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RECYCLED TIRES AS COARSE AGGREGATE IN CONCRETE PAVEMENT MIXTURES

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July 2013

COLORADO DEPARTMENT OF TRANSPORTATION
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16. Abstract
The reuse potential of tire chips as coarse aggregates in pavement concrete was examined in this research by investigating the effects of low- and high-volume tire chips on fresh and hardened concrete properties. One concrete control mixture was designed, which well exceeds CDOT Class P concrete requirements. The coarse aggregate component of the mixture was replaced in 100%, 50%, 30%, 20%, and 10% by volume using tire chips. The fresh concrete properties, compressive strength, flexural strength, splitting strength, permeability, and freeze/thaw durability were tested in the lab to evaluate the potential of including tire chips in concrete paving mixes. The testing results indicate tire chips can be used to replace coarse aggregate in concrete pavement mixtures. Two mixtures with 10% coarse aggregate replaced by tire chips had the best performance. The workability was comparable to the control mixture, and the air content reached 6%. At 28 days of age, the average compressive strength of the two mixtures was significantly less than the control but still exceeded CDOT's specification of 4200 psi; the averaged flexural and splitting tensile strengths were higher than 900 psi and 590 psi respectively. In addition, the two mixtures exhibited moderate resistance to chloride-ion penetration at 28 days of age and high freeze/thaw durability. The rubberized mixtures investigated in this study sustained a much higher deformation than the control mixture when subjected to compressive, flexural, and splitting loadings.

Implementation
Additional testing will need to be done to evaluate mix optimization and alternate sources of materials. This optimization could be best done by a profit-driven contractor. It's anticipated this would take eighteen months for research and three years of service to evaluate the pavement performance with final results in five years.

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Recycled Tires as Coarse Aggregate in Concrete Pavement Mixtures

Final Report

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EXECUTIVE SUMMARY

Colorado has roughly one-third of the stockpiled tires in the country. In addition, the number of tires stockpiled in Colorado is rising every year. The Colorado Senate Bill 09-289 requires elimination of all waste tire mono-fills in Colorado by the year of 2019. In the early 1990s, recycled waste tire particles' usage expanded into a relatively new product called rubberized concrete. Rubberized concrete uses portland cement as its binder. Research has shown that rubberized concrete has a positive outlook for inception into selected markets such as pavement applications.

The reuse potential of tire chips as coarse aggregates in pavement concrete was examined in this research by investigating the effects of low- and high-volume tire chips on fresh and hardened concrete properties. An extensive literature review covering published research reports, journal articles, and other documents since early 1980s was performed on the rubberized concrete focusing on tire chips as coarse aggregate replacement. One concrete control mixture was designed, which well exceeds CDOT Class P concrete requirements. The coarse aggregate component of the mixture was replaced in 100%, 50%, 30%, 20%, and 10% by volume using tire chips. The fresh concrete properties, compressive strength, flexural strength, splitting strength, permeability, and freeze/thaw durability were tested in the lab in order to determine if there is a promise in developing the paving concrete mixes including tire chips. The testing results indicate tire chips can be used to replace coarse aggregate in concrete pavement mixtures.

Two mixtures with 10% coarse aggregate replaced by tire chips and normal cement content had the best performance. The workability was comparable to the control mixture, and the air content reached 6%. At 28 days of age, the average compressive strength of the two mixtures was 4735 psi. Although this strength was significantly less than the 7058 psi of the control, it did exceed CDOT field strength requirement of 4200 psi. The average flexural strength (957 psi) was slightly higher than the control (907 psi) and significantly exceeded CDOT's required 650 psi. The averaged splitting tensile strength is higher than 590 psi. In addition, the two mixtures exhibited moderate resistance to chloride-ion penetration at 28 days of age and high freeze/thaw durability. The rubberized mixtures investigated in this study sustained a much higher deformation than the control mixture when subjected to compressive, flexural, and splitting loadings.

Implementation

The testing results from this study indicate tire chips can be used to replace coarse aggregate up to 10 percent in concrete pavement mixtures. Additional testing will need to be done to evaluate mix optimization and alternate sources of material and/or combinations of materials. This optimization could be best done by a profit-driven contractor. They would design a mix that would be stable and controllable on a construction project using materials that would be available at the project. A researcher could take the contractor's mix and play around with it by re-proportioning the mix to see what effects the changes would have. After a mixture is determined applicable, its incorporation into a pilot project would follow. In-service monitoring would be necessary and evaluated. It's anticipated this part will take eighteen months for this research and three years of service to evaluate the pavement performance with final results in five years.

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1. INTRODUCTION

1.1 Background

In the United States, more than 270 million used tires are scraped each year (1). It's estimated that about 4,595.7 thousand tons of tires were produced in 2007, 89.3% of which by weight were consumed in end-use markets (2). But there were still about 489.9 thousand tons of scraped tires added to existing stockpiles throughout the United States each year. At the end of 2009, about 113.6 million scrap tires were stockpiled in the United States (3). In 2009, Colorado had about 45 million tires stored, roughly one-third of the stockpiled tires in the country. The number of tires stockpiled in Colorado is still rising every year (4). In 2011, a total of 5,097,944 Colorado-generated tires were processed in Colorado waste tire processors and a Utah-based waste tire processing facility, which was almost equivalent to the number of waste tries (5,014,143) generated in Colorado (5). Figure 1-1 shows a decline in the number of waste tires added to stockpiles in Colorado. In 2011, there were only 69,452 additional waste tires stockpiled compared to 604,151 tires in 2010, and 572,121 tires in 2009. However, according to Colorado Department of Public Health and Environment (5), 60,274,182 waste tires were still stored at the tire mono-fills at the end of 2011.

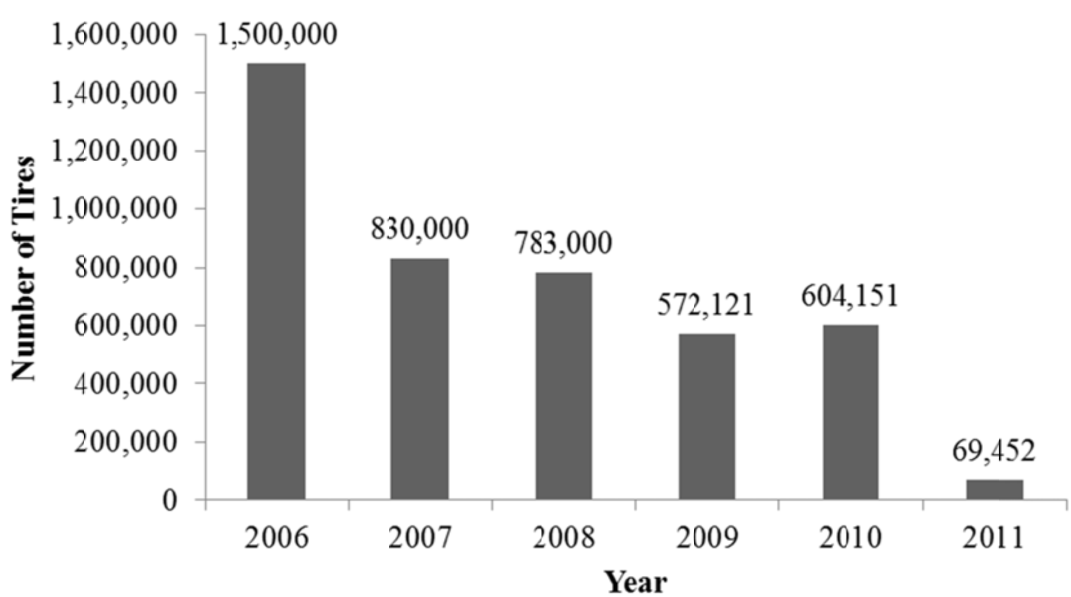


Figure 1-1 Annual Waste Tires Added to Stockpiles in Colorado

Federal regulations classify waste tires as non-hazardous waste. However, the stockpiles are depleting land resources, and they are vulnerable to fire. The combustion of tires releases volatile gases, heavy metals, oil, and other hazardous compounds. In addition, the stockpiles provide breeding grounds for rats, mosquitoes, and other vermin (1). The Colorado Senate Bill 09-289 requires elimination of all waste tire mono-fills in Colorado by the year of 2019. Some innovative solutions have been developed to meet the challenge of waste tire stockpiling problem. Whole tires could be used as tire bales for highway embankments and retaining wall construction. Granulated rubber could be incorporated to asphalt binders for asphalt pavement. It has been successful to incorporate waste tires in asphalt pavement. Better skid resistance, reduced fatigue cracking, and longer pavement life were revealed in rubberized asphalt (1). Some schools use processed waste tires as a gravel replacement in playgrounds. Tire chips or shreds could be used for thermal insulation and they could potentially be used as an alternative to soil/aggregate materials in civil engineering applications. In Colorado, the top 5 end-use markets for recycled waste tires in 2011 are included in Table 1-1.

Table 1-1 2011 Top 5 Recycled Waste Tire End-Use Markets in Colorado

Market	2011, Tires	% of Waste Tires Generated
Tire-derived Fuel	1,948,465	38.9%
Alternative daily cover	1,295,711	25.8%
Crumb Rubber	683,741	13.6%
Used Tires	468,786	9.3%
Fencing/Windbreaks	259,588	5.2%

In the early 1990s, recycled waste tire usage expanded into a relatively new product called rubberized concrete (6-7). Rubberized concrete uses portland cement as its binder. Research has shown that rubberized concrete has a very positive outlook for inception into selected markets such as pavement applications (8). A recent research study completed by the University of Colorado at Denver for the Colorado Department of Public Health and Environment indicated the feasibility of using commercially processed crumb rubber as a partial replacement for the fine aggregate in CDOT Class P pavement concrete mixes (8). Volumetric portions ranging from 10 to 50% replacements of sand were tested for fresh and hardened concrete properties. From the five replacement values, the 20 and 30% replacement mixtures performed adequately to fulfill

CDOT Class P concrete requirements. The recycled waste tire particles did not exhibit any type of unusual rate of strength gain behaviors with the different replacement quantities. The leaching tests were performed to examine the environmental sustainability of the rubberized concrete mixtures. According to these tests, this material would pose no threat to human health.

As a potential solution to help eliminate the waste tire mono-fills in Colorado by 2019, the reuse potential of tire chips as coarse aggregates in concrete pavement was examined in this study. The effects of low- and high-volume tire chips on concrete properties were investigated in this research.

The current requirements for various concrete classes are given in CDOT *Standard for Road and Bridge Construction* specification guide Section 601. CDOT Class P concrete is used in pavements. Concrete within this class are typically designed at low slumps for use in slip-form paving machines or curb and gutter machines. Maximum aggregate sizes range from 1 ½ to ¾-inch depending on placement types and whether or not dowels are being used in transverse joints. Modulus of rupture (flexural strength) of the pavement concretes is specified as 650 psi in the field and 700 psi in the laboratory at 28-days. The required field compressive strength is 4500 psi at 28 days of age. The minimum cementitious material content is 520 lbs./cy. The maximum water to cementitious material ratio is 0.44. The concrete is required to have 4-8% air to ensure a good durability to resist freeze/thaw cycling. The rubberized concrete mixtures are expected to have the same range of air content to have a good freeze/thaw resistance.

1.2 Study Objectives

The primary objectives of this research study are to:

- Examine the effects of increasing the coarse aggregate replacement percentage with recycled tire chips on concrete fresh properties, compressive strength, split-tension, flexural strength, permeability and freeze/thaw resistance, and determine an optimum replacement percentage of coarse aggregate with recycled tire chips for pavement concrete mixtures.
- Provide recommendations for the use of recycled tire chips as a coarse aggregate replacement in a concrete mixture designed for field implementation.

The main benefit of the research is to find an alternative to recycle waste tires in concrete. If tire chips can successfully replace the coarse aggregate in paving concrete mixes, the people of Colorado will benefit from the value gained in extending natural resources, reducing land space needed for waste products, and potentially decreasing costs associated with the product development and construction.

1.3 Scope of Study

This research evaluated the reuse potential of recycled tire chips as coarse aggregate in CDOT Class P pavement concrete mixes. An extensive literature review was performed on the rubberized concrete focusing on the tire chips as coarse aggregate replacement. Chapter 2 summarized the research findings which are related to the engineering properties of tire chips, design, construction, and performance evaluation of the rubberized concrete mixtures since early 1980s. One concrete control mixture was designed, which well exceeded CDOT Class P concrete requirements. The coarse aggregate component of the mixture was replaced in 100%, 50%, 30%, 20%, and 10% by volume using tire chips. The fresh concrete properties, compressive strength, flexural strength, splitting strength, permeability, and freeze/thaw durability were tested in the lab in order to determine if there is a promise in developing the pavement concrete mixtures including tire chips. Chapter 3 discussed the experimental designs and testing methods to measure the fresh and hardened concrete properties. Analyses of experiments results were presented in Chapter 4. Finally, Chapter 5 summarized the conclusions and provided recommendations.

2. LITERATURE REVIEW

This literature review covered published research reports, journal articles, and other documents that discussed the utilization of scrap tires in civil engineering applications focusing on rubberized concrete with tire chips incorporated.

2.1 Typical Compositions of Waste Tires

Waste tires are the tires removed from automobiles and trucks. The typical weights of an automobile tire and a truck tire are 20 lbs. and 100 lbs. respectively. The major materials used to manufacture tires include natural & synthetic rubber (41%), carbon black (28%), steel (14-15%), fabric, filler, accelerators and antiozonants (16-17%) (1). The percentages are given by weight.

2.2 Classification of Recycled Waste Tire Particles

Table 2-1 includes the terminology for recycled waste tire particles defined by ASTM D-6270 *Standard Practice for Use of Scrap Tires in Civil Engineering Applications*.

Table 2-1 ASTM D-6270 Terminology for Recycled Waste Tire Particles

Classification	Lower Limit, in (mm)	Upper Limit, in (mm)
Chopped Tire	Unspecified dimensions	
Rough Shred	1.97X1.97X1.97 (50X50X50)	30X1.97X3.94 (762X50X100)
Tire Derived Aggregate	0.47 (12)	12 (305)
Tire Shreds	1.97 (50)	12 (305)
Tire Chips	0.47 (12)	1.96 (50)
Granulated Rubber	0.017 (0.425)	0.47 (12)
Ground Rubber	-	<0.017 (0.425)
Powered Rubber	-	<0.017 (0.425)

Chopped tires are produced in tire cutting machines. These machines cut waste tires into relatively large pieces. The primary shredding process can produce scrap tires with a size as large as 12-18 in. long by 4-9 in. wide (1). Rough shreds, tire derived aggregates, tire shreds and tire chips are produced from the secondary shredding, which cut the tires down to 0.5 – 3 in.. Granulated rubbers, ground rubbers and powered rubbers are manufactured through cracker mill process, granular process, or micro-mill process, two stages of magnetic separation and screening (1,9). The commonly known crumb rubber consists of tire particles passing through No. 4 Sieve.

2.3 Basic Material Properties of Tire Rubber

This section presents the engineering properties necessary for design of scrap tires in civil engineering applications, e.g. specific gravity, modulus of elasticity (MOE), etc. As discussed above, tires are made of natural and synthetic rubber elastomers derived from oil, gas, and metallic intrusions. Other compositions e.g. carbon black, polymers, steel, and additives are incorporated to enhance performance of tires. The basic tire properties are summarized in Table 2-2 and compared with the properties of mineral aggregates.

Table 2-2 Basic engineering properties of tire rubber compared with mineral aggregates

Properties	Tire Rubber	Mineral Aggregates	References
Specific Gravity	1.02 -1.27	2.6-2.8	Humphrey and Manion, 1992; Ahmed, 1993
Modulus of Elasticity	180 - 750 psi	6,000-12,000 psi[a]	Beatty, 1981; Kulhawy and Mayne, 1990
Possion's Ratio	0.5	0.15-0.45	Beatty, 1981; Kulhawy and Mayne, 1990

[a] Dense, drained sand

The specific gravity of tire rubbers can be estimated using ASTM C 127 &128 *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse/Fine Aggregate*. The tire chips do not float when submerged in water, but the crumb rubber particles do float on the water and do not displace water. Kardos (8) implemented a de-airing agent to resolve this issue. The specific gravity of tire rubber is less than half of the mineral aggregates, which means a legal 80,000-pound gross weight tractor-trailer delivering recycled tire chips would provide 2 to 2-1/2 times the volume of virgin coarse aggregate per delivery. Modulus of elasticity is the ratio between the stress applied and the strain measured, which indicates materials' capability to resist deformation. The MOE of sand ranges from 6,000 psi to 12,000 psi and the gravel is much larger. Compared to sand and gravel, tire rubber has a much lower modulus of elasticity. When incorporated in concrete, tire rubber behaves as weak inclusions. Some theoretical models were developed by researchers to explain the compressive failure modes of the rubberized concrete cylinders (10). The Poisson's ratio of tire is 0.5, which is the ratio of contraction to extension of tire rubber under uniaxial tensile testing .

2.4 Fresh Concrete Properties of Rubberized Concrete

Slump, air content, and unit weight are usually used to evaluate the behaviors of fresh concrete. Raghvan et al (11) reported a comparable or better workability was achieved for mortars with rubber particles included than a control mortar without rubber particles, while other researchers found a decreased slump with an increase in rubber content (12). Khatib and Bayomy (12) also noted that the slump of the mixture was almost zero when rubber accounts for 40% of total aggregate volume. Mixtures with finer particles were more workable than those with coarse tire chips. Higher air content in rubberized concrete was reported than control mixtures (12-13). Air is easily trapped by the rough surface of the tire particles created during the milling process. Rubber also has hydrophobic tendencies to repel water and cause air to adhere to rubber particles. Khatib and Bayomy (12) reported there is a decrease in unit weight with increase in rubber content as a percentage of total aggregate volume. This is due to the low specific gravity of rubber particles as indicated in Table 2-2. The increased air content due to the increased rubber further decreases the unit weight of mixtures. The influence of rubber particles on the fresh concrete properties are summarized below:

- Slump and unit weight of concrete mixtures decreases with increase in rubber content.
- Air content increases as the rubber content increases.

2.5 Hardened Concrete Properties of Rubberized Concrete

2.5.1 Compressive, Splitting Tensile, and Flexural Strength Properties

The size, surface texture, and contents have been reported to affect compressive and tensile strength of the rubberized concrete mixtures (10, 12, 14-16). Eldin and Senouci (10) noted when coarse aggregate was 100% replaced by tire chips, there was approximately an 85% reduction in compressive strength and a 50% reduction in splitting tensile strength. The rubberized concrete mixtures demonstrated a ductile failure under compressive and tensile loads and they were capable to absorb a large amount of energy.

The rubberized concrete experienced a loss in compressive and tensile strength with increased tire particle content. The primary cause of strength loss is a result of poor adhesion of the cementitious products to the surface of the rubber particles. The tire chips could be chemically treated to improve the interfacial transition zone (ITZ) bond between the rubber tire chips and the cementitious material within the rubberized concrete mixture. Those methods include (1, 17-18):

- Polyacrylamide pretreated
- Pressure ageing vessel pretreated
- Silane pretreated
- Sodium hydroxide soak
- Magnesium oxychloride cement

The mixtures with pretreated rubber particles were reported to achieve 16%-57% higher compressive strength than concrete containing untreated rubber aggregates (1).

2.5.2 Toughness and Impact Resistance

Toughness indicates energy absorption capacity of a specimen, which is defined as the area under load-deflection curve of a flexural specimen. Researchers have reported the rubberized concrete mixtures were able to carry additional loads after the ultimate load, and they have higher toughness than control mixtures without rubber particles (10-12; 19). As the rubber content increases, the rubberized concrete specimens tend to fail gradually as opposed to brittle. The impact resistance of concrete increased when rubber aggregates were incorporated into the concrete mixtures (10; 16; 20-21).

2.5.3 Durability of Rubberized Concrete

A limited amount of literature is available concerning the durability of concrete mixture containing rubber aggregates. The rapid freezing and thawing (ASTM C 666, Procedure A) durability was investigated by Savas et al. (22) for rubberized concrete mixtures with 10%, 15%, 20%, and 30% granulated rubber by weight of cement. After 300 freeze/thaw cycles, the mixtures with 10% and 15% rubber particles had a durability factor higher than 60, but the other mixtures with 20% and 30% failed the testing. The loss of weight of all mixtures increased with increases in freezing and thawing cycles. Research performed by Paine et al (23) indicates crumb rubber could be potentially used as a freeze/thaw resisting agent in concrete.

A concrete sample with good resistance to chloride penetration will pass 1000-2000 coulombs (low permeability) tested by ASTM C 1202 *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. Gesoğlu and Güneyisi (24) evaluated the effects of chloride penetration in the rubberized concrete with silica fume incorporated. Rubber exasperates the chloride ion penetration significantly. But the use of silica fume can remarkably decrease the magnitudes of chloride penetration especially for the rubberized concretes.

2.5.4 Summary

In summary, literature has shown the following influences of rubber particles on hardened concrete properties:

- As rubber content increases, 28-day compressive and tensile strength decrease.
- The compressive strength of rubberized concrete can be increased by pretreating the tire particles chemically.
- Rubberized concrete experiences a ductile failure under compressive and tensile loads.
- Higher toughness can be achieved in rubberized concrete than control mixture without rubber aggregates.
- Limited literature on durability indicates that durable rubberized concrete mixtures can be achieved at certain replacement levels.

3. EXPERIMENTAL DESIGN

This study further investigated the use of recycled tire chips as coarse aggregate in Colorado pavement concrete. The fresh and hardened concrete properties were evaluated based on the following:

- Do the fresh and hardened concrete properties test results meet the current CDOT Class P specification?
- What is the maximum replacement rate of the coarse aggregate by the tire chips?

3.1 Mixture Proportions

Nine mixtures were batched in two phases. Mixtures 1-6 were made in the first phase and Mixtures 7-9 were made in the second phase. The first phase testing was designed to examine if there is a promise to use tire chips to replace coarse aggregate in pavement concrete mixtures. The second phase was to investigate the optimum cement content among the mixtures. The proportioning of the concrete mixtures is summarized in Table 3-1. The mix design followed American Concrete Associate (ACI) absolute volume method of concrete mix design.

Table 3-1 Mixture Proportions

Mixture	Identification	Water lbs./cy.	Cement lbs./cy.	Rock lbs./cy.	Tire lbs./cy.	Sand lbs./cy.	AEA fl oz/cwt
1	0Tire_660	264	660	1790	0	1116	0.5
2	100Tire_660	264	660	0	757	1116	0.5
3	50Tire_660	264	660	894	379	1116	0.5
4	30Tire_660	264	660	1253	227	1116	0.5
5	10Tire_660_1	264	660	1611	76	1116	0.5
6	10Tire_660_2	264	660	1611	76	1116	0.5
7	20Tire_660	264	660	1432	151	1116	0.5
8	30Tire_570	228	570	1253	227	1286	0.5
9	10Tire_570	228	570	1611	76	1286	0.5

The portland cement content in Mixtures 1-7 was 660 lbs./cy. and it was 570 lbs./cy. in Mixtures 8 and 9. A water to cement ratio of 0.40 was kept constant among all the mixtures. Mixture 1 was the control mixture. The coarse aggregate in mixtures 2-6 was replaced in 100%, 50%, 30%, 10% (volume) respectively by the tire chips. In order to determine the maximum replacement rate and optimum cement content among the mixtures, mixtures 7-9 were designed. 20% of coarse aggregate by volume was replaced by tire chips in Mixture 7, and 30% and 10% were in Mixture 8 and 9 respectively. A constant dosage of air entraining agent (AEA) was used in all mixtures. The moisture contents in the aggregates were measured and proportions were adjusted. The mixtures with 10% tire chips were batched twice to verify the repeatability of the testing results.

3.2 Materials

3.2.1 Cement

An ASTM Type I portland cement provided from Holcim, Inc. was used in this study. The specific gravity of this cement was 3.15 and the blaine fineness was 217 yd^2/lb.

3.2.2 Virgin Mineral Aggregates

The coarse and fine aggregates were provided by Bestway Aggregate. The physical properties of the aggregates are shown in Table 3-3. Both the coarse and fine aggregates met the ASTM C 33 specification. Tables 3-3 and 3-4 show the ASTM C 33 grading limits and sieve analysis results for the fine and coarse aggregates respectively**.**

Table 3-2 Physical Properties of Fine and Coarse Aggregates

Material	Absorption Capacity	Specific Gravity
Fine Aggregate	0.70%	2.61
Coarse Aggregate	0.80%	2.59

Table 3-3 ASTM C 33 – Grading Limits and Sieve Analysis for the Fine Aggregate

Sieve Size		% passing		
U.S	Metric(mm)	ASTM C33 Upper Limit	ASTM C33 Lower Limit	Sand Analysis
3/8 inch	9.5	100	100	100
NO.4	4.75	100	95	99.8
NO.8	2.36	100	80	90.1
NO.16	1.18	85	50	65
NO.30	0.6	60	25	35.8
NO.50	0.3	30	5	12.9
NO.100	0.15	10	0	2

Table 3-4 ASTM C 33 – Grading Limits and Sieve Analysis for the Coarse Aggregate

Sieve Size		% passing		
U.S	Metric(mm)	ASTM C 33 Upper limit	ASTM C 33 Lower Limit	Rock Analysis
1.5 inch	37.5	100	100	100
1 inch	25	100	90	100
3/4 inch	19	-	-	80
1/2 inch	12.5	60	25	36.7
3/8 inch	9.5	-	-	15.4
NO.4	4.75	10	0	1
NO.8	2.36	5	0	0.1

3.2.3 Tire Chips

Two types of tire chips with nominal size of ¾ in. and ½ in. were purchased from Front Range Tire Recycle Inc. (Figure 1-1Figure 3-1) with a cost of $0.18 per pound ($360 per ton). Compared to virgin aggregates, it does not have economic advantages. The specific gravity of the tire chips was measured to be 1.1 according to ASTM C 127 *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*. The tire chips did not float when submerged in water. In addition, sieve analyses were performed for the two sizes of tire chips. The results are summarized in Table 3-5 and illustrated in Figure 3-2.

(a) ½ in.

(b) ¾ in

Figure 3-1 Tire chips

Table 3-5 ASTM C 33 – Grading Limits for Coarse Aggregate and Sieve Analysis of Tire Chips

Sieve Size		% passing			
U.S	Metric(mm)	ASTM C 33 Upper limit	ASTM C 33 Lower Limit	Tire chips (1/2 inch)	Tire chips (3/4 inch)
1.5 inch	37.5	100	100	100	100
1 inch	25	100	90	100	100
3/4 inch	19	-	-	100	100
1/2 inch	12.5	60	25	87.5	11.5
3/8 inch	9.5	-	-	42.1	0
NO.4	4.75	10	0	0	0
NO.8	2.36	5	0	0	0

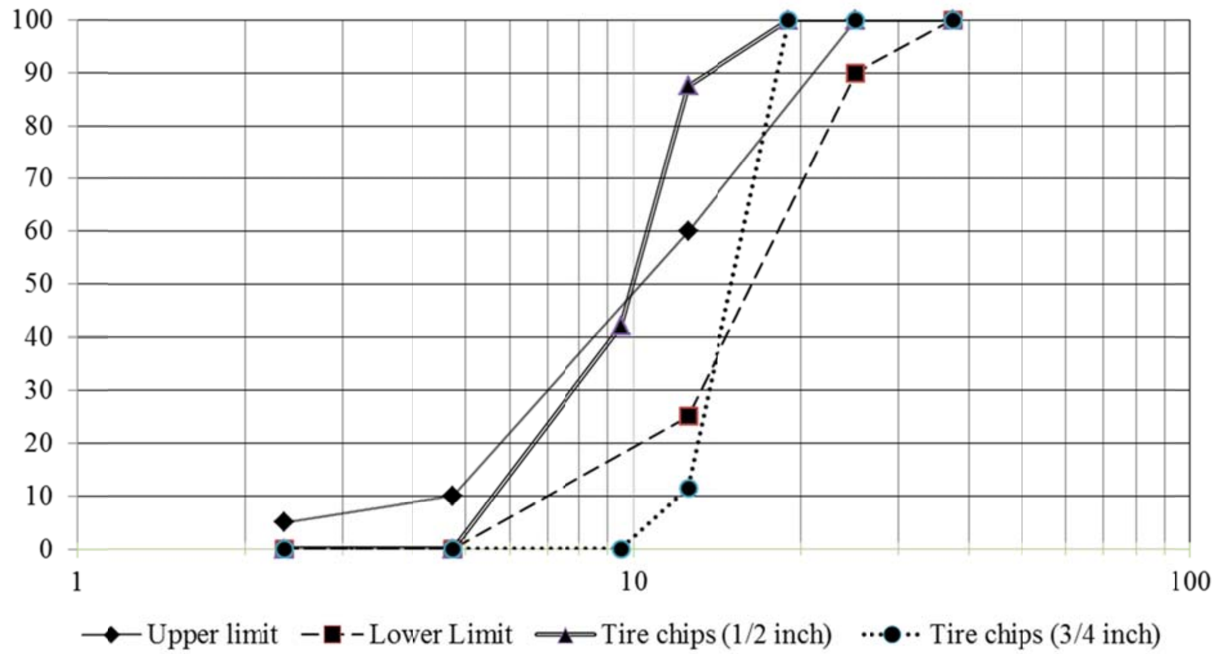


Figure 3-2 ASTM C 33 – Grading Limits for Coarse Aggregate and Sieve Analysis of Tire Chips

Neither tire chip sizes (¾ in. or ½ in.) met the ASTM C 33 grading requirements. Table 3-5 shows the ½ in tire chips exceeded the ASTM C 33 upper limit and the ¾ in. tire chips fell below the lower limit at the ½ in. sieve. In order to fulfill the requirement, the tire chips combined with 60% ½ in. and 40% ¾ in. rubber particles were used for batching the concrete mixtures in this study.

3.2.4 Chemical Admixtures

Sika Air admixture was used in all concrete mixtures to achieve the specified 4-8% air content. The AEA contained a blend of high-grade saponified rosin and organic acid salts. Typical addition rates ranged from 0.5 to 3 fl oz per 100 lbs. of cementitious material. As shown in Table 3-1, the lower limit of the dosage was used in all mixtures.

Sika Plastocrete 161, a commercially available lignin polymer type A high range water reducing admixture (HRWRA) was used during mixing of the concrete. The manufacturer's recommended addition rates ranged from 2 to 6 fl. oz/100 lbs of cementitious materials. The target slump is 1-2 in. for all mixtures. But it is discussed later that the mixtures containing high-volume tire chips had zero inch slump even with excessive high range water reducer incorporated.

3.3 Test Methods

The batching followed ASTM C 192 *Standard Practice for Making and Curing Concrete Test Specimens in the laboratory*. Both fresh and hardened concrete properties were examined for each mixture. The fresh concrete properties investigated include slump (ASTM C 143), unit weight (ASTM C 138), and air content (ASTM C 231 & ASTM C 173). Hardened concrete properties tested in this research include compressive strength (ASTM C 39), flexural strength (ASTM C 78), splitting tensile strength (ASTM C 496), resistance to freezing and thawing (ASTM C666, Procedure A), and rapid chloride ion penetrability (ASTM C 1202). The fresh and hardened concrete tests are shown in Table 3-6.

Table 3-6 Fresh and Hardened Concrete Tests

Fresh Concrete Tests	Standard	Time of Test
Slump	ASTM C 143	At Batching
Unit Weight	ASTM C 138	At Batching
Air Content (Pressure Meter)	ASTM C 231	At Batching
Air Content (Roller Meter)	ASTM C 173	At Batching
Hardened Concrete Tests	**Standard**	**Time of Test**
Compressive Strength	ASTM C 39	3,14,28 days
Modulus of Rupture	ASTM C 78	28 days
Freeze-Thaw Resistance	ASTM C 666	28 and Subsequent days
Rapid Chloride Ion Penetration	ASTM C 1202	28days
Splitting Tensile	ASTM C 496	28 days

The compressive strength of each mixture was tested at 3, 7, and 28 days of age, using three 4 × 8 in. cylinders for each test date. Rapid chloride ion penetration and splitting tensile tests were performed at 28 days of age, using two 4 × 8 in. cylinders each. Concrete beams were made for flexural strength and freeze/thaw resistance testing. The flexural strength was measured at the 28 days of age using two beams. DK-4000 Dynamic Resonance Frequency Tester was used to measure the transverse resonant frequencies of two concrete prisms of each mixture used for the freeze/thaw testing. The tester complies with ASTM C 214. The averaged experimental results are presented in Chapter 4, followed by discussions on the findings.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Fresh Concrete Properties

The fresh concrete properties of the nine mixtures are summarized in Table 4.1. The effects of tire chips on the slump, air content, and unit weight are discussed in the following sections.

Table 4-1 Fresh Concrete Properties

Mixture	Identification	Slump (in.)	Unit weight (lbs./ft^{3})	Air Content Pressure (%)	Air Content Roller (%)
1	0Tire_660	1	145	5	-
2	100Tire_660	0	93	18	3.5
3	50Tire_660	1	121	11	10.75
4	30Tire_660	1.75	127	10	7.25
5	10Tire_660_1	2	139	6	5.75
6	10Tire_660_2	1.5	141	6	5.25
7	20Tire_660	1.25	138	3.25	-
8	30Tire_570	0.75	131	6	-
9	10Tire_570	0.25	143	4.75	-

4.1.1 Slump

The slumps and the dosage rates of HRWRA are plotted in Figure 4-1. The slump of the control mixture, 0Tire_660, was 1 in. with HRWRA dosage rate of 5 fl. oz per 100 lb of cement. Comparing the slumps of Mixture 1-6 in the first phase of batching, the slump increased as the rubber content decreased. At rubber content of 100% of the coarse aggregate, the slump was zero even with excessive HRWRA 5 fl oz/cwt incorporated. To achieve the target 1-2 in. slump, 7.8 fl oz/cwt and 7.3 fl oz/cwt dosage rates of HRWRA were used in Mixture 3, 50Tire_660, and Mixture 4, 30Tire_660, respectively. The dosage rates were a little higher than the manufacturer’s recommendation ranging from 2 to 6 fl. oz/100 lbs. of cementitious materials. Mixture 5 and 6, two mixtures with 10% tire chips by volume of coarse aggregate, were incorporated with 5 fl. oz per 100 lb HRWRA. The slumps were 2 in. and 1.25 in., which were higher than the control mixture. This means the tire chips was not detrimental to the workability of the concrete at the rubber content of 10% of the coarse aggregate volume. The three mixtures in phase two were incorporated with excessive HRWRA with dosage rates 26.20 fl oz/cwt, 28.90 fl oz/cwt, and 26.20/cwt respectively. The slump of Mixture 7, 20Tire_660, was 1.25 in., but too much HRWRA was used in the mixture. This is opposite to the above slump changing trend. The exact cause is unknown. Additional batches are recommended to investigate this phenomenon. The last two mixtures, 30Tire_570 and 10Tire_570, had lower slumps than Mixtures 4-6 due to their reduced cement content. Cement is beneficial to the workability.

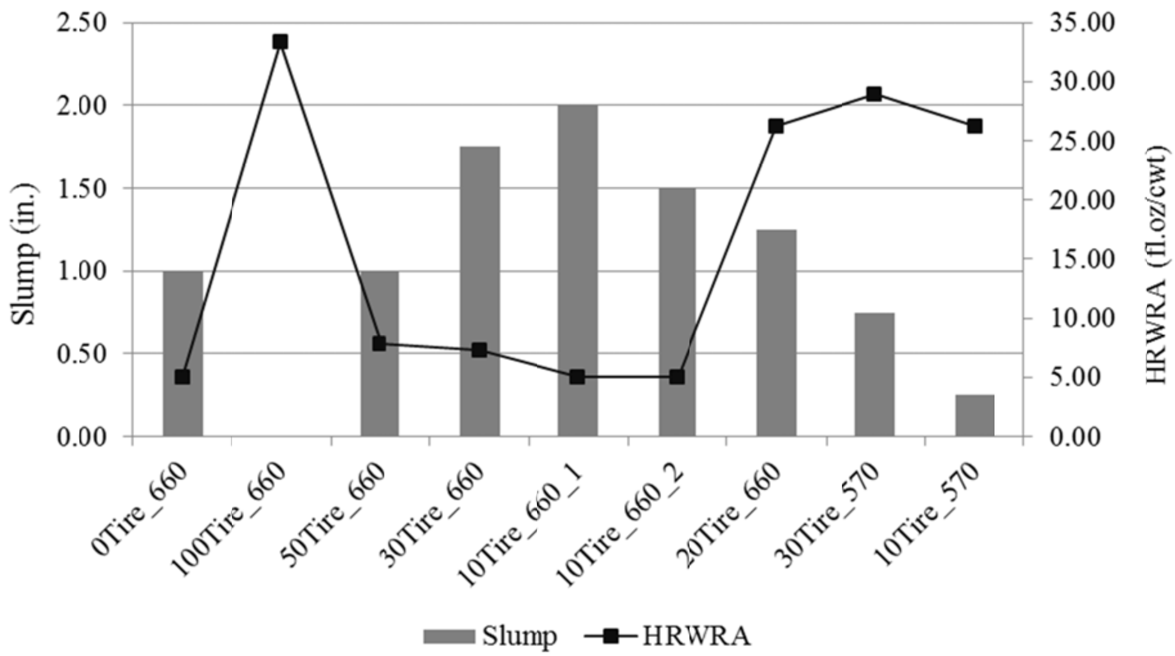


Figure 4-1 Slump and HRWRA

4.1.2 Air Content

A constant dosage of AEA, 0.5 fl oz/cwt of cement was used in all mixtures. The air content in the control mixture was 5%. Mixture 2, 100Tire_660, had the highest air content of 18% measured by a pressure meter, and Mixture 7, 20Tire_660, had the lowest air content of 3.3%. High air contents were obtained in the mixtures with more than 30% tire chips. Table 4-1 hows as the tire chips content increased, air content increased. The relationship between the air content (%) and the tire chips contents by total aggregates volume (%) is plotted in Figure 4-2. The results measured by a roller meter show the mixture 100Tire_660 had a low air content of 3.5%. This might be because the air trapped by the rough surfaces of high-volume tire particles was released during the testing using the roller meter. The results measured from roller meter also show the general increase trend of air content due to the increase rubber content except for Mixture 100Tire_660.

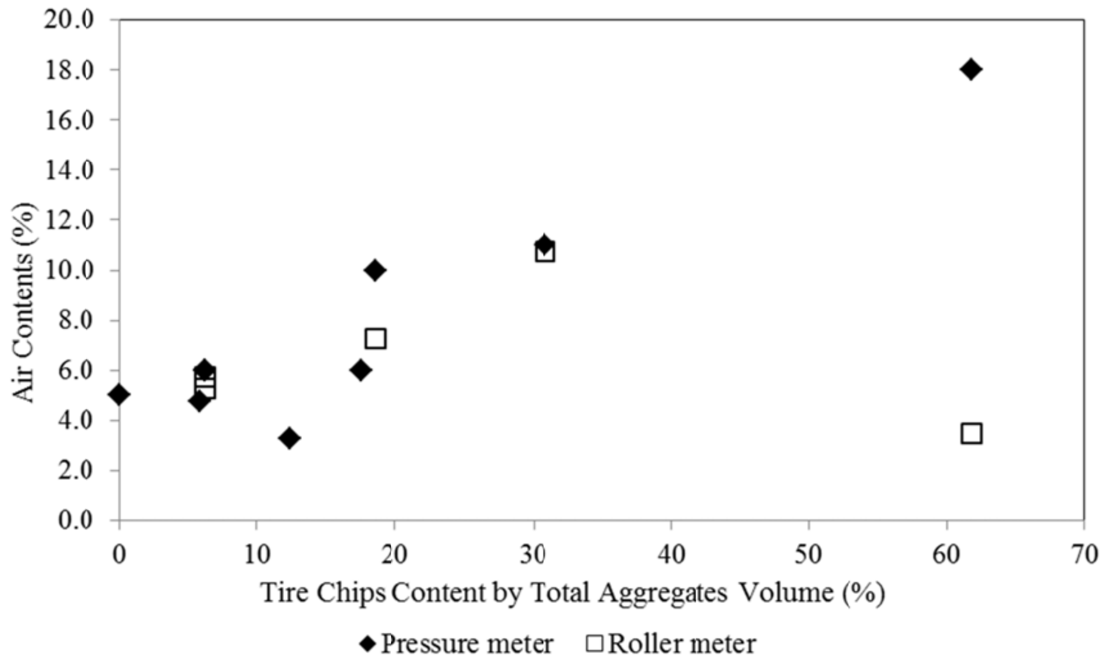


Figure 4-2 Air Content vs. Tire Chips Content by Total Aggregate Volume (%)

4.1.3 Unit Weight

The unit weights of the nine concrete mixtures are listed in Table 4-1 and plotted verses the tire chips contents by total aggregate volume in Figure 4-3. The mixtures with tire chips incorporated had lower unit weight than the control mixture without rubber aggregate, but only high tire chips contents (> 30%) changed the unit weight dramatically. The difference between the control mixture and Mixture 7, 20Tire_660, is 4.8% (within 5%). Figure 4-3 shows the unit weight is proportional to the tire chips content by total aggregates volume. As the rubber aggregate increased, the unit weight decreased linearly regardless of the cement content.

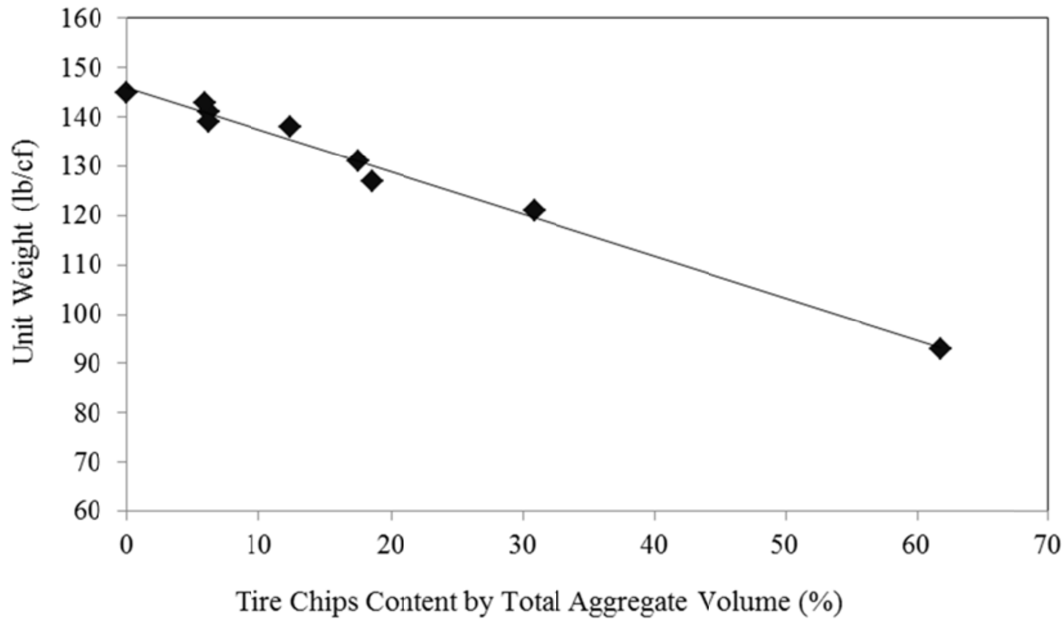


Figure 4-3 Unit Weight vs. Tire Chips Content by Total Aggregate Volume (%)

4.2 Hardened Concrete Properties

4.2.1 Compressive Strength

The compressive strengths of the nine mixtures are listed in Table 4-2 and plotted in Figure 4-4. The 3-day, 14-day, and 28-day compressive strengths of the eight rubberized concrete mixtures ranged between 392-3699 psi, 370-3913 psi, and 515-4835 psi respectively. They had lower compressive strengths than the control mixture at 3, 14, and 28 days of age. The 100Tire_660 had the lowest strength at 3, 14, and 28 days of age compared to all other mixtures. The 10Tire_660_2 had highest strength at 3 days of age among the mixtures with rubber aggregates. And the other mixture with 10% tire chips by volume of coarse aggregate, 10Tire_660_1, had the highest compressive strength at 28 days of age. Only the two mixtures with 10% tire chips by volume of coarse aggregate had strengths exceeding 4500 psi at 28 days. Only one of the 10% mixtures would meet CDOT’s laboratory 15% overdesign criteria for project approval.

Table 4-2 Compressive Strength

Mixture	Identification	3-day (psi)	14-day (psi)	28-day (psi)
1	0Tire_660	5335	6383	7058
2	100Tire_660	392	370	515
3	50Tire_660	1146	1139	1421
4	30Tire_660	1668	1813	2371
5	10Tire_660_1	2932	3419	4835
6	10Tire_660_2	3699	3913	4614
7	20Tire_660	2194	2305	2408
8	30Tire_570	475	912	860
9	10Tire_570	475	580	1064

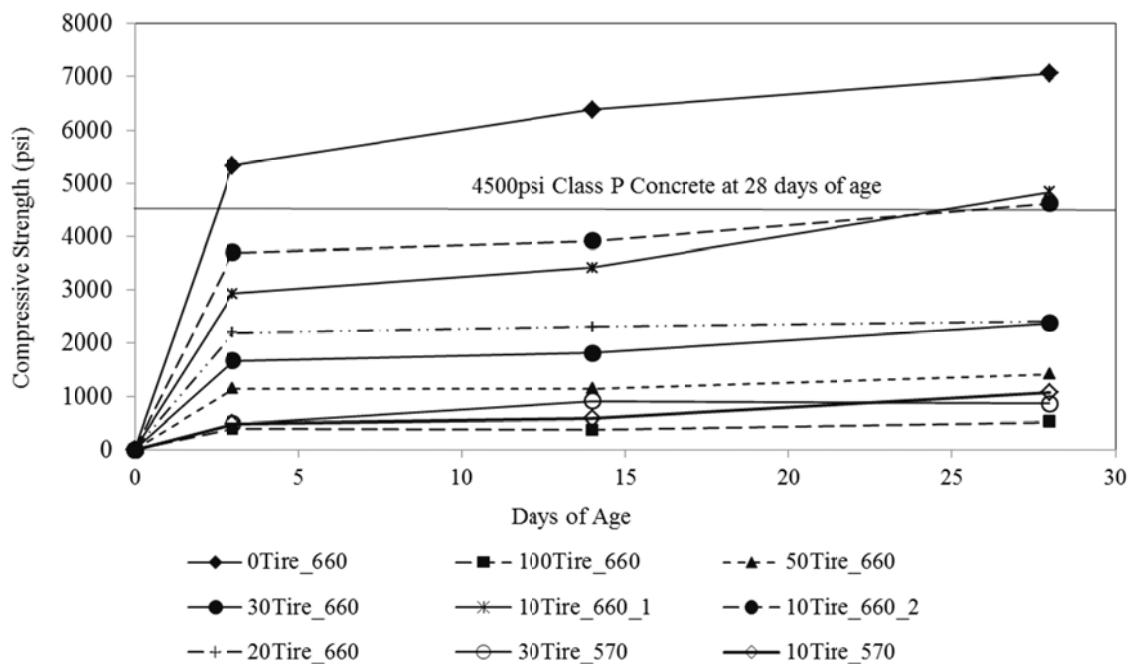


Figure 4-4 Compressive Strength Development

Two factors which are cement content and tire chips content affected the compressive strength development of the mixtures. Mixture 8, 30Tire_570, and Mixture 9, 10Tire_570, had 570 lb/cy cement, which was lower than other mixtures with 660 lb/cy cement. Comparing to the compressive strengths of Mixture 4, 30Tire_660, and Mixture 5&6, 10Tire_660, the compressive strengths of Mixture 8 and 9 were lower than Mixture 4, 5&6 at 3, 14, and 28 days of age respectively. In addition, the 3-day compressive strengths of the mixtures with 660 lbs./cy. cement had already reached more than 60% of the 28-day strengths. The 3-day compressive strength of Mixture 8 and 9 only achieved 55% and 45% of the 28-day strengths respectively. The other factor is the tire chips content. The results illustrated in Figure 4-5show a reduction in compressive strength with the increase of tire chips content for the mixtures in phase 1. The initial 28-day compressive strength of 7058 psi was reduced to 515 psi when 100% coarse aggregate was replaced by tire chips. This represents a 92.6% reduction in the 28-day strength when full replacement of coarse aggregate occurs. The mixtures with 10% tire chips experienced the least reduction, which was 36% at 28 days. Figure 4-5 also confirms the effect of cement content on the compressive strength of the mixtures. The compressive strengths of the mixtures with 570 lbs./cy. cement were even lower and they were below the strength reduction trend line formed by other mixtures.

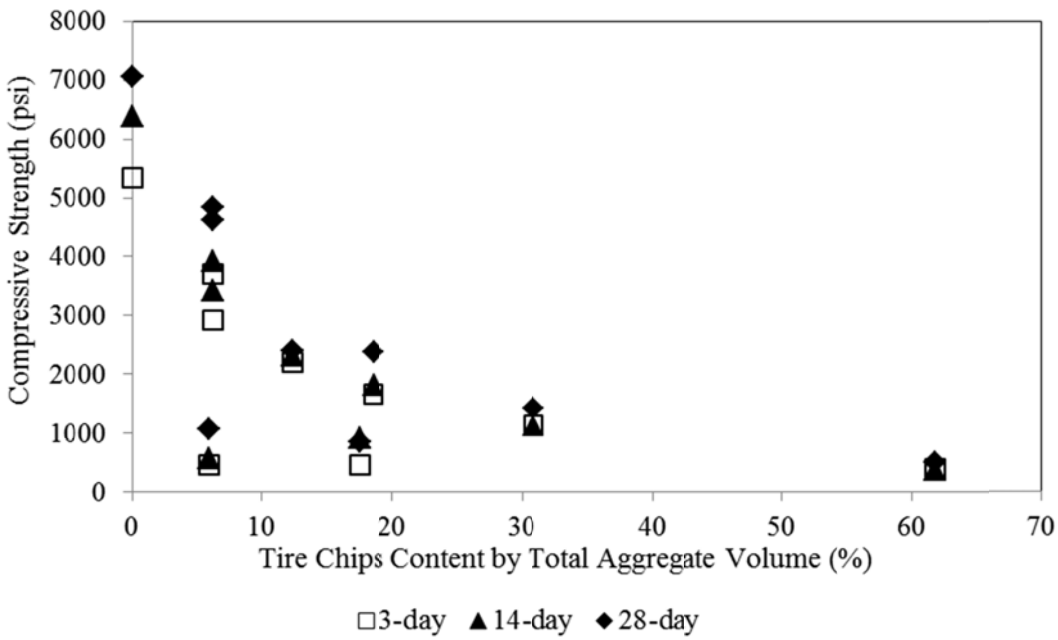


Figure 4-5 Effect of Tire Chips Content on Compressive Strength

One positive effect to include tire chips in concrete is the rubber aggregate changed the failure mode of concrete mixtures. Figure 4-6 shows the failure modes of the control mixture and the mixture with 10% tire chips by volume of coarse aggregate. The mixtures with tire chips sustained a much higher deformation than the control mixture.

(a) Mixture 1, 0Tire_660 (b) Mixture 5, 10Tire_660_2

Figure 4-6 Failure Modes of the Control Mixture and Rubberized Concrete at 28 days

4.2.2 Flexural Strength

Table 4-3 shows the flexural strengths of all nine concrete mixtures at 28 days of age, which are plotted in Figure 4-7. The flexural strength of the control mixture was 907 psi at 28 days of age. The mixtures with rubber aggregate had flexural strengths ranging from 415 to 991 psi. The two mixtures with 10% tire chips by volume of coarse aggregate had highest flexural strengths at 28 days, which were 924 psi and 991 psi respectively. It is concluded that the flexural strength of concrete mixtures can be increased by replacing certain level (~10%) of coarse aggregate. Figure 4-8 shows the failure mode of Mixture 10Tire_660 compared with the control mixture due to the flexural loading. The control mixture was separated into two halves after failure, but the rubberized concrete mixture was not. The two mixtures with 570 lbs./cy. cement had good performance in flexural strength. Visual observations during the test indicated that the beams from the two mixtures had relatively large deflections before failure. This confirms that the mixtures with less cement content are less stiff. Because the tire chips can bridge cracks caused the flexural loading, the less stiff specimens with tire chips can withstand additional loading after cracking. Figure 4-7 also indicates as the tire chips content decreased, the flexural strength increased. The relationship between flexural strength and tire chips content is plotted in Figure 4-9, which clearly illustrates the trend except the two data points from two mixtures with lower cement content.

Table 4-3 Flexural Strength at 28 days

Mixtures	Identification	28-day (psi)
1	0Tire_660	907
2	100Tire_660	415
3	50Tire_660	552
4	30Tire_660	659
5	10Tire_660_1	924
6	10Tire_660_2	991
7	20Tire_660	654
8	30Tire_570	943
9	10Tire_570	886

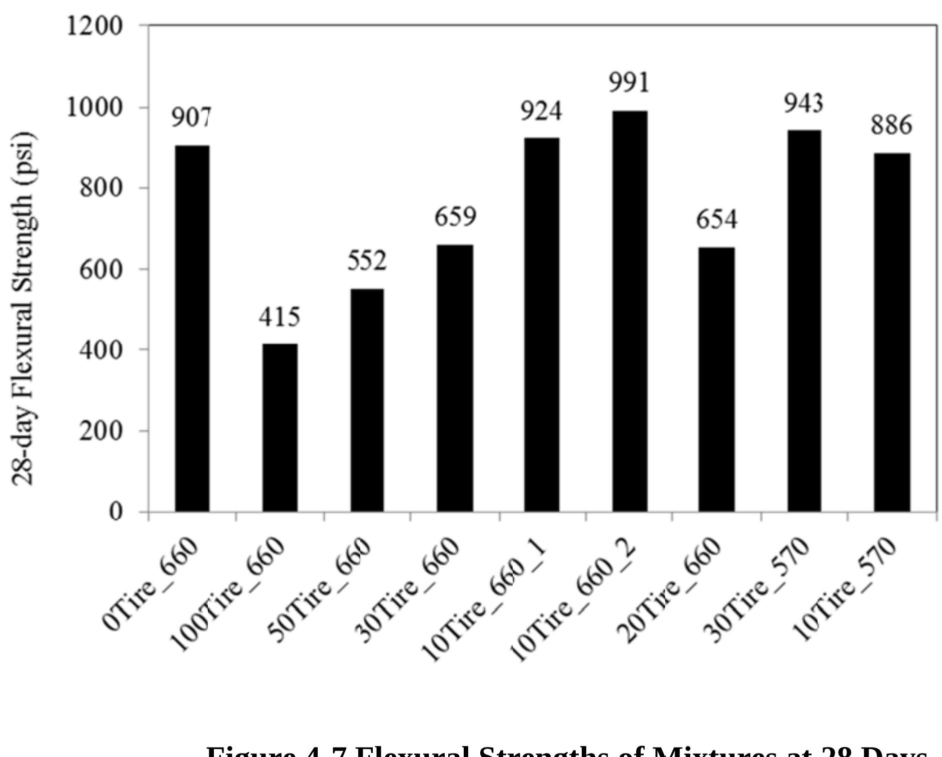


Figure 4-7 Flexural Strengths of Mixtures at 28 Days

(a) 0Tire_660 (b) 10Tire_660_2

Figure 4-8 Flexural Failure Modes

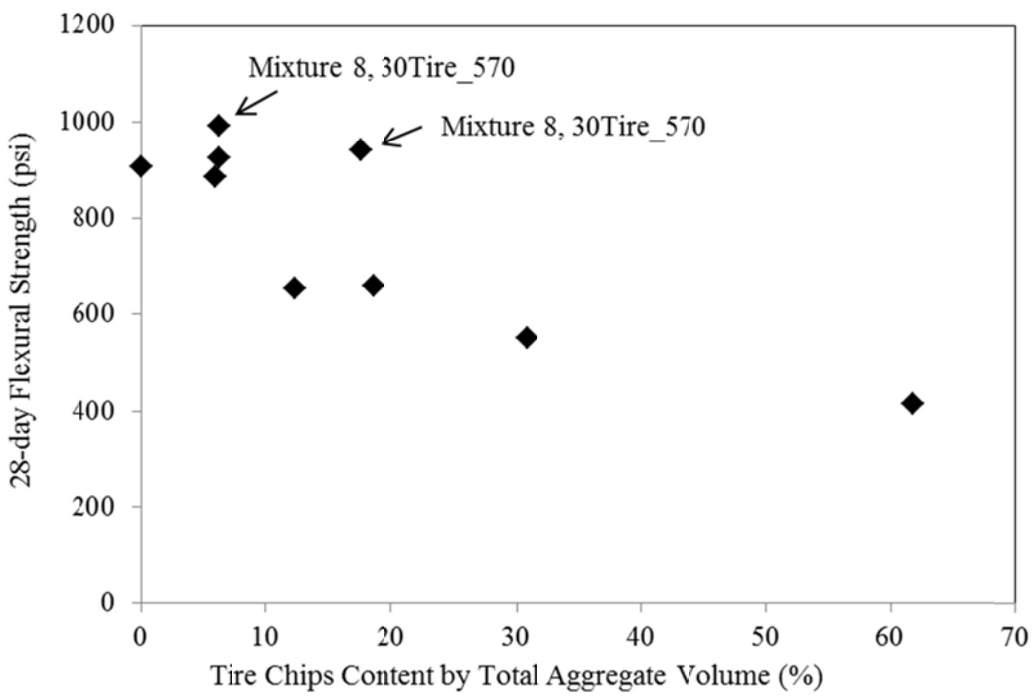


Figure 4-9 Flexural Strength vs. Tire Chips Content by Total Aggregate Volume

4.2.3 Splitting Tensile Strength

The splitting tensile strengths of the nine mixtures are summarized in Table 4-4, and plotted in Figure 4-10. The control mixture had the highest splitting tensile strength, and the mixture with full replacement of coarse aggregate had the lowest. The splitting tensile strengths of the rubberized concrete ranged from 170 psi to 662 psi. The mixture 10Tire_660_1 had the highest splitting tensile strength among all mixtures with rubber aggregates. Similar to flexural strength testing, Figure 4-11 shows the rubberized concrete cylinders were not separated into two halves when they failed because of bridging of cracks by the tire particles. In addition, both Figure 4-10 and Figure 4-12 indicate a decrease trend of the splitting tensile strength due to the increased tire chips content.

Table 4-4 Splitting Strength at 28 Days

Mixtures	Identification	28-day (psi)
1	0Tire_660	806
2	100Tire_660	170
3	50Tire_660	295
4	30Tire_660	347
5	10Tire_660_1	662
6	10Tire_660_2	531
7	20Tire_660	611
8	30Tire_570	450
9	10Tire_570	497

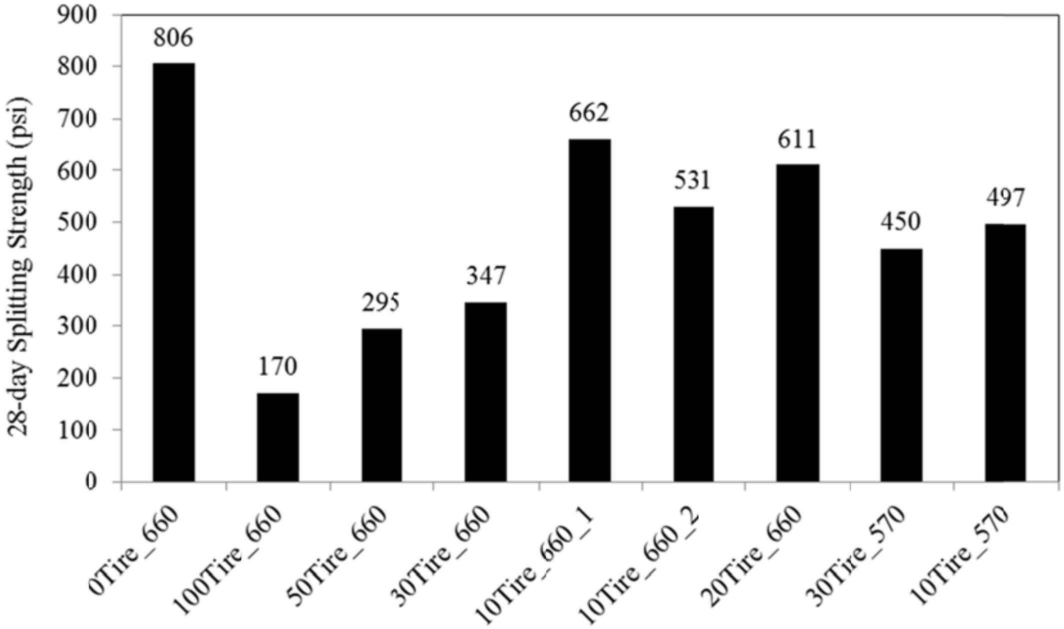
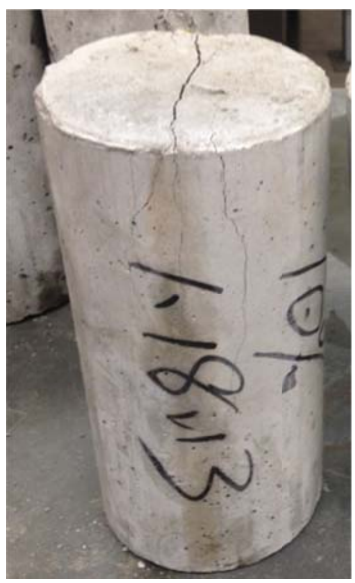


Figure 4-10 Splitting Strength at 28 Days of Age

(a) 0Tire_660



(b) 10Tire_660_2

Figure 4-11 Splitting Failure Modes

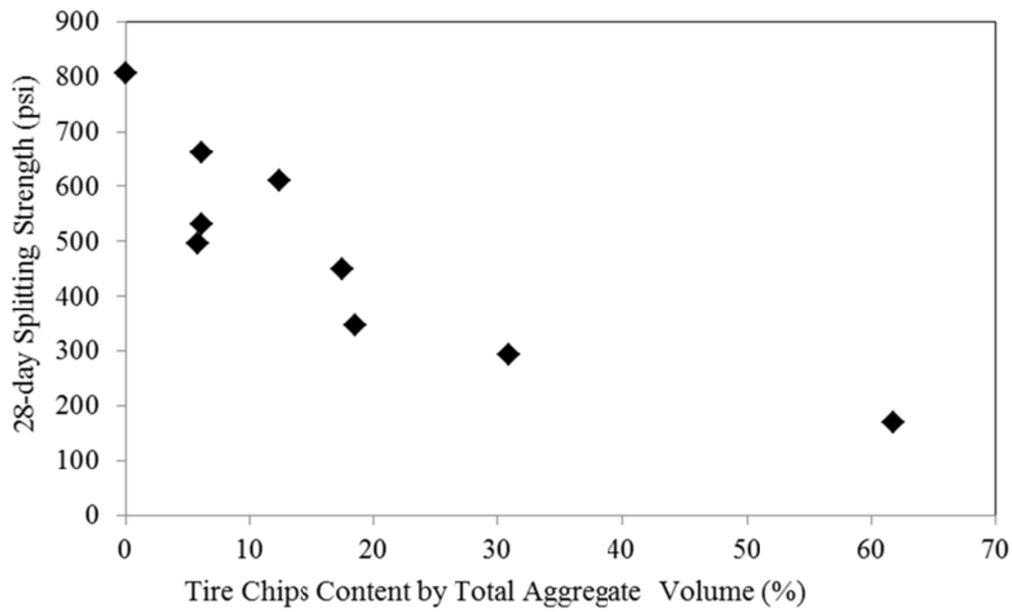


Figure 4-12 Splitting Strength vs. Tire Chips Content by Total Aggregate Volume

4.2.4 Rapid Chloride-ion Penetration

Table 4-5 shows that all mixtures with rubber aggregate exhibited moderate to high resistance to chloride-ion penetration at 28 days of age except Mixture 30Tire_570. Two specimens were tested for each mixture. The total charge passed for the two specimens of Mixture 30Tire_570 were 5661 Coulombs and 2708 Coulombs respectively. Cracking was found in one 2 in. thick specimen with higher permeability when the testing was completed. The cracking might be generated during the specimen preparation. If only 2708 Coulombs is taken to represent the permeability condition at 28 days of age. Mixture 30Tire_570 showed moderate resistance to chloride-ion penetration.

The relationship between total charge passed and tire chips content is plotted in Figure 4-13 to investigate the effect of tire chips content on the permeability of the concrete mixtures. However, no obvious trend is obtained. The relationship between total charge passed and air contents measured using pressure meter (ASTM C 231) is illustrated in Figure 4-14. The total charge passed increased as the air contents increased except three data points from Mixture 30Tire_570, Mixture 50Tire_660, and Mixture 100Tire_660. Mixture 30Tire_570 had one cracking specimen and high testing result. Both Mixture 50Tire_660 and 100Tire_660 had high-volume tire particle contents. As discussed in Chapter 2, air is easily trapped by the rough surfaces of the tire particles. The readings from pressure meter were high. Roller meter was used to measure the air contents for rubberized mixture in phase 1. The results are summarized in Table 4-1. Using the air contents measured from roller meter and 2708 Coulombs reading for Mixture 30Tire_570, the results of total charge passed vs. air contents are plotted in Figure 4-15. The figure indicates an increase of total charge passed due to increase of the air content except one data point from Mixture 50Tire_660. Additional batches are recommended to investigate the abnormal point. The relationship between the air content and tire chips content was revealed in Figure 4-2. The general trend is as the tire content increases, the air content increases. But Figure 4-13, Figure 4-14, and Figure 4-15 illustrate the permeability was more affected by the air content than the tire chips content. The tire chips content is only one factor influencing the air content of rubberized concrete.

Table 4-5 Rapid Chloride-ion Penetration Tests Results

Mixtures	Identification	28-day (Coulombs)	ASTM C1202
1	0Tire_660	1785	Low
2	100Tire_660	2183	Moderate
3	50Tire_660	1356	Low
4	30Tire_660	2889	Moderate
5	10Tire_660_1	2257	Moderate
6	10Tire_660_2	2146	Moderate
7	20Tire_660	1516	Low
8	30Tire_570	4185	High
9	10Tire_570	1648	Low

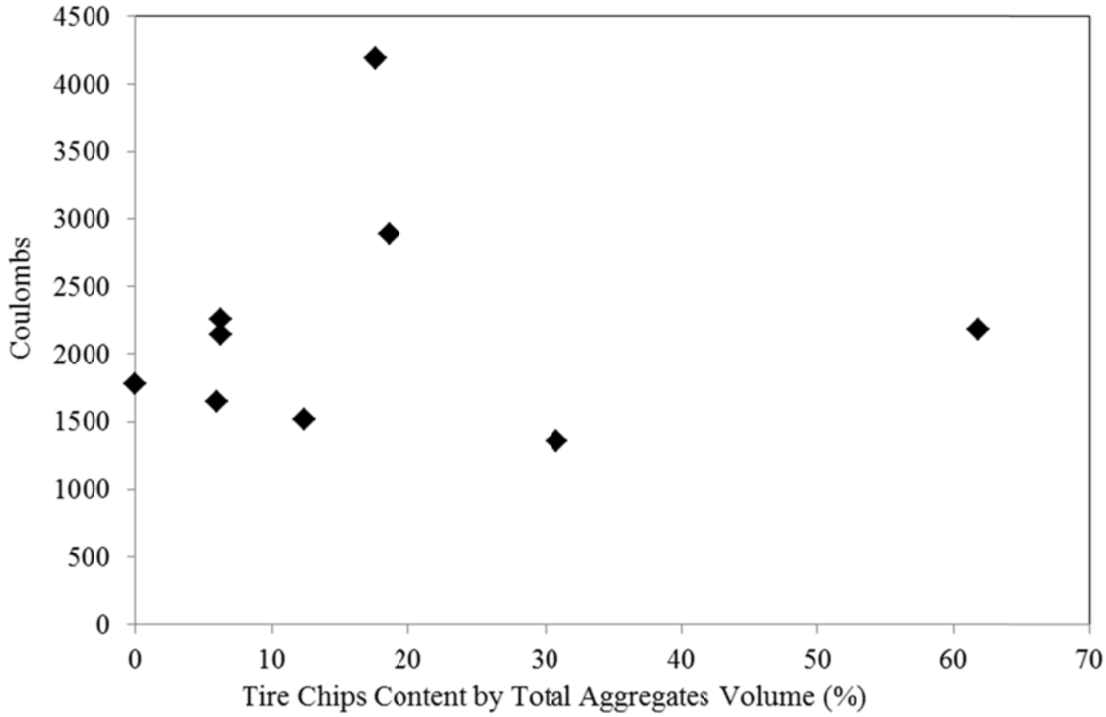


Figure 4-13 Coulombs vs. Tire Chips Content by Total Aggregates Volume

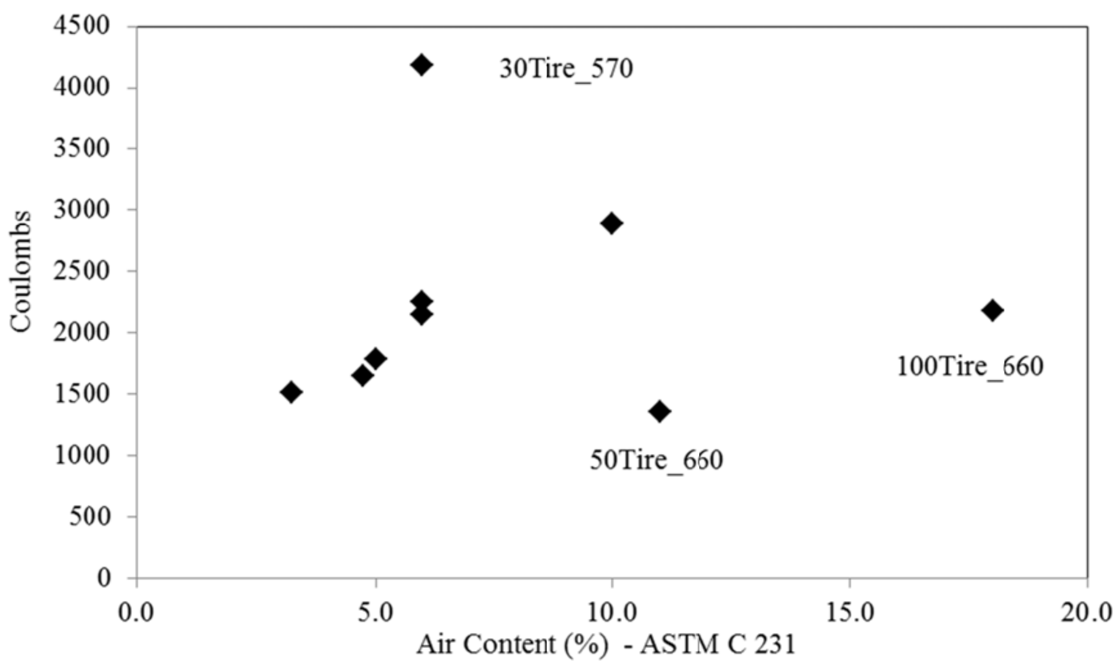


Figure 4-14 Coulombs vs. Air Content (Pressure Method)

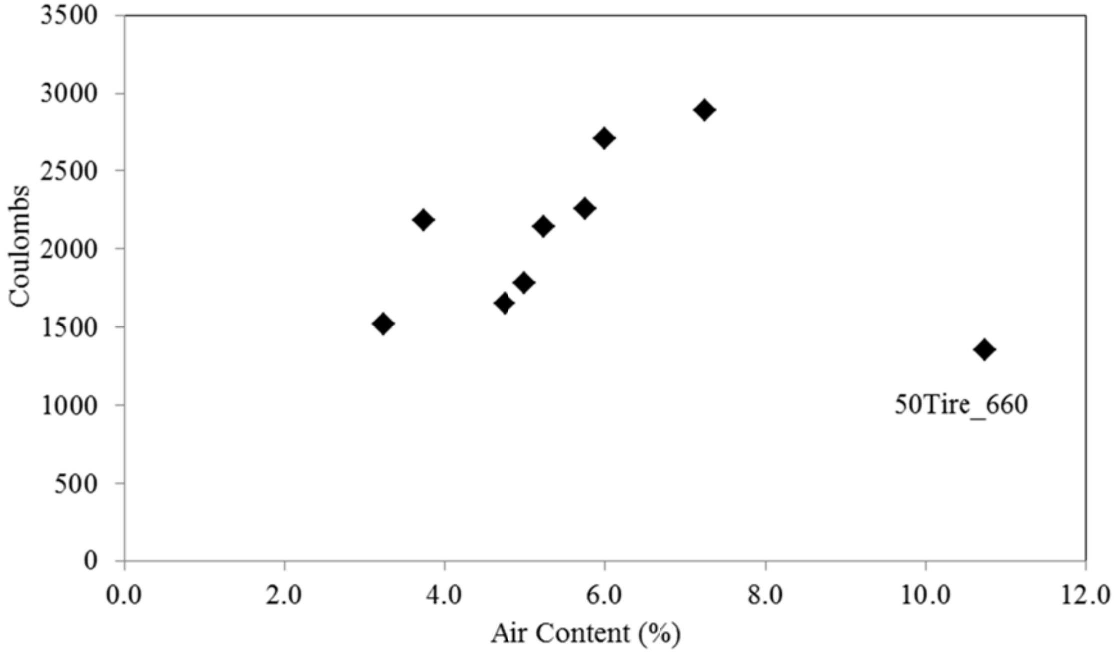


Figure 4-15 Coulombs vs. Air Content (Volumetric Method)

4.2.5 Freeze/Thaw Resistance

The freeze/thaw durability of the concrete mixtures was determined from the transverse resonant frequency and by calculating the durability factors. The change of the transverse resonant frequencies of the nine mixtures and the durability factors are listed in Table 4-6 and Table 4-7. As shown in Table 4-7, Mixture 100Tire_660 had low resistance to freeze/thaw cycling, primarily a result of a low adhesion between the cement paste and rubber particles. The surface deterioration of all concretes was observed after 300 cycles of freezing and thawing. But it did not cause significant mass loss except Mixture 100Tire_660. The concrete mixtures with 10-50% tire chips by volume of coarse aggregate exhibited an excellent resistance to freezing and thawing. The transverse resonant frequency is a function of mass and stiffness of the concrete prisms. The relationship between initial and final frequencies and tire chips content are illustrated in Figure 4-16. The decreasing trend means as the tire chips content increases, the stiffness of the concrete beams decreases. The concrete prisms with more tire chips are less stiff. Figure 4-16 also indicates the effect of cement content on the stiffness of the concrete prisms. The two mixtures with lower cement content had lower stiffness.

Table 4-6 Resistance to Freeze /Thaw Cycling

Mixtures	Identification	0 Cycles (Hz)	36 Cycles (Hz)	72 Cycles (Hz)	108 Cycles (Hz)	144 Cycles (Hz)	180 Cycles (Hz)	216 Cycles (Hz)	252 Cycles (Hz)	288 Cycles (Hz)	324 Cycles (Hz)
1	0Tire_660	2178	2129	2100	2109	2090	2100	2080	2090	2080	2119
2	100Tire_660	938	859	645	645	645	645	586	586	664	664
3	50Tire_660	1572	1562	1533	1553	1514	1523	1475	1475	1523	1484
4	30Tire_660	1768	1768	1738	1748	1719	1738	1719	1709	1748	1728
5	10Tire_660_1	2021	1973	1914	1914	1914	1914	1914	1914	1914	1914
6	10Tire_660_2	1973	1963	1953	1953	1953	1953	1953	1953	1953	1953
7	20Tire_660	1855	1797								
8	30Tire_570	1426	1279			Testing in Progress					
9	10Tire_570	1387	1250								

Table 4-7 Durability Factor

Mixtures	Identification	Initial (Hz)	Final (Hz)	Durability Factor
1	0Tire_660	2178	2119	95
2	100Tire_660	938	645[a]	11
3	50Tire_660	1572	1484	89
4	30Tire_660	1768	1728	96
5	10Tire_660_1	2021	1914	94
6	10Tire_660_2	1973	1953	98
7	20Tire_660	1855		
8	30Tire_570	1426		
9	10Tire_570	1387		

[a] Frequency was measured at 72 cycles

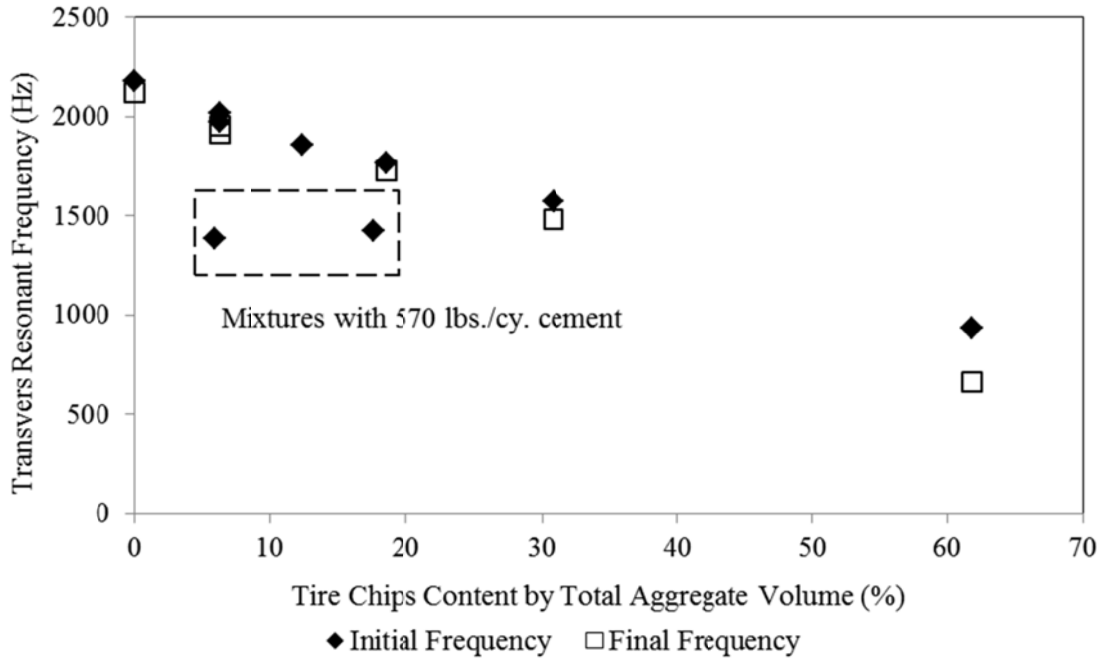


Figure 4-16 Transverse Resonant Frequency vs. Tire Chips Content by Total Aggregate Volume

5. CONCLUSIONS AND RECOMMENDATIONS

Colorado has about one-third of the stockpiled tires in the U.S.. The stockpiles are consuming land resources and are vulnerable to fire. They are potential threats to the environment and human's health. In order to help achieve the goal of Colorado Senate Bill 09-289, which requires elimination of all waste tire mono-fills in Colorado by 2019, this study investigated the reuse potential of tire chips as coarse aggregate in pavement concrete mixtures. The rubberized concrete does not reduce the cost and even reduce the environmental impacts of concrete itself, but it helps eliminate the waste tire stockpiles and reduce the potential threats of the stockpiles to the environment. Volumetric portions ranging 10% to 100% replacements of coarse aggregate were tested for fresh and hardened concrete properties. Nine mixtures were batched in two phases. The first phase was designed to examine if there is a promise to replace coarse aggregate by tire chips in pavement concrete mixtures. And the second phase was to investigate the optimum cement content among the mixtures. This study evaluated and reported the fresh concrete properties including slump, air content, unit weight, and hardened properties including compressive, flexural, splitting tensile strengths, permeability and freeze/thaw resistance of rubberized concrete mixtures. A summary of the major findings from this study are reported blow.

(1) The slump increased as the rubber contents decreased. The tire chips were not detrimental to the workability of the concrete when10% of the coarse aggregate by volume was replaced by tire chips. The mixtures with high-volume tire chips or low cement content were not workable. Low slumps were obtained with excessive HRWRA for these mixtures.

(2) A general trend of increased air content due to the increased tire chips content was revealed. But a significant discrepancy of air contents measured from pressure meter and roller meter was observed for Mixture 100Tire_660.

(3) As the rubber aggregate increased, the unit weight decreased linearly regardless of the cement content.

(4) Compressive strength dropped 32% with 10% replacement of coarse aggregate and dropped more with higher replacement levels. This results in only two mixtures with

10% tire chips by volume of coarse aggregate met the Class P concrete compressive strength requirement at 28 days of age. Both cement content and tire chips content affected the compressive strength of the rubberized mixtures. The mixtures with low cement content had lower compressive strengths. A reduction in compressive strength was observed with increase of tire chips content.

(5) The flexural strength was increased by replacing 10% of coarse aggregate. The flexural strengths of two mixtures exceeded 900 psi at 28 days of age. The mixtures with less cement withstood additional flexural loading after cracking. The flexural strength testing also finds as the tire chips content decreased, the flexural strength increased.

(6) The splitting tensile strength decreased by at least 18% with a 10% replacement coarse aggregate and decreased further as the tire chips content increased.

(7) The mixtures with tire chips sustained a much higher deformation than the control mixture when subjected to compressive, flexural, and splitting loadings.

(8) Mixtures with rubber aggregates exhibited moderate to high resistance to chloride-ion penetration at 28 days of age. The permeability of the rubberized concrete mixtures was more affected by the air content than the tire chips content.

(9) The measurement of transverse resonant frequencies of concrete prisms revealed the beams with more tire chips were less stiff. The two mixtures with lower cement content had lower stiffness.

(10) Mixture 100Tire_600 had low resistance to freeze/thaw cycling, but other rubberized mixtures showed an excellent resistance to freezing and thawing.

The following is a summary for the recommended practices for designing a CDOT Class P pavement concrete using tire chips:

(1) Tire chips can be used to replace coarse aggregate in concrete pavement mixtures. Mixture 10Tire_660 had the best performance among all rubberized concrete mixtures. It’s recommended to pretreat the surfaces of the rubber particles in order to enhance the adhesion between the cement paste and the rubber particles.

(2) All mixtures had low slumps in this study. It’s recommended to optimize the mixture design to improve the workability of the rubberized concrete mixtures, e.g. incorporation of fly ash in rubberized concrete mixtures.

(3) The mixtures with 570 lbs./cy. cement had lower strengths at the 28 days of age. It’s recommended to use 660 lbs./cy. or more cement and not reduce the cement content for the rubberized concrete.

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