UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

THE PERFORMANCE OF CONCRETE CONTAINING HIGH VOLUMES OF RECYCLED MATERIALS FOR USE IN PAVEMENT APPLICATIONS

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

LEXIS D. ALLEN
Norman, Oklahoma
2017

THE PERFORMANCE OF CONCRETE CONTAINING HIGH VOLUMES OF RECYCLED MATERIALS FOR USE IN PAVEMENT APPLICATIONS

A THESIS APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY

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Acknowledgements

I could not have finished my accelerated master's degree and the completion of this thesis without the help and support from so many wonderful people.

Firstly, I would like to express my deepest appreciation towards Dr. Jeffery Volz, my advisor and dear friend. He spent countless hours mentoring me in areas of research and life in general; he was always equipped to eliminate stress and confusion with encouraging words; he always believed in me, but he was especially supportive when I did not believe in myself. I count it a great blessing to have been impacted by his kindness.

Secondly, I would like to give a huge thanks to the research team who helped me in the lab. Jon Drury, Trevor Looney, Amy Crone (now Amy McDaniel – congrats!), Rex McLauchlin, CJ Alsenay, and Mitchell Gordon – each one gave their valuable time. They offered knowledge and showed support in their unique, individual ways.

Thirdly, I must mention the wonderful support and understanding from my work family at Poe & Associates, Inc. My boss and colleague always offered flexibility with a smile; my coworkers frequently showered me with words of encouragement followed by positive words for the future.

Lastly, I would like to express my sincerest gratitude for the support, love, and encouragement from my biological family as well as my church family. There were countless pep talks, free meals, many hugs, and emergency "therapy" sessions all in the name of boosting my morale. Never could I have accomplished what I have without them; I am exceedingly blessed.

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Abstract

America's roadway system is in need of a more sustainable, efficient, and innovative plan to improve the condition if its infrastructure. As a possible solution, this research focuses on using recycled concrete aggregate and waste by-products to not only provide a structurally sound system but also decrease cost and increase sustainability, all while diminishing negative environmental impacts.

A variety of tests were performed in order to determine the success of a possible solution. Typical aggregate tests were performed on each aggregate used (sand, coarse #57 rock, recycled coarse concrete aggregate, recycled fine concrete aggregate) and compared to Oklahoma Department of Transportation (ODOT) Class A standards. Upon meeting ODOT's standards, the coarse aggregates were tested for texture and angularity. After aggregate testing was complete, a series of four mix designs were developed. The first mix design, Series No. 1, varied only the percentage of recycled concrete aggregate used to replace coarse #57 rock. The second mix design, Series No. 2, varied only the percentage of fly ash used to replace cement. Series No. 3 varied the percentage of recycled concrete aggregate (which replaced coarse #57 rock) and varied the percentage of fly ash (which replaced cement). The final mix, Series No. 4, varied the percentage of recycled fine aggregate in place of sand. Series Nos. 1 through 3 were studied extensively, focusing on fresh and hardened concrete properties and behaviors. Series No. 4 was essentially studied for workability data and strength results.

Results from this research prove that concrete containing high volumes of recycled materials can meet ODOT Class A strength requirements. More study is required to determine the durability of sustainable concrete.

1 Introduction

The following chapter will introduce the reasons for investigating the performance of concrete containing high volumes of recycled materials in pavement applications. It also includes a discussion of the scope, objectives, and goals of this research study as well as providing an outline of this thesis.

1.1 Background and Justification

One popular subject that repeatedly makes its way into every-day discussion is the state of America's roads. Every four years, The American Society of Civil Engineers performs and publishes a study that describes, via letter grade, the condition of each states' roads as well as a nation-wide grade. The 2017 report card for America's infrastructure was given a letter "D" grade, which in words means "poor, at risk." The report reads, "state and local governments have reconsidered road materials… converting from asphalt to gravel." Additionally, "at least 27 states have de-paved their roads, especially in the last 5 years."

Another article (Ingraham, 2015) further explains that the poor condition of America's major roadways increases the cost of living by $515 for the average American driver. For Oklahomans, the increased cost of wear on the vehicle is $760 per driver. This additional expense covers general wear and tear of the vehicle due to ruts, cracks, and potholes.

It is clear that there is a shortage of money to replace a majority of America's roadway system but there is undeniably a need. America's roadway system is in need of a more sustainable, efficient, and innovative plan to improve the condition if its infrastructure. As a possible solution, this research focuses on using recycled concrete aggregate and waste by-products to not only provide a structurally sound system but also decrease cost and increase sustainability, all while diminishing negative environmental impacts.

Concrete is the most popular building material used across the globe. For infrastructure, concrete pavement makes up a considerable portion of the interstate, highway, and local roadway system. Figure 1.1 is a detailed diagram which demonstrates the process of obtaining cement, the major ingredient in concrete.

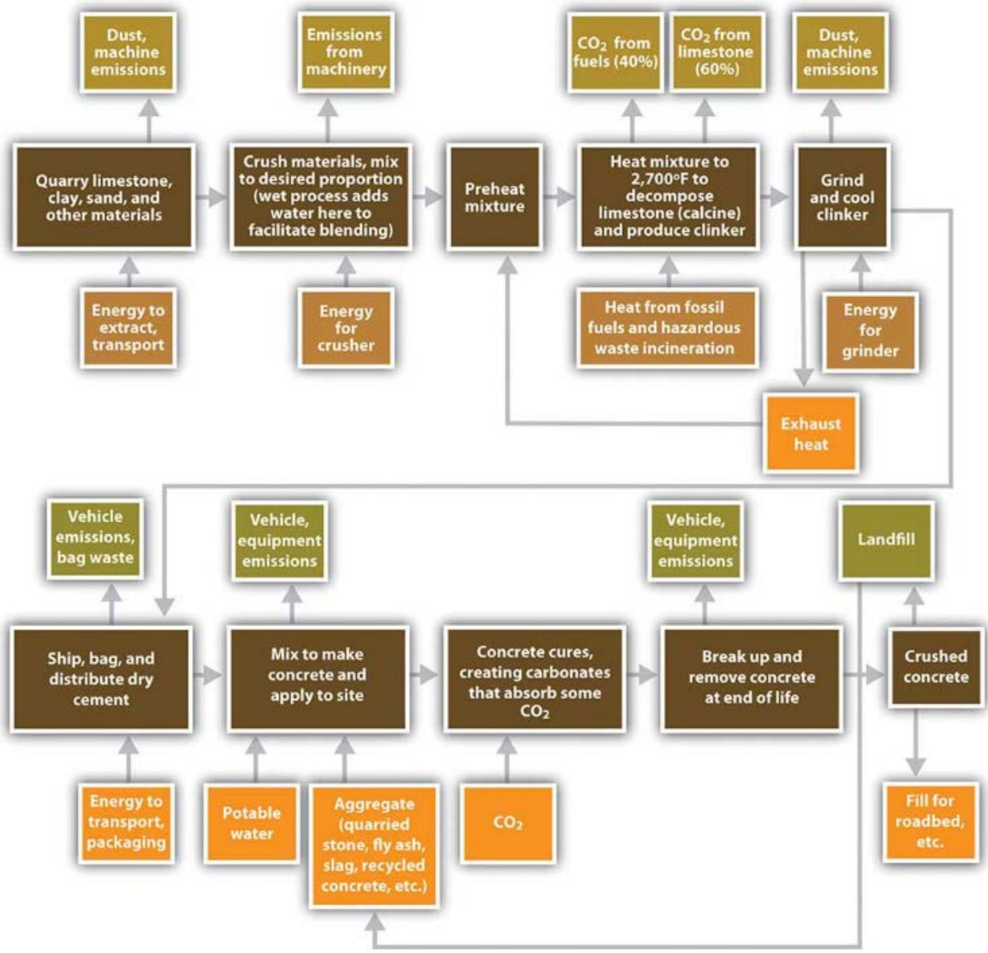

Figure 1.1 Environmental Impacts of Concrete Production by Phase (Pamphilon, 2004)

1.1.1 Greenhouse Gas Emissions

As Figure 1.1 describes, cement production starts by first exhausting natural resources from quarries. The mined limestone and shale becomes a very fine powder after much manipulation and exerted energy. The energy used for crushing the rock and refining the powder is a major leading cause in the world's greenhouse gas emissions. The ever-growing demand of concrete, and therefore cement production, accounts for approximately five percent of the earth's annual greenhouse gas emissions (Chemistry World, 2008).

1.1.2 Diminishing Natural Resources

The poor condition of America's roadway system will only increase the demand for concrete as time goes on. As such, the components of concrete will be greatly exhausted. Concrete is made of fine aggregate, coarse aggregate, water, and cement. The Federal Highway Administration (FHWA) reported in 2008 that two billion tons of aggregate per year are produced, and this is expected to increase to two and a half billion tons of aggregate per year by 2020 (Volz, 2014).

1.1.3 Overuse of Disposal Sites

Due to the ever-present need for pavement rehabilitation and replacement of America's roads, the disposed concrete must have a residing place post-extraction. Landfills are typically the chosen location if there exists no other reason to reuse the old concrete. According to FHWA, the annual amount of wasted concrete is approximately 123 million tons (Volz, 2014). An increase in the amount of concrete wasted is also predicted.

1.2 Project Scope

This research focuses on ways to create more sustainable concrete for pavement applications. Specifically, a more sustainable mix design will be investigated by incorporating high volumes of recycled materials like, firstly, recycled concrete aggregate in place of virgin aggregate and, secondly, fly ash replacing a portion of the cement.

1.3 Objectives and Goals

1.3.1 Objectives

The objective of this research is to provide a guideline for material selection and optimization of high volumes of recycled materials for use in concrete pavement. In order to provide such guidelines, certain objectives will be investigated:

a. Ensure recycled aggregate used meets industry standards
b. Evaluate fresh concrete properties
c. Evaluate hardened concrete properties
d. Evaluate the durability of various mixes

1.3.2 Goals

The goal of this research is to improve the state of the environment by decreasing negative impacts of concrete production as well as provide a durable concrete material.

1.4 Outline

This thesis consists of seven chapters. Chapter 1 contains a brief background and justification for the study as well as the scope, objectives, and goals of the research.

Chapter 2 provides a summary of the relevant literature on the need for sustainable options, properties of recycled concrete aggregate (RCA) and fly ash, as well as properties of concrete containing those two waste products.

Chapter 3 outlines the testing and summarizes the results for the aggregates used to develop the concrete mixtures evaluated during this study. Chapter 4 details the mix designs that were developed for this study based on replacing the virgin aggregate and cement from traditional concrete mixes. Chapter 5 investigates the effect of the RCA fines on the behavior of various concrete mixes.

Chapter 6 discusses the durability tests performed on several candidate mixes containing combinations of recycled materials. Then, Chapter 7 summarizes the findings, conclusions, and recommendations of this research study.

2 Literature Review

2.1 Introduction

The following chapter contains a review of literature applicable to this research study. The topics investigated include sustainability, properties of concrete containing recycled aggregate (RCA), properties of concrete containing fly ash, and properties of concrete containing both RCA and fly ash, and durability of concretes containing RCA or fly ash.

2.2 Need for Sustainability

Communities all over the world recognize concrete as the most valuable and popular building material. In fact, it accounts for approximately five percent of the earth's annual greenhouse gases due to such a high demand (Chemistry World, 2008). The biggest component of concrete production that leads to such staggering carbon dioxide release is cement. It is intuitive that the Earth's growing human population will contribute to new facilities, some being structures and some being infrastructure. However, possibly not so obvious, rehabilitation projects of pavement systems and bridges also play a key role in rising concrete demand. Therefore, as concrete demand increases, so increases the demand of cement. Figure 2.1 graphically shows the rapid increase in cement production between the years 1926 and 2000.

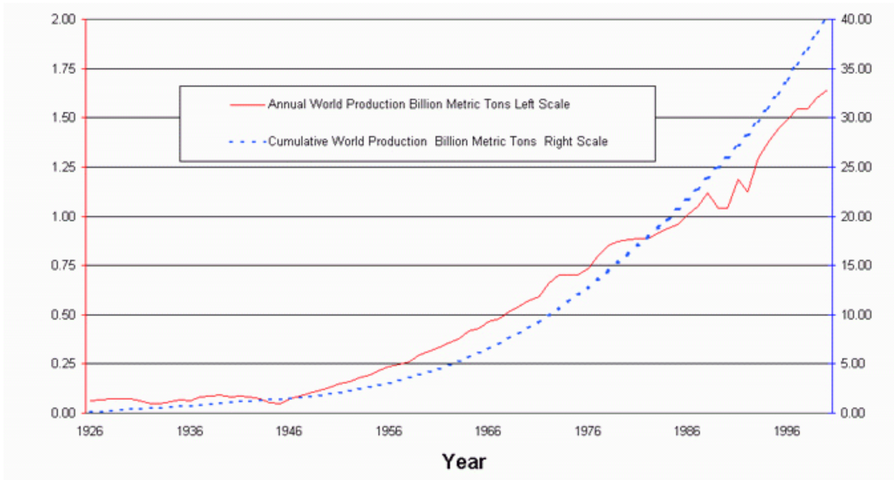

Figure 2.1 World Cement Production 1926-2000 (Pamphilon, 2004)

2.2.1 Exhausted Resources

Concrete is composed of cement, coarse aggregate, fine aggregate, and water. Of those, coarse aggregates and fine aggregates are extracted from natural sand pits or quarries. According to the Portland Cement Association, forty-one percent of a typical concrete mix design is coarse aggregate or crushed stone and twenty-six percent is fine aggregate or sand. Federal Highway Administration (FHWA) released in 2008 that two billion tons of aggregate are produced each year. This number is expected to increase to two and a half billion by 2020 (Volz, 2014). Therefore, increased demand of concrete production overly exhausts the natural resources currently available. The world is in desperate need of an alternative concrete mix design that preserves the world's resources while also providing good-quality concrete.

2.2.2 The Landfill Over Use

When concrete is demolished and, if not recycled, disposed of, it takes its place in a landfill. FHWA estimates that the annual amount of concrete waste is 123 million tons (Volz, 2014). If the demand of concrete continues to increase exponentially, concrete waste disposal will become a significant problem if concrete reuse does not quickly become the alternate solution.

2.2.3 Environmental Impact of Concrete

Growing populations of impactful countries like India and China and their growing needs for more infrastructure, more buildings, and more infrastructure maintenance all lead to a growing need for industrial processes and increasing construction demand. On an international level, building construction consumes approximately 25% of global annual wood harvest; 40% of stone, sand, and gravel; and 16% of water. Additionally, 50% of the global output of greenhouse gases are generated by building construction (Joseph and Tretsiakova-McNally, 2010). This means that in order to decrease greenhouse gases, a more sustainable approach to construction processes, with cognizant awareness of energy consumption, is a key component to decrease global emissions and preserve the world as we know it. Areas such as treatment and production of raw materials, construction processes, and demolition and disposal are all easy targets for decreasing the negative environmental impacts. The use of high volumes of recycled materials specifically in pavement applications is an approach that appeals to most all of the aforementioned areas of consideration.

2.3 Recycled Concrete Aggregate Properties

Recycled concrete aggregate (RCA) is produced by crushing in-place concrete, reclaiming coarse aggregate. However, the reclaimed coarse aggregate is not in the same condition as it once was when incorporated into the mix as virgin coarse aggregate. The properties of RCA often vary from traditional virgin aggregate sources. As such, it only makes sense that the physical and mechanical characteristics of concrete containing recycled materials would perform differently compared to concrete containing virgin, or non-recycled, aggregate. One key note regarding the properties of recycled concrete aggregate is this: recycled concrete aggregate is hardly consistent. This will be discussed in further detail in the following subsections.

2.3.1 Microstructure

The differences in RCA's microstructure versus virgin coarse aggregate is part of the reason why the mechanical and physical properties of concrete containing RCA differs from all virgin coarse aggregate concrete. When concrete comprised of only virgin aggregate is mixed, the bonding that occurs between the aggregate and the mortar – comprised of sand, water, and cement – is called the interfacial transition zone (ITZ). Conventional concrete has one ITZ.

The ITZ of conventional concrete is formed while the fresh concrete is being mixed. The cement particles are suspended in water, which decreases their ability to efficiently consolidate if in the presence of an aggregate particle such as a coarse rock. While mixing, the shear stresses of the large aggregates exacerbate this phenomenon, causing the water to separate from the cement particles that surround the larger aggregates (Thomas and Hamilin, 2008). Therefore, the small region surrounding the larger aggregates contains fewer cement particles, more air pockets, and is consequentially weaker.

Concrete containing recycled aggregates has two ITZ zones – one of which is between the recycled aggregates and the old mortar, and the second zone is between the RCA and the new mortar. Figure 2.2 shows an annotated, close-up view of concrete with RCA.

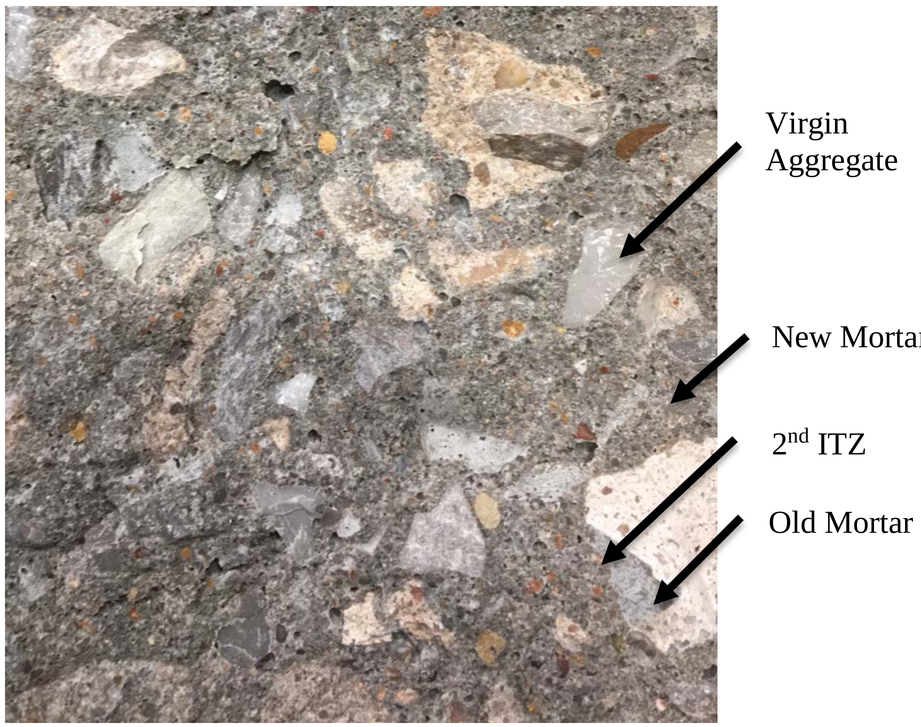

Figure 2.2 Microstructure of RCA Concrete

The larger the particle, the larger the ITZ. In the same vein, increasing the number of large particles also increases the total percentage of the concrete that is in the ITZ. Since RCA is generally larger than virgin aggregate, due to the old mortar that encapsulates the recycled aggregate, the ITZ is larger than in conventional concrete. Therefore, the concrete is typically weaker because of the two interfacial transition zones. Simply put, there are additional planes of weakness in the RCA concrete because of the double ITZ.

2.3.2 Fresh Concrete Properties

Fresh concrete properties include slump characteristics, air content percentages, unit weight, workability, and finishability.

Slump is affected by a few different qualities. RCA is manufactured by grinding up demolished concrete. The virgin coarse aggregate found in the demolished concrete is not restored to its original shape. Rather, the virgin coarse aggregate is left with various depths of dried mortar surrounding the exterior surface. It is in this state that the once virgin aggregate is termed “recycled coarse aggregate” or “recycled concrete aggregate.” Figure 2.3 depicts an up-close comparison of what virgin coarse aggregate and RCA looks like prior to mixing. From the figure, it is easy to recognize that RCA has more rounded edges than the virgin coarse aggregate. This is due to the dried mortar on the surface of the recycled aggregates. Additionally, Figure 2.3 shows the difference in surface texture – virgin aggregate’s texture appears to be smooth while RCA’s texture is rough. This difference in texture is the single-most important reason for decreased slump of fresh concrete containing RCA.

Figure 2.3 Up-Close Comparison of Virgin Coarse Aggregate (left) and RCA (right)

The air content of fresh concrete with large percentages of recycled aggregate yields a higher percentage compared to concrete containing virgin aggregate. This phenomenon is also caused by the variability in dried mortar depth surrounding RCA's surface. The dried mortar is rough because it houses air pockets that create disturbances in the texture. Furthermore, those same air pockets cause the air content to generally be higher in concrete containing RCA. The inconsistency of dried mortar depth causes tremendous variability in the air content of each batch of concrete. Nonetheless, the air content is always higher for concrete with recycled aggregates.

The unit weight of concrete with RCA is typically found to be within 85-95% of virgin aggregate concrete (Obla et. al, 2007). Workability suffers as RCA replacement percentages increase. This is due to the dried mortar's surface roughness and air pockets that absorb significant water from the mix. Additionally, finishability suffers due to the same reasons.

2.3.3 Hardened Concrete Properties

The compressive strength of RCA concrete is typically found to be less than concrete with virgin aggregate, depending on the percentage of RCA replacement. McNeil stated that factors like water-cement ratio, RCA replacement percentage, and depth of residual mortar surrounding RCA affects the compressive strength of RCA concrete (McNeil, 2013). The quality of RCA also affects the compressive strength up to 25% (Hansen, 1986). Salau et al. realized that compressive strength was jeopardized because of the residual mortar's low strength. The same authors continued by attributing this occurrence to a low specific gravity and high absorption/porosity of RCA (Salau et al., 2014). Concrete is only as strong as its weakest link. In the case of RCA, the weakest link comes down to either the first or second ITZ.

According to a study performed by Purdue University in 2013, mixes containing 30 to 50 percent of recycled concrete aggregate had noticeably higher compressive strengths than 100 percent RCA replacement. In the same study, it was found that optimal RCA replacement is at 30 percent. The separate studies performed by Volz (2014) and Andal et al. (2016) also concur with 30 percent being the maximum RCA replacement percentage without negatively affecting the response and behavior of the concrete.

Tensile and flexural strength of RCA concrete is generally observed to be less than conventional concrete. According to one author, "a reduction of up to 10% in split tensile strength was observed when virgin aggregate was substituted with recycled aggregate" due to the dependence on binder quality rather than type of recycled aggregate (Yehia et al., 2015). The results of RCA on flexural strength are varied. Some studies show that the flexural strength can be reduced by 10% of virgin aggregate concrete, while other studies show that the presence of RCA does not affect flexural strength (Malešev et al., 2010).

Shear strength of recycled aggregate concrete has been directly correlated with the tensile strength of the concrete in structural applications. It has been observed that the decrease in tensile strength results in a lower shear strength between the recycled aggregate particles and the virgin aggregate particles (Ceia et al., 2016). Therefore, as the ratio of recycled aggregate to virgin aggregate increases, it is understood that the tensile strength, and thus shear strength, decreases. The research group at Missouri University of Science and Technology found supportive results. According to their results, the shear strength of beams made of recycled aggregate concrete was less than conventional concrete beams (Arezoumandi et al., 2014). There is still an obvious need for further study of recycled aggregate concrete behavior.

2.4 Fly Ash Properties

Fly ash is the product that results from burning coal. Since it is common knowledge that the burning of coal produces a large percentage of electrical power, it is intuitive that the amount of fly ash produced is an equally large quantity. The National Precast Concrete Association sponsored an article that describes how fly ash is produced: “Fly ash is captured with electrostatic precipitators, scrubbers or filter fabric baghouses in power plants, then sluiced to settling basins (wet) prior to disposal or stored in silos (dry) for sale or disposal.” Fly ash has become the earth’s largest industrial waste byproduct (McCraven, 2013). Figure 2.4 shows the amount produced and use of fly ash based on 2001 statistics.

Table 2.1 Fly Ash Production and Use (FHWA, 2001)

	Million Metric Tons	**Million Short Tons**	**Percent**
Produced	61.84	68.12	100.0
Used	19.98	22.00	32.3

Fly ash is a very fine powder, and the particles are similar to very small ball bearings. Figure 2.5 shows a close-up view of fly ash particles. Fly ash has high silica content and forms calcium silica hydrate by reacting with lime, which produces a cementitious material. Because of the calcium, silica, alumina, and iron content in the ash, it has been proven to be a good replacement for cement in concrete mix designs.

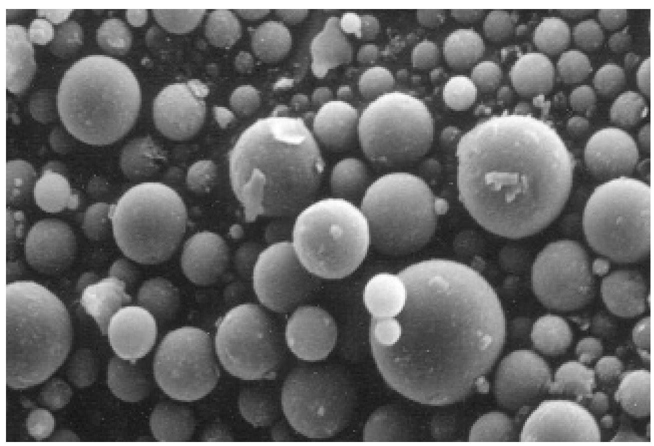

Figure 2.4 Fly Ash Particles at 2000x Magnification (FHWA, 2001)

2.4.1 Fresh Concrete Properties

Fresh concrete properties like slump and air content are affected by the presence of fly ash in a concrete mix design. Due to the spherical shape of fly ash's particles and the ball bearing-like behavior, the slump is increased and the workability is improved. The presence of fly ash also reduces the water demand (Naik and Ramme, 1990). When fly ash is used with portland cement, some of the lime in the cement becomes free and reacts with the fly ash. The result is an additional, improved cementitious material (FHWA, 2001).

Air content of concrete with any amount of fly ash is usually higher than the air content for conventional concrete. The particle structure causes the workability to increase, therefore causing the paste to entrap air as it has less resistance to movement. In fact, concrete made with fly ash has a lower unit weight than conventional concrete. This lower unit weight contributes around 30% more cementitious paste per pound (Fly Ash for Concrete, 2014). Additionally, since the fly ash itself is made from burning coal, there are sometimes small portions of unburned carbon (Hill et al., 2006). Increased carbon content in the fly ash causes an increase in reaction with the air entraining admixtures, which causes a flux in the overall air content of the concrete mix. Concrete containing fly ash needs more air entrained admixtures compared to conventional concrete.

2.4.2 Hardened Concrete Properties

The percentage of fly ash replacement is a key factor in identifying the hardened concrete properties. As the percentage of fly ash replacement increases, the early-age strength decreases (Thomas, 1987). However, as the age of the concrete increases, the strength of concrete containing up to 50% fly ash replacement exceeds the compressive strength for conventional concrete, as shown in Figure 2.6.

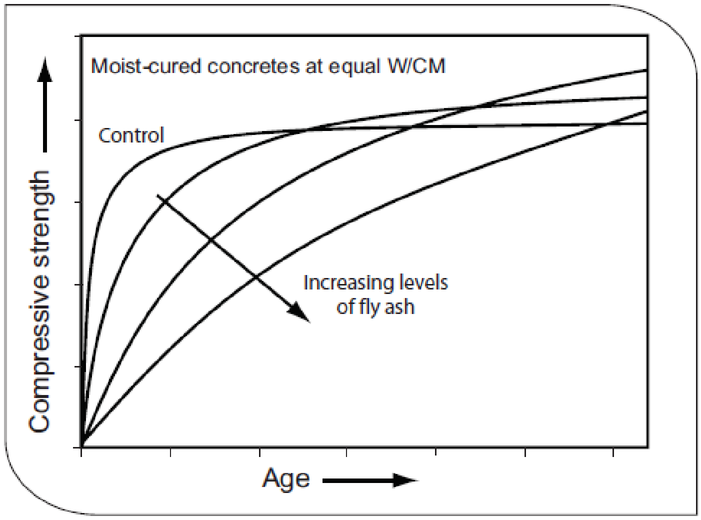

Figure 2.5 Compressive Strength of Fly Ash Concrete vs. Age (Thomas, 1987)

The presence of fly ash has been proven to not affect tensile strength, flexural strength, or the elastic modulus at low or moderate levels of fly ash replacement (Thomas, 1987). However, after a minimum of 28 days, concrete containing fly ash has been proven to have a higher modulus of elasticity due to unreacted fly ash particles that act as fine aggregate (Malhotra, 2005). Additionally, "long-term flexural and tensile strength of high-volume fly ash concrete may be much improved due to the continuing pozzolanic reaction strengthening the bond between paste the aggregate (Thomas, 1987)."

2.5 Properties of Recycled Concrete Aggregate and Fly Ash Combined

2.5.1 Fresh Concrete Properties

Sinhgad College of Engineering performed a study on the effects of recycled aggregate and fly ash in concrete in 2015. Their scope included the effects of coarse aggregate replacement with recycled aggregate, cement replacement with fly ash, and the combination of the two. Their results indicated that increasing the amount of RCA reduces the workability of the concrete; increasing the amount of fly ash improves the workability; and, therefore, the combination of the two is nearly comparable to the workability of conventional concrete when 30% of RCA and 30% of fly ash is in the mix (Bajad, 2015).

Other studies show that fresh concrete properties for mixes containing both RCA and fly ash are highly variable and inconsistent. Improving some of the deficiencies can be accomplished by proper selection and grading of recycled materials (Sagoe-Crentsil et al., 1998).

2.5.2 Hardened Concrete Properties

Students at North Carolina A and T State University performed in 2011 hardened concrete tests on concrete containing 25% RCA replacement and varying amounts of fly ash replacement. Their results indicated that concretes containing only 25% RCA replacement had lower compressive strengths than conventional concrete. However, with increasing amounts fly ash, the students found that compressive strength was steadily higher than even conventional concrete strengths (James et al., 2011).

The flexural and tensile strengths were found to be less than conventional concrete no matter what percentage of RCA and/or fly ash was used in the mix. The same students also found that the elastic modulus was slightly less than conventional concrete for all mixes containing any percentage of RCA and/or fly ash.

2.6 Effect of Recycled Fines

Part of the complication of using recycled coarse aggregate in concrete is the effect of the fines that are attached to the surface of large, coarse aggregate. The presence of fines has been noted to decrease workability due to increased water absorption and angularity of the small particles (Andal et al., 2016). Additionally, recycled fine aggregates have been proven to decrease the compressive strength (Yehia et al., 2015). In fact, "reduction is reported to be between 5% and 24% when just coarse RCA was used and between 15% to 40% when all of the RCA (including fine fraction) was used. Strength reduction becomes more significant when the fines RCA content surpasses 60% of the total fine aggregate" (Obla et al., 2007).

2.7 Durability

2.7.1 Recycled Aggregate Concrete

The nature of recycled coarse aggregate has been previously discussed and revealed to have large portions of void space and air pockets due to the inconsistent depth of dried mortar surrounding the coarse aggregate. This highly-variable depth causes inconsistent air content. Once tested in environmental chambers that simulate several freezing and thawing cycles, the air pockets fill with water, expand, and continually deteriorate the concrete. Thus, the durability of recycled coarse aggregate generally suffers compared to conventional concrete (Yehia et al., 2015).

2.7.2 Fly Ash Concrete

The durability of concrete is directly affected by permeability. Fly ash has a low permeability rate. The pozzolanic activity requires a strong bond between the paste and the aggregates, which fills all capillaries and water channels (Fly Ash for Concrete, 2014). Therefore, fly ash has a high resistance to water penetration and is resistant to rapid deterioration.

2.7.3 RCA and Fly Ash Concrete

The variability of air content and void space for recycled coarse aggregate makes it difficult to predict the concrete's resistance to deterioration when exposed to harsh environments and requires further study.

3 Aggregate Testing

3.1 Introduction

The aggregates used in this research were river sand, #57 crushed stone, and recycled concrete aggregate. This chapter discusses the testing and evaluation of these aggregates. Dolese Bros. Co. located in Oklahoma City, Oklahoma, provided the river sand and #57 rock. Metro Materials, a material supply company in Norman, Oklahoma, provided the recycled concrete aggregate.

3.2 Aggregate Testing

All aggregates were tested in accordance with American Society for Testing and Materials (ASTM) standards. Five tests were performed on coarse and fine aggregates in order to later ensure high-quality concrete that would be composed of such acceptable aggregates. The five aggregate tests performed were dry rodded unit weight (DRUW), density and absorption for both fine and coarse aggregates, abrasion resistance, and a sieve analysis for both fine and coarse aggregates. Table 3.1 presents the traditional tests and associated ASTM standards used in this study.

3.3 ODOT Specifications

In order for the tests described in Table 3.1 to be acceptable, all results must comply with ODOT 2009 Specifications, which is the latest publication and current standard. The requirements listed in the ODOT 2009 specifications are applicable to many areas of interest. However, for this research, the requirements for aggregates, materials, fresh and hardened concrete properties, and strength requirements are most relevant for the scope of this research.

Table 3.1 Aggregate Tests and ASTM References

Aggregate Property	**ASTM Reference**	**Description**
Dry Rodded Unit Weight	ASTM 29	Bulk density and air voids
Density and Absorption	ASTM C 127	Density, specific gravity, and absorption for coarse aggregate
Density and Absorption	ASTM C 128	Density, specific gravity, and absorption for fine aggregate
Abrasion Resistance	ASTM C 131	Resistance to degradation of small-size coarse aggregate by abrasion and impact in Los Angeles Machine
Sieve Analysis	ASTM C 136	Sieve analysis of fine and coarse aggregates fineness modulus

ODOT requires that all aggregates, within the appropriate aggregate size category, fall within a range of acceptable upper and low boundary percentages. Tables 3.2 and 3.3 denote the ranges for all coarse aggregate and fine aggregate sieve sizes, respectively. Figures 3.1 and 3.2 are aggregate gradation plots using the upper and lower bounds provided in Tables 3.2 and 3.3, respectively.

Table 3.2 ODOT Range for Acceptable Coarse Aggregate Gradation

Sieve Size/No.	Sieve Opening (mm)	Percent Passing, Lower Bound	Percent Passing, Upper Bound
1.5”	37.5	100%	100%
1”	25	95%	100%
1/2”	9.5	25%	60%
#4	4.75	0%	10%
#8	2.36	0%	5%
#200	0.075	0%	2%

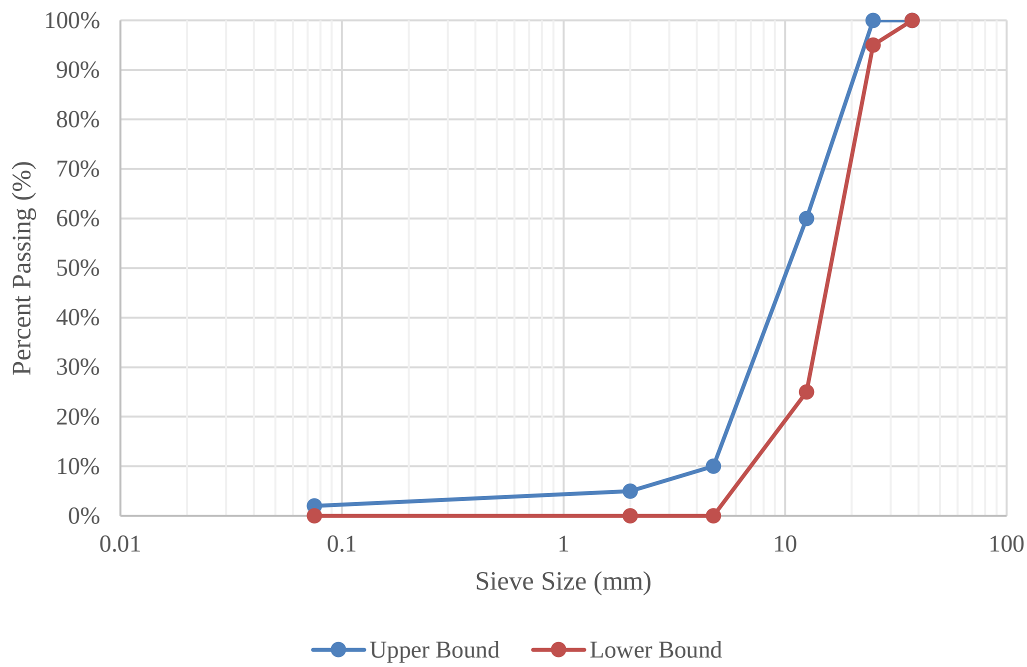

Figure 3.1 Acceptable ODOT Coarse Aggregate Range

Table 3.3 ODOT Range for Acceptable Fine Aggregate Gradation

Sieve Size/No.	Sieve Opening (mm)	Percent Passing, Lower Bound	Percent Passing, Upper Bound
3/8”	9.5	100%	100%
#4	4.75	95%	100%
#8	2.36	80%	100%
#16	1.18	50%	85%
#30	0.6	25%	60%
#50	0.3	5%	30%
#100	0.15	0%	10%
#200	0.075	0%	3%

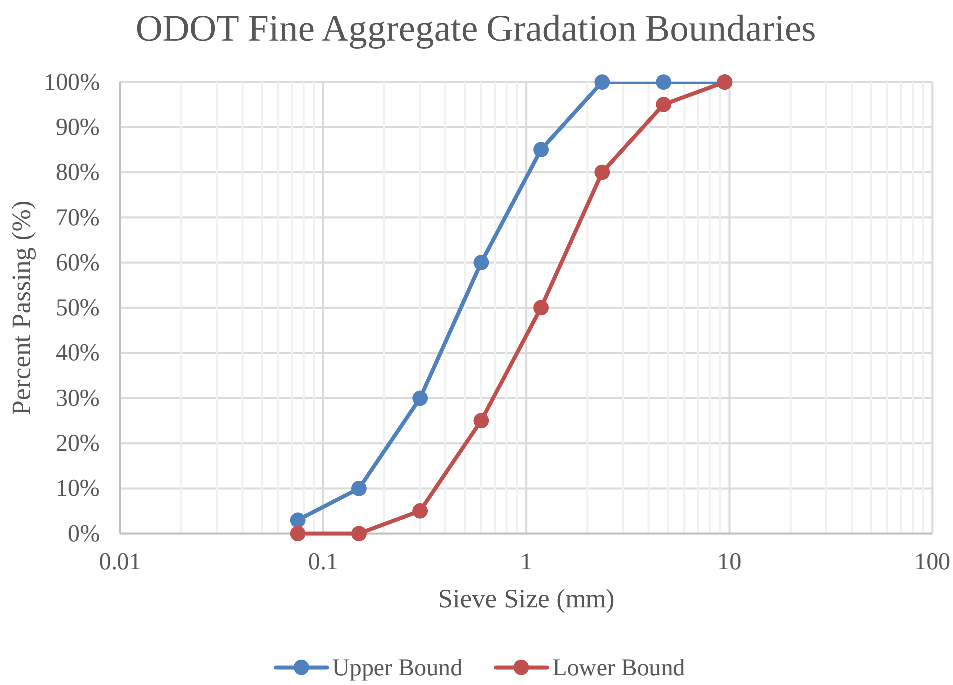

Figure 3.2 Acceptable ODOT Fine Aggregate Range

3.4 Aggregate Testing Results

The following tables and figures present the results of the aggregate tests listed in Table 3.1. Table 3.4 and Figure 3.3 indicate the gradation results for the #57 rock. Table 3.5 and Figure 3.4 indicate the gradation results for the river sand. Table 3.6 and Figure 3.5 indicate the gradation results for the coarse RCA. Table 3.7 and Figure 3.6 indicate the gradation results for the fine RCA. Figures 3.3 thru 3.7 also include the upper and lower bounds contained within the ODOT Specifications (2009). Finally, Table 3.8 indicates the specific gravities, dry-rodded unit weights, absorptions, and abrasion results for the #57 rock, river sand, and RCA coarse and fine aggregates.

Table 3.4 #57 Rock Gradation

Sieve Size/No.	Sieve Opening (mm)	ODOT Lower Bound	Percent Passing	ODOT Upper Bound
1.5"	37.5	100%	100.0%	100%
1"	25	95%	99.3%	100%
1/2"	12.5	25%	69.0%	60%
#4	4.75	0%	1.3%	10%
#8	2	0%	0.5%	5%
#200	0.075	0%	0.0%	0%

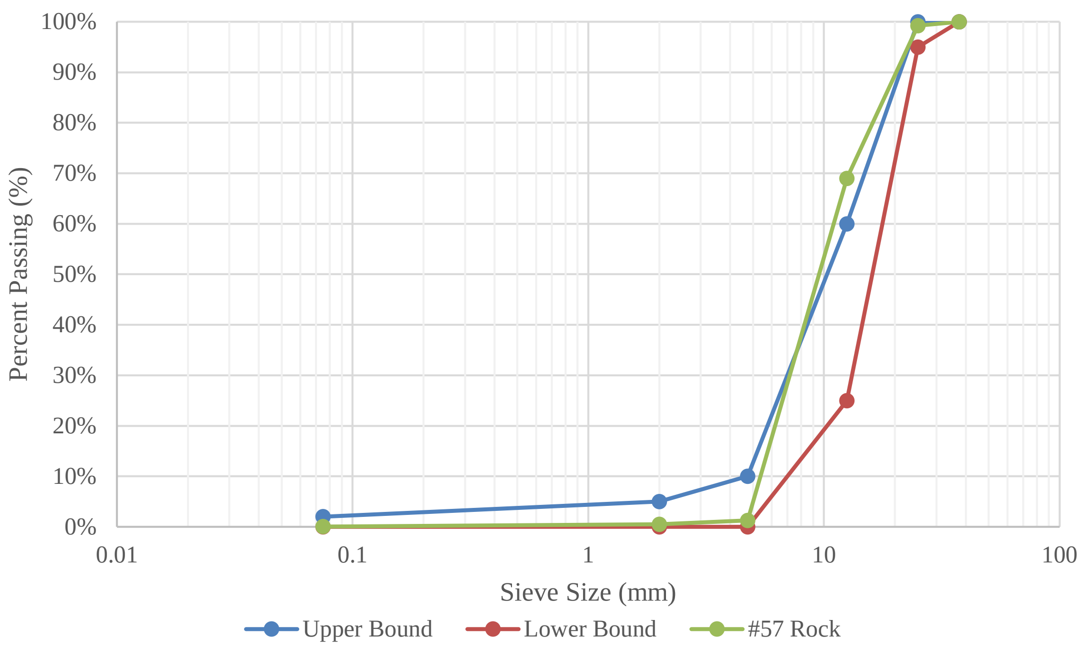

Figure 3.3 #57 Rock Gradation with ODOT Boundaries

Table 3.5 River Sand Gradation

Sieve Size/No.	Sieve Opening (mm)	ODOT Lower Bound	Percent Passing	ODOT Upper Bound
3/8”	9.5	100%	100%	100%
#4	4.75	95%	99%	100%
#8	2.36	80%	95%	100%
#16	1.18	50%	80%	85%
#30	0.6	25%	47%	60%
#50	0.3	5%	14%	30%
#100	0.15	0%	2%	10%
#200	0.075	0%	0%	3%

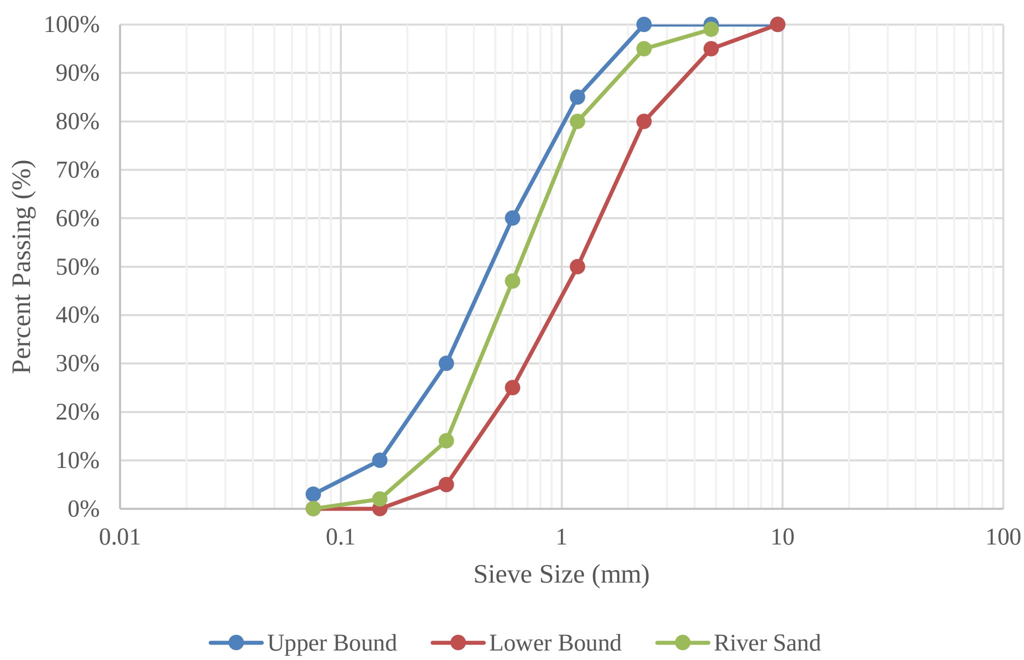

Figure 3.4 River Sand Gradation with ODOT Boundaries

Table 3.6 Recycled Concrete Aggregate Coarse Gradation

Sieve Size/No.	Sieve Opening (mm)	ODOT Lower Bound	Percent Passing	ODOT Upper Bound
1.5"	37.5	100%	100.0%	100%
1"	25	95%	84.9%	100%
1/2"	12.5	25%	35.4%	60%
#4	4.75	0%	4.9%	10%
#8	2	0%	3.4%	5%
#200	0.075	0%	0%	0%

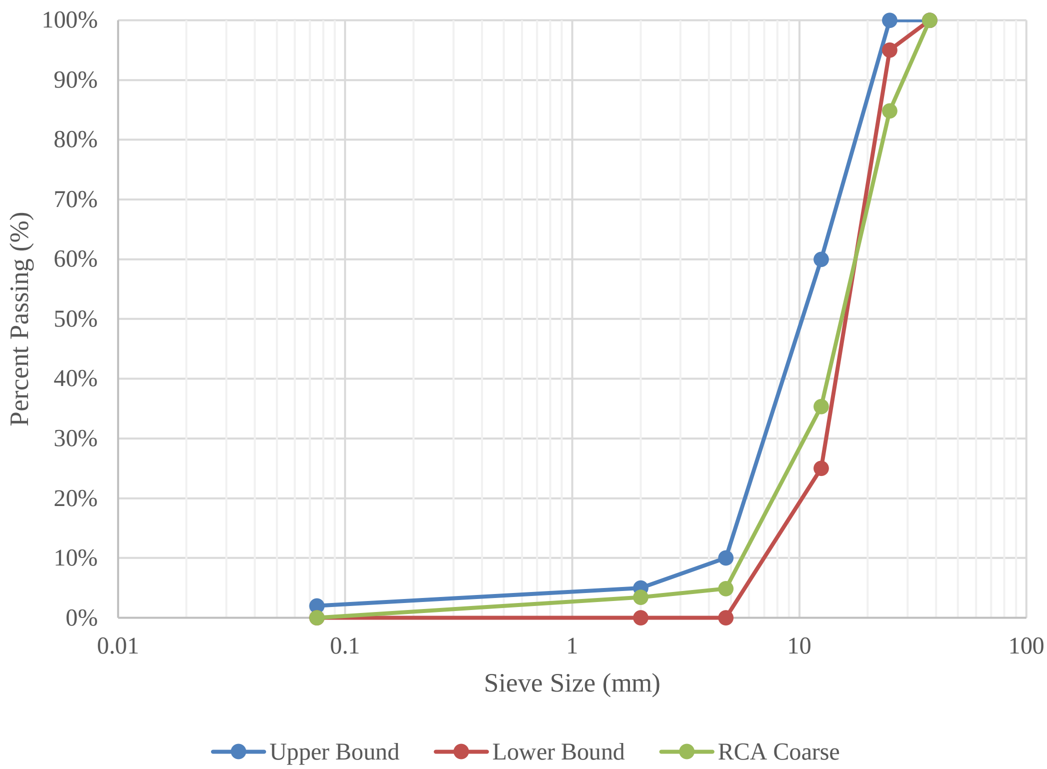

Figure 3.5 Gradation Curve for RCA Coarse

Table 3.7 RCA Fines Gradation

Sieve Size/No.	Sieve Opening (mm)	ODOT Lower Bound	Percent Passing	ODOT Upper Bound
3/8”	9.5	100%	100%	100%
#4	4.75	95%	100%	100%
#8	2.36	80%	80%	100%
#16	1.18	50%	60%	85%
#30	0.6	25%	40%	60%
#50	0.3	5%	21%	30%
#100	0.15	0%	9%	10%
#200	0.075	0%	5%	3%

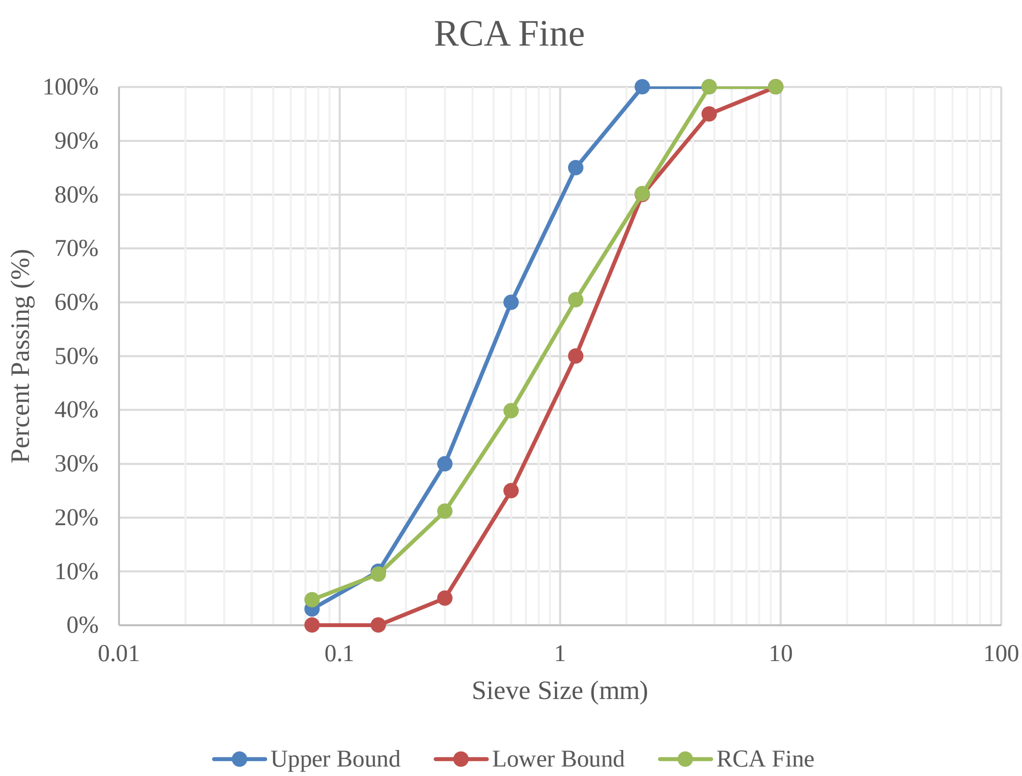

Figure 3.6 Gradation Chart for RCA Fines

Table 3.8: Aggregate Testing Results

Aggregate	Specific Gravity	DRUW (pcf)	Absorption (%)	LA Abrasion (%)
River Sand	2.58	-	0.40	-
Fine RCA	2.41	-	6.82	-
Limestone	2.64	101.5	0.86	24
Coarse RCA	2.38	91.5	4.27	37

3.5 Aggregate Imaging System

3.5.1 Introduction

The Aggregate Imagine System (AIMS) is a computer-automated video system that directly analyzes texture, angularity, and shape of both coarse and fine aggregates. Research done in the past has shown that there are repeatable trends when using the AIMS. Due to the more descriptive, rapid and automated nature of the AIMS, it is a valid replacement for several Superpave consensus property tests (FHWA, 2006). The Federal Highway Administration (FHWA) has published a short booklet that discusses the AIMS capabilities and outputs (FHWA, 2006). The booklet also defines ranges for each category (texture, angularity, and shape). The following subsection of Chapter 3 will briefly discuss the concepts of particle geometry.

Form, angularity (or roundness), and surface texture are all terms that completely describe an aggregate's particle geometry. Figure 3.7 depicts all three terms on one single aggregate. "Form, the first order property, reflects variations in the proportions of a particle. Angularity, the second order property, reflects variations at the corners, that is, variations superimposed on the shape. Surface texture is used to describe the surface distinguished because of their different scales with respect to particle size, and this feature can be used to order them" (FHWA, 2006).

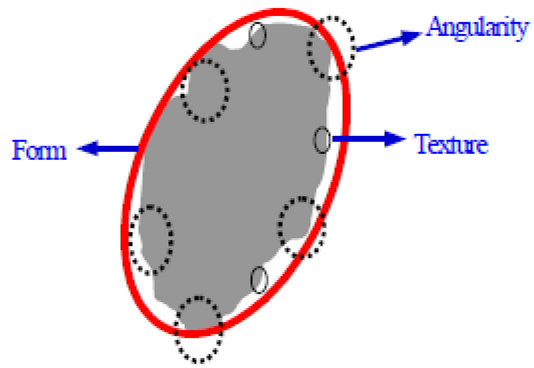

Figure 3.7 Aggregate Shape Properties (FHWA, 2006)

This research focuses mainly on the angularity and texture of recycled concrete aggregate in comparison to #57 coarse rock or limestone. The AIMS was used for both fine and coarse recycled concrete aggregate since AIMS has the ability to determine texture and angularity. Texture can be analyzed for aggregates ranging from 4.75 mm up to 37.5 mm, and angularity can be measured for particles ranging from 0.15 mm up to 4.75 mm in size. Aggregate angularity is determined by placing each aggregate on a glass grid that has backlighting used to create simple, black and white images, resulting in an easy way to calculate the aggregate's form.

The AIMS can measure texture for aggregates on the same grid. However, this calculation is more complicated and therefore has a wider range for miss-calculation and over conservatism. Instead of using backlighting underneath the glass grid, a top lighted ring mounted around the outside of the microscope lens is used. "The computer control system automatically adjusts the lighting intensity when using the top lighting scheme for dark verses light colored aggregates" (FHWA, 2006). The contrast of dark verses light colored aggregates, along with the computer's ability to determine the aggregate depth measurement, is how the texture index is calculated.

AIMS researchers and developers used the results from several investigations to create a cluster analysis approach, shown in Figure 3.8.

For this research, texture and angularity of three samples of recycled aggregate and three samples of limestone was analyzed using the AIMS machine.

3.5.2 AIMS RCA Texture Results

The AIMS can measure aggregate texture on a range from 0 to 800. FHWA states that a texture index value of 500 or above is typical for a highly rough aggregate. A texture index value of 150 or less is classified as polished aggregate. Figure 3.9 shows the overall output values for RCA particles analyzed for texture. For comparison purposes, gravel has an average texture index value of 148 and limestone has an average texture index value of 187 according to FHWA.

Texture	
Total Particles	168
Average:	148.1
Std. Deviation	49.8
Median	137.0
Mode	129.5

Figure 3.8 AIMS Overview of RCA Particles Analyzed

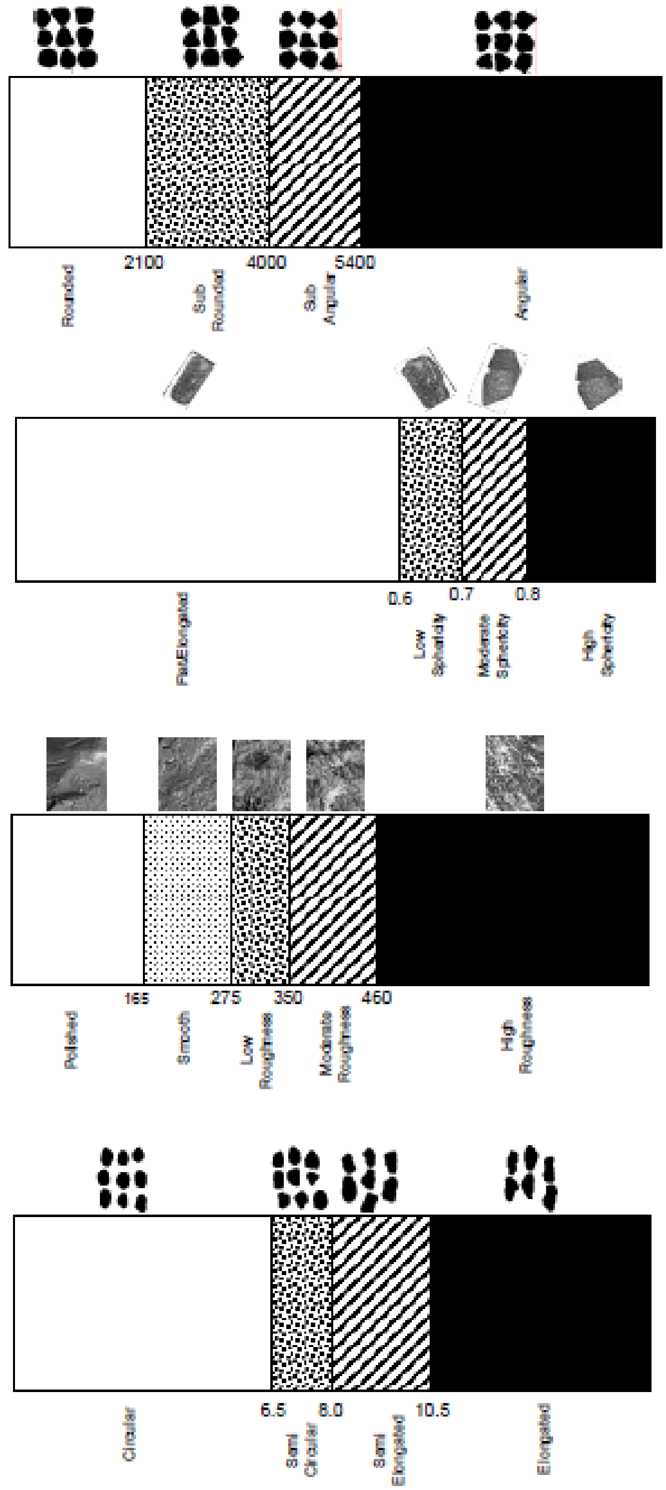

Figure 3.9 Aggregate Shape Classification Chart (FHWA, 2006)

Figure 3.10 displays the texture index values for all three samples analyzed. Figure 3.10 reveals that 60% of the RCA used in this research is categorized as low texture particles. The caveat, however: this version of AIMS very conservatively analyzes texture.

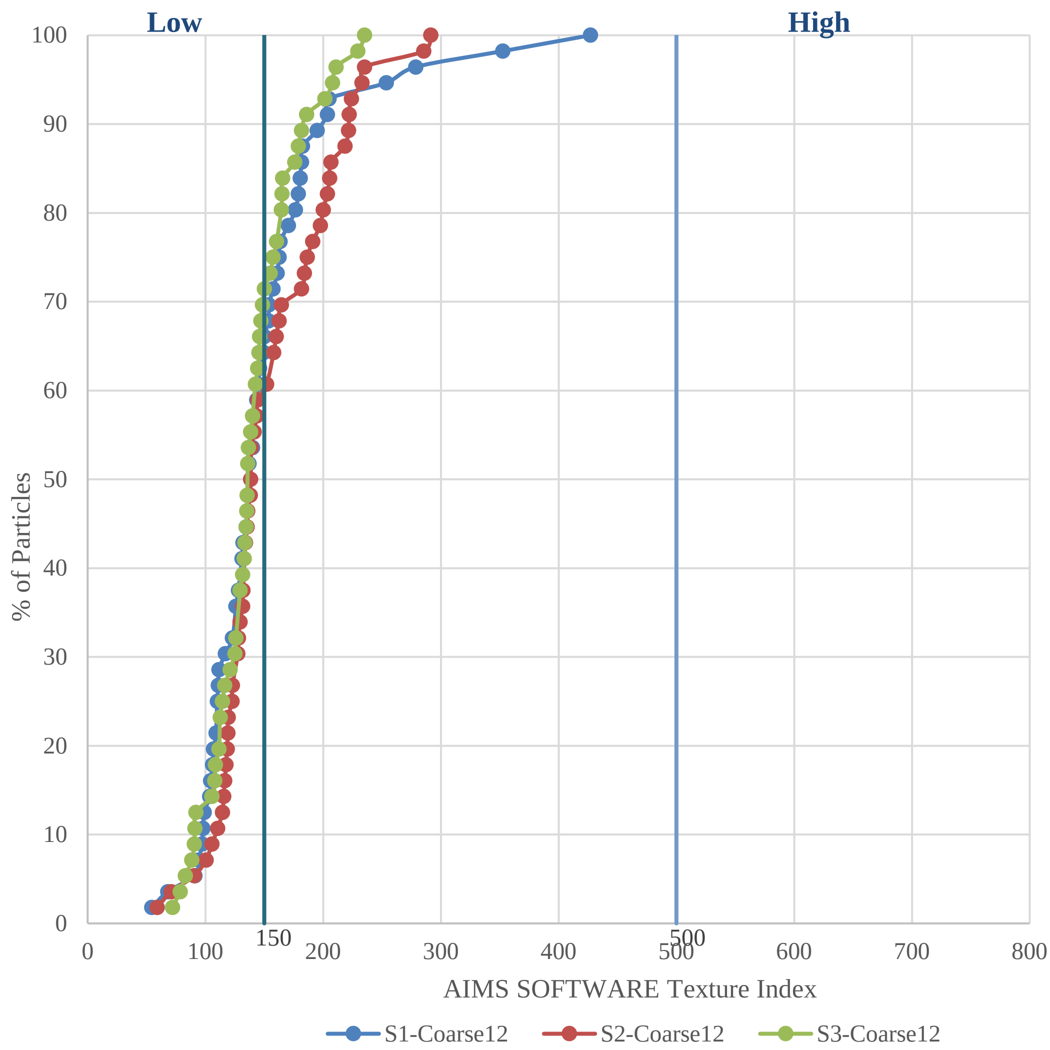

Figure 3.10 AIMS RCA Texture Index Analysis

3.5.3 AIMS RCA Angularity Results

The AIMS can measure aggregate angularity on a range from 0 to 8000. FHWA states that an angularity index value of 5000 or above is typical for a highly angular aggregate. An angularity index value of 2000 or less is classified as round aggregate. Figure 3.11 shows the overall output values for RCA particles analyzed for angularity. For comparison purposes, gravel has an average angularity index value of 2400, crushed limestone has an average angularity index value of approximately 2800, and granite has an average angularity index value of approximately 3000 according to FHWA.

Gradient Angularity	
Total Particles	131
Average:	3043.7
Std. Deviation	1190.4
Median	2750.7
Mode	

Figure 3.11 Overview of Angularity for RCA Samples Analyzed

Figure 3.12 plots the angularity indices for all three samples analyzed. From Figure 3.12, it is apparent that approximately 80% of the RCA used in this research is in the middle range.

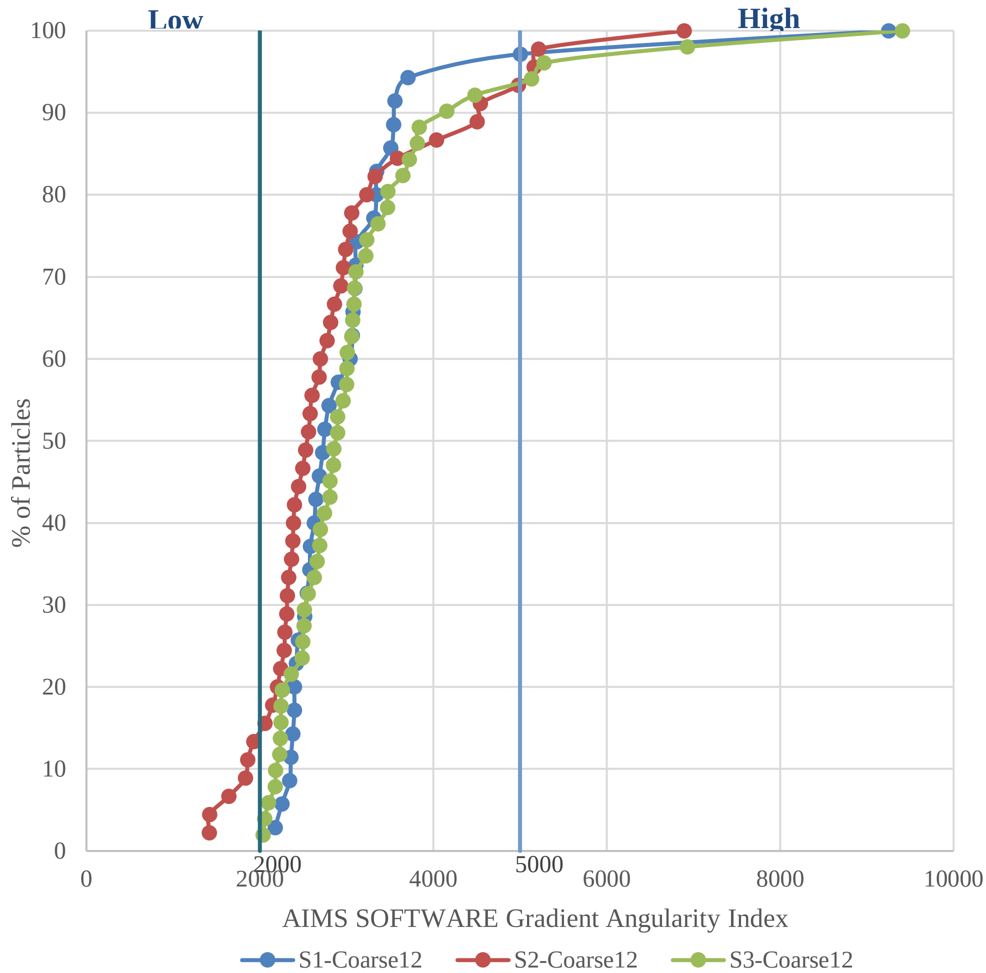

Figure 3.12 AIMS RCA Gradient Angularity Analysis

3.5.4 AIMS Limestone Texture Results

The AIMS can measure aggregate texture on a range from 0 to 800. FHWA states that a texture index value of 500 or above is typical for a highly rough aggregate. A texture index value of 150 or less is classified as polished aggregate. Figure 3.13 shows the overall output values for limestone particles analyzed for texture. For comparison purposes, gravel has an average texture index value of 148 and limestone has an average texture index value of 187 according to FHWA.

Texture	
Total Particles	167
Average:	208.2
Std. Deviation	119.4
Median	172.5
Mode	113.0

Figure 3.13 Overview of Texture for Limestone Samples Analyzed

Figure 3.14 plots the texture indices for all three limestone samples analyzed. From Figure 3.14, it is apparent that approximately 55% of the limestone used in this research is in the middle range.

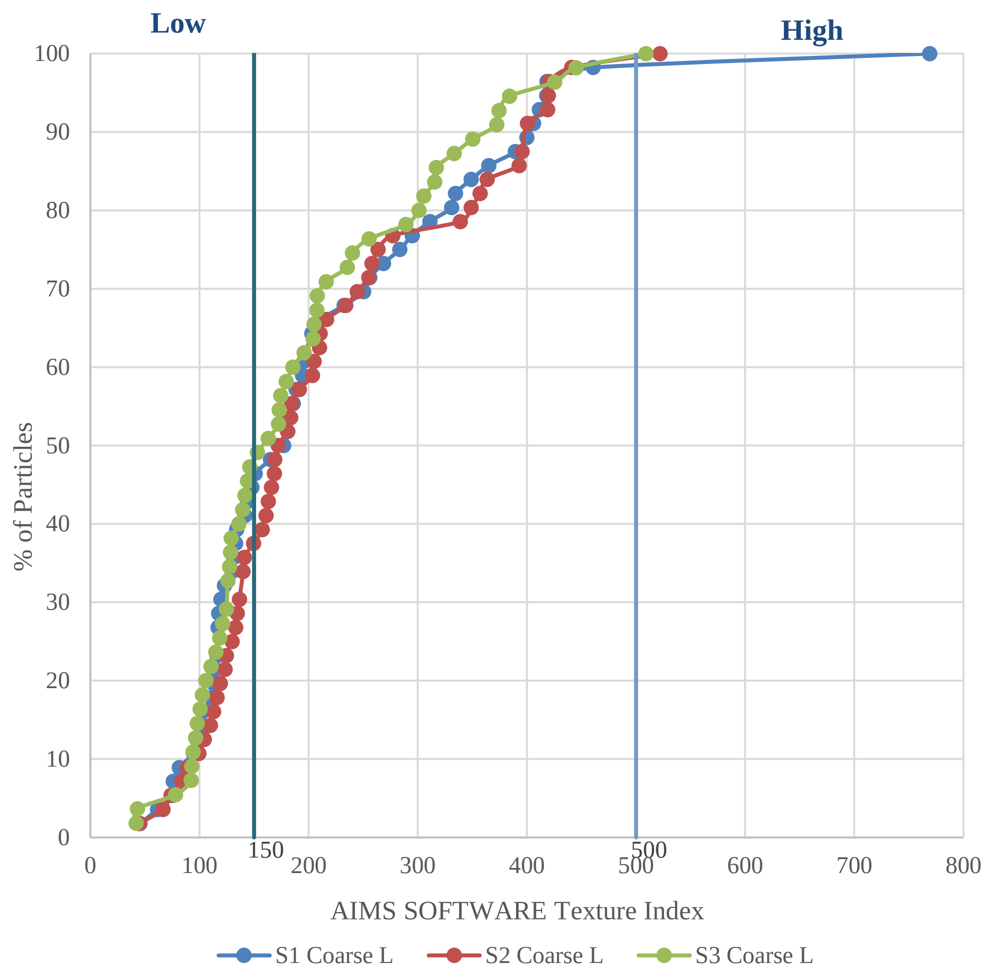

Figure 3.14 AIMS Limestone Texture Analysis

3.5.5 AIMS Limestone Angularity Results

The AIMS can measure aggregate angularity on a range from 0 to 8000. FHWA states that an angularity index value of 5000 or above is typical for a highly angular aggregate. An angularity index value of 2000 or less is classified as round aggregate. Figure 3.15 shows the overall output values for limestone particles analyzed for angularity. For comparison purposes, gravel has an average angularity index value of 2400, limestone has an average angularity index value of approximately 2800, and granite has an average angularity index value of approximately 3000 according to FHWA.

Gradient Angularity

Total Particles	146
Average:	3224.1
Std. Deviation	1103.9
Median	3061.4
Mode	

Figure 3.15 Overview of Angularity for Limestone Samples Analyzed

Figure 3.16 plots the angularity indices for all three limestone samples analyzed. From Figure 3.16, it is apparent that approximately 90% of the limestone used in this research is in the middle range.

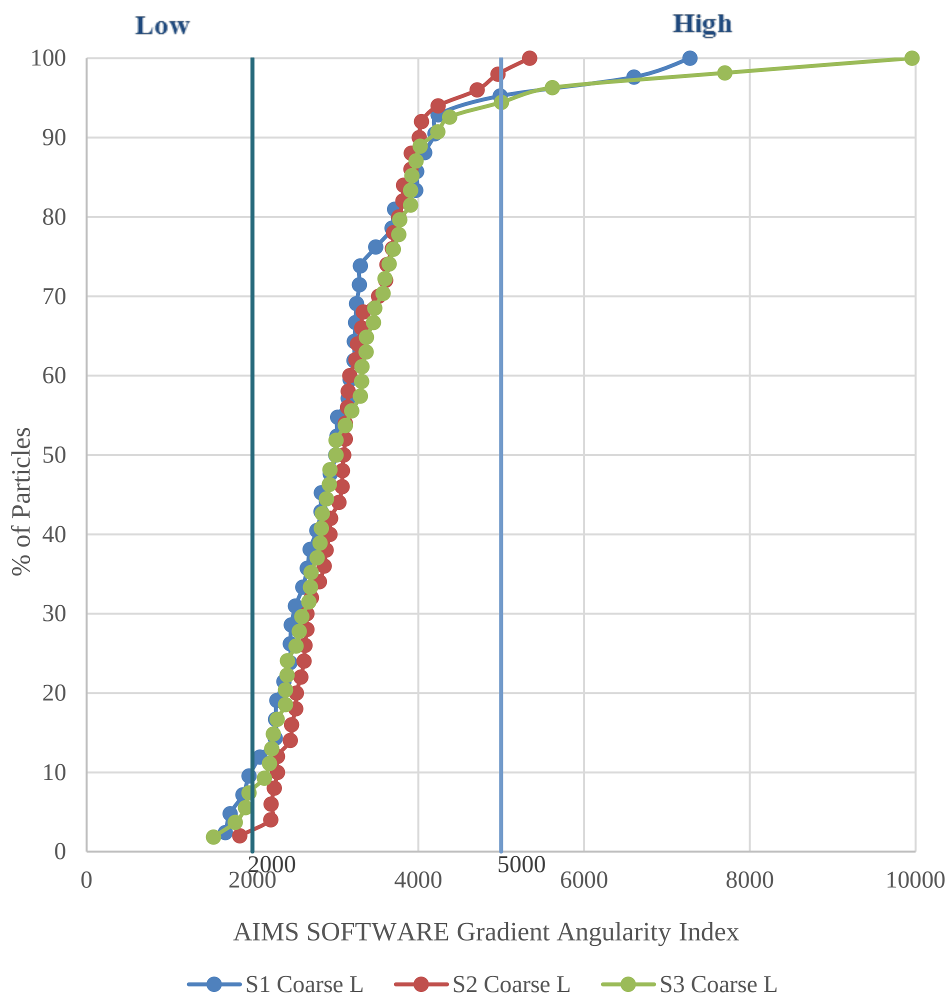

Figure 3.16 AIMS Limestone Gradient Analysis

3.5.6 Summary of AIMS Results

A concise summary of the AIMS results for RCA and limestone used in this research is shown in Table 3.9. As the table indicates, the RCA used for all testing related to this research proved to be less rough and less angular than the limestone according to the AIMS analysis. Other studies show that limestone originating from Oklahoma quarries has an average texture index between approximately 237 and 260

(Zaman et al., 2014). Therefore, the limestone used in this research provides less texture than anticipated.

Table 3.9 AIMS Results - FHWA vs. Research Results

Aggregate	FHWA		Research Results	
	Texture	Angularity	Texture	Angularity
RCA	-	-	148	3043
Limestone	187	2783	208	3224
Granite	239	2991	-	-
Gravel	148	2397	-	-

However, as previously mentioned in Chapter 3, the AIMS is known for over-conservative results when analyzing texture. In fact, samples of RCA were analyzed multiple times, with the second test series using unwashed aggregate to determine if this might affect the texture results. The AIMS indicated an even smoother texture for the unwashed RCA, directly opposite to the anticipated result. It seems that the AIMS has difficulty with lighter colored aggregate in terms of accurately determining texture, and the RCA is much lighter than the virgin limestone due to the adhered mortar and even more so prior to washing off loose grains of mortar surrounding the aggregate.

When performing a sort of tactile test – comparing the feeling of the surface of RCA versus limestone with touch – it is easily distinguishable that the RCA is rougher than the limestone. Therefore, the RCA texture result provided by AIMS should be disregarded.

3.6 Summary

This chapter analyzed the aggregates used in this research in accordance with all ASTMs listed in Table 3.1 and compared the results to ODOT's 2009 Specifications.

Furthermore, the texture and angularity of the RCA and limestone were analyzed using FHWA's AIMS technique.

The gradation of the river sand used within the context of this research was found to be within acceptable ODOT boundaries for fine aggregate. The gradation of the #57 coarse rock was within the boundaries specified by the ODOT standards except at the 1/2-in.-sieve size, as shown in Figure 3.3. The tested #57 had 69% passing the 1/2-in.-sieve size versus an upper bound limit of 60%. Since ODOT does not have a given standard for recycled concrete aggregate gradations, the RCA coarse aggregate was compared to the ODOT limits for #57 coarse rock, and the RCA fine aggregate was compared to the ODOT limits for conventional fine aggregate material. The gradation of the RCA fine aggregate used within the context of this research was found to be within the acceptable ODOT boundaries for fine aggregate. The gradation of the RCA coarse aggregate was within the boundaries specified by the ODOT standards except at the 1-in.-sieve size, as shown in Figure 3.5. The tested RCA had 84.9% passing the 1-in.-sieve size versus a lower bound limit of 95%.

The specific gravities of each aggregate type, shown in Table 3.8, show very slight changes overall. The dry-rodded unit weight of limestone and RCA vary by approximately 10 pounds per cubic foot. Absorption for RCA is considerably higher than the other aggregates used in this study, which is consistent with other research results. Additionally, coarse RCA has a much higher chance of being reduced to a smaller size, according to the LA Abrasion results of 37%.

4 Mix Development

4.1 Introduction

Concrete production uses a considerable amount of non-renewable natural resources and generates a significant amount of greenhouse gases. To obtain a more sustainable solution requires examining the two main components of concrete – aggregates and cement. Recycling concrete as aggregate for new concrete reduces construction waste, diverts material from already over-burdened landfills, and lowers demand for virgin aggregate. Using supplementary cementitious materials – such as fly ash, blast furnace slag, and glass powder – also diverts materials from landfills and reduces the carbon footprint of concrete.

In an attempt to investigate the performance of concrete containing a high volume of recycled materials, the mix designs developed within the scope of this research were made of proportions of RCA and fly ash. Three series of mixes were used to gather data, analyzed, and compared to a control mix. The analysis of fresh and hardened concrete properties was key to the completion of this study. Table 4.1 lists the fresh and hardened concrete tests performed on the different mixes, including the appropriate ASTM reference.

Table 4.1: Fresh and Hardened Concrete Tests with ASTM References

Test Category	Test	ASTM Reference
Fresh	Air Content	C 231
	Slump	C 143
	Unit Weight	C 138
Hardened	Compressive Strength	C 39
	Modulus of Elasticity	C 469
	Modulus of Rupture	C 78
	Split Cylinder	C 496

The hardened concrete tests were more time-dependent than the fresh concrete tests. Modulus of elasticity, modulus of rupture, and split cylinder tests all required specimens be tested at the age of 28 days. However, compressive strengths were identified at various concrete ages. This portion of the research focused on developing a strength versus time curve, capturing the strength of each mix at ages of 1, 7, 14, 28, and 56 days.

To fully understand the effects of the various recycled materials on the performance of the concrete, incremental additions of either RCA or fly ash were incorporated into the mix designs. Table 4.2 displays the breakdown of mixes performed for this research. The control mix was used as the baseline for comparing all other results. As such, it was not proportioned to contain any recycled materials. The control mix followed ODOT's standard for Class A concrete in pavement applications. Series No. 1 specifically focused on behavior of concrete with varying percentages of recycled concrete aggregate in place of coarse aggregate. Series No. 2 focused on the effects of replacing cement with fly ash. Finally, Series No. 3 combined the two previous series and incorporated total replacement of coarse aggregate with RCA while varying the amount of fly ash replacement of cement.

Table 4.2: Breakdown of Mix Designs

Test Name	Varying Mixes in the Series
Control	N/A
Series No. 1	25%, 50%, 75%, 100% RCA replacement
Series No. 2	20%, 40%, 60% fly ash replacement
Series No. 3	40%, 50%, 60% fly ash replacement with 100% RCA replacement

Table 4.3 describes the identification scheme of each specimen in relation to the batch it derived from. The description denotes a condensed synopsis of the appropriate

batch while the column of percentages reveals the pertinent replacement of either coarse aggregate or cement.

Table 4.3 Identification Scheme for Specimens and Mixes

Naming Scheme	Description	
C	Control	
1-25	Series No. 1 RCA Replacement	25%
1-50		50%
1-75		75%
1-100		100%
2-20	Series No. 2 Fly Ash Replacement	20%
2-40		40%
2-60		60%
3-40	Series No. 3 100% RCA & FA Replacement	40%
3-50		50%
3-60		60%

4.2 Control Mix

As previously mentioned, the control mix was modeled after ODOT's standard Class A concrete mix for pavement applications, the requirements for which are shown in Table 4.4.

Table 4.4: ODOT Requirements for Class A Concrete (ODOT 2009)

Class of Concrete	Minimum Cement Content	Air Content	Water-Cement Ratio	Slump	Minimum 28-Day Compressive Strength
	(lb/yd)	(%)	(lb/lb)	(in.)	(psi)
A	517	6 ± 1.5	0.25 – 0.48	2 ± 1	3,000

This mix design, shown in Table 4.5, contains all virgin aggregate and no supplementary cementitious materials. The fresh and hardened concrete test results of the control mix will be compared to the results of mixes containing various amounts of recycled materials in order to analyze the performance effects of concrete containing recycled materials.

Table 4.5: Control Mix Design

Cement	Water	River Sand	Coarse Aggregate	Air Entraining Admixture	Water Reducer Admixture
(lb)	(lb)	(lb)	(lb)	(oz/cwt)	(oz/cwt)
517	248	1,744	1,685	0.3	4.5

The fresh concrete properties for the control mix are shown in Table 4.6, and photographs of the air content test and slump test are shown in Figures 4.1 and 4.2, respectively. The modulus of rupture (MOR), modulus of elasticity (MOE), and split cylinder strength properties for the control mix are shown in Table 4.7. Photographs of the MOR testing are shown in Figures 4.3 and 4.4. Table 4.8 contains the compressive strength-time data for the control mix, and Figure 4.5 is a plot of the compressive strength-time data. Photographs of the compressive strength testing are shown in Figures 4.6 and 4.7.

Table 4.6: Fresh Concrete Properties for Control Mix

ID	Fresh Concrete Properties		
	Slump (in.)	Air Content (%)	Unit Weight (lb/ft^3)
C	3.25	6.4	142.9

Figure 4.1 Air Content Reading

Figure 4.2 Control Slump Reading

Table 4.7: Hardened Concrete Properties for Control Mix

ID	Hardened Concrete Properties		
	Modulus of Rupture (psi)	Modulus of Elasticity	Split Cylinder Strength (psi)
C	870	3,915,610	392
	741	3,598,105	401
	795	3,767,161	363
Avg	**802**	**3,760,292**	**385**

Figure 4.3 Control MOR Loading

Figure 4.4 Control MOR Beam After Loading

Table 4.8. Compressive Strengths for Control Mix

Hardened Concrete properties					
Compressive Strengths					
ID	1-Day (psi)	7-Day (psi)	14-Day (psi)	28-Day (psi)	56-Day (psi)
C	2610	4100	4670	4355	5460
	2605	3615	4730	4880	5460
	2535	3925	4405	4890	5535
Avg	**2583**	**3880**	**4602**	**4708**	**5485**

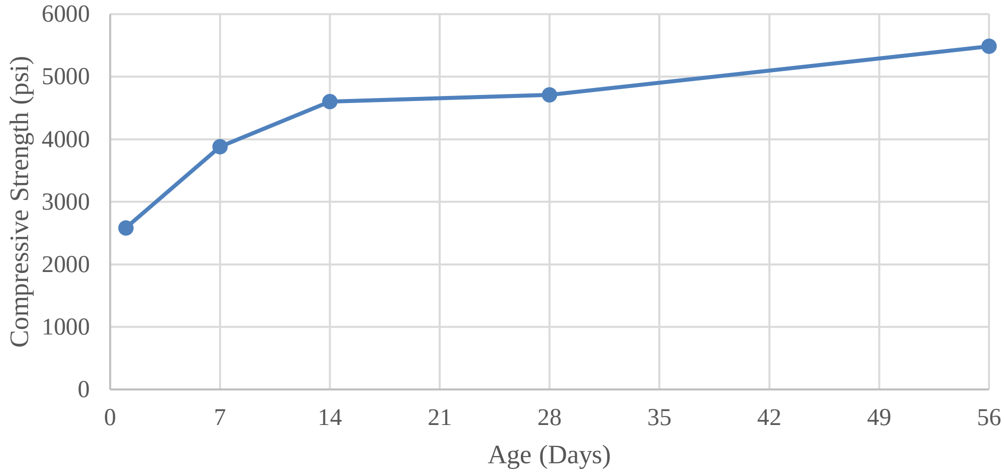

Figure 4.5 Compressive Strength vs. Time Plot for Control Mix

Figure 4.6 Control 1-Day Specimen Post-Loading

Figure 4.7 Control 28-Day Specimen Post-Loading

4.3 Series No. 1: Recycled Concrete Aggregate Replacement

Series No. 1 varied the percentage of RCA replacement by weight while maintaining constant percentages for the remaining concrete constituents. Specifically, this series increased the percentage of RCA replacement by increments of 25 %. Table 4.9 displays the mix designs used for Series No. 1.

Table 4.9: Series No. 1 Mix Design

ID	Cement (lb)	Water (lb)	River Sand (lb)	Coarse Aggregate (lb)	RCA (lb)	Air Entraining Admixture (oz/cwt)	Water Reducer Admixture (oz/cwt)
1-25	517	248	1,743	1,263	393	0.3	4.5
1-50	517	248	1,700	842	786	0.3	4.5
1-75	517	248	1,658	421	1,179	0.3	4.5
1-100	517	248	1,615	0	1,572	0.3	4.5

4.3.1 Fresh Concrete Properties

Table 4.10 displays the fresh concrete properties for Series No. 1, with a photograph of one of the slump tests shown in Figure 4.8. The table indicates decreasing slump and air content with increasing amounts of RCA replacement. However, the unit weight of each variation found in Series No. 1 is closely comparable to each other and is marginally less than the unit weight found for the control mix.

Table 4.10: Fresh Concrete Properties for Series No. 1 Mix

ID	Fresh Concrete Properties		
	Slump (in.)	Air Content (%)	Unit Weight (lb/ft^3)
1-25	7.75	10.75	138.2
1-50	5.25	9.5	139.4
1-75	3.5	8.5	138.8
1-100	1.25	5.5	141.0

Figure 4.8 1-50 Slump Reading

4.3.2 Hardened Concrete Properties

Tables 4.11 and 4.12 display the hardened concrete properties of each mix in Series No. 1. The data in Table 4.11 includes the modulus of rupture, modulus of elasticity, and split cylinder strength at an age of 28 days. The data in Table 4.12 includes the compressive strengths at 1, 7, 14, 28, and 56 days after mixing. One of the MOR fracture surfaces is shown in Figure 4.9, and the test setup for the MOE testing is shown in Figure 4.10. Figure 4.11 is a plot of the compressive strength-time data, while Figure 4.12 shows one of the compressive strength test specimens after failure.

Table 4.11: Hardened Concrete Properties for Series No. 1 Mix

ID	**Hardened Concrete Properties**		
	Modulus of Rupture (psi)	Modulus of Elasticity	Split Cylinder Strength (psi)
1-25	663	3,126,842	394
	687	2,984,132	361
	750	3,139,307	332
1-25 Avg	**700**	**3,083,427**	**362**
1-50	697	3,429,384	342
	726	3,942,640	435
	695	3,482,129	438
1-50 Avg	**706**	**3,618,051**	**405**
1-75	789	2,864,134	399
	791	3,204,269	267
	713	3,395,445	399
1-75 Avg	**764**	**3,154,616**	**355**
1-100	713	3,940,397	381
	710	4,612,831	360
	765	4,569,381	332
1-100 Avg	**729**	**4,374,203**	**358**

Figure 4.9 1-50 MOR Fracture Surface

Figure 4.10 MOE Test Apparatus

Table 4.12. Compressive Strengths for Series No. 1

Hardened Concrete properties					
	Compressive Strengths				
ID	1-Day	7-Day	14-Day	28-Day	56-Day
	(psi)	(psi)	(psi)	(psi)	(psi)
1-25	2145	3455	3845	4370	4520
	2195	3475	3830	4405	4625
	2145	3425	3525	4340	4495
1-25 Avg	**2162**	**3452**	**3733**	**4372**	**4547**
1-50	2445	3990	4310	4775	5270
	2430	3960	4570	4460	5300
	2355	3770	4370	4885	5175
1-50 Avg	**2410**	**3907**	**4417**	**4707**	**5248**
1-75	2395	3840	4220	4920	4810
	2335	3975	4275	4645	4680
	2410	3805	4155	4715	5030
1-75 Avg	**2380**	**3873**	**4217**	**4760**	**4840**
1-100	2915	4645	5365	4250	5650
	2855	4685	4780	5260	5515
	2915	5110	5370	5320	5690
1-100 Avg	**2895**	**4813**	**5172**	**4943**	**5618**

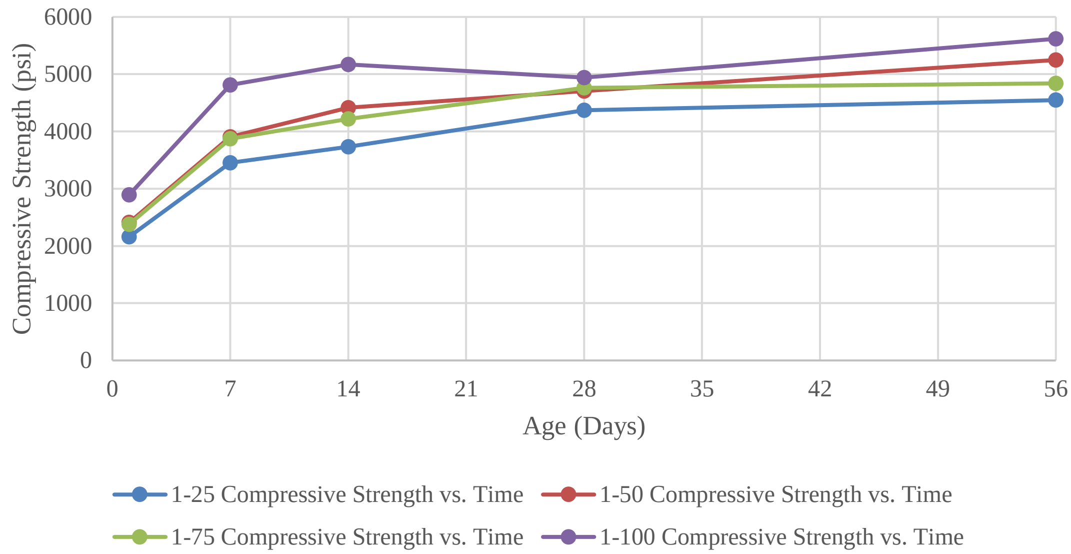

Figure 4.11 Compressive Strength vs. Time Plot for Series No. 1

Figure 4.12 1-50 28-Day Specimen Post-Loading

4.3.3 Discussion

As anticipated, the increase in percentage of RCA resulted in a decrease in slump (Table 4.9). It was believed, prior to testing, that the angular nature of RCA is what causes a decrease in slump. However, after further investigation, other feasible options for decreased slump were identified.

Figures 4.13 and 4.14 capture a close-up view of both virgin and recycled coarse aggregate. It is easy to see that coarse aggregate is actually more angular than RCA. Virgin aggregate has more defined corners and edges, while RCA is much more rounded and dull. Also depicted in the same figures is the differences in the surfaces of the two types of coarse aggregate. Notice that virgin aggregate has a smoother, clean surface while RCA's aggregate surface appears to be rough with fine particles loosely attached to the aggregates' surfaces. Therefore, the decrease in slump is likely more attributable to RCA's rough and irregular surface caused by the residual mortar adhered to the original virgin aggregate. Furthermore, RCA contains fine aggregate particles derived from the original crushed concrete. These fines are more angular and rough than typical natural sand, which has a negative influence on workability.

Figure 4.13 Virgin Coarse Aggregate

Figure 4.14 Recycled Coarse Aggregate

Not only was the slump affected by the rough surface of the RCA and the amount of recycled fines in the mix, but general workability was also noticeably impacted. The control mix offered little resistance to rodding or tamping. RCA, however, required much more effort to fill the molds.

Beyond slump, also displayed in Table 4.9 are air content percentages for Series No. 1. The trend shown there makes it seem that increasing percentages of RCA cause a decrease in air content. However, that trend is more than likely incorrect. The control mix had an air content similar to the air content found for mix 1-100 and most dissimilar to mix 1-25. Intuitively, the control mix and 1-25 mix should be more similar by nature due to the small amount of RCA replacement. Therefore, these findings lead one to believe that RCA's absorption is highly variable and inconsistent.

Lastly measured under the category of "fresh concrete properties" was unit weight. The control mix was found to have the highest unit weight when compared to the unit weight values obtained for specimens in Series No. 1. However, most of the unit weight values only varied slightly compared to the control.

Of the hardened properties measured, the compressive strengths for all mixes in Series No. 1 provided interesting results (Figure 4.11). The mix containing 100% recycled aggregate (1-100) proved to be the strongest mix over the entire 56-day period. Second in compressive strength was 1-50. The weakest mix was found to be 1-25. These results were not expected; the anticipated results were expected to show that increasing the percentage of RCA would decrease the compressive strength of the specimen. The unexpected nature of these results could be caused by a few different reasons.

RCA has two interfacial transitions zones (ITZs): one ITZ occurring between virgin aggregate and virgin paste; and the second ITZ occurring between old paste and new paste. Multiple layers of paste results in a higher possibility for air voids. In Chapter 3, Table 3.8 displays the differences in #57 and RCA absorption. Therefore, increased air voids directly correlate to increased absorption. Furthermore, an increased absorption percentage causes difficulty in controlling the water-cement ratio as more voids allow for more water to be absorbed by the aggregate rather than contributing to the concrete as a whole. This increased absorption and decreased availability of water used in mixing the concrete leads to a higher compressive strength.

The modulus of elasticity, modulus of rupture, and split cylinder strength were the remaining three hardened concrete properties measured. The modulus of elasticity was practically unchanged with increased amounts of RCA, with the exception of a slight increase in the 1-100 mix. Similarly, the modulus of rupture and tensile strength were hardly affected by the increased percentage of RCA replacement.

4.4 Series No. 2: Fly Ash Replacement

Series No. 2 varied the percentage of cement replaced by weight with fly ash while the remaining concrete constituents were held constant. Table 4.13 displays the mix designs used for this series.

Table 4.13: Series No. 2 Mix Design

ID	Cement (lb)	Fly Ash (lb)	Water (lb)	River Sand (lb)	Coarse Aggregate (lb)	Air Entraining Admixture (oz/cwt)	Water Reducer Admixture (oz/cwt)
2-20	414	103	248	1,786	1,685	0.3	3.0
2-40	310	207	248	1,786	1,685	0.3	3.0
2-60	207	310	248	1,786	1,685	0.3	3.0

4.4.1 Fresh Concrete Properties

Table 4.14 displays the fresh concrete properties found for Series No. 2. Mix 2-20 provided the lowest slump, highest air content, and lowest unit weight. Mixes 2-40 and 2-60 provided essentially equal values for slump, air content, and unit weight.

Table 4.14: Fresh Concrete Properties for Series No. 2 Mix

ID	Fresh Concrete Properties		
	Slump (in.)	Air Content (%)	Unit Weight (lb/ft^3)
2-20	5.75	11	139.4
2-40	7.5	8	140.6
2-60	7.5	7.5	142.9

4.4.2 Hardened Concrete Properties

Tables 4.15 and 4.16 display the hardened concrete properties of each mix for Series No. 2. The data in Table 4.15 includes the modulus of rupture, modulus of elasticity, and split cylinder strength at an age of 28 days. The data in Table 4.16 includes the compressive strengths at 1, 7, 14, 28, and 56 days after mixing. One of the split cylinder test specimens is shown in Figure 4.15 after failure, and Figure 4.16 reveals the fracture surface of the same specimen. Figure 4.17 compares the compressive strength of each mix in Series No. 2 over a 56-day period, while Figure 4.18 shows one of the compressive strength test specimens after failure.

Table 4.15: Hardened Concrete Properties for Series No. 2 Mix

ID	Hardened Concrete Properties		
	Modulus of Rupture (psi)	Modulus of Elasticity	Split Cylinder Strength (psi)
2-20	680	4,992,412	435
	714	4,613,212	375
	758	5,360,479	438
2-20 Avg	**717**	**4,988,701**	**416**
2-40	764	4,761,342	385
	754	4,869,925	362
	729	5,073,401	397
2-40 Avg	**749**	**4,901,556**	**381**
2-60	637	5,276,135	384
	636	4,633,219	379
	581	4,243,389	324
2-60 Avg	**618**	**4,717,581**	**362**

Figure 4.15 2-40 Split Cylinder Test Post-Loading

Figure 4.16 2-40 Split Cylinder Fracture Surface

Table 4.16. Compressive Strengths for Series No. 2

Hardened Concrete properties					
Compressive Strengths					
ID	1-Day (psi)	7-Day (psi)	14-Day (psi)	28-Day (psi)	56-Day (psi)
2-20	1580	3965	4005	4450	4970
	1480	3820	3890	4365	5040
	1595	3639	3920	4475	4760
2-20 Avg	**1552**	**3808**	**3938**	**4430**	**4923**
2-40	675	2875	3760	4390	5085
	740	3260	3730	4410	4710
	710	3165	3645	4355	4770
2-40 Avg	**708**	**3100**	**3712**	**4385**	**4855**
2-60	70	2445	3125	3475	4360
	85	2050	3090	3705	4215
	75	2205	3150	3720	3695
2-60 Avg	**77**	**2232**	**3122**	**3633**	**4090**

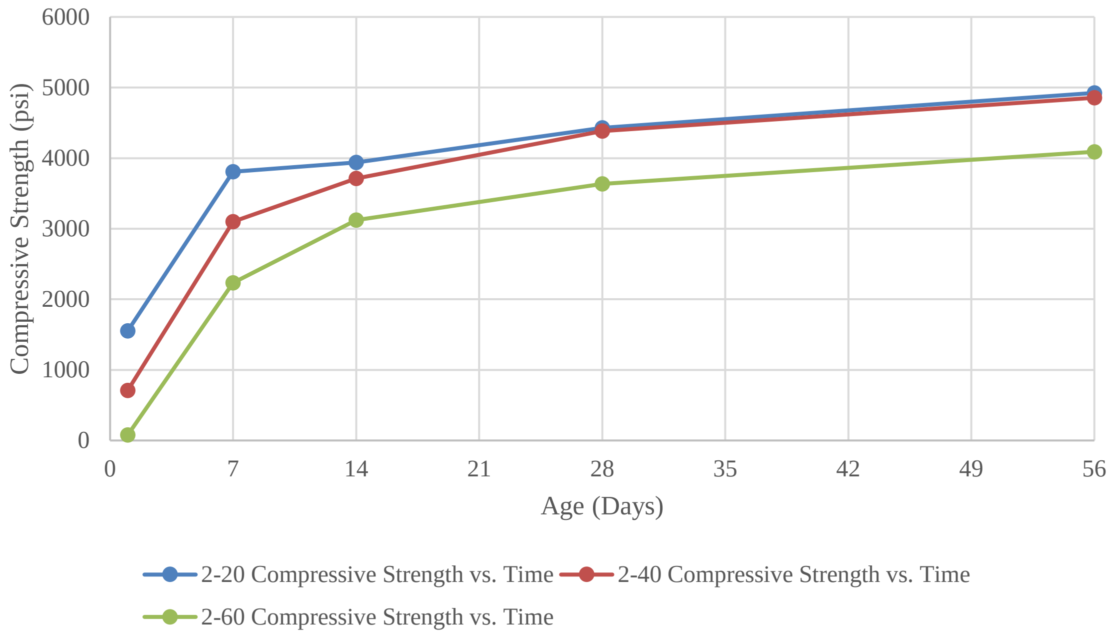

Figure 4.17 Compressive Strength vs. Time Plot for Series No. 2

Figure 4.18 2-40 28-Day Specimen Post-Loading

4.4.3 Discussion

The fresh concrete properties of the three mixes cast for this series were much different than that of the control mix. Slump and air content were noticeably higher for the mixes containing fly ash instead of cement. The use of fly ash in concrete increases the workability, flowability, and decreases the amount of water required as fly ash particles are rounded in shape with little friction. In this series, the water reducing agent was reduced from 4.5 oz./cwt to 3.0 oz./cwt in order to maintain a useable slump value.

The compressive strength for this mix showed anticipated qualities associated with high amounts of fly ash replacement. Fly ash takes at least 14 or 28 days to begin to react with the excess lime produced by the hydrating cement, which is represented in the findings for this series in Figure 4.18. Additionally, there seems to be a cap on how much fly ash can be used to replace cement. Many pieces of literature state that the maximum fly ash content used in concrete to yield results closely resembling control-type characteristics is 35% cement replacement with fly ash (Bajad, 2015; Tangchirapat, 2013). The compressive strengths of each specimen in this series concur with such literature with Mix 2-60 barely reaching 3000 psi at 14 days and only reaching 3600 psi at 28 days, or 76% of the 28-day control mix compressive strength.

The modulus of rupture varied slightly among the three mixes tested in this series. Mix 2-40 resulted in the highest MOR, but like in many other cases, the overall difference between each mix was minimal. Similarly, the moduli of elasticity and split tensile strengths were generally unaffected.

4.5 Series No. 3: Recycled Concrete Aggregate and Fly Ash Replacement

Series No. 3 attempts to combine the two previous series. In this series, all coarse aggregate is replaced with RCA and the amount of cement replaced with fly ash is varied at 40%, 50%, and 60%. The mix designs for this series are shown in Table 4.17.

Table 4.17: Series No. 3 Mix Design

ID	Cement (lb)	Fly Ash (lb)	Water (lb)	River Sand (lb)	RCA (lb)	Air Entraining Admixture (oz/cwt)	Water Reducer Admixture (oz/cwt)
3-40	310	207	248	1,615	1,572	0.3	4.5
3-50	259	259	248	1,615	1,572	0.3	4.5
3-60	207	310	248	1,615	1,572	0.3	4.5

4.5.1 Fresh Concrete Properties

The fresh properties for Series No. 3 are shown in Table 4.18. Of the three mixes tested, slump is closely comparable between each, as is unit weight.

Table 4.18: Fresh Concrete Properties for Series No. 3 Mix

ID	Fresh Concrete Properties		
	Slump (in.)	Air Content (%)	Unit Weight (lb/ft^3)
3-40	8.75	7.2	136.3
3-50	8.25	9	133.9
3-60	8.25	7.8	135.9

4.5.2 Hardened Concrete Properties

Tables 4.19 and 4.20 provide the hardened concrete properties of each mix for Series No. 3. The data in Table 4.19 includes modulus of rupture, modulus of elasticity, and split cylinder strength at an age of 28 days. The data in Table 4.20 includes the compressive strengths at 1, 7, 14, 28, and 56 days after mixing. Figure 4.19 compares the compressive strength of each mix in Series No. 3 over a 56-day period, while Figure 4.20 shows one of the compressive strength test specimens after failure.

Table 4.19: Hardened Concrete Properties for Series No. 3 Mix

ID	**Hardened Concrete Properties**		
	Modulus of Rupture (psi)	Modulus of Elasticity	Split Cylinder Strength (psi)
3-40	536	3,698,911	282
	526	3,198,131	223
	538	3,448,665	185
3-40 Avg	**533**	**3,448,569**	**230**
3-50	478	3,721,986	186
	500	3,681,143	180
	504	3,623,899	195
3-50 Avg	**494**	**3,675,676**	**187**
3-60	453	3,119,890	161
	412	2,963,510	181
	455	3,301,743	184
3-60 Avg	**440**	**3,128,381**	**175**

Table 4.20. Compressive Strengths for Series No. 3

Hardened Concrete properties					
Compressive Strengths					
ID	1-Day (psi)	7-Day (psi)	14-Day (psi)	28-Day (psi)	56-Day (psi)
3-40	600	2655	3015	3690	4100
	545	2645	3055	3420	4015
	620	2485	3055	2970	4030
3-40 Avg	**588**	**2595**	**3042**	**3360**	**4048**
3-50	345	2270	2815	3180	3680
	375	2330	2675	3230	3700
	355	2365	2680	3160	3625
3-50 Avg	**358**	**2322**	**2723**	**3190**	**3668**
3-60	105	1915	1795	2625	3075
	115	1900	2170	2620	3125
	120	1970	2260	2650	3155
3-60 Avg	**113**	**1928**	**3122**	**2632**	**3118**

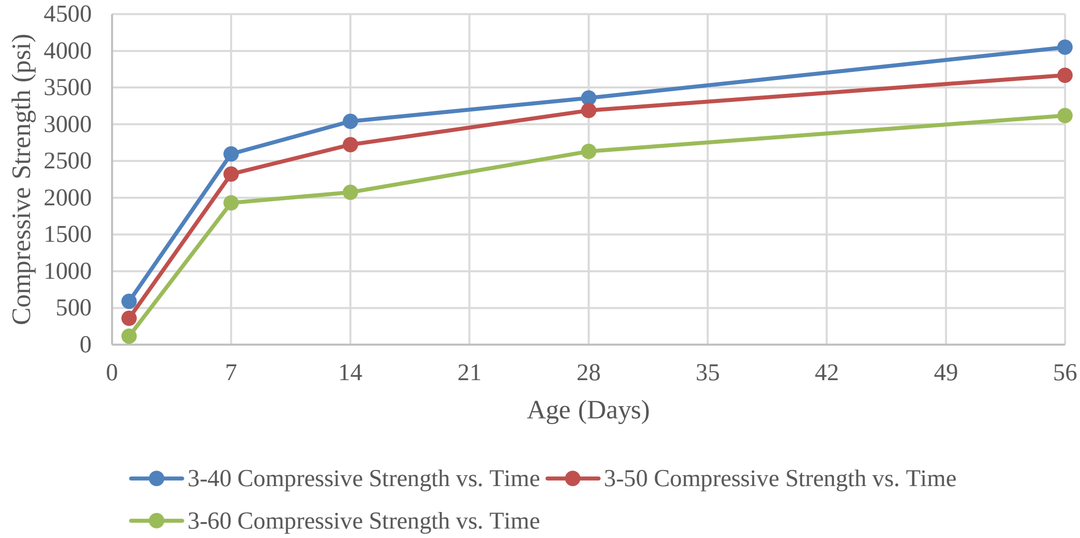

Figure 4.19 Compressive Strength vs. Time Plot for Series No. 3

Figure 4.20 3-60 28-Day Specimen Post-Loading

4.5.3 *Discussion*

Of the fresh concrete test results, slump provided the most interesting findings. In Series No. 1, the data proved that increased RCA replacement yielded decreased slump. In series No. 2, the results showed that increased fly ash replacement increased the slump. Therefore, it was anticipated that these two qualities of RCA and fly ash, respectively, would cancel each other out and yield results for Series No. 3 most similar to the slump found for the control mix. However, that preconceived notion was proven incorrect. The roundedness of the RCA coupled with the ball bearing-like qualities of the fly ash seemed to have amplified the slump, as shown in Table 4.17.

The air content for Series No. 3 remained steady, with the exception of one outlier. Due to the constant amount of RCA replacement, a consistent air content seems reasonable. Similarly, the unit weight for each mix in this series was also relatively equal. However, the unit weight of each mix of Series No. 3 was noticeably smaller than that of the control mix, which is likely due to the decreased specific gravity of fly ash compared to cement.

The combination of RCA and fly ash greatly affected the compressive strengths. It was anticipated that RCA’s double ITZ would be the cause of lower compressive strengths. Additionally, increasing the percentage of fly ash also decreases compressive strength. Therefore, the low compressive strengths resulting from the tests performed for Series No. 3 were exactly as anticipated. In fact, 3-60 was unable to reach the 3000 psi standard at 28 days, although it did surpass this minimum value by 56 days.

As a whole, the hardened concrete properties were similar. Mix 3-60 provided the lowest results for modulus of rupture, modulus of elasticity, and split tensile strength, but all of the mixes in Series No. 3 were low compared to the control.

4.6 Comparative Analysis

This portion of Chapter 4 will briefly review the main points found in previous discussion sections. Following this brief review, the chapter will conclude with several analyses of each series of mix designs compared to the control mix.

The presence of recycled concrete aggregate in a concrete mix design caused the slump to decrease with increasing percentages of RCA replacement due to the rough, highly frictional aggregate surface. Unexpectedly, increasing RCA replacement caused the air content to decrease. This result is non-representative of RCA behavior in general, however. Typically, increasing RCA causes increasing air content due to the inconsistent porosity of the recycled aggregate and mortar. As a residual effect of high porosity, strength is usually jeopardized.

Fly ash in concrete caused the slump to increase with increasing fly ash replacement. This is intuitive due to the physical appearance of fly ash and the particles' similarities to small ball bearings. As the percentage of fly ash replacement increased, the strength decreased.

Combining RCA and fly ash in the same concrete mix design amplified the negative effect of each on compressive strength, with a value below the 3000 psi threshold for the mix containing 100% RCA with 60% fly ash. On the other hand, the fly ash did have the beneficial effect of counteracting the decrease in slump normally associated with increasing amounts of RCA replacement.

Figures 4.21, 4.22, and 4.23 provide graphical presentations of strength gain for each series (Series No. 1, No. 2, and No. 3, respectively) compared to the results for the Control mix. Series No. 2 and Series No. 3 behaved as expected compared to the Control mix, namely decreasing compressive strength for increasing amounts of fly ash replacement. Comparing Figures 4.22 and 4.23 reveals that the substitution of 100% of the coarse aggregate with RCA exacerbated the drop in compressive strength with the addition of fly ash, which was expected. However, Series No. 1 did not follow the expected result of decreasing compressive strength with increasing percentage of RCA. This result is most likely due to a high variability in porosity of the RCA compared with virgin aggregate, the result of which reduces the ability to accurately control the water-cement ratio for mixes containing RCA.

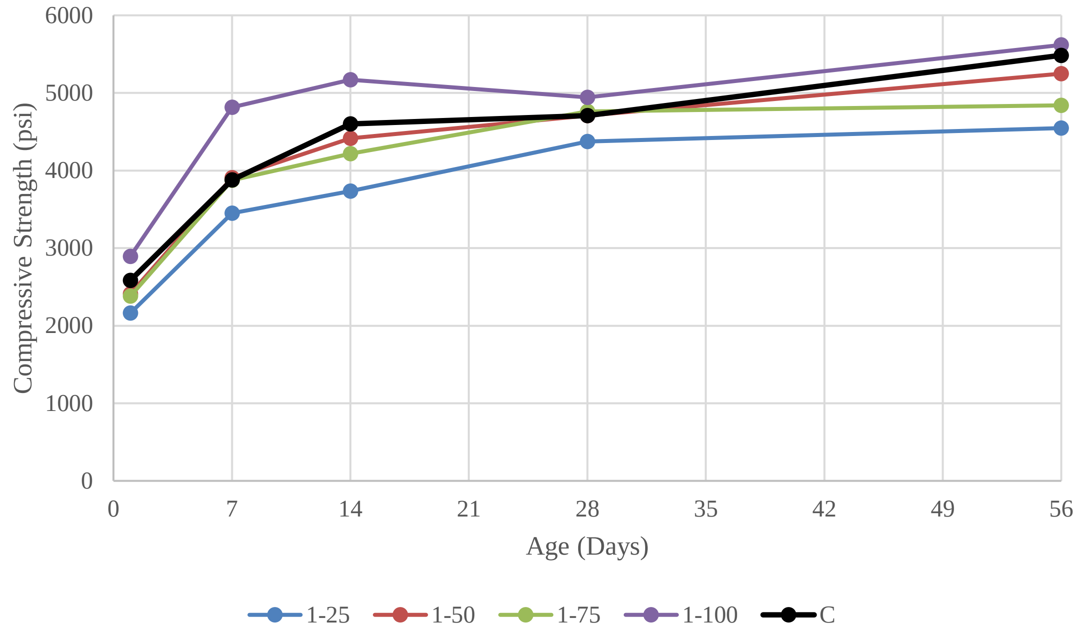

Figure 4.21 Series No. 1 & Control Compressive Strength vs. Time

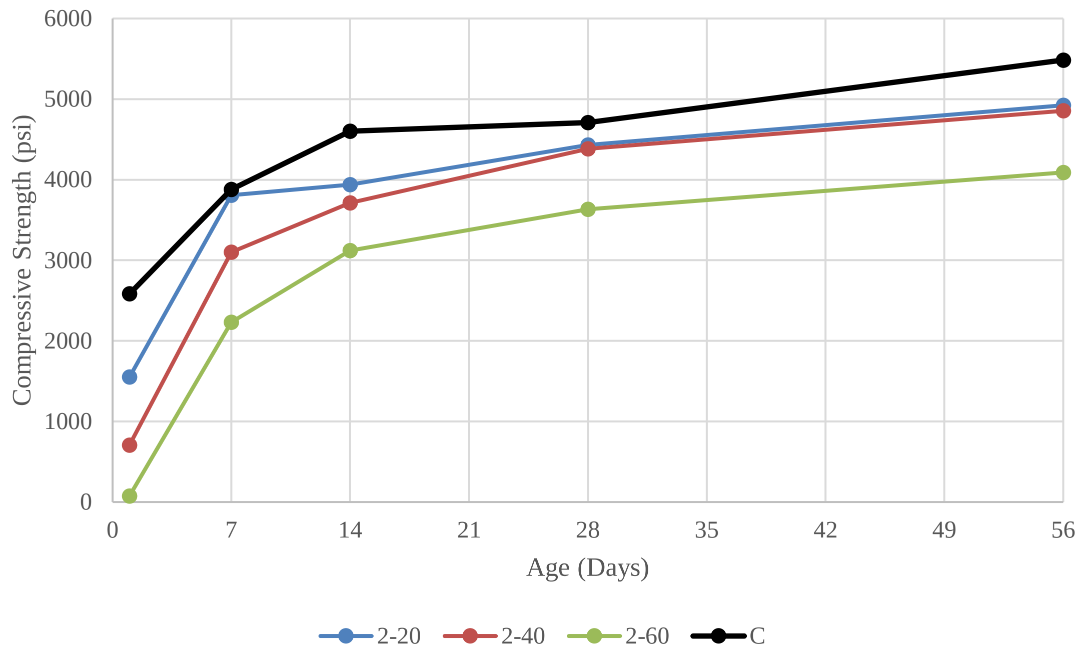

Figure 4.22 Series No. 2 & Control Compressive Strength vs. Time

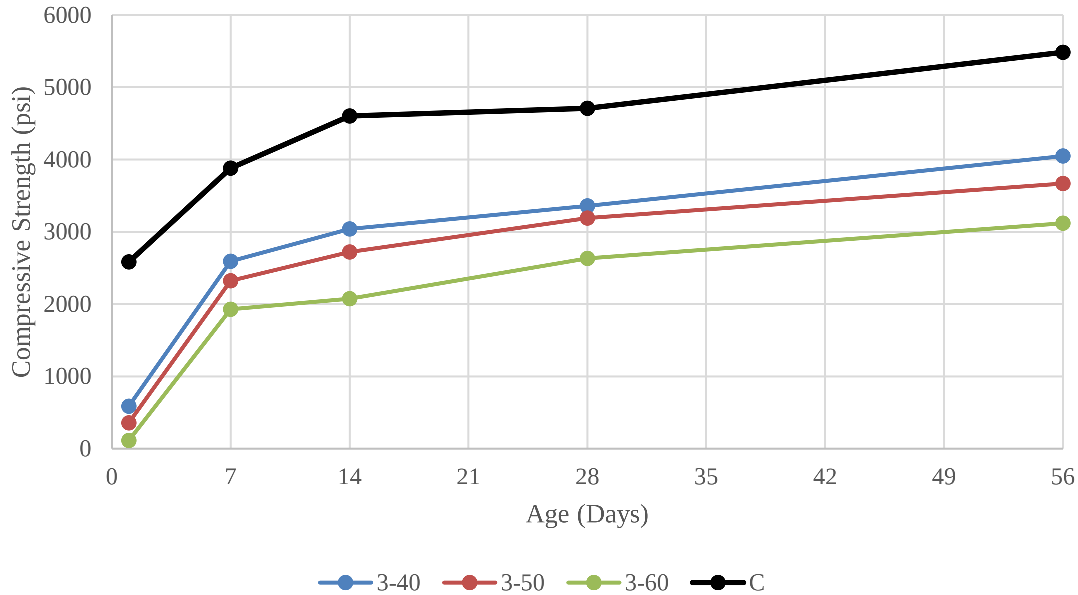

Figure 4.23 Series No. 3 & C Control Compressive Strength vs. Time

Figures 4.24, 4.25, and 4.26 show normalized modulus of rupture values for each series of mix designs compared to the control mix. Normalization is based on the conventional relationship of MOR to compressive strength. Therefore, the normalized values were calculated in order to adequately compare between the series of mixes and the control values. Equation 4.1 displays the conventional relationship between the modulus of rupture, f_r, and the average 28-day compressive strength.

$$f_r = 7.5\lambda\sqrt{f'_c} \qquad \text{(Eq. 4.1)}$$

where λ is a factor for lightweight concrete.

From this equation, a graph plotting the modulus of rupture divided by the square root of the compressive strength will yield a unitless number for comparison between concretes of different strength, with a value of approximately 7.5 for typical concrete. However, Figure 4.24 shows that the control mix for this research provided a higher value closer to 12. More importantly, it appears that increasing RCA content causes only a slight decrease in the normalized modulus of rupture. However, the decreased normalized MOR value is between 10 and 11, which is still higher than the typical 7.5.

In the same vein, Figures 4.25 and 4.26 show that increasing fly ash content and fly ash with RCA, respectively, cause the same decrease in normalized MOR. However, more noticeably, fly ash with recycled aggregate causes a much lower normalized value, yet still larger than 7.5. However, it is clear that the combination of RCA and fly ash has a significant negative effect on MOR as a function of concrete strength.

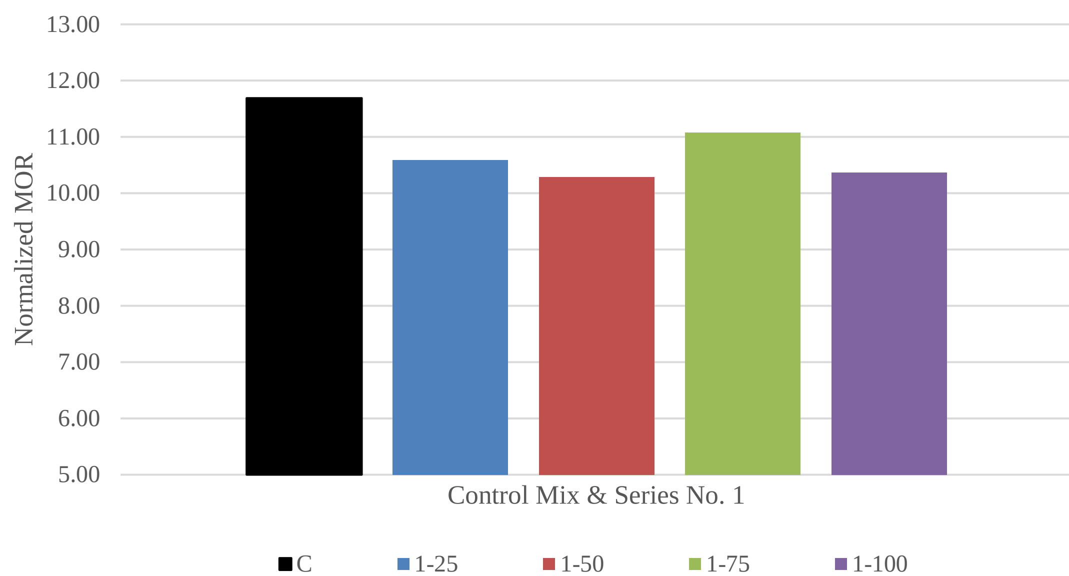

Figure 4.24 Normalized MOR for Series No. 1 & Control

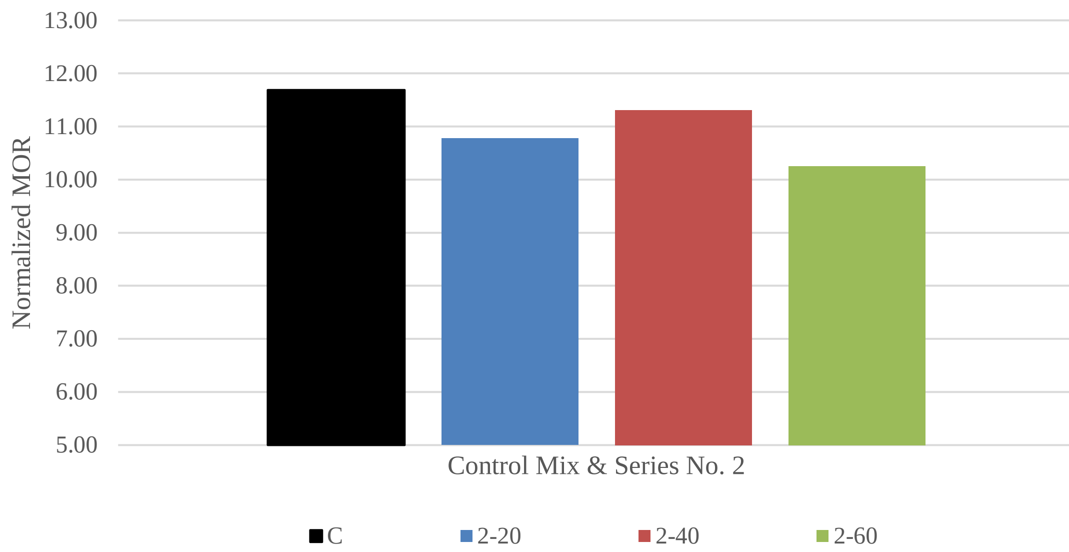

Figure 4.25 Normalized MOR for Series No. 2 & Control

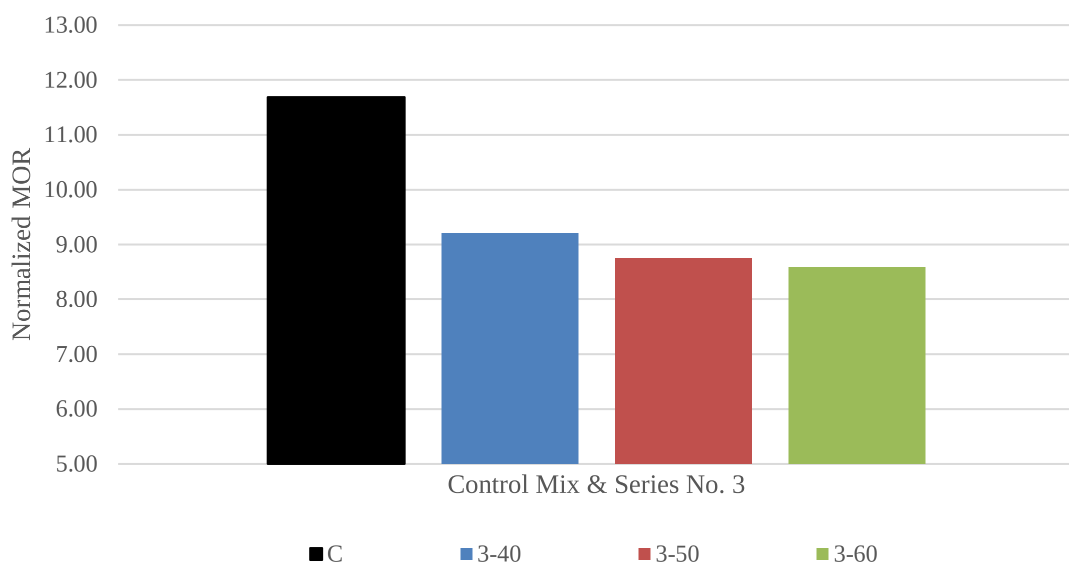

Figure 4.26 Normalized MOR for Series No. 3 & Control

Figures 4.27, 4.28, and 4.29 graphically present a comparison of normalized modulus of elasticity values for each mix to the control. Normalization of the MOE values was based on the conventional relationship between MOE and the compressive strength, as shown by Equation 4.2.

$$E_c = 57{,}000\sqrt{f'_c} \qquad \text{(Eq. 4.2)}$$

With the relationship given in Equation 4.2, typical concrete should reach a value of approximately 57,000 when plotting the MOE divided by the square root of the average 28-day strength. The control mix in this research reached approximately 55,000 as shown in Figures 4.27, 4.28, and 4.29.

Figure 4.27 shows an interesting comparison. All of the mixes included in Series No. 1, excluding the 100% RCA replacement, Mix 1-100, indicated a decreased modulus of elasticity but yet very inconsistent numbers. Mix 1-100 shows a large spike in normalized modulus of elasticity. These varying values again prove the inconsistencies in RCA. Without the Mix 1-100 outlier, the overall trend would present a decrease in MOE with increasing RCA replacement.

Figure 4.28 displays that fly ash improves, beyond the control mix, the modulus of elasticity of the mix. In fact, it appears that as fly ash replacement increases, so increases the modulus of elasticity.

Figure 4.29 shows a middle ground between the results found in Figures 4.27 and 4.28. The large increase in MOE with the presence of fly ash is brought down slightly by the increase of RCA replacement. Concrete containing fly ash and 100% RCA replacement provides a larger MOE than the control mix and above the 57,000 conventional value given in Equation 4.2.

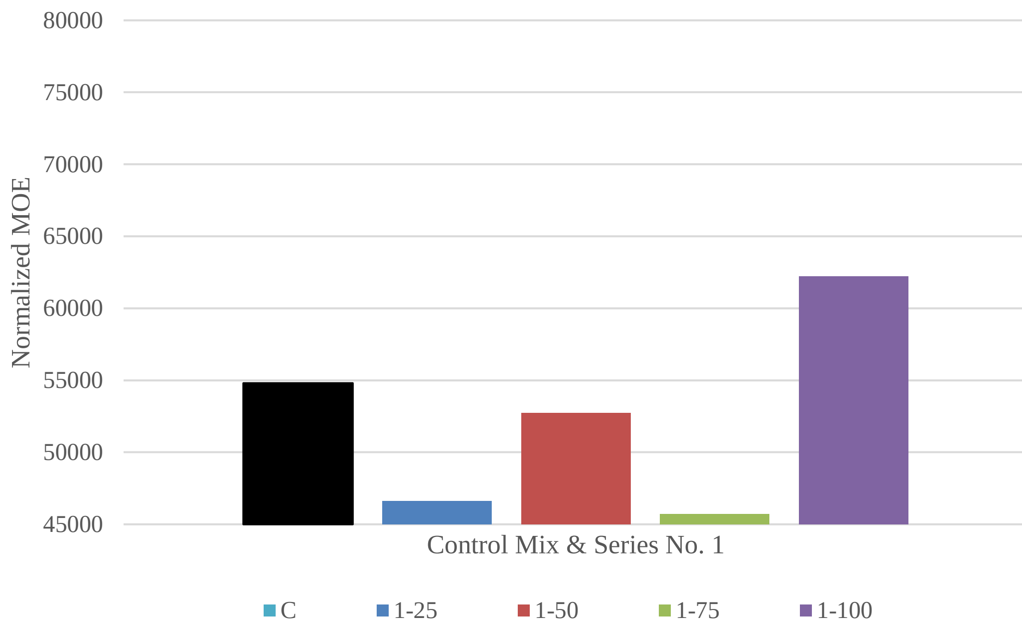

Figure 4.27 Normalized MOE for Series No. 1 & Control

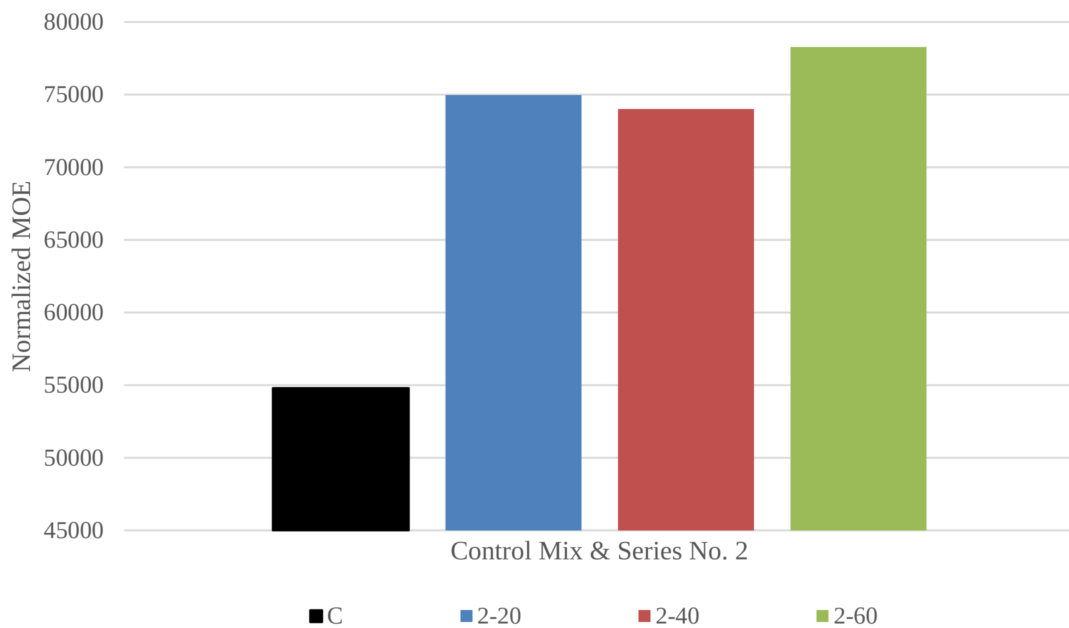

Figure 4.28 Normalized MOE for Series No. 2 & Control

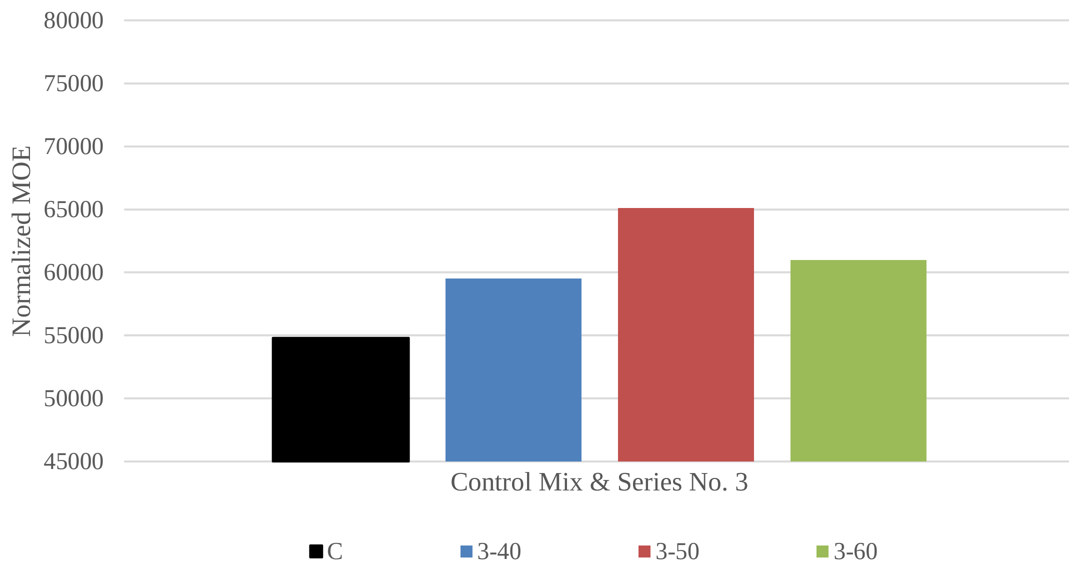

Figure 4.29 Normalized MOE for Series No. 3 & Control

Figures 4.30, 4.31, and 4.32 graphically compare the normalized splitting tensile strength of the mixes in Series No. 3 to the Control mix. Equation 4.3 shows the numerical relationship between the splitting tensile strength, f_{tsp}, and the compressive strength (CEB-FIP 1999).

$$f_{tsp} = 1.57{f'}_c^{2/3} \qquad \text{(Eq. 4.3)}$$

From Equation 4.3, typical concrete should reach a unitless value of 1.57 when dividing the splitting tensile strength by the average compressive strength raised to the two-thirds power. The control mix for this research reached a unitless value closer to 1.4.

Figure 4.30 shows that increasing RCA content yields very little change in the normalized splitting tensile strength compared to the control mix.

Figure 4.31 shows that increasing fly ash provides an increase in the normalized splitting tensile strength. With the increase, the average unitless value reached is close to the 1.57 predicted by Equation 4.3.

Figure 4.31 shows that increasing fly ash with 100% RCA replacement causes a drastic decrease in the normalized splitting tensile strength of the concrete.

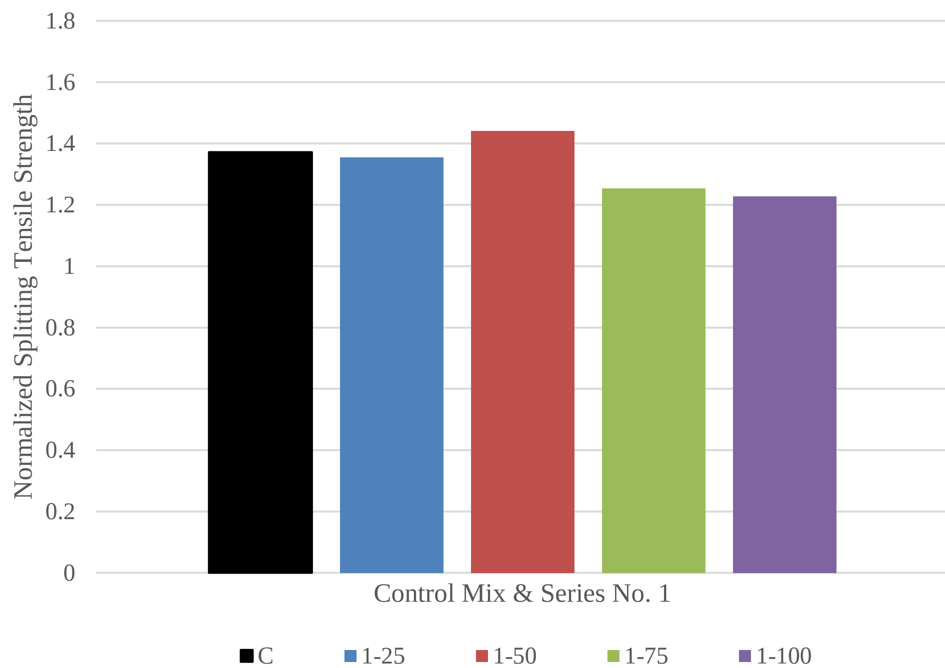

Figure 4.30 Normalized Splitting Tensile Strength for Series No. 1 & Control

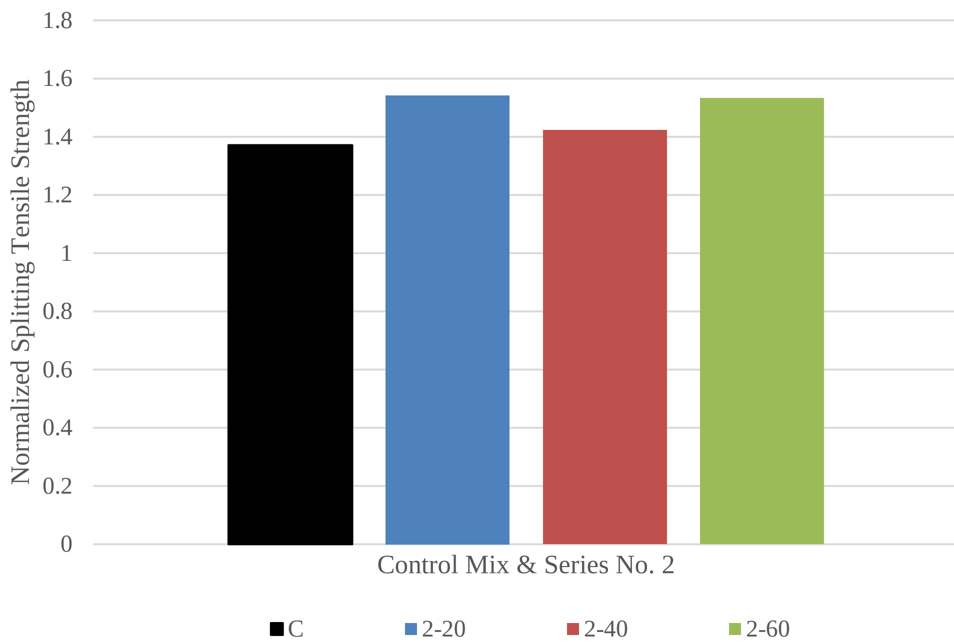

Figure 4.31 Normalized Splitting Tensile Strength for Series No. 2 & Control

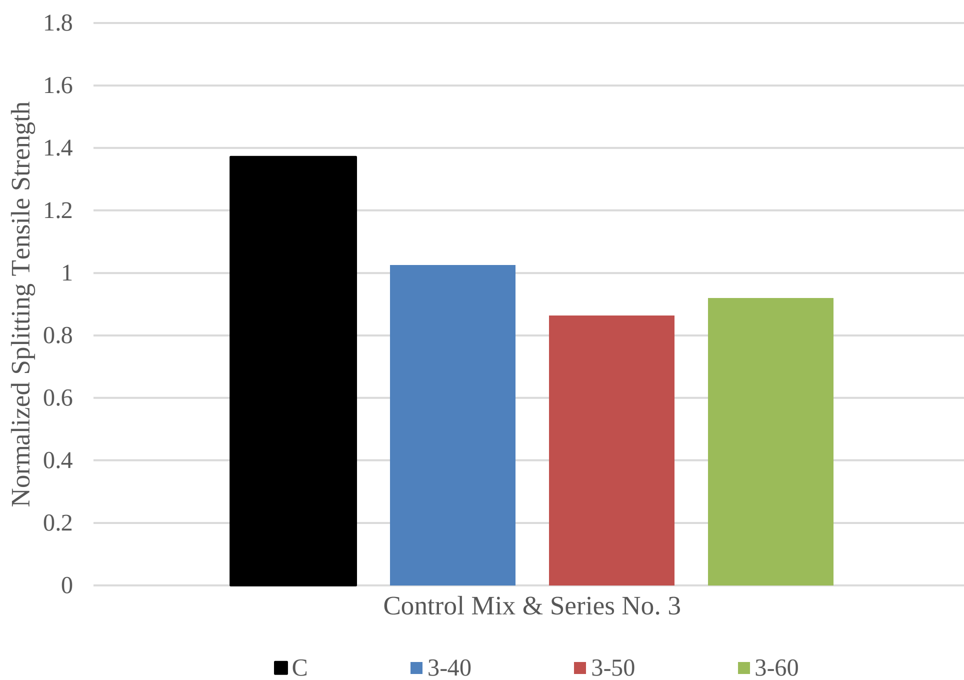

Figure 4.32 Normalized Splitting Tensile Strength for Series No. 3 & Control

5 Fines Study

5.1 Introduction

An additional aspect of this research was to study the effects of increasing the amount of reclaimed fine aggregate in the mix. In general, concrete mixes containing RCA have an undesirable decrease in workability. One potential cause for this is the amount of fine aggregates present. Figure 5.1 again shows the rough texture of RCA. The fine aggregates attached to the surface of the larger particles is what creates a challenge when in regards to workability and increased water absorption. The RCA fines were removed from the RCA source material by sieving over a #4 sieve.

Figure 5.1 Rough RCA Surface

This portion of the research was chosen to continue with the original naming scheme found in the preceding chapters; the RCA fines study will be referred to from this point forward as Series No. 4. Table 5.1 describes the various mixes studied in this series. Table 5.2 displays the naming scheme for each mix.

Table 5.1 Breakdown of RCA Fines Study

Test Name	Varying Mixes in the Series
Series No. 4	5%, 15%, 25%, 35% RCA Fine Aggregate Replacement with 100% RCA Coarse Aggregate Replacement

Table 5.2 Naming Scheme of Series No. 4

Naming Scheme	Description	%RCA Fines
4-5	Series No. 4: RCA Fines Replacement with 100% RCA Coarse Aggregate Replacement	5%
4-15		15%
4-25		25%
4-35		35%

5.2 Series No. 4: Recycled Fine Aggregate Replacement

Table 5.3 displays the mix design for each mix in Series No. 4. The only change between the mixes involved the substitution of RCA fines for river sand. It should also be noted that the standard RCA coarse aggregate material contained 4% to 5% RCA fines.

Table 5.3 Series No. 4 Mix Design

ID	Cement	Water	River Sand	Added RCA Fines	RCA Coarse	Air Entraining Admixture	Water Reducer Admixture
	(lb)	(lb)	(lb)	(lb)	(lb)	(oz/cwt)	(oz/cwt)
4-5	517	248	1559	0	1588	0.15	2.5
4-15	517	248	1384	175	1588	0.15	2.5
4-25	517	248	1225	333	1588	0.15	2.5
4-35	517	248	1066	492	1588	0.15	2.5

5.2.1 Workability Discussion

In several studies, authors have stated that workability suffers due to the presence of recycled fine aggregate (Andal et al, 2016). However, this portion of the research was found to be contrary to those studies. Mix 4-5 closely resembled the previously discussed 1-100 mix. Both 1-100 and 4-5 were difficult to work with and difficult to finish as paste seemed minimal. With increased RCA fines, the workability and finishability noticeably improved. Figures 5.2, 5.3, and 5.4 show the consistency of each mix by displaying the concrete of mixes 4-15, 4-25, and 4-35 in the air pot and slump cone.

Figure 5.2 Mix 4-15 Close-Up in Air Pot and Slump Cone

Figure 5.3 Mix 4-25 Close-Up in Air Pot and Slump Cone

Figure 5.4 Mix 4-35 Close-Up in Air Pot and Slump Cone

It is easy to see how the paste improved with increasing percentages of RCA fines replacement. With increased paste, workability was better and the finishability was noticeably improved.

5.2.2 Fresh Concrete Properties

The fresh concrete properties, which include slump, air content, and unit weight, are summarized in Table 5.4.

Table 5.4 Fresh Concrete Properties for Series No. 4

ID	**Fresh Concrete Properties**		
	Slump (in.)	Air Content (%)	Unit Weight (lb/ft^3)
4-5	0.25	4.5	143.9
4-15	0.5	7.4	138.3
4-25	0.75	4.5	140.7
4-35	0.75	3.5	141.5

5.2.3 Hardened Concrete Properties

The scope of this portion of the research was intended to be much more of a topical investigation rather than as in-depth as Chapter 4. Therefore, the only hardened property measured was the compressive strengths of each of the mixes at 28 days. Table 5.5 displays the compressive strength test results. Figure 5.5 shows the specimen from batch 4-35 after loading. Figure 5.6 displays a graph of each mix's average compressive strength for comparison.

Table 5.5 Compressive Strength for Series No. 4

ID	**Compressive Strength at 28 Days** (psi)
4-5	4355
	4880
	4890
4-5 Avg	**4708**
4-15	4490
	5645
	5530
4-15 Avg	**5222**
4-25	4975
	5040
	5065
4-25 Avg	**5027**
4-35	5440
	5495
	5450
4-35 Avg	**5462**

Figure 5.5 4-35 At 28-Day Strength Post-Loading

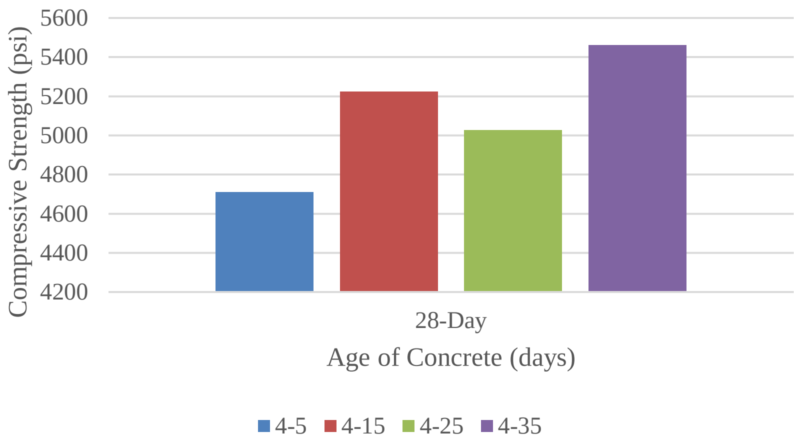

Figure 5.6 Comparison of 28-Day Compressive Strength for Series No. 4

5.2.4 Discussion

Of the fresh concrete test results, slump provided the most linear results. As the percentage of recycled fines were incorporated into the mix, the slump increased. However, since all of the mixes proved to have less than one inch for slump, any change is somewhat negligible.

The air content for Series No. 4 remained fairly steady, with the exception of one outlier. It is interesting to note that the mix with the highest recorded air content was mix 4-15, and the lowest recorded air content was for mix 4-35. This result is intuitively reverse, which proves how inconsistent and unpredictable recycled aggregate can be.

Similarly, the unit weight for each mix in this series was also relatively equal. However, the unit weight of each mix of Series No. 4 was noticeably lower than that of the control mix, which is likely due to the decreased specific gravity of the recycled fines compared to natural sand.

The compressive strengths for Series No. 4 proved to be slightly inconsistent. The mix with the lowest 28-day compressive strength was 4-5, which is equivalent to the control mix. The mix with the highest 28-day compressive strength was 4-35, which had the largest fines replacement with recycled fine aggregate. However, the compressive strength for 4-25 was lower than that of 4-15. The correlation of increased recycled fines percentage and increased compressive strength is therefore slightly disturbed.

5.3 Summary

This section briefly discussed the results of concrete with increasingly high percentages of recycled fines. Unlike previous research studies, incorporating more than 5% of recycled fine aggregate can produce concrete with acceptable and satisfactory qualities. Results in this chapter proved that strength is sufficient and workability is achievable when using concrete with large amounts of recycled fine aggregates. It is recommended that further research be conducted to discern the appropriate and plausible uses for recycled concrete fines.

6 Durability Testing

6.1 Introduction

The performance of each specimen during durability testing is somewhat the climax of this research. Aggregate strength, gradation, moisture content, specific gravity, absorption, shape, and texture are all characteristics of aggregates that contribute to the strength and durability of concrete. Incorporating high volumes of recycled materials into various mix designs alters the aforementioned characteristics and then in turn affects the longevity of the concrete. Therefore, if concrete with large percentages of RCA replacement provides high-strength concrete but has a much shorter lifespan than concrete with virgin coarse aggregate, then the question arises if RCA use is economical and therefore reasonable in pavement applications.

Two different durability tests were preferred – freeze-thaw and ponding. Table 6.1 lists the two tests performed with the associated ASTM references. For this portion of the research, not all of the previously developed mix designs were used for durability testing. The mix designs selected for durability testing are displayed in Table 6.2. The same identification scheme was used to mark and describe durability specimens as was done in previous portions of this report.

Table 6.1 Durability Tests Performed with Respective ASTM References

Test Category	Test	ASTM Reference
Durability	Freeze-Thaw	C 666
	Ponding	C 672

Table 6.2 Mixes Used Per Durability Test

Durability Test	Mixes Used
Freeze-Thaw	C, 1-25, 1-100, 2-20, 2-60, 3-40, 3-60
Ponding	C, 1-100, 3-40, 3-60

Limiting the mixes to the ones mentioned in Table 6.2 was due to the size of the testing apparatus. The Freeze-Thaw apparatus could house more specimens, and the ASTM had no stipulation on number of duplicate specimens per mix. On the contrary, the ASTM for ponding specimens required at least two specimens per mix be cast. Therefore, the number of mixes to be tested was limited to the four most representative.

6.2 Freeze-Thaw

6.2.1 Freeze-Thaw Testing

As previously stated, the freeze-thaw testing method was performed in accordance with ASTM C666. The stipulations of the standard require either (a) a record of change in specimen length or (b) a record of modulus of elasticity per every 36 cycles. This research aligns with option (b). In order to obtain the Modulus of Elasticity, a frequency meter was used. Figures 6.1 and 6.2 display the test set-up using the Emodumeter prior to testing (0 cycles). Freeze-thaw testing began once the specimens reached an age of fourteen days.

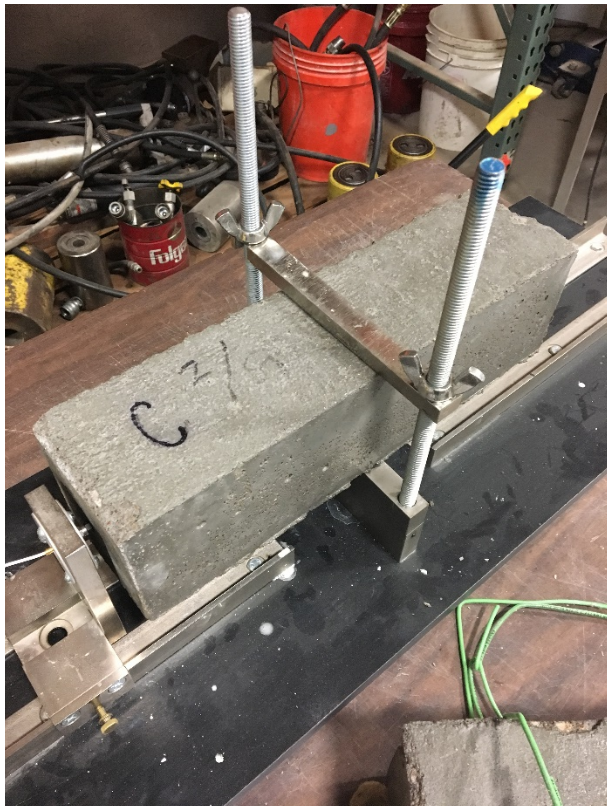

Figure 6.1 Control Specimen in MOE Apparatus at 0 Cycles

Figure 6.2 Control Specimen Undergoing MOE Testing at 0 Cycles

After the first 36 cycles, the Freeze-Thaw apparatus was shut off. Figure 6.3 depicts the condition of each of the specimens just after shutting the machine off. As shown in the picture, the specimens were undergoing a round of freezing. The wire shown was a coated wire 1/8” thick, and it ensured that the specimen was encased in at least 1/8” water. It also provided a handle for removing each specimen from the trays.

Figure 6.3 Freeze-Thaw Specimens After 36 Cycles

After the specimens were fully thawed, they were then placed in a lime bath for 24 hours as shown in Figure 6.4. Soaking for at least 24 hours ensured that the specimens were of the same moisture level at each cycle of testing. Then, modulus of elasticity values were determined using the Emodumeter, and the condition of each specimen was noted. Figures 6.5 through 6.8 depict the conditions of Specimens 2-60, 1-100, and Control, respectively, after 36 cycles. It is obvious that the mix containing high amounts of fly ash are noticeably affected on the exterior by the rapid freezing and thawing conditions after just approximately one week of undergoing 36 cycles.

Specimens were placed back in the freeze-thaw chamber for another approximate 36 cycles. In accordance with ASTM C666, this process was repeated until the modulus of elasticity was tested to be 60% of the original value. However, the specimens continued to undergo freeze-thaw testing.

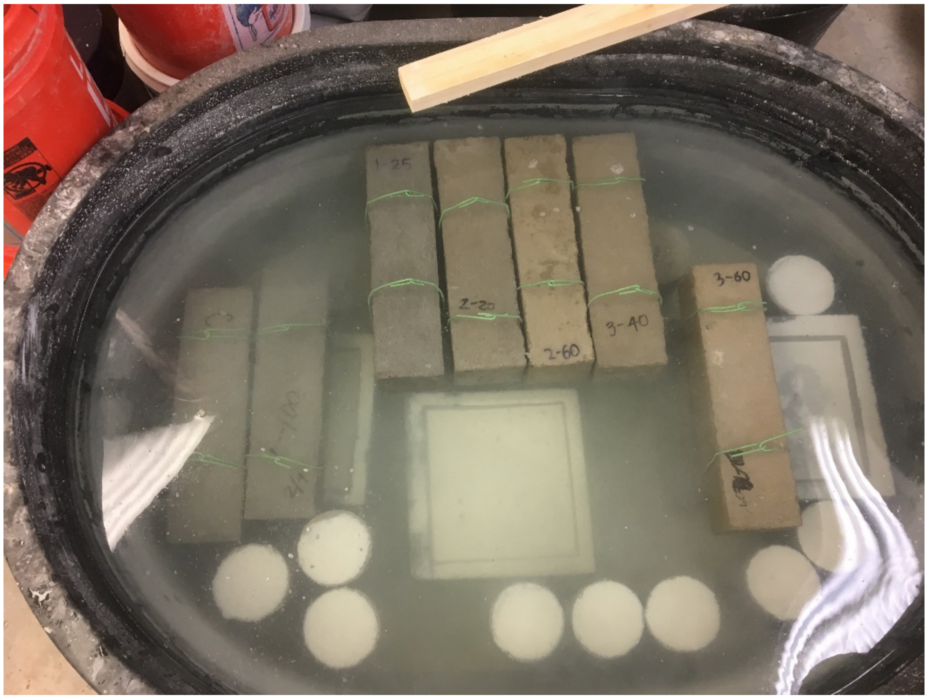

Figure 6.4 24-Hour Soaking after 36 Cycles

Figure 6.5 Condition of 2-60 After 36 Cycles

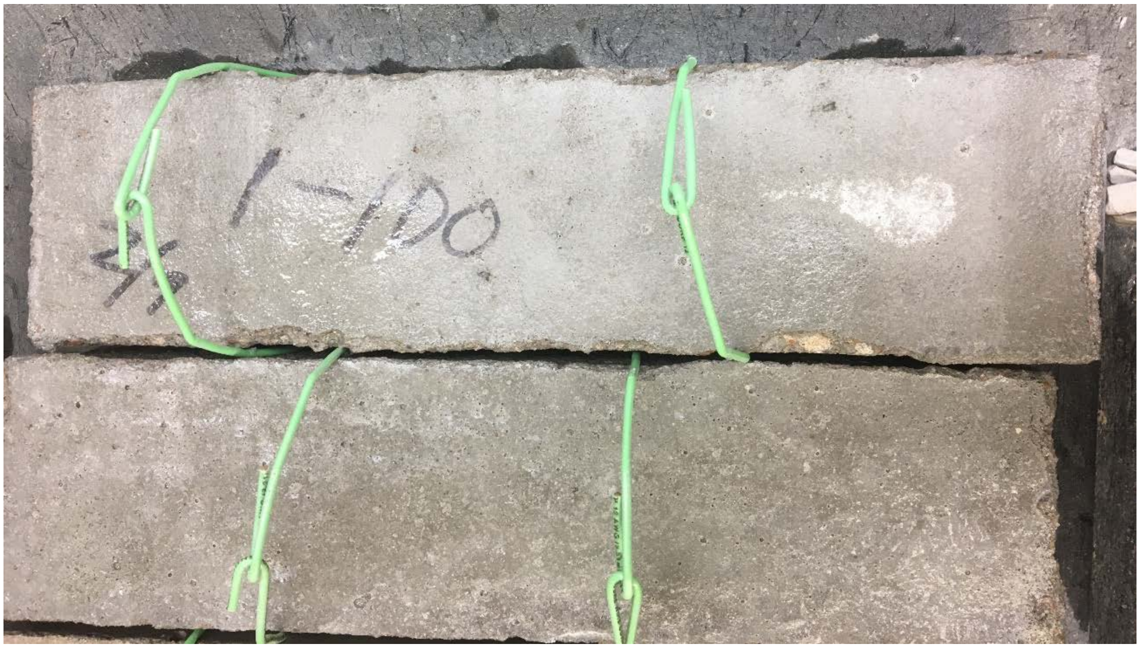

Figure 6.6 Condition of 1-100 After 36 Cycles

Figure 6.7 Close-Up of 1-100 After 36 Cycles

Figure 6.8 Condition of Control After 36 Cycles

Figures 6.9 through 6.12 show the conditions of select specimens after 300 cycles. An end and side view of the control specimen is shown in Figure 6.9. Figure 6.10 captures the final condition of 1-100. A side view of 2-60 is presented in Figure 6.11, and a top view of specimen 3-60 is shown in Figure 6.12.

Figure 6.9 End and Side View of Control After 300 Cycles

Figure 6.10 Side View of 1-100 After 300 Cycles

Figure 6.11 Side View of 2-60 After 300 Cycles

Figure 6.12 Top View of 3-60 After 300 Cycles

6.2.2 Freeze-Thaw Results

According to ASTM C666, the freeze-thaw cycles are to stop once the specimens reach 60% of their original modulus of elasticity or at 300 cycles, whichever occurs first. Table 6.3 displays the original versus the 60% modulus of elasticity for each respective specimen. Table 6.4 shows the modulus of elasticity values for each specimen with increasing number of freeze-thaw cycles. The cells highlighted in yellow represent the specimens that have reached 60% of their original modulus of elasticity values. Figure 6.9 is a visual representation of the decline in modulus of elasticity versus number of cycles.

Table 6.3 Original Modulus of Elasticity vs. 60% Modulus of Elasticity

ID	Original MOE	60% of Original MOE
C	7,657,993	4,594,796
1-25	7,048,834	4,229,300
1-100	6,468,683	3,881,210
2-20	7,251,887	4,351,132
2-60	6,468,683	3,881,210
3-40	6,091,585	3,654,951

Table 6.4 Modulus of Elasticity (psi) of Each Specimen per Number of Cycles

ID	Number of Cycles							
	0	36	73	108	148	185	225	304
C	7,657,993	7,454,940	7,251,887	6,468,683	4,235,102	-	-	0
1-25	7,048,834	6,657,232	6,468,683	6,468,683	5,206,855	4,873,268	3,219,838	1,174,806
1-100	6,468,683	6,280,134	6,091,585	5,728,991	5,206,855	4,380,140	3,640,447	2,465,642
2-20	7,251,887	7,251,887	7,251,887	7,251,887	7,251,887	7,251,887	7,251,887	7,251,887
2-60	6,468,683	6,468,683	6,468,683	6,468,683	6,468,683	6,468,683	6,468,683	6,280,134
3-40	6,091,585	5,917,540	5,728,991	5,554,945	4,699,223	3,785,485	3,219,838	1,102,287
3-60	5,728,991	5,554,945	5,380,900	4,873,268	3,785,485	3,495,410	2,828,236	870,226

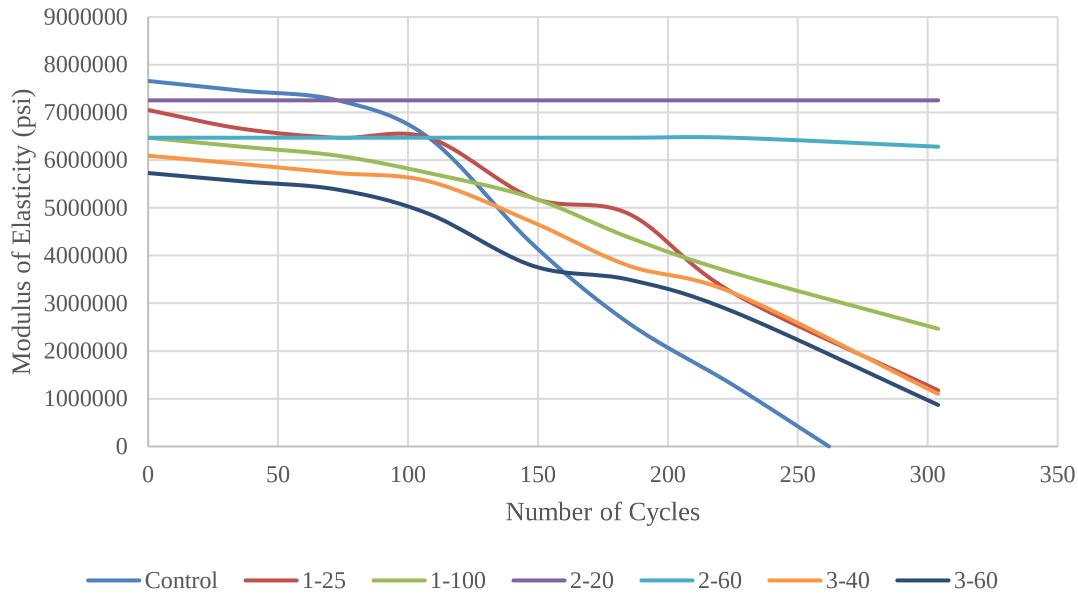

Figure 6.13 MOE of Each Specimen per Number of Cycles

6.3 Ponding

6.3.1 Ponding Testing

The ponding specimens were cast and tested according to ASTM C 672. The purpose of this test is to visually inspect the surface quality of concrete after being exposed to deicing chemicals such as a salt solution. Specifically, this research focuses on the optimal mix design that provides the best resistance to salt scaling after an extended exposure to heating and freezing cycles. The specimens were called to have at least a one-inch dike surrounding a ponded area of at least 72 square inches. The depth of concrete below the ponded area was three inches.

The ASTM specified 14 days of moist curing followed by 14 days of air curing. Figure 6.10 shows how moist curing was achieved. Wet burlap was placed over all of the specimens, and plastic was tightly placed on top. This allowed for evaporated moisture to remain contained and still effective. Figure 6.15 shows the specimens at 14 days old, having completed the time requirement for moist curing, and ready to begin 14 days of air curing. Then, Figure 6.16 shows the specimens released of the formwork.

Figure 6.14 Ponding Specimens - Moist Curing

__Figure 6.15 Ponding Specimens Prior to Demolding at Age 14 Days__

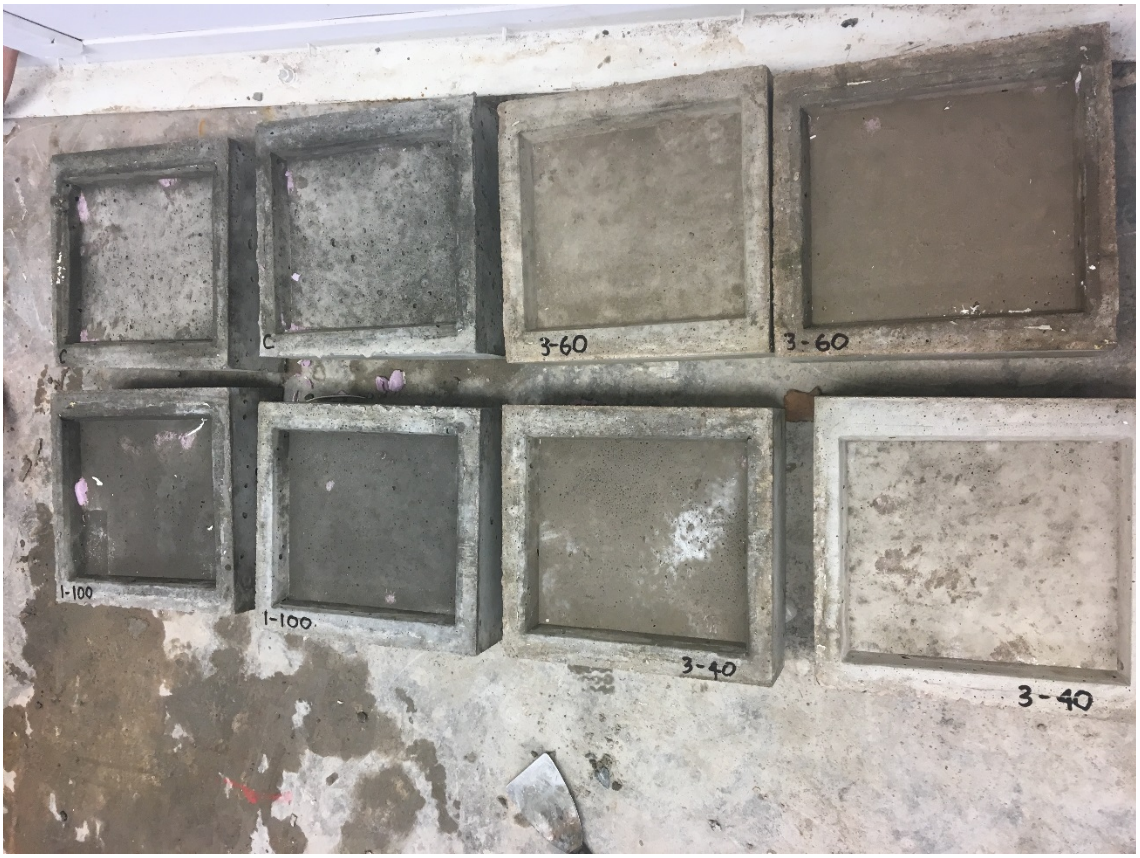

Figure 6.16 Ponding Specimens - Air Curing

6.3.2 Ponding Results

ASTM C 672 requires a visual examination take place every 25 cycles. Table 6.4 provides the visual rating scale used, and Table 6.5 provides the ratings of each specimen cast per 25 cycles according to the same specimen identification scheme used throughout.

Table 6.5 Visual Rating of Specimen Surfaces According to ASTM C 672

Rating	Condition of Surface
0	No scaling
1	Very slight scaling (1/8 in. depth max, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

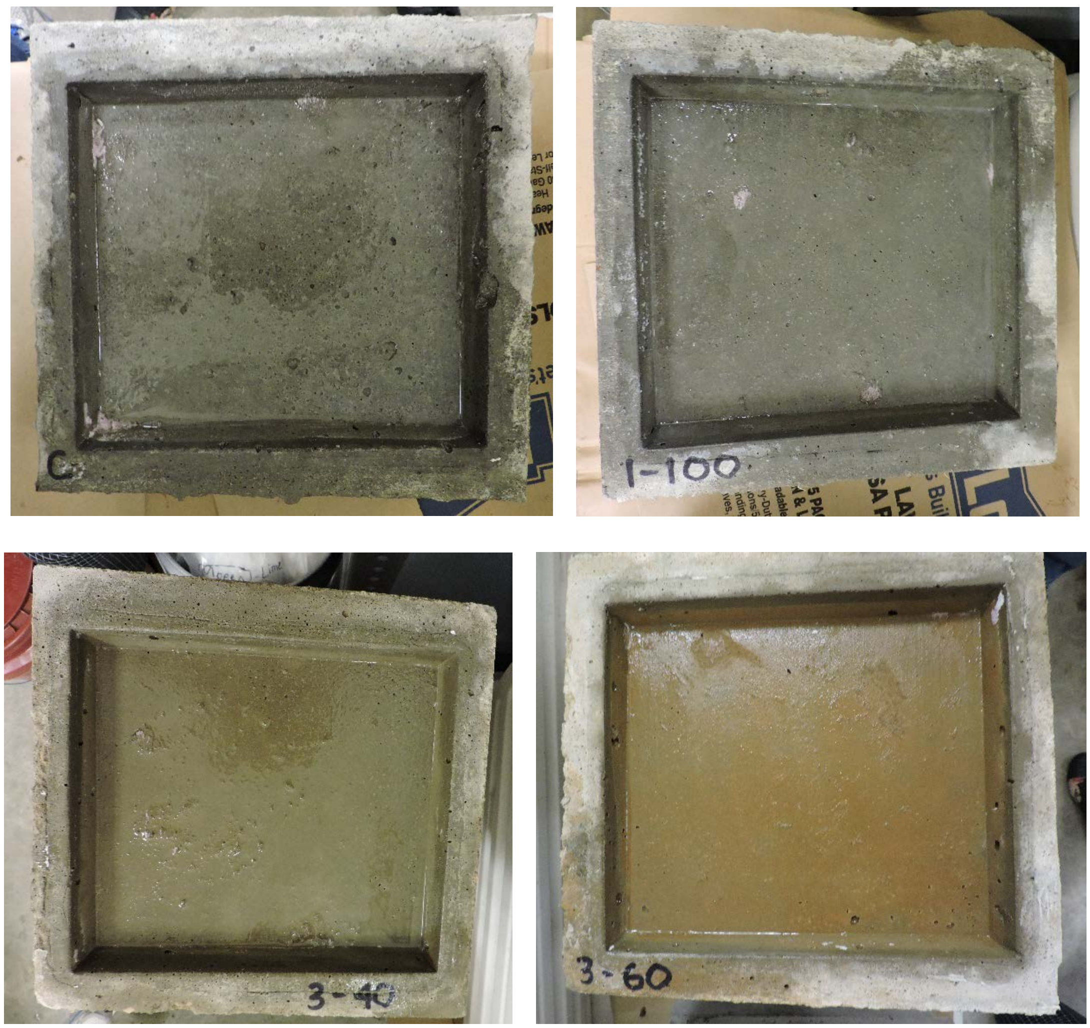

Figure 6.17 After 25 Cycles

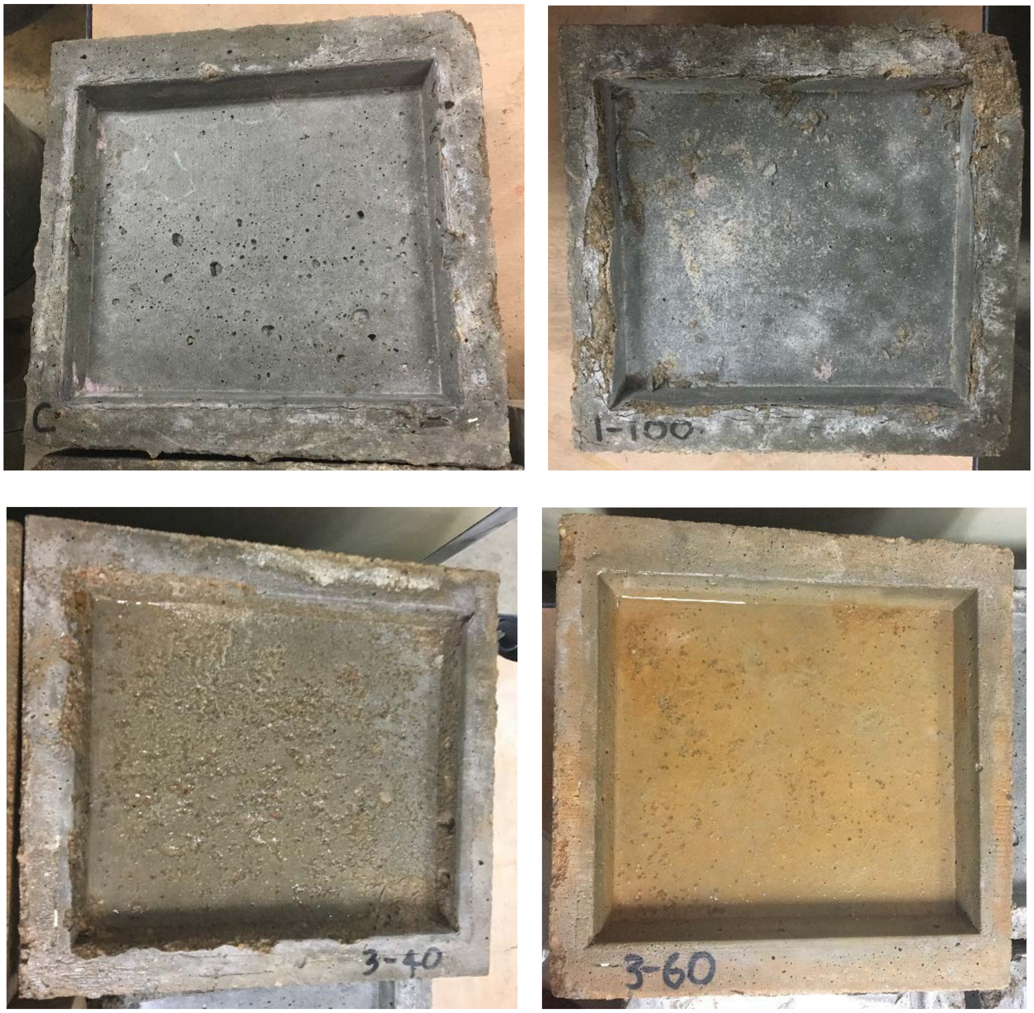

Figure 6.18 After 50 Cycles

Table 6.6 Rating of Each Mix Per 25 Cycles

ID	Rating per Number of Cycles				
	5	10	15	25	50
C	0	0	0	0	0
1-100	0	0	0	0	0
3-40	0	0	0	0	0
3-60	0	0	0	0	0

6.4 Summary

This section of research focused on the behavior of specific concrete specimens after being subjected to two different durability tests, the Freeze-Thaw test and the Ponding test.

Simply stated, the main goal of the freeze-thaw test was to record the degradation of the concrete specimens as they were exposed to up to 300 cycles of freezing and thawing. The integrity of each concrete specimen was evaluated by using an Emodumeter, a machine that calculated the modulus of elasticity after a wave traveled longitudinally through the length of the concrete specimen. Ideally, the best mix design would yield a concrete specimen that endured 300 cycles of freezing and thawing with very little decrease in modulus of elasticity.

Mix 2-20 maintained the highest modulus of elasticity after 300 cycles. In fact, at 300 cycles, the specimen still preserved 97% of its original modulus of elasticity even though the concrete specimen itself was highly eroded visually. Mix 2-20 had the second highest modulus of elasticity value after 300 cycles. It is obvious that fly ash has certain natural properties that keep its particles more tightly bound than what appears on the outside of the specimen. Mix 1-100 surprisingly had the third highest modulus of elasticity value after 300 cycles, maintaining 38% of its original modulus of elasticity value. The mix that performed the worst was the control mix where the specimen reached a modulus of elasticity value of 0 psi after approximately 250 cycles.

The second durability test used in this research was the ponding test. The goal of this test was to evaluate the condition of eight specimens after experiencing 50 freezing and thawing cycles in the environmental chamber. The major difference between the ponding test and the freeze-thaw test was the humidity component. The freeze-thaw test had no requirements for humidity, while the ponding test required at least 50% humidity at all times. Unlike the freeze-thaw test, the method of evaluating the degradation of the concrete specimen was done visually instead of with a piece of equipment.

After 50 cycles, the four concrete mix designs showed very little degradation in the areas where water ponded. However, a few of the concrete specimens appeared to have major degradation around the outside dam. Mix 1-100 had the most visible erosion around the outside dam, while Mix 3-40 experienced more degradation to the base of the ponding portion. The mix that underwent 50 cycles and showed the least amount of degradation was Mix 3-60.

Based on the two durability tests, it appears that the RCA does not diminish the longevity of the concrete compared to the control mix, which had virgin limestone aggregate and no fly ash. Furthermore, the mixes containing fly ash had better freeze-thaw performance in terms of modulus of elasticity than the control mix but showed severe degradation at the surface. Additional studies using lower water-cement ratios for all mixes is recommended to ensure adequate durability of pavement concrete.

7 Findings, Conclusions, and Recommendations

The following chapter will briefly summarize the findings, conclusions, and recommendations from this research study. As a reminder, Series No. 1 varied the percentage of RCA replacement of coarse aggregate; Series No. 2 varied the percentage of fly ash replacement of cement with all virgin aggregates; Series No. 3 varied the percentage of fly ash replacement of cement with 100% RCA coarse aggregate; and Series No. 4 varied the percentage of RCA fines with 100% RCA coarse aggregate and no fly ash replacement.

7.1 Findings:

The following findings were observed during the course of this study:

- Coarse RCA source material fell within ODOT gradation limits for #57 except at the 1-in.-sieve size (84.9% passing vs. 95% passing requirement)
- Fine RCA source material fell within ODOT gradation limits for fine aggregate
- Coarse RCA had higher absorption (4.27% vs. 0.86%), lower specific gravity (2.38 vs. 2.64), and lower DRUW (91.5 pcf vs. 101.5 pcf) compared to #57 limestone aggregate
- Fine RCA had higher absorption (6.82% vs. 0.40%) and lower specific gravity (2.41 vs. 2.58) compared to natural sand
- Coarse RCA had higher LA abrasion loss (37% vs. 24%) compared to #57 limestone aggregate but still satisfies ODOT limits
- Coarse RCA is less angular than #57 limestone coarse aggregate

- Coarse RCA has a lower texture index than #57 limestone coarse aggregate but is considerably rougher to the touch
- For Series No. 1, as the percentage of RCA increased, the slump decreased and the air content decreased
- For Series No. 2, as the percentage of fly ash increased, the slump increased
- For Series No. 3, as the percentage of fly ash increased, the slump remained essentially unchanged
- For Series No. 1, there was no trend in compressive strength for increasing amounts of RCA replacement
- For Series No. 2, as the percentage of fly ash increased, the compressive strength decreased
- For Series No. 3, as the percentage of fly ash increased, the compressive strength decreased, and Mix 3-60 (100% RCA and 60% fly ash) required 56 days to reach the 3,000 psi target
- Except for Mix 1-100 (100% RCA, no fly ash), all mixes had lower compressive strengths than the control concrete
- For Series No. 1, as the percentage of RCA increased, the normalized modulus of rupture (MOR) and normalized split tensile strength (tensile strength) decreased while the normalized modulus of elasticity (MOE) had no specific trend

- For Series No. 2, as the percentage of fly ash increased, the normalized MOR decreased, the normalized MOE increased, and the normalized tensile strength had no specific trend
- For Series No. 3, as the percentage of fly ash increased, the normalized MOR and normalized tensile strength decreased while the normalized MOE increased
- For Series No. 4, as the percentage of fine RCA increased, the slump had a slight increase and the compressive strength increased
- In terms of freeze-thaw resistance, only the two Series No. 2 mixes (20% and 40% fly ash replacement with virgin aggregates) met the ODOT requirements, although both specimens suffered severe surface damage
- In terms of salt scaling resistance, none of the mixes suffered any noticeable deterioration after 50 cycles

7.2 Conclusions:

Based on the previously outlined findings, the following conclusions were developed:

- The decrease in slump with increasing percentage of RCA replacement is likely due to the rougher texture of RCA compared to virgin limestone aggregate as well as the 4% to 5% attached RCA fines, which are both rougher and more angular than natural sand
- The lack of any noticeable trend in compressive strength with increasing percentage of coarse RCA replacement is likely due to the variable and relatively high porosity of RCA compared to virgin aggregate and possibly a

rate of absorption effect (i.e., additional mix water to saturate the aggregate does not get fully absorbed)

- Coarse RCA reduces the normalized MOR and normalized tensile strength likely due to the double interfacial transition zone
- It is possible to develop concrete containing high volumes of recycled material that meet ODOT Class A strength requirements
- Concrete containing up to 47% recycled material (Mix 3-60) met ODOT Class A strength requirements but required 56 days
- Durability behavior of concrete containing high volumes of recycled material is mixed with no definitive conclusions possible

7.3 Recommendations:

The goal of this study was to identify ways in which to create a more sustainable concrete mix design by using recycled materials and waste by-products while simultaneously decreasing greenhouse gas emissions and lowering cement production. The findings and conclusions previously mentioned led to the following recommendations:

- Investigate the rate of absorption of RCA coarse and fine aggregate
- Investigate the fresh properties, hardened properties, and durability of lower water-cement ratio mixes containing large amounts of recycled material
- Further investigate the effect of high amounts of RCA fine replacement of sand on the fresh and hardened properties of concrete mixes

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