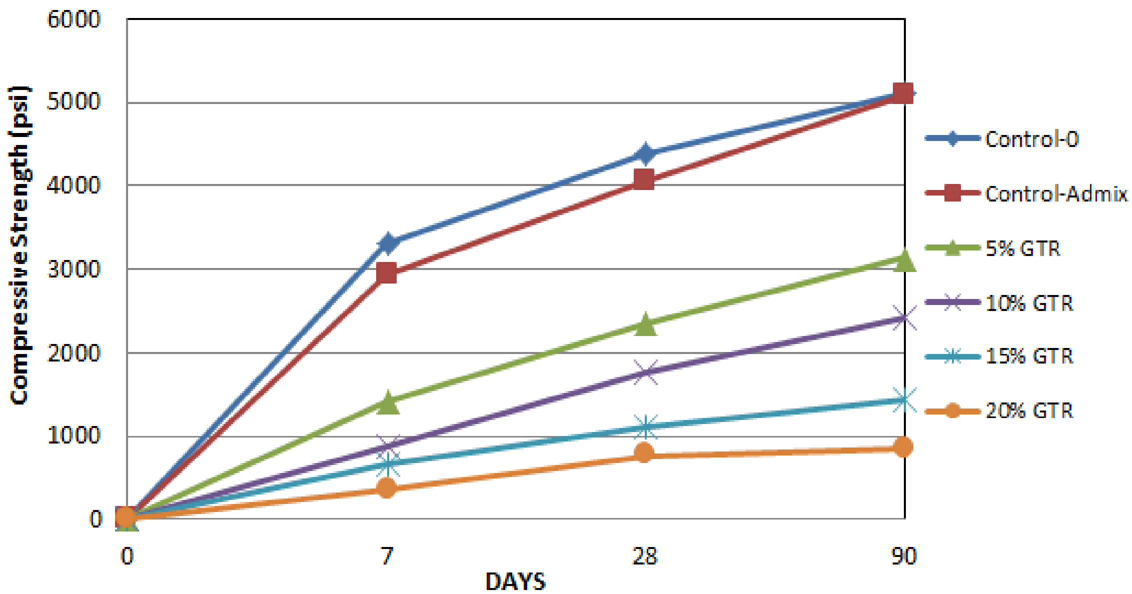


Figure 3.11. Final test results for GTR concrete compressive strength

The main failure patterns in the compressive strength tests for all mix-types were cone on both ends and cone on one end with vertical cracks. These failure patterns are typical for concrete mixes.

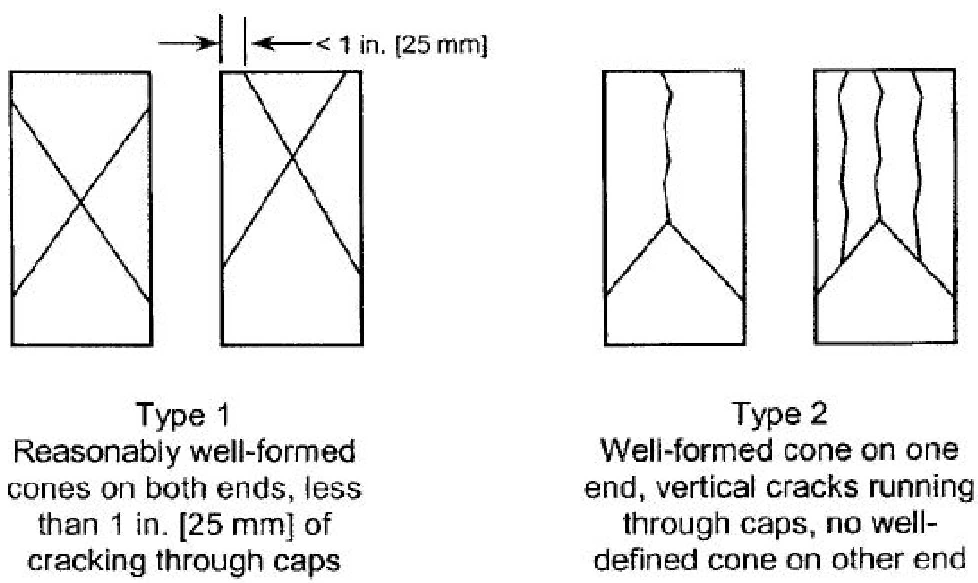


Figure 3.12. Fracture types 1 and 2 cylindrical concrete specimens (ASTM C39)

Control specimens displayed sudden failure modes while GTR specimens showed a gradual failure and possible residual strength or toughness. These results reveal that while there is a considerable decrease in compressive strength when GTR is used, there also appears to be increased toughness, because GTR specimens did not break into pieces at failure. Similarly, Eldin and Senouci (1993) determined that rubber concrete experiences gradual failure under compressive loading, and Kaloush (2005) stated that crumb rubber concrete remains intact at failure. Results from a limited test on stress-strain relationships are shown in Figures 3.13 and 3.14.

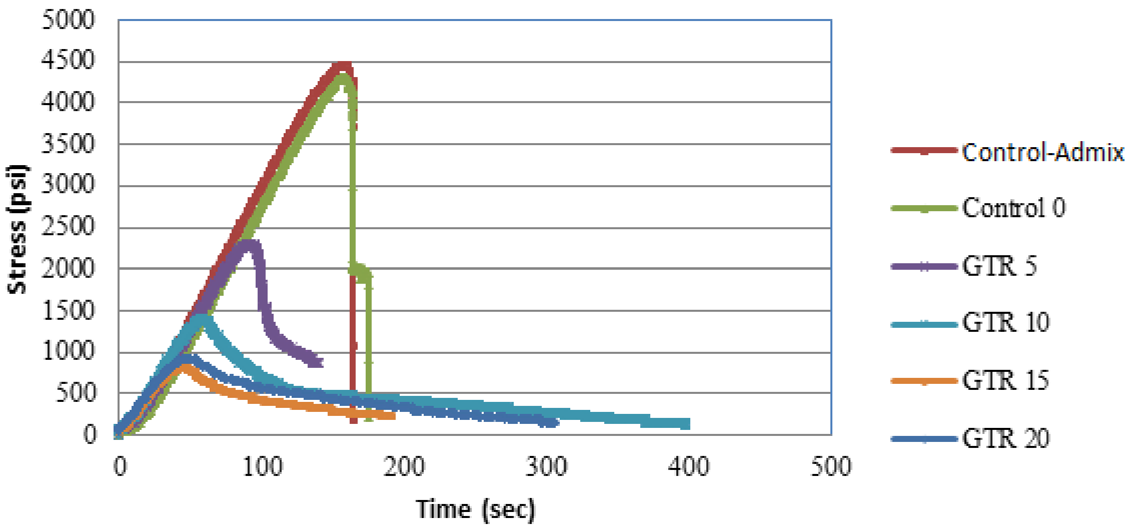


Figure 3.13: Stress-time graph for specimens under compression

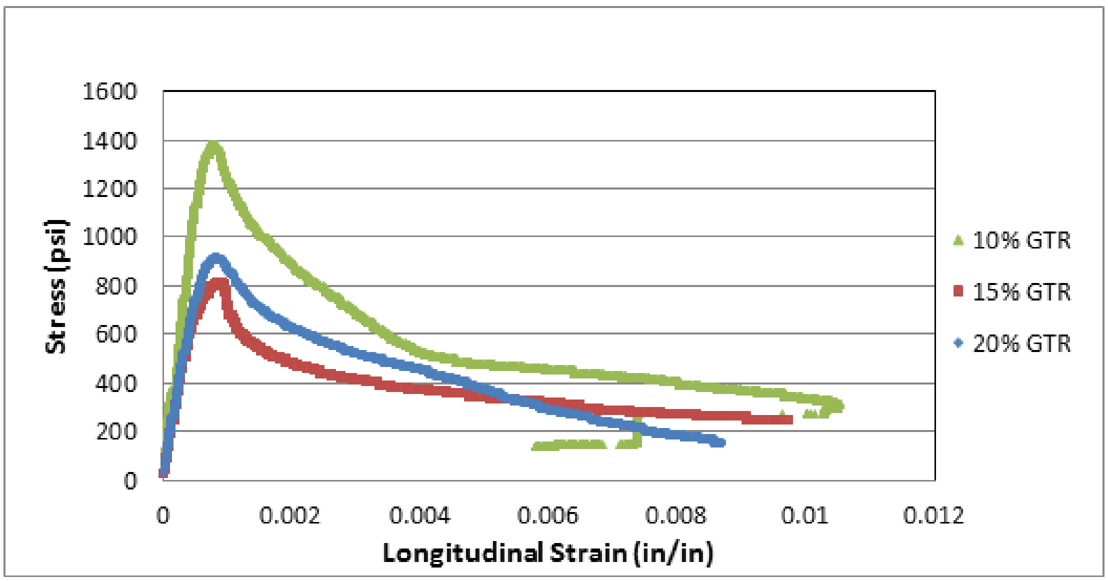


Figure 3.14: Stress-Strain graph for GTR specimens under compression

3.2.4 Flexural strength

Flexural strength (modulus of rupture) in concrete specimens generally decreased as the proportion of GTR increased (Figure 3.15). However, 15% and 20% GTR samples in particular displayed signs of increased toughness, because they did not break completely into pieces immediately at failure. In comparison, the control samples fell apart at failure. This observation demonstrates that while adding GTR to concrete decreases the overall strength of concrete, the rubber particles tend to improve its residual strength. This reduced mechanical strength behavior can be justified with the reasons previously given in the section on compressive strength.

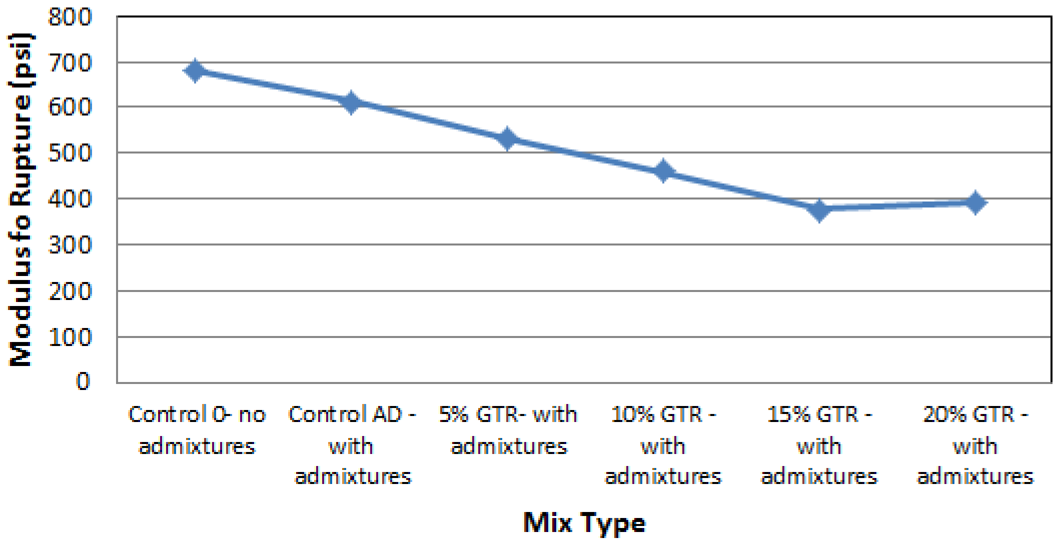


Figure 3.15. Final test results for GTR concrete flexural strength

3.2.5 Split tensile strength

Control specimens displayed higher split tensile strength as compared to GTR specimens. Split tensile strength consistently decreased as the percentage of rubber increased in the mix (Figure 3.16).

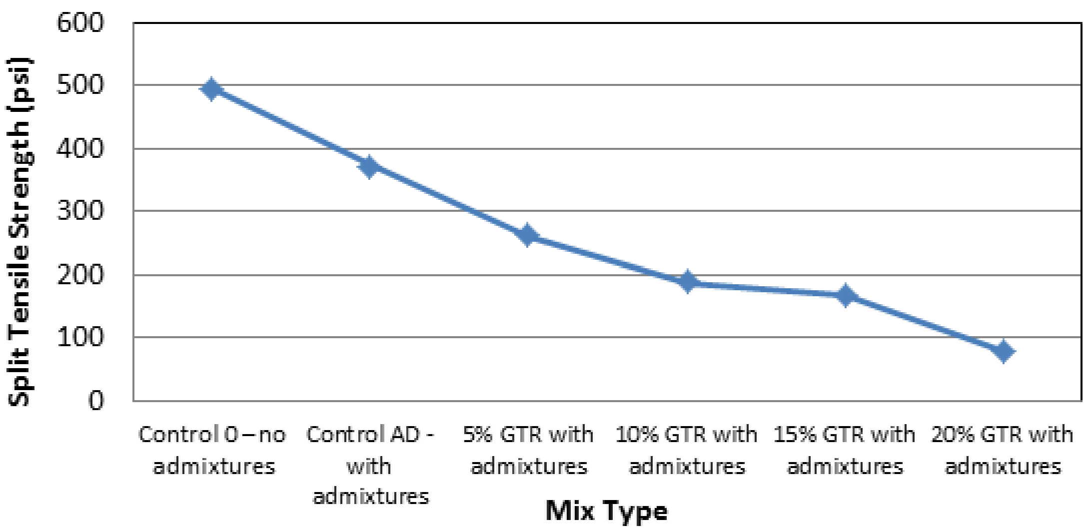


Figure 3.16. Final test results for GTR concrete split tensile strength

3.2.6 Modulus of Elasticity

The modulus of elasticity also decreased as the percentage of GTR increased in the concrete mix (Table 3.4 and Figure 3.17). The modulus of elasticity of concrete is influenced by the modulus of elasticity of the individual components of the concrete mix and the various proportions in which they occur (Turatsinze & Garros, 2008). Between aggregates and cement paste, the aggregates contribute most to the modulus since they are of the greatest proportions. The modulus of elasticity for aggregates range from 6.50 x 10^6 to 12.30 x 10^6 psi and that for hardened cement paste is between 1.45 x 10^6 and 4.35 x 10^6 psi. The modulus of normal concrete is between 4.35 x 10^6 and 7.25 x 10^6 psi. The modulus of elasticity of GTR alone is much lower at 180 to 750 psi (Beatty, 1981). It can therefore be seen that as the amount of GTR increases in a mix, the modulus of elasticity decreases due to the aggregated effects of the individual concrete components.

The Poisson's ratio for GTR mix types did not appear to be significantly different from those of the control mixes (Table 3.4). The Poisson's' ratio for GTR by itself is 0.5 (Beatty, 1981), but its influence on the GTR mixes cannot be clearly ascertained.

Table 3.4. Final test results for GTR concrete modulus of elasticity

Mix Type	Modulus of Elasticity (10^6 psi)	Poisson's Ratio
Control 0 – no admixtures	3.95	0.23
Control AD - with admixtures	4.10	0.21
5% GTR with admixtures	3.05	0.21
10% GTR with admixtures	2.20	0.21
15% GTR with admixtures	1.60	0.26
20% GTR with admixtures	1.65	0.22

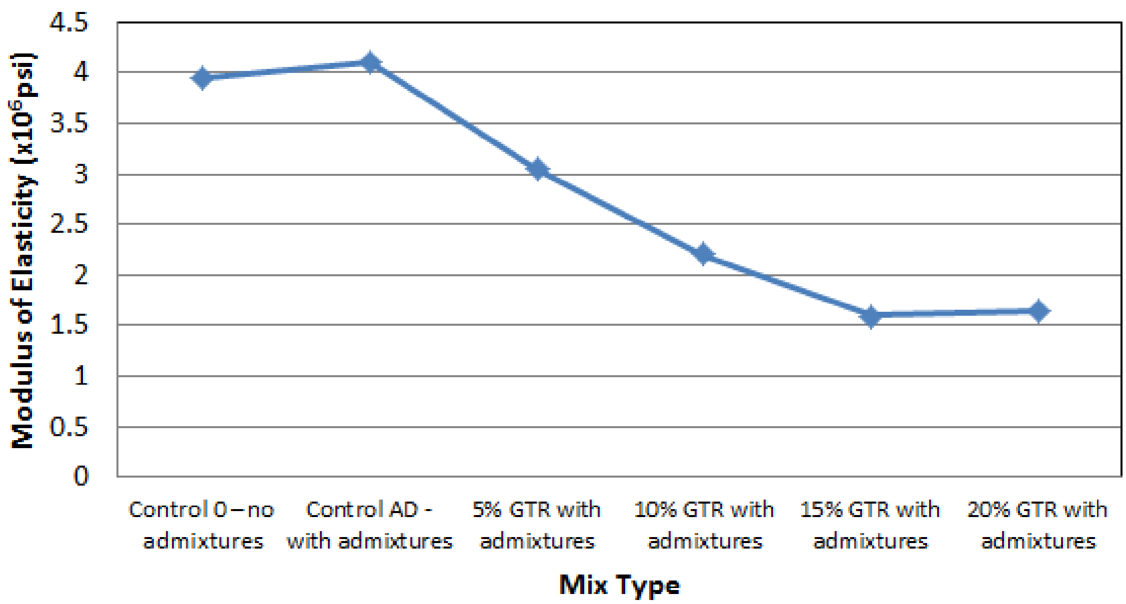


Figure 3.17. Final test results for GTR concrete modulus of elasticity

3.2.7 Coefficient of thermal expansion (CTE)

The coefficient of thermal expansion (CTE) tests were conducted in accordance with AASHTO T 336. Three cylindrical specimens (4-inch by 8-inch) for each mix type were cast for testing. Except for the 15% GTR, CTE results for all GTR specimens were lower than that of the control specimen (Table 3.5 and Figure 3.18). Appendix B shows more detailed results from the CTE test. Generally, all CTE results were within the range for normal concrete, that is, 8 to 12 in/in ^oC (Mindess, Young, & Darwin, 2003), but higher than that expected for concrete with limestone as coarse aggregates (7.8 in/in ^oC). This increase in CTE may be attributed to using fly ash as a component in the mix (Kaloush et al., 2005).

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Table 3.5. Final test results for GTR concrete coefficient of thermal expansion

Mix	Cylinder Label	CTE$_{TOTAL}$ (x 10^{-6} / °C)			Corrected CTE (x 10^{-6} / °C)		
		Data	Mean	Std Dev	Data	Mean	Std Dev
Control (No admixtures)	A	9.920	9.860	0.730	10.424	10.070	0.726
	B	9.102			9.235		
	C	10.558			10.552		
Control (with admixtures)	A	8.724	9.487	0.718	9.406	9.734	0.384
	B	10.149			10.157		
	C	9.588			9.640		
5% GTR	A	9.381	9.535	0.393	9.458	9.753	0.276
	B	9.243			9.799		
	C	9.982			10.004		
10% GTR	A	9.767	9.301	0.438	9.833	9.552	0.250
	B	9.238			9.355		
	C	8.898			9.469		
15% GTR	A	10.105	10.130	0.032	10.135	10.151	0.032
	B	10.166			10.188		
	C	10.118			10.129		
20% GTR	A	8.202	9.754	1.521	8.979	10.043	1.143
	B	9.818			9.900		
	C	11.242			11.251		

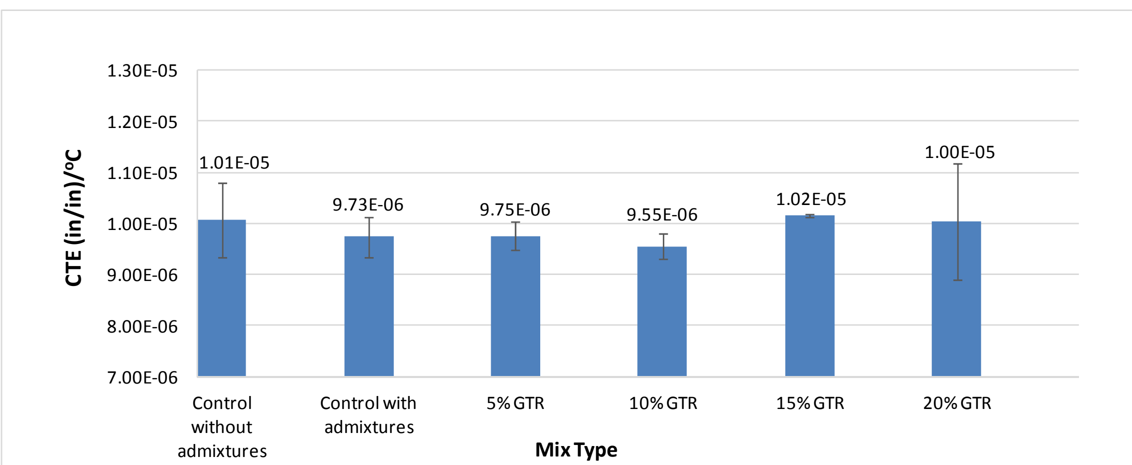


Figure 3.18. Final test results for GTR concrete coefficient of thermal expansion

3.2.8 Plastic Shrinkage

Time tests revealed that as the percentage of GTR used in the mix increased, so did its setting time (Tables 3.6, 3.7 and Figure 3.19). This shows that the presence of GTR in concrete has an effect on the hydration process. In the control specimen, continuous crack widths at the center were between 0.40 mm and 0.5 mm, while closer to the ends (but 1 in. away from the sides of the mold) crack width values between 0.1 mm and 0.30 mm were recorded. These crack widths were perpendicular to the riser at the center of the mold, but shifted slightly away from the center as they progressed to the ends of the risers. The average crack width for the control was 0.48 mm; this is close to the threshold value of 0.5 mm expected for plain concrete by ASTM C1579. The variation in the crack widths is shown in Figures 3.21 to 3.23. Compared to control specimens, results from GTR concrete plastic shrinkage crack measurements showed that including GTR in concrete decreases and slows down the propagation of plastic shrinkage cracks. However, it should be noted also that among the GTR concrete specimens, it was observed that increases in the GTR content caused a slight increase in the mean crack width.

Slump of the fresh concrete mix was reduced as the percent of rubber increased (Figure 3.20). As a result, the bleeding potential decreased, facilitating plastic shrinkage and the associated cracks. Thus the more propagation of plastic shrinkage cracks as the amount of rubber in the concrete mix increases. It is a common knowledge that concrete with low bleeding potential such as, concrete with high proportions of fines or low slump, are more prone to plastic shrinkage cracking (CCAA, 2005). This may be a contributory factor to the increase in crack width beyond 10% GTR replacement.

Table 3.6. Results from plastic shrinkage tests: slump and setting times

Amount of GTR*	No. of samples	Fresh concrete properties			
		Average slump (in.)	Initial Setting Time (mins.)	Final Setting Time (mins.)	Evaporating Rate (kg/m^2/h)
0	4	3.75	216.5	411.0	0.763
5%	3	5.25	315.0	536.0	0.773
10%	3	4.00	373.0	647.0	0.736
15%	3	3.25	363.0	852.0	0.648
20%	3	2.50	475.0	946.0	0.669

** Percentage of fine aggregate*

Table 3.7 Results from plastic shrinkage tests: crack observations

Amount of GTR*	No. of samples	No. of crack positions	Description of cracks	Mean crack width (inch)	Std Dev of crack width (inch)
0	4	70	Continuous on all samples	0.017	0.007
5%	3	8	None on 2 samples; discontinuous on 1 sample	0.009	0.004
10%	3	19	Discontinuous on all samples	0.008	0.013
15%	3	35	Discontinuous on all samples	0.012	0.014
20%	3	47	Discontinuous on all samples	0.013	0.009

** Percentage of fine aggregate*

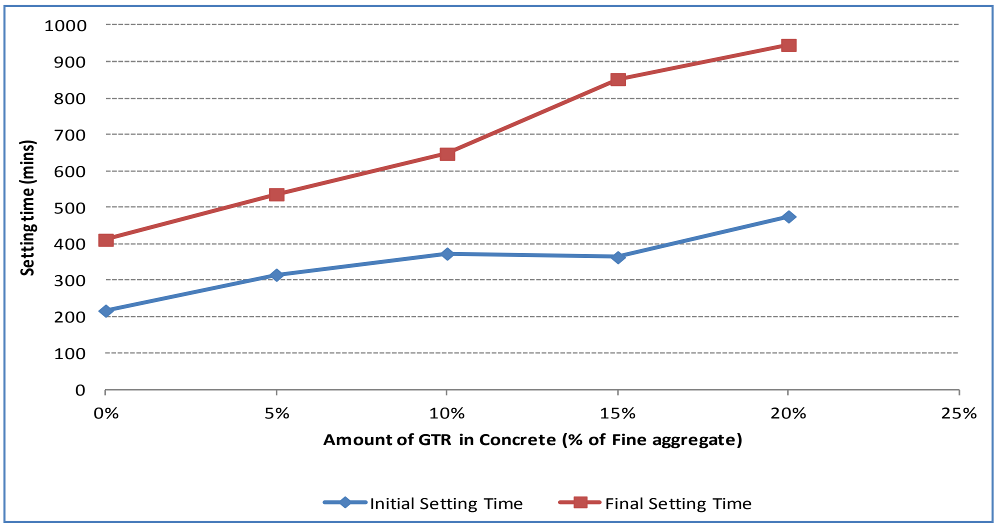


Figure 3.19. Variation in setting times during plastic shrinkage test

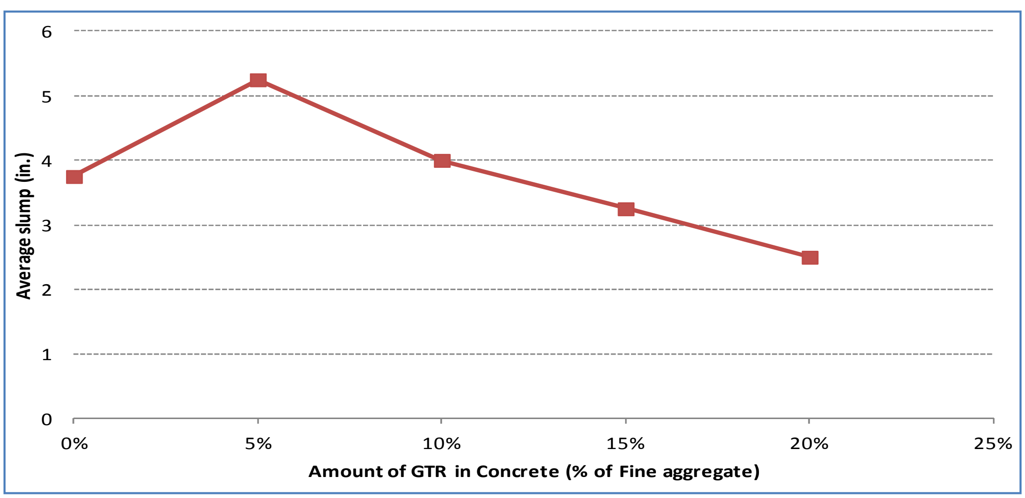


Figure 3.20. Variation in slump during plastic shrinkage test

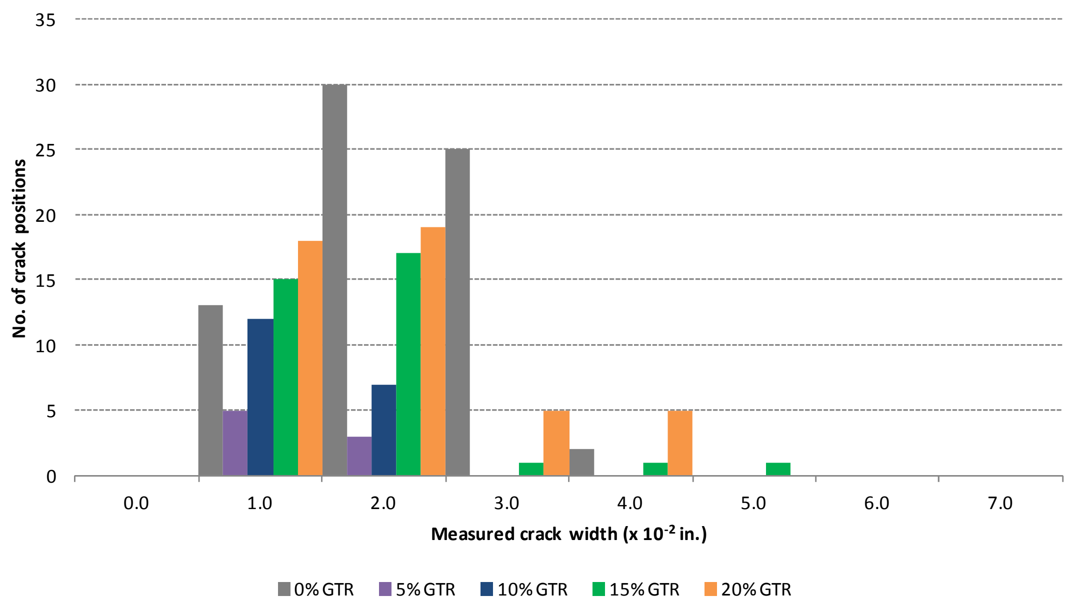


Figure 3.21. Distribution of measured crack widths due to plastic shrinkage

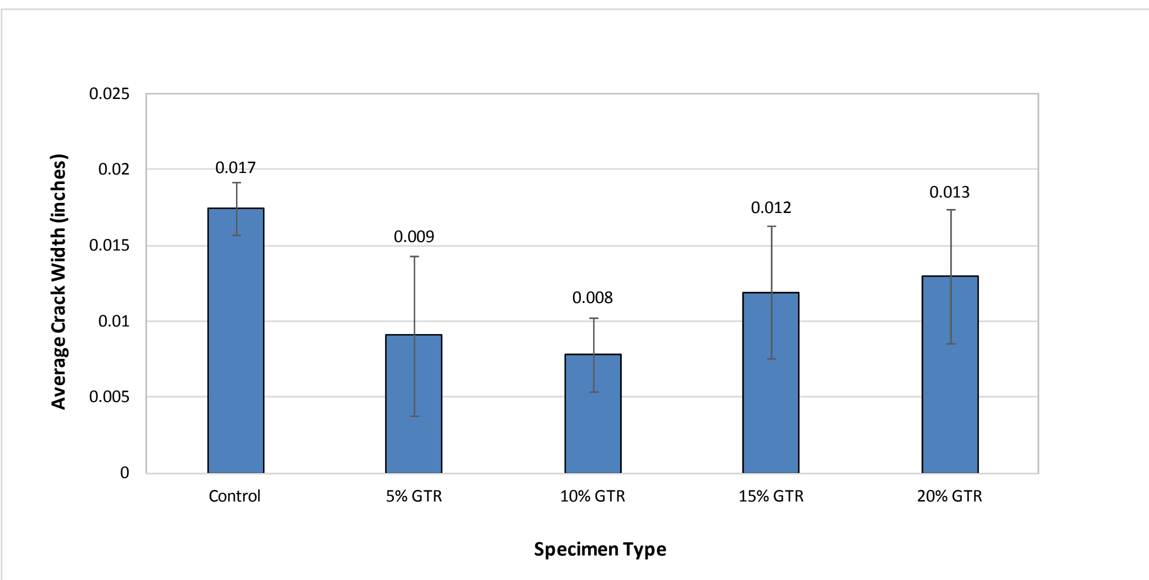


Figure 3.22. Average crack width for both testing stages

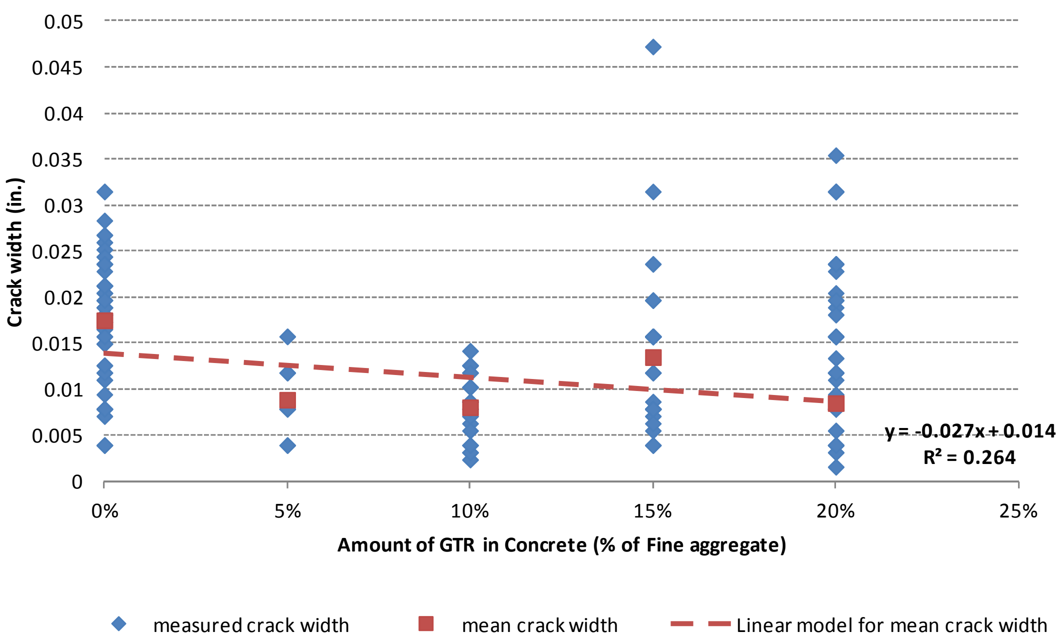


Figure 3.23. Variation in crack widths due to plastic shrinkage

Delays in setting increase the possibility of plastic shrinkage cracking because concrete would not have developed sufficient tensile strength to resist the tensile stress of early shrinkage (NRMCA 2014). Increases in setting time actually mean that GTR concrete remains in the plastic state for a longer period of time, which may facilitate plastic shrinkage cracks. Similarly, retarded concrete is more prone to plastic shrinkage cracks because it remains longer in the plastic state (CCAA 2005). This delay in setting time may account for increases in crack width that accompany GTR increases.

The increase in air voids as a result of GTR in concrete may also be a reason for the increase in the number of plastic shrinkage cracks at higher GTR percentages. As previously discussed, the air content of concrete increases as the amount of GTR in the mix increases. These voids may reduce the rate of bleeding in concrete, which would increase the potential for plastic shrinkage crack propagation. However, it can be reasonably concluded that the inclusion of GTR in concrete mix reduces plastic shrinkage cracks. Some illustrative images on the plastic shrinkage cracks are shown in Figures 3.24 to 3.28.

Figure 3.24. Images of plastic shrinkage crack on control specimens

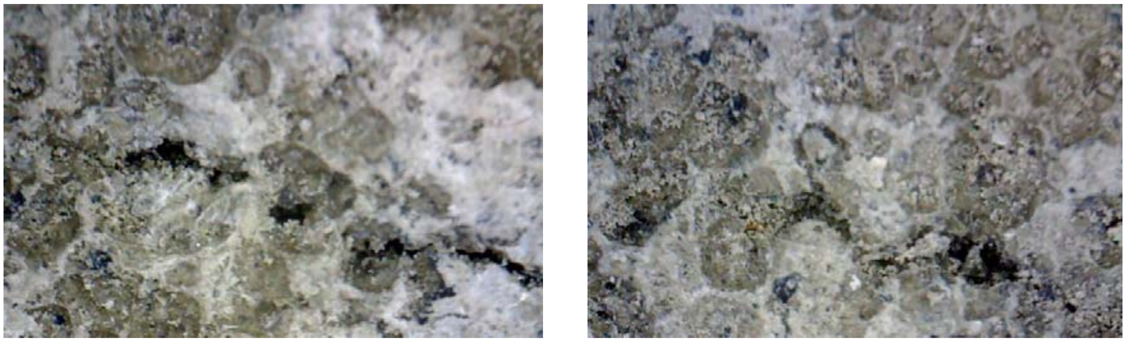


Figure 3.25. Images of plastic shrinkage crack on 5% GTR specimens

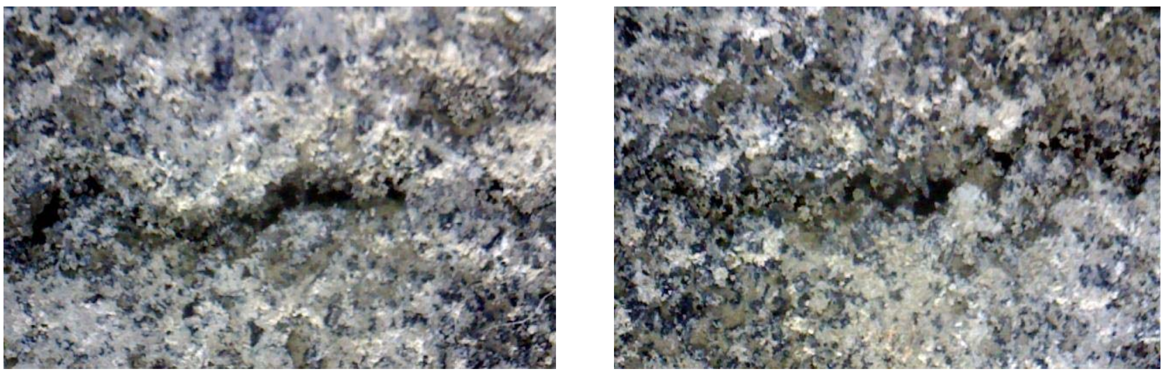


Figure 3.26. Images of plastic shrinkage crack on 10% GTR specimens

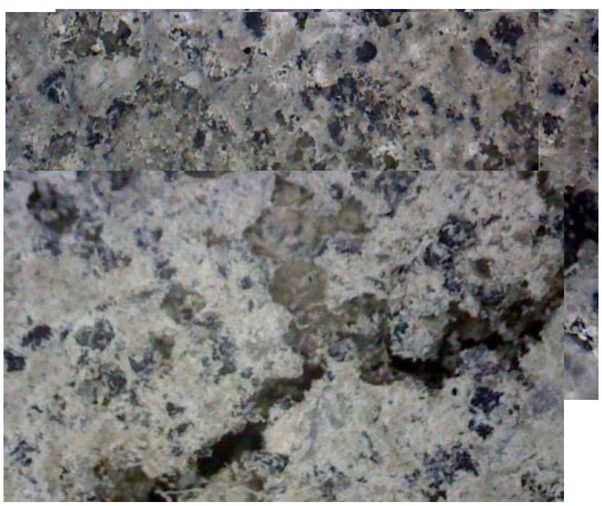


Figure 3.27: Images of plastic shrinkage crack on 15% GTR specimens

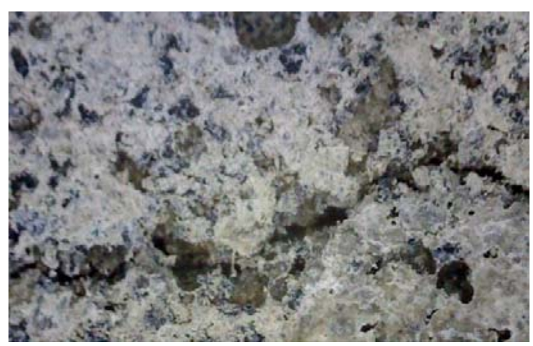


Figure 3.28: Images of plastic shrinkage crack on 20% GTR specimens

3.2.9 Drying (free) shrinkage

The dry shrinkage tests were conducted for only 10% GTR concrete, along with control specimens from a normal concrete mix. The results below are considered preliminary findings since other GTR content variations were not considered. The dry shrinkage tests ran for 21 days. The average free shrinkage strain on 10% GTR specimens was slightly lower than that of control specimens (Figure 3.29). These results were from two cast concrete prism samples for both control and 10% GTR mixes. Further studies are requisite before more assertive conclusions can be drawn. Zhang, Li, and Paramasivam (2005) found in their initial results that shrinkage in normal concrete with granite was higher than that of light weight concrete for the first 6 months of testing. They also observed that shrinkage decreased as the density of aggregates decreased, which corresponded to an increase in the porosity of aggregates and water absorption. GTR, which has a lower density and reduces the modulus of concrete, may aid in preventing free shrinkage cracks. These preliminary results are similar to preliminary results from Zhang, Chen, and Chen and Sun (2005), who concluded that because of rubber particles' soft nature, including them in cement reduces its dry shrinkage. However, Turatsinze and Garros (2008) found higher free shrinkage in cement with rubber aggregates. They explained that the low elastic modulus of rubber offers less restraint to cement paste shrinkage.

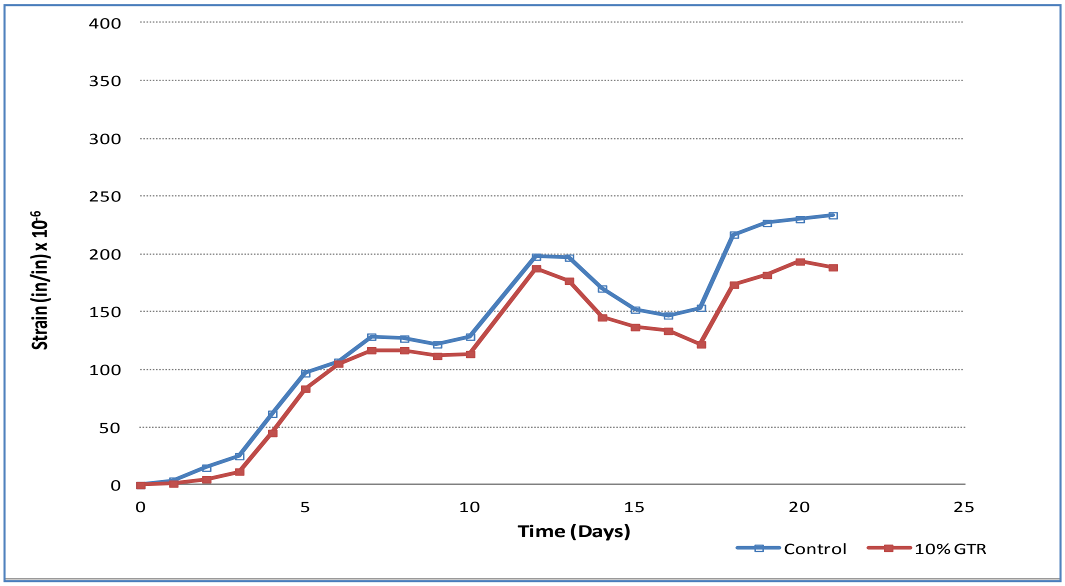


Figure 3.29.Variation in drying shrinkage strains with time

3.2.10 Scanning Electron Microscope (SEM) Analysis

In addition to the tests conducted, a high magnification microscope was utilized to determine the constituents and the nature of GTR, which may contribute to its properties in concrete. Previous researchers have attributed low strength characteristics of rubber concrete to possible bonding issues between rubber and mortar. This test was intended to discover the actual properties of GTR as an independent material and examine how rubber particles are bonded in concrete samples. Samples of GTR as an independent material and 20% GTR concrete were viewed under the SEM.

Control specimens showed the presence of needle-like ettringites (Figure 3.30). The surface morphology of GTR particles showed striations as seen in Figure 3.31 Finally, the samples of concrete with 20% GTR are seen in Figure 3.32; needle-like ettringites are on the interface of the cement matrix with the rubber, indicating no signs of bonding deficiencies.

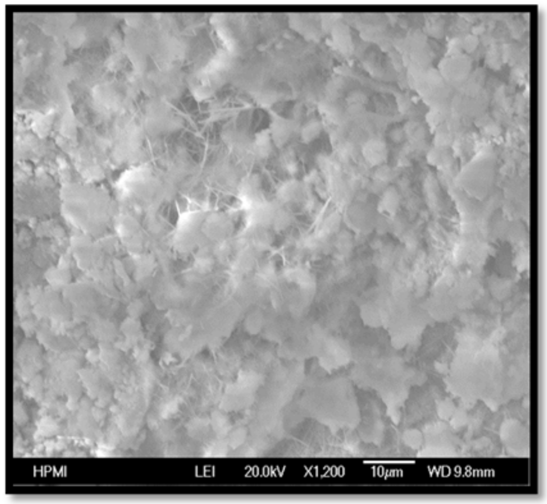
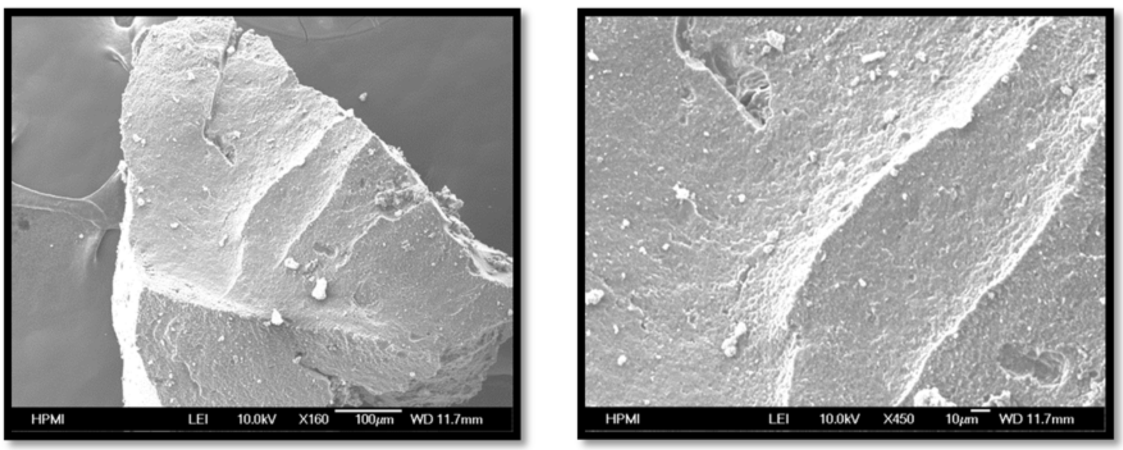
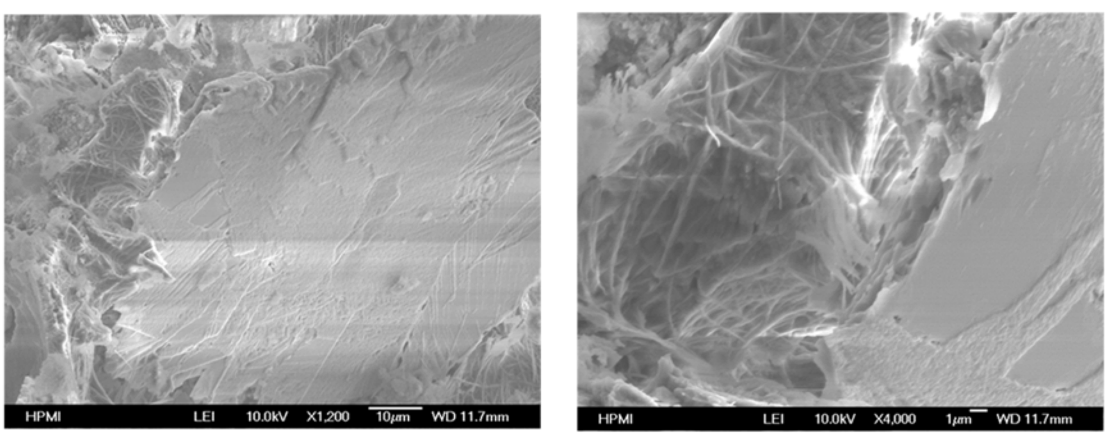


Figure 3.30. Control specimen (x1200 zoom)



a. b.

Figure 3.31. GTR particle a. (x160 zoom) and b. (x450 zoom)



a. b.

Figure 3.32. 20% GTR concrete a. (x1200) and b. (x4000 zoom)

3.3 Modified test procedures

Based on observations during the research, some of the test methods described above needed to be slightly revised. This includes the following modifications: pretreating the GTR before use; reducing the water-to-cement ratio while increasing cementitious materials; and adding a defoaming agent to the GTR concrete during mixing.

3.3.1 Pretreatment of GTR

Pretreatment was done on GTR mixes that replaced 15% and 20% of fine aggregates by weight. For each GTR concrete mix, control specimens were cast. The mix design did not include admixtures. The amount of cement used was 500 lbs. per cubic yard of concrete, and the designed water-to-cement ratio was 0.5. However, moisture content analysis found that the actual w/c ratio was 0.56 and the moisture content of GTR after air drying for 3 days was 7.6%.

Test results on pretreated GTR concrete were compared to second stage test results from GTR concrete mixes with admixtures (Table 3.8 and Figure 3.33). At 28 days, 15% and 20% pretreated GTR concrete had an improved compressive strength of about 50% and 35% respectively. Furthermore, comparing the 28 days compressive strength of previous mixes with admixtures to the results from pretreated GTR concrete showed that 15% and 20% pretreated GTR concrete had an increased compressive strength of about 15% and 21% respectively. It is therefore evident that pretreating GTR by washing with water improves the compressive strength of GTR concrete. Similar conclusions were drawn by Eldin and Senouci (1993), who also pretreated rubber particles by soaking and thoroughly washing with water to remove contaminants.

Table 3.8. Compressive Strength Results for Pretreated 15% GTR Concrete

Mix Type	28 days Compressive Strength (psi)
Control for test batch	4391.14
15% GTR with admixtures	1107.27
20% GTR with admixtures	764.09
Control for test batch	4187.42
15% GTR pretreated	1672.43
Control for test batch	4256.98
20% GTR pretreated	1032.75

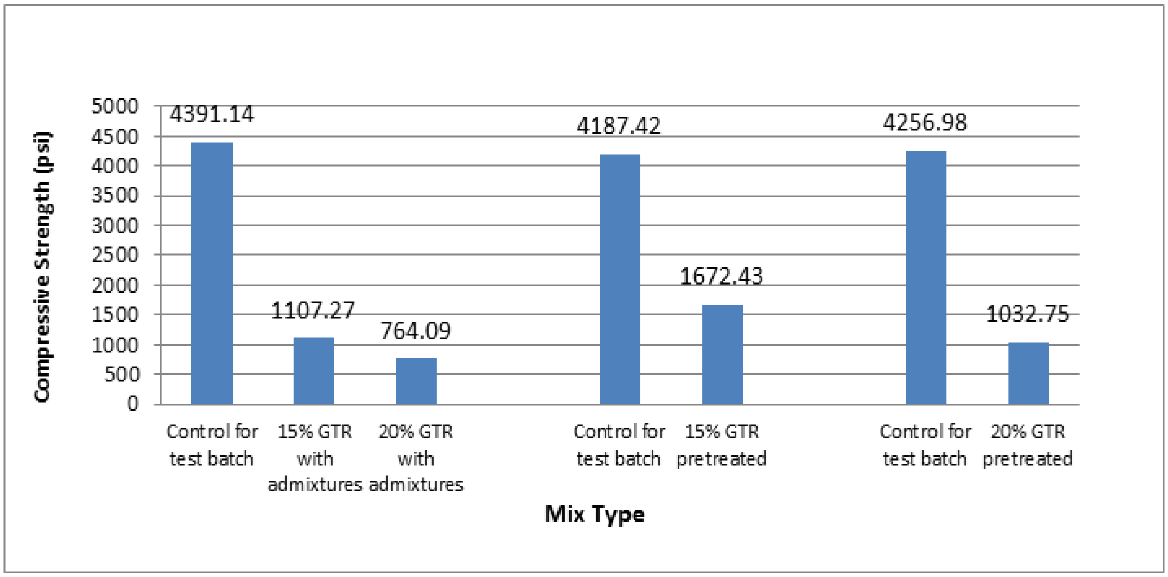


Figure 3.33. Compressive Strength results for pretreated 15% GTR Concrete

3.3.2 Reduced water/cement ratio

Compressive strength tests were conducted on GTR concrete with a reduced water/cement ratio, targeting 0.40. To study the effects on workability, the total amount of water remained constant for all mixes. Moisture content analysis was performed on aggregates (based on absorption values) to determine the actual water-to-cement ratio of the concrete mix. The results indicated that the actual water-to-cement ratio used was 0.44. Table 3.9 shows the slump decrease and increase in air content when GTR is not pretreated.

Table 3.9. Data on Freshly Poured Concrete for Reduced w/c Concrete Tests

	Control with fly ash and admix	15% GTR (Pretreated) with fly ash and admix	15% GTR (Not Pretreated) with fly ash and admix
Unit weight of concrete (lb/cf)	147.40	135.00	134.20
Slump (in.)	2.50	1.75	1.00
Temperature of concrete (°F)	95.00	87.00	85.00
Air content (%)	2.75	4.75	6.00
Water Reducer (oz)	1.30	1.30	1.30
Air Entrainer (oz)	0.25	0.25	0.25
Total Water (lbs)	37.70	37.70	37.70

As shown in Table 3.10 and Figure 3.34, at 28 days the control Portland cement concrete had an average compressive strength of 5690 psi while 15% GTR concrete (not pretreated) had 3064 psi. The slightly lower strength (2929 psi) for the pretreated specimen can be attributed to moisture still present in the pretreated GTR from the washing. In both cases, pretreated or not, reducing the water/cement ratio and increasing cementitious material contributed to an increase in the compressive strength of GTR concrete. These results are much higher than the 1100 psi obtained using the 0.5 water/cement ratio earlier in the study. Additionally, it also indicates that 15% GTR concrete can be used to meet the compressive strength requirements for Class I pavements (3000 psi).

Table 3.10. Average compressive strength results for Reduced w/c Concrete Tests

Specimen Type	Compressive Strength (psi)			
	3-Day	7-Day	28-Day	90-Day
Control	3630	4500	5690	6770
15% GTR (Pretreated)	1750	2380	2920	3790
15% GTR (Not Pretreated)	1890	2310	3060	3660

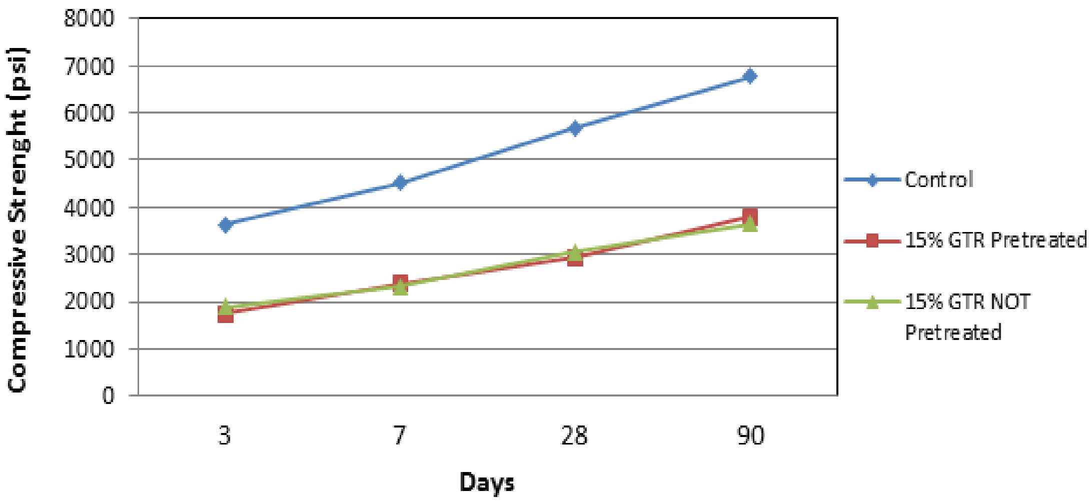


Figure 3.34. Compressive strength results of GTR concrete after reducing w/c ratio

3.3.3 GTR Concrete with Defoaming Agent

GTR concrete mixtures were prepared using a lower water/cement ratio, and also incorporated a defoaming agent. Table 3.11 shows the test results from freshly poured 15% GTR concrete with two different dosages of C-64 defoaming agent.

Table 3.11. Test Results on Freshly Poured 15% GTR Concrete Mixtures with Defoaming Agent

	15% GTR Concrete with 2.5 ml of Defoaming agent	15% GTR Concrete with 10 ml of Defoaming agent
Unit weight of concrete (lb/cf)	135.40	137.80
Slump (in.)	2.25	1.50
Temperature of concrete (degF)	78.00	78.00
Air content (%)	5.75	4.75
Water Reducer (oz)	0.56	0.56
Air Entrainer (oz)	-	-
Defoaming agent	0.15	0.60
Total Water (lbs)	16.60	16.60

A dosage of 2.5 ml of defoamer per gallon of water showed only a marginal improvement in foam reduction, but a 10 ml dosage reduced the foam more (Figure 3.35). Using 10 ml of defoaming agent per gallon of water decreased air content and increased both densification and foam reduction. Compared to the results shown in Table 3.9, using the defoamer appears to make the GTR concrete slightly denser, adding about 3 lb/cf with use of 10 ml dosage. The air content was slightly reduced from 5.75% to 4.75%. It is also evident that the increase in dosage of defoaming agent from 2.5 ml/gal of water to 10 ml/gal of water resulted in a 5% increase in the 28 day compressive strength of 15% GTR concrete (Table 3.12). However, both values are still less than the compressive strength obtained without a defoaming agent in the low water/cement ratio (Table 3.10).

a. dosage of 2.5 ml/gal water b. dosage of 10 ml/gal water

Figure 3.35. Observed foaming solution in 15% GTR concrete after use of defoaming agent

Table 3.12. Compressive Strength Results on 15% GTR Concrete Mixtures with Defoaming Agent

Specimen Type	7-day Compressive Strength (psi)	28-day Compressive Strength (psi)
15% GTR with 2.5ml /gal of water defoamer	1750	2570
15% GTR with 10ml /gal of water defoamer	1890	2690

3.4 Summary

Initial tests using both rubber chips and GTR as partial aggregate replacement in concrete confirmed previous research on their effects on the mechanical properties of concrete. Further research focusing on GTR revealed more findings than the existing literature, particularly in the tests on the Coefficient of Thermal Expansion (CTE), plastic shrinkage, and other modified tests such as lowering the water/cement ratio and using defoaming agents.

4. Ready mix plant implementation

This section reports the activities done at the concrete ready mix plant. As part of the study, the research team was required to work with a ready-mix plant and to implement results from the laboratory experiments, in terms of the mix design and actual mixing at the plant. This task helped identify and recommend methods for storing GTR at the ready mix plant and developed procedures for introducing the GTR into and mixing inside the ready-mix trucks.

The test site was the ARGOS Ready Mix Concrete Plant, located in Tallahassee and very close to the research team's laboratory at the Florida A&M University (FAMU)-Florida State University (FSU) College of Engineering. This particular plant in Tallahassee is a truck-mixed type of plant, where all the materials are batched at the plant and mixed completely in the individual cement trucks. In general, for the conducted tests, all quality control aspects of ready mix concrete production were followed, especially those required for truck-mixed plants.

The on-site tests had three goals: first, incorporating, on a larger scale than laboratory environment, the GTR into the typical batching and mixing operations at the ready mix plant; secondly, evaluating the issues related to storage and other quality requirements at the plant; and third, pouring a set of concrete slabs for long-term monitoring and testing of the GTR concrete.

4.1 Lessons learned

The preparation for the ready mix operations as well as pertinent lessons learned from the laboratory experiments conducted earlier is summarized in the following paragraphs.

4.1.1 GTR storage and lumps

Some minor lumps occur in the GTR when stored in plastic bags, but they are easily crumbled when placed in the stationary drum mixer. Absorbed moisture was observed to be of no significance in the stored GTR (in plastic bags) before use, but the container plastic bag for the GTR may be punctured if not protected well.

4.1.2 Residue GTR in mixer

If old (stationary) drum mixers are used, with remnant hardened concrete chunks on the inside surface and blades, a significant amount of the GTR may adhere to these uneven surfaces instead of being thoroughly mixed into the concrete (Figure 4.1a).

4.1.3 Foaming and air content in fresh GTR concrete

Large amount of foaming carbonate solution was observed in the rinsed water from the drum mixer after emptying the concrete (Figure 4.1b). The foaming reflects the large amount of carbonates utilized in the production of the GTR at the manufacturing plant. The carbonate content is not seriously detrimental to the properties of the GTR concrete, but it may be slightly responsible for the relatively high air content. As discussed in the previous section of this report, an approach to resolving this problem was to add a defoaming agent (admixture). Previous literature has recommended including defoaming agents in ready-mix trucks in order to improve upon the quality and strength properties of rubber concrete. Kaloush et. al (2005) included defoaming agents in the production of crumb rubber concrete. There is, however, limited literature on the use of this admixture in rubber concrete. Yet defoaming agents or defoamers as they are generally called, are marketed to reduce concrete air voids and help densify concrete with expected improved mechanical properties.

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a. GTR residue particles b. foaming in after rinse

Figure 4.1. Initial observation of foaming solution and GTR particles on rough blades on mixing drum

The defoamer used for this research is C-64 Concrete Defoamer and Densifying Admixture supplied by Fishstone. The producer describes C-64 as a highly concentrated defoamer and densifying admixture specially designed for self-consolidating type concrete. One quart of C- 64 is sufficient to treat over 200 cu. ft. of concrete. According to the supplier, the following are the expected benefits of this defoaming agent: reduce trapped air in concrete; reduce bug holes thus greatly reducing the need to slurry surface; improve densification of concrete; increase compressive strength; develop stronger/denser concrete. The recommended dosage is 5-20 ml per gal of mix water. For our ongoing study, trial mixes of fresh concrete were prepared in the laboratory using 15% GTR. With trial dosages of 2.5 ml and 10 ml of defoamer per gallon of water, significant reductions were observed in the foam formed in the after rinse of the drum mixer.

The unit weight of the fresh mix increased, indicating densification, while the slump and air content of the fresh concrete mixes was reduced due to the use of the defoamer. The control 15% GTR concrete has a unit weight of 135 lb/ft^3, slump of 3 in. and air content of 6%. With the 2.5 ml and 10 ml dosages, the unit weights were recorded as 135.4 lb/ft^3 and 137.8 lb/ft^{3}respectively, and the slump as 2.25 in. and 1.75 in respectively; the air content was 5.75% and 4.75% respectively. It is recommended that at least 20 ml/gal of water be used on the ready mix batching and mixing for the GTR concrete

4.1.4 Low slump in fresh GTR concrete

It was observed that when a water-reducing admixture is not used, the slump of fresh concrete decreases with addition of GTR. This may drastically reduce the workability of the fresh concrete, especially if the coarse and fine aggregates are very dry or weather is very hot, due to absorption of water expected for the actual mixing.

4.1.5 Relevant documents

In planning the proposed tests at the Ready Mix Plant, the following documents were reviewed and applied when necessary:

- Florida Department of Transportation (FDOT), Concrete Production, Memorandum Topic No. 675-000-000, Materials Manual, Section 9.2, Volume I, Effective January 1, 2005, Revised November 8, 2012.
- Florida Department of Transportation (FDOT), Concrete Batch Plant Operator Study Guide, Originally written by District 2 Materials Office: Tom Byron, Bobby Ivery, and Jim Flaherty, Revision by State Materials Office, 2004.

- Florida Department of Transportation (FDOT), Standard Specifications for Road and Bridge Construction, Sections 346 "Portland Cement Concrete," 347 "Portland Cement Concrete - Class NS," and 919 "Ground Tire Rubber for Use in Asphalt Rubber Binder," 2013.
- ASTM Designation: C 94/C 94M, Standard Specification for Ready-Mixed Concrete, Published March 2004.

4.2 Batching and mixing at plant

To ascertain how to implement GTR concrete on a large scale, the research team discussed with both the GTR supplier (Global Tire Recycling, Wildwood, Florida) and the Concrete Ready Mix Plant (ARGOS in Tallahassee, Florida) about their previous experiences with the respective materials and their incorporation in various FDOT materials in the past. FDOT had used GTR in Asphaltic concrete (AC) mixes as well as fibers in Portland cement concrete mixes. In both cases, the research team learned that the most convenient approach for the plants was to introduce these additional materials at the end of the mixing sequence, typically in pre-packed bags. According to the GTR supplier, initial use of GTR in AC by FDOT required the GTR to be packaged in clear thin plastic sheets that could melt into the hot asphalt; this process eased the introduction of the GTR into the asphalt at the plants. Similarly, at Concrete Ready Mix Plants (Argos Personnel), fibers were typically introduced into concrete mixing by "tossing" the fibers already packaged in biodegradable bags, with the bag shredded and mixed into the concrete.

The GTR is now packaged in 50 lb. plastic transparent and tougher bags (Figure 4.2). On our proposed task for the GTR concrete at the plant, the GTR bag cannot be "tossed" into the mixer. Instead, the GTR would have to be emptied from the bag directly into the mixer. The Concrete Ready Mix Plants (Argos Personnel) insisted that the truck operator will have no time to weigh out the exact amount of GTR; it had to be in pre-weighed bags, ready to be opened and poured into the mixer. In other words, the Truck Mixer Operator had to tear the GTR bag open and add GTR material to the other batched materials for the concrete. The GTR was added first to the mixture. Therefore, since the GTR cannot be weighed precisely at the plant like the other concrete material components, the approach adopted was to have the required amount of GTR bagged in convenient portions so the operator could simply add the required quantities. The mix design requirements were then conveniently estimated for this purpose, such that the required quantity of GTR was specified to the nearest 5 lbs.; ASTM C 94 actually allows specifying the quantity of materials in bags.

4.3 Handling, storage and quality of GTR

Regarding the storage and quality issues, the GTR supplier indicated that for prior FDOT projects using GTR in AC mixes, the GTR was not stored at the plant sites, but ordered on an as-needed basis and delivered to the plant exactly when needed to be mixed into the asphalt. The Concrete Ready Mix Plants (Argos Personnel) also indicated that while the GTR bags may be stored at the plant site, the GTR cannot be not stored in silos, stockpiles, or introduced through their computer-based weighting batching system. Aggregates are typically loaded through conveyor belts from stockpiles/silos and cements from hopper batches, with all materials weighed and introduced through a computerized scale system. It is expected that the GTR will be handled and stored in appropriate locations to avoid contamination and moisture absorption.

GTR in itself due to its impervious and nonabsorbent nature results in a low absorption, mostly accounted for by the presence of Calcium carbonate and few impurities in the delivered material. This low absorption is owing to the fact that the 40 mesh grade was rid of most impurities during manufacturing. Moisture may, however, develop on the surface of GTR due to ambient conditions such as high humidity or exposure to rainfall. Thus it is imperative to store all GTR bags delivered by the manufacturer in a safe and dry environment where they would not be exposed to moisture. It is also important to keep GTR covered and away from very windy conditions. GTR is a light- weight material, hence prone to scattering when exposed to windy conditions. The manufacturer should also be alerted to ensure that all delivered bags are free from cuts or holes which may lead to loss of material during transportation and handling.

Figure 4.2. Processing and bagging GTR at Recycling Plant

4.4 Mix design

The materials needed to mix the GTR concrete are identified and summarized below, including the proposed mix design for two batches of 4.5 CY (121.5 CF) each (Table 4.1).

Cement: Type I Portland cement

Coarse Aggregate: Crushed Limestone Grade 57 Fine Aggregate: Silica sand

GTR: 40 Mesh GTR, FDOT Type B (Standard Specifications Section 919) Water: Potable water

Mineral Admixture (Pozzolan): Fly ash

Chemical Admixture (water-reducer): Type A, ADVA 140 Manufactured by GRACE

Defoaming agent and densifying admixture: C 64 Manufactured by Fishstone

Table 4.1. Mix design for ready mix plant activities

MIX DESIGN SUMMARY	1 CY DESIGN		4.5 CY BATCHES	
	Control Class I Pavement Mix	Control Class I Pavement Mix with 15% GTR	Control Class I Pavement Mix	Control Class I Pavement Mix with 15% GTR
Expected yield (CY)	1	1	4.5	4.5
Material	Weight (lb)	Weight (lb)	Weight (lb)	Weight (lb)

Portland Cement Type I/II	**500**	**500**	**2250**	**2250**
Fly Ash	**125**	**125**	**563**	**563**
Water required for mixing only	**281**	**281**	**1266**	**1266**
Additional water due to aggregate absorption	***72***	***70***	***325***	***317***
Coarse aggregate: Crushed Limestone Grade 57	**1764**	**1764**	**7936**	**7936**
Fine aggregate: Silica sand	**1235**	**869**	**5556**	**3912**
GTR*	**0**	**130**	**0**	**587**
Water reducer (Type A, ADVA 140) oz.	**20.3**	**20.3**	**91.1**	**91.1**
Defoaming/densifying agent (C 4) oz.	**0.0**	**11.5**	**0.0**	**51.9**

** For the 4.5 CY GTR mix, use 590 lb GTR for batching, i.e., 11 of 50 lb standard GTR bags and one 40 lb custom bag.*

4.5. Sample testing

According to the FDOT Materials Manual, a minimum of 3 CY batching is recommended. The proposed plant tests were done in two batches of 4.5 CY each. Some tests were conducted using the concrete mixes produced at the Ready Mix plants. One of the major issues observed and tested was the uniformity of the fresh concrete mix from the truck. Samples were taken for tests for the following properties:

1. Unit weight
2. Slump
3. Air content
4. Temperature (Ambient and Mixture)
5. Compressive strength
6. Flexural strength
7. Split tensile strength

These tests should indicate uniformity of GTR concrete mixes, when the results are evaluated based on the requirements in the ASTM C94 (Table A1.1 Requirements for Uniformity of Concrete). The unit weight of fresh concrete is a good indication of the well-dispersed mixing of the GTR into the cement matrix. The test samples were taken after discharge of about 15 % and 85 % of the load from the truck (ASTM C94 Section 10. 4 and Note 14). Samples were taken at the times described above to ensure uniformity in the concrete. Observations made included seeing whether GTR stuck to the drum interior and blades, but no remnants of GTR appeared inside the drums. Also, the research team observed water washed from the drum at the end of the tests. Foam was observed in the rinsed water.

4.6 Concrete slab for long term tests

In order to conduct some long-term monitoring of the GTR concrete, test slabs on the ground were constructed as follows: 6 ft. x 6 ft. x 11.5 in. deep 15% GTR concrete slab (SLAB1GTR); 5 ft. x 30 ft. x 4 in. deep sidewalk slab using normal strength concrete (control) (SLAB2CONTROL); and 5 ft. x 30 ft. x 4 in. deep sidewalk using 15% GTR concrete (SLAB2GTR). The SLAB1GTR will be utilized to obtain core samples (4” x 8 in.) for compressive strength tests periodically over 12 months. The sidewalk slabs were observed primarily for shrinkage cracks and other surface-related defects. Construction of SLAB1GTR involved excavation and subgrade compaction before placing the 15% GTR concrete (Figure 4.3). The sidewalks were constructed according to the FDOT 2015 Design Standards Index 310 Concrete Sidewalk and also following the FDOT Standard Specifications Section 522. According to the FDOT Standard Plans for Concrete Sidewalk on Uncurbed Roadways (assumed in this test), there are two types of sawed joints required: D Saw Cut Joints, which are 3/16 " wide 2" Deep (12 Hour) Max. 5' Centers; and E Saw Cut Joints which are 1/2 " wide 2" Deep (96 Hour) Max. 30' Centers (Figure 4.4). No joints were provided on the sidewalks in this study because the primary objective on the sidewalk tests is to observe the extent of surface (shrinkage) crack formations on the control and GTR concrete samples. The choice of the 30 ft. length for the sidewalk was based on the maximum length required for the Type E saw joint.

The sidewalk slabs were constructed as follows: excavate and compact the subgrade, place 2 in. of gravel layer and compact, place 4 in. of concrete, then finish surface and cure. The typical cross section is shown in Figure 4.5. A comparison was made of the observations of both sidewalk samples over 12 months and the extent of cracks was documented.

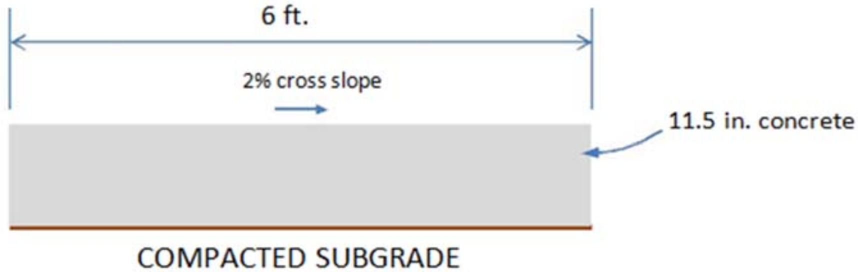

Figure 4.3. Proposed cross section for 6 ft. square concrete slab

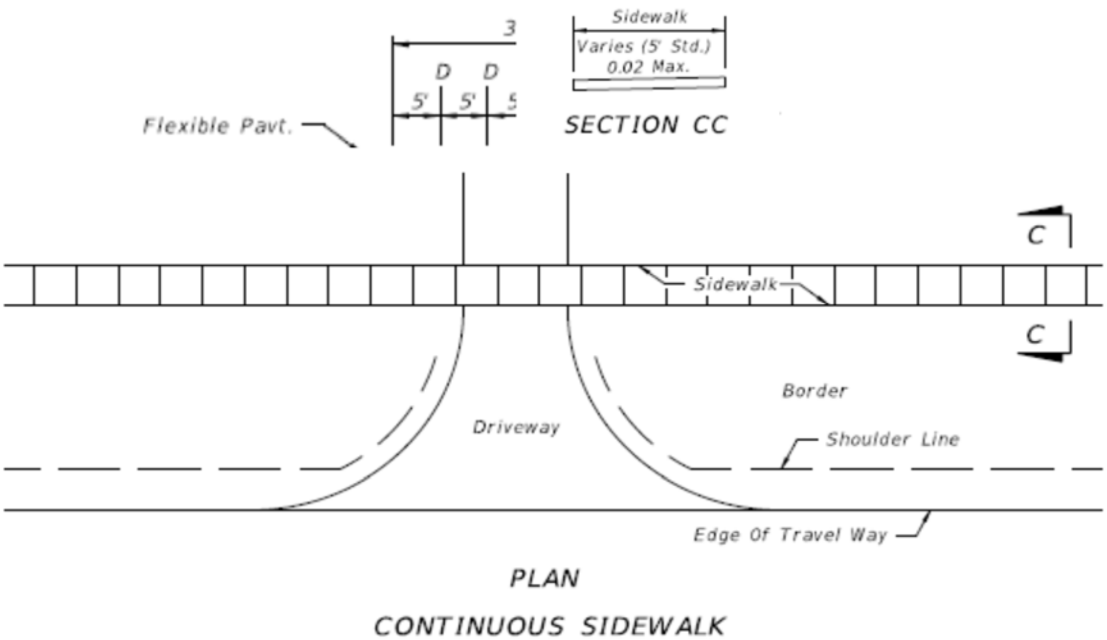

Figure 4.4. General layout and cross-section for concrete sidewalks (Source: FDOT Standard index 310)

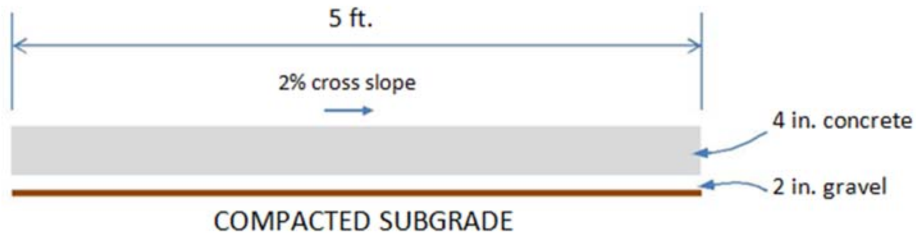

Figure 4.5. Proposed typical cross section for concrete sidewalk slabs (each slab is 30 ft. long)

Below are representative pictures (Figures 4.6 to 4.11) describing ready mix plant activities as well as steps taken to construct concrete slabs at the FAMU-FSU College of Engineering.

Figure 4.6. Clearing construction site with the aid of a backhoe and staking the site

Figure 4.7. Setting up the formwork for slabs and filling with compacted coarse aggregates

Figure 4.8. Placing the weighed bags of GTR into the Ready Mix truck

Figure 4.9. Loading Ready Mix truck with aggregates and other constituents.

Figure 4.10. GTR concrete sampling at the Ready Mix plant for slump and air content tests.

Figure 4.11. Placing and finishing of slabs at the FSU College of Engineering

4.6.1 Observations and results

Concrete samples were taken from the ready mix truck after discharge of about 15% and 85% of the load from the truck for GTR concrete. An increase occurred in the slump between first and second samples collected from the ready mix truck from 3 inches to 5.5 inches. Furthermore, a reduction developed in the unit weight of between both samples from 132.8 lb/cf to 128.4 lb/cf. Similar observations were made during laboratory tests using admixtures for GTR concrete, which indicated that longer mix times led to an increase in the slump. It may therefore be necessary to adjust the duration of mixing for GTR concrete by reducing the 90 minute limit mixing time for the regular ready mix concrete; this reduction will help maintain the consistency of GTR concrete mixes. It was further observed that no GTR residue accumulated in the ready mix truck nor any evidence of inadequate mixing of GTR concrete during ready mix activities. The air content of GTR concrete was determined 5.1 % at the ready mix plant and that for control was 2.25%. A summary of tests on freshly poured concrete can be found in Table 4.2 below:

Table 4.2 Test results on freshly poured concrete during ready mix activities

Tests on Concrete	Control	15% GTR (after pouring 15% of concrete)	15% GTR (after pouring 85% of concrete)
Slump (in)	2	3	5.5
Temperature (degF)	80	82	82
Unit Weight (lb/ft^3)	147	132.8	128.4

To monitor the hydration energy and temperature inside the concrete mixes, thermocouples were inserted in freshly poured concrete samples for both control and 15% GTR concrete (Figure 4.12). This set-up was monitored for 10 days. Results as seen in Figure 4.13 indicate that there is no significant difference in concrete temperatures of control and 15% GTR concrete. Concrete temperatures ranged between 60 ˚F and 85 ˚F with temperatures after 3 days of recording being largely influenced by ambient air conditions. . The evolution of heat in concrete takes place during the early stages in the hydration process, and this rate decreases with time. It was observed that concrete temperatures within the first 60 hours of readings ranged between 75 ˚F and 79 ˚F. Concrete temperatures for control and GTR concrete were determined as 80 ˚F and 82 ˚F respectively, as seen in Tables 4.2. These ranges of concrete temperatures are adequate because concrete for highway work and commercial construction are often between 55 ˚F and 90 ˚F at discharge points from ready mix trucks.

Figure 4.12. Thermocouple Set-up for Evaluating Concrete Temperature

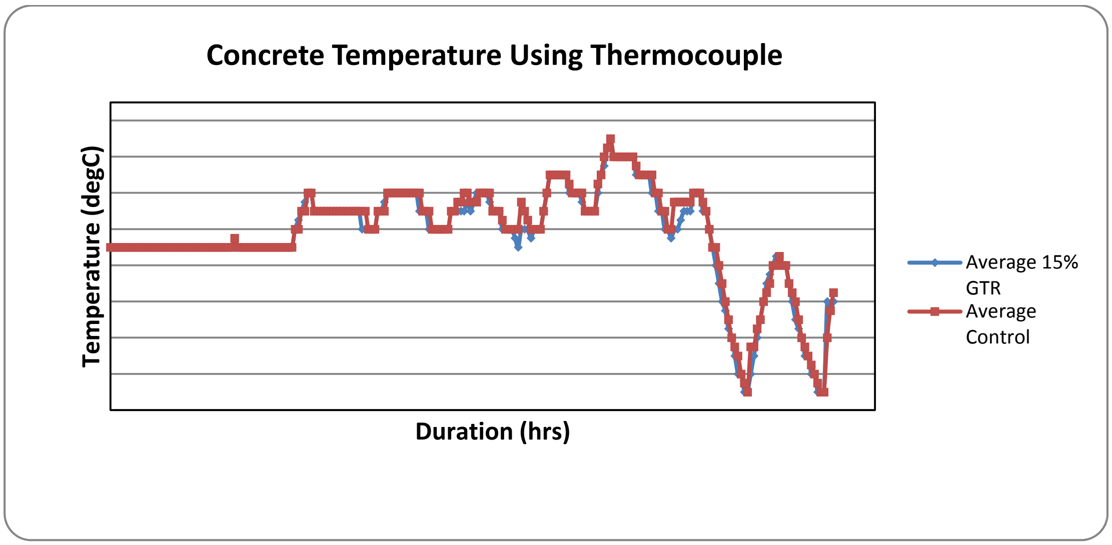

Figure 4.13. Concrete temperature results determined from thermocouple set-up

Mechanical properties of concrete samples were determined from cylindrical and beam specimens cast from ready mix concrete discharged during concrete pouring. The sample labeled 15% GTR-A represents samples collected just after 15% of GTR concrete was discharged from the ready mix truck, while sample 15% GTR-B refers to concrete samples collected immediately after 85% of GTR concrete was discharged. Compressive strength results as seen in Figure 4.14 and Table 4.3 indicate a 28-day compressive strength of 5960 psi for control concrete, 2720 psi for 15% GTR-A and 1820 psi for 15% GTR-B. The variation in compressive strengths between 15% GTR-A and 15% GTR-B can be attributed to the increased mixing time between discharging 15% and 85% of GTR concrete from the ready mix truck. The total mixing time until 85% of concrete was discharged from the ready mix truck was 65 minutes, well within the 90-minute time frame for ready mix concrete production. As seen in Table 4.3, split tensile strength and flexural strength (Modulus of Rupture) results also indicated similar reduction based on the duration of the mixing. While control specimens exhibited the highest split tensile and flexural strengths, 15% GTR-A had reduced strengths in comparison to control specimens but indicated higher strengths when compared with the strengths 15% GTR-B concrete specimens.

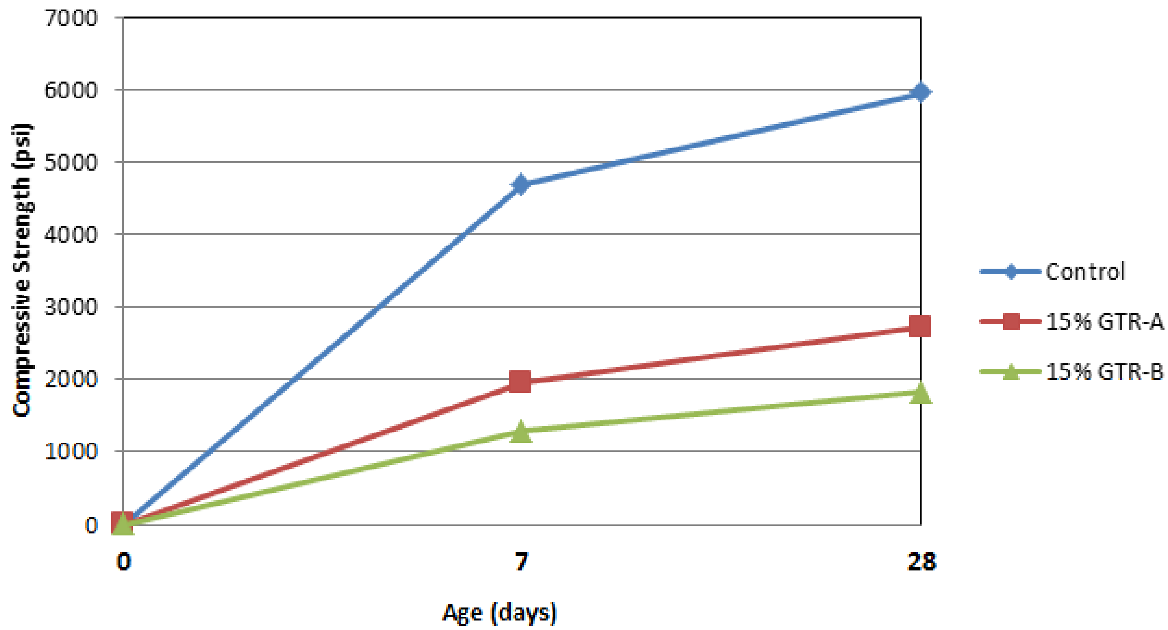

Figure 4.14. Plot of 7-Day and 28-Day compressive test results on ready mix concrete

Table 4.3. Mechanical properties of the Ready Mix Concrete Samples

Specimen Type	7-day Compressive Strength (psi)	28-day Compressive Strength (psi)	28-day Split Tensile Strength (psi)	28-day Modulus of Rupture (psi
Control	4710	5960	380	790
15% GTR -A	1950	2720	225	465
15% GTR -B	1290	1820	180	400

After 28 days of casting the slab, cylindrical concrete cores (4-inch by 8-inch) were drilled from the cast 6 ft by 6 ft concrete slab for compressive strength tests (Figure 4.15). Tests were carried out in accordance with ASTM C42/C 42M Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. Generally, test specimens are obtained when doubt exists about the in-place concrete quality due either to low strength test results during construction or signs of distress in the structure. Another use of this method is to provide strength information on older structures (ASTM C42/C 42M). The 28-day compressive strength results obtained from drilled cylindrical cores from 15% GTR concrete slab were 2640 psi, 2840 psi, and 2440 psi, with an average of 2640 psi. It is also important to note that this particular test slab was poured within the first 15% of concrete discharged from the ready mix truck hence the compressive strengths are comparable to that of 15% GTR-A concrete specimens.


Figure 4.15. Coring and testing concrete specimens for compressive strength Testing

Test slabs/sidewalks for both Control and GTR concrete were monitored daily for ambient humidity, ambient temperature, slab surface temperature, and any crack formation on the slabs due to either plastic and drying shrinkage (daily log data is shown inTable 4.4). The slab surface temperatures will indicate energy absortption or reflection by the type of concrete slab (GTR concrete or control). The surface temperature is a very important measure of the concrete's ability to reduce the heat island effects typically monitored as part of energy sustainability. Regarding the crack monitoring, there were no indications of plastic shrinkage cracks formed on both slabs after closely observing the slabs for 24 hours after placement. Both slabs indicated no drying shrinkage cracks for 53 days of monitoring. However, on Day 54 of monitoring, a continuous crack was observed across the entire width of the control slab but none was observed on the GTR concrete slab. As shown in Figure 4.16, this crack, located at 12.5 ft from the north end of the 30 ft. long slab, was continuous and distinct, and measured approximately at 0.58mm in width.

Figure 4.16. Shrinkage crack observed on control concrete slab

4.7 Summary

Lessons learned from the laboratory tests and handlings of the materials were reflected in studying the production of GTR concrete at a ready mix concrete plant. Issues related to storage and batching of GTR with other concrete materials were studied, as well as the mixing duration and discharge of concrete. The project also identified necessary steps to ensure successful operations. Test slabs cast from the ready mix concrete were also observed over several days, yielding valuable findings in terms of drying shrinkage properties of GTR concrete.

Table 4.4. Daily log of observations on the concrete slabs

Day	Time	Temperature (degF)			Humidity (%)	Cracks Observation
		Control Slab	GTR Slab	Ambient		
9/26/2014	5:30 PM	95/96	92	77	73.9	None
9/29/2014	5:30 PM	79	78	78	88.8	None
9/30/2014	5:30 PM	82/81	82/81	80	75.5	None
10/1/2014	2:00 PM	92	90	86	65.7	None
	5:30 PM	91	91	82	68.5	None
10/2/2014	10:30 AM	82	84	86	68.1	None
	5:00 PM	100/101	103/104	89	55.4	None
10/3/2014	5:30 PM	89/90	90/91	84	74.7	None
10/6/2014	7:15 PM	71/72	71/70	77	67	None
10/7/2014	6:55 PM	81/80	81/80	70	68.2	None
10/8/2014	5:00 PM	92	94/95	86	57.8	None
10/9/2014	4:45 PM	103	99/100	100	36	None
10/10/2014	6:00 PM	91	91	84	56.3	None
10/13/2014	3:30 PM	89	90/91	84	68.9	None
10/14/2014	-	-	-	-	-	None
10/15/2014	-	-	-	-	-	None
10/16/2014	5:55PM	79/80	80/81	80	35.5	None
10/17/2014	3:20PM	91/92	96/97	84	36.1	None
10/20/2014	5:30PM	81/80	80/81	80	37.2	None
10/21/2014	3:50PM	92	93	87	38.3	None
10/22/2014	5:45PM	81/82	83/84	82	35.1	None
10/23/2014	-	-	-	-	-	None
10/24/2014	5:00 PM	84/85	86/87	84	35.4	None
10/27/2014	5:30 PM	85	86	85	36.8	None
10/28/2014	5:15 PM	87	90	80	40	None
10/29/2014	6:00 PM	78/79	78/79	75	82.8	None
10/30/2014	5:30 PM	74/75	74/75	78	38.6	None
10/31/2014	4:00 PM	82	86/87	78	29.5	None
11/3/2014	4:30 PM	72/73	75/76	71	21.2	None
11/4/2014	5:30 PM	-	-	-	-	None
11/5/2014	4:30 PM	-	-	-	-	None
11/6/2014	5:00 PM	77	77	78	56	None
11/7/2014	-	-	-	-	-	None
11/10/2014	4:45 PM	72	73	72	55	None
11/11/2014	-	-	-	-	-	None
11/12/2014	4:30 PM	70/71	71/72	73	65.2	None
11/13/2014	-	-	-	-	-	None
11/14/2014	4:30 PM	58/59	59/60	64	27	None
11/17/2014	5:00 PM	58/59	54/55	59	71	None
11/18/2014	5:15 PM	46/47	44/45	66	18.7	Crack on Control Slab
11/19/2014	3:30 PM	56/57	60/61	75	12.4	Crack on Control Slab
11/26/2014	3:00 PM	52/53	54/55	65	23	Crack on Control Slab

5. Sustainability analyses

As commonly used in daily communication, to sustain essentially means supporting a process and maintaining continuity. The essence of sustainability is to ensure the support and nourishment of life for the longest possible time. According to the World Commission on Environment and Development of the United Nations, sustainability means "meeting the needs of the present without compromising the ability of the future generations to meet their own needs" (UNFCCC 2004).

The three main spheres of sustainability are environmental, economic, and social. In order for the goals of sustainable development to be realized, these three components must remain well-balanced throughout the whole planet—both presently and in the foreseeable future. Currently, the environment is perhaps the most significant component, and the engineer interprets the absence of a net negative impact on the environment to imply sustainability. The term sustainable is also synonymous with environmentally-friendly and "green."

The importance of sustainability and green building is highlighted by LEED, or Leadership in Energy & Environmental Design, a green building certification program that recognizes best-in-class building strategies and practices. In order to receive this certification, building projects must satisfy preconditions and earn points to attain different levels of certification. These prerequisites and credits are different for each rating system, and teams select the most suitable for their projects. LEED 2009 for New Construction and Major Renovations certifications are awarded using the following scale: Certified (40–49 points), Silver (50–59 points), Gold(60–79 points), Platinum (80 points and above).

5.1 Concrete Sustainability

Critical to the production of concrete are the embodied energy derived from component material and concrete production, environmental impact, and the wise use of materials and resources. Production of Portland cement, an essential constituent of concrete, leads to the release of a significant amount of carbon dioxide CO_2 and other greenhouse gases (GHGs) (Malhotra 2004). Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature of approximately 1500°C. The resulting clinker is then inter-ground with gypsum resulting in the formation of a fine powder. The processes result in high-embodied energy associated with Portland cement. Furthermore, the reaction between limestone and shale producing clinker also results in the production of CO_2.

Approximately 0.8 to 1.0 tons of CO_2 are produced per ton of cement (Hanle et al. ND, Van Dam and Taylor 2009), with the U.S. national average currently listed as 0.927 tons of CO_2 equivalent produced per ton of cement (Van Dam and Taylor 2011). In 2008, the total U.S. greenhouse gas (GHG) emissions were estimated at 7 billion metric tons of CO_2 equivalent, 40 million tons (about 0.6 percent) of which were generated through the manufacturing of Portland cement (EPA 2010). This is compared to 5 to 7 percent reported for the rest of the world (Malhotra 2000).

Most concrete formulations constitute large quantities of coarse and fine aggregate, a moderate amount of cement and water, and a small portion of admixture(s). Therefore, in order to undertake an environmental impact assessment of concrete manufacture, it is requisite to take into consideration the impact of the constituent materials in concrete.

Aggregates are usually obtained by mining. They may be crushed and washed, and they are usually separated into various size fractions and reconstituted in order to satisfy various grading requirements. Modest amounts of energy are used in each of the production steps. The main wastes are dust and water, neither of which is expressly detrimental to the environment.

The water in concrete is normally ordinary tap water with no further processing; hence it has very little embodied energy and produces no waste. It is only an environmental issue in locations where the water is already insufficient for basic needs.

Mixing large batches of concrete at ready-mix concrete plants and hauling the mixture to the construction site require modest amounts of energy and produce small amounts of waste. The major wastes in this process include dust, unused concrete, and wash water contaminated with concrete.

It is therefore necessary to also consider the embodied energy or energy required to produce the concrete and its constitute materials. This information is not readily available. But Struble and Godfrey (2004) reported the energy consumption associated with production of Portland cement (Table 5.1) and concrete (Table 5.2) while energy consumption producing crumb rubber as presented by Utomo et al. (2010) is shown in Table 5.3. Obviously, these limited data cannot be used to make a good comparison or make a strong inference on the sustainable use of GTR in concrete.

Table 5.1 Energy used in the production of Portland cement (Struble and Godfrey 2004)

Production Step	Energy(MJ/kg cement)
Extraction of raw materials	0.044
Transportation of raw materials	0.089
Crushing and grinding of raw materials	0.386
Pyroprocessing	4.041
Grinding cement	0.188
Transportation of cement	0.133
Total	4.881

Table 5.2 Energy used in the production of concrete (Struble and Godfrey 2004)

Constituent	Energy(MJ/kg concrete)
Coarse aggregate	0.028
Fine aggregate	0.028
Portland cement	0.735
Water	0
Manufacturing	0.102
Total	0.893

Table 5.3 Energy consumption in production of high-grade crumb rubber (Utomo et al. 2010).

Stages	Energy(MJ/kg)	Percentage (%)
Field latex receiving	0.00290	0.49
Latex coagulating	0.01449	2.43
Milling	0.14439	24.20
Shredding	0.17801	29.83
Drying	0.20851	34.95
Bale pressing	0.04836	8.11
Total	0.59666	100.00

As seen from the discussions above, the issue of sustainability is very comprehensive and cannot be completely covered in this study. But some pertinent aspects of sustainability where the GTR concrete may contribute will be presented using established models for evaluating sustainability of concrete products. One such model is the Building for Environmental and Economic Sustainability (BEES) Model, which is discussed in the following paragraph.

5.2 The Building for Environmental and Economic Sustainability (BEES) Model

Developed and presented by the National Institute of Standards and Technology (NIST), and the American Concrete Institute (ACI), the Building for Environmental and Economic Sustainability (BEES) methodology and software evaluates the sustainability of manufactured products, particularly concrete construction products, by measuring the life-cycle environmental and economic performance of the products. The BEES model analyzes all stages in the life of the product: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management (Lippiatt and Ahmad 2014).

The BEES model identifies and quantifies the environmental input and outputs (Figure 5.1) as well as the production process (Figure 5.2). The BEES model assesses impact (consequence) of each environmental output (e.g., relating carbon dioxide emission to global warming) using state-of-the-art methods recently developed by the U.S. Environmental Protection Agency (EPA). Twelve environmental impacts are assessed: global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, smog, ozone depletion, ecological toxicity, human health, criteria air pollutants, and water intake.

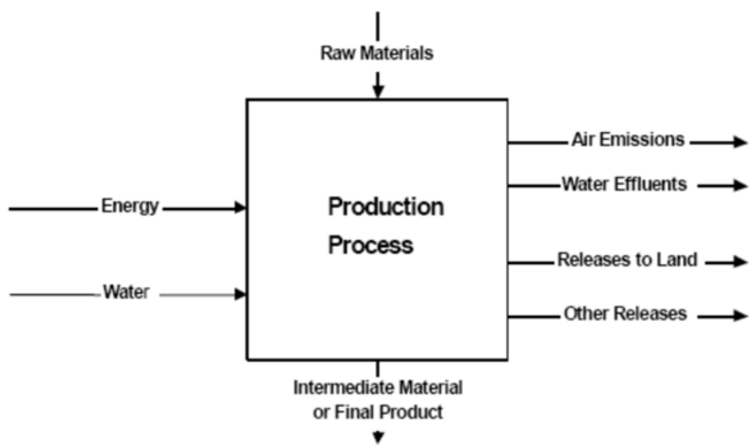

Figure 5.1 Sustainability model BEES' inventory data categories (Lippiatt and Ahmad 2014).

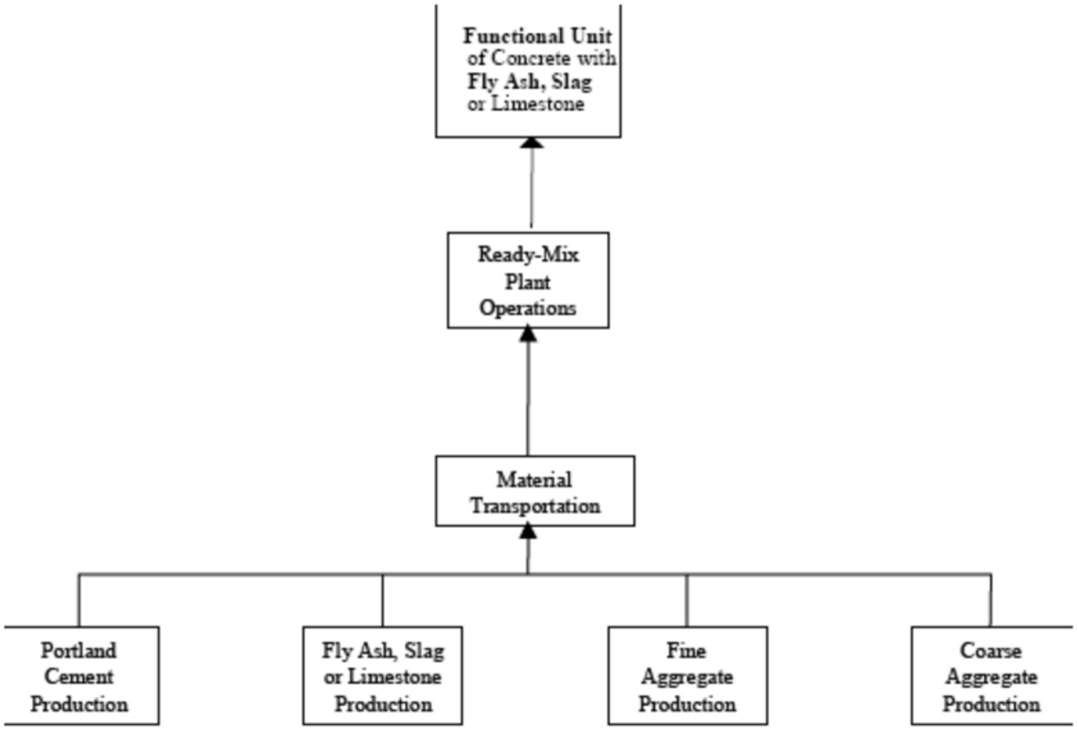

Figure 5.2 Concrete production processes (Lippiatt and Ahmad 2014).

The overall environmental performance of a product is computed from the performance scores for all impact categories which may be synthesized into a single score; this score can be used to compare various products.

In measuring a product's economic performance, the BEES model is based on the ASTM standard method for life-cycle costing (LCC) of construction-related investments, using a 50-year study period. Over the study period, the LCC model sums all relevant costs associated with the product. To compare products that provide similar functions, for example paving for a parking lot, their LCCs are used to determine which is the least cost means of fulfilling that function over the study period, typically including costs of purchase, installation, maintenance, repair, and replacement.

The BEES model computes an overall performance measure to synthesize the environmental and economic results into a single score, as illustrated in Figure 5.3. At each level of scoring, relative weights can be assigned to the various criteria and scores, to obtain a weighted overall performance score.

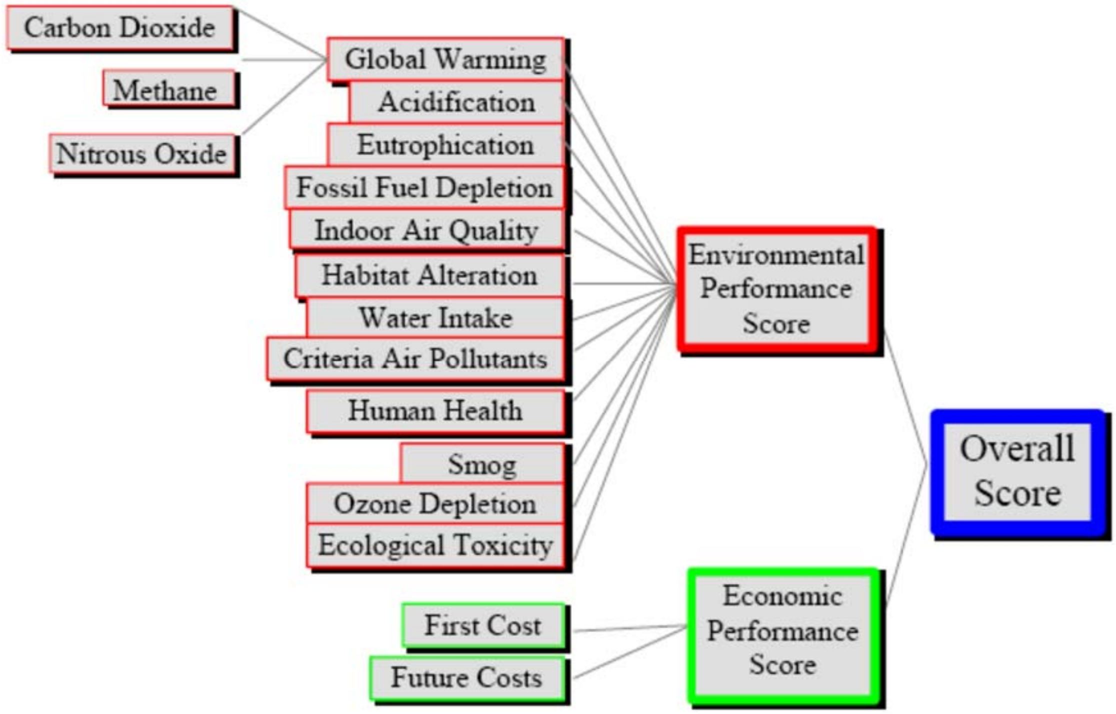

Figure 5.3: Deriving the BEES model's overall performance score (Lippiatt and Ahmad 2014).

5.2.1 The GTR concrete's evaluation under the BEES model

In terms of the environmental performance under the BEES model, GTR concrete will score positively in the following criteria: Global Warming; Habitat Alteration; Human Health; and Ecological Toxicity. GTR serves as a partial replacement of sand in the concrete. Being a mined or quarried product, replacing sand with GTR may reduce the negative effects associated with producing and transporting the fine aggregates (energy consumption, global warming, fossil fuel depletion, etc.). Incorporating GTR in concrete, and thus reusing waste rubber tires, also reduces the unhealthy stockpiling of waste rubber tires which constitute fire hazards, locations for breeding mosquitoes, and other negative environmental effects.

In terms of economic performance, using GTR concrete should score very well under the BEES model, due to its relatively lower life cycle cost, when compared to using the conventional concrete. First the lower unit weight of GTR concrete will mean smaller concrete member sizes, reducing the cost of concrete needed in the original construction. Secondly, GTR concrete has various characteristics that will increase durability of the concrete and reduce future maintenance costs – lower modulus means flexible sections that may not crack as much as conventional concrete and reduced cracking under plastic and drying shrinkage strains.

The cost implications of reduced drying shrinkage cracking were best demonstrated by the absence of cracks in the 30 ft. long slabs cast in this study. By FDOT specifications, major joints are required every 10 ft. length of 4 in. deep concrete sidewalk slabs. Eliminating such joints on 30 ft. lengths of sidewalk slabs will also reduce the initial costs of concrete sidewalks. According to NRMCA (2000) and reported in Enduse (2014), the cost to place, finish, cure, cut, and seal joints is \$6.50/SY on a 5 in. PCC pavement. This cost is equivalent to about \$0.72/SF. Assuming a typical 5 ft. wide sidewalk slab, this cost translates to about \$4.50/LF of sidewalk, including cost time adjustment of 25% for inflation from 2000 to now. Also according to an FHWA research reported by Texas DOT (Texas 2012), saw-cutting for concrete pavements cost \$6.52/lane-feet., based on RS Means Heavy Civil 2012. This cost is about \$0.54/SF assuming 12 ft. lanes. With 5 ft. wide sidewalks, the cost is about

$2.72/LF of sidewalk. It should be noted that this is just for the saw-cutting. Thus significant initial construction costs can be reduced from by using GTR concrete.

5.3 Summary

While non-comprehensive, a case has been presented on how the use of GTR in concrete contributes to sustainability. There is much interest in the sustainability of concrete both in its production and its applications including its use as pavement slabs. The GTR is a recycled material that improves some properties of concrete, with these improved properties making the GTR concrete more sustainable both environmentally and economically.

6. Conclusions and recommendations

As stated at the beginning of this report, FDOT had identified some issues related to inadequate flexibility in its roadway concrete pavements, with the pavements being of high strength mixtures that are not flexible enough, as well as induced expansion and contraction in the pavement caused by temperature changes. This research was done to investigate whether these problems can be addressed by replacing some of the fine or coarse aggregate component with crumb rubber, specifically, Ground Tire Rubber (GTR). The study was to determine whether the GTR would provide some flexibility in the concrete pavement and address the temperature sensitivity issues. The research also intended to find out the general effects of adding the GTR to conventional pavement concrete, in terms of the mechanical properties and workability. Finally, the research was required to evaluate the practical implementation, at a ready mix plant, of the proposed use of GTR as a component in the concrete.

6.1 Conclusions

The first primary conclusion from this study is that, because the modulus of elasticity is reduced, the pavement concrete is more flexible with addition of GTR as a partial replacement of the fine aggregate. Regarding the expansion and contraction in the concrete pavement, based on the results of the tests for the coefficient of thermal expansion (CTE), it was not, however, conclusive from this study that adding GTR will significantly affect the CTE of the concrete. This study yielded several valuable findings on the various effects of adding GTR to concrete, particularly in terms of the following concrete properties: air content, workability, unit weight, compressive strength; flexural strength; tensile strength, modulus of elasticity and Poisson's ratio; impact resistance or toughness; interface bonding, evaluated through use of the Scanning Electron Microscope (SEM); plastic shrinkage; and dry free shrinkage. The final task on the study, i.e., ready mix plant implementation, including casting and monitoring the test slabs on the ground, was also successful and produced some useful observations.

It should be noted also that the primary focus was on GTR, but the research did some preliminary tests using tire rubber chips (as partial coarse aggregate replacement) in concrete to evaluate their effects on the concrete's mechanical properties. Some of the specific results on the rubber chip concrete, as well as those from the overall study, are presented later in this section of the report.

Based on the tasks performed on this study, the following conclusions can be made:

- the optimal content for GTR for use as a component in the paving concrete mixture is 15% by weight of the fine aggregate;
- at a water/cementitious ratio of 0.44, concrete with GTR of 15% by weight of the fine aggregate, using water-reducing admixtures, can achieve a 28-day compressive strength of about 3000 psi;
- slump was observed to typically decrease with the addition of GTR but use of the water-reducer will eliminate this problem;
- temperature trend relative to time in a fresh mix of GTR concrete is same as that of the control conventional concrete (studied using thermocouples);
- unit weight of the GTR concrete is less than that of the conventional concrete, making it useful for lightweight applications and reducing the dead loads from self weight;
- air content will always increase with addition of GTR to the concrete, as well as foam formation on the surface of washout water. Use of a defoaming agent will reduce the foam and air content but will make the concrete denser;

- the flexural strength, split tensile strength, and modulus of elasticity of GTR concrete mixes, being directly related to the compressive strength, are also lower than those of the conventional concrete but with use of the water-reducer, their values can be increased;
- GTR concrete appears to have a higher impact resistance and is tougher than conventional concrete; yet based on the stress strain curves, this cannot be proven to be uniformly true at this time, but the GTR concrete has a non-brittle mode of failure in compression and flexure;
- examining GTR concrete under the Scanning Electron Microscope (SEM) indicated that good bonding occurs between the rubber particles and the cement matrix in the concrete.
- pretreatment of GTR by simple washing and drying may improve the compressive strength of the GTR concrete, but the GTR drying process may be demanding in order to avoid extra unwanted moisture collecting in the concrete.
- the coefficient of thermal expansion (CTE) results did not support a strong correlation of CTEs with addition of GTR to the concrete mixture;
- GTR concrete has very good plastic and dry shrinkage attributes and an ability to resist shrinkage crack formations when compared to the conventional concrete. These characteristics were demonstrated through controlled laboratory tests and also by long-term monitoring of concrete slabs cast on grade;
- the ready mix plant operations required less time to mix before placement (when compared to the 90 minutes mixing duration allowed for conventional concrete); also, the compressive, flexural, and split tensile strengths were higher for samples taken at 15% of the dispatch, than for those sampled at 85% of the entire mix, while the slump was also observed to increase with the time spent in the mixer.

Some preliminary tests were done on concrete mixes without the use of admixtures., using specimens cast by adding 0% to 40% GTR (by weight of fine aggregate) at 10% increments and 0% to 30% Rubber Chips at 10% increments. Final tests were conducted using concrete with various admixtures, i.e., water reducer, air-entraining agent and fly ash and adding 0% to 20% GTR at 5% increments. The range in the amount of GTR added in the final tests was refined based on the results of the preliminary tests, considering the ease of handling (workability), and the strength values of the samples. Other tests were also done towards the end of the study, including an evaluation of the pretreatment of the GTR, reducing the water/cement ratio, and addition of a defoaming agent to reduce foams formation and air voids content.

In the preliminary tests done without admixtures, the properties of fresh rubber concrete, after adding rubber chips or GTR, were observed to be affected as follows: the slump and unit weight are reduced, and the air content is increased. For instance, 20% GTR concrete had a slump of 0.5 in. and air content of about 6%, compared with the control concrete which had a slump and air content of 2.5 in. and 2% respectively. In terms of the mechanical properties of the hardened concrete, adding rubber to the concrete decreased all the strength values and the modulus of elasticity. The rubber chips concrete were observed at comparable concrete contents, to be slightly stronger than the GTR concrete. The 28-day modulus of elasticity ($x10^6$ psi) at 20% GTR and 20% Rubber Chips were 1.85 and 2.60 respectively, compared with 3.70 $x10^6$ psi for the control concrete.

In the final tests, use of a water-reducer enabled the slump to be maintained at about 1.5 in. in all the GTR mixes, compared to 2 in. for the control concrete mix. Air content was still high at about 6%. The unit weight dropped from 145 lb/ft^3 for the control concrete to about 130 lb/ft^3 for 15% GTR concrete. Despite the overall reduction in the mechanical properties, it was possible to achieve with 10% GTR and 15% GTR in concrete mixtures with admixtures compressive strength values of about 1800 psi and 1100 psi respectively at 28 days. The strength at 90 days for 10% GTR and 15% GTR concrete were about 2400 psi and 1400 psi respectively. The flexural strength and split tensile strength at 28 days were about 450 psi and 160 psi respectively for 15% GTR, compared to about 725 psi and 360 psi respectively for the control concrete.

The 28-Day modulus of elasticity (x10^6 psi) and Poisson's ratio for 15% GTR were obtained as 1.6 and 4.1 respectively, compared to 4.1 and 0.21 respectively for the control concrete. For the coefficient of thermal expansion tests, the CTE values obtained were 10.1 x10^{-6} (in/in)/°C for 15% GTR compared to 9.86 x10^{-6} (in/in)/°C for the control concrete. The CTE results were within the range for normal concrete, that is, 8 to 12 x10^{-6} (in/in)/°C, but the trend of the results was not strong in supporting that adding GTR to concrete increases or decreases the CTE values of the concrete.

These results described above for the final tests on the compressive strength were based on a water/cement ratio of 0.50. By reducing the water/cement ratio to 0.44, the compressive strength values of 15% GTR concrete was increased to about 3000 psi and 3800 psi at 28 days and 90 days respectively, compared to 5700 psi and 6800 psi respectively for the control concrete.

To investigate the interactions among the internal components of the GTR concrete, thermocouples were inserted in the fresh mixes of 15% GTR concrete and also that of a conventional concrete. The temperature trends were same in both relative to time, indicating that the GTR does not interfere in the hydration process, being a very exothermic process. Another effort to study the GTR at a detailed level involved using the Scanning Electron Microscope (SEM), to examine the bonding between rubber particles and other components of the cement matrix within concrete. Observation of needle-like ettringites on the interface of the cement matrix with the rubber indicated that there is good bonding.

For plastic shrinkage tests, which also include setting time tests, a modification of the ASTM C1579 specifications was adopted, requiring the construction of an environmental chamber (described as a fan box in ASTM C1579), as well as the fabrication of two specified molds for the testing. The concrete mix design for the plastic shrinkage tests were revised according to specification requirements in terms of the maximum size aggregate, and with no admixtures. Results obtained from setting time tests showed that GTR delays the setting in concrete. For 15% GTR concrete, the initial and final setting times were 360 min. and 850 min. respectively, compared to 215 min. and 410 min. respectively for the control concrete. In terms of plastic shrinkage cracks observed on the samples, the control concrete had continuous cracks identified at 70 locations, with an average crack width of 0.44 mm, while 15% GTR had discontinuous cracks at 35 locations and an average crack width of 0.34 mm. Results from plastic shrinkage crack measurements showed that the inclusion of GTR in concrete helps in decreasing and slowing down the formation and propagation of plastic shrinkage cracks. When compared to the control concrete, the crack frequency decreased generally with addition of GTR. But it was observed that while the crack widths remained fairly constant, incrementally increasing the percentage of rubber content also caused a slight increase in frequency of crack positions relative to other GTR concrete samples. The, 20% GTR concrete had more cracks than 15% GTR concrete, which also had more than 10% GTR concrete.

A limited drying (free) shrinkage) test was conducted using control concrete and 10% GTR concrete. It was observed that the GTR concrete exhibited less shrinkage strain. It should be noted that this was a limited test and further tests are needed. The behavior of GTR concrete in free shrinkage was demonstrated favorably during the ready mix plant tests when two 4 in. thick 30 ft. sidewalk concrete slabs were cast on grade, one with 15% GTR concrete and the other as control with conventional concrete. Both slabs were continuously monitored for several weeks. It was observed on Day 54 that while the GTR concrete slab had not cracked anywhere, the control concrete slab had a continuous crack across the entire the width at a location about 12 ft. from the top edge of the slab. Both slabs were also observed continuously for temperatures at the surface relative to the ambient temperature; this experiment estimated the concrete's contribution to the heat island effect, a very important factor of sustainability (energy conservation). There was no significant difference in the surface temperatures for both slabs.

Lessons from the ready mix plant operations also suggest that the GTR packaging is very important as the GTR cannot be introduced into the mixers like other conventional components of the concrete. Customizing packaging to allow ease introduction is recommended, e.g., 50 lb. standard bags (manufacturer's size) and a last bag packed in the order of 5 lbs. Storage is very important as the GTR may absorb moisture if not kept dry. For the fresh concrete, it was observed that extended mixing time of the GTR concrete may lead to increase in the slump and reduction in eventual strength of the hardened concrete.

The GTR is a recycled material that improves some properties of concrete, with these improved properties making the GTR concrete more sustainable both environmentally and economically. GTR serves as a partial replacement of sand in the concrete. Sand being a mined or quarried product, using GTR to replace sand may reduce the negative effects associated with producing and transporting the fine aggregates (energy consumption, global warming, fossil fuel depletion, etc.). The use of GTR, which is reusing waste rubber tires, reduces the unhealthy stockpiling of waste rubber tires, which constitute fire hazards and locations for breeding mosquitoes, etc. Economically, using GTR will lower the overall life cycle cost of the concrete members when compared to the conventional concrete: lesser unit weight implies smaller member size and cost; lower modulus and reduced cracking from plastic and dying shrinkage strains implies lower maintenance cost and reduction or elimination of construction joints on concrete pavement slabs.

6.2 Recommendations

The GTR concrete can be used in the following applications: Class I pavement slabs; sidewalk slabs; curbs and inlets; or other applications where the compressive strength of 3000 psi or less is adequate and also where the concrete may be vulnerable to plastic and dry shrinkage. These applications may require a relatively low water-cement ratio (slightly less than 0.50) and use of water-reducing admixtures. The ready mix plant operations will require dry-safe storage of the GTR, customized packaging (bag sizes or bag material) of the GTR for convenient batching, and less time required for mixing before placement (when compared to the 90 minutes mixing duration allowed for conventional concrete).

It is recommended that future research be done on the CTE of GTR concrete. The results from the CTE tests on this study were not conclusive, as there may be factors influencing the CTE of concrete other than those investigated in this study. For instance, fly ash has been suspected of influencing the CTE results, as well the type of coarse aggregate (limerock versus granite). Detailed plastic shrinkage tests were performed in this study but the dry (free) shrinkage tests were preliminary. It is recommended that future research be done to explore, in more detail, the behavior of GTR concrete under drying shrinkage. Pretreatment of GTR has been suggested by other researchers but its effect was investigated minimally in this study; it may be necessary to study this further in the future. Finally, observations at the ready mix plants showed useful results but also indicated that an extended time of mixing GTR concrete in the truck will significantly influence the slump (increased) and compressive strength (decreased) of the concrete mix; a future study of these behaviors is therefore recommended.

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Appendix A. Sample detailed laboratory results

Table A.1. Detailed final test results for 7-Day compressive strength

Specimen Description	Compression Test	Avg. diameter	Avg. length	Weight (lbs)	Avg Compressive Strength (psi)
Control (no admixtures)	Cylinder 1	6.025	11.800	28.2	**3316.57**
	Cylinder 2	6.025	11.750	28.1	
Control (with admixtures)	Cylinder 1	6.033	11.763	28.1	**2930.87**
	Cylinder 2	6.050	11.888	28.2	
5% GTR	Cylinder 1	6.025	11.800	26.0	**1411.41**
	Cylinder 2	6.017	11.813	26.3	
10% GTR	Cylinder 1	6.025	11.950	25.8	**886.36**
	Cylinder 2	6.092	11.825	24.6	
15% GTR	Cylinder 1	6.025	11.800	23.3	**677.48**
	Cylinder 2	6.042	11.825	25.6	
20% GTR	Cylinder 1	5.983	11.738	23.0	**361.55**
	Cylinder 2	5.983	11.838	21.4	

Table A.2. Detailed final test results for 28-Day compressive strength

Specimen Description	Compression Test	Avg. Diameter (in)	Avg. Length (in)	Weight (lbs)	Avg. Compressive Str (psi)
Control 0	Cylinder 1	6.02	11.775	28.2	
	Cylinder 2	6.03	11.813	28.2	**4391.139**
	Cylinder 3	6.02	11.688	28.2	
Control AD	Cylinder 1	6.03	11.925	28.4	
	Cylinder 2	6.01	11.750	27.7	**4052.120**
	Cylinder 3	6.03	11.763	27.7	
5% GTR	Cylinder 1	6.05	11.825	26.2	
	Cylinder 2	6.02	11.863	26.3	**2353.840**
	Cylinder 3	6.03	11.825	26.8	
10% GTR	Cylinder 1	6.03	12.013	25.1	
	Cylinder 2	6.03	11.975	26.8	**1753.409**
	Cylinder 3	6.02	11.975	27.0	
15% GTR	Cylinder 1	6.02	11.900	25.0	
	Cylinder 2	6.02	11.813	23.2	**1107.271**
	Cylinder 3	6.03	11.863	25.8	
20% GTR	Cylinder 1	5.95	11.750	21.2	
	Cylinder 2	5.97	11.625	21.2	
	Cylinder 3	5.97	11.800	23.2	**764.089**
	Cylinder 4	5.96	11.750	23.2	
	Cylinder 5	6.03	11.800	23.5	
	Cylinder 6	6.05	11.800	23.3	

Table A.3. Detailed final test results for 90-Day compressive strength

Specimen Type	Avg. Length (in)	Avg. Diameter (in)	Weight (lb)	Max Load (lbs)	Avg. Compressive Strength (psi)
Control 0- 1	11.688	6.042	27.9	144597.66	
Control 0- 2	11.738	6.008	28.0	150688.48	**5098.849**
Control 0- 3	11.688	6.033	28.0	141350.45	
Control -AD- 1	11.688	6.033	27.6	161564.94	
Control-AD- 2	11.800	6.025	27.5	133701.42	**5091.531**
Control-AD- 3	11.625	6.025	27.6	140840.33	
5% GTR- 1	11.900	6.025	26.2	85053.96	
5% GTR- 2	11.750	6.017	26.6	91026.54	**3136.158**
5% GTR- 3	11.700	6.025	26.4	92014.90	
10% GTR- 1	11.850	6.017	25.9	65535.35	
10% GTR- 2	11.650	6.042	25.2	61204.83	**2421.864**
10% GTR- 3	11.863	6.025	26.5	80644.04	
15% GTR- 1	11.900	6.025	24.5	42596.19	
15% GTR- 2	11.963	6.025	24.9	51732.43	**1448.420**
15% GTR- 3	11.950	6.017	24.8	29524.66	
20% GTR- 1	11.725	5.983	23.2	35299.07	
20% GTR- 2	11.613	5.950	21.1	18727.29	**851.717**
20% GTR- 3	11.838	5.933	21.4	17343.02	

Table A.4. Detailed final test results for 28-Day split tensile strength

Specimen Description	Split Tensile Test	Avg. Diameter (in)	Avg. Length (in)	Weight (lbs)	Average Split Tensile Strength (psi)
Control 0	Cylinder 1	6.025	11.938	28.7	**494.99**
	Cylinder 2	6.017	11.938	28.9	
Control AD	Cylinder 1	6.025	12.063	28.7	**373.30**
	Cylinder 2	6.025	12.038	28.2	
5% GTR	Cylinder 1	6.033	12.113	27.4	**260.77**
	Cylinder 2	6.042	12.025	27.3	
10% GTR	Cylinder 1	6.033	12.150	25.8	**188.10**
	Cylinder 2	6.042	12.125	25.4	
15% GTR	Cylinder 1	6.025	12.113	24.8	**167.28**
	Cylinder 2	6.042	11.988	25.4	
20% GTR	Cylinder 1	6.092	12.000	21.4	**77.67**
	Cylinder 2	6.008	12.050	21.9	

Table A.5. Detailed final test results for 28-Day flexural strength

Specimen	Flexural Test	Avg. Width	Avg. Depth	Avg. Length	Avg. MR per Specimen Type
Control 0	Beam 1	6.000	5.988	21.125	
	Beam 2	6.000	6.038	21.156	**679.37**
	Beam 3	6.000	6.000	21.125	
Control AD	Beam 1	6.050	6.050	21.125	
	Beam 2	6.000	6.025	21.281	**614.67**
	Beam 3	6.050	6.013	21.188	
GTR 5	Beam 1	6.025	6.025	21.188	
	Beam 2	6.000	6.000	21.188	**533.09**
	Beam 3	6.038	6.038	21.188	
GTR 10	Beam 1	6.025	6.088	21.094	
	Beam 2	6.013	6.000	21.125	**458.54**
	Beam 3	6.025	5.988	21.281	
GTR 15	Beam 1	6.013	6.013	21.188	
	Beam 2	6.000	6.025	21.375	**377.84**
	Beam 3	6.013	6.000	21.094	
GTR 20	Beam 1	6.000	5.975	21.313	
	Beam 2	6.025	6.025	21.188	**393.08**
	Beam 3	6.025	6.050	21.188	

Table A.6. Detailed final test results for 28-Day modulus of elasticity

Specimen Description	Modulus Test	Weight (lbs)	0.4 *fc'	Modulus 1	Modulus 2	Avg. E. Modulus
Control 0	Cylinder 1	28.2		3,750,000	3,800,000	3,775,000
	Cylinder 2	28.5	50005.33	3,900,000	3,850,000	3,875,000
	Cylinder 3	28.3		4,200,000	4,250,000	4,225,000
Avg. (E.Modulus)						3,958,333
Control AD	Cylinder 1	28.2		4,100,000	4,050,000	4,075,000
	Cylinder 2	27.7	46188.00	4,000,000	3,900,000	3,950,000
	Cylinder 3	28.4		4,200,000	4,300,000	4,250,000
Avg. (E.Modulus)						4,091,667
5% GTR	Cylinder 1	26.5		2,800,000	2,800,000	2,800,000
	Cylinder 2	27.3	26898.67	3,450,000	3,450,000	3,450,000
	Cylinder 3	26.5		3,000,000	2,900,000	2,950,000
Avg. (E.Modulus)						3,066,667
10% GTR	Cylinder 1	25.2		2,050,000	2,000,000	2,025,000
	Cylinder 2	25.3	19984.00	2,250,000	2,250,000	2,250,000
	Cylinder 3	25.4		2,350,000	2,450,000	2,400,000
Avg. (E.Modulus)						2,225,000
15% GTR	Cylinder 1	23.5		1,900,000	1,800,000	1,850,000
	Cylinder 2	23.7	12613.33	1,550,000	1,500,000	1,525,000
	Cylinder 3	23.5		1,450,000	1,450,000	1,450,000
Avg. (E.Modulus)						1,608,333
20% GTR	Cylinder 1	23.2		1,650,000	1,600,000	1,625,000
	Cylinder 2	23.5	10331.57	1,700,000	1,700,000	1,700,000
	Cylinder 3	23.3		1,600,000	1,600,000	1,600,000
Avg. (E.Modulus)						1,641,667

Appendix B: Coefficient of thermal expansion (CTE) test results

Table B1. CTE test sample preparation

Florida Department of Transportation
State Materials Office
CTE Test - Sample Preparation

Specimen Description	CTE Specimen	Date	Diameter (in)			Length (in)			SSD Weight (g)	SSD Density (lb/ft^3)
			D1	D2	D Average	L1	L2	L Average		
Control_0	A	07/25/13	4.020	4.019	4.020	7.014	7.021	7.018	3410.9	145.9
	B		3.996	4.040	4.018	6.932	6.950	6.941	3380.2	146.3
	C		4.012	4.030	4.021	6.996	7.013	7.005	3397.0	145.5
	Average		4.009	4.030	4.020	6.981	6.995	6.988	3396.0	145.9
Control_ADMIX	A	07/25/13	3.996	4.034	4.015	6.953	6.969	6.961	3336.6	144.2
	B		4.006	4.045	4.026	7.010	6.994	7.002	3360.6	143.7
	C		3.983	4.063	4.023	6.991	6.946	6.969	3360.4	144.5
	Average		3.995	4.047	4.021	6.985	6.970	6.977	3352.5	144.1
GTR_5_ADMIX	A	07/25/13	4.026	4.022	4.024	6.978	6.982	6.980	3146.7	135.0
	B		3.991	4.041	4.016	6.984	6.987	6.986	3142.7	135.3
	C		3.988	4.053	4.021	6.997	6.989	6.993	3181.6	136.5
	Average		4.002	4.039	4.020	6.986	6.986	6.986	3157.0	135.6
GTR_10_ADMIX	A	07/25/13	4.041	4.002	4.022	6.975	6.963	6.969	3047.0	131.1
	B		4.030	3.999	4.015	6.953	6.967	6.960	3143.7	135.9
	C		4.019	4.032	4.026	6.991	7.000	6.996	3155.2	135.0
	Average		4.030	4.011	4.021	6.973	6.977	6.975	3115.3	134.0
GTR_15_ADMIX	A	07/25/13	4.025	4.027	4.026	6.991	6.993	6.992	3096.1	132.5
	B		3.998	4.036	4.017	6.985	6.996	6.991	3088.1	132.8
	C		3.970	4.056	4.013	7.028	7.029	7.029	3095.2	132.6
	Average		3.998	4.040	4.019	7.001	7.006	7.004	3093.1	132.6
GTR_20_ADMIX	A	07/26/13	4.009	4.024	4.017	6.933	6.940	6.937	2772.4	120.2
	B		3.997	4.048	4.023	6.961	6.963	6.962	2799.3	120.5
	C		4.012	4.032	4.022	7.002	7.000	7.001	2775.3	118.9
	Average		4.006	4.035	4.020	6.965	6.968	6.967	2782.3	119.9

Table B1. CTE test sample preparation (Cont'd)

Florida Department of Transportation
State Materials Office
CTE Test - Sample Preparation
Differences in Diameters

Specimen Description	CTE Specimen	Date	Diameter (in)		F-Test. Analysis of Variance 1 way			Qualification	
			USF	SMO	F Calculated	F Limit (95%)	F Limit (99%)	95%	99%
Control_0	A	07/25/13	4.042	4.020	0.3538	7.7086	21.1977	Acceptable	Acceptable
	B		4.042	4.018					
	C		4.000	4.021					
	Average		4.028	4.020					
Control_ADMIX	A	07/25/13	4.000	4.015	10.9504			Not Acceptable	Acceptable
	B		3.975	4.026					
	C		4.000	4.023					
	Average		3.992	4.021					
GTR_5_ADMIX	A	07/25/13	4.050	4.024	0.0433			Acceptable	Acceptable
	B		4.000	4.016					
	C		4.000	4.021					
	Average		4.017	4.020					
GTR_10_ADMIX	A	07/25/13	4.050	4.022	0.0926			Acceptable	Acceptable
	B		4.025	4.015					
	C		4.000	4.026					
	Average		4.025	4.021					
GTR_15_ADMIX	A	07/25/13	4.000	4.026	0.0627			Acceptable	Acceptable
	B		4.075	4.017					
	C		4.000	4.013					
	Average		4.025	4.019					
GTR_20_ADMIX	A	07/26/13	4.050	4.017	0.0478			Acceptable	Acceptable
	B		4.000	4.023					
	C		4.000	4.022					
	Average		4.017	4.020					

Table B1. CTE test sample preparation (Cont'd)

Florida Department of Transportation
State Materials Office
CTE Test - Sample Preparation
Differences in SSD Densities

Specimen Description	CTE Specimen	Date	SSD Density (lb/ft^3)		F-Test. Analysis of Variance 1 way			Qualification	
			USF	SMO	F Calculated	F Limit (95%)	F Limit (99%)	95%	99%
Control_0	A	07/25/13	144.2	145.9	2.9659	7.7086	21.1977	Acceptable	Acceptable
	B		144.5	146.3					
	C		146.0	145.5					
	Average		144.9	145.9					
Control_ADMIX	A	07/25/13	142.9	144.2	0.7616			Acceptable	Acceptable
	B		145.1	143.7					
	C		149.9	144.5					
	Average		146.0	144.1					
GTR_5_ADMIX	A	07/25/13	136.3	135.0	1.3444			Acceptable	Acceptable
	B		133.7	135.3					
	C		133.2	136.5					
	Average		134.4	135.6					
GTR_10_ADMIX	A	07/25/13	131.7	131.1	0.0095			Acceptable	Acceptable
	B		135.6	135.9					
	C		134.2	135.0					
	Average		133.8	134.0					
GTR_15_ADMIX	A	07/25/13	131.9	132.5	5.7185			Acceptable	Acceptable
	B		131.8	132.8					
	C		130.1	132.6					
	Average		131.3	132.6					
GTR_20_ADMIX	A	07/26/13	120.1	120.2	0.8497			Acceptable	Acceptable
	B		120.6	120.5					
	C		120.3	118.9					
	Average		120.3	119.9					

Table B1. CTE test sample preparation (Cont'd)

Florida Department of Transportation
State Materials Office
CTE Test - Samples Preparation
Height of the Cylinders

Sample ID	Length using Micrometer (in)					Length (in)	Difference	Diameter using Caliper (in)		
	Δ 1	Δ 2	Δ 3	Δ Average	7.000 + Δ Ave	Caliper	Mic/Cal (%)	1	2	average
Control_0_A	-0.01230	-0.00985	-0.01250	-0.01155	6.98845	7.01750	-0.4	4.020	4.019	4.020
Control_0_B	-0.09215	-0.09885	-0.08340	-0.09147	6.90853	6.94100	-0.5	3.996	4.040	4.018
Control_0_C	-0.01705	-0.01565	-0.00720	-0.01330	6.98670	7.00450	-0.3	4.012	4.030	4.021
Control_ADMIX_A	-0.06360	-0.07640	-0.06545	-0.06848	6.93152	6.96100	-0.4	3.996	4.034	4.015
Control_ADMIX_B	-0.02545	-0.02015	-0.02435	-0.02332	6.97668	7.00200	-0.4	4.006	4.045	4.026
Control_ADMIX_C	-0.05830	-0.04440	-0.03890	-0.04720	6.95280	6.96850	-0.2	3.983	4.063	4.023
GTR_5_A	-0.04000	-0.03630	-0.03875	-0.03835	6.96165	6.98000	-0.3	4.026	4.022	4.024
GTR_5_B	-0.02845	-0.02535	-0.03090	-0.02823	6.97177	6.98550	-0.2	3.991	4.041	4.016
GTR_5_C	-0.03200	-0.02740	-0.03315	-0.03085	6.96915	6.99300	-0.3	3.988	4.053	4.021
GTR_10_A	-0.05435	-0.05845	-0.05255	-0.05512	6.94488	6.96900	-0.3	4.041	4.002	4.022
GTR_10_B	-0.05700	-0.06270	-0.06260	-0.06077	6.93923	6.96000	-0.3	4.030	3.999	4.015
GTR_10_C	-0.02520	-0.03875	-0.03540	-0.03312	6.96688	6.99550	-0.4	4.019	4.032	4.026
GTR_15_A	-0.03380	-0.03545	-0.03730	-0.03552	6.96448	6.99200	-0.4	4.025	4.027	4.026
GTR_15_B	-0.02800	-0.03250	-0.02735	-0.02928	6.97072	6.99050	-0.3	3.998	4.036	4.017
GTR_15_C	0.00130	0.00055	-0.00570	-0.00128	6.99872	7.02850	-0.4	3.970	4.056	4.013
GTR_20_A	-0.09805	-0.10110	-0.09795	-0.09903	6.90097	6.93650	-0.5	4.009	4.024	4.017
GTR_20_B	-0.06280	-0.06085	-0.06750	-0.06372	6.93628	6.96200	-0.4	3.997	4.048	4.023
GTR_20_C	-0.01825	-0.02775	-0.01965	-0.02188	6.97812	7.00100	-0.3	4.012	4.032	4.022

Δ (delta) is the infinitesimal measure between a pattern "7.00000 inches" stainless steel cylinder and the concrete cylinder analyzed.
Each concrete cylinder was measured at one side in three radii, separated by 120 degrees.

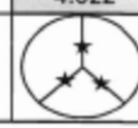

Table B2. CTE test results

Florida Department of Transportation
State Materials Office
Coefficient of Thermal Expansion. Florida State University Samples

Mix	Cylinder	Casted	Tested	Age (Days)	Length (in)	Diameter (in)	CTE $_{Total}$ (x 10^{-6} / °C)	Length Corr.Factor (x 10^{-6} / °C)	CTE (CTE $_{Total}$ - LengthCF) (x 10^{-6} / °C)	CTE (CTE $_{Total}$ - LengthCF) (x 10^{-6} / °F)
Control_0	A	7/25/2013	9/3/2013	40	6.98845	4.01950	9.92013	-0.50351	10.42364	5.79091
	B	7/25/2013	9/3/2013	40	6.90853	4.01800	9.10154	-0.13306	9.23460	5.13033
	C	7/25/2013	9/3/2013	40	6.98670	4.02100	10.55801	0.00609	10.55192	5.86218
	AVERAGE			40	6.96123	4.0195	9.85989		10.07005	5.59447
Control_ADMIX	A	7/25/2013	9/4/2013	41	6.93152	4.01500	8.72409	-0.68153	9.40563	5.22535
	B	7/25/2013	9/4/2013	41	6.97668	4.02550	10.14897	-0.00807	10.15704	5.64280
	C	7/25/2013	9/4/2013	41	6.95280	4.02300	9.58765	-0.05281	9.64047	5.35582
	AVERAGE			41	6.95367	4.02117	9.48691		9.73438	5.40799
GTR_5	A	7/25/2013	9/5/2013	42	6.96165	4.02400	9.38056	-0.07733	9.45789	5.25438
	B	7/25/2013	9/5/2013	42	6.97177	4.01600	9.24285	-0.55568	9.79853	5.44363
	C	7/25/2013	9/5/2013	42	6.96915	4.02050	9.98163	-0.02188	10.00351	5.55750
	AVERAGE			42	6.96406	4.02042	9.53501		9.75331	5.41851
GTR_10	A	7/25/2013	9/5/2013	42	6.94488	4.02150	9.76671	-0.06657	9.83328	5.46294
	B	7/25/2013	9/6/2013	43	6.93923	4.01450	9.23787	-0.11751	9.35538	5.19743
	C	7/25/2013	9/6/2013	43	6.96688	4.02550	8.89771	-0.57095	9.46866	5.26037
	AVERAGE			42	6.95376	4.02048	9.30077		9.55244	5.30691
GTR_15	A	7/25/2013	9/6/2013	43	6.96448	4.02600	10.10504	-0.03044	10.13548	5.63082
	B	7/25/2013	9/6/2013	43	6.97072	4.01700	10.16645	-0.02168	10.18814	5.66008
	C	7/25/2013	9/9/2013	46	6.99872	4.01300	10.11816	-0.01090	10.12906	5.62726
	AVERAGE			44	6.97192	4.01912	10.12988		10.15089	5.63938
GTR_20	A	7/26/2013	9/9/2013	45	6.90097	4.01650	8.20202	-0.77706	8.97908	4.98838
	B	7/26/2013	9/9/2013	45	6.93628	4.02250	9.81802	-0.08216	9.90019	5.50010
	C	7/26/2013	9/9/2013	45	6.97812	4.02200	11.24186	-0.00882	11.25069	6.25038
	AVERAGE			45	6.93846	4.02033	9.75397		10.04332	5.57962
REPETITIONS. Quality Control Purpose.										
GTR_5_REP	A	7/25/2013	9/10/2013	47	6.96165	4.02400	9.95483	-0.03564	9.99047	5.55026
GTR_10_REP	B	7/25/2013	9/10/2013	47	6.93923	4.01450	9.48153	-0.07639	9.55791	5.30995
GTR_15_REP	C	7/25/2013	9/10/2013	47	6.99872	4.01300	10.18438	-0.47141	10.65579	5.91988