EVALUATION OF RECYCLED CONCRETE FOR USE AS AGGREGATES IN NEW CONCRETE PAVEMENTS

By

DANIEL GILBERT MJELDE

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

WASHINGTON STATE UNIVERSITY
Department of Civil and Environmental Engineering

JULY 2013

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of DANIEL GILBERT MJELDE find it satisfactory and recommend that it be accepted.

_____
David McLean, Ph.D., Co-Chair

_____
Haifang Wen, Ph.D., Co-Chair

_____
William Cofer, Ph.D.

ACKNOWLEDGEMENTS

I am greatly appreciative of the financial support provided by the Washington State Department of Transportation and the Pacific Northwest Transportation Consortium.

I would like to express my deepest gratitude to Dr. David McLean for offering me a graduate research assistantship and for serving as co-chair of my committee. I am also profoundly grateful for the constant support and guidance he provided.

I thank Dr. Haifang Wen for serving as co-chair of my committee and for providing advice throughout my research. I also thank Dr. William Cofer for serving on my committee.

My thanks to Spencer Boyle and Tim Spry for their hard work and friendship throughout this project. I gratefully acknowledge the always eager assistance of Kevin Stewart, Neil Hartman, and Kyle Spangenberg. I also thank Miles Pepper and the WSU CEA Shops staff.

Finally, I would like to thank my family for always being there for me.

EVALUATION OF RECYCLED CONCRETE FOR USE AS AGGREGATES

IN NEW CONCRETE PAVEMENTS

Abstract

by Daniel Gilbert Mjelde, M.S.
Washington State University
July 2013

Committee Co-Chairs: David McLean and Haifang Wen

The primary objective of this research is to determine if recycled concrete aggregate (RCA) sourced from demolished pavements in the central region of Washington State can be effectively utilized in new concrete pavements. The effects of two variables on concrete properties were evaluated in this study: the percentage of natural coarse aggregate replaced by RCA, and the incorporation of a 20% substitution of cement with Type F fly ash along with varying percentages of RCA replacement. Eight concrete batches were produced and a series of fresh and hardened concrete samples were created from each batch. The fresh concrete samples were tested for slump, air content, and density, and the hardened concrete samples were tested for compressive strength, modulus of rupture, and coefficient of thermal expansion. Tests were performed on the RCA to determine the absorption, specific gravity, Los Angeles abrasion loss, degradation value, and alkali-silica reactivity.

Incorporating RCA into a concrete mix decreased the workability of the fresh concrete. In contrast, substituting fly ash increased the workability of fresh concrete and could be utilized to counter the slump reduction caused by the addition of RCA. A higher percentage of RCA

substitution correlated to a lower fresh concrete density. The percentage of RCA substitution did not have an influence on compressive strength, modulus of rupture, or coefficient of thermal expansion. All of the concrete mixes with RCA investigated in this study, including up to a 45% substitution of RCA, met all Washington State Department of Transportation (WSDOT) requirements for portland cement concrete pavements.

The conclusions from this study indicate that coarse RCA can be suitable for use as an aggregate source for concrete pavements. Further, the restriction of 30% substitution of RCA recommended in previous studies may be overly restrictive. In order meet the WSDOT minimum degradation value for aggregates, it is recommended that the RCA be washed and fine materials removed prior to use.

TABLE OF CONTENTS

CHAPTERS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background

As many of the vast expanse of highways across the United States are nearing the end of their service lives, the task of replacing them is becoming a growing concern (FHWA 2007). There are many factors that must be considered for projects of this magnitude. As part of the replacement process, the existing roads are demolished, and the debris material has to be transported away and disposed of in a safe manner. Typically, all of this material is dumped in landfills (FHWA 2007).

Another issue with replacing roads is that the supply of quality virgin natural aggregates is dwindling, and as a result the cost of using these virgin aggregates continues to increase. Transportation agencies and researchers across the country have been investigating ways to mitigate these issues. One of the promising solutions being researched is the recycling of the demolished concrete pavements for use as aggregates in the new concrete pavements.

The use of recycled concrete as aggregates (RCA) would help to alleviate several of the concerns presented by the replacement of so many miles of highway. Pavements being demolished could be processed and then used as aggregate in constructing new concrete roadways. Using RCA in new pavements would reduce the demand on landfills, reduce the need for expensive virgin aggregates, and could potentially reduce overall project costs.

Currently, it is not common practice in the United States to use RCA in new concrete pavements (Garber, et al. 2011). Some of the main reasons that the use of RCA in new concrete pavements is limited include government agency restrictions, the resulting concrete's inability to meet certain performance specifications and requirements, and lack of consistent quality (Garber,

et al. 2011). There is also a common misconception among contractors and others in the pavement industry that RCA is not acceptable for use as aggregate in new pavements. Further, some states, such as Arizona, New Mexico, and Utah, prohibit the use of RCA (Anderson, Uhlmeyer and Russel 2009). Other states, such as Delaware, Georgia, and Kansas, will only allow it to be used in sub-base applications (Anderson, Uhlmeyer and Russel 2009).

The Federal Highway Administration (FHWA) has a policy in place regarding the use of recycled materials. The FHWA Recycled Materials Policy (Wright 2006) is as follows:

1. Recycling and reuse can offer engineering, economic and environmental benefits.
2. Recycled materials should get first consideration in materials selection.
3. Determination of the use of recycled materials should include an initial review of engineering and environmental suitability.
4. An assessment of economic benefits should follow in the selection process.
5. Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications.

The FHWA clearly encourages the use of recycled materials such as RCA. However, there are no specific guidelines detailing how RCA should be properly prepared or utilized.

The Washington State Department of Transportation (WSDOT) currently does not allow the use of RCA in concrete pavements. The WSDOT Standard Specifications for Road, Bridge, and Municipal Construction requires that all aggregates be free from any adherent coatings

(WSDOT 2012). Further, it indicates that no concrete rubble may be used as coarse aggregates for portland cement concrete pavement.

1.2 Scope and Objectives

The primary objective of this research is to determine if RCA sourced from demolished pavements in the central region of Washington State can be effectively utilized in new concrete pavements. The effects of two variables on concrete properties were evaluated in this study: the percentage of natural coarse aggregate replaced by RCA, and the incorporation of a 20% substitution of cement with Type F fly ash along with varying percentages of RCA replacement. Eight concrete batches were produced and a series of fresh and hardened concrete samples were created from each batch. The fresh concrete samples were tested for slump, air content, and density, and the hardened concrete samples were tested for compressive strength, modulus of rupture, and coefficient of thermal expansion. Tests were also performed on the RCA to determine the absorption, specific gravity, Los Angeles abrasion loss, degradation value, and alkali-silica reactivity.

This study is part of a larger research project that is investigating the properties of concretes made incorporating RCA obtained from three geographically-dispersed sources in Washington State. The methods used to investigate the other two RCA sources are identical to those used in this study. The overall goal of the research project is to evaluate the use of RCA for widespread application in concrete pavements in Washington State and beyond.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, previous research regarding RCA characteristics and the influences of RCA on fresh and hardened concrete are presented and discussed.

2.2 RCA Properties

It is critical to be able to accurately define the properties of RCA. This is because the properties of any concrete made with RCA are very dependent upon the quality of the RCA used (Limbachiya, Meddah and Ouchagour 2012). It is generally thought that if there is less mortar surrounding the RCA, the quality and effectiveness of the RCA will increase. The basis of this thought is the assumption that the RCA will exhibit properties similar to the original virgin aggregate used in the RCA source material (Garber, et al. 2011). Further, the better the source material used, the better the final concrete produced. Even if the RCA source concrete is not of the highest quality, it is still possible that the RCA could be used effectively in new concrete. However, the properties of the RCA must be accurately established before the effectiveness of the RCA can be determined for use in particular applications.

2.2.1 Specific Gravity

The specific gravity of RCA is typically lower than that of natural coarse aggregate. This is due to the mortar present on the aggregate. This mortar makes the material less dense than natural aggregate because of its porosity and entrained-air structure (Anderson, Uhlmeyer and Russel 2009).

The specific gravity of RCA is an important parameter because replacing natural coarse aggregate with RCA can result in a different total volume of batched concrete. If the specific gravity differences are not accounted for (i.e., substitution is by weight), the total yield of concrete will be greater than expected. Additionally, this would result in the overall proportions of aggregate to cement and to water being different. However, if the specific gravity difference is accounted for and the RCA is substituted based on volume, then the overall mix proportions will be as intended. Therefore, accounting for specific gravity differences can be important when incorporating RCA.

2.2.2 LA Abrasion Loss

Another important physical property of coarse aggregate is abrasion loss. The Los Angeles abrasion test is a method to determine how much an aggregate sample will abrade when impacted by steel spheres in a rotating drum. Typically, natural coarse aggregates yield an abrasion loss of between 15-30% (Anderson, Uhlmeyer and Russel 2009). Based on previous research, the abrasion loss for RCA can range from 20-45% (Anderson, Uhlmeyer and Russel 2009). The wide range of values comes from variations in quality of the aggregates.

Many pavement specifications, such as those in the WSDOT Specifications, require coarse aggregates to possess a maximum abrasion loss of 35% (WSDOT 2012). Thus, not all RCA sources would be acceptable based on this criterion. One of the major causes of the increased abrasion loss in RCA is that the bond between cement and natural aggregate is weaker than the inner structure of natural coarse aggregate (Amorim, de Brito and Evangelista 2012).

However, despite this weaker bond, many RCA samples do pass the Los Angeles abrasion limits and consequently would be acceptable for use in new concrete pavement.

2.2.3 Degradation Factor

The degradation factor is a measure of how much an aggregate will degrade when abraded in the presence of water (WSDOT 2012). In order for an aggregate to be used in a new concrete pavement, WSDOT requires it to possess a minimum degradation factor of 30 (WSDOT 2012).

2.2.4 Alkali-Silica Reactivity

The alkali-silica reaction in concrete is a major concern that impacts the durability of concrete. The alkali-silica reaction (ASR) is a chemical process that forms a gel within or around an aggregate. This gel swells as it draws water from the surrounding cement (Portland Cement Association 2002). As it absorbs the water, the gel expands, creating pressures within the concrete that can cause it to crack. For ASR to occur there must be sufficient moisture, a high-alkali pore solution, and a reactive form of silica in the aggregate. The alkali-silica reaction will not occur if any component is missing.

There is the possibility of increased ASR risk in concrete that incorporates RCA. One reason for this is that the additional crushing operation of RCA exposes more new surfaces to allow the reaction to take place (Anderson, Uhlmeyer and Russel 2009). Furthermore, if the source concrete for the RCA is known to exhibit ASR, the new concrete incorporating the RCA will most likely experience ASR (Ideker, et al. 2011). Therefore, ASR needs to be taken into

consideration for concretes made with RCA. However, the effects of ASR can be mitigated if the source material is identified as reactive (Ideker, et al. 2011). This can be accomplished by incorporating fly ash or low-alkali cement into the concrete mix design.

2.3 Fresh Concrete Properties

Three of the most important properties of fresh concrete are the workability, air content, and density. Previous research has shown that RCA has an influence on each of these properties.

2.3.1 Workability

Concrete mixtures made with RCA are typically less workable than those with only natural aggregates. This decreased workability comes from two sources. First, RCA has a more angular shape than natural aggregates which increases the friction between aggregates (Amorim, de Brito and Evangelista 2012). This is due to the crushing processes used in producing RCA. Second, the adhered mortar portion of the aggregate has increased water absorption. This higher absorption can reduce the effective mix water, thus making the mix harsher and less workable (Garber, et al. 2011). The decreased workability of RCA mixtures can be mitigated by adding more water to the mix design or by adding a water-reducing admixture.

2.3.2 Air Content

Concrete mixtures incorporating RCA tend to have slightly higher air contents than concrete mixtures with only natural aggregates. This is due to the entrained air of the adhered mortar portion of the RCA (Anderson, Uhlmeyer and Russel 2009). In an attempt to counter this

issue, it is recommended that as much of the mortar be removed from the RCA as is reasonable before incorporating it into a concrete mixture.

2.3.3 Density

The density of concrete mixtures incorporating RCA is typically lower than that of concrete made with only natural aggregates. The mortar portion of the RCA has an entrained air structure that is less dense than the rock it is adhered to. Therefore, as more RCA is incorporated into a concrete mixture, the resulting concrete density will be lower (Anderson, Uhlmeyer and Russel 2009).

2.4 Hardened Concrete Properties

Incorporating RCA can have several effects on hardened concrete properties. Five of these properties are compressive strength, modulus of rupture, coefficient of thermal expansion, drying shrinkage, and durability. One study found that up to a 30% substitution of RCA has no significant negative effects on hardened concrete properties (Limbachiya, Meddah and Ouchagour 2012).

2.4.1 Compressive Strength

Conclusions on the effects of RCA on compressive strength fall into two camps. Some research concludes that there is no difference in compressive strengths between normal and RCA concretes (Amorim, de Brito and Evangelista 2012). It is speculated that the stronger interfacial transition zone between the more angular aggregates and the new cement paste accounts for the

lack of a reduction in compressive strength. However, other research indicates that the compressive strength of concretes made incorporating RCA are typically lower than those with only natural aggregate (Anderson, Uhlmeyer and Russel 2009). Several factors have been suggested as contributing to cause the reduction in strength. RCA concretes typically require a higher water-cement ratio to achieve needed workability. An increased water-cement ratio has the effect of lowering the compressive strength of concrete. Further, RCA concretes usually have a higher air content. Concretes with higher air contents tend to have lower compressive strengths.

2.4.2 Modulus of Rupture

Modulus of rupture is defined as the flexural tensile strength of concrete when subjected to a flexural loading. Similar to the compressive strength, the modulus of rupture of concrete incorporating RCA has been reported to be lower than that of concrete with just natural aggregate. One study found that the flexural strength of RCA concrete can be up to eight percent lower than concrete with only natural coarse aggregate (Anderson, Uhlmeyer and Russel 2009). This strength reduction may be a result of the relatively weaker bond strength between the new cement paste and the mortar adhered to the RCA (Limbachiya, Meddah and Ouchagour 2012). Further, as with the compressive strength, the higher water-cement ratio and air content of RCA concretes may contribute to the reduced flexural strength.

2.4.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion is a material property that is used to define the expected length change of a material when subjected to a temperature loading. Ordinary concrete

typically has a coefficient of thermal expansion ranging from 3.2 to 7.0 millionths per degree Fahrenheit (Portland Cement Association 2002). The coefficient of thermal expansion of concrete is influenced by many factors, with aggregate type having the most effect (Portland Cement Association 2002). One report indicates that incorporating RCA decreases the coefficient of thermal expansion of hardened concrete (Smith and Tighe 2009).

2.4.4 Drying Shrinkage

The drying shrinkage of hardened concrete depends upon the ability of the aggregates to restrain the paste from shrinking. Since RCA has mortar adhered to the aggregate, there is less aggregate to restrain the drying shrinkage. Therefore, RCA concretes typically have an increased drying shrinkage (Anderson, Uhlmeyer, & Russel, 2009).

2.4.5 Durability

A major concern with the durability of concrete is the cracking that can come from the natural cycle of freezing and thawing. When water penetrates the aggregate and cement paste and then freezes, harmful expansion can occur. Concretes with an entrained-air structure are highly resistant to the harmful effects of the freeze-thaw cycle (Portland Cement Association 2002). It is anticipated that concretes incorporating RCA will be more resistant to freeze-thaw effects as a result of the porosity of the adhered mortar portion of the RCA (Anderson, Uhlmeyer and Russel 2009).

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 Introduction

Eight different concrete batches were produced from a reference portland cement concrete pavement (PCCP) mix design. The reference mix design used in this study, PCCP mix design C8022, was supplied by Central Pre-Mix located in Spokane, Washington. This reference mix design was provided by WSDOT to be representative of a typical PCCP mix. The reference mix design is given in Appendix A.

A series of fresh and hardened concrete samples were created from each of the eight batches. Two mix variables were evaluated in this study. The first variable evaluated was the percentage of natural coarse aggregate replaced by RCA. The second variable evaluated was the incorporation of a 20% substitution of cement with Type F fly ash along with different percentages of RCA replacement. Parameters for each of the eight batches are listed in Table 3.1.

Table 3.1. Parameters of the Eight Concrete Batches

Mix No.	Percent RCA Substitution	Percent Fly Ash Substitution
1	0%	0%
2	15%	0%
3	30%	0%
4	45%	0%
5	0%	20%
6	15%	20%
7	30%	20%
8	45%	20%

3.2 Materials

All of the materials used in this research project, with the exception of the RCA, met WSDOT's requirements and were the same as those used in the reference PCCP mix design.

3.2.1 Natural Aggregates

The natural aggregates used in this research project came from WSDOT-approved aggregate pits. These were the same pits specified in the reference mix design. The coarse aggregate conforms to AASHTO Grading No. 467, and the fine aggregate conforms to Class 1 fine aggregate grading.

The reference mix design specified five different aggregate components. In order to facilitate the concrete batching procedures for the test mixes, a coarse aggregate stockpile and a fine aggregate stockpile were created by combining appropriate amounts of these five components.

3.2.2 RCA

The RCA utilized in this research project was produced from panels of PCCP constructed in 1970 that were part of Interstate 90 near Roslyn, Washington. After removal from the roadway, the panels were crushed and sieved to 1.25 in. minus by Ellensburg Cement Products located in Ellensburg, Washington. The panels were first crushed by a jaw crusher, then by a standard cone crusher, and finally by a high-speed short head cone crusher The RCA was transported to Washington State University and then stockpiled in a covered building.

The as-delivered RCA stockpile consisted of both coarse and fine materials. Approximately 25% of the as-delivered RCA stockpile consisted of fine RCA material. The remaining 75% consisted of coarse RCA material. The RCA was sieved using 3/4 in., 3/8 in., and No. 4 sieves in a mechanical sieve shaker. For this research project, only coarse RCA material was incorporated. Therefore, all fine RCA materials passing the No. 4 sieve were discarded. The material retained on the three sieves was washed to remove any remaining fine material and then laid out on tarps for drying. Once the three sieved and washed size components were dry, they were recombined to conform to AASHTO Grading No. 467. This process yielded a new stockpile of graded RCA ready to be incorporated into a concrete mixture.

3.2.3 Cementitious Materials

Two cementitious materials were incorporated in this research project. The cement was a Type I-II portland cement produced in Durkee, Oregon. The fly ash used was Type F fly ash from Centralia, Washington.

3.2.4 Admixtures

Two admixtures were incorporated in this research project. The air-entraining admixture was Daravair 1000. The water-reducing admixture was WRDA 64. Both products were manufactured by W.R. Grace, Inc.

3.3 Test Methods

In this section, the test methods used to determine the RCA characteristics, fresh concrete properties, and hardened concrete properties are presented.

3.3.1 RCA Characteristics Tests

Four tests were used to characterize the properties of the RCA investigated in this research project. The specific gravity and absorption properties were determined using AASHTO T 85, "Specific Gravity and Absorption of Coarse Aggregate." The Los Angeles abrasion loss was determined using AASHTO T 96, "Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine." The degradation value was determined using WSDOT T 113, "Method of Test for Determination of Degradation Value." The alkali-silica reactivity of the RCA was determined using AASHTO T 303, "Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction." The ASR samples were created using processed RCA that was crushed to yield the proper size components.

3.3.2 Fresh Concrete Tests

Three tests were performed on fresh concrete samples from the eight concrete mixes in order to determine the relevant properties of the fresh concrete for use in PCCP. Air content of the concrete was determined using AASHTO T 152, "Air Content of Freshly Mixed Concrete by the Pressure Method." Slump was determined using AASHTO T 119, "Slump of Hydraulic

Cement Concrete." Concrete density was determined using AASHTO T 121, "Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete."

3.3.3 Hardened Concrete Tests

Tests were performed on hardened concrete samples from the eight concrete mixes to determine the relevant properties of the hardened concrete for use in PCCP. These properties included the compressive strength, modulus of rupture, and coefficient of thermal expansion.

Compressive strengths of the eight concrete batches were determined using AASHTO T 22, "Compressive Strength of Cylindrical Concrete Specimens." Compression tests were performed on cylinders with a diameter of 6 in. and a height of 12 in. A total of fourteen samples were tested in compression for each of the eight batches. Three samples were tested at an age of 7 days, 3 samples were tested at an age of 14 days, 5 samples were tested at an age of 28 days, and 3 samples were tested at an age of 90 days. In accordance with WSDOT field operating procedure for AASHTO T 22, all samples were tested in a wet condition and were capped with steel caps lined with neoprene pads. Tests were performed using a Tinius Olsen Universal Testing Machine.

The modulus of rupture of the concrete batches was determined using AASHTO T 177, "Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)." All tests were performed on beams with a length of 21 in., a width of 6 in., and a depth of 6 in. A total of 5 samples were tested, all at an age of 14 days. All samples were tested in a wet condition. Steel rollers as supports and loading point along with moist leather shims placed between the beams and rollers were used. Tests were performed using a Tinius Olsen Universal Testing Machine.

The coefficient of thermal expansion of the concrete batches was determined using AASHTO T 336, "Coefficient of Thermal Expansion of Hydraulic Cement Concrete." All samples tested were cylinders with a diameter of 4 in. and a height of 8 in. Three samples were tested, all at an age of 28 days. Prior to testing, all samples were cut to a height of 7 in. using a lapidary saw. The samples were placed in a stainless steel support frame with an attached submersible linear variable differential transformer (LVDT). The support frame was placed in a temperature-controlled water bath, and the water temperature was monitored by submersible thermocouples. A data acquisition system recorded the temperature of the water bath and the displacement of the concrete sample. The setup was calibrated with an aluminum sample prior to running tests.

3.4 Concrete Batching

In this section, the procedures for preparing the materials, mixing the concrete, and creating the samples are presented.

3.4.1 Material Preparation

Aggregate quantities in the reference mix design are based on aggregates in a saturated surface dry (SSD) condition. This means that the aggregates have reached their absorption capacity yet have no excess water on their surfaces. Since aggregate moisture was not controlled in any of the previous processing phases, all three stockpiles were in an unknown moisture condition. Therefore, the moisture condition of each of the three stockpiles needed to be accounted for in order to achieve SSD conditions during batching.

To achieve SSD conditions, the unknown moisture condition was accounted for at the time of batching using the following procedure. The first step was to determine the absorption capacity of each of the three aggregate stockpiles. Then, the actual moisture content of each aggregate stockpile was determined on the day prior to batching. This was accomplished by weighing a sample obtained from each stockpile, oven drying the sample to a completely dry condition, and then calculating the moisture content of the aggregate from these values. This procedure was done before each of the eight batch days in order to correctly manage moisture conditions of the aggregates in the batching process.

With the absorption capacity of each aggregate stockpile known, the differences between the actual aggregate moisture conditions and their absorption capacities were calculated. If an aggregate was below the SSD condition, additional water was added in the mixing process to effectively bring the aggregate to the SSD condition. Since additional water weight was being added, the same weight of aggregate was removed to keep the overall weight of materials in the batch constant. If an aggregate was above the SSD condition, water was subtracted from the overall mix water to account for the excess water in the aggregate. Since water weight was being removed, the same weight of aggregate was added to keep the overall weight of materials in the batch the same. This dynamic water adjustment procedure ensured that all of the aggregates were effectively in the SSD condition and that the specified amount of water in the mix design would be available for hydrating the cementitious materials.

The individual required weights of the coarse aggregate, fine aggregate, RCA, cement, fly ash, and water were known at this stage of the batching procedure. The applicable quantities of these materials were weighed out and placed in buckets. At the conclusion of the material

preparation phase, all of these materials were in buckets and were ready to be blended in the mixer.

The weight of water and the volume of admixtures used were not held constant for the eight concrete batches. WSDOT specified for this study that the slump and air contents of each batch fall within acceptable ranges. The acceptable range for air content was 4% to 7%, and the acceptable range for slump was 1 in. to 3 in. Therefore, the total weight of water and the volume of each admixture were adjusted as the concrete was mixing in order to keep the slump and air content within the acceptable ranges. Both ranges were approached from the low end, and additional water and/or admixtures were added to reach the acceptable ranges.

3.4.2 Concrete Mixing Procedure

The interior surface of the concrete mixer was coated with a slurry of cement and water. This mixture was poured into the spinning mixer, and then the contents of the mixer were dumped, leaving behind a thin coating of the slurry within the drum.

With the mixer stopped, all of the coarse aggregate, fine aggregate, and RCA were placed into the mixer. A picture of the aggregates being placed into the mixer is presented in Figure 3.1.

Figure 3.1. Aggregates Being Placed into Mixer

A portion of the mix water was added in at this stage in order to facilitate the aggregates absorbing water and to reduce dust from the mixing process. The mixer was then run until the aggregates were well blended.

With the mixer still running, the cementitious materials were added into the mixer. Except for ten pounds, all of the remaining water was then poured into the mixer. The mixer was run until there was a well-blended and homogeneous concrete mixture. During this mixing, the slump was controlled by incrementally adding the withheld ten pounds of water in order to achieve a visually-estimated slump of 1 in. Once the estimated slump of 1 in. was achieved and the concrete mixture was well-blended and homogeneous, the mixer was stopped and the slump was measured. If the slump was within the acceptable 1 in. to 3 in. range, the batching procedure moved forward and the admixtures were added. However, if the slump was below the acceptable range, more of the withheld water was added. The concrete was allowed to mix further and the

slump was measured again. If the slump was not in the specified range after all of the water was added, then water-reducing admixture was added in the next step of the procedure. Any remaining mix water was weighed and the amount deducted from the reference water amount so as to correctly reflect the effective water in each batch.

The next step in the batching procedure was to add in the admixtures. If additional slump was required, a water-reducing admixture (WRA) was added. The volume of WRA initially added was based on previous experience. An air-entraining admixture (AEA) was always added into the concrete mixture. The initial volume of AEA incorporated was based on previous experience. Since there are many factors that influence the air content of a concrete mixture, the actual volume of AEA differed slightly between batches. With the mixer running, the admixtures were poured in and the mixer was allowed to run for 5 minutes. After this time period, the air content and slump were measured. If the air content was within the acceptable 4% to 7% range, and the slump was within its acceptable range, then the mixing process was finished. However, if the air content was too low, additional AEA was added. Further, if the slump was still too low, additional WRA was added. After adding in any additional admixtures, the mixer was run for three minutes, and the slump and air content were measured again to ensure that both the air content and slump were in the specified ranges. After these measurements, the mixing procedure was finished.

The density of the final mix product was then measured. After this, the concrete was ready to be cast into the various molds for the hardened concrete tests.

3.4.3 Sample Preparation

All samples were prepared following the methods described in AASHTO R 39, “Making and Curing Concrete Test Specimens in the Laboratory.” For each of the eight batches, 14 cylinders were prepared for the compressive strength tests, 3 cylinders were prepared for the coefficient of thermal expansion tests, and 5 beams were prepared for the modulus of rupture tests. After the cylinder samples were filled, their surfaces were smoothed with a trowel and then covered with plastic caps. After the beam molds were filled, their surfaces were smoothed with a trowel and then covered with a damp towel and a sheet of plastic. All samples were allowed to cure for 24 hours.

After the 24-hour curing period, all samples were de-molded. The samples were then stored in curing tubs filled with lime-saturated water, as shown in Figure 3.2.

Figure 3.2. Curing Tub Filled With Samples

Samples were stored in the curing tubs in accordance with AASHTO R 39, “Making and Curing Concrete Test Specimens in the Laboratory.” The temperature of the water in the curing tubs was maintained at 23 degrees Celsius. All samples remained fully submerged in the curing tubs until being tested.

CHAPTER 4: TEST RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, results are presented and discussed from tests performed on samples from each of the eight concrete mixes. Information presented includes natural aggregate and RCA properties, fresh concrete test results, and hardened concrete test results.

4.2 Natural Aggregate Characteristics

Since they were obtained from WSDOT-approved pits, both the coarse and fine natural aggregates met all WSDOT requirements for aggregates being used in concrete pavements. Sieve analyses were performed on all five of the individual natural aggregate components, and the results were the same as the gradations given in the reference mix design. Sieve analyses were also performed on the coarse and fine aggregate stockpiles produced by blending appropriate amounts from the five component aggregate sources. The blended coarse aggregate conformed to AASHTO Grading No. 467, and the blended fine aggregate conformed to Class 1 fine aggregate grading. The SSD bulk specific gravity of the blended coarse aggregate was 2.63 and its absorption capacity was 1.2%. The SSD bulk specific gravity of the blended fine aggregate was 2.59 and its absorption capacity was 2%.

4.3 RCA Characteristics

The SSD bulk specific gravity of the processed RCA was 2.52 and its absorption capacity was 3.3%. As anticipated, the specific gravity of the RCA was less than that of the natural coarse aggregate. Furthermore, the absorption capacity of the RCA was higher than that of the natural

coarse aggregate. The differences in the values for the RCA and the natural coarse aggregate are most likely due to the porosity present in the adhered mortar portion of the RCA.

The Los Angeles abrasion loss for the processed RCA was 29%. This is below the WSDOT maximum allowable limit of 35%. Therefore, based on this criterion, the RCA used in this study is an acceptable aggregate source.

The degradation value of the as-delivered RCA was 15. This is below the WSDOT allowable minimum of 30. However, the degradation value of the processed RCA was 55. Since the processed RCA exceeded the WSDOT minimum value, removing the fine RCA material was an important element of preparing the RCA for use in PCCP. The degradation values of combined samples of natural coarse and fine aggregates and differing percentages of RCA substitution were also determined. The degradation values of the combined aggregates for RCA substitutions of 15%, 30%, and 45% were 77, 75, and 73, respectively. Thus, the degradation value is essentially constant for combined aggregates containing different percentages of RCA. In order to ensure an RCA aggregate source meets the WSDOT minimum degradation value, it is recommended that all fine RCA material be removed from any RCA aggregate source. Based on the degradation value requirement, the RCA used in this study is an acceptable aggregate source.

The 14-day average ASR expansion of the processed and crushed RCA was 0.068%. According to AASHTO T 303, "Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction," an aggregate is considered to be alkali-silica reactive if the 14-day expansion is greater than 0.1%. Therefore, the RCA source is not alkali-silica reactive. The original concrete pavement that the RCA was produced from was constructed in 1970, and WSDOT procedure at the time was to reject any aggregates that were alkali-silica

reactive. Based on this expansion criterion, the RCA used in this study would be an acceptable aggregate source and no ASR mitigation techniques would be required.

4.4 Fresh Concrete Test Results

A labeling system was developed to denote the eight concrete mixes evaluated in this study. The first letter of the label indicates the material used: X indicates a reference batch consisting of only natural aggregates, while A indicates the RCA source investigated in this study. The first number indicates the percentage of natural coarse aggregate that was replaced by RCA. The second number indicates the percentage of cement that was replaced by fly ash. Therefore, A-45-20 indicates that the RCA from source A (the RCA investigated in this study) was used, that 45% of the natural coarse aggregate was replaced by RCA, and that 20% of the cement was replaced by fly ash.

The final quantities of all materials used in each of the eight concrete mixes are presented in Appendix B. The water/cementitious materials ratio along with the measured slump, air content, and density for each of the eight fresh concrete mixes are presented in Table 4.1.

Table 4.1. Fresh Concrete Measurements

	Water/Cementitious Materials Ratio	Slump (in.)	Air Content	Density (pcf)
X-0-0	0.44	2.50	4.1%	146.4
A-15-0	0.44	1.50	4.9%	144.2
A-30-0	0.43	1.50	4.5%	145.2
A-45-0	0.44	2.25	4.9%	142.8
X-0-20	0.40	1.75	4.1%	146.8
A-15-20	0.40	1.25	4.2%	145.4
A-30-20	0.42	2.00	4.5%	144.8
A-45-20	0.40	1.50	4.5%	144.6

Slump measurements were taken at various stages of the mixing process (described in detail in Chapter 3). However, the value listed in Table 4.1 is the final slump measurement taken at the end of the mixing process. In each of the eight batches, the final slump is within the acceptable 1 in. to 3 in. range. By comparing slumps for mixes with similar water/cementitious materials ratios, it is evident that adding RCA decreases the workability of fresh concrete. Both the X-0-0 and A-15-0 mixes had a water/cementitious materials ratio of 0.44, yet the 15% substitution of RCA decreased the slump by 1 in. Furthermore, the A-45-0 mix was the only mix to require WRA to reach an acceptable slump range. Based on these results, increasing the percentage of RCA substitution decreases the workability of a mix. In addition, the mixes that incorporated fly ash had increased workability compared to the mixes without. This is evidenced by the fly ash mixes having significantly lower water/cementitious materials ratios than the mixes without fly ash, while maintaining similar slump measurements.

As required in AASHTO T 152, “Air Content of Freshly Mixed Concrete by the Pressure Method,” an aggregate correction factor was determined in order to account for air voids present in the aggregates. An aggregate correction factor of 0.5% was determined for use in all eight mixes. After accounting for this correction factor, the final measured air content was found to be within the acceptable 4% to 7% range for all eight mixes. Due to the batching procedure in which air content was controlled, differing volumes of AEA were added to each mix. Appendix B presents the volumes of AEA incorporated into each mixture. Since the volume of AEA was not held constant between mixes, it is not possible to draw any definitive conclusions regarding the influence of RCA on air content of fresh concrete.

A plot of fresh concrete density versus percentage of RCA substitution is presented in Figure 4.1.

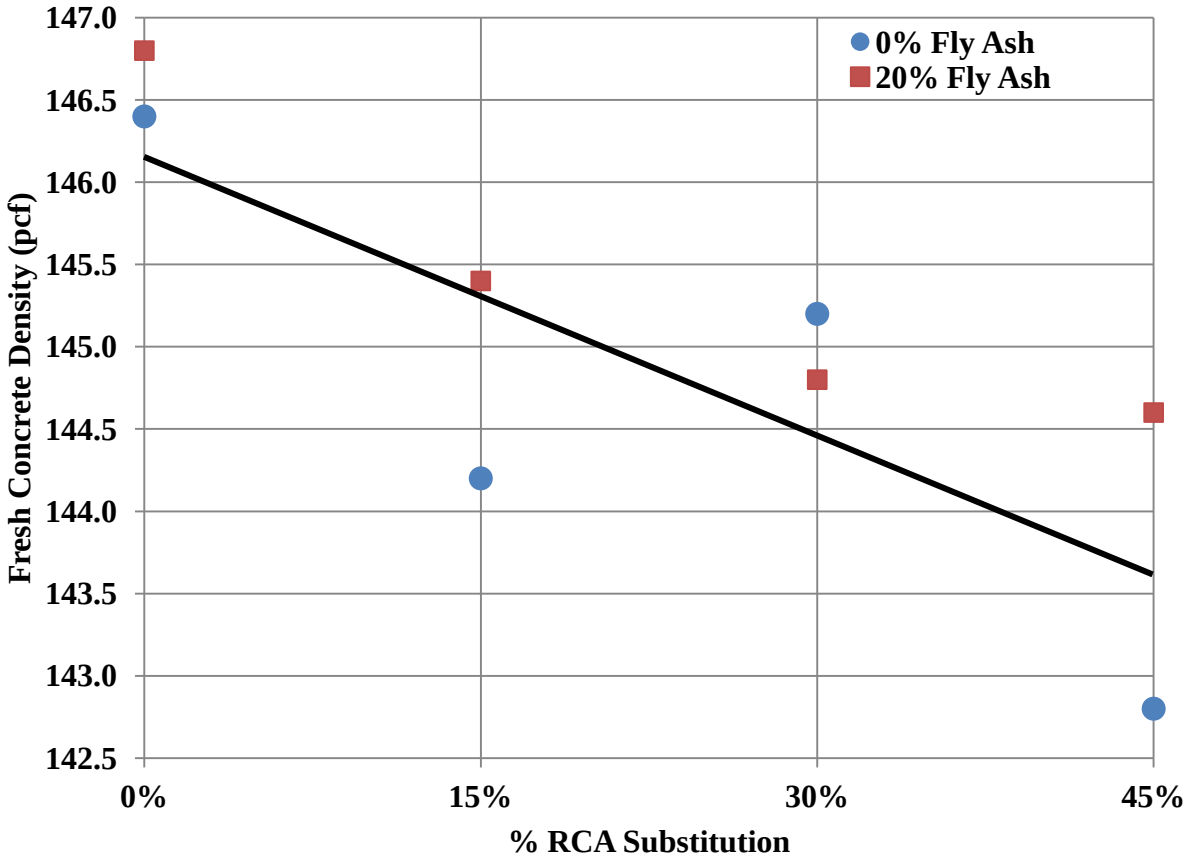

Figure 4.1. Fresh Concrete Density versus % RCA Substitution

The linear trend line indicates that a higher percentage of RCA substitution correlates to a lower fresh concrete density. This is because the RCA is less dense than natural aggregate. However, the air content of the concrete also has an effect on the fresh concrete density, as can be seen in Figure 4.2 showing a plot of fresh concrete density versus air content.

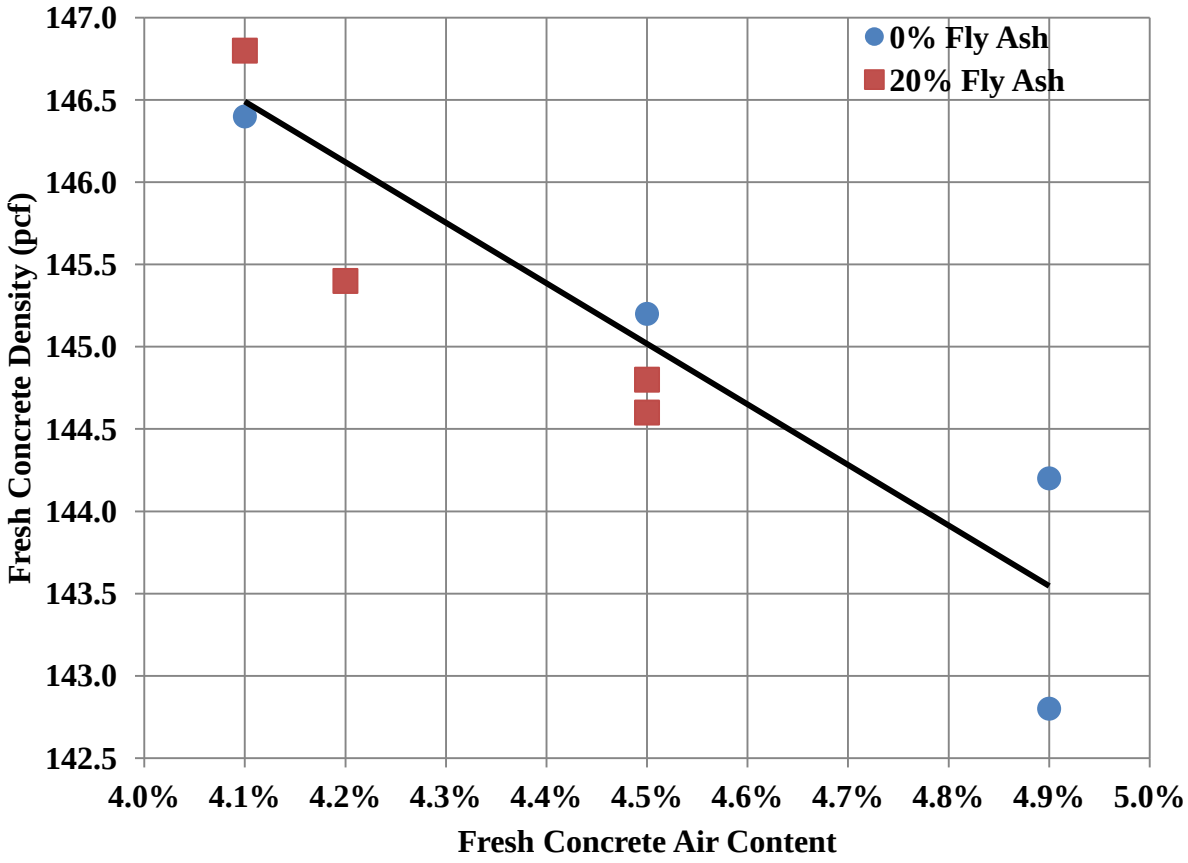

Figure 4.2. Fresh Concrete Density versus % Air Content

4.5 Hardened Concrete Test Results

This section presents and discusses the test results for compressive strength, modulus of rupture, and coefficient of thermal expansion for samples produced from each of the eight mixes. In order to compare the eight data sets for each hardened concrete test and determine if there are statistically-significant differences between them, an analysis of variation (ANOVA) was performed. This was accomplished using Microsoft Excel using the "Single Factor ANOVA"

function. Statistical analyses were performed on all data points from each of the three hardened concrete tests using a confidence interval of 95%.

4.5.1 Compressive Strength

Test data for all compression samples is presented in Appendix C. The average compressive strength and coefficient of variation for samples tested at ages of 7, 14, 28, and 90 days for each of the eight mixes are presented in Table 4.2.

Table 4.2. Compressive Strength Average Test Results

	7-Day (psi)	CV	14-Day (psi)	CV	28-Day (psi)	CV	90-Day (psi)	CV
X-0-0	4186	1.3%	4919	0.5%	5321	3.5%	6002	0.3%
A-15-0	3753	4.2%	4180	10.5%	4921	3.3%	5418	1.5%
A-30-0	4330	0.1%	4868	1.4%	5474	4.0%	5901	1.1%
A-45-0	3839	3.4%	4619	0.8%	5130	1.8%	5573	2.6%
X-0-20	3709	4.4%	4568	6.0%	5337	1.6%	6281	1.7%
A-15-20	3904	4.4%	4655	3.4%	5592	2.8%	6555	2.5%
A-30-20	3737	1.7%	4503	2.1%	5290	5.4%	6269	2.5%
A-45-20	3763	4.0%	4497	3.8%	5503	4.0%	6403	1.5%

The coefficients of variation are relatively small and range from 0.1% to 10.5%.

A plot of the 28-day compressive strength versus the percentage of RCA substitution is presented in Figure 4.3.

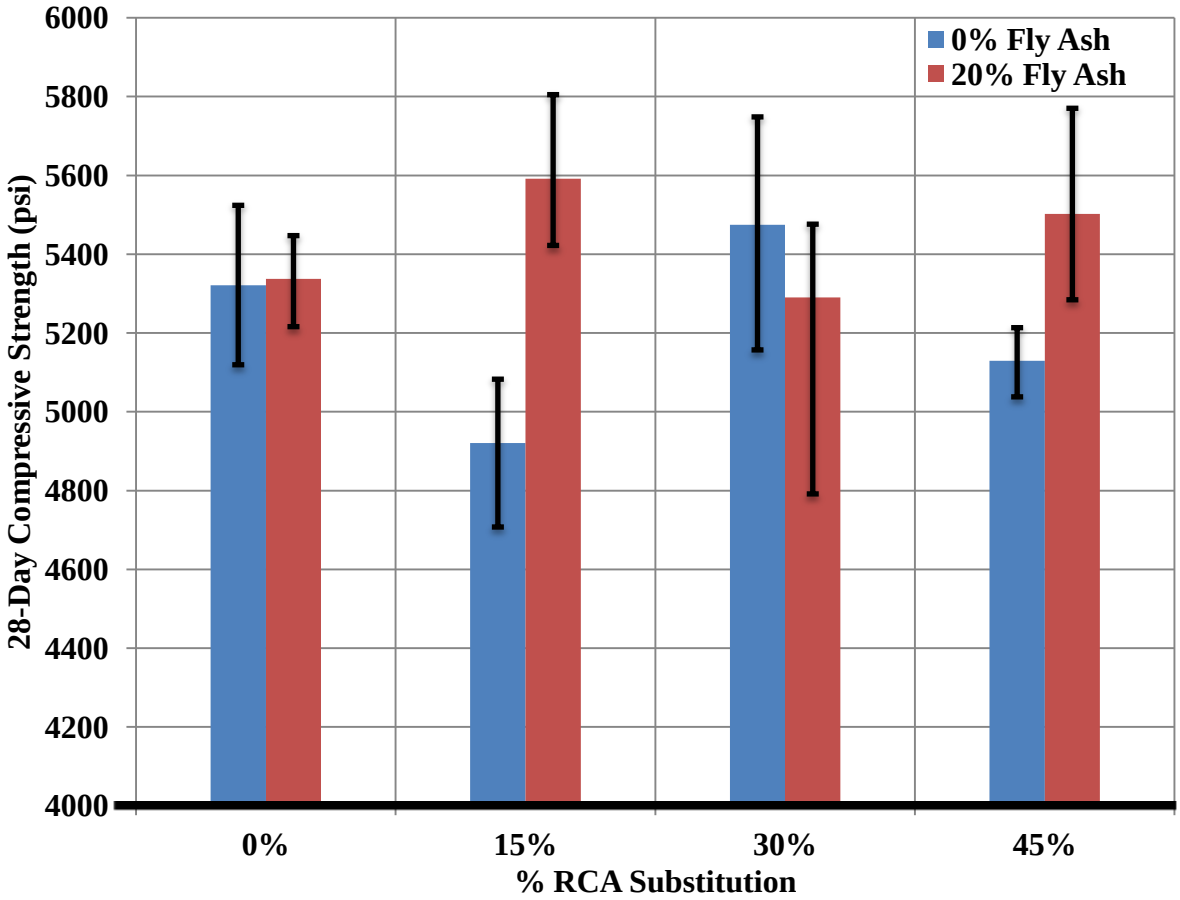

Figure 4.3. 28-Day Compressive Strength versus % RCA Substitution

WSDOT requires PCCP mixes to have a minimum 28-day compressive strength of 4,000 psi. This minimum value is indicated by the horizontal black bar at the bottom of Figure 4.3. The highest and lowest values of compressive strength are indicated by the error bars. All samples tested exceeded the WSDOT minimum strength for PCCP mixes.

An ANOVA statistical analysis of the 28-day compressive strengths indicates that there are statistically-significant differences between several of the eight data sets. For example, there is a statistically-significant difference between X-0-0 and A-15-0 and also between A-15-0 and

A-30-0. However, there is no statistically-significant difference between X-0-0 and A-30-0. Thus, even though there may be a statistically-significant difference between some data sets, it is not due to the varying percentage of RCA substitution. The differences are most likely due to the differing water/cementitious materials ratios and air contents.

A plot of the 28-day compressive strength versus water/cementitious materials ratio is presented in Figure 4.4.

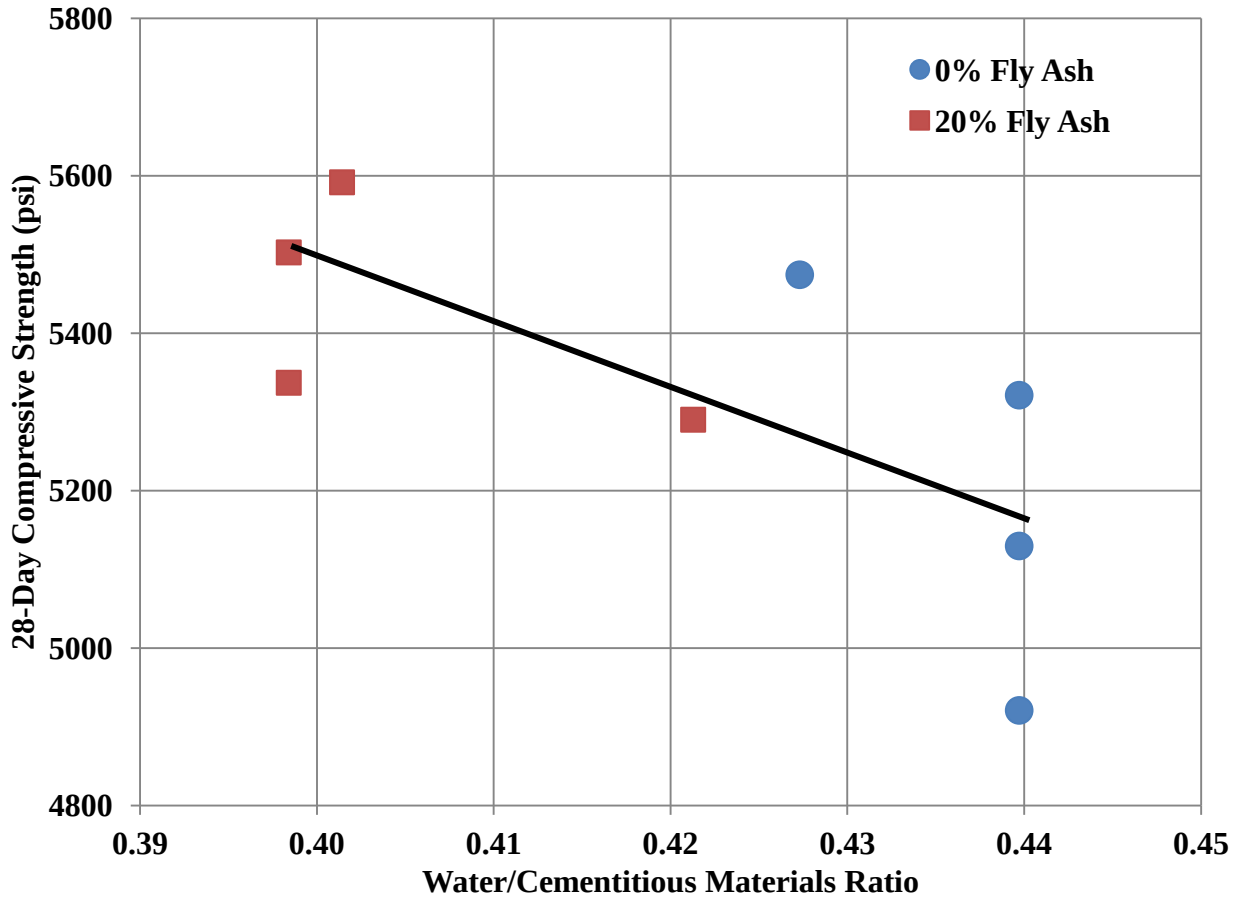

Figure 4.4. 28-Day Compressive Strength versus Water/Cementitious Materials Ratio

The negatively-sloped trend line indicates that a lower water/cementitious materials ratio results in a higher 28-day compressive strength.

A plot of 28-day compressive strength versus percent air content is presented in Figure 4.5.

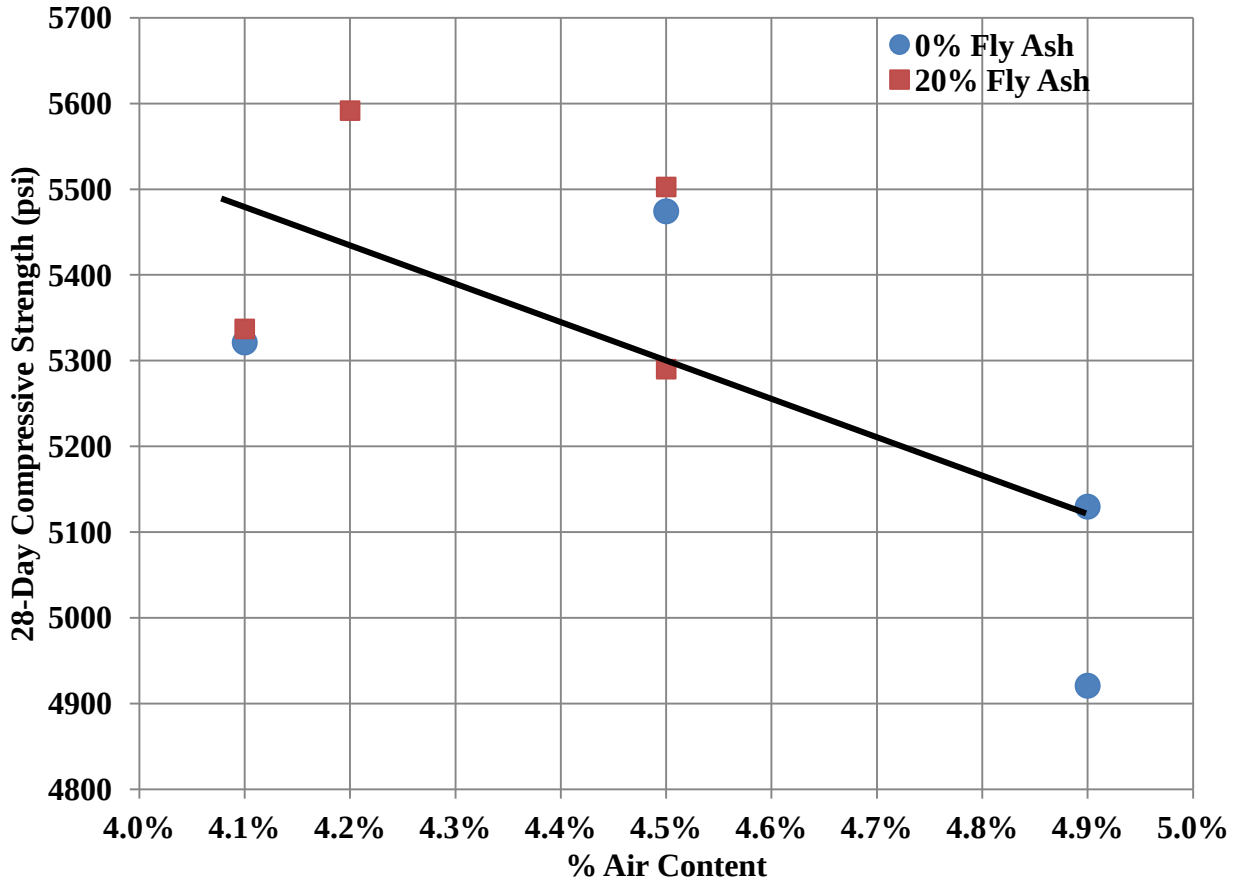

Figure 4.5. 28-Day Compressive Strength versus % Air Content

The negatively-sloped trend line indicates that a lower percent air content results in a higher 28-day compressive strength. It is apparent that both water/cementitious materials ratio and percent air content have a significant effect on the 28-day compressive strength.

For each of the eight mixes, the percentages of the 28-day compressive strengths at ages of 7 and 14 days are presented in Table 4.3.

Table 4.3. Percentages of 28-Day Compressive Strengths at Ages of 7 and 14 Days

	7-Day / 28-Day Compressive Strength	14-Day / 28-Day Compressive Strength
X-0-0	78.7%	92.4%
A-15-0	76.3%	85.0%
A-30-0	79.1%	88.9%
A-45-0	74.8%	90.0%
X-0-20	69.5%	85.6%
A-15-20	69.8%	83.3%
A-30-20	70.6%	85.1%
A-45-20	68.4%	81.7%

The mixes that incorporated the 20% fly ash substitution had lower early-age compressive strength gain. At an age of seven days, these mixes reached a maximum of 70.6% of their 28-day compressive strength, while the mixes without fly ash reached a minimum of 74.8% of their 28-day compressive strength.

4.5.2 Modulus of Rupture

Test data for all modulus of rupture samples is presented in Appendix D. The average values of modulus of rupture (MOR) and coefficient of variation for samples at an age of 14 days for each of the eight concrete mixes are presented in Table 4.4.

Table 4.4. Modulus of Rupture Average Test Results

	14-Day MOR (psi)	CoV
X-0-0	773	5.5%
A-15-0	763	2.7%
A-30-0	774	5.0%
A-45-0	725	3.5%
X-0-20	779	6.4%
A-15-20	781	2.8%
A-30-20	721	6.3%
A-45-20	747	4.9%

The coefficients of variation are small, and they range from 2.7% to 6.4%.

A plot of the modulus of rupture versus the percentage of RCA substitution is presented in Figure 4.6.

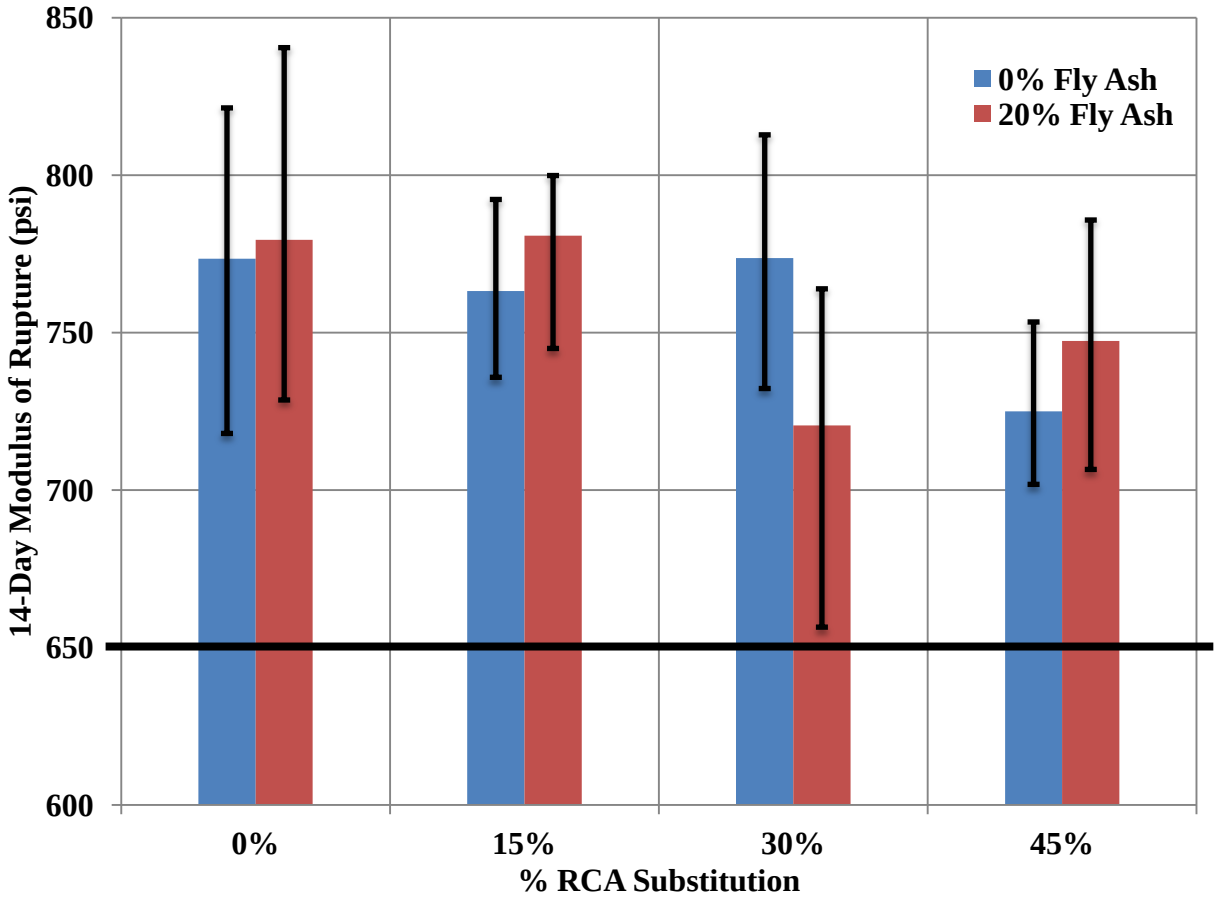

Figure 4.6. 14-Day Modulus of Rupture versus % RCA Substitution

WSDOT requires PCCP mixes to achieve a minimum value of 14-day modulus of rupture of 650 psi. This minimum value is indicated by the horizontal black bar in Figure 4.6. The highest and lowest tested values of modulus of rupture are indicated by the error bars. Every sample tested exceeded the WSDOT minimum MOR value for PCCP mixes.

An ANOVA statistical analysis indicated that there were no statistically-significant differences between any of the eight data sets. Therefore, the percentage of RCA substitution did not significantly influence the modulus of rupture. Further, a 20% fly ash substitution did not

significantly influence the modulus of rupture. The differences in the average modulus of rupture values between mixes are likely due to a combination of the effects of varying water/cementitious materials ratios and air contents.

4.5.3 Coefficient of Thermal Expansion

The values of coefficient of thermal expansion for each tested sample are presented in Appendix E. The values for the average coefficient of thermal expansion and coefficient of variation for samples at an age of 28 days for each of the eight concrete mixes are presented in Table 4.5.

Table 4.5. Coefficient of Thermal Expansion Average Test Results

	28-Day Coefficient of Thermal Expansion (in/in °F)	**CoV**
X-0-0	3.83E-05	1.0%
A-15-0	3.98E-05	0.8%
A-30-0	3.94E-05	1.5%
A-45-0	3.92E-05	0.3%
X-0-20	3.53E-05	16.2%
A-15-20	3.90E-05	2.5%
A-30-20	3.95E-05	1.4%
A-45-20	3.92E-05	2.0%

With the exception of the X-0-20 mix, the coefficients of variation are small and range from 0.3% to 2.5%. The relatively high coefficient of variation of the X-0-20 mix was due to one of

the three samples having a relatively low coefficient of thermal expansion. This low value was most likely caused by an error in the testing procedure.

An ANOVA statistical analysis indicated that there were no statistically-significant differences between any of the data sets. Therefore, the percentage of RCA substitution did not significantly influence the coefficient of thermal expansion. Further, a 20% fly ash substitution did not significantly influence the coefficient of thermal expansion.

Ordinary concrete typically has a coefficient of thermal expansion ranging from 3.2 to 7.0 millionths per degree Fahrenheit (Portland Cement Association 2002). Each of the eight concrete mixes yielded a coefficient of thermal expansion within this reported range. Therefore, based on the results of this study, RCA concrete has similar thermal expansion behavior as ordinary concrete.

4.6 Summary and Conclusions

The RCA investigated in this study had a lower specific gravity and a higher absorption than natural coarse aggregates. This is due to the adhered mortar portion of the RCA. The processed RCA had a Los Angeles abrasion loss below the WSDOT maximum value. The degradation value of the as-delivered RCA was below the WSDOT allowable minimum of 30. However, the degradation value of the processed RCA was above the minimum value, indicating the importance of washing and removing the fine materials when preparing the RCA for use in PCCP. Further, the degradation value is essentially constant for combined aggregates containing different percentages of RCA. The processed RCA was not alkali-silica reactive. Therefore, no mitigation techniques would be required to incorporate it in PCCP.

Increasing the percentage of RCA substitution decreased the workability of a fresh concrete mix, and incorporating a 20% substitution of fly ash significantly increased the workability of a fresh concrete mix. Due to the procedure in which air content was controlled to meet a specified range, no definitive conclusions can be drawn regarding the effect of RCA on air content. Since the RCA has a lower density than natural coarse aggregate, a higher percentage of RCA substitution correlated to a lower fresh concrete density. Further, higher air content results in lower fresh concrete density.

All samples from the eight concrete mixes exceeded the WSDOT minimum allowable 28-day compressive strength of 4,000 psi. Lower water/cementitious materials ratios and lower air contents resulted in higher 28-day compressive strengths. Further, the percentage of RCA substitution does not appear to have a significant effect on 28-day compressive strength. The incorporation of a 20% fly ash substitution decreased the early-age compressive strength gain.

All samples from the eight concrete mixes exceeded the WSDOT minimum allowable modulus of rupture of 650 psi. The percentage of RCA substitution did not have a significant effect on modulus of rupture.

Each concrete mix had a coefficient of thermal expansion within the range of typical ordinary concrete. Therefore, the RCA concretes in this study have similar thermal expansion behavior as ordinary concrete.

A previous study indicated that values of RCA substitution should be restricted to 30% in order to not negatively influence the fresh or hardened concrete properties (Limbachiya, Meddah and Ouchagour 2012). However, based on the results of this study, this substitution limit of 30% may be overly restrictive. Both mixes incorporating 45% RCA met all WSDOT requirements.

CHAPTER 5: CONCLUSIONS

5.1 Summary

The primary objective of this research was to determine if recycled concrete aggregate (RCA) sourced from demolished pavements in the central region of Washington State can be effectively utilized in new concrete pavements. This research investigated the effects of RCA on several properties that are critical in the design of new concrete pavements. Two variables were evaluated in this study: the percentage of natural coarse aggregate replaced by RCA, and the incorporation of a 20% substitution of cement with Type F fly ash along with varying percentages of RCA replacement. Eight concrete batches were produced and a series of fresh and hardened concrete samples were created from each batch. The fresh concrete samples were tested for slump, air content, and density, and the hardened concrete samples were tested for compressive strength, modulus of rupture, and coefficient of thermal expansion. Tests were performed on the RCA to determine the absorption, specific gravity, Los Angeles abrasion loss, degradation value, and alkali-silica reactivity.

5.2 Conclusions

In this section, the major conclusions reached in this study regarding the effects of RCA on critical concrete properties are presented.

Effect of RCA on Degradation Value – Processing the RCA by washing the RCA and then removing the fine materials had a significant effect on increasing the degradation value. Further, the degradation value was essentially constant for combined aggregates containing different

percentages of processed RCA. In order to ensure an RCA aggregate source meets the WSDOT minimum degradation value, it is recommended that all fine materials be removed from any RCA aggregate source.

Effect of RCA on Fresh Concrete Workability – Incorporating RCA into a concrete mix decreased the workability of the fresh concrete. In contrast, substituting fly ash increased the workability of fresh concrete and could be utilized to counter the slump reduction caused by the addition of RCA.

Effect of RCA on Air Content – Since the volume of AEA was not held constant between mixes, it is not possible to draw any definitive conclusions regarding the influence of RCA on air content of fresh concrete.

Effect of RCA on Fresh Concrete Density – A higher percentage of RCA substitution correlated to a lower fresh concrete density. A higher air content also correlated to a lower fresh concrete density.

Effect of RCA on Compressive Strength – The percentage of RCA substitution did not have a significant influence on compressive strength, and concretes made incorporating amounts of RCA of up to 45% substitution for natural coarse aggregates all exceeded the WSDOT minimum 28-day compressive strength of 4,000 psi. A lower water/cementitious materials ratio and a lower air content correlated to a higher 28-day compressive strength. The incorporation of a 20%

fly ash substitution decreased the early-age compressive strength gain, but increased the late-age compressive strength gain.

Effect of RCA on Modulus of Rupture – The percentage of RCA substitution did not have a significant influence on the modulus of rupture, and concretes made incorporating amounts of RCA of up to 45% substitution for natural coarse aggregates all exceeded the WSDOT minimum 14-day modulus of rupture of 650 psi.

Effect of RCA on Coefficient of Thermal Expansion – The percentage of RCA substitution did not have a significant influence on the coefficient of thermal expansion. Further, the RCA concretes in this study had similar thermal expansion behavior as ordinary concrete.

Optimum RCA Substitution Percentage for PCCP – All of the concrete mixes with RCA investigated in this study, including up to a 45% substitution of RCA, met all WSDOT PCCP requirements. Therefore, the restriction of 30% substitution of RCA recommended in previous studies may be overly restrictive.

5.3 Recommendations

Based on the results of this research project, RCA can be an acceptable aggregate source for PCCP. The RCA should be washed and fine materials removed prior to use. This study did not establish a maximum effective RCA substitution percentage. A 45% RCA substitution was the maximum amount investigated in this study, and the resulting concrete mixes passed all

WSDOT requirements for PCCP. Increasing the percentage of RCA substitution reduces the workability of the fresh concrete. However, this lower workability can be mitigated by incorporating fly ash or water-reducing admixture.

This study is part of a larger research project that is investigating the properties of concretes made incorporating RCA obtained from three geographically-dispersed sources in Washington State. At the completion of this research project, more general conclusions will be reached on the use of RCA obtained from sources across the state.

Future research should investigate if higher percentages of RCA substitution beyond those evaluated in this study can still produce viable PCCP mixes. Future research should also investigate the long-term durability of concretes incorporating RCA.

REFERENCES

Amorim, Pedro, Jorge de Brito, and Luis Evangelista. *Concrete Made with Coarse Concrete Aggregate: Influence of Curing on Durability.* ACI Materials Journal, 2012, 195-204.

Anderson, Keith W, Jeff S Uhlmeyer, and Mark Russel. *Use of Recycled Concrete Aggregate in PCCP: Literature Search.* Olympia: Washington State Department of Transportation, 2009.

FHWA. "Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement." 2007 йил 3-July. https://www.fhwa.dot.gov/pavement/t504037.cfm.

Garber, S, et al. *Development of a Technology Deployment Plan for the Use of Recycled Concrete Aggregate in Concrete Paving Mixtures.* Ames: National Concrete Pavement Technology Center, 2011.

Ideker, Jason H, Matthew P Adams, Jennifer Tanner, and Angela Jones. *Durability Assessment of Recycled Concrete Aggregates for Use in New Concrete.* Portland: Oregon Transportation Research and Education Consortium, 2011.

Jitendra, Jain, Kho Pin Verian, Jan Olek, and Nancy Whiting. *Durability of Pavement Concretes Made with Recycled Concrete Aggregates.* West Lafayette: Purdue University, 2011.

Limbachiya, Mukesh, Mohammed Meddah, and Youssef Ouchagour. *Use of Recycled Concrete Aggregate in Fly-Ash Concrete.* London: Kingston University, 2012, 439-449.

Portland Cement Association. *Design and Control of Concrete Mixtures.* Skokie, IL: Portland Cement Association, 2002.

Smith, James T, and Susan L Tighe. "Recycled Concrete Aggregate Coefficient of Thermal Expansion." *Transportation Research Board: Journal of the Transportation Research Board* (Transportation Research Board of the National Academies), 2009: 53-61.

Wright, Frederick G. "FHWA Recycled Materials Policy." 2006 йил 20-November. http://www.fhwa.dot.gov/legsregs/directives/policy/recmatpolicy.htm.

WSDOT. *Materials Manual.* Olympia, WA: Washington State Department of Transportation, 2012.

WSDOT. *Standard Specification for Road, Bridge, and Municipal Construction.* Olympia, WA: Washington State Department of Transportation, 2012.

APPENDIX A: REFERENCE MIX DESIGN

Washington State Department of Transportation

Concrete Mix Design

Contractor	Submitted By	Date
Acme Concrete Paving	Craig L. Matteson Central Pre-Mix Concrete Co.	7/8/2011

Concrete Supplier	Plant Location
Central Pre-Mix Concrete Co.	1901 N. Sullivan Road or Crestline & Magnesium

Contract Number	Contract Name
8022	Sullivan To Barker Road - Additional Lanes

This mix is to be used in the following Bid Item No(s): 6.0 Sack14 Day Cement Concrete Pavement

Concrete Class: *(check one only)*

☐ 3000 ☐ 4000 ☐ 4000D[a] ☐ 4000P[a] ☐ 4000W ☐ Concrete Overlay ☒ Cement Concrete Pavement[d]

☐ Other

Remarks: To be used for slip-form and mixer placements with air content adjustments.

Mix Design No. 320244 **Plant No.** 1, 2 or 4

Cementitious Materials	Source	Type, Class or Grade	Sp. Gr.	Lbs/cy
Cement	Ash Grove Durkee, OR	Type I-II	3.15	564
Fly Ash[a]				
GGBFS (Slag)				
Latex				
Microsilica				

Concrete Admixtures	Manufacturer	Product	Type	Est. Range (oz/cy)
Air Entrainment	WR Grace	Daravair 1000		2 to 25
Water Reducer	WR Grace	WRDA 64	A & D	15-35
High-Range Water Reducer				
Set Retarder	WR Grace	Recover *(if needed)*	D	0-15
Other				

Water (Maximum) 248 lbs/cy Is any of the water Recycled or Reclaimed? ☐ Yes[e] ☒ No

Water Cementitious Ratio (Maximum) .44 Mix Design Density 144.4 +/- lbs/cf[d]

Design Performance	1	2	3	4	5	Average[f]
28 Day Compressive Strength (cylinders) psi	5,090	5,050	5,020	4,840	4,740	4,950
14 Day Flexural[d] Strength (beams) psi	875	885	905	875	910	890

Agency Use Only (Check appropirate Box)

☑ **This Mix Design MEETS CONTRACT SPECIFICATIONS and may be used on the bid items noted above**

☐ **This Mix Design DOES NOT MEET CONTRACT SPECIFICATIONS and is being returned for corrections**

Reviewed By: [signature] 7/13/2011

PE Signature Date

DOT Form 350-040 EF Revised 6/06

Distribution: Original - Contractor

Copies To - State Materials Lab-Structural Materials Eng. ; Regional Materials Lab; Project Inspector

Mix Design No. 320244 **Plant No.** 1, 2 or 4

Aggregate Information

Concrete Aggregates	Component 1	Component 2	Component 3	Component 4	Component 5	Combined Gradation
WSDOT Pit No.	PS C-173	PS C-173	PS C-173	PS C-173	PS C-297 & PS C-120	
WSDOT ASR 14-day Results (%) [b]	☒ Yes ☐ No	☒ Yes ☐ No	☒ Yes ☐ No	☒ Yes ☐ No	☒ Yes ☐ No	
Grading[c]	11/2" Round Combined	3/4" Round Combined	3/8" Round Combined	Coarse Sand Combined	Blend Sand Combined	
Percent of Total Aggregate	23	34	07	11	25	100%
Specific Gravity	2.69	2.68	2.67	2.64	2.64	
Lbs/cy (ssd)	700	1040	220	350	770	1.5" NMA Specification
Percent Passing						
2 inch						100 100
1-1/2 inch	100					100 87-100
1 inch	39.7	100				86.0
3/4 inch	4.9	95.9				77.0 62-88
1/2 inch	1.1	55.2	100			62.0
3/8 inch	.8	25.5	99.8	100	100	51.8 43-64
No. 4		1.1	33.4	98.1	99.4	38.4 29-47
No. 8		.9	3.2	59.9	96.1	31.1 19-34
No. 16		.8	.9	24.9	83.9	24.0 12-25
No. 30		.7	.8	8.9	53.1	14.4 7-18
No. 50		.6	.7	4.1	19.8	5.5 3-14
No. 100		.5	.6	2.2	6.3	2.0 0-10
No. 200	.5	.4	.5	1.5	3.5	1.3 0-2.0

Fineness Modulus: N/A (Required for Class 2 Sand)

ASR Mitigation Method Proposed [b]: **Using Low Alkali Cement**

Notes:

a Required for Class 4000D and 4000P mixes.

b Alkali Silica Reactivity Mitigation is required for sources with expansions over 0.20% - Incidate method for ASR mitigation.
For expansion of 0.21% - o.45%, acceptable mitigation can be the use of low alkali cement or 25% type F fly ash.
Any other proposed mitigation method or for pits with greater than 0.45% expansion, proof of mitigating measure, either ASTM C1260 / AASHTO T303 test results must be attached.
If ASTM C 1293 testing has been submitted indicating 1-year expansion of 0.04% or less, mitigation is not required.

c AASHTO No. 467, 57, 67, 7, 8; WSDOT Class 1, Class 2; or combined gradation. See Standard Specification 9-03.1.

d Required for Cement Concrete Pavements.

e Attach test results indicating conformance to Standard Specification 9-25.1.

f Actual Average Strength as determined from testing or estimated from ACI 211.

DOT Form 350-040 EF
Revised 6/06

APPENDIX B: MIX DESIGN QUANTITIES

	Coarse Aggregate (lb/cy)	Fine Aggregate (lb/cy)	RCA (lb/cy)	Cement (lb/cy)	Fly Ash (lb/cy)	Effective Mix Water (lb/cy)	AEA (oz./cy)	WRA (oz./cy)
Reference Mix Design	1898	1183	0	564	0	248	2 to 25	15 to 35
X-0-0	1898	1183	0	564	0	248	6.0	0.0
A-15-0	1613	1183	273	564	0	248	9.0	0.0
A-30-0	1328	1183	545	564	0	241	9.6	0.0
A-45-0	1044	1183	818	564	0	248	8.0	2.9
X-0-20	1898	1183	0	451	113	225	8.0	0.0
A-15-20	1613	1183	273	451	113	226	8.8	0.0
A-30-20	1328	1183	545	451	113	238	7.6	0.0
A-45-20	1044	1183	818	451	113	225	8.3	0.0

APPENDIX C: COMPRESSIVE STRENGTH DATA

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
X-0-0-COMP-7-1	118034	4175
X-0-0-COMP-7-2	117027	4139
X-0-0-COMP-7-3	120020	4245
X-0-0-COMP-14-1	139924	4949
X-0-0-COMP-14-2	138801	4909
X-0-0-COMP-14-3	138513	4899
X-0-0-COMP-28-1	155466	5498
X-0-0-COMP-28-2	144745	5119
X-0-0-COMP-28-3	149825	5299
X-0-0-COMP-28-4	146040	5165
X-0-0-COMP-28-5	156186	5524
X-0-0-COMP-90-1	169354	5990
X-0-0-COMP-90-2	170059	6015
X-0-0-COMP-90-3	-	-

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-15-0-COMP-7-1	101590	3593
A-15-0-COMP-7-2	110579	3911
A-15-0-COMP-7-3	106203	3756
A-15-0-COMP-14-1	126511	4474
A-15-0-COMP-14-2	124079	4388
A-15-0-COMP-14-3	103995	3678
A-15-0-COMP-28-1	143709	5083
A-15-0-COMP-28-2	140039	4953
A-15-0-COMP-28-3	135952	4808
A-15-0-COMP-28-4	142845	5052
A-15-0-COMP-28-5	133102	4708
A-15-0-COMP-90-1	155783	5510
A-15-0-COMP-90-2	152559	5396
A-15-0-COMP-90-3	151206	5348

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-30-0-COMP-7-1	122395	4329
A-30-0-COMP-7-2	122567	4335
A-30-0-COMP-7-3	122294	4325
A-30-0-COMP-14-1	135462	4791
A-30-0-COMP-14-2	139103	4920
A-30-0-COMP-14-3	138369	4894
A-30-0-COMP-28-1	154833	5476
A-30-0-COMP-28-2	145810	5157
A-30-0-COMP-28-3	157942	5586
A-30-0-COMP-28-4	162533	5748
A-30-0-COMP-28-5	152775	5403
A-30-0-COMP-90-1	165181	5842
A-30-0-COMP-90-2	168836	5971
A-30-0-COMP-90-3	166519	5889

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-45-0-COMP-7-1	111213	3933
A-45-0-COMP-7-2	104300	3689
A-45-0-COMP-7-3	110148	3896
A-45-0-COMP-14-1	130569	4618
A-45-0-COMP-14-2	129562	4582
A-45-0-COMP-14-3	131677	4657
A-45-0-COMP-28-1	147407	5213
A-45-0-COMP-28-2	144500	5111
A-45-0-COMP-28-3	142442	5038
A-45-0-COMP-28-4	145795	5156
A-45-0-COMP-28-5	140801	4980
A-45-0-COMP-90-1	154790	5475
A-45-0-COMP-90-2	155740	5508
A-45-0-COMP-90-3	162187	5736

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
X-0-20-COMP-7-1	103080	3646
X-0-20-COMP-7-2	110047	3892
X-0-20-COMP-7-3	101443	3588
X-0-20-COMP-14-1	125316	4432
X-0-20-COMP-14-2	124122	4390
X-0-20-COMP-14-3	138024	4882
X-0-20-COMP-28-1	147479	5216
X-0-20-COMP-28-2	150890	5337
X-0-20-COMP-28-3	150070	5308
X-0-20-COMP-28-4	154013	5447
X-0-20-COMP-28-5	152045	5377
X-0-20-COMP-90-1	179227	6339
X-0-20-COMP-90-2	179529	6350
X-0-20-COMP-90-3	174031	6155

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-15-20-COMP-7-1	108838	3849
A-15-20-COMP-7-2	106432	3764
A-15-20-COMP-7-3	115861	4098
A-15-20-COMP-14-1	131879	4664
A-15-20-COMP-14-2	127072	4494
A-15-20-COMP-14-3	135937	4808
A-15-20-COMP-28-1	155869	5513
A-15-20-COMP-28-2	153308	5422
A-15-20-COMP-28-3	164130	5805
A-15-20-COMP-28-4	160935	5692
A-15-20-COMP-28-5	156258	5526
A-15-20-COMP-90-1	184393	6522
A-15-20-COMP-90-2	181169	6408
A-15-20-COMP-90-3	190466	6736

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-30-20-COMP-7-1	105011	3714
A-30-20-COMP-7-2	107716	3810
A-30-20-COMP-7-3	104239	3687
A-30-20-COMP-14-1	124942	4419
A-30-20-COMP-14-2	130137	4603
A-30-20-COMP-14-3	126899	4488
A-30-20-COMP-28-1	135477	4792
A-30-20-COMP-28-2	150070	5308
A-30-20-COMP-28-3	153135	5416
A-30-20-COMP-28-4	154344	5459
A-30-20-COMP-28-5	154833	5476
A-30-20-COMP-90-1	181400	6416
A-30-20-COMP-90-2	172650	6106
A-30-20-COMP-90-3	177687	6284

Sample Name	Ultimate Load (lb)	Compressive Strength (psi)
A-45-20-COMP-7-1	101623	3594
A-45-20-COMP-7-2	110004	3891
A-45-20-COMP-7-3	107543	3804
A-45-20-COMP-14-1	122049	4317
A-45-20-COMP-14-2	131677	4657
A-45-20-COMP-14-3	127734	4518
A-45-20-COMP-28-1	149408	5284
A-45-20-COMP-28-2	151868	5371
A-45-20-COMP-28-3	163151	5770
A-45-20-COMP-28-4	157899	5585
A-45-20-COMP-28-5	-	-
A-45-20-COMP-90-1	183458	6489
A-45-20-COMP-90-2	178219	6303
A-45-20-COMP-90-3	181414	6416

APPENDIX D: MODULUS OF RUPTURE DATA

Sample Name	Ultimate Load (lb)	Actual Width (in)	Modulus of Rupture (psi)
X-0-0-MOR-14-1	6860	6.070	808
X-0-0-MOR-14-2	6565	6.055	821
X-0-0-MOR-14-3	6006	6.090	718
X-0-0-MOR-14-4	6630	6.069	771
X-0-0-MOR-14-5	6230	6.041	750
A-15-0-MOR-14-1	6199	6.040	758
A-15-0-MOR-14-2	6217	6.060	759
A-15-0-MOR-14-3	6498	6.030	792
A-15-0-MOR-14-4	6152	5.990	770
A-15-0-MOR-14-5	5945	5.960	736
A-30-0-MOR-14-1	6233	6.000	779
A-30-0-MOR-14-2	6595	6.035	813
A-30-0-MOR-14-3	6593	6.035	809
A-30-0-MOR-14-4	5916	6.000	736
A-30-0-MOR-14-5	5956	6.040	732
A-45-0-MOR-14-1	6032	6.015	753
A-45-0-MOR-14-2	5732	6.065	702
A-45-0-MOR-14-3	6031	6.025	752
A-45-0-MOR-14-4	5711	6.000	704
A-45-0-MOR-14-5	5734	6.000	713
X-0-20-MOR-14-1	6592	6.045	818
X-0-20-MOR-14-2	6745	6.019	841
X-0-20-MOR-14-3	6202	5.990	777
X-0-20-MOR-14-4	5906	6.036	734
X-0-20-MOR-14-5	5838	6.010	729

A-15-20-MOR-14-1	6548	6.060	784
A-15-20-MOR-14-2	6623	6.125	779
A-15-20-MOR-14-3	6514	6.060	796
A-15-20-MOR-14-4	6201	6.040	745
A-15-20-MOR-14-5	6582	6.030	800

A-30-20-MOR-14-1	5639	6.400	656
A-30-20-MOR-14-2	5952	5.960	701
A-30-20-MOR-14-3	5672	5.930	717
A-30-20-MOR-14-4	6101	5.990	764
A-30-20-MOR-14-5	6221	6.010	764

A-45-20-MOR-14-1	5854	6.040	718
A-45-20-MOR-14-2	6307	6.000	786
A-45-20-MOR-14-3	6036	6.025	741
A-45-20-MOR-14-4	5747	6.040	707
A-45-20-MOR-14-5	6428	6.035	784

APPENDIX E: COEFFICIENT OF THERMAL EXPANSION DATA

Sample Name	28-Day Coefficient of Thermal Expansion (in/in °F)
X-0-0-CTE-28-1	3.84E-05
X-0-0-CTE-28-2	3.87E-05
X-0-0-CTE-28-3	3.79E-05
A-15-0-CTE-28-1	3.98E-05
A-15-0-CTE-28-2	3.95E-05
A-15-0-CTE-28-3	4.01E-05
A-30-0-CTE-28-1	3.98E-05
A-30-0-CTE-28-2	3.87E-05
A-30-0-CTE-28-3	3.97E-05
A-45-0-CTE-28-1	3.90E-05
A-45-0-CTE-28-2	3.93E-05
A-45-0-CTE-28-3	3.92E-05
X-0-20-CTE-28-1	3.84E-05
X-0-20-CTE-28-2	2.87E-05
X-0-20-CTE-28-3	3.89E-05
A-15-20-CTE-28-1	3.79E-05
A-15-20-CTE-28-2	3.97E-05
A-15-20-CTE-28-3	3.95E-05
A-30-20-CTE-28-1	4.01E-05
A-30-20-CTE-28-2	3.91E-05
A-30-20-CTE-28-3	3.93E-05
A-45-20-CTE-28-1	3.85E-05
A-45-20-CTE-28-2	4.00E-05
A-45-20-CTE-28-3	3.90E-05