EVALUATION OF RECYCLED CONCRETE AGGREGATE PRODUCED FROM DEMOLISHED RUNWAY PANELS AS A SUBSTITUTE FOR COARSE AGGREGATES IN NEW PORTLAND CEMENT PAVEMENTS

By

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AS A SUBSTITUTE FOR COARSE AGGREGATES

IN NEW PORTLAND CEMENT PAVEMENTS

Abstract

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The goals of this study were to investigate the effects of substituting recycled concrete aggregate (RCA) for natural aggregate (NA) in concrete intended for new portland cement concrete pavements (PCCP), and to investigate the effects of substituting fly ash for portland cement while simultaneously substituting RCA for NA. The RCA investigated in this study was produced from demolished runway panels at Fairchild Air Force Base in eastern Washington. Eight concrete mixes were prepared in this study, based on the same reference mix design, which incorporated different amounts of RCA as a substitute for coarse aggregate (0%, 15%, 30% and 45%) and fly ash as a substitute for portland cement (0% and 20%).

The slump, air content and density of the fresh concrete were determined. Cylinder and beam specimens from each of the eight mixes were tested to investigate the effects of RCA and fly ash on the hardened concrete properties, including compressive strength, modulus of rupture (MOR), coefficient of thermal expansion (CTE) and drying shrinkage. Properties of the RCA were also

determined, including specific gravity, absorption, Los Angeles abrasion loss, degradation, and alkali-silica reactivity (ASR).

It is recommended that the RCA be washed and any fine materials removed prior to use to meet the Washington State Department of Transportation (WSDOT) degradation requirement. The RCA used in this study did show signs of being alkali-silica reactive, but further tests are needed to confirm that this expansion is due to the alkali-silica reaction. If the RCA is confirmed to be reactive, this situation can be mitigated through the use of low-alkali cement or fly ash substitution. It was found that fresh concrete density decreased with the addition of RCA. Substituting RCA for coarse aggregate at rates up to 45% was found to have no statistically-significant effects on compressive strength, MOR, and CTE values. It is recommended that additional research be conducted with RCA substitution rates greater than 45%.

Based on the results of this study, the use of RCA as a substitute for natural coarse aggregate seems promising for use in new PCCP in Washington State.

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CHAPTER 1: INTRODUCTION

1.1 Background

According to the American Society of Civil Engineers “32% of America’s major roads are in poor to mediocre condition…” (ASCE, 2013). There is an urgent need to rehabilitate or replace these roadways to ensure that quality and safety standards are maintained. These projects will require an immense amount of aggregates, which is a concern as aggregates are a nonrenewable natural resource and quality aggregates are becoming increasingly scarce.

Roadway owners and transportation agencies concerned with our nation’s dependence on this dwindling supply of natural aggregates (NA) have been looking for effective ways to mitigate this dependence. Using recycled concrete aggregate (RCA) in portland cement concrete pavements (PCCP) could prove to be an economical and sustainable way to alleviate our dependence on natural aggregates. RCA is produced from the rubble of demolished pavements and structures. In addition to alleviating our dependence on natural aggregates, recycling these demolished pavements could greatly diminish the amount of waste that would normally be dumped into landfills (FHWA, 2007).

Currently, RCA is commonly used as a base material for concrete pavements, but it is utilized much less in new PCCP (Anderson et al., 2009). A number of states, including Alabama, Colorado, Florida, Kansas, Minnesota, Nevada, Ohio, Tennessee, Texas, and West Virginia, do allow the use of RCA in PCCP applications, provided that the RCA meets the applicable requirements for aggregate properties. Other states prohibit the use of RCA because they have not yet adequately evaluated the use of RCA in PCCP, or because they have concerns regarding the consistent performance of PCCP made with RCA (Anderson et al., 2009).

Reasons why RCA is currently not widely used in PCCP include: many transportation agencies prohibit the use of RCA; there are concerns with expansion caused by a detrimental reaction known as the alkali-silica reaction (ASR); and there are concerns with the consistent performance of concretes incorporating RCA. While some of these concerns are well founded, there are potential steps that can be taken to mitigate any adverse effects that RCA may have on the strength and durability properties of concrete.

1.2 Scope and Objectives

The goals of this study were two-fold: to investigate the effects of substituting NA with different amounts of RCA; and to investigate the effects of substituting portland cement with fly ash while simultaneously substituting NA with RCA. The RCA investigated in this study was produced from demolished runway panels at Fairchild Air Force Base in eastern Washington. In addition to the study reported in this thesis, two complementary investigations are underway examining concrete incorporating RCA from two other sources in Washington State. The three studies are part of a bigger project funded by the Washington State Department of Transportation and the Pacific Northwest Transportation Consortium. All three studies used the same materials (apart from the RCA, which came from different regions of Washington) and followed the same batching procedure and testing procedures.

In an attempt to better understand the effects that RCA and fly ash have on new PCCP, each study evaluated eight mixes of concrete prepared based on the same mix design but incorporating RCA from the three different sources. For each of the eight mixes, a number of fresh concrete tests were performed, including measuring the slump, air content, and density of concrete. Tests of cylinders and beams from each of the eight mixes were performed in order to investigate the effects of RCA and fly ash on the hardened concrete properties, including compressive strength, modulus of rupture (MOR), coefficient of thermal expansion (CTE), and drying shrinkage. Properties of the RCA were also investigated, including specific gravity and absorption, Los Angeles (LA) abrasion loss, degradation, and alkali-silica reactivity (ASR).

The overall objective of this project is to investigate the viability of incorporating RCA in new PPCP in Washington State. Recommendations regarding the use of RCA in new PCCP are given at the end of this thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter discusses the findings from other research projects on the properties of RCA and how RCA substitution for NA and fly ash substitution for portland cement affects the fresh and hardened properties of concrete.

2.2 Properties of RCA

This section discusses several of the relevant properties of RCA including specific gravity, LA abrasion loss, degradation value, and alkali-silica reactivity.

2.2.1 Specific Gravity

Specific gravity is a property of an aggregate that describes its density relative to that of water. RCA tends to have lower specific gravities than NA due to the air-entrained adhered mortar portion of the RCA. A literature review by the Washington State Department of Transportation (WSDOT) reports that the specific gravity of RCA ranges between 2.1 and 2.4, while the specific gravity of NA ranges between 2.4 and 2.9 (Anderson et al., 2009). Mjelde (2013) reported a specific gravity of 2.52 for RCA obtained from demolished panels of Interstate 90 near Roslyn, Washington.

If RCA is substituted by weight without accounting for the specific gravity, the total volume of batched concrete will be larger than intended. When the specific gravity is accounted for, the substitution is made on a volumetric basis while the total weight of the aggregates fluctuates, resulting in a consistent volume yield of the concrete.

2.2.2 LA Abrasion Loss

The LA abrasion loss test is used to determine how much material loss will occur when an aggregate is abraded by steel balls in a rotating drum. The hardness of the aggregate determines the outcome of this test.

Typical values of LA abrasion loss for RCA range between 20% to 45%, while the loss range is between 15% to 30% for NA (Anderson et al., 2009). Mjelde (2013) reported an LA abrasion loss of 29% for the RCA used in his study. This increase in material loss for RCA has been attributed to the weak bond between the mortar and aggregate, while NA has a stronger inner structure (Amorim et al., 2012). In order to be approved for use in pavements, WSDOT requires coarse aggregate to have a LA abrasion loss equal to or less than 35% (WSDOT, 2012).

2.2.3 Degradation Value

The degradation value is a number that quantifies the amount of material loss due to abrasion of an aggregate in the presence of water (WSDOT, 2012). WSDOT requires that aggregates have a degradation value that equals or exceeds 30 in order to be approved for use in pavements (WSDOT, 2012). Mjelde (2013) reported degradation values of 15 and 55 for the as-delivered RCA (containing fine and coarse RCA material, no NA) and the processed RCA (containing only coarse RCA material, no NA), respectively, used in his study.

2.2.4 ASR

ASR is a chemical process that occurs when the alkali present in cement reacts with a reactive form of silica present in the aggregate (Kosmatka and Panarese, 1988). In addition to these two components, a high moisture content and warm environment must also be present in order for the reaction to occur (Kosmatka and Panarese, 1988). When all of these components are present, an expansive gel is formed within the concrete. This gel swells as it absorbs water from its surrounding materials, causing internal pressure to grow within the concrete until it is relieved by the concrete cracking (Kosmatka and Panarese, 1988). This reaction can be detrimental to the durability of concrete if actions are not taken to mitigate it.

Concrete incorporating RCA has been reported to run a higher risk of experiencing problems with ASR (Anderson et al., 2009). The crushing process used to break down the RCA exposes more surface area for the reaction to occur when compared to NA. However, there are effective ways to mitigate the ASR reaction when necessary. WSDOT recommends "using low alkali, Type II cement, blending the RCA with quality conventional aggregates, and using fly ash" as a substitute for cement (Anderson et al., 2009). Expansion due to ASR reactivity is reported to be reduced by up to 70% when Type F fly ash is used in concrete (Kosmatka and Panarese, 1988). Mjelde (2013) reported a 14-day ASR expansion of 0.068% for mortar bars containing processed and crushed RCA. This value is below 0.10%, which is the maximum allowable expansion, specified by AASHTO T 303, "Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction".

2.3 Properties of Fresh Concrete

This section discusses the effects of RCA substitution on several of the relevant properties of fresh concrete including workability, air content, and density.

2.3.1 Workability

Concrete workability can be a concern regardless of whether or not RCA is used to replace NA, but a mix with RCA "tends to lose workability faster and is often a harsher mix" (Garber et al., 2011). This harshness is due to the more angular surface typical of RCA, compared to NA, which is a result of the crushing process used to obtain it. One study found that "the RCA's average shape index is 120% higher than the NCA's (natural coarse aggregate), meaning that RCA is more angulated than the NCA" (Amorim et al., 2012). The workability of a mix affects slump, how easily the concrete can be placed, and how well it will consolidate.

While adding more water is a possible solution to this problem, it can become detrimental if the water-cement ratio becomes too high, negatively impacting the strength properties of the hardened concrete. As an alternative, a water-reducing admixture (WRA) can be added during the batching process. This admixture acts to improve the workability of the mix while not adding any additional water to the mix. While not always the case, fly ash substitution for cement is also reported to decrease the effective water requirement from one to ten percent in order to achieve a target slump (Kosmatka and Panarese, 1988). One or both of these two additions to the mix are often necessary for controlling slump and maintaining a proper water/cement ratio.

2.3.2 Air Content

Mixes containing RCA tend to have higher air contents than NA mixes. "This is due to the higher porosity of the recycled aggregates themselves and to the entrained air in the original mortar mix" (Anderson et al., 2009). Higher air contents tend to lead to lower concrete strengths, as there is less net concrete volume to transfer loads within the concrete (Kosmatka and Panarese, 1988).

To mitigate the higher-than-normal air content of concrete with RCA, it is recommended that as much of the mortar be removed as is reasonably possible from the RCA before it is incorporated into the mix (Anderson et al., 2009).

2.3.3 Density

Concrete mixes with RCA will typically have a lower density than mixes using only NA (Anderson et al., 2009). This is due to the lower specific gravity of RCA compared to NA. Mjelde (2013) reported fresh concrete densities in the range of 142.8 pcf to 145.4 pcf for concretes with partial RCA substitution.

2.4 Properties of Hardened Concrete

This section discusses the effects of RCA substitution for NA on several of the relevant properties of hardened concrete including compressive strength, modulus of rupture (MOR), coefficient of thermal expansion (CTE), drying shrinkage, and freeze-thaw durability.

2.4.1 Compressive Strength

According to the literature review by the WSDOT, concrete containing RCA will have a slightly lower compressive strength than normal concrete assuming that the water-cement ratio and air content are similar (Anderson et al., 2009). The literature review reported that the elastic modulus of the RCA is on the average 20% to 40% less than mixes utilizing only NA with the same water-cement ratios (Anderson et al., 2009). Therefore, a mix containing RCA with a lot of mortar on it is likely to have lower compressive strength than a normal concrete mix.

Contrary to these findings, other studies have found that there are no significant differences between the compressive strength of normal concrete and RCA concrete (Mjelde, 2013). The report by Amorim et al. (2012), speculates that "The fact that RCA has a better interfacial transition zone with the new cement paste and the possible presence of unhydrated cement on the RCA are considered as possible justifications for the maintenance of performance." All of the compressive strengths in Mjelde's study were above the WSDOT requirement of 4000 psi at an age of 28 days for concrete incorporating up to 45% coarse RCA (Mjelde, 2013).

Fly ash has been shown to increase the long-term compressive strength gain of concrete (Kosmatka and Panarese, 1988). Mjelde (2013) reported that fly ash decreased the early-age strength gain of concrete without affecting the long-term strength gain.

2.4.2 Modulus of Rupture

Modulus of rupture (MOR) is the tensile strength of concrete when subjected to flexural loading. The WSDOT report by Anderson et al. (2009) states that the MOR can be reduced by up to eight percent when RCA is substitute for coarse aggregate. It is thought that there is a direct correlation between the reduction in flexural strength and the quality of the mortar-aggregate bond of the RCA (Anderson et al., 2009) (Limbachiya et al., 2012). Mjelde (2013) reported 14-day MOR values, for concrete incorporating up to 45% RCA, that were all above the WSDOT requirement of 650 psi. He also found that RCA had little or no effect on the MOR of concrete.

Just as with the compressive strength, fly ash has been found to increase the long-term flexural strength gain of concrete (Kosmatka and Panarese, 1988). This increase in flexural strength could provide the concrete with greater resistance to cracking, as cracking is directly related to the tensile strength of the concrete.

2.4.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) is a property of the aggregate that defines how much a material will expand or contract when subjected to temperature change. A recent study found that RCA substitution has the effect of lowering the CTE of concrete (Smith and Tighe, 2009). The CTE of the concrete has also been reported to be mainly affected by the type of aggregates used in the concrete (Kosmatka and Panarese, 1988). CTE values for normal concrete are reported to range from 3.2 to 7.0 millionths per degree Fahrenheit (Kosmatka and Panarese, 1988).

2.4.4 Drying Shrinkage

Normal concrete exposed to air with 50% relative humidity is reported to experience drying shrinkage from 400 to 800 millionths (Kosmatka and Panarese, 1988). According to Anderson et al. (2009), concrete with RCA undergoes greater amounts of drying shrinkage than concrete with only NA due to excess water that is present in the fresh cement paste. The increased porosity introduced by the RCA also lowers the stiffness of the concrete, rendering it less able to restrain deformation when compared to normal concrete (Amorim et al., 2012). Furthermore, RCA mixes are reported to be affected the most in dry regions when compared to the durability of a NA mix (Amorim et al., 2012). This is likely due to the high porosity of RCA that allows water to evaporate much more readily than NA, increasing the amount of drying shrinkage experienced.

Regarding the effects of fly ash substitution on drying shrinkage, two seemingly conflicting conclusions have been reported. According to Limbachiya et al. (2012), “all fly ash concretes have exhibited a lower magnitude of drying shrinkage…In fact, ashes are known by their capability to reduce shrinkage strains…” However, the PCA reports that below a 40%

substitution rate of fly ash for cement, there is little to no observable effect on the drying shrinkage (Kosmatka and Panarese, 1988).

2.4.5 Freeze-Thaw Durability

Freeze-thaw durability describes the ability of a concrete to resist damage when undergoing expansion and contraction due to cycles of freezing and thawing. Freeze-thaw durability is largely dependent on the air void system and the amount of entrained air present in the concrete (FHWA, 2007). The literature review by the WSDOT postulated that RCA concrete will be more resistant to freeze-thaw effects due to the increased porosity of the RCA, which allows for more air-entraining admixture (AEA) to settle into the pores of the cement paste (Anderson et al., 2009). Including AEA in the mix will also improve freeze-thaw durability. According to Kosmatka and Panarese (1988), air entrained concrete is highly resistant to freeze-thaw deterioration. They further explain, saying that "water displaced by ice formation in the paste is accommodated so that it is not disruptive; the microscopic air bubbles in the paste provide chambers for the water to enter and thus relieve the hydraulic pressure generated" (Kosmatka and Panarese, 1988).

2.4.6 Summary of Mjelde's Results

The following is a summary of main observations and conclusions reached in the study by Mjelde (2013) using RCA produced from demolished interstate panels in central Washington State. The experimental procedures used by Mjelde were the same that were used for this study, except that his study used a different source of RCA. In his report, Mjelde concluded the following:

1. RCA decreased the workability of fresh concrete
2. Fly ash increased the workability of fresh concrete
3. RCA decreased the density of fresh concrete
4. Based on the results of his study, RCA did not appear to influence the compressive strength or modulus of rupture

Since all eight of his concrete mixes met the WSDOT requirements for PCCP, he recommended that further studies be conducted in which greater percentages of coarse RCA substitution are investigated. As long as RCA is substituted for only coarse aggregates, Mjelde postulated that RCA would be suitable for use in PCCP based on the WSDOT requirements.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 Introduction

In this project, concrete incorporating three different sources of RCA were investigated. This thesis focuses on concrete with RCA from one of those sources, designated as source B. For each source of RCA, eight batches of concrete were made: six of which utilized RCA as a substitute for varying portions of the coarse aggregate, and two did not contain any RCA. Two components were varied in the batches: the amount of RCA substitution, and the amount of fly ash substitution. RCA was substituted by volume for natural coarse aggregate at 0%, 15%, 30%, and 45%, and fly ash was substituted by weight for portland cement at 0% and 20% while at the same time varying the amount of RCA substitution. Fresh and hardened concrete samples were produced from each batch for testing. RCA substitution rates and fly ash substitution rates for each of the eight mixes are presented in Table 3.1.

Table 3.1 Parameters of the Eight Concrete Mixes

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%

A reference portland cement concrete pavement (PCCP) mix design was provided by WSDOT for use in this study (mix C8022) and is given in Appendix A.

3.2 Materials

This section discusses the materials used for the project including details of the NA, RCA, cementitious materials, and admixtures.

3.2.1 Natural Aggregates

The NA used in this study was supplied from WSDOT-approved pits. The aggregates were delivered in five separate components: 1.5 in. round combined, 3/4 in. round combined, 3/8 in. round combined, coarse sand combined, and blend sand combined. Additional information on these components is given in the reference mix design C8022 in Appendix A.

In order to facilitate the batching process, the NA components were recombined into a coarse aggregate stockpile and a fine aggregate stockpile. The coarse aggregate stockpile conformed to AASHTO Grading No. 467, and the fine aggregate stockpile conformed to the Class 1 gradation (WSDOT, 2012). All NA was stored in an indoor facility at Washington State University.

3.2.2 RCA

The source B RCA was obtained from demolished runway panels at Fairchild Air Force Base located near Spokane, WA. Two methods of crushing were used to produce the RCA. A jaw crusher was used first to break up the panels into pieces of manageable sizes, and then the pieces were processed through a comb crusher to produce RCA with a nominal maximum size of 1.25 in.

In this study, RCA was substituted only for coarse aggregates; therefore, the gradation of the RCA used for batching had to conform to AASHTO Grading No. 467 (WSDOT, 2012). In its delivered state, the RCA did not meet these grading requirements. To meet the grading requirements, the as-delivered RCA was sieved using a mechanical shaker through 3/4 in., 3/8 in., and No. 4 sieves, washed to remove the fine particles still present in the RCA, and then recombined into a new stockpile which met the AASHTO Grading No. 467. The RCA was stored in an indoor facility located at Washington State University. There was approximately a 26% yield of useable RCA after the as-delivered product was sieved and recombined. All material below the no. 4 sieve was discarded.

3.2.3 Cementitious Materials

Two cementitious materials were used in this project. The cement was Type I/II and was produced by Ash Grove Cement in Durkee, Oregon. The fly ash was Type F and came from Centralia, Washington.

3.2.4 Admixtures

Two admixtures were used for this project: Daravair 1000 air entraining admixture (AEA) and WRDA 64 water-reducing admixture (WRA). Both admixtures were manufactured by WR Grace & Co.

3.3 Concrete Batching

This section discusses the batching process including preparing materials and specimen molds, mixing the concrete, and making the test specimens.

3.3.1 Material Preparation

Prior to batching, the specific gravity and absorption values of the recombined aggregate stockpiles were obtained. Since these properties do not change over time, these properties were determined only once.

Proportions listed in the reference mix design are based on aggregates being in the saturated surface dry (SSD) condition at the time of batching. However, none of the aggregates for this project were in their SSD state at the time of their use. In the SSD state, aggregates have a moisture content equal to that of their absorption capacity; there is no excess water present on the surface of the aggregate, nor does the aggregate absorb water from the mix.

In order to correctly account for moisture conditions for batching, the moisture contents of the aggregates were determined the day prior to batching. A sample of aggregate was taken from each of the stockpiles being used and weighed in its existing condition, dried in an oven, and then weighed again to obtain the dry weight. Once the existing and dry weights were known, the moisture content was calculated. If the moisture content of the aggregate was higher than its absorption capacity, then the moisture condition in the aggregate exceeded the SSD state; water had to be subtracted from the batch water and additional aggregate had to be added equal to the weight of batch water taken out in order to maintain a similar total weight of batch material. If the moisture content of the aggregate was lower than its absorption capacity, then the aggregate had not yet reached its SSD condition; in this case water had to be added to the mix water and aggregate weight had to be reduced by the amount of water added to the batch water. This process of dynamically adjusting batch proportions ensured that all aggregates were effectively in their SSD condition during mixing.

After adjusting the batch material proportions, the aggregates, cement, and fly ash were then weighed out and placed in buckets nearby the mixer. Admixtures were measured out into graduated cylinders and also placed nearby.

The range of acceptable slump and air content for the batches was specified by the WSDOT. The acceptable range for the slump was 1 to 3 in., and the acceptable range for the air content was 4% to 7%. To meet these criteria, WRA and AEA were added to the mixer in a manner that allowed the slump and air content to be approached from below their minimum target values in order to avoid overshooting the targets. It should be noted that weight of water and the volume of admixtures used were not held constant among the eight batches of concrete. This was done so that each batch would meet the slump criterion.

Final batch quantities for each of the eight mixes, on a cubic yard (CY) basis, are given in Appendix B.

3.3.2 Concrete Mixing Procedure

To begin the mixing process, cement slurry (cement and water) was poured into a running concrete mixer and allowed to coat the interior of the mixing drum. Once the drum was fully coated, the excess cement slurry was dumped out.

Next, all of the aggregates for the given batch were placed into the mixer. Once all of the aggregates were inside, the mixer was turned on and a portion of the mix water was added. The mixer was allowed to run for approximately three minutes to allow the aggregates to become well blended. A picture of the aggregates being placed in the mixer can be seen in Figure 3.1.

Figure 3.1 Placing Aggregate in the Mixer

The next step was to add the cementitious materials and an additional portion of the mix water while the mixer was still running. Some water was withheld for the purpose of insuring that the slump did not exceed the specified range based on visual inspection. After approximately two minutes of additional mixing, the mixer was stopped, any concrete sticking to the drum wall was scraped off, and then the mixer was turned back on. The mixer was kept running for a total of approximately five minutes since the addition of the cementitious materials.

Once it was determined, based on visual inspection, that the lower limit of slump had been approached, the mixer was stopped and the slump was measured. If the slump was within the acceptable range, the mixing procedure was continued. If the slump was below the acceptable range, then the concrete used for the slump test was placed back into the mixer, the mixer was turned on, additional water was added to the mixer and the batch allowed to mix for an additional two to three minutes, and then the slump was measured again. If the slump was still not within the acceptable range and all the mix water had been added, WRA was added to the concrete during the next step. A picture of the slump test being performed can be seen in Figure 3.2.

Figure 3.2 Measuring Slump of Fresh Concrete

After an acceptable slump was achieved, the AEA was added to the running mixer and allowed to mix for another five minutes. AEA was always added, with the dosage being based on past experience. WRA was only added if the slump was not in the target range after all mix water had been added.

After the five minutes of additional mixing, the mixer was turned off, and the slump and air content were measured. If both the slump and air content were found to be within their acceptable ranges, the mixing procedure was terminated and the process progressed to the sample preparation stage. However, if either the slump or the air content were found to be below the target range, additional volumes of the appropriate admixture were added to the concrete and mixing was resumed for another three minutes. The mixer was then stopped in order to measure the slump and air content again to make sure they were within their acceptable limits.

At this point, the mixing process was over. The fresh concrete density was measured, and any remaining mix water was recorded. A picture of the density test being performed can be seen in Figure 3.3.

Figure 3.3 Tamping the Fresh Concrete for the Density Test

3.3.3 Sample Preparation

All test specimens were prepared following the guidelines given in AASHTO R 39, “Making and Curing Concrete Test Specimens in the Laboratory”. For each batch of concrete, 14 compression cylinders, 3 CTE cylinders, 5 flexure beams, and 3 shrinkage beams were created. All cylindrical test specimens were filled and tamped with a rod using the specified procedures, while the beams were filled and vibrated on a shake table. The tops of the test specimens were then smoothed with a trowel. The cylinders were capped with plastic caps, and the beams were covered with a moist towel followed by a plastic sheet to help keep the moisture in. The test specimens then sat for 24 hours, after which they were de-molded and placed in lime-saturated water for curing. Pictures of the preparation of compression cylinders and flexure beams are given in Figures 3.4 and 3.5, respectively.

Figure 3.4 Preparation of Compression Cylinders

Figure 3.5 Preparation of Flexure Beam

3.4 Test Methods

This section discusses the test methods used for this project including the RCA tests, fresh concrete tests, and hardened concrete tests.

3.4.1 RCA Tests

Four tests were used to characterize the RCA used in this project. AASHTO T 85, “Specific Gravity & Absorption of Coarse Aggregate”, was used to determine the specific gravity and absorption of the RCA. AASHTO T 96, “Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine”, was used to quantify the LA abrasion loss of the RCA. WSDOT T 113, “Method of Test for Determination of Degradation Value”, was used to determine the degradation value of the RCA. Lastly, AASHTO T 303, “Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction”, was used to determine the ASR reactivity of the RCA.

3.4.2 Fresh Concrete Tests

Three tests were used to characterize the fresh concrete. AASHTO T 119, “Slump of Hydraulic Cement Concrete”, was used to determine the slump of the freshly batched concrete. AASHTO T 152, “Air Content of Freshly Mixed Concrete by the Pressure Method”, was used to determine the air content of the freshly batched concrete. A Type B meter was used for this project, and a correction factor of 0.5 was determined for all rates of RCA substitution. Lastly, AASHTO T 121, “Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete”, was used to determine the density of the freshly batched concrete.

3.4.3 Hardened Concrete Tests

Types, ages and number of specimens for the hardened concrete tests carried out for each of the eight concrete batches are given in Table 3.2.

Table 3.2 Hardened Concrete Tests

Day	Test (number of specimens tested)
0	Slump (1) Air Content (1) Density (1)
1	Shrinkage (3)
7	Compression (3)
14	Flexure (5) Compression (3)
28	Compression (5) Shrinkage (3)
32	Shrinkage (3)
35	Shrinkage (3)
42	Shrinkage (3)
56	Shrinkage (3)
84	Shrinkage (3)
90	Compression (3)
140	Shrinkage (3)
252	Shrinkage (3)

Four tests were used to characterize the properties of the hardened concrete. AASHTO T 22, "Compressive Strength of Cylindrical Concrete Specimens", was used to determine the compressive strength of the hardened concrete. Fourteen compression cylinders were created from each batch of concrete. The cylinders were 12 in. long and had a diameter of 6 in. All compression cylinders were capped on the top and bottom with neoprene-lined steel caps to mitigate the effects of improper load transfer due to imperfections on the loading surfaces for testing, and all cylinders were tested in a wet condition. A Tinius Olsen Universal Testing Machine was used to perform this test. The loading rate was controlled during testing at approximately 60,000 lbs/min. A picture of the compression test setup can be seen in Figure 3.6.

Figure 3.6 Compression Cylinder Loaded in Tinius Olsen Universal Testing Machine

AASHTO T 177, “Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)”, was used to determine the MOR of the hardened concrete. Five MOR beams were created from each batch of concrete. The beams had 6-in. square cross-sections and a length of 21 in. The beams were supported on steel rollers at a span of 18 in., and another steel roller was placed at the top center of the beam where the load was applied. Moist leather shims placed between the beam and the steel cylinders were used to evenly distribute the load at these contact points. All beams were tested in a wet condition. This test was performed using the Tinius Olsen Universal Testing Machine. The loading rate was controlled during testing at approximately 1,200 lbs/min. A picture of the flexural test setup can be seen in Figure 3.7.

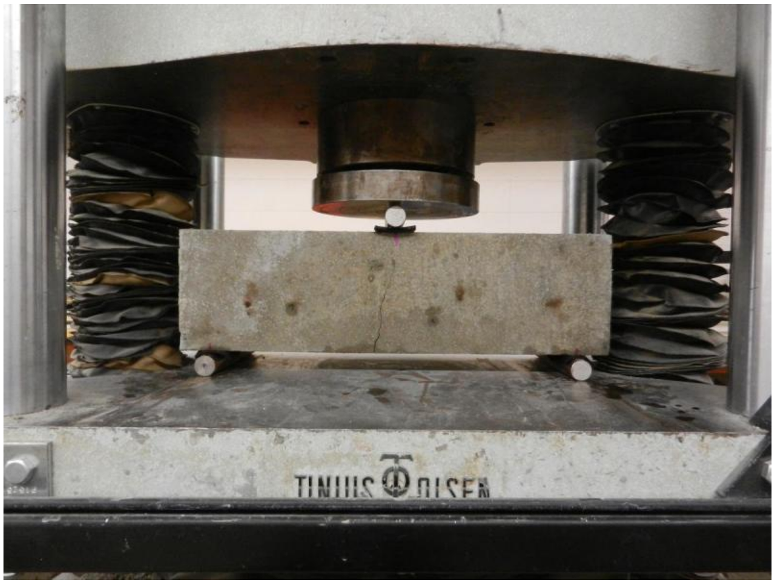

Figure 3.7 Flexural Beam Loaded in the Tinius Olsen Universal Testing Machine

General procedures but not all requirements of AASHTO T 160, "Length Change of Hardened Hydraulic Cement Mortar and Concrete", were used to quantify the amount of drying shrinkage of test specimens. Three beams were created from each batch of concrete. The beams had 4-in. square cross-sections, a specimen length of 11.25 in., and a gauge length of 10 in. The beams were initially moist cured in lime-saturated water for the first 28 days and were then moved to a sealed chamber where they were air cured for the remainder of their testing cycle. The air-cured specimens were supported on rollers consisting of 1-in. diameter PVC pipes. A length comparator manufactured by ELE International was used to perform the shrinkage tests. A picture of the test setup can be seen in Figure 3.8.

Figure 3.8 Shrinkage Beam Loaded in the Length Comparator

The following is a description of the process used for the shrinkage tests in this project. As previously stated, after being water-cured for the first 28 days, the specimens were air cured in a sealed room. The relative humidity of the room was approximately controlled through the combined use of a standard humidifier and dehumidifier. De-ionized water was used in the humidifier. The relative humidity ranged from 40% to 50%, and the temperature ranged from 68 to 86 degrees Fahrenheit. The relative humidity and temperature were recorded on days that shrinkage measurements were taken. This project lacked an atmometer, and therefore the rate of evaporation was not monitored.

AASHTO T 336, “Coefficient of Thermal Expansion of Hydraulic Cement Concrete”, was used to determine the CTE of concrete specimens. Three cylinders were created from each batch. The cylinders were originally 8 in. in length with a diameter of 4 in. Before testing the specimens, a lapidary saw was used to cut the specimen length to 7 in. in order to conform to the test specification.

One specimen was tested at a time, with three tests run for each batch. A single test took approximately six hours to run. The specimen was mounted in a custom-made stainless steel frame that was fabricated by the Washington State University College of Engineering and Architecture shop and conforms to the frame described in the test specification. A submersible linear variable differential transformer (LVDT) was used to actively monitor the length change of the specimen during testing, and water temperature was monitored through the use of submersible thermocouples. A data acquisition system was used to record the water temperature and length change of the specimen every two seconds during testing. The support frame and specimen, which were fully immersed, were placed in a temperature-controlled water bath, manufactured by Neslab, during the testing. Two thermocouples were used to monitor water temperature: one monitored surface temperature and the other measured temperature at the bottom of the water bath. Pictures of the stainless steel frame and water bath can be seen in Figures 3.9 and 3.10, respectively.

Figure 3.9 CTE Cylinder Loaded in the Frame

Figure 3.10 Water Bath Containing Frame and Specimen

CHAPTER 4: TEST RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained in this study, including the measured NA and RCA properties, results from tests on fresh concrete samples, and results from tests on hardened concrete samples.

4.2 Natural Aggregate Properties

The NA used in this project came from WSDOT-approved pits; therefore all NA conformed to WSDOT requirements for aggregates used in concrete pavements. Sieve analyses were run on all of the individual NA components and confirmed the gradations to be the same as those specified in the reference mix design. After the creation of the blended fine and coarse NA stockpiles, a sieve analysis was performed on a sample from each stockpile and confirmed that the coarse NA stockpile conformed to the requirements of AASHTO Grading No. 467 and the fine NA stockpile conformed to the requirements of the Class 1 gradation (WSDOT, 2012). The SSD bulk specific gravity and percent absorption of both NA stockpiles are given in Table 4.l.

Table 4.1 Properties of NA Stockpiles

	Natural Aggregate Source	
Property	**Fine Stockpile**	**Coarse Stockpile**
SSD Bulk Specific Gravity	2.59	2.63
Absorption	1.96%	1.17%

4.3 RCA Properties

The unprocessed RCA did not conform to the WSDOT requirements for coarse aggregates used in concrete pavements. After being processed and appropriately recombined into a coarse RCA stockpile, a sieve analysis was performed and confirmed that the processed RCA stockpile met the requirements of AASHTO Grading No. 467. The coarse RCA stockpile had a SSD bulk specific gravity of 2.53 and an absorption of 3.87%. When compared to values for the NA, the RCA's lower SSD bulk specific gravity and higher absorption can be explained by the porous, air-entrained adhered mortar portion of the RCA. As comparisons, the RCA used in the study by Mjelde (2013) had an SSD bulk specific gravity of 2.52 and an absorption value of 3.3%.

The WSDOT specifies a maximum limit for LA abrasion loss of 35%. For the RCA used in this study, the LA abrasion loss was found to be 20% and therefore meets the WSDOT requirement. Mjelde (2013) determined an LA abrasion loss of 29% for his RCA source.

WSDOT's minimum permitted degradation value is 30. The degradation value for a 90 lbs sample of the as-delivered source B RCA which did not contain any NA was determined to be 37; therefore, it conforms to this WSDOT requirement. The degradation value was also determined for three 50 lbs samples of combined fine and coarse NA samples from the stockpiles, with different levels of coarse RCA substituted in from the processed RCA stockpile at rates of 15%, 30%, and 45%. Additionally, the degradation value was determined for a 50 lbs sample of processed RCA with no NA blended in. All three of the blended 50 lbs samples contained the same amount of fine NA. All of the degradation results for this study (source B RCA) as well as those obtained by Mjelde (2013) for the source A RCA are given in Table 4.2.

Table 4.2 Degradation Value Test Results

		WSDOT Minimum Requirement	As-delivered RCA	Processed RCA	Combined Aggregates: 15% RCA Substitution	30% RCA Substitution	45% RCA Substitution
Degradation Value	Source B	30	37	49	77	75	70
	Source A (Mjelde)		15	55	77	75	73

Based on the results of this study, the source B RCA passed all of the degradation tests. It can be seen that removing the fine material from the RCA had a beneficial effect on the degradation value; therefore, it is recommended that the fine RCA material be removed before using this source in concrete pavements. The degradation value was relatively unaffected by the addition of RCA when it was combined with NA.

The 14-day average ASR expansion of the portland cement mortar bars made using the source B RCA was determined to be 0.17%. The maximum average expansion specified by AASHTO T 303 is 0.10%; therefore, the RCA used in this study may be ASR reactive and is potentially capable of causing deleterious expansion if used in PCCP. AASHTO T 303 suggests that additional testing be conducted on RCA exhibiting deleterious expansion to investigate if it is due to the alkali-silica reaction or some other source.

If the RCA from source B is to be used in PCCP, action may need to be taken to mitigate the effects of ASR by using fly ash as a substitute for cement or by using a low-alkali portland cement. In contrast, the source A RCA used in Mjelde's study conformed to the AASHTO requirement, exhibiting an ASR expansion of 0.068%. Mjelde concluded that no mitigative techniques were needed, with regards to ASR, if using his RCA source in PCCP (Mjelde, 2013).

4.4 Fresh Concrete Test Results

This section discusses the effects of RCA and fly ash substitution on the fresh concrete test properties including slump, air content and density.

The labeling convention used to designate the eight concrete mixes produced for this project is as follows. The first character in the label is a letter which designates which source of RCA was used in the mix; hence, this will either be X (indicating the reference design mix with no RCA), A (Mjelde's source), or B (the source used for this study). The second character is a number that indicates the percentage of RCA substitution for coarse NA used in the batch. The third character is a number that indicates the percentage of fly ash substitution used. For example: X-0-20 denotes that no RCA was used and 20% of the portland cement was replaced with fly ash; B-15-0 denotes that 15% of coarse NA was replaced with source B RCA and no fly ash was used.

Table 4.3 lists a number of pertinent results from the fresh concrete tests for each batch including water/cementitious materials ratio, slump, air content, and density.

Table 4.3 Fresh Concrete Test Results

	Water/Cementitious Materials Ratio	Slump (in.)	Air Content	Density (pcf)
X-0-0	0.43	1.6	4.3%	145.8
B-15-0	0.44	1.1	4.1%	146.2
B-30-0	0.43	1.5	5.0%	143.4
B-45-0	0.43	1.25	4.3%	145.8
X-0-20	0.40	1.75	4.1%	146.8
B-15-20	0.41	1.75	4.7%	145.8
B-30-20	0.42	1.75	4.2%	145.4
B-45-20	0.41	2.0	4.7%	143.4

It is apparent that fly ash had an effect on the water/cementitious materials ratios. As can be seen in Table 4.3, the mixes containing fly ash have water/cementitious materials ratios that are all lower than the non-fly ash mixes. This trend is a result of the batching process followed for this project. In order to control the slump so that it was within the range specified by WSDOT (1 to 3 in.), it was necessary to withhold a portion of the mix water from the batches containing fly ash.

Based on the results obtained in this study, replacing 20% of the portland cement with Type F fly ash had the effect of increasing the workability of fresh concrete thereby permitting lowering the water/cementitious materials ratio of the fresh concrete while still maintaining the slump within the target range. Since the slump was controlled for each batch, it is not possible to comment on the effects that RCA had on the workability of concrete. By looking at the slumps of mixes with similar water/cementitious materials ratios, Mjelde (2013) found that RCA decreased the workability of fresh concrete while including fly ash in a mix increased the fresh concrete workability.

To conform to AASHTO T 152, “Air Content of Freshly Mixed Concrete by the Pressure Method”, an aggregate correction factor is needed to correct the measured air content in order to account for voids present within the aggregate particles. An aggregate correction factor of 0.5% was determined for all levels of RCA substitution. All eight of the concrete mixes were within the WSDOT-specified air content range after this correction factor was subtracted from the measured air content. Even though the aggregate correction factor was the same for all eight mixes (which may suggest that RCA has little effect on the air content of freshly mixed concrete), it is difficult to reach a conclusion regarding the effects of RCA on the air content of fresh concrete. There are two reasons for this: the amount of AEA added was not held constant among the eight mixes, and some mixes underwent greater mixing times when the air content was found to be outside the acceptable range after the first addition of AEA. Mjelde (2013) also reported an air correction factor of 0.5% and reached the conclusion that the effects of RCA on air content could not be commented on due to the varying amounts of AEA added to each mix.

A plot of fresh concrete density as a function of percent RCA substitution can be seen in Figure 4.1.

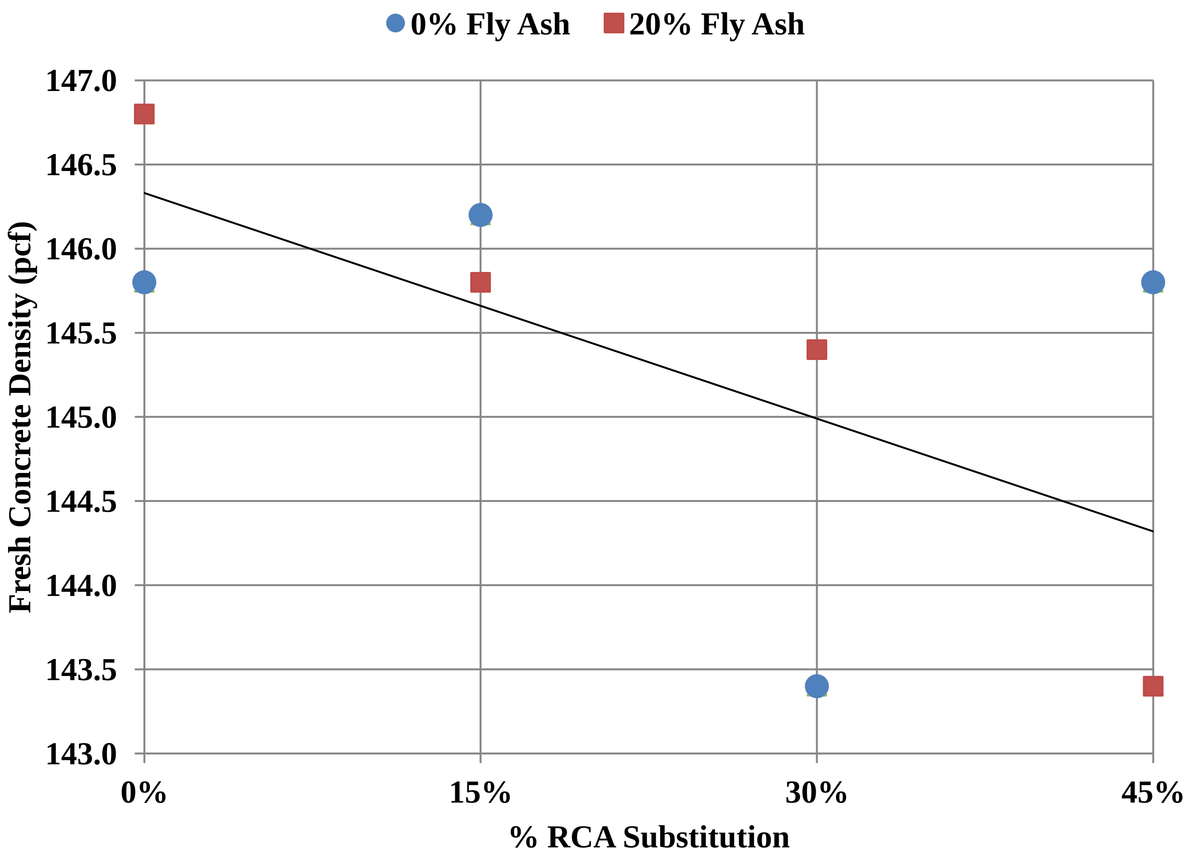

Figure 4.1 Fresh Concrete Density vs % RCA Substitution

For the results of this study, as can be seen from the trend in Figure 4.1, an increased rate of RCA substitution had the effect of decreasing the density of fresh concrete. This trend is expected due to the lower SSD bulk specific gravity of RCA compared to that of NA. It should be noted that slope of the trend is exaggerated due to the scale of Figure 4.1. The same trend was also seen in the results obtained by Mjelde (2013).

Another factor affecting density is the air content of fresh concrete. Figure 4.2 is a plot of the fresh concrete density versus the percentage of air content.

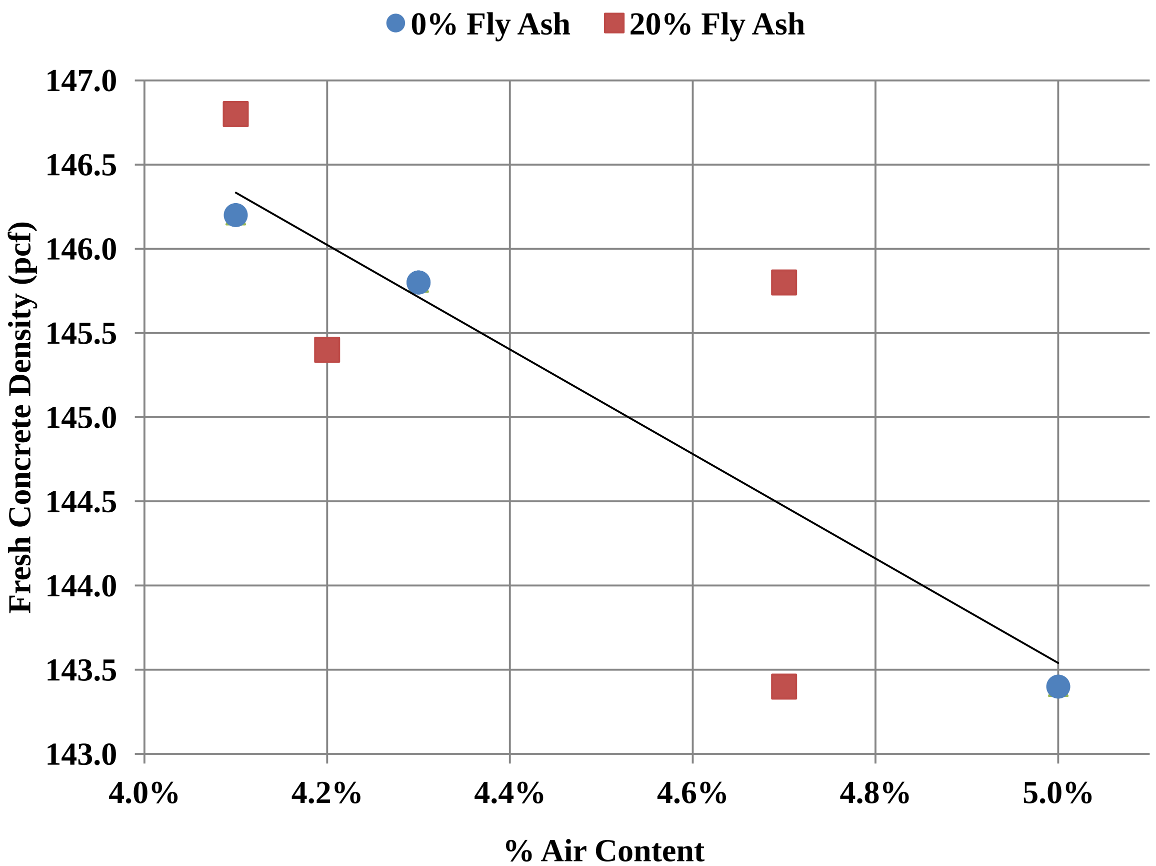

Figure 4.2 Fresh Concrete Density vs % Air Content

The negatively-sloping trend in the figure above indicates that density was reduced by the air content in the fresh concrete for the results of this study. Again, it should be noted that the slope of the trend in Figure 4.2 is exaggerated due to the scale of the graph. A similar conclusion on the effect of air content on fresh concrete density was reached in the study by Mjelde (2013) for the source A RCA.

4.5 Hardened Concrete Test Results

This section discusses the effects of RCA and fly ash substitution on the hardened concrete properties including compressive strength, MOR, CTE, and drying shrinkage. An analysis of variations (ANOVA) was performed using Excel's "Single Factor ANOVA" function with a confidence interval of 95%. This analysis compares paired data sets and determines if there is a statistically-relevant difference between them.

4.5.1 Compressive Strength

All of the compressive strength test results are given in Appendix C. A summary table of the average compressive strengths and coefficients of variation (CoV) is given in Table 4.4.

Table 4.4 Average Compressive Strengths and Coefficients of Variation

	7-Day (psi)	CoV	14-Day (psi)	CoV	28-Day (psi)	CoV	90-Day (psi)	CoV
X-0-0	3750	1.8%	4348	2.3%	4834	1.6%	5515	0.7%
B-15-0	3977	4.1%	4877	1.1%	5396	1.0%	6101	2.3%
B-30-0	3867	2.5%	4823	1.2%	5312	2.2%	5787	3.2%
B-45-0	4091	8.0%	5164	2.4%	5515	2.9%	6119	4.8%
X-0-20	3709	4.4%	4568	6.0%	5337	1.6%	6281	1.7%
B-15-20	3618	1.0%	4381	1.1%	5184	0.9%	6208	1.7%
B-30-20	3631	2.2%	4380	3.0%	5222	2.0%	6185	2.9%
B-45-20	3303	1.3%	4089	1.0%	4756	1.7%	5795	0.4%

As evident from Table 4.4, all of the average 28-day compressive strengths are above the WSDOT minimum required strength of 4000 psi. The average 28-day compressive strengths range from 4756 psi to 5515 psi, and the 28-day CoV values range from 0.9% to 2.9%. The 28-day compressive strength plotted against the percentage of RCA substitution is given in Figure 4.3. The data range bars represent the maximum and minimum strength values of each data set. Note that all of the minimum tested values also exceeded the WSDOT minimum strength requirement.

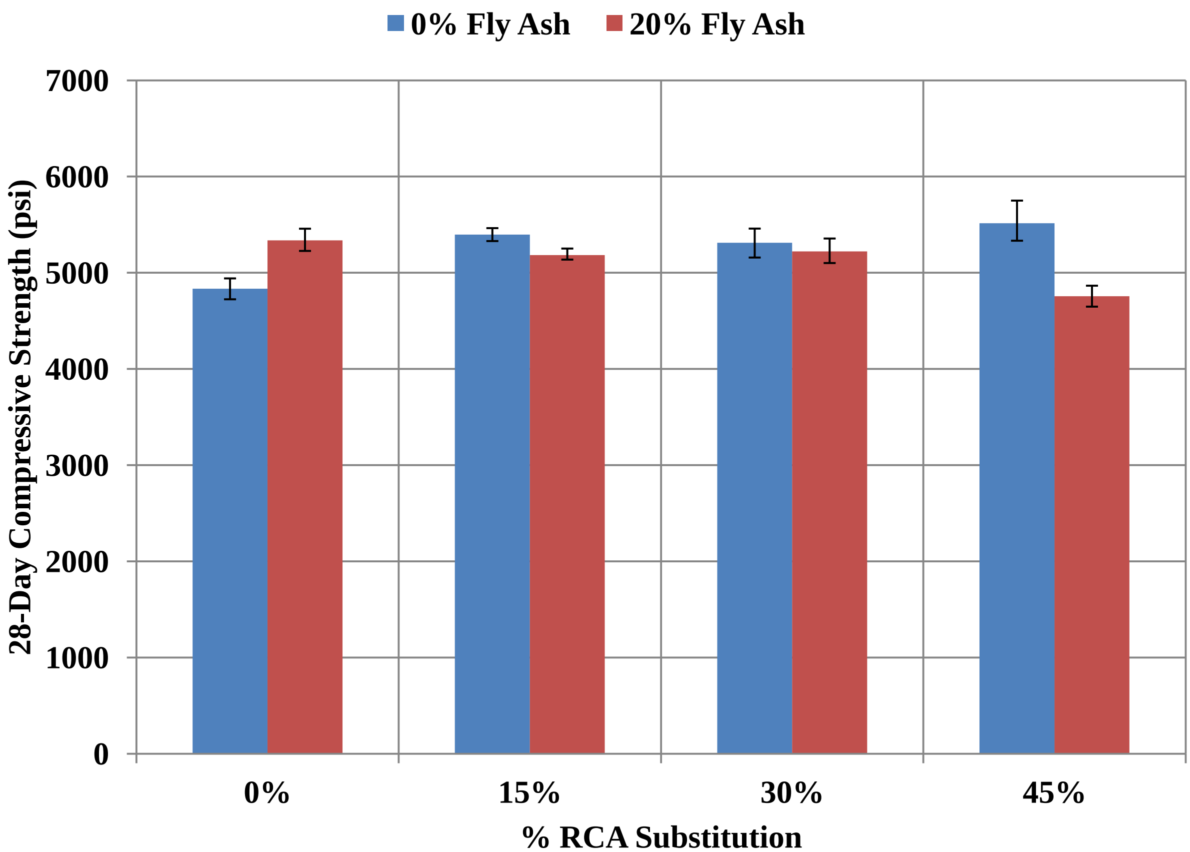

Figure 4.3 Average 28-Day Compressive Strength vs % RCA Substitution

The ANOVA statistical analysis concluded that there was no statistically-significant variation between any of the data sets. Therefore, for the results obtained in this study, the use of RCA and the use of fly ash had no significant effect on the compressive strength of the concrete. Further supporting this statement, the 90-day compressive strength is plotted against the percentage of RCA substitution in Figure 4.4 and shows that the compressive strengths are quite similar in value, regardless of the percentage of RCA substitution or the use of fly ash.

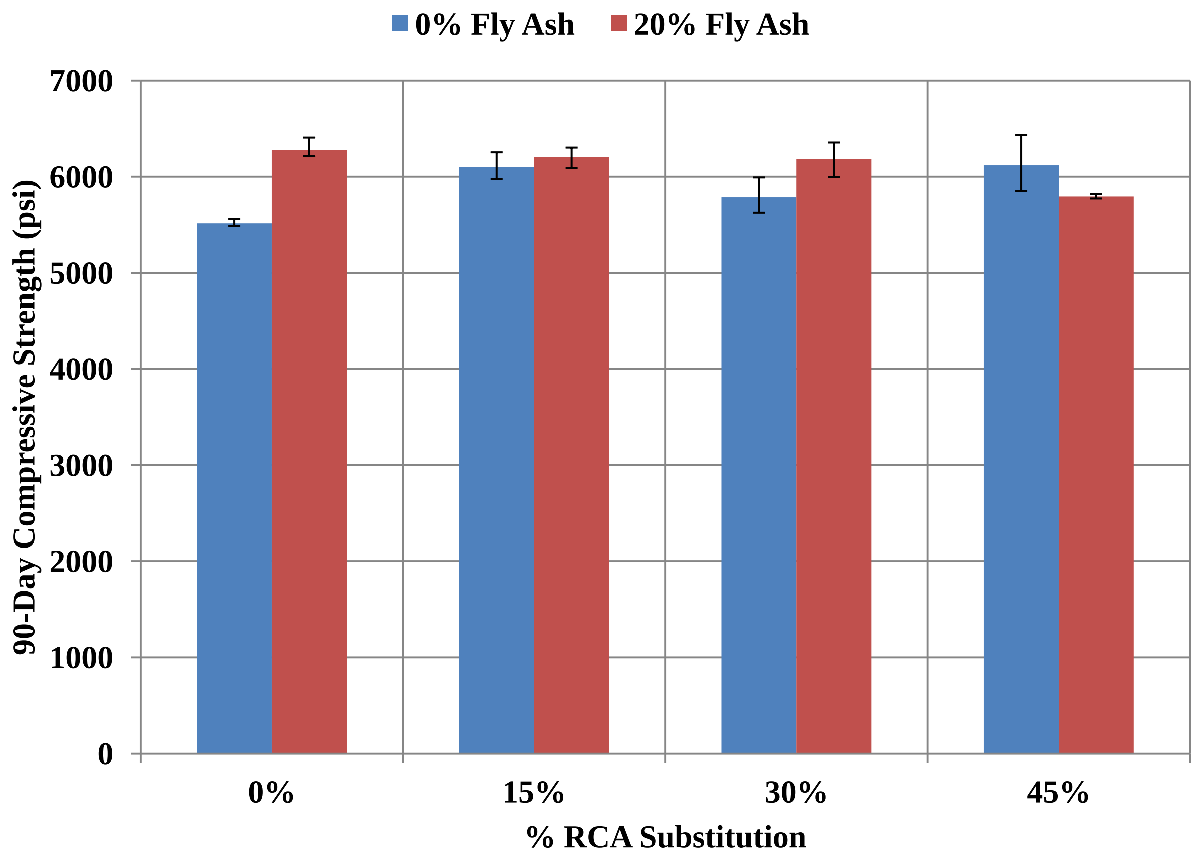

Figure 4.4 Average 90-Day Compressive Strength vs % RCA Substitution

Due to the lack of statistically-relevant variation between data sets, it is likely that the small variations evident in the data are due to the differences in water/cementitious materials ratios and air contents in the various batches. Mjelde (2013) also found that the source A RCA and fly ash appeared to have little to no effect on the 28-day compressive strength of RCA based on the results from the ANOVA statistical analysis.

The 28-day compressive strength plotted as a function of water/cementitious materials ratio is given in Figure 4.5.

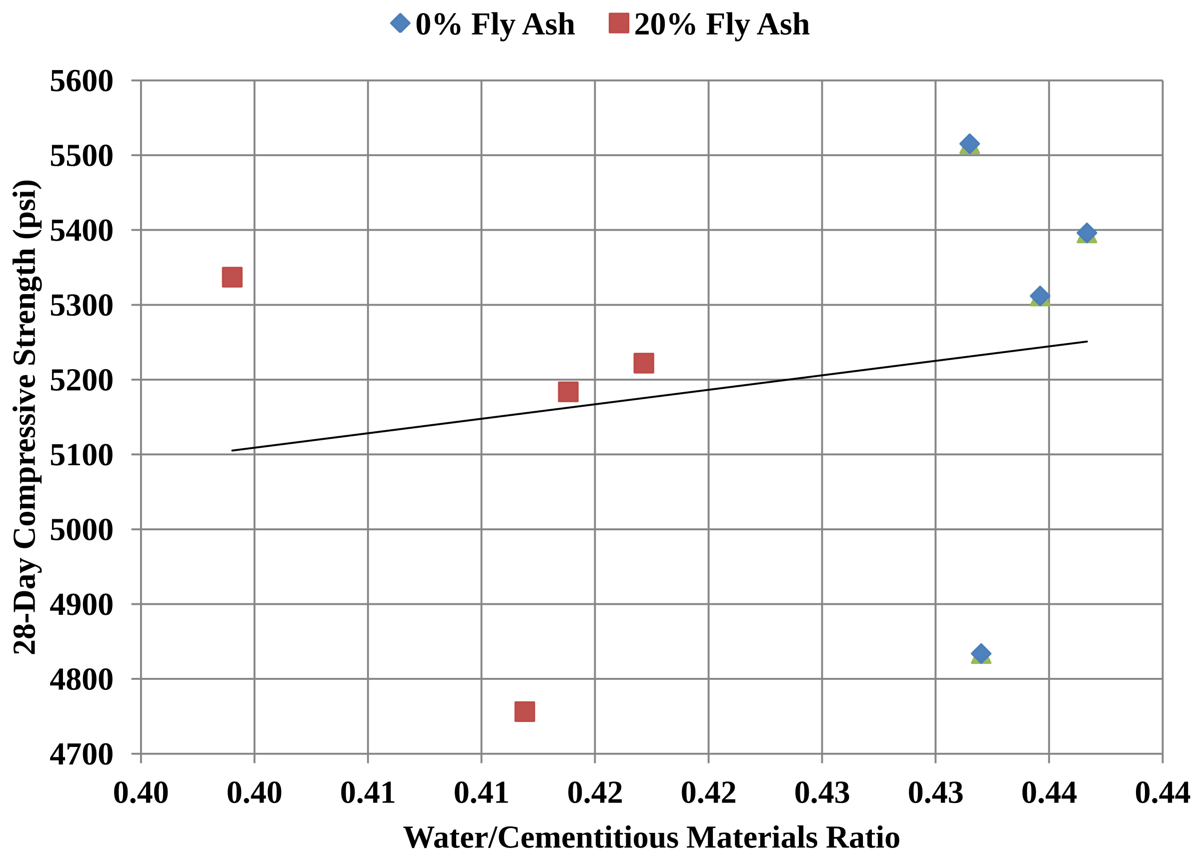

Figure 4.5 28-Day Compressive Strength vs Water/Cementitious Materials Ratio

The slightly positive-sloping trend in Figure 4.5 indicates that the 28-day compressive strength increases as the water/cementitious materials ratio increases. This is counter to the well-accepted observation that compressive strength increases as the water/cement ratio decreases. The other-than-expected trend is almost certainly due to inherent variations in the concrete batching process and/or materials. Mjelde's results showed a downward sloping trend when looking at the effects of the water/cementitious materials ratio on the 28-day compressive strength, meaning that compressive strength increased as the water/cementitious materials ratio decreased (Mjelde, 2013).

A plot of the 28-day compressive strength versus the percent air content is given in Figure 4.6.

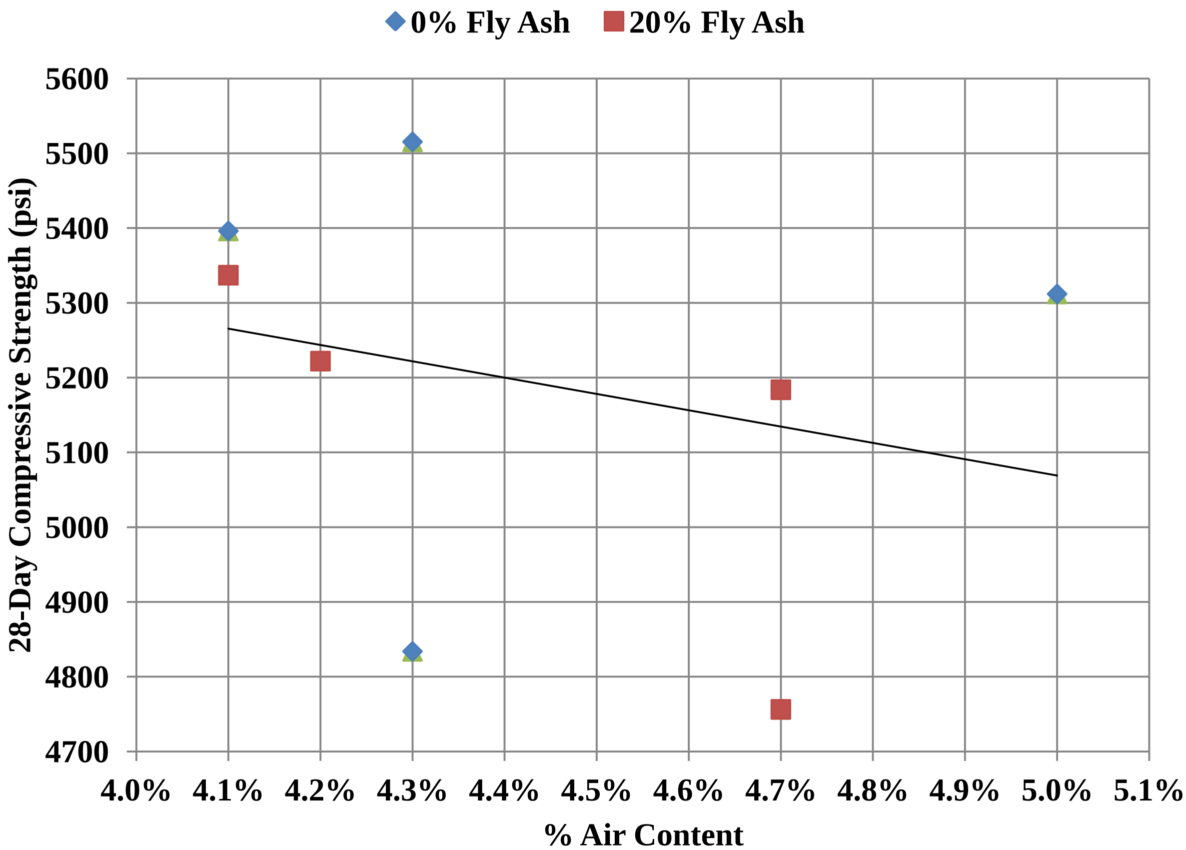

Figure 4.6 28-Day Compressive Strength vs % Air Content

The negatively sloping trend of Figure 4.6 indicates that the 28-day compressive strength decreases as the air content increases. This trend is consistent with results in other literature. Mjelde (2013) also found that the 28-day compressive strength decreased as the air content increased.

The 7-day and 14-day percentages of the 28-day compressive strength for all eight concrete mixes are given in Table 4.5. Figure 4.7 presents the data from Table 4.5 in a bar chart.

Table 4.5 28-Day Compressive Strength Gains at 7 and 14 Days

	7-Day / 28-Day Compressive Strength	14-Day / 28-Day Compressive Strength
X-0-0	77.6%	89.9%
B-15-0	73.7%	90.4%
B-30-0	72.8%	90.8%
B-45-0	74.2%	93.6%
X-0-20	69.5%	85.6%
B-15-20	69.8%	84.5%
B-30-20	69.5%	83.9%
B-45-20	69.5%	86%

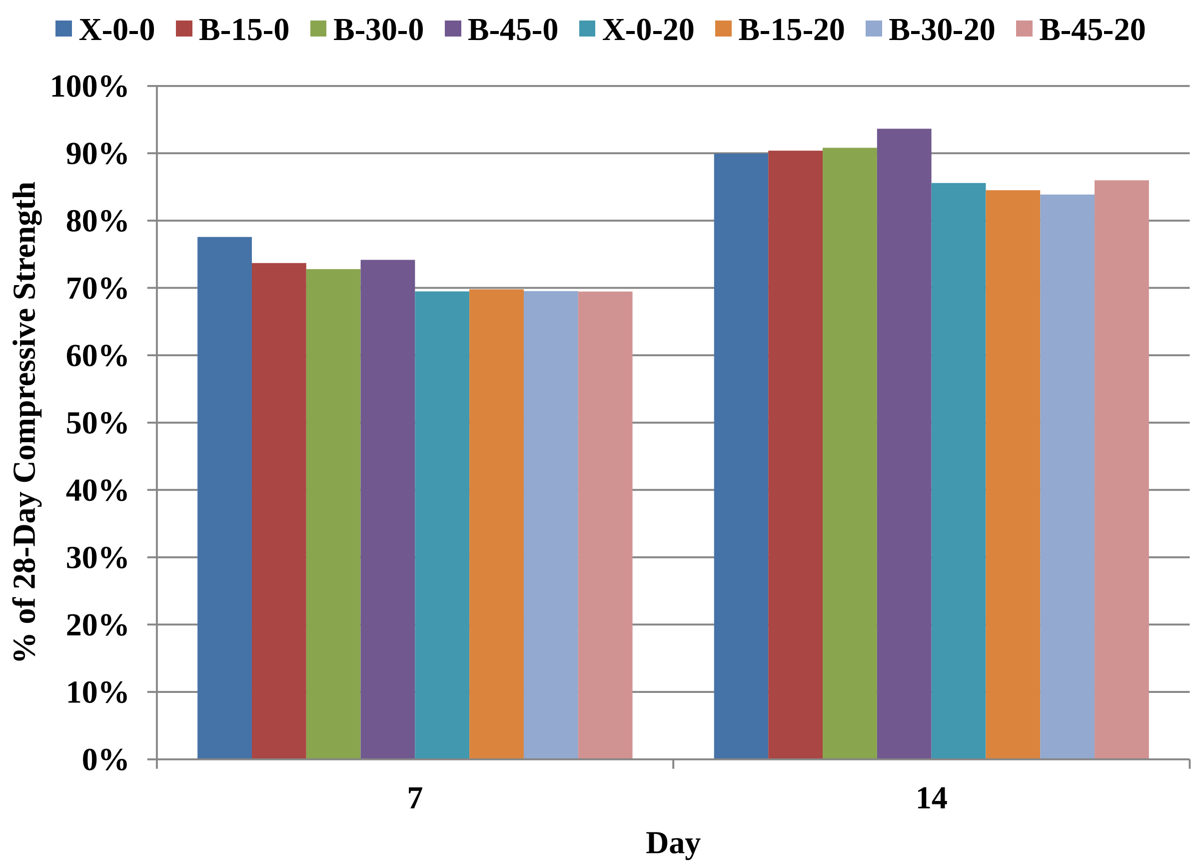

Figure 4.7 % of 28-Day Compressive Strength at 7 and 14 Days

The data in Table 4.5 shows that the mixes containing fly ash had slower strength gains at 7 days and 14 days compared to the mixes without fly ash. For mixes containing fly ash, the maximum 7-day strength was 69.8% of the 28-day strength (compared to a minimum of 72.8% for the mixes without fly ash), and the maximum 14-day compressive strength was 86% of the 28-day strength (compared to a minimum of 89.9% for the mixes without fly ash). Mjelde (2013) found that his mixes containing fly ash had a maximum 7-day compressive strength of 70.6% (compared to a minimum of 74.8% for the mixes without fly ash), and mixes containing fly ash had a maximum 14-day compressive strength of 85.6% (compared to a minimum of 85.0% for the mixes without fly ash).

Data for the 7-day, 14-day, and 28-day compressive strengths as a percentage of the 90-day compressive strengths are given in Table 4.6. Figure 4.8 presents the data from Table 4.6 in a bar chart.

Table 4.6 90-Day Compressive Strength Gains at 7, 14, and 28 Days

	7-Day / 90-Day Compressive Strength	14-Day / 90-Day Compressive Strength	28-Day / 90-Day Compressive Strength
X-0-0	68%	78.8%	87.7%
B-15-0	65.2%	79.9%	88.4%
B-30-0	66.8%	83.4%	91.8%
B-45-0	66.9%	84.4%	90.1%
X-0-20	59%	72.7%	85%
B-15-20	58.3%	70.6%	83.5%
B-30-20	58.7%	70.8%	84.4%
B-45-20	57%	70.6%	82.1%

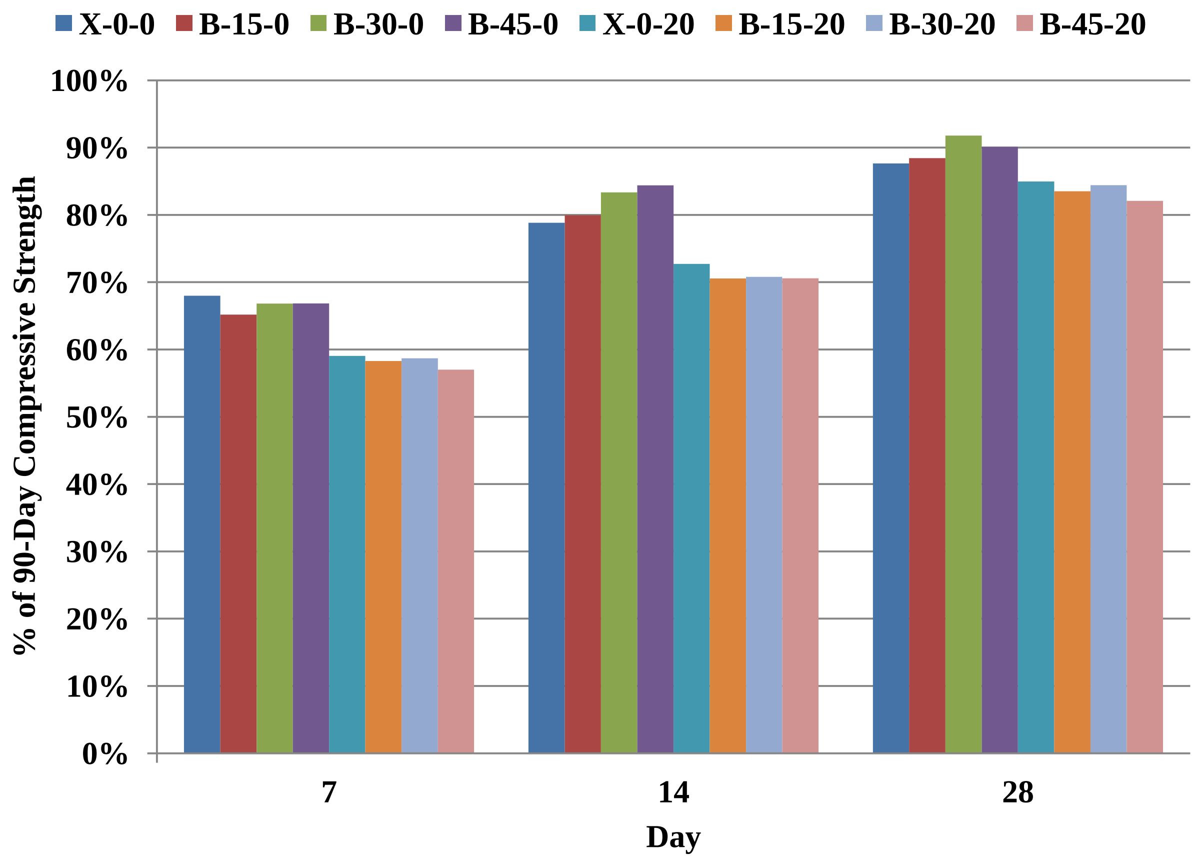

Figure 4.8 % of 90-Day Compressive Strength at 7, 14, and 28 Days

The data in Table 4.6 shows that the mixes containing fly ash had slower strength gain for all ages compared to the mixes without fly ash. For mixes containing fly ash, the maximum 7-day strength gain was 59% (compared to a minimum of 65.2% for the mixes without fly ash); the maximum 14-day compressive strength gain was 72.7% (compared to a minimum of 78.8% for the mixes without fly ash); the maximum 28-day compressive strength gain was 85% (compared to a minimum of 87.7% for the mixes without fly ash).

Based on the results for this study, fly ash appears to decrease the 7-, 14-, and 28-day strengths of the concrete. Mjelde (2013) also reported that fly ash decreased the early-age strengths of his concrete samples.

4.5.2 Modulus of Rupture

All MOR test data is given in Appendix D. Table 4.7 contains the average 14-day MOR values and the corresponding CoVs for all eight of the concrete mixes.

Table 4.7 Average 14-Day MOR Values and CoVs

	14-Day MOR (psi)	CoV
X-0-0	801	2.9%
B-15-0	846	3.5%
B-30-0	789	5.2%
B-45-0	772	8.5%
X-0-20	777	6.3%
B-15-20	775	6.9%
B-30-20	777	4.3%
B-45-20	726	2.2%

The WSDOT requires a minimum MOR of 650 psi. All of the average MOR values exceeded this requirement, with a minimum value of 726 psi and a maximum value of 846 psi. The CoVs range from 2.2% to 8.5%. A plot of the 14-day MOR as a function of the percentage of RCA substitution is given in Figure 4.9. The data range bars represent the maximum and minimum tested values. Note that all of the minimum tested values also exceeded the WSDOT minimum MOR requirement.

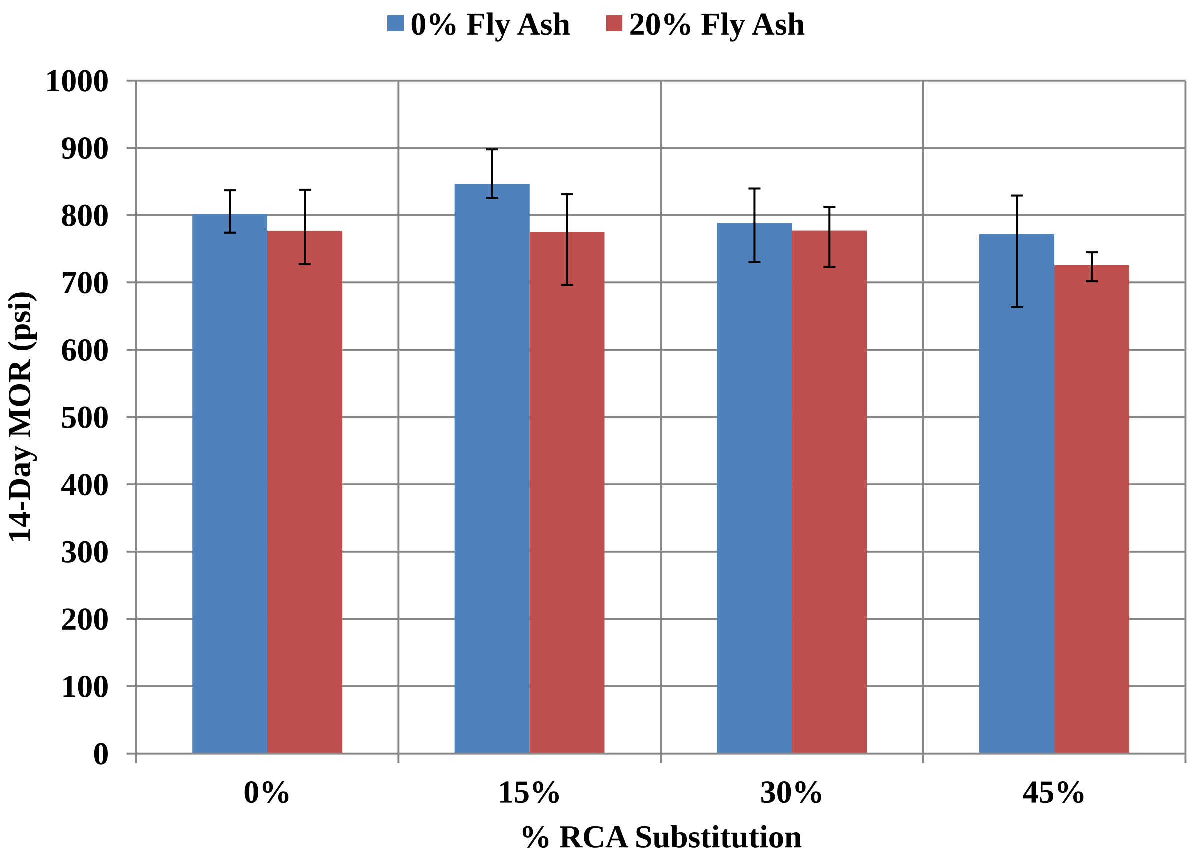

Figure 4.9 Average 14-Day MOR vs % RCA Substitution

An ANOVA statistical analysis determined that there are statistically-relevant variations between some of the paired data sets. Table 4.8 summarizes the important comparisons by group, whether or not the comparisons showed that a statistically-relevant variation exists, and the final conclusion regarding any statistical difference in the group.

Table 4.8 MOR ANOVA Statistical Analysis Summary

Group	Case	Comparison	Statistically-Relevant Difference?	Conclusion
1	**Change RCA, Hold Fly Ash Constant**	X-0-0 **vs** B-15-0	Yes	No
		B-15-0 **vs** B-30-0	Yes	
		X-0-0 **vs** B-30-0	No	
2	**Change RCA, Hold Fly Ash Constant**	X-0-20 **vs** B-15-20	No	No
		B-15-20 **vs** B-30-20	No	
		X-0-20 **vs** B-30-20	No	
3	**Change RCA, Hold Fly Ash Constant**	B-15-0 **vs** B-30-0	Yes	No
		B-30-0 **vs** B-45-0	No	
		B-15-0 **vs** B-45-0	No	
4	**Change RCA, Hold Fly Ash Constant**	B-15-20 **vs** B-30-20	No	No
		B-30-20 **vs** B-45-20	Yes	
		B-15-20 **vs** B-45-20	No	
5	**Change Fly Ash, Hold RCA Constant**	X-0-0 **vs** X-0-20	No	No
		B-15-0 **vs** B-15-20	Yes	
		B-30-0 **vs** B-30-20	No	
		B-45-0 **vs** B-45-20	No	

In group 1, the percent of RCA substitution was changed while the percentage of fly ash substitution remained constant at 0%. Even though the first two comparisons indicate that a statistical variation exists, the fact that X-0-0 and B-30-0 are not statistically different confirms the null hypothesis that RCA does not have a statistically-significant effect on the MOR for this group.

Group 2 is similar to group 1, except that the fly ash substitution rate was held constant at 20%. This time, however, none of the comparisons show a statistically-significant variation;

therefore the null hypothesis is confirmed again, indicating that RCA does not have a statistically-significant effect on the MOR for this group.

Groups 3 and 4 are similar to groups 1 and 2, respectively, except that they are comparing different data sets. In each of the groups, only one comparison shows that a statistically-significant variation exists. Again, the null hypothesis is confirmed, indicating that RCA substitution does not produce any statistically-significant variation within either group.

In group 5, the percentage of RCA substitution was held constant between comparisons while the amount of fly ash was varied. Only the comparison of B-15-0 and B-15-20 indicates that a statistically-significant variation exists. However, since the rest of the groups do not, it is difficult to make any statements regarding the effects of fly ash substitution on the MOR.

Based on the results of groups 1 through 4, it can be concluded that RCA had no statistically-significant effect on the MOR. It is likely that the variations seen in the data are due to the varying water/cementitious materials ratios and air contents.

Based on the result of group 5, it can be concluded that substituting portland cement with Type F fly ash had no statistically-significant effect on the MOR.

Mjelde (2013) also found that his RCA and the addition of fly ash had no statistically-significant effect on MOR and that the variations seen in his data were due to the variations of the water/cementitious materials ratios and air contents.

4.5.3 Coefficient of Thermal Expansion

Results for all of the 28-day CTE tests are given in Appendix E. The average CTE value for each concrete mix and its corresponding CoV are given in Table 4.9.

Table 4.9 Average CTE Values and CoVs

	28-Day CTE (mm/mm °C)	CoV
X-0-0	9.29E-06	5.2%
B-15-0	9.48E-06	11.4%
B-30-0	9.35E-06	1.7%
B-45-0	8.92E-06	5.4%
X-0-20	9.34E-06	3.5%
B-15-20	9.06E-06	1.6%
B-30-20	9.11E-06	6.1%
B-45-20	9.95E-06	3.2%

The minimum 28-day CTE is 8.92E-06 per degree Celsius, and the maximum is 9.95E-06 per degree Celsius. The CoVs range from 1.6% to 11.4%.

An ANOVA statistical analysis determined that there are no statistically-relevant variations between any of the paired CTE data sets. Therefore, based on the results of this study, it is evident that neither the RCA nor fly ash had a significant effect on the CTE of PCCP.

Based on the literature review, normal concrete has a CTE that ranges from 3.2 to 7.0 millionths per degree Fahrenheit (5.7 to 12.6 millionths per degree Celsius) (Kosmatka and Panarese, 1988). All eight of the concrete mixes have CTE values within this range. Therefore, based on the results obtained in this study, PCCP made with source B RCA would be expected to have thermal expansion behavior similar to that of normal concrete.

4.5.4 Drying Shrinkage

All of the drying shrinkage data is given in Appendix F. The average drying shrinkage strains for each mix and the corresponding CoV values are given in Table 4.10. Note that a positive value indicates contraction of the specimen for Table 4.10.

Table 4.10 Average Drying Shrinkage Strains and CoVs

	Average Drying Shrinkage Strain (in/in)			
Day	**X-0-0**	**CoV**	**B-15-0**	**CoV**
1	0.00E+00	0.0%	0.00E+00	0.0%
28	-5.33E-05	10.8%	3.67E-05	128.9%
32	3.33E-05	62.4%	1.83E-04	36.3%
35	1.23E-04	23.4%	2.03E-04	24.3%
42	2.90E-04	11.9%	2.27E-04	25.9%
56	3.90E-04	10.3%	3.73E-04	13.5%
84	4.13E-04	15.7%	5.00E-04	12.5%
Day	**B-30-0**	**CoV**	**B-45-0**	**CoV**
1	0.00E+00	0.0%	0.00E+00	0.0%
28	-9.67E-05	26.0%	6.00E-05	0.0%
32	5.33E-05	84.5%	1.80E-04	14.7%
35	7.67E-05	61.6%	2.70E-04	3.7%
42	3.20E-04	15.6%	2.77E-04	2.1%
56	4.10E-04	14.6%	4.20E-04	4.8%
84	5.07E-04	6.9%	5.83E-04	2.0%
Day	**X-0-20**	**CoV**	**B-15-20**	**CoV**
1	0.00E+00	0.0%	0.00E+00	0.0%
28	1.20E-04	438.1%	-4.33E-05	74.2%
32	1.80E-04	289.2%	3.33E-05	91.7%
35	2.95E-04	181.0%	1.27E-04	19.9%
42	4.65E-04	112.6%	2.40E-04	11.0%
56	5.45E-04	98.1%	4.27E-04	13.7%
84	6.35E-04	83.4%	4.97E-04	8.4%

Day	B-30-20	CoV	B-45-20	CoV
1	0.00E+00	0.0%	0.00E+00	0.0%
28	-3.33E-06	1135.8%	-9.33E-05	97.2%
32	2.33E-05	65.5%	1.10E-04	24.1%
35	1.97E-04	32.3%	9.67E-05	26.0%
42	2.27E-04	28.0%	2.63E-04	11.6%
56	3.73E-04	18.2%	4.33E-04	3.5%
84	4.50E-04	15.6%	5.70E-04	7.0%

From Table 4.10, the minimum 84-day average drying shrinkage strain is 4.13E-04 and the maximum is 6.35E-04. The CoVs for the 84-day strains range from 2.0% to 83.4%. The exceptionally large 28-day CoV of 1136% for mix B-30-20 is due to the fact that two of the specimens contained in the average expanded while the third specimen shrank. Additionally, the large CoVs at early ages are due to the very small measurements being made.

A plot of the average drying shrinkage strain versus days is given in Figure 4.10. Note that a positive value indicates contraction of the specimen for Figure 4.10.

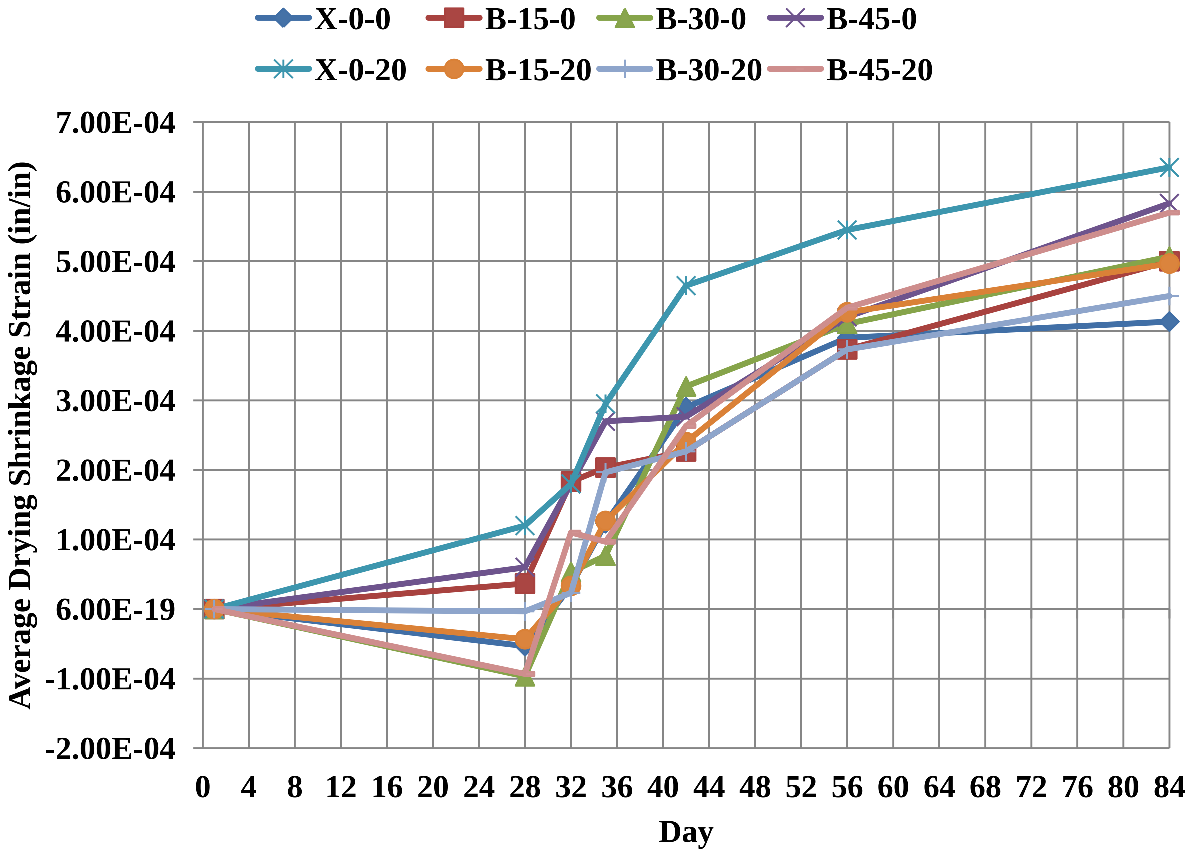

Figure 4.10 Average Drying Shrinkage Strain vs Day

An ANOVA statistical analysis determined that there are statistically-relevant variations between some of the paired data sets. Table 4.11 summarizes the important comparisons by group, whether or not the comparisons showed that a statistically-relevant variation exists, and the final conclusion regarding any statistical difference in the group.

Table 4.11 Average Drying Shrinkage Strain ANOVA Statistical Analysis Summary

Group	Case	Comparison	Statistically-Relevant Difference?	Conclusion
1	Change RCA, Hold Fly Ash Constant	X-0-0 **vs** B-15-0	Yes	No
		B-15-0 **vs** B-30-0	Yes	
		X-0-0 **vs** B-30-0	No	
2	Change RCA, Hold Fly Ash Constant	X-0-20 **vs** B-15-20	No	No
		B-15-20 **vs** B-30-20	No	
		X-0-20 **vs** B-30-20	No	
3	Change RCA, Hold Fly Ash Constant	B-15-0 **vs** B-30-0	No	No
		B-30-0 **vs** B-45-0	No	
		B-15-0 **vs** B-45-0	No	
4	Change RCA, Hold Fly Ash Constant	B-15-20 **vs** B-30-20	No	No
		B-30-20 **vs** B-45-20	No	
		B-15-20 **vs** B-45-20	No	
5	Change Fly Ash, Hold RCA Constant	X-0-0 **vs** X-0-20	No	No
		B-15-0 **vs** B-15-20	No	
		B-30-0 **vs** B-30-20	No	
		B-45-0 **vs** B-45-20	No	

In group 1, the percent of RCA substitution was changed while the percentage of fly ash substitution remained constant at 0%. Even though the first two comparisons indicate that a statistical variation exists, the fact that X-0-0 and B-30-0 are not statistically different confirms the null hypothesis that RCA does not have a statistically-significant effect on the drying shrinkage strain for this group.

Group 2 is similar to group 1, except that the fly ash substitution rate was held constant at 20%. Using the same logic as was used for case 1, the null hypothesis is confirmed again, indicating that RCA does not have a statistically-significant effect on the drying shrinkage strain for this group.

Groups 3 and 4 are similar to groups 1 and 2, respectively, except that they are comparing different data sets. Neither of the groups show that a statistically-significant variation exists. Again, the null hypothesis is confirmed, indicating that RCA substitution does not produce any statistically-significant variation within either group.

In group 5, the percentage of RCA substitution was held constant between comparisons while the amount of fly ash was varied. All comparisons indicate that there is no statistically-significant variation that exists.

Based on the results of groups 1 through 4, it can be concluded that RCA had no statistically-significant effect on the drying shrinkage strain. It is likely that the variations seen in the data are due to the varying water contents in the various mixes.

Based on the result of group 5, it can be concluded that substituting portland cement with Type F fly ash had no statistically-significant effect on the drying shrinkage strain.

Normal concrete is reported to experience drying shrinkage strains between 400 and 800 millionths (Kosmatka and Panarese, 1988). While the 84-day average drying shrinkage strains in Figure 4.8 have not yet reached a plateau, it appears that the final drying shrinkage strains for the mixes of this study will be within this range. Thus, it is likely that PCCP incorporating source B RCA and fly ash will have similar drying shrinkage behavior as that of normal concrete.

4.6 Summary and Conclusions

The RCA investigated in this study (source B) had a lower SSD bulk specific gravity and a higher absorption value than those for NA. Results obtained by Mjelde (2013) for the source A RCA also had a lower SSD bulk specific gravity and a higher absorption value than that of NA. These attributes are a result of the porous, air-entrained mortar within the RCA.

The source B RCA lost 20% of its material in the LA abrasion test. Results obtained by Mjelde (2013) for the source A RCA lost 29% of its material for the same test. The degradation values for the source B RCA were 37 and 49 for the as-delivered and processed state, respectively. Both of these values meet the degradation requirement. Mjelde's (2013) source A RCA had degradation values of 15 and 55 for the as-delivered and processed state, respectively. In its as-delivered state, the source A RCA did not meet the degradation requirement; however, the processed source A RCA did meet the degradation requirement. Based on the results of this study and those obtained in the study by Mjelde (2013), it is recommended that the RCA be processed to remove the fine materials and the RCA be washed before incorporating it into new PCCP.

The ASR expansion for the source B RCA investigated in this study exceeded the AASHTO maximum expansion value. Further tests are needed to confirm that the expansion is a result of ASR. If so, it may be necessary to use low-alkali portland cement or that cement be substituted with fly ash if the source B RCA is to be incorporated into new PCCP. In contrast, results obtained by Mjelde (2013) for the source A RCA did not exhibit expansion above the AASHTO maximum due to the ASR reaction. Therefore, no mitigative techniques are needed to incorporate the source A RCA into new PCCP, with regards to its ASR behavior.

No conclusions were reached on the effects of RCA substitution on the workability of fresh concrete because the water content and/or addition of WRA were varied in each batch in order to produce a slump within a specified range. For a fly ash substitution rate of 20%, the results of both this study and those by Mjelde (2013) indicate that the workability of fresh concrete increases and thereby allows for lower water/cementitious materials ratios while maintaining the target slump range.

No conclusions were reached with regard to the effects of RCA substitution on the air content of fresh concrete because the amount of AEA was varied in each batch in order to produce an air content within a specified range.

Due to the lower density of RCA compared to that of NA, this study and that by Mjelde (2013) show that the density of fresh concrete decreases as the percentage of RCA substitution increases. It was also found that the air content has a significant effect on the density of fresh concrete, based on the results of both this study and that by Mjelde (2013).

All 28-day compressive strengths from both this study and that by Mjelde (2013) exceeded the WSDOT minimum compressive strength value of 4000 psi. Both studies found that RCA has no statistically-significant effect on the compressive strength of concrete based on ANOVA single factor statistical analyses. Small variations evident in the compressive strength values are likely due to the variations of the water/cementitious materials ratios and air contents. Both studies found that fly ash decreased early-age compressive strengths.

All of the 14-day MOR values for both this study and that of Mjelde (2013) exceeded the WSDOT minimum required MOR value of 650 psi. Based on the findings of both studies, it was determined that that RCA had no statistically-significant effect on MOR. Again, the variations in strength are likely due to differences in the water/cementitious materials ratio and air content. It was also found that fly ash substitution had no statistically-significant effect on MOR.

Based on the results of this study, it appears that RCA and fly ash have no statistically-significant effect on the thermal expansion behavior of PCCP. All eight of the mixes were found to have CTEs within the range reported for that of normal concrete.

The drying shrinkage behavior of concrete mixes with RCA and/or fly ash appear to be similar to that of normal concrete, although this statement is based on data which had not yet fully reached a plateau. All of the 84-day drying shrinkage strains were within the reported range of 400 to 800 millionths (Kosmatka and Panarese, 1988). It appears that RCA and fly ash have no statistically-significant effect on the drying shrinkage strain of PCCP.

Considering the largely positive results of this study and those obtained by Mjelde (2013), it is recommended that further research be conducted to investigate the effects of RCA on the durability of PCCP. Given that all eight mixes from both studies met the WSDOT and AASHTO requirements (apart from the ASR results of this study), it is also recommended that larger amounts of RCA substitution be investigated in future studies. For the source B RCA used in this study, additional tests should be performed to confirm that the observed expansion is caused by ASR. If so, it may be necessary to use low-alkali portland cement or that cement be substituted with fly ash if the source B RCA is to be incorporated into new PCCP.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The goals of this study were two-fold: to investigate the effects of substituting natural aggregates (NA) with recycled concrete aggregate (RCA) in concrete intended for application in new portland cement concrete pavements (PCCP), and to investigate the effects of substituting portland cement with fly ash while simultaneously substituting NA with RCA. The RCA investigated in this study was produced from demolished runway panels at Fairchild Air Force Base in eastern Washington. Eight concrete mixes were prepared in this study based on the same reference mix design but incorporating differing amounts of RCA as a substitute for coarse aggregate (0, 15%, 30% and 45%) and fly ash as a substitute for portland cement (0 and 20%).

Fresh concrete properties for each of the eight batches were determined, including slump, air content, and density of concrete. Cylinder and beam specimens from each of the eight mixes were tested to investigate the effects of RCA and fly ash on the hardened concrete properties, including compressive strength, modulus of rupture (MOR), coefficient of thermal expansion (CTE), and drying shrinkage. Properties of the RCA were also determined, including specific gravity and absorption, LA abrasion loss, degradation, and alkali-silica reactivity. Conclusions on the effects of incorporating RCA in concrete mixes with and without fly ash were reached.

5.2 Conclusions

This section presents the major conclusions reached on the effects of RCA and fly ash on concrete based on the results of this study.

Effects of RCA on Degradation Value

Removal of the fine material and washing of the RCA noticeably increased the degradation value. It is thus recommended that all fine material be removed from the RCA and that the processed RCA be washed prior to its use in PCCP. The degradation value is largely unaffected by the RCA when it is combined with coarse and fine NA.

Effects of RCA on Fresh Concrete Density

The density of fresh concrete decreased as the percentage of RCA substitution increased. The RCA is less dense than NA due to the adhered mortar portion of the RCA, resulting in the fresh concrete density being lower than a mix containing all NA.

Effects of RCA and Fly Ash on Compressive Strength

RCA and fly ash did not have a statistically-significant effect on the compressive strength of concrete for RCA substitution rates of up to 45% and a fly ash substitution rate of 20%. All of the concrete mixes in this study had 28-day compressive strengths that exceeded the WSDOT minimum of 4000 psi. Small variations in strength evident in the test data are likely due to differing water/cementitious materials ratios and air contents. Substituting fly ash for portland cement decreased the early-age strength gain of concrete.

Effects of RCA and Fly Ash on Modulus of Rupture

RCA and fly ash did not have statistically-significant effects on the MOR values of concrete for RCA substitution rates of up to 45% and a fly ash substitution rate of 20%. All of the concrete mixes in this study had 14-day MOR values that exceeded the WSDOT minimum of

650 psi. Small variations in strength evident in the data are likely due to differing water/cementitious materials ratios and air contents.

Effects of RCA and Fly Ash on Coefficient of Thermal Expansion

RCA and fly ash did not have a statistically-significant effect on the CTE values of concrete for RCA substitution rates of up to 45% and a fly ash substitution rate of 20%. All of the concrete mixes for this study had 28-day CTE values that were within the range reported for concretes made with only NA.

Effects of RCA and Fly Ash on Drying Shrinkage

RCA and fly ash did not have a statistically-significant effect on the drying shrinkage behavior of concrete for RCA substitution rates of up to 45% and a fly ash substitution rate of 20%. All of the 84-day average drying shrinkage strains for this study were within the range reported for concretes made with only NA.

5.3 Recommendations

Given the good performance of the concrete mixes with RCA obtained in this study, it is recommended that additional research be conducted to investigate RCA substitution rates beyond 45%. Although the source B RCA did show signs of being ASR reactive, the specification recommends that additional testing be conducted to confirm that the expansion was due to the alkali-silica reaction. Using low-alkali cement or fly ash substitution may mitigate this reaction. It is recommended that the RCA be washed and all fine materials be removed prior to use in PCCP.

Based on the results of this study as well as those by Mjelde (2013), the use of RCA as a substitute for natural coarse aggregate seems promising for use in new PCCP in Washington State.

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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 appropriate 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] PE Signature 7/13/2011 Date

DOT Form 350-040 EF Revised 6/05

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 QUANTITIES FOR 1 CY

	Coarse Aggregate (lbs/CY)	Fine Aggregate (lbs/CY)	RCA (lbs/CY)	Cement (lbs/CY)	Fly Ash (lbs/CY)	Effective Mix Water (lbs/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	1182	0	564	0	244	9.0	0.0
B-15-0	1613	1182	274	564	0	246	8.0	0.0
B-30-0	1328	1182	548	564	0	245	8.9	0.0
B-45-0	1044	1182	821	564	0	243	8.2	1.5
X-0-20	1898	1182	0	451	112	225	8.0	0.0
B-15-20	1613	1182	274	451	113	233	8.2	0.0
B-30-20	1328	1182	548	451	113	235	7.4	0.0
B-45-20	1044	1182	821	451	113	232	8.3	0.0

Aggregate weights are given for aggregates in their SSD condition.

APPENDIX C: COMPRESSIVE STRENGTH TEST DATA

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
X-0-0-COMP-7-1	103823	3672
X-0-0-COMP-7-2	106939	3782
X-0-0-COMP-7-3	107313	3795
X-0-0-COMP-14-1	120610	4266
X-0-0-COMP-14-2	126165	4462
X-0-0-COMP-14-3	122035	4316
X-0-0-COMP-28-1	139780	4944
X-0-0-COMP-28-2	133635	4726
X-0-0-COMP-28-3	136844	4840
X-0-0-COMP-28-4	137103	4849
X-0-0-COMP-28-5	136009	4810
X-0-0-COMP-90-1	156359	5530
X-0-0-COMP-90-2	156747	5544
X-0-0-COMP-90-3	154675	5471

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
B-15-0-COMP-7-1	110824	3920
B-15-0-COMP-7-2	117689	4162
B-15-0-COMP-7-3	108809	3848
B-15-0-COMP-14-1	136470	4827
B-15-0-COMP-14-2	137693	4870
B-15-0-COMP-14-3	139549	4936
B-15-0-COMP-28-1	150660	5329
B-15-0-COMP-28-2	153193	5418
B-15-0-COMP-28-3	154459	5463
B-15-0-COMP-28-4	151681	5365
B-15-0-COMP-28-5	152862	5406
B-15-0-COMP-90-1	168188	5948
B-15-0-COMP-90-2	173254	6128
B-15-0-COMP-90-3	176075	6227

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
B-30-0-COMP-7-1	107874	3815
B-30-0-COMP-7-2	112436	3977
B-30-0-COMP-7-3	107687	3809
B-30-0-COMP-14-1	137779	4873
B-30-0-COMP-14-2	134671	4763
B-30-0-COMP-14-3	136671	4834
B-30-0-COMP-28-1	152243	5384
B-30-0-COMP-28-2	146026	5165
B-30-0-COMP-28-3	149609	5291
B-30-0-COMP-28-4	148530	5253
B-30-0-COMP-28-5	154531	5465
B-30-0-COMP-90-1	157783	5580
B-30-0-COMP-90-2	164893	5832
B-30-0-COMP-90-3	168160	5947

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
B-45-0-COMP-7-1	110579	3911
B-45-0-COMP-7-2	110033	3892
B-45-0-COMP-7-3	126410	4471
B-45-0-COMP-14-1	142010	5023
B-45-0-COMP-14-2	148818	5263
B-45-0-COMP-14-3	147234	5207
B-45-0-COMP-28-1	158892	5620
B-45-0-COMP-28-2	155294	5492
B-45-0-COMP-28-3	149307	5281
B-45-0-COMP-28-4	161093	5697
B-45-0-COMP-28-5	155121	5486
B-45-0-COMP-90-1	180552	6386
B-45-0-COMP-90-2	174377	6167
B-45-0-COMP-90-3	164101	5804

Sample Name	Ultimate Load (lbs)	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 (lbs)	Compressive Strength (psi)
B-15-20-COMP-7-1	102997	3643
B-15-20-COMP-7-2	102821	3637
B-15-20-COMP-7-3	101055	3574
B-15-20-COMP-14-1	124525	4404
B-15-20-COMP-14-2	124813	4414
B-15-20-COMP-14-3	122236	4323
B-15-20-COMP-28-1	146141	5169
B-15-20-COMP-28-2	147896	5231
B-15-20-COMP-28-3	146889	5195
B-15-20-COMP-28-4	147263	5208
B-15-20-COMP-28-5	144644	5116
B-15-20-COMP-90-1	172822	6112
B-15-20-COMP-90-2	174952	6188
B-15-20-COMP-90-3	178781	6323

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
B-30-20-COMP-7-1	105248	3722
B-30-20-COMP-7-2	101698	3597
B-30-20-COMP-7-3	101048	3574
B-30-20-COMP-14-1	125878	4452
B-30-20-COMP-14-2	126050	4458
B-30-20-COMP-14-3	119560	4229
B-30-20-COMP-28-1	149991	5305
B-30-20-COMP-28-2	143867	5088
B-30-20-COMP-28-3	146817	5193
B-30-20-COMP-28-4	151077	5343
B-30-20-COMP-28-5	146500	5181
B-30-20-COMP-90-1	180148	6371
B-30-20-COMP-90-2	170074	6015
B-30-20-COMP-90-3	174449	6170

Sample Name	Ultimate Load (lbs)	Compressive Strength (psi)
B-45-20-COMP-7-1	92505	3272
B-45-20-COMP-7-2	94803	3353
B-45-20-COMP-7-3	92900	3286
B-45-20-COMP-14-1	115070	4070
B-45-20-COMP-14-2	114796	4060
B-45-20-COMP-14-3	117012	4138
B-45-20-COMP-28-1	135520	4793
B-45-20-COMP-28-2	133447	4720
B-45-20-COMP-28-3	134498	4757
B-45-20-COMP-28-4	131389	4647
B-45-20-COMP-28-5	137549	4865
B-45-20-COMP-90-1	163151	5770
B-45-20-COMP-90-2	163929	5798
B-45-20-COMP-90-3	164432	5816

APPENDIX D: MODULUS OF RUPTURE TEST DATA

Sample Name	Ultimate Load (lbs)	Actual Width (in.)	MOR (psi)
X-0-0-MOR-14-1	6373	6.019	792
X-0-0-MOR-14-2	6776	6.036	837
X-0-0-MOR-14-3	6273	6.039	774
X-0-0-MOR-14-4	6447	6.018	801
X-0-0-MOR-14-5	6517	6.040	804
B-15-0-MOR-14-1	6810	6.025	844
B-15-0-MOR-14-2	6709	6.045	826
B-15-0-MOR-14-3	6778	6.037	837
B-15-0-MOR-14-4	7214	6.013	898
B-15-0-MOR-14-5	6647	6.019	826
B-30-0-MOR-14-1	6784	6.030	840
B-30-0-MOR-14-2	6292	6.035	777
B-30-0-MOR-14-3	6505	6.010	810
B-30-0-MOR-14-4	6328	6.021	785
B-30-0-MOR-14-5	5944	6.052	730
B-45-0-MOR-14-1	6148	6.035	760
B-45-0-MOR-14-2	6571	6.035	812
B-45-0-MOR-14-3	6478	6.055	795
B-45-0-MOR-14-4	5307	6.001	663
B-45-0-MOR-14-5	6744	6.050	829
X-0-20-MOR-14-1	6592	6.045	812
X-0-20-MOR-14-2	6745	6.019	838
X-0-20-MOR-14-3	6202	5.990	778
X-0-20-MOR-14-4	5906	6.036	729
X-0-20-MOR-14-5	5838	6.010	727

B-15-20-MOR-14-1	6429	6.015	800
B-15-20-MOR-14-2	6054	6.040	747
B-15-20-MOR-14-3	5626	6.030	696
B-15-20-MOR-14-4	6733	6.038	831
B-15-20-MOR-14-5	6503	6.048	800
B-30-20-MOR-14-1	6237	6.000	780
B-30-20-MOR-14-2	6587	6.041	812
B-30-20-MOR-14-3	6359	6.014	791
B-30-20-MOR-14-4	6238	6.000	780
B-30-20-MOR-14-5	5767	5.992	723
B-45-20-MOR-14-1	6028	6.035	745
B-45-20-MOR-14-2	5819	6.033	719
B-45-20-MOR-14-3	5895	6.020	732
B-45-20-MOR-14-4	5973	6.061	732
B-45-20-MOR-14-5	5668	6.029	702

APPENDIX E: COEFFICIENT OF THERMAL EXPANSION TEST DATA

Sample Name	28-Day Coefficient of Thermal Expansion (mm/mm/°C)
X-0-0-CTE-28-1	9.21E-06
X-0-0-CTE-28-2	9.81E-06
X-0-0-CTE-28-3	8.86E-06
B-15-0-CTE-28-1	9.45E-06
B-15-0-CTE-28-2	1.06E-05
B-15-0-CTE-28-3	8.41E-06
B-30-0-CTE-28-1	9.51E-06
B-30-0-CTE-28-2	9.20E-06
B-30-0-CTE-28-3	9.33E-06
B-45-0-CTE-28-1	9.47E-06
B-45-0-CTE-28-2	8.56E-06
B-45-0-CTE-28-3	8.72E-06
X-0-20-CTE-28-1	9.57E-06
X-0-20-CTE-28-2	19.3E-06*
X-0-20-CTE-28-3	9.11E-06
B-15-20-CTE-28-1	8.89E-06
B-15-20-CTE-28-2	9.16E-06
B-15-20-CTE-28-3	9.13E-06
B-30-20-CTE-28-1	9.36E-06
B-30-20-CTE-28-2	8.48E-06
B-30-20-CTE-28-3	9.50E-06
B-45-20-CTE-28-1	9.65E-06
B-45-20-CTE-28-2	10.3E-06
B-45-20-CTE-28-3	9.92E-06

*****This data point is judged an outlier and was excluded from calculations.

APPENDIX F: DRYING SHRINKAGE TEST DATA

NOTE: **Lx** is the shrinkage strain (in./in.). A negative value denotes shrinkage, while positive denotes expansion.

X-0-0			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	5.00E-05	6.00E-05	5.00E-05
32	-5.00E-05	-1.00E-05	-4.00E-05
35	-1.40E-04	-9.00E-05	-1.40E-04
42	-3.30E-04	-2.70E-04	-2.70E-04
56	-4.30E-04	-3.50E-04	-3.90E-04
84	-4.80E-04	-3.50E-04	-4.10E-04

B-15-0			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	1.39E-18	-9.00E-05	-2.00E-05
32	-1.40E-04	-2.60E-04	-1.50E-04
35	-1.70E-04	-2.60E-04	-1.80E-04
42	-1.60E-04	-2.70E-04	-2.50E-04
56	-3.20E-04	-4.20E-04	-3.80E-04
84	-4.30E-04	-5.50E-04	-5.20E-04

B-30-0			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	1.20E-04	7.00E-05	1.00E-04
32	-1.00E-05	-5.00E-05	-1.00E-04
35	-4.00E-05	-6.00E-05	-1.30E-04
42	-2.70E-04	-3.20E-04	-3.70E-04
56	-3.50E-04	-4.10E-04	-4.70E-04
84	-4.70E-04	-5.10E-04	-5.40E-04

B-45-0			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	-6.00E-05	-6.00E-05	-6.00E-05
32	-1.50E-04	-1.90E-04	-2.00E-04
35	-2.80E-04	-2.60E-04	-2.70E-04
42	-2.70E-04	-2.80E-04	-2.80E-04
56	-4.00E-04	-4.20E-04	-4.40E-04
84	-5.70E-04	-5.90E-04	-5.90E-04

X-0-20			
Day	**Lx 1***	**Lx 2**	**Lx 3**
1			
28	N/A	-1.40E-04	-1.00E-04
32	N/A	-2.10E-04	-1.50E-04
35	N/A	-3.00E-04	-2.90E-04
42	N/A	-5.00E-04	-4.30E-04
56	N/A	-5.70E-04	-5.20E-04
84	N/A	-6.70E-04	-6.00E-04

B-15-20			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	8.00E-05	3.00E-05	2.00E-05
32	-4.00E-05	-1.39E-18	-6.00E-05
35	-1.30E-04	-1.00E-04	-1.50E-04
42	-2.50E-04	-2.10E-04	-2.60E-04
56	-4.50E-04	-3.60E-04	-4.70E-04
84	-5.10E-04	-4.50E-04	-5.30E-04

B-30-20			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	3.00E-05	2.00E-05	-4.00E-05
32	-1.00E-05	-2.00E-05	-4.00E-05
35	-1.60E-04	-1.60E-04	-2.70E-04
42	-1.90E-04	-1.90E-04	-3.00E-04
56	-3.50E-04	-3.20E-04	-4.50E-04
84	-4.50E-04	-3.80E-04	-5.20E-04

B-45-20			
Day	**Lx 1**	**Lx 2**	**Lx 3**
1			
28	8.00E-05	1.90E-04	1.00E-05
32	-8.00E-05	-1.20E-04	-1.30E-04
35	-7.00E-05	-1.00E-04	-1.20E-04
42	-2.30E-04	-2.70E-04	-2.90E-04
56	-4.20E-04	-4.30E-04	-4.50E-04
84	-6.10E-04	-5.30E-04	-5.70E-04

*****This specimen was damaged and no meaningful data could be collected.