FEASIBILITY OF RECLAIMED ASPHALT PAVEMENT AS AGGREGATE IN PORTLAND CEMENT CONCRETE

FHWA/MT-13-009/8207

Final Report

prepared for
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

in cooperation with
THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

November 2013

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RESEARCH PROGRAMS

MDT

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November 2013

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Access No.	3. Recipient's Catalog No.
FHWA/MT-13-009/8207		

4. Title and Subtitle Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete	5. Report Date November 2013 6. Performing Organization Code
7. Author(s) Mike Berry, Jerry Stephens, Bethany Bermel, Adam Hagel, and David Schroeder	8. Performing Organization Report Code
9. Performing Organization Name and Address Civil Engineering Western Transportation Institute PO Box 174250 Montana State University – Bozeman Bozeman, Montana 59717-4250	10. Work Unit No. (TRAIS) 11. Contract or Grant No. MSU G&C #4W2781 MDT Project #8207
12. Sponsoring Agency Names and Addresses Research Programs Montana Department of Transportation 2701 Prospect Avenue Helena, Montana 59620-1001	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code 5401

15. Supplementary Notes

16. Abstract

This research effort was focused on evaluating the feasibility of using minimally processed reclaimed asphalt pavement (RAP) as aggregate replacement in concrete pavements. This research demonstrated that concretes with up to 50 percent of the fine aggregates and 100 percent of the coarse aggregates replaced with RAP were suitable for concrete pavement. A statistical experimental design procedure (response surface methodology – RSM) was used to investigate proportioning RAP concrete mixtures to achieve desired performance criteria. Based on the results of the RSM investigation, two concrete mixtures were selected for further evaluation: a high RAP mix with fine and coarse aggregate replacement rates of 50 and 100 percent respectively, and a "high" strength mix with one half of the RAP used in the high RAP mix. Both mixes met MDT concrete pavement specifications for slump (1.5 inches), air content (6 percent), and 28-day compressive and tensile strengths (3,000 psi and 500 psi, respectively). These two concrete mixtures were subjected to a suite of mechanical and durability tests to evaluate their potential use in Montana roadways. Mechanical properties tested were compressive and tensile strength, elastic modulus, shrinkage, and creep. Durability tests included alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze-thaw resistance, and scaling. Overall, both mixes performed adequately in these mechanical and durability tests, although it is important to note that the inclusion of RAP had an obvious negative impact on nearly every property tested relative to those of control mixes made with 100 percent conventional aggregates.

17. Key Words	18. Distribution Statement
Reclaimed asphalt pavement, RAP, concrete, mechanical properties, durability, aggregate gradation, aggregates by source, experiments, mix-design, Portland cement concrete, recycled materials	No restrictions. This document is available through NTIS, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	188	

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ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support for this project provided by the Montana Department of Transportation (MDT) and the Research and Innovative Technology Administration (RITA) at the United States Department of Transportation through the Western Transportation Institute at Montana State University. We also wanted to recognize and thank the MDT Research Section and the technical panel for their participation in this project. In particular, we would like to thank Bob Weber of MDT for his insight and support throughout this research process.

UNIT CONVERSIONS

Measurement	Metric	English
Length	1 cm	0.394 in
	1 m	3.281 ft
	1 km	0.621 mile
Area	1 cm^2	0.155 in^2
	1 m^2	1.196 yd^2
Volume	1 m^3	1.308 yd^3
	1 ml	0.034 oz
Force	1 N	0.225 lbf
	1 kN	0.225 kip
Stress	1 MPa	145 psi
	1 GPa	145 ksi
Unit Weight	1 kg/m^3	1.685 lbs/yd^3
Velocity	1 kph	0.621 mph

EXECUTIVE SUMMARY

This research investigated the feasibility of using reclaimed asphalt pavement (RAP) to replace virgin aggregates in concrete pavements. Specifically, this research considered using minimally processed RAP (i.e., simply fractionating into fine and coarse components with no washing or crushing) in this capacity for roadways in the state of Montana. A statistical experimental design procedure (response surface methodology – RSM) was used to investigate mix proportioning in concrete mixtures containing RAP to achieve desired performance criteria. The RSM investigation involved two phases: an initial study with a broad range of variables and responses, and a more focused follow-on investigation. In this initial RSM study, the mix variables consisted of w/c ratio, paste content, air entrainment admixture dosage rate, and fine and coarse RAP replacement rates. The chosen responses were slump, entrained air content, 7- and 28-day compressive strength, and 28-day flexural strength. The target values for these responses (consistent with MDT performance criteria for concrete pavements) were 1.5 inches for slump, entrained air content of 6 percent, 7- and 28-day compressive strengths of 2,000 psi and 3,000 psi respectively, and 28-day flexural strength of 500 psi. Prior to implementing this RSM investigation a series of trial batches were performed to set appropriate ranges for the mix variables, most notable of which were the ranges for the RAP replacement rates. Based on these preliminary mixes, along with insight from previous research, a range of 0 to 50 percent was chosen for the fine aggregate replacement rate, while the replacement rate for the coarse RAP ranged from 50 to 100 percent. After completion of the preliminary mixes, the initial RSM study commenced. Thirty trial batches were performed to collect performance data for the RSM analysis. This analysis was successful in that it revealed the basic relationships between the mix variables and responses. In particular, it quantified the effects of including RAP aggregates at various replacement rates.

This initial RSM study was purposefully broad in the range of variables considered and subsequent observed responses, and based on its results, a follow-on more focused RSM investigation was conducted that more closely targeted the desired performance region. In this study, three mix variables were considered: w/c ratio, paste content, and air dosage rate. The chosen responses for this study were slump, air content, and 28-day compressive strength. Sixteen trial batches (specified by the RSM methodology) were performed to obtain data for the subsequent analysis. The resulting RSM models successfully modeled the responses, and were used to develop several mixes with different target performance parameters.

Based on the RSM models, two concretes were ultimately selected for further evaluation: a high RAP mix (HR) and a high strength mix (HS). These mixes were identical sans the RAP replacement rates; the HR mix, as the name implies, had a relatively large amount of RAP with 50 percent of the fines and 100 percent of the coarse aggregates replaced with RAP. The HS mix was designed to have a higher strength by using half of the RAP (25 percent of the fines were

replaced and 50 percent of the coarse). It should be noted that both mixes had slumps and air contents that were consistent with MDT specifications. Once selected, these two concrete mixtures were evaluated with a suite of mechanical and durability tests to evaluate their potential use in Montana roadways. The mechanical properties tested were compressive and tensile strength, elastic modulus, shrinkage, and creep. The durability tests included alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze-thaw resistance, and scaling.

In regards to mechanical properties, both mixes met all MDT specification requirements for both compressive and flexural strengths, and had adequate elastic moduli. Further, both mixes did not exhibit excessive deformations associated with shrinkage or creep. However, the amount of RAP had an obvious and significant negative impact on the mechanical properties. As was expected, the strength and stiffness of the concretes decreased with increasing RAP, and the deformations associated with creep and shrinkage both increased with increasing RAP content.

Both the HR and HS mixes demonstrated adequate durability for use in concrete pavements in Montana, with the HS mix generally performing better than the HR mix. Both concretes had void rates less than 12 percent, which is indicative of adequate performance in pavements. For the abrasion tests, both mixes lost very little mass and had wear depths less than 1.0 mm. Both concretes were rated as "Moderate" for likelihood of chloride ion penetration. The HR and HS mixes had durability factors of 94 and 98 respectively, after being exposed to 300 freeze-thaw cycles. A durability factor of 80 or more has been cited as being indicative of acceptable freeze-thaw resistance. For scaling resistance, the HR mix was rated as "moderately susceptible", while the HS mix was rated as "slightly susceptible". Test results indicated that RAP aggregate may have issues associated with ASR; however, the test results were clouded by an issue associated with the high temperatures used with this test method.

Based on the results from this study, the following conclusions can be made:

1) Response surface methodology is a useful and efficient tool for concrete mix development. Both RSM analyses had resulting response surfaces that fit the data well (with R^2 values generally greater than 0.9) and adequately characterized the behavior of the mixes (consistent with conventional concrete knowledge). In regards to mixture optimization, the initial RSM analyses highlighted the importance of selecting appropriate ranges of independent variables, as the resulting responses from this study were too far from the target responses. The follow-on investigation with a modified region of interest was successfully used to develop several optimum degrees of performance. When carried out in the lab, these mixes performed as predicted; all measured responses were close to the predicted responses, and all were well within the 95 percent confident intervals.

2) This research demonstrated that both the HR and HS mixes had adequate mechanical properties and durability to be used in concrete pavements in the state of Montana. That

being said, the inclusion of RAP in concrete was generally found to have a negative impact on its mechanical and durability properties, with the HS mix generally outperforming the HR mix. The negative impact of including RAP is postulated to be due to: (1) the decreased bond between the asphalt coating on the RAP and the hardened paste, and (2) the conglomerations of asphalt and smaller particles found within the coarse fraction of RAP. Furthermore, the nature of the RAP aggregates significantly affected the accuracy of traditional techniques for accounting for aggregate moisture content.

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1 INTRODUCTION

1.1 Background Information

Each year, the US highway industry produces over 100 million tons of reclaimed asphalt pavement (RAP) through standard rehabilitation and construction of the nation's roads (Huang, Shu, & Li, 2005). Although this product has been reused in several applications, usually in hot plant mixes, a large portion of this material remains unused. With a sizeable share of RAP wasted in stockpiles and landfills, the exploration of further uses for this construction byproduct is warranted. Using RAP as aggregate in Portland cement concrete pavement (PCCP) is one possible application for this recyclable material. Portions of virgin aggregate used to produce concrete pavement may be replaced with RAP, creating a pavement that is both efficient and environmentally friendly. Previous research has demonstrated the feasibility of producing concrete with RAP aggregate; however, these prior studies have focused on short-term mechanical properties of the concrete and have not significantly addressed its long-term mechanical properties and durability.

1.2 Objectives

The Montana Department of Transportation (MDT) is interested in using RAP as a replacement aggregate in PCCP to create a more flexible and "green" paving material. The objective of this specific research effort is to evaluate the potential of using RAP aggregates in PCCP in the state of Montana. Montana has some unique climate conditions that can have harsh effects on roadway construction materials, and this research will attempt to characterize the response of PCCP containing RAP to this adverse environment through a series of mechanical and durability tests.

1.3 Scope

The project objectives were realized through the following tasks:

- A literature review was performed that summarized the general material behaviors documented in past RAP concrete studies.
- A statistical method (response surface methodology-RSM) was used to develop suitable mixes containing a substantial amount of RAP aggregate. RSM was used to designate a test matrix of trial batches to be experimentally evaluated. Data from these trial batches were then used to create analytical models consisting of a set of regression equations to be used to investigate the effects of the various concrete constituents, and ultimately for optimization. This task was carried out in two phases: the first phase consisted of an experimental design with five independent variables over a wide range of values, whereas the second phase consisted of an experimental design with three independent variables

over a modified region of interest. The resulting model from the second phase was then used to develop an optimized mix suitable for use in concrete pavements.

- Following the experimental testing and model development, two mixtures were selected for further and more thorough performance evaluation, namely a relatively high strength mix and a mix that included a relatively high proportion of RAP. Mechanical properties of interest consisted of compressive and tensile strength, elastic modulus, and creep and shrinkage tendencies. Durability tests were conducted to evaluate alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze-thaw resistance, and scaling

2 LITERATURE REVIEW

Several laboratory studies researching the properties of concrete containing RAP have been completed. Specific test methods, results, and conclusions from five such prominent studies are summarized in this chapter. This chapter concludes with a discussion of a FHWA study focused on applying statistical methods to concrete mixture design, This activity was viewed to be fundamental to accomplishing the project objectives, and this study shaped the manner in which the mixture design effort was executed.

2.1 Research by Delwar, Fahmy, and Taha

Delwar, Fahmy, and Taha (1997) performed one of the first studies on the use of RAP in concrete. The main goals of their research were to investigate the feasibility of using RAP as aggregate in Portland cement concrete (PCC) and to determine key material properties and characteristics of the resulting material.

RAP millings for use in the concrete test mixtures were obtained from an asphalt producer in Spokane, Washington. The research team processed the material through a set of sieves, removing any aggregate larger than ¾-inch and fractionating the material on the No. 4 sieve. Standard concrete sand and gravel, as well as type I/II cement were purchased from a company in Moscow, Idaho for use in the study. Mixes containing 10 different aggregate arrangements with two different water-to-cementitious material (w/c) ratios were tested for compressive strength and stress-strain characteristics. Data on the slump, air content, and unit weight of the wet concrete were also recorded.

Strength data collected through laboratory testing showed that the inclusion of RAP decreased the overall compressive strength of the concrete material. They found that similar to regular concrete, high water-cement ratios yielded a lower strength material, and for all percentages of RAP replacement aggregate considered, longer curing periods were necessary for achieving higher strengths. A beam made with RAP Concrete was tested in three-point bending, yielding a modulus of rupture of 685-psi. Researchers commented that with this relatively high flexural capacity, the concrete may lend itself towards application as a pavement material.

Stress-strain curves were generated for several of the concrete mixtures, and it was determined that for any strain value the higher the RAP content, the lower the associated stress. This observation indicated that the stiffness of the RAP aggregate concrete decreases as the amount of RAP in the mixture is increased. The stress-strain curves also showed that concretes with higher RAP contents failed at increased strain levels, indicating that the material was more flexible than conventional concrete. In light of this possibly promising behavior in some applications, Delwar and his colleagues (1997) suggested that concrete containing RAP be further evaluated to determine its durability properties.

2.2 Research by Huang, Shu, and Li

Huang, Shu, and Li of the University of Tennessee and Louisiana State University expanded the available information on concrete containing RAP with their work (Huang et al., 2005). The objective of their study was to further research the effect of the inclusion of RAP aggregates on the toughness and brittle failure behavior of Portland cement concrete. The study hypothesized that the fine layer of asphalt coating the individual pieces of aggregate protects the particles from breakage and facilitates the increased dissipation of energy in the event of a crack. This concept is illustrated in Figure 1 below. With this micro-level understanding, researchers surmised that the use of RAP aggregate in PCC would arrest crack propagation, making the final product tougher.

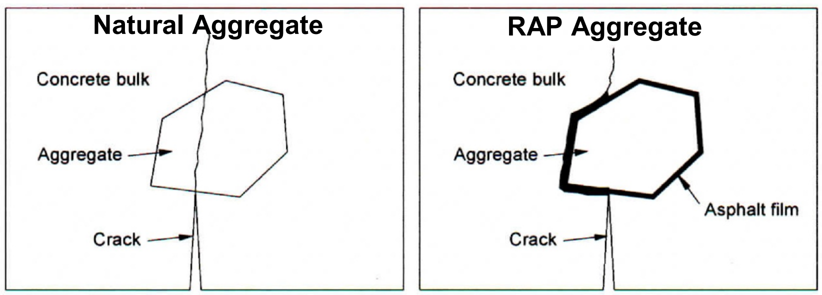


Figure 1: Crack Propagation Through Natural Aggregate and RAP Aggregate (Huang et al., 2005)

In their laboratory investigation, four different mix designs were evaluated, consisting of: (1) a control mix with all natural aggregates, (2) a mix with coarse RAP aggregate and natural fine aggregate, (3) the opposite design containing coarse natural aggregate and fine RAP material, and finally (4) a concrete mixture using only the RAP aggregate. The researchers chose to manufacture RAP material in the laboratory for use in this work (they did not use pavement that was reclaimed from a roadway). Sufficient asphalt was applied to virgin aggregate to coat the particles with approximately 8-µm of bituminous material. The laboratory-made RAP was then aged for 12 hours at 120ºC. It was stated that utilizing a lab-produced RAP provided more control in the experiment. A standard mechanical mixer was used for concrete batching, and ASTM rodding techniques were applied to consolidate the wet concrete. No unusual behaviors were encountered in the batching/mixing process, and the researchers concluded that concrete containing RAP could be mixed and cast by conventional means. Results from the study also indicate that the air content of the concrete was unaffected by the added RAP. Further, while the material containing RAP had a low slump, the wet concrete was still found to be workable. Strength tests showed that as the amount of RAP in the mix was increased, both the compressive and splitting tensile strength decreased as compared to the control mix. This decrease in strength was anticipated, as asphalt is a much softer material than conventional aggregate, and it and does not bond as well to the cement paste.

Further analysis indicated that the RAP concrete had a much higher toughness than the standard mix design. The test data further indicates that coarse RAP had a greater positive effect on increased toughness compared to fine RAP. The authors concluded that fine RAP had more adverse outcomes on the concrete than the coarse RAP.

2.3 Research by Huang and Shu

After Huang and Shu's initial research on RAP concrete, they performed additional testing on specimens that included admixtures to help improve the performance of the material (Huang & Shu, 2005). Both silica fume and a high-range water reducing agent (HRWRA) were added to help reduce the loss of strength observed when RAP aggregate was used. Several mixes were produced with different percentages of coarse and/or fine RAP aggregate (10, 30, 50, or 100 percent by weight) used as a replacement for virgin aggregate.

Testing revealed that at low contents of RAP the concrete had a higher slump and increased workability; however, with higher levels of RAP the slump and workability both decreased dramatically. Air content appeared to be unaffected by RAP content. Strength testing showed that the use of RAP aggregate in PCC increased the toughness of the material, and as the percentage of reclaimed asphalt in the concrete increased, so did the toughness index. It should be mentioned that the greatest increase in toughness was seen in the mix design using 100 percent fine RAP aggregate. The test results also showed that regardless of the fractionation of the RAP used, the resulting concrete experienced a significant reduction in elastic modulus and strength compared to the control mix. They also found that the replacement rate of RAP was inversely related to the compressive strength, split tensile strength, and Young's modulus; thus, as the RAP content increased, the material's performance decreased. All of these results confirmed the findings from the previous study, and researchers moved on to test the effects of silica fume and high range water-reducing admixtures (HRWRA) in the RAP concrete.

Based on their experiments, the researchers concluded that silica fume did not improve the strength and modulus of elasticity of the concrete. Relatively speaking, the performance of the concrete that included silica fume was identical to that of the concrete without silica fume. The researchers believed this outcome was due to poor consolidation as a result of low slump and a relatively short curing time of only 28 days. Although silica fume was unsuccessful as an admixture, the high-range water reducing agent proved to be advantageous for improving the strength and Young's modulus of the concrete containing RAP. Conversely, the study also concluded that when the water reducer was used in conjunction with the silica fume, its positive effects on the concrete pavement were negated. It was ultimately determined that the HRWRA alone had the capability to improve the compressive strength, split tensile strength, and elastic modulus of the concrete containing RAP.

2.4 Research by Hossiney

In 2008, Nabil Hossiney from the University of Florida worked with the Florida Department of Transportation (FDOT) to study the performance of RAP concrete used in a rigid pavement application (Hossiney, 2008). In their study four concrete mixtures containing reclaimed asphalt pavement were evaluated in a laboratory setting. The tested material properties were then used in a finite element model to assess how the concretes would behave as a pavement under typical Florida roadway conditions.

The reclaimed asphalt pavement used in the research was obtained from an asphalt plant in Gainesville, Florida. The natural aggregate consisted of a porous limestone coarse rock and a standard silica sand fine material. The mixtures evaluated in the study included 0, 10, 20, and 40 percent RAP aggregate. Typical ASTM tests were done on the wet concrete and in the cured state. The material was tested for compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, shrinkage, and coefficient of thermal expansion.

Laboratory test results indicated that the compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the hardened material were inversely related to the amount of RAP in the mix; these material properties all decreased as the RAP replacement rate was increased. It was also found that the coefficient of thermal expansion was unaffected by the inclusion of reclaimed asphalt pavement in the concrete mixture, and shrinkage tendencies of the material decreased as the RAP content increased.

The material properties, characterized through the laboratory testing, were then input into a finite element model of a typical Florida pavement section constructed with the RAP concrete. FEACONS IV (Finite Element Analysis of Concrete Slabs version IV), a program developed at the University of Florida, was used to perform a stress analysis of a pavement configuration with each of four tested concrete mixtures. The maximum stresses occurring in the concrete slab were analyzed for each of the four varying concrete mixtures, and a stress ratio was calculated (defined as the ratio of the maximum stress to the compressive strength of the concrete). This analysis found that as the RAP content increased, the stress ratio decreased. For pavement applications, a lower stress ratio is desirable, indicating that the material can withstand more fatigue cycles suggesting that RAP concrete may perform well when employed as a PCCP.

2.5 Research by Brand, Roesler, Al-Qadi, and Shangguan

The Illinois State Toll Highway Authority sponsored a research program in 2012 to investigate the use of fractionated reclaimed asphalt pavement (FRAP) in concrete pavement (Brand, Roesler, Al-Qadi, & Shangguan, 2012). In this research, the virgin coarse aggregate was partially replaced with RAP at various rates (0, 20, 35, and 50 percent), while the fine virgin aggregate was not replaced with RAP. The researchers evaluated the concretes' performance relative to numerous mechanical and durability tests. The mechanical properties investigated were compressive and tensile strengths, elastic and dynamic moduli, and shrinkage. As for durability, the concretes were evaluated for chloride permeability, freeze/thaw resistance, fracture toughness, and alkali silica reactivity. The researchers found that compressive strength, tensile strength, and elastic moduli decreased with increasing RAP content; whereas, shrinkage was relatively unaffected by including RAP. The presence of RAP did not significantly affect the rapid chloride penetration tests; however, it did affect freeze-thaw resistance, although all concretes maintained adequate durability factors after 300 cycles. Fracture toughness was shown to decrease with increasing RAP content. The ASR tests indicated that the RAP was not reactive.

The RAP used in a majority of this research was either washed or dry sieved to remove dirt and finer RAP particles. This process was found to be costly; therefore, the researchers investigated the effect of not washing the RAP prior to concrete batching, and found that further processing the RAP did not affect strength properties.

Overall, the researchers concluded that a concrete containing up to 50 percent coarse RAP replacement may be suitable for pavements in Illinois.

2.6 Application of Response Surface Methodology to Concrete Mixtures, Federal Highway Administration

Although response surface methodology (RSM) has been used in many areas of research, it has not been widely employed in civil engineering; however, the Federal Highway Administration (FHWA) has investigated this statistical procedure's usefulness in developing concrete mixtures (Simon, 2003). The FHWA used this procedure to optimize concrete mixture proportioning based on a number of performance criteria, including: plastic state concrete properties, mechanical properties of the cured product, and cost. As a part of their study, the FHWA team applied the central composite design (CCD) method and used five independent variables to define their concrete mixture. These variables included: water-to-cement (w/c) ratio, fine aggregate, coarse aggregate, high-range water-reducing admixture (HRWRA), and silica fume.

As part of this research, a total of 31 concrete batches as specified by the CCD experiment design were produced over a six-week period. From each batch, ten 100-by-200-mm cylinders were cast, and two slump tests and one air content test were conducted. The responses used in the analysis included: one-day compressive strength, 28-day compressive strength, rapid chloride test (RCT) charge passed, as well as cost estimated as dollars per cubic meter. Desirability functions were defined for each of the responses, dictating which value is optimum for each dependent variable. The researchers successfully implemented this procedure and used it to develop several optimum mixes.

Upon successful completion of their RSM study, the FHWA went on to develop and sponsor a software program specifically designed to perform the calculations necessary to apply RSM methodology for concrete mix design. The software is entitled "COST" and is available online as an interactive website, where the user is required to enter various parameters pertaining to their experiment. This application is ideal for the following two scenarios:

- The end goal is to set concrete mixture proportions based on material specifications and cost.

- The objective is to maximize or minimize certain response parameters (dependent variables) in a manner that is irrelevant to the cost of the final product.

It should be noted that the COST program was not used in this project because it was not capable of handling the number of independent variables used in this research.

3 MATERIALS

One of the first steps in this project was to determine sources for the materials to be used, i.e., the RAP, natural aggregates, cement, fly ash, and concrete admixtures. The research team believed it was important to use materials similar to those typically used on roadway projects. MDT provided direction on typical properties of PCCP material used on its projects, and researchers reviewed sources across the state to find suitable materials for the study. This chapter discusses the different mix ingredients that were evaluated as part of this research, as well as the properties of the materials that were chosen for use in this study.

3.1 Reclaimed Asphalt Pavement

An appropriate RAP source proved to be the most difficult item to secure. RAP from multiple locations across Montana was evaluated both qualitatively and quantitatively, and throughout this process, much was learned about the production, character, and variability of this material. Based on the literature review and conventional concrete practice, RAP characteristics of interest in the mix design process include its asphalt content, particle gradation, moisture condition, age/weathered condition, and unit weight. These various characteristics vary with the RAP source, based on among other things, the characteristics of the asphalt pavement from which the RAP was produced.

3.1.1 Material Characteristics

Several sources suggest that the typical hardened asphalt cement content for RAP ranges from 3 to 7 percent (FHWA, 1997), and according to MDT, RAP that is about 5 to 7 percent asphalt is most representative of a Montana pavement. MDT also has a number of specifications for aggregates to be used in Portland cement concrete pavements, among which is aggregate gradation. The gradation requirements can be found in Table 1 and Table 2 for the fine and coarse aggregate, respectively (MDT, 2006).

Table 1: MDT Fine Aggregate Gradation Specifications

Sieve Size	Percent Passing (ASTM)	Percent Passing (MDT)
3/8-in	100	100
No. 4	95 to 100	95 to 100
No. 8	80 to 100	80 to 100
No. 16	50 to 85	50 to 85
No. 30	25 to 60	25 to 60
No. 50	10 to 30	5 to 30
No. 100	2 to 10	0 to 10
No. 200	--	0 to 3

Table 2: MDT Coarse Aggregate Gradation Specifications

Sieve Size	Percentages By Weight Passing Square Mesh Sieves Designated Sizes			
	No. 1	No. 2	No. 3	No. 4
	No. 4 to 1 ½”	No. 4 to ¾”	No. 4 to 1 ½”	No. 4 to ½”
2”	100	--	100	--
1 1/2”	95-100	--	90-100	--
1”	--	100	20-55	--
3/4”	35-70	90-100	0-15	100
1/2”	--	--	--	90-100
3/8”	10-30	20-55	0-5	40-70
No. 4	--	0-10	--	0-15
No. 8	--	0-5	--	0-5

*Note: Nos. 1, 2, 3, and 4 correspond to AASHTO/ASTM designations 467, 67, 4, and 7 respectively.

It should be noted that RAP aggregates may have moisture contents as high as 5 to 8 percent, depending on where and how long the material has been stockpiled (FHWA, 1997). The material’s absorption characteristics can cause issues with the apparent mix water available to react with the Portland cement, which must be considered when RAP is used as an alternative aggregate in concrete mixtures. The weathering experienced by RAP can also cause the asphalt retained within the RAP to harden slightly. Further exposure also causes the milled material to physically break down or conglomerate. As was found in reviewing RAP sources for this project (as reported on below), the length of time the RAP has been stockpiled greatly affects its physical characteristics as an aggregate.

The unit weight of RAP material is highly dependent upon the original natural aggregate that was used in the pavement and the moisture content of the stockpiled product. There is a fairly limited amount of data available characterizing this physical property; however, it has been concluded that the unit weight of the milled or processed RAP is slightly lower than that of standard virgin aggregate, and ranges from 120 to 140-pcf.

3.1.2 Source

With these characteristics of reclaimed asphalt pavement in mind, the research team evaluated five potential sources for RAP aggregate to be used in this project. These sources included: I-15 near Hardy Creek, an unprocessed material from Main Street of Lewistown, the same Lewistown RAP after processing, I-90 west of Big Timber, and U.S. Highway 191 south of Harlowton.

3.1.2.1 Hardy Creek RAP

The first RAP material evaluated came from I-15 near the Hardy Creek exit, about 30 miles south of Great Falls. A typical sample of the material collected from this site is shown in Figure 2 below. The pavement was milled on March 29, 2010 and was sampled the same day. In a qualitative comparison to the other RAP samples, the Hardy Creek material appeared to contain the largest amount of ¾-inch plus aggregate particles. Having been recently milled off the roadway, the material stockpile was soft and relatively easy to dig into. At the time of sampling, the Hardy Creek material had just been taken off the roadway and was generally "loose" with no large clumps of aggregate that would warrant crushing.

Figure 2: Hardy Creek RAP Sample

3.1.2.2 Unprocessed RAP from Lewistown

The second RAP material investigated was collected from a stockpile in Lewistown, Montana. This RAP is shown in Figure 3. The material was milled off of Lewistown's Main Street in the summer of 2008; the sample was obtained on April 12, 2010. A portion of material from this site was crushed by Casino Creek Concrete in Lewistown, and both the natural-state and processed RAP were evaluated. Based on simple visual assessment, the unprocessed Lewistown material was significantly more weathered than the other RAP materials. The stockpile had been open to the elements for about two years, and the exposure clearly affected some of the physical characteristics of the material. In general, the particles were much smaller in size relative to some of the other "younger" RAP sources, and unlike the other sources, the aggregate was rounded with hardly any angular faces. The unprocessed Lewistown material was placed in a burn oven, and it was found to have an asphalt content of about 7 percent. This value is on the high end of the range normally expected for RAP. In visually contrasting this sample to the other RAP materials, the Lewistown RAP appeared darker. The dark hue of the aggregate could be attributed to the material's high water content, as the stockpile had been exposed to harsh weather conditions for an extended period of time. The stockpile as a whole had become very hard, and the material was beginning to clump together in large chunks. While the individual particles were smaller in size than generally observed at the other sites, they typically were clumped together, requiring that the pile undergo some sort of processing/crushing prior to use. It was also suspected that the coarse and fine aggregates of the stockpile became segregated as the material aged.

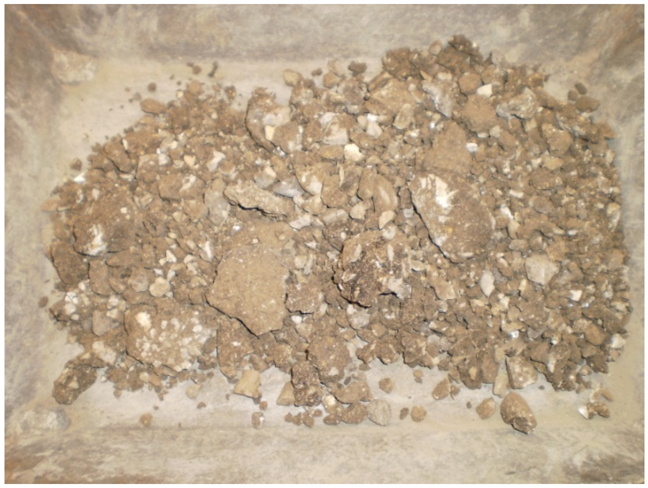


Figure 3: Unprocessed Lewistown RAP Sample

3.1.2.3 Processed RAP from Lewistown

As mentioned, a portion of the material from Lewistown was crushed at a local concrete plant. The mechanical processing greatly changed the physical qualities of the RAP aggregate, creating a material that was comprised of uniformly sized angular particles. The crusher was set to break up the larger chunks of material (material retained on a 34-inch screen), with the smaller clumps bypassing the equipment and being sent to a separate pile. The majority of the RAP was in this latter category, and thus bypassed the crusher. . The material that bypassed the crusher became very segregated and unevenly graded. The material that did go through the crusher was broken down into particles that ranged in size from the No. 16 to the No. 4 sieve. The crushed aggregates were much more angular relative to their original shape, and the distribution of the asphalt throughout the material was visibly changed. Prior to processing, the particles appeared to be evenly coated with a thin layer of asphalt, but after being sent through the crusher, many of the particles had clean faces from being broken down, and it was fairly evident that other aggregate consisted entirely of asphalt. The processed Lewistown material is pictured in Figure 4. The dark material on the far left is from the waste pile, the smaller aggregates in the middle are from the fine pile produced by the crusher, and the material on the far right is from the coarse pile from the crusher.

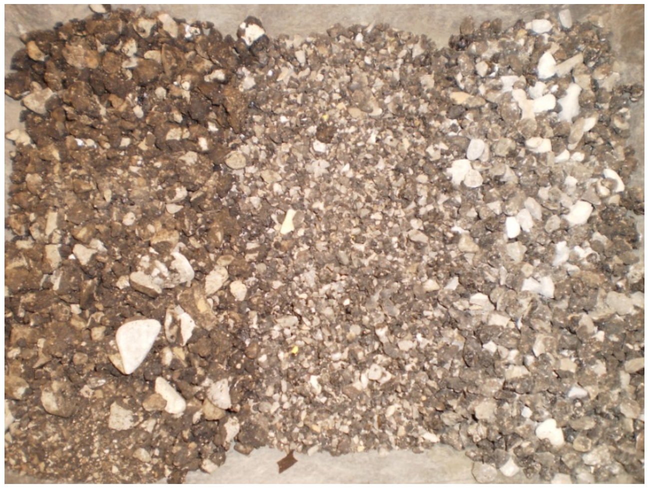


Figure 4: Processed Lewistown RAP Sample

3.1.2.4 Big Timber RAP

RAP aggregate from I-90 just west of Big Timber was also evaluated for use in this study. This material is shown in Figure 5. The material was milled on April 21, 2010 and the RAP was sampled from a stockpile by MSU researchers on April 22, 2010. The material in the stockpile was very dry and loose, and it was not exposed to any sort of precipitation from the time it was milled until it was sampled. A sieve analysis performed on this material showed it to be well graded, with an even distribution of particles. The milling process created angular faces on the aggregates, and the stockpile was clean of deleterious materials.

Figure 5: Big Timber RAP Sample

3.1.2.5 Harlowton RAP

A final RAP sample was collected from U.S. Highway 191 just south of Harlowton, Montana. A sample of the material collected at Harlowton is shown in Figure 6. A portion of the roadway was milled on April 21, 2010 and the material was sampled from a stockpile on the following day. A sample of this material is shown in Figure 6. The stockpile was loose, but it did appear moist. Weather records indicated that there was a small precipitation event that occurred while the material was stockpiled. The Harlowton RAP was similar to the sample collected at Big Timber in that both materials were well graded with angular particles.

Figure 6: Harlowton RAP Sample

3.1.3 Processing

Due to the material's age (freshly milled), asphalt content (within the range of 5 to 7 percent typical of Montana RAP), and availability, the RAP from I-15 near Hardy Creek was chosen for this study. Ten yards of the Hardy Creek RAP was transported to the Montana State University campus, where it was processed for use as a replacement aggregate in concrete pavement.

Relative to minimizing the cost and environmental impact of its use in concrete, ideally the RAP would require no processing prior to its addition to the mixture. Thus, the RAP processing method employed in this study embodied a minimalistic philosophy. The material was screened to remove all particles ¾ inch and larger (more specifically, the particles retained on a ¾ inch screen), with the remaining RAP then being fractionated on a No. 8 sieve. Fractionating on this sieve was found to yield coarse and fine fractions with gradations closely matching MDT specifications (as is shown in the material properties reported in the next section of this report). The RAP material was not processed beyond what is described herein (e.g., washing). Once processed, the RAP was placed in 1-cubic-yard sling bags and covered for future use.

3.1.4 Material Properties of Hardy Creek RAP

The fine and coarse Hardy Creek RAP aggregates were tested for standard material properties, including gradation. The gradation curves are presented in Figure 7 and Figure 8 for the fine and coarse RAP aggregate, respectively. As previously mentioned, the physical properties of RAP have a tendency to change during extended stockpiling; therefore, it is important to note that these gradation curves represent the material immediately after processing. The fine aggregate is completely enveloped by the MDT specification limits; however, the coarse aggregate is slightly finer and more poorly graded than is required by the specifications.

Relative densities, absorption capacity and average moisture contents of the fine and coarse fractions of the RAP aggregate are reported in Table 3 and Table 4, respectively.

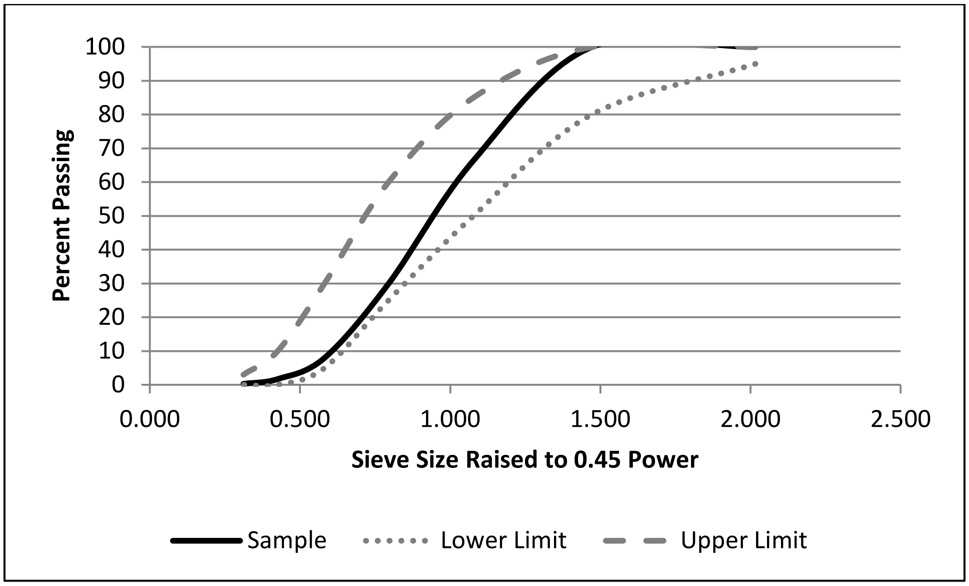


Figure 7: Fine RAP Gradation Curve

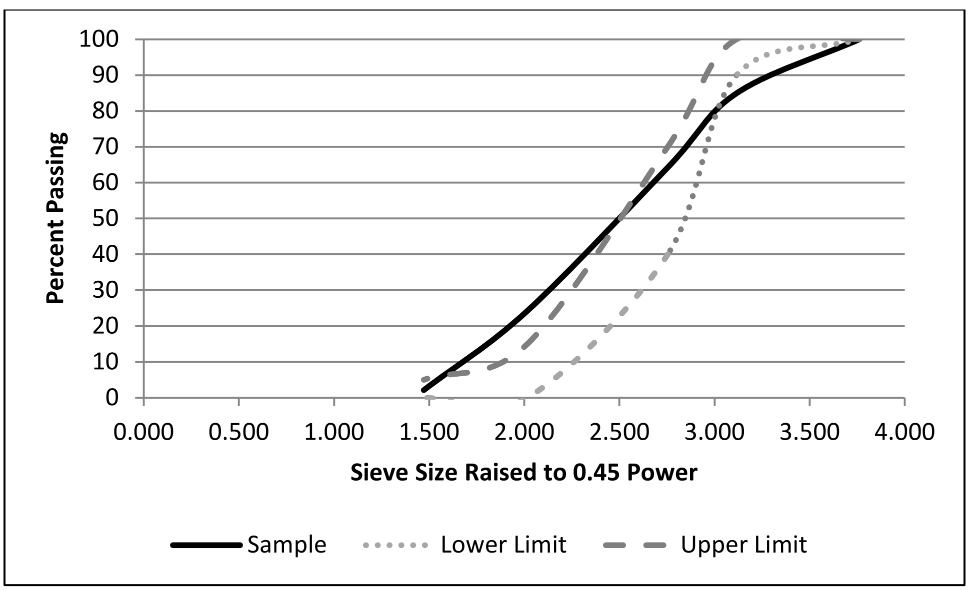


Figure 8: Coarse RAP Gradation Curve

Table 3: ASTM C128a Fine RAP Aggregate Test Results

Property	Value	Units
Relative Density (Specific Gravity) (oven dry)	2.06	unitless
Relative Density (Specific Gravity) (saturated surface dry)	2.18	unitless
Apparent Relative Density (Apparent Specific Gravity)	2.34	unitless
Density (oven dry)	128.56	pcf
Density (saturated surface dry)	136.04	pcf
Apparent Density	146.06	pcf
Absorption Capacity	5.82	percent
Average Moisture Content	3.81	percent

Table 4: ASTM C127 Coarse RAP Aggregate Test Results

Property	Value	Units
Relative Density (Specific Gravity) (oven dry)	2.41	unitless
Relative Density (Specific Gravity) (saturated surface dry)	2.50	unitless
Apparent Relative Density (Apparent Specific Gravity)	2.67	unitless
Density (oven dry)	150.24	pcf
Density (saturated surface dry)	156.38	pcf
Apparent Density	166.63	pcf
Absorption Capacity	4.09	percent
Average Moisture Content	1.97	percent

The asphalt contents of the combined, fine, and coarse RAP were determined in accordance with ASTM D6307 and are provided in Table 5. As can be seen in this table, the fine RAP had a higher asphalt content than the coarse RAP (8.5 versus 5.5 percent, respectively).

Table 5: Asphalt Contents of RAP Aggregates

Aggregate Type	Asphalt Content (%)
Combined	6.7
Fine	8.5
Coarse	5.5

To further investigate the nature of the fine and coarse RAP aggregates, the gradation of the aggregates after removing the asphalt were then determined. The gradations for the fine and coarse aggregates after removal of the asphalt are provided in Figure 9 and Figure 10, respectively. The upper and lower gradation limits specified by MDT are also included in these figures for perspective, along with the gradation of the aggregates prior to removing the asphalt.

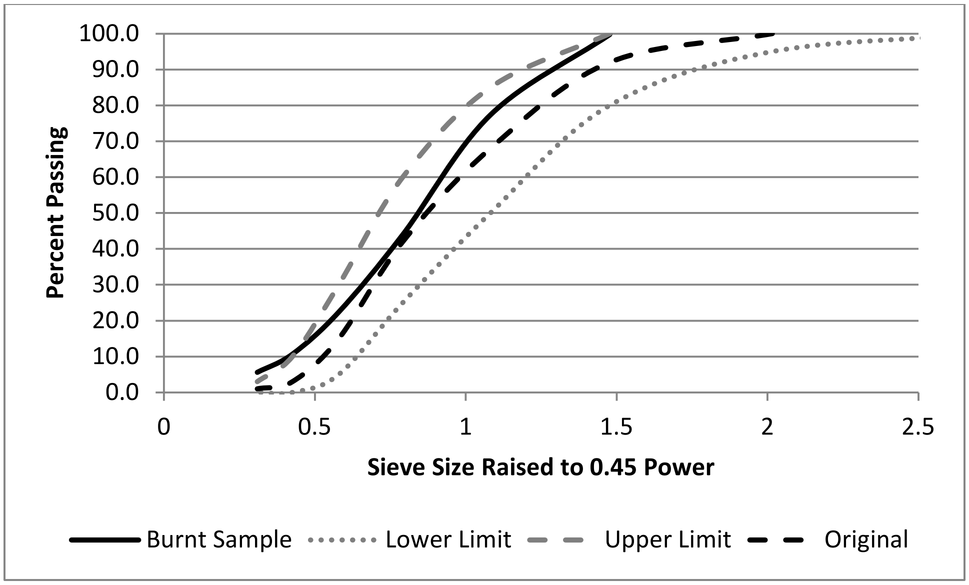


Figure 9: Gradation of Fine RAP after Removal of Asphalt

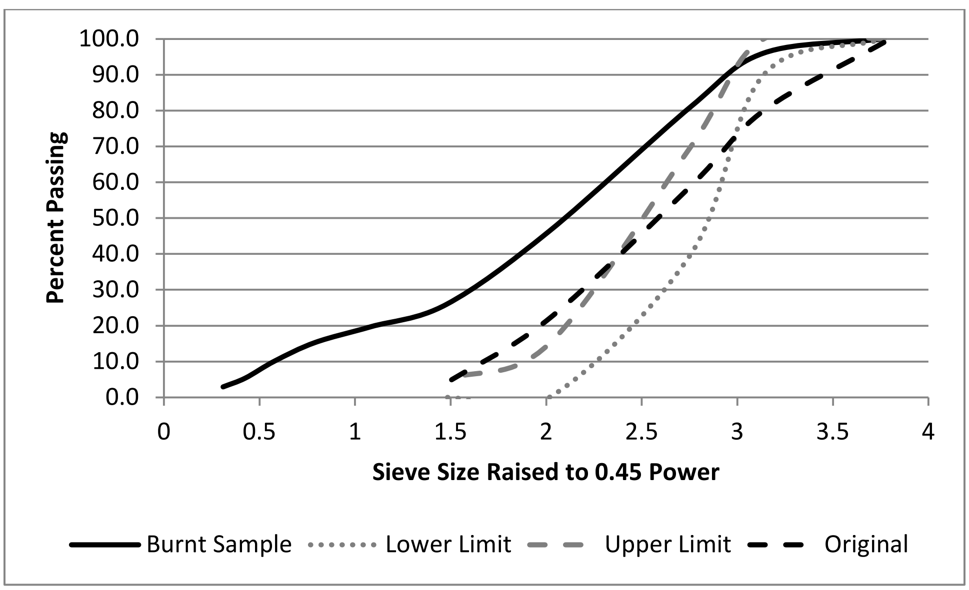


Figure 10: Gradation of Coarse RAP after Removal of Asphalt

Removal of the asphalt did not significantly alter the gradation of the fine RAP aggregate (Figure 9). Fine aggregate particle size nominally and relatively uniformly decreased when the asphalt was removed. The impact on gradation of removing the asphalt was more pronounced for the coarse aggregate, with many of the apparently conglomerate particles breaking down into a much finer composition (Figure 10). These conglomerations can be observed in cores taken from concretes made with this material (Figure 11). These conglomerated particles are suspected to have a significant effect on the hardened concrete properties.

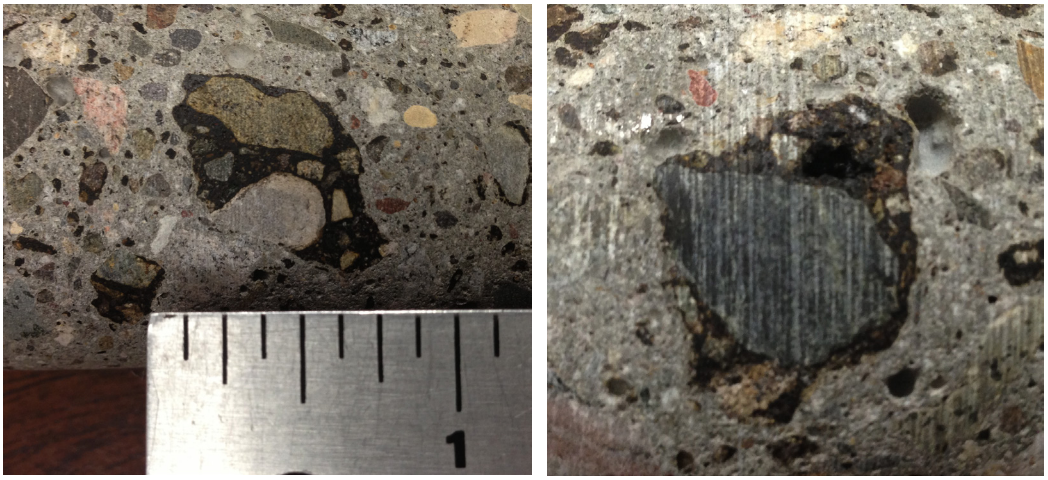


Figure 11: Bonded Asphalt Particles

3.2 Natural Aggregate

As noted in the literature review, the inclusion of RAP has been observed to have significant adverse effects on the end concrete product; therefore, in an attempt to produce a better material, RAP was blended with virgin aggregate for each of the concrete mixtures produced in this study. This section describes the source and material properties for the natural aggregates used in this study.

3.2.1 Source

Natural aggregates used in this study were purchased from Kenyon Noble, a local concrete supplier in the Bozeman area.

3.2.2 Material Properties

The fine aggregate was ordinary concrete sand; the coarse aggregate consisted of a standard cracked-face rock. These aggregates were reportedly in conformance with ASTM C33. The natural aggregates were tested for density, relative density, and absorption. Results of these tests are provided in Table 6 and Table 7. Further, the fines' average uncompacted void space was 39 percent and the coarse material was 28 percent fractured.

Table 6: ASTM C128a Fine Natural Aggregate Test Results

Property	Value	Units
Relative Density (Specific Gravity) (oven dry)	2.55	unitless
Relative Density (Specific Gravity) (saturated surface dry)	2.61	unitless
Apparent Relative Density (Apparent Specific Gravity)	2.72	unitless
Density (oven dry)	159.24	pcf
Density (saturated surface dry)	163.07	pcf
Apparent Density	168.25	pcf
Absorption Capacity	2.42	percent
Average Moisture Content	1.82	percent

Table 7: ASTM C127 Coarse Natural Aggregate Test Results

Property	Value	Units
Relative Density (Specific Gravity) (oven dry)	2.70	unitless
Relative Density (Specific Gravity) (saturated surface dry)	2.73	unitless
Apparent Relative Density (Apparent Specific Gravity)	2.78	unitless
Density (oven dry)	168.33	pcf
Density (saturated surface dry)	170.20	pcf
Apparent Density	173.54	pcf
Absorption Capacity	1.11	percent
Average Moisture Content	0.54	percent

Gradation curves for both fractions of the natural aggregates are shown in Figure 12 and Figure 13. Similar to the RAP material, the fine aggregate was within the bounds given by MDT specifications, while the coarse aggregate was outside of its specified limits across certain particle sizes. Further, the natural coarse material contained more large particles than the RAP coarse aggregate.

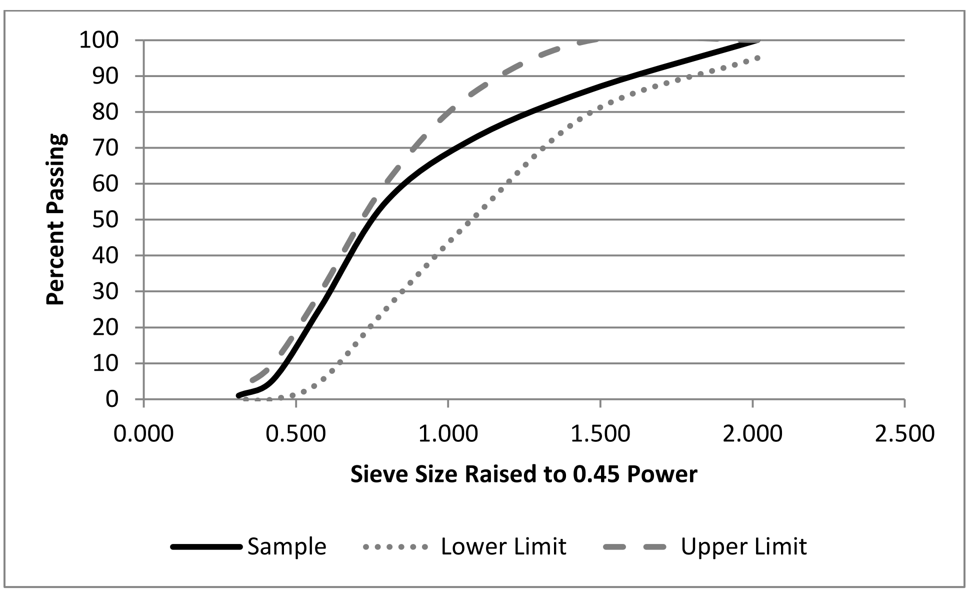


Figure 12: Fine Natural Aggregate Gradation Curve

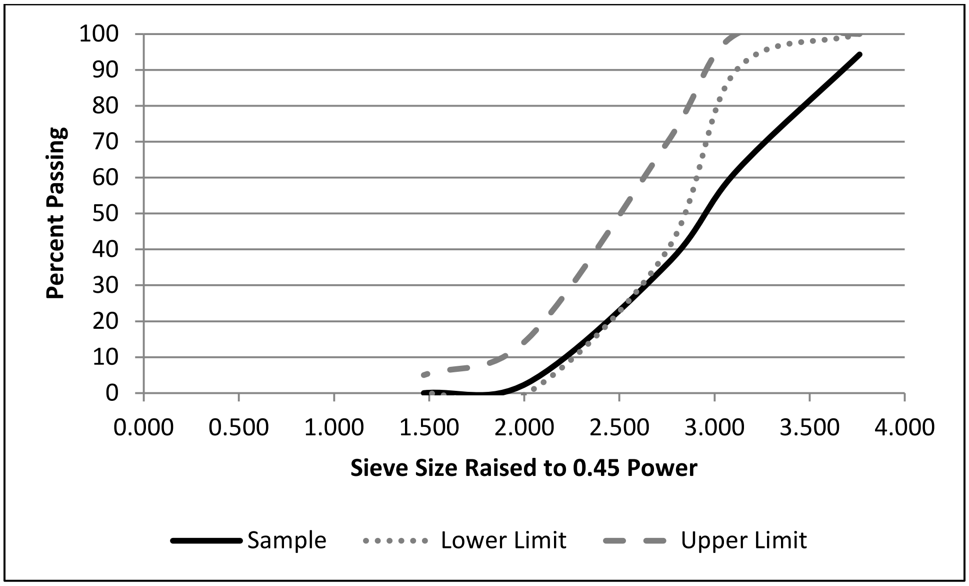


Figure 13: Coarse Natural Aggregate Gradation Curve

3.3 Combined Aggregate

The concrete mixtures evaluated in this research effort included a mixture of natural and RAP aggregates. In this section, the results of a gradation study on a mixture of 50 percent natural aggregates and 50 percent RAP aggregates (by weight) are presented. It should be noted that the concrete mixtures studied in this research used a variety of replacement rates; therefore, the combined gradation curves for the actual mixes used in this research would vary from the curve shown. However, these curves provide an example of how the inclusion of natural aggregates can affect the aggregate gradation of a partial RAP replacement mix. The following curves represent the average gradation for three separately mixed samples that were tested. The combined gradation for the fine material fell in the middle of MDT's specified fine aggregate gradation limits (Figure 14), while the coarse material was outside these limits (Figure 15), being generally more uniform in size than allowed by the limits.

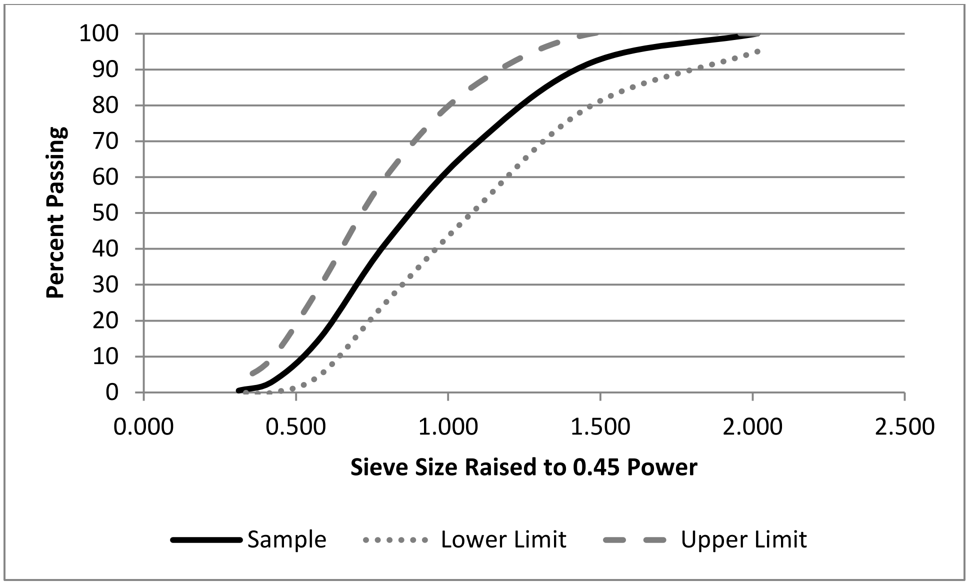


Figure 14: Combined fine gradation curve

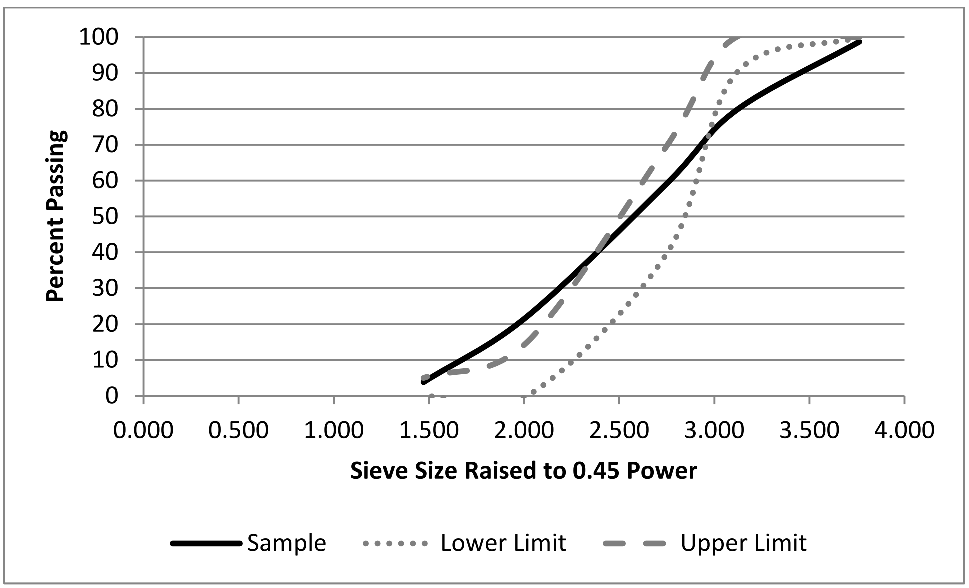


Figure 15: Combined Coarse Gradation Curve

3.4 Portland Cement

Type I/II Portland cement was used as the primary binder in this study, per MDT specifications. The cement was obtained from the Holcim cement plant near Trident, MT. The chemical and physical properties (ASTM C15) of the cement used in this project are provided in Table 8.

Table 8: Chemical and Physical Properties of Portland Cement, ASTM C150

Item	Limit	Result
Chemical Properties		
SiO_2 (%)	NA	20.4
Al_2O_3 (%)	6.0 max	4.2
Fe_2O_3 (%)	6.0 max	3.1
CaO (%)	NA	64.4
MgO (%)	6.0 max	2.2
SO_3 (%)	3.0 max	2.8
Loss on Ignition (%)	3.0 max	2.5
Insoluable Residue (%)	0.75 max	0.44
CO_2 (%)	NA	1.7
Limestone (%)	5.0 max	3.9
$CaCO_3$ in Limestone (%)	70 min	99
Inorganic Processing Addition	5.0 max	1.9
Potential Phase Compositions:		
C_3S (%)	NA	59
C_2S (%)	NA	14
C_3A (%)	8.0 max	6
C_4AF (%)	NA	9
C_3S+4.75C_3A (%)	NA	87.5
Physical Properties		
Air Content (%)	12 max	7
Blaine Fineness (m^2/kg)	260 min	413
Autoclave Expansion	0.80 max	0.03
Compressive Strength (MPa) (psi):		
3 days	10.0 (1450) min	26.9 (3900)
7 days	17.0 (2470) min	32.2 (4680)
Initial Vicat (minutes)	45 - 375	127
Mortar Bar Expansion (%) (C 1038)	NA	0.006
Heat of Hydration (kJ/kg) (cal/g):		
7 days	NA	352 (84)

3.5 Fly Ash

A baseline replacement of 15 percent fly ash by weight of cement was incorporated into each mix design. The benefits of using fly ash in concrete are at least two fold: the amount of Portland cement required in the mix is reduced, and a common waste stream is beneficially used, rather than landfilled. A Class C fly ash from the J.E. Corette power plant near Billings, Montana was used throughout this study. Headwaters Resources, the fly ash supplier that distributes the Corette coal ash, provided the material properties listed in Table 9. The use of this fly ash at this prescribed replacement rate was found to have no noticeable abnormal effect on the concrete mixture when compared to RAP control mixes that did not contain fly ash.

Table 9: Chemical and Physical Properties of Fly Ash, ASTM C 618

Fly Ash Tests on ASTM Standard Requirements		
Chemical Properties		
Item	Limit	Result
SiO_2 (%)	NA	31.59
Al_2O_3 (%)	NA	17.03
Fe_2O_3 (%)	NA	5.76
Sum of Constituents	50.0 min	54.38
SO_3 (%)	5.0 max	2.14
CaO (%)	NA	28.27
Moisture (%)	3.0 max	0.02
Loss on Ignition (%)	6.0 max	1.00
Available Alkalis, as Na_2O (%)	5.0 max	1.77
Physical Properties		
Fineness (% retained on #325)	34 max	11.10
Strength Activity Index (% of control)		
7 days	75 min	110
28 days	75 min	15
Water Requirement (% control)	105 max	93
Autoclave Soundness (%)	0.8 max	0.13
True Particle Density	NA	2.74

3.6 Air-Entraining Admixture

MICRO AIR by BASF was used to entrain air in the concrete mixtures examined in this study. MDT specifies a range of 5 to 7 percent entrained air for concrete pavements. The range of air-entraining dosages used in this research was based on the manufacturer’s suggestions and a number of preliminary RAP in PCCP screening concrete mixtures.

4 EXPERIMENTAL DESIGN

A statistical method (i.e., response surface methodology - RSM) was used in this research to develop and optimize the concrete mixtures. RSM is a collection of techniques useful for developing, improving, and optimizing processes. It is also important in the design and development of new products, as well as improving the design of existing products (Myers & Montgomery, 2002). RSM is commonly used in many applications in which the relationships between input variables and responses are not exactly known, and therefore mechanistic models are not available.

Although RSM is commonly used in the industrial world, its use in concrete mixture design is fairly limited (Khayat, Ghezal, & Hadriche, 2000; Long, Lemieux, Hwang, & Khayat, 2012; Simon, 2003; Sonebi, 2010). RSM offers advantages over traditional methods employed for determining concrete mixture proportions (e.g., ACI 211.1); traditional methods are not capable of accounting for interactions between constituents, and there is no means to achieve an optimized mixture (Simon, 2003). In contrast, RSM is capable of doing both with minimal trial batches.

In RSM, the *response* is a performance measure or quality characteristic of the process or of the resulting product from that process. For example, in the case of concrete mixtures, slump, air content, and 28-day compressive strength are considered responses. *Input variables* or *independent variables* are subject to the control of the engineer, and potentially influence the responses. In concrete mixtures, these input variables could be w/c ratio, paste-content, and air-entraining admixture dosage rate.

The procedure of fitting a response surface to a given process involves designating a set of trial batches that encompass a range of input variables using a statistical experimental design procedure. These trial batches are then carried out, and the various responses are measured. Data from the trial batches are then compiled to create a model consisting of a set of complex regression equations that can accurately depict the behaviors and interactions of the mix ingredients and the specified end responses (Simon, 2003). This model can then ultimately be used for optimization. The experimental design procedure used in this research was the Central Composite Design (CCD). CCD is an augmented factorial design, which is capable of estimating second-order models for each of the responses of interest without requiring the completion of a three-level factorial experiment. Thus, a reduced number of trial batches, in comparison to other experimental designs, is used to obtain the same statistically verified results (Simon, 2003). In addition to factorial points, this experimental design includes several center point runs to provide an estimate of the pure error, which is associated with the testing procedures. Axial points (outside the region of interest) are also included to allow for efficient estimation of pure quadratic terms in the regression equations.

The experimental design was implemented in multiple phases in this research. First, initial screening mixes were carried out to identify the general effects of including RAP aggregates in concrete, and to determine appropriate independent variables and ranges for the variables. An initial CCD-based investigation was then conducted using five independent variables. A follow-on CCD-based study was then carried out for three selected variables over a refined region of interest suggested by the initial and broader CCD investigation. Key findings from both studies are presented in this chapter; further analyses and results are provided in Appendices A and B for the initial and follow on studies, respectively.

4.1 Responses and Variables

The mixture responses chosen for this study were slump, air content, 7- and 28-day compressive strengths, and 28-day modulus of rupture. Target values for these responses are specified by MDT (MDT, 2006) for concrete pavements, and are provided in Table 10. These responses were measured in substantial accordance to ASTM (2009) test procedures. Slump was measured for each of the trial concrete mixtures per ASTM C 143. Air content was measured for each of the concrete mixtures according to ASTM C231. Compressive and tensile strengths were measured according to ASTM C39 and ASTM C78, respectively.

Table 10: Responses and Target values

Response	Specification
Slump	1.5±0.75 inches
Air Content	5 to 7 percent
7-Day Compressive Strength	Minimum of 2,000 psi
28-Day Compressive Strength	Minimum of 3,000 psi
28-Day Modulus of Rupture	Minimum of 500 psi

Prior to executing the experimental design, several “screening” mixes were performed to qualitatively observe how the RAP would generally affect the concrete behavior, and to determine important mix parameters and their subsequent ranges. The results of this screening experiment revealed that the RAP had the following effects on the concrete mixtures:

- the fine RAP appeared to have more adverse effects on the strength of the cured product than the coarse RAP
- preliminary mixes consistently contained about 2.5 percent entrapped air
- form release oil used on steel specimen molds appeared to react with the asphalt coating the aggregates, leaving an oily residue on the outside of the specimens
- bleed water and shrinkage appeared to be non-issues

- high water-cement ratios as well as high RAP contents resulted in compressive strengths below target values

Further, based on these trial mixes, five mix parameters were chosen for the independent variables based on the significance of their impact on the properties of concrete containing RAP: water-to-cementitious material ratio (w/c), paste volume, fine RAP replacement rate, coarse RAP replacement rate, and air-entraining admixture dosage rate. Ranges for these parameters were set based on the results of the screening mixes and on the knowledge and experience of the research team. The initial experimental design used all five of these parameters over the ranges specified in Table 11. The fine and coarse RAP contents in the mixtures were defined as replacement percentages; that is, the alternative RAP material replaced the specified percentage of the natural aggregate (by volume).

As was stated earlier, a follow on statistical experimental design was subsequently carried out with fixed replacement rates, and over a modified region of interest that provided more appropriate responses. The ranges used in the follow on statistical experimental design are also provided in Table 11. As can be seen in this table, in the follow on study the ranges for paste content and air-entraining admixture were reduced, and the fine and coarse replacement rates were fixed at 0.5 and 1.0, respectively.

Table 11: Independent Variables and Ranges

Variable	Initial Design	Follow-on Design
w/c Ratio	0.35 to 0.45	0.35 to 0.45
Paste Volume Fraction	0.27 to 0.40	0.30 to 0.40
Fine RAP Replacement Fraction	0.00 to 0.50	0.50 (fixed)
Coarse RAP Replacement Fraction	0.25 to 1.00	1.0 (fixed)
Air-Entraining Admixture Dosage Rate (mL/100#)	50 to 250	52-200

The screening mixes also provided insight into two other mix parameters: the coarse-to-fine aggregate ratio and fly ash replacement rate. Mixes with a coarse-to-fine aggregate ratio of 1.36 (by weight) performed well in the screening mixes, and therefore, this value was chosen for the mixes in this study. This ratio is consistent with ranges typically observed in conventional concrete. A Class C Fly ash was included in the mixtures to reduce the environmental impact of this concrete. A replacement rate of 15 percent (by weight) was chosen because this replacement rate was found to have no noticeable abnormal effect on the concrete mixture when compared to RAP control mixes that did not contain fly ash.

The absolute volume method was used to proportion the mixes once the w/c ratio, paste volume (or paste content), and coarse to fine aggregate ratio were prescribed. For the initial CCD study, the mix water was adjusted based on the measured moisture content (on the day of mixing) of both the virgin and RAP aggregates. However, this proved to be a significant source of scatter in this initial CCD study. Adjusting for the moisture content in the RAP aggregates based on what appeared to be the saturated, surface dry (SSD) state of the RAP was particularly problematic. Therefore, the mixes were not adjusted for moisture content in the follow-on study. This issue is discussed in greater detail in Appendix A. An example of the mix calculator used to proportion the mixes is provided in Appendix D.

4.2 Concrete Batching and Test Specimen Preparation

Each of the concrete test batches were mixed according to ASTM C192. A 10-ft^3 electric portable mixer was used for the preparation of each concrete batch. Mixing proceeded as follows:

1. With the mixer off, all of the coarse aggregates, approximately one quarter of the mixing water, and the air-entraining admixture were placed in the mixer.
2. The mixer was turned on, and after 30 seconds of mixing the remaining fine aggregates, cement, fly ash, and mix water were added.
3. The constituents were mixed for three minutes.
4. The mixer was then turned off, and the material was allowed to rest for an additional three minutes.
5. The mixer was restarted, and the material was mixed for a final two minutes.

When moisture content corrections were made (i.e. in the initial experimental design), the aggregates for the concrete batches were sealed in buckets at least 24-hours prior to mixing, and the moisture content of each of the four aggregate materials was measured to calculate necessary mix water adjustments.

Slump and air content tests were performed per ASTM specification, as described in the previous section. Strength test specimens were then cast in two lifts and consolidated via external vibration with a basic shake table. After the specimens were allowed to set for 24-hours, they were de-molded and placed in a cure room until the specified test date.

4.3 Initial Experimental Design

An initial experimental design was carried out for all five independent variables presented in the previous section over the full range presented earlier. While key findings are presented in this section, details of this study are provided in Appendix A. For five variables, the CCD methodology used in this research designates a total of 30 trial batches, which consist of 16 factorial runs, 10 one-factor-at-a-time runs at the axial points, and four center point runs. The design points for this CCD are provided in Table 12, while the 30 trial batches resulting from these design points are provided in Table 13. The factorial points in Table 12 are the bounds of the factorial runs, and designate the *region of interest*, which corresponds to the region in which the resulting response surface models are most applicable.

Once designated, these mixes were performed in a laboratory setting, and the responses were recorded. The resulting responses are included in Table 13, with the summary statistics for these responses provided in Table 14. Regression equations were then fit to this data, and the resulting response surfaces were evaluated for statistically significant variables and goodness of fit. Included in Table 14 are the variables that were determined to be statistically significant and the R^2 values for each response surface. Statistical significance was assessed by analysis of variance (ANOVA) calculations; in particular, variables with p values less than 0.05 were designated "significant". The R^2 values quantify the goodness of fit of the resulting response surface model to the collected data: an R^2 equal to 1.0 corresponds to a perfect fit, while a value close to 0 corresponds to a poor fit. As can be seen in the table, the resulting response surface models for each response had R^2 values near 0.90, indicating a good fit for each response. It should be noted that the response surface models were further evaluated via predicted-versus-observed scatter plots (Appendix A) and residual plots. These plots did not reveal any systematic variance, and therefore, provided another positive indicator of model performance.

Table 12: Design Points for Initial Experimental Design

Independent Variable	Axial Low	Axial High	Factorial Low	Center	Factorial High
w/c Ratio	0.35	0.45	0.3750	0.4000	0.4250
Paste Volume	0.27	0.40	0.3025	0.3350	0.3675
Fine RAP Replacement	0.00	0.50	0.1250	0.2500	0.3750
Coarse RAP Replacement	0.25	1.00	0.4375	0.6250	0.8125
Air Dosage Rate (mL/100#)	50.0	250.0	100.0	150.0	200.0

Despite the good fit for each response, these response surface models were found difficult to use in developing an optimum PCCP mix (i.e., a mixture with the target properties given in Table 10), as the observed properties of the trial mixtures were generally too distant from the target response values. Notably, the target responses for slump and air content were 1.5 inches and 6 percent, while the average responses for the trial mixtures in the initial experimental design were 4.75 inches and 9.84 percent. However, this study provided valuable insight into the effects of the independent variables on all five responses for the larger *region of interest*.

Referring to Table 15, of particular interest was the effect of RAP replacement rate on concrete compressive strength, the only response significantly correlated with RAP use. To evaluate this effect further, the 28-day compressive strength response surface is plotted as a function of fine and coarse RAP replacement rates in Figure 16 (with the other three variables –w/c ratio, paste volume, and air dosage- held constant at their center points), while cross-sections of this response surface are provided in Figure 17. As can be seen in these figures, as expected, an increase in both fine and coarse replacement rates result in a decrease in compressive strength. However, the effect of the fine aggregate replacement rate is decreased with increasing coarse RAP replacement. For example, at 0.8 coarse RAP replacement the fine aggregate replacement rate has little to no effect on the compressive strength (for the range of fine aggregate replacement rates considered).

Table 13: Summary of Mixes and Measured Results for Initial Experimental Design

	Independent Variables					Measured Responses					
Mix ID	w/c Ratio	Paste Volume	Fine RAP Replacement	Coarse RAP Replacement	Air Dosage (mL/100#)	Slump (inches)	Air Content (%)	7-Day *fc* (psi)	28-Day *f'c* (psi)	28-Day MOR (psi)	Environmental Factor
17.1	0.35	0.335	0.25	0.625	150	0.19	3.8	3559	4282	870	0.875
18.2	0.45	0.335	0.25	0.625	150	7.75	13.0	1440	1823	444	0.875
30.3 (C)	0.4	0.335	0.25	0.625	150	6.00	13.0	1529	2154	487	0.875
25.4	0.4	0.335	0.25	0.625	50	5.88	6.8	2609	3246	652	0.875
3.5	0.375	0.3025	0.375	0.4375	100	2.63	7.2	2524	3193	608	0.8125
28.6 (C)	0.4	0.335	0.25	0.625	150	4.25	10.0	1986	2585	461	0.875
1.7	0.375	0.3025	0.125	0.4375	200	1.25	6.2	3268	3660	685	0.5625
26.8	0.4	0.335	0.25	0.625	250	4.75	13.0	1562	1927	450	0.875
27.9 (C)	0.4	0.335	0.25	0.625	150	5.13	12.0	1940	2339	525	0.875
8.10	0.375	0.3675	0.375	0.8125	100	4.06	6.8	2297	2876	564	1.1875
22.11	0.4	0.335	0.5	0.625	150	3.75	8.5	1937	2318	450	1.125
11.12	0.425	0.3025	0.375	0.4375	200	5.00	12.0	1664	1879	424	0.8125
2.13	0.375	0.3675	0.125	0.4375	100	5.38	9.5	2815	3335	639	0.5625
19.14	0.4	0.27	0.25	0.625	150	5.38	9.5	2339	2971	565	0.875
12.15	0.425	0.3025	0.375	0.8125	100	2.13	8.0	1988	2431	531	1.1875
4.16	0.375	0.3025	0.375	0.8125	200	1.13	6.6	2283	2639	541	1.1875
15.17	0.425	0.3675	0.375	0.4375	100	8.50	10.0	2130	2362	538	0.8125
29.18 (C)	0.4	0.335	0.25	0.625	150	5.25	12.0	1843	2213	505	0.875
24.19	0.4	0.335	0.25	1	150	5.38	13.0	1480	1795	470	1.25
21.20	0.4	0.335	0	0.625	150	4.13	11.0	2020	2579	510	0.625
6.21	0.375	0.3675	0.125	0.8125	200	6.38	12.5	1798	2178	516	0.9375
7.22	0.375	0.3675	0.375	0.4375	200	6.00	10.5	2072	2592	533	0.8125
10.23	0.425	0.3025	0.125	0.8125	200	5.13	12.5	1472	1809	391	0.9375
23.24	0.4	0.335	0.25	0.25	150	4.50	10.0	2412	3150	607	0.5
9.25	0.425	0.3025	0.125	0.4375	100	3.25	8.0	2578	3209	476	0.5625
20.26	0.4	0.4	0.25	0.625	150	7.50	10.0	2252	2833	549	0.875
14.27	0.425	0.3675	0.125	0.8125	100	7.13	9.5	2130	2555	498	0.9375
16.28	0.425	0.3675	0.375	0.8125	200	7.13	13.5	1516	1722	403	1.1875
13.29	0.425	0.3675	0.125	0.4375	200	8.13	11.5	1722	2622	606	0.5625
2.30	0.375	0.3025	0.125	0.8125	100	0.75	5.3	2772	3420	716	0.9375

Table 14: Response Statistics for Initial Experimental Design

Response	Observed Range	Observed Average	R^2	Statistically Significant Variables
Slump (inches)	3/16 to 8.5	4.75	0.86	w/c, paste content
Air Content (%)	3.80 to 13.50	9.84	0.90	w/c, paste, air dosage
7-Day Compressive Strength (psi)	1440 to 3559	2131	0.93	w/c, coarse RAP, air dosage
28-Day Compressive Strength (psi)	1722 to 4282	2623	0.92	w/c, fine RAP, coarse RAP, air dosage
28-Day Rupture Strength (psi)	391 to 870	541	0.90	w/c, air dosage

The magnitude of the effect of including RAP is significant; the compressive strength is reduced by nearly 70 percent when the RAP replacement rates are at the maximum values considered in this study as compared to the minimum values. Nonetheless, the decision was made to continue to pursue mix designs that maximized RAP replacement rates to recycle as much RAP as possible, recognizing that increased amounts of cementitious materials would be required to approach the typically targeted minimum of 3,000 psi for PCCP.

Replacement rates of 0.5 and 1.0 were chosen for the fine and coarse aggregates, respectively. The 1 to 2 ratio of fine to coarse replacement rates is consistent with the yields obtained from the screening process described in the previous chapter. That is, the screening process resulted in twice the amount of coarse RAP aggregate as fine RAP aggregate.

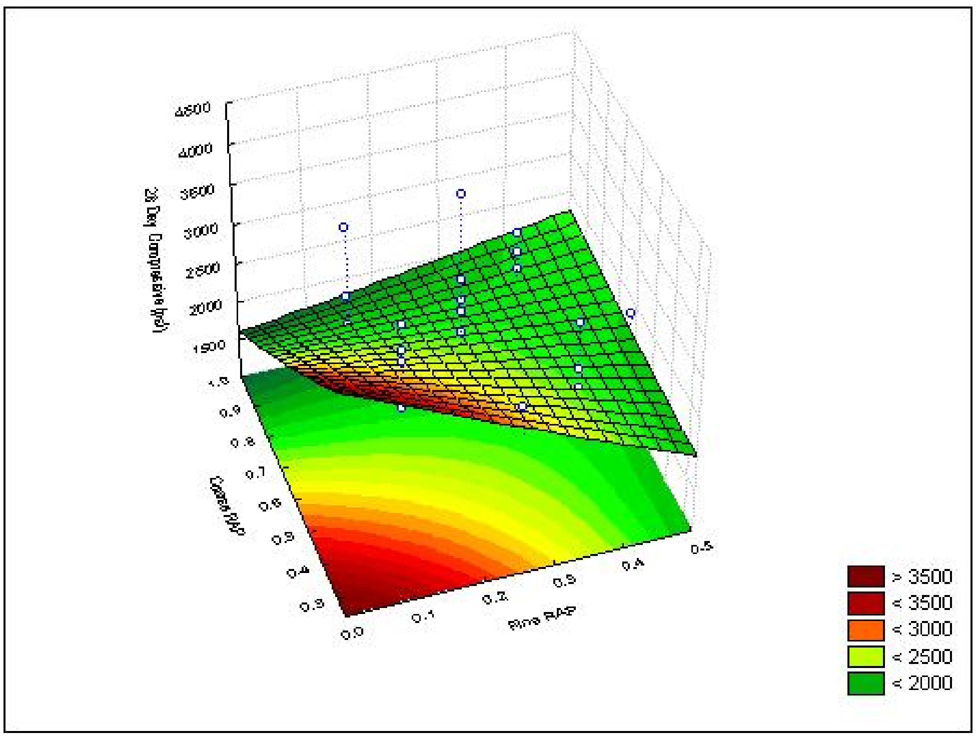


Figure 16: 28-day Compressive Strength vs. Coarse and Fine RAP Replacement Rates

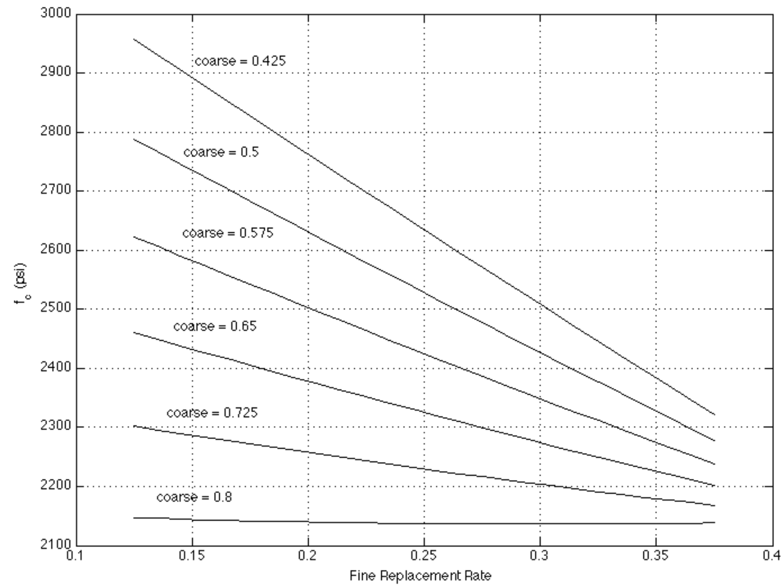


Figure 17: Effect of Fine and Coarse Replacement on 28-day Compressive Strength

Another key observation made during this initial study was that traditional methods for adjusting for aggregate moisture content may not be applicable for the RAP aggregates due to the nature of the oil coated RAP aggregates. This phenomenon is discussed in greater detail in A.3.2.

4.4 Follow-on Experimental Design

Upon completion of this initial study, a second CCD analysis was carried out with a modified region of interest and fixed replacement rates of 0.5 and 1.0 for the fine and coarse aggregates, respectively. This follow-on CCD produced mixtures with properties more consistent with target responses for concrete pavements.

The design points for this CCD are provided in Table 15. A total of 16 trial batches were used in this study, of which 14 were unique mixes and 2 were replicates at the center point. The mix parameters for these 16 trial batches are provided in Table 16 along with the resulting measured responses for each mix. Summary statistics for these mixes are provided in Table 17. The responses used in this experimental design were: slump, air content, and 7- and 28-day compressive strengths; 28-day modulus of rupture was not included as a response. This decision was made due to the strong correlation observed in the initial study between the compressive strength and modulus of rupture, and therefore little was gained by including this response. This decision minimized the amount of material required per mix, and allowed the research team to reduce trial batches from 2.9 cubic feet to 1.5 cubic feet.

As intended, the mixtures used in this CCD had properties more suitable for a PCCP mixture (i.e., average slump of around 2 inches and air content of 5.78 percent compared to target realizations of these responses of 1.5 inches and 6 percent, respectively). Furthermore, the resulting response surfaces from this CCD were determined to fit the data well. Goodness of fit statistics for response surfaces are provided in Table 17, along with the statistically significant variables for each response. The R^2 values indicate a good fit for each of the resulting response surfaces. Slump, 7-day and 28-day compressive strengths had R^2 values greater than 0.93, with the air content having the least R^2 value of 0.82. As was done in the initial study, statistical significance was evaluated via ANOVA calculations with a p-value threshold of 0.05. The response surfaces were further evaluated with residual plots and measured-versus-predicted scatter plots (Appendix C). These plots revealed no systematic variance of the residuals.

Table 15: Design Points for Follow-on Experimental Design

Independent Variable	Axial Low	Axial High	Factorial Low	Center	Factorial High
w/c Ratio	0.32	0.48	0.35	0.4	0.45
Paste Volume	0.27	0.43	0.3	0.35	0.4
Air Dosage Rate (mL/100#)	1.55	250.45	52	126	200

Table 16: Summary of Mixes and Measured Responses for Follow-on Experimental Design

	Independent Variables			Measured Responses			
Mix ID	w/c Ratio	Paste Volume	Air Dosage (mL/100#)	Slump (inches)	Air Content (%)	7-Day f'c (psi)	28-Day f'c (psi)
16.1 (C)	0.4	0.35	126	2.25	6	2424	2847
2.2	0.35	0.3	200	0	4.5	2592	3317
14.3	0.4	0.35	250	2.75	8	2130	2587
7.4	0.45	0.4	52	8.75	5	2174	2749
4.5	0.35	0.4	200	1.25	5.3	2882	3521
5.6	0.45	0.3	52	0.13	3.3	1919	2414
13.7	0.4	0.35	2	0.5	3.8	2590	3166
12.8	0.4	0.43	126	6.5	6.6	2396	2749
11.9	0.4	0.27	126	0	7	1937	2137
9.10	0.32	0.35	126	0	3.5	3047	3464
1.11	0.35	0.3	52	0	8	2923	3050
3.12	0.35	0.4	52	1.75	2	3092	3735
6.13	0.45	0.3	200	1.13	6.5	1793	2297
15.14 (C)	0.4	0.35	126	1.88	5.4	2423	3061
10.15	0.48	0.35	126	7.75	8.5	1557	1927
8.16	0.45	0.4	200	8.25	9	1772	2133

Table 17: Response Statistics for Follow-on Experimental Design

Response	Observed Range	Observed Average	R^2	Statistically Significant Variables
Slump (inches)	0 to 8.75	2.06	0.98	w/c, paste content, w/c and paste interaction
Air Content (%)	2 to 9	5.78	0.83	w/c, air dosage, w/c and paste interaction
7-Day Compressive Strength (psi)	1557 to 3092	2353	0.98	w/c, paste, air dosage
28-Day Compressive Strength (psi)	1927 to 3735	2822	0.93	w/c, paste content

The response surfaces obtained in this study are directly used in the following section to develop suitable pavement mixes; therefore, the equations defining these response surfaces are provided here. The response surfaces for each response have the following general form.

$$y = \beta_0 + \beta_1 WC + \beta_2 PC + \beta_3 AD + \beta_4 WC^2 + \beta_5 PC^2 + \beta_6 AD^2 + \beta_7 WC \cdot PC + \beta_8 WC \cdot AD + \beta_9 PC \cdot AD$$

where: y is the particular response of interest, WC is the water to cementitious material ratio, PC is the paste content, AD is the air dosage rate, and β_0 through β_9 are coefficients obtained via regression for each response. The resulting β coefficients for each variable and response are tabulated in Table 18.

Table 18: Response Surface Equations for Follow-on Experimental Design

β Number	Variable	βs for Slump	βs for Air Content	βs for 7-Day f'c	βs for 28-Day f'c
0	-	110.5183	91.3646	-55.4693	-10729.6297
1	WC	-367.7477	-150.966	-1008.3762	14896.0771
2	PC	-300.2103	-278.4931	-5516.2940	62445.3344
3	AD	0.0243	-0.1705	24541.9826	18.8215
4	WC^2	227.2334	-33.5769	-24666.7723	-10841.0297
5	PC^2	138.8451	79.5602	-0.4911	-57807.5308
6	AD^2	0	0	0.0012	0.0067
7	WC*PC	637.5	470	-11180.6348	-35915.9655
8	WC*AD	0.0338	0.25	0.4391	-26.5079
9	PC*AD	-0.0676	0.2568	-5.2066	-33.0139

These response surfaces are plotted in this section to provide perspective on the validity and general shape of the various surfaces. Figure 18 is a plot of the slump response surface as a function of w/c ratio and paste content (the most statistically significant variables for this response). Figure 19 is a compilation of various cross-sections from this surface, and shows slump plotted versus paste content for various w/c ratios. In these figures, the air dosage rate is held constant at the center point (126 mL/100 pounds of cementitious material). As can be seen in these figures, slump is expected to increase as a function of w/c ratio and paste content. The presence of these fairly intuitive relationships helps to confirm the validity of the response surface model.

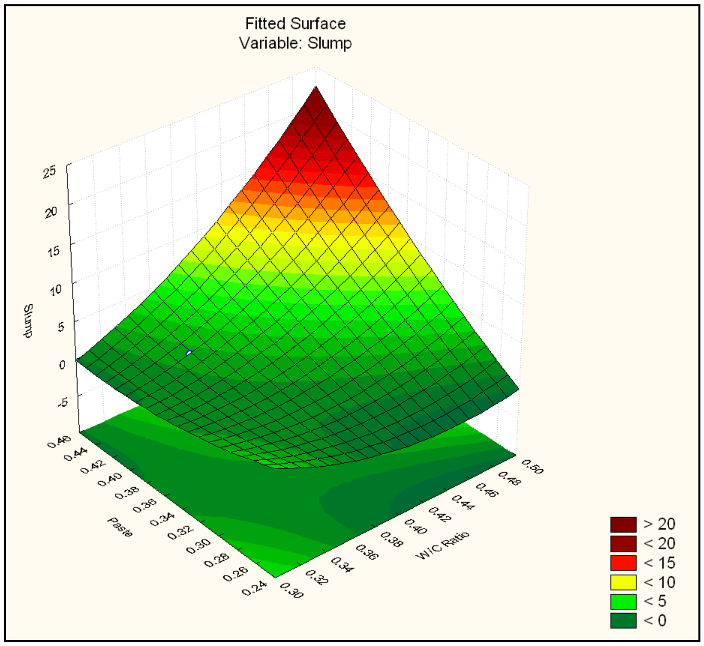


Figure 18: Response Surface for Slump vs. w/c ratio and Paste Content

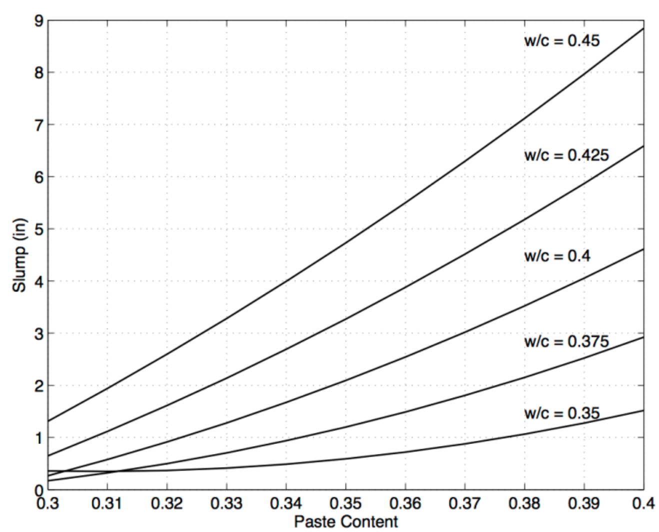


Figure 19: Slump vs. Paste Content for Various w/c Ratios

The air content response surface is shown in Figure 20 as a function of its most statistically significant variables: w/c ratio and air dosage rate, while several cross-sections of this response are shown in Figure 21. The paste volume is held at its center point in these figures (0.35). As is expected, the air content is projected to increase in a mixture with increasing air dosage and w/c ratio. However, the trend of increasing air content with increasing air dosage rate decreases with decreasing w/c ratio, indicating that the effect of the air entraining admixture is diminished with decreasing w/c ratios.

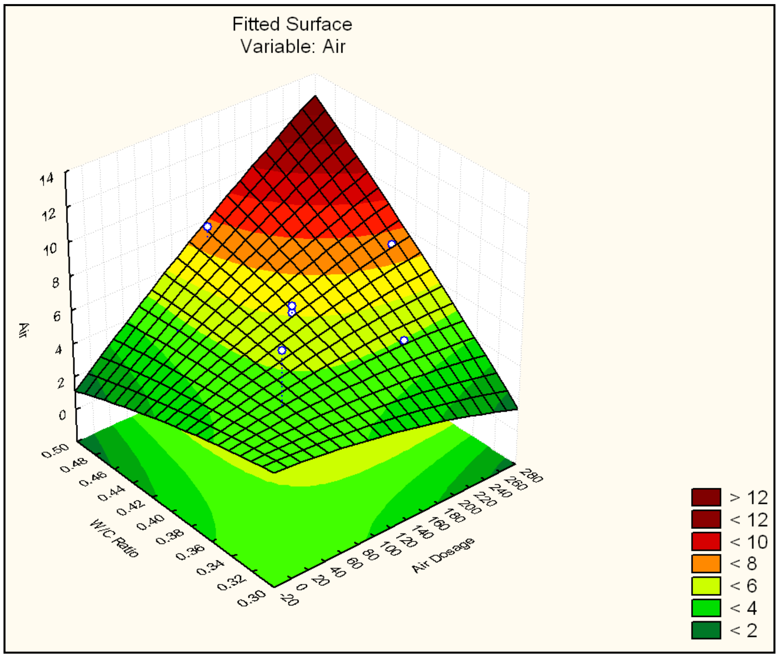


Figure 20: Response Surface for Air Content vs. w/c ratio and Air Dosage Rate

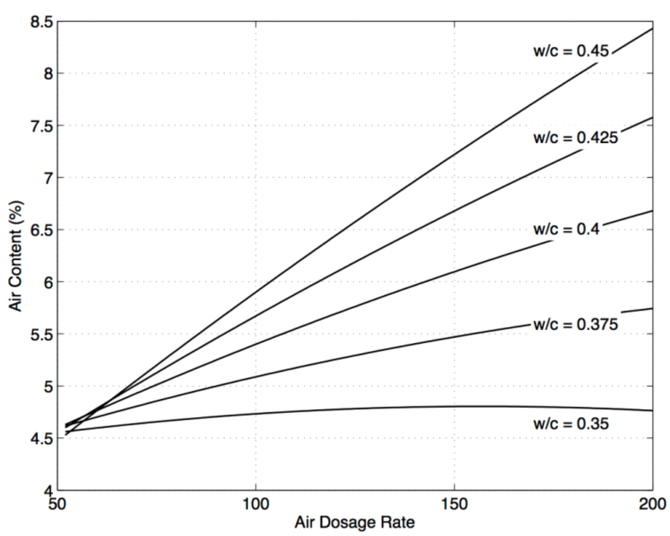


Figure 21: Air Content vs. Air Dosage Rate for Various w/c Ratios

Finally, the 7- and 28-day compressive strength response surfaces are plotted versus w/c ratio and paste volume in Figure 24 through Figure 25 (with an air dosage rate of 126 mL/100 pounds of cementitious material). As can be observed in these figures, the compressive strength of a mixture is expected to increase with decreasing w/c ratio. As for the effect of the paste content on strength, the compressive strength is predicted to increase as the paste volume is increased up to a point, and then hold steady or decrease slightly beyond this point. The trend of increasing strength with increasing paste content is consistent with what was observed in the preliminary mixes; however, the opposite trend has been observed in conventional concrete, i.e., decreased compressive strength with increasing paste content (Kolias & Georgiou, 2005). In conventional concrete, this trend has been attributed to the theory that cracks propagate more readily in high-paste mixes than in low-paste mixes (less aggregates in the path of the crack). For the RAP concrete, the trend of increasing strength with increasing paste content is postulated to be due to the fact that the RAP aggregates are significantly softer than the cement and conventional aggregates (due to residual asphalt). Therefore, the effect of the RAP aggregates would be similar to having voids within the concrete. Increasing the amount of paste (and therefore decreasing the amount of RAP) should positively affect the strength of the concrete to a point.

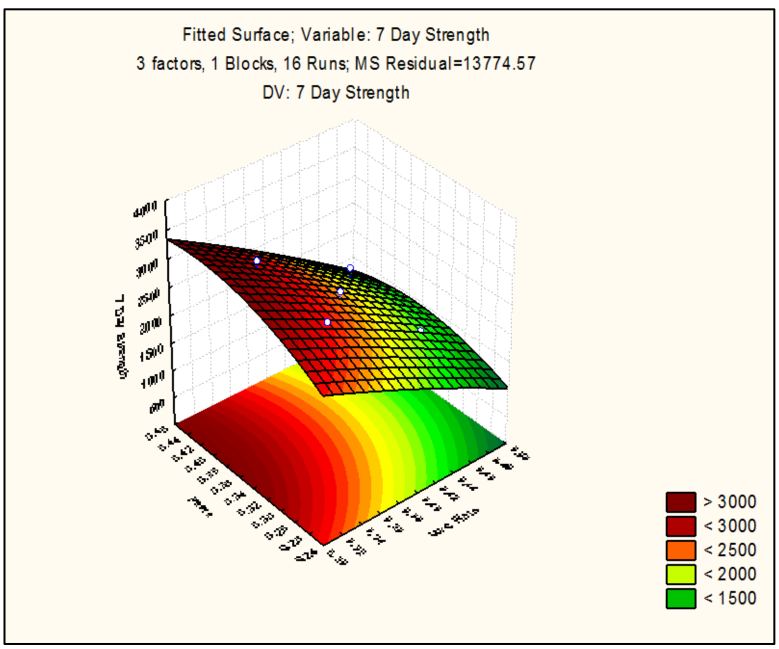


Figure 22: Response Surface for 7-Day Compressive Strength vs. w/c Ratio and Paste Content

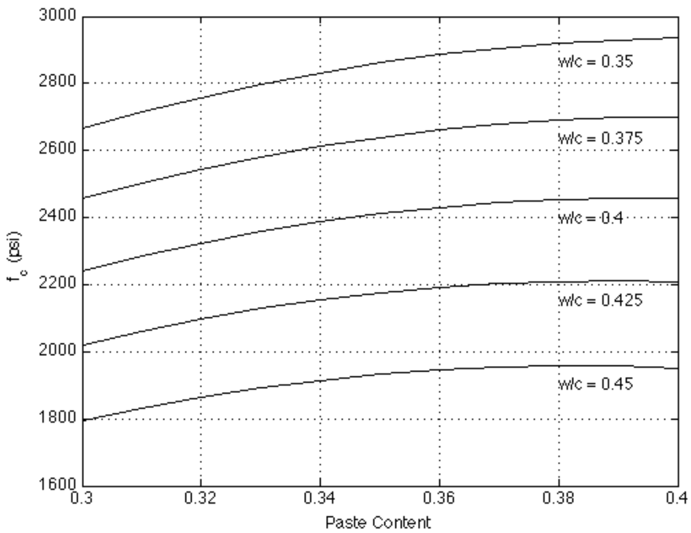


Figure 23: 7-Day Compressive Strength vs. Paste Content for Various w/c Ratios

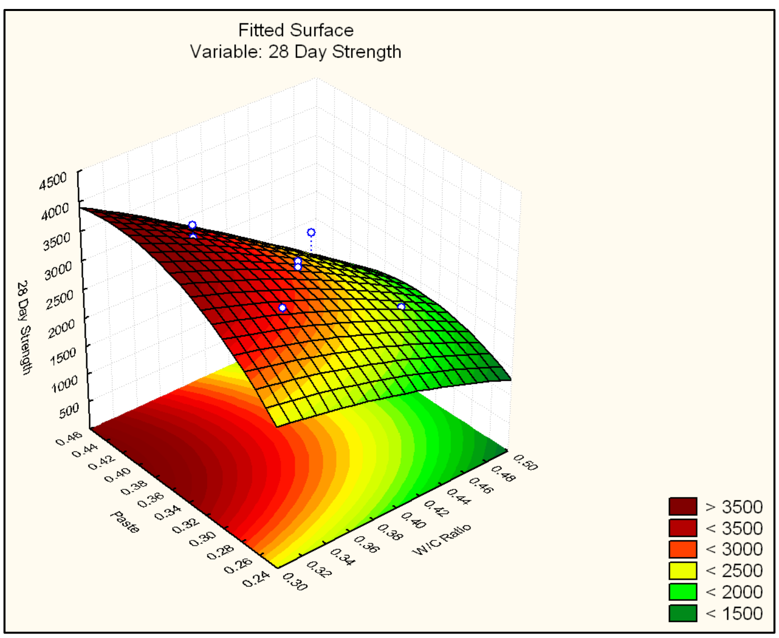


Figure 24: Response Surface for 28-Day Compressive Strength vs. w/c Ratio and Paste Content

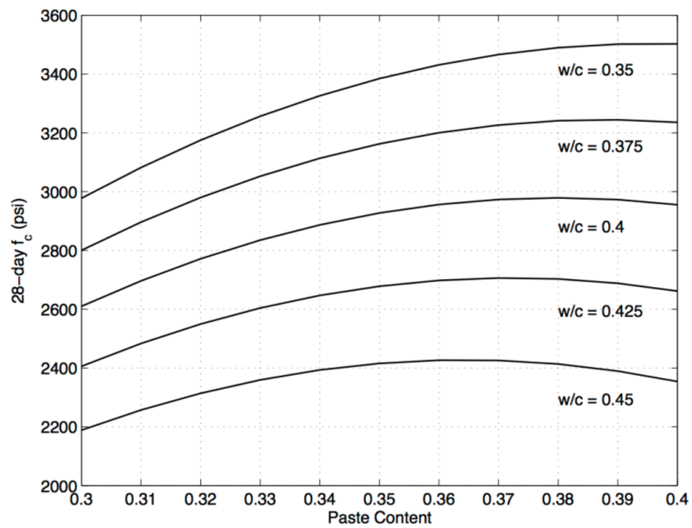


Figure 25: 28-Day Compressive Strength vs. Paste Content for Various w/c Ratios

The following section describes how these response surfaces were used to determine mix designs suitable for concrete pavement applications.

5 OPTIMIZATION AND SELECTION OF MIXES

In the previous chapter, response surfaces (second-order regression equations) were developed for slump, air content, and 28-day compressive strength, as functions of the independent variables: w/c ratio, paste content, and air entraining admixture dosage rate. These response surfaces quantify the effects that each independent variable has on a given response, as well as the significance of this effect. Thus, they can be used to obtain a "desirable" result, and often this "desirable" result may be a function of multiple responses. For example, MDT specifies a "desirable" concrete for pavements as having a 1.5-inch slump, air content of 6 percent, and a 28-day compressive strength of at least 3,000 psi.

To address this issue of obtaining target results for multiple responses, RSM analyses often use desirability functions, in which the analyst's priorities on the response values are built into the optimization procedure (Myers & Montgomery, 2002). The optimization procedure involves creating a desirability function for each response, and then using the geometric mean of these desirability functions to generate a single composite response (Myers & Montgomery, 2002). This approach was used in the initial CCD analysis (as described in Appendix A); however, a simpler and more robust approach was used in the follow-on CCD analysis. For a set of target responses, this simpler approach simultaneously solved the three response surface equations (presented in the previous chapter) for the three unknown independent variables. That is, the three response surface equations (for slump, air content, and 28-day compressive strength) were solved for the three independent variables (w/c ratio, paste volume, and air dosage rate) that would yield specified target response values. It should be noted that the response surfaces are nonlinear, and, therefore, multiple solutions may exist. However, during this analysis, only solutions within or near the prescribed region of interest were considered valid. It should also be noted that in cases where an exact solution does not exist, this methodology does not allow for compromise between target responses; whereas, the "desirability" method mentioned above allows for this compromise.

5.1 Mix Development and Trial Mixes

The approach described above was used in the follow-on study to develop three mixes with different target performance parameters. The first mix (Trial Mix 1) was developed by targeting MDT specified values for slump (1.5 inches), air content (6 percent), and minimum 28-day compressive strength (3,000 psi) for PCCP. To obtain this strength, the resulting mix was rich in cement, and would be expensive to produce. Therefore, a second mix (Trial Mix 2) was developed by targeting the same slump and air used for the first mix, but with a lesser compressive strength of 2,300 psi. A third mix (Trial Mix 3) was developed that targeted the maximum achievable strength for this concrete while staying within the prescribed limits of slump and air content. A summary of the resulting mixes obtained using the response surface equations developed in the follow-on CCD analysis are presented in Table 19 along with the predicted responses and their respective 95% confident intervals (CI).

As can be seen in Table 19, Trial Mix 1 had a w/c ratio of 0.386, a paste content of 0.346, and an air dosage rate of 180.3 mL/100 pounds of cementitious material. This mix is rich in cement (around 7.5 sacks per cubic yard), and would therefore be expensive to produce. Thus, as mentioned previously, Trial Mix 2 was developed to reduce the amount of cement by reducing the required strength of the concrete from 3,000 psi to 2,300 psi. Relative to Trial Mix 1, Trial Mix 2 had an increased w/c ratio (0.442) and a decreased paste volume (0.307). The total cement content of Trial Mix 2 was less than in Trial Mix 1 (6.1 versus 7.5 sacks per cubic yard, respectively). Trial Mix 3 was intended to maximize strength while staying within the limits for air and slump prescribed by MDT. For this mix, in order to maximize strength, the lower limits for slump (0.75 inches) and air content (5 percent) were targeted, while the strength was maximized. These targets yielded a mix with a w/c ratio of 0.34, a paste content of 0.42, and an air dosage rate of 253.3 mL/100 pounds of cement. This mix is consistent with general concrete knowledge: the w/c ratio was minimized to increase strength and the paste content was increased to maintain the required slump. This mix is just outside the prescribed region of interest for this RSM study. That is, the w/c ratio, paste content, and air dosage rate are just outside of the factorial low and factorial high points used in this study. Because of this, the 95 percent confidence intervals on the expected responses are significantly larger for this mix when compared to the other two mixes.

Table 19: Summary of Trial Mixes and Results

Variable/Response	Trial Mix 1		Trial Mix 2		Trial Mix 3		MDT Specifications	
w/c Ratio	0.386		0.442		0.34		-	
Paste Volume	0.346		0.307		0.42		-	
Air Dosage (mL/100#)	180.3		135.3		253.3		-	
	Predicted (95% CI)	Measured	Predicted (95% CI)	Measured	Predicted (95% CI)	Measured	Low	High
Slump (in)	1.5 (0.44 to 2.56)	1.0	1.50 (0.48 to 2.5)	0.75	0.75 (-2.4 to 3.9)	2.0	0.75	2.25
Air Content (%)	6 (4.0 to 8.0)	5.0	6.0 (4.12 to 7.9)	5.4	5.0 (-0.8 to 10.8)	5.1	5	7
7-Day fc (psi)	2437 (2261 to 2612)	2489	1880 (1713 to 2047)	1753	2720 (2202 to 3239)	2795	-	-
28-Day fc(psi)	3000 (2705 to 3320)	2949	2300 (1967 to 2633)	2269	3300 (2267 to 4331)	3279	3000	-

Once developed, these mixes were then carried out in the lab to verify their performance, as well as to verify the effectiveness of this mix design methodology. As can be seen in Table 19, overall, all measured responses were easily within the 95% confidence intervals and all responses were either within the limits or close to the limits prescribed by MDT (with the exception of 28-day strength for Trial Mix 2). In regards to Trial Mix 1, the measured slump was within 0.5 inches of the predicted slump, and the air content was within 1 percent. As for compressive strengths, the model accurately predicted both the 7- and 28-day compressive strengths, with both of these measured strengths within 2 percent of the predicted strengths. With respect to Trial Mix 2, the measured slump was within 0.75 inches of the targeted 1.5 inches; whereas, the air content was within 0.6 percent. This model again accurately predicted the 7- and 28-day compressive strengths: the 7-day measured strength was within 7 percent of the predicted strength, and the 28-day strength was within 2 percent. Trial Mix 3 had a slump of 2 inches, which is 1.25 inches higher than the predicted slump, but within the prescribed limits of the MDT specifications. The air content for this mix was only 0.1 percent higher than the predicted air content. The 7- and 28-day strengths were accurately predicted by the models: the predicted strengths were within 2.7 and 0.6 percent of the observed 7- and 28-day strengths, respectively.

It should be noted that the differences between the predicted and measured responses is attributed to both inaccuracies in the model as well as variability inherent in the testing methods.

Overall, the response surface models developed in this study accurately predicted the responses and served as an efficient tool for developing mix designs.

5.2 Selection of Mixes for Further Evaluation

Upon completion of the trial mixes discussed previously, the research team worked with MDT to select mixes for further evaluation. Trial Mix 1 was selected, despite being somewhat rich in cement, because it met all specified requirements including the minimum specified compressive strength of 3,000 psi. This strength was deemed necessary to ensure that the concrete had adequate mechanical and durability properties to be used as concrete pavement. Also, the decision was made to develop a higher-performance mixture with a strength of at least 4,000 psi. Trial Mix 3 described in the previous section was specifically pursued to create a mix with a maximum possible strength while complying with all other target performance parameters (i.e., slump of 1.5 inches, air content of 6 percent, and fine and coarse RAP replacement rates of 0.5 and 1.0, respectively). However, this mix only achieved a compressive strength of 3279 psi. Therefore, in pursuit of a higher strength mix, the decision was made to consider using one-half the RAP replacement rates used in Trial Mix 3, which is 0.25 and 0.50 for the fine and coarse RAP, respectively, with the expectation that this approach would yield higher compressive strengths. Based on the results of the initial CCD experiment, cutting the RAP replacement rates in half was expected to increase the strength by around 35 percent (see Figure 17), while not affecting the slump and air content. This mix was carried out in the lab and these expectations were verified. This mix had a slump of 0.75 inches, an air content of 5 percent, and a 28-day compressive strength of 4,089 psi (which corresponds to an increase of around 39 percent). Since this mix had all of the desired qualities, it too was selected as a mix for further evaluation.

For the remainder of this document, the selected mix with the full replacement rate of RAP (Trial Mix 1) will be referred to as the High RAP (HR) Mix, and the higher performance mix (with half the RAP) will be referred to as the High Strength (HS) mix. The basic performance of these two mixes is summarized in Table 20.

Table 20: High RAP vs. High Strength Mixes

Property/Response	High RAP (HR)	High Strength (HS)
W/C	0.386	0.386
Air Dosage Rate (mL/100# of cement)	180.3	180.3
Paste Content	0.346	0.346
Fine RAP Replacement Rate (% by volume)	50	25
Coarse RAP Replacement Rate (% by volume)	100	50
Slump (in)	1.00	1.00
Air Content (%)	5.00	5.00
7-Day Compressive Strength (psi)	2489	3588
28-Day Compressive Strength (psi)	2949	4194

6 MECHANICAL PROPERTIES OF SELECTED RAP MIXTURES

The two concrete mixtures developed in the previous chapter (HR and HS) were evaluated using a full suite of mechanical and durability tests to assess their potential for use as concrete pavements. This chapter reports on the results of the mechanical tests, while the following chapter reports the results of the durability tests. A summary of the mechanical properties tested in this research is provided in Table 21.

Multiple batches of both concrete mixtures were required to complete all of these tests, and although some variation was observed between mixes, this variation was not substantial. The mixtures evaluated in this, and the following chapter, are provided in Table 22, along with average slump, air content, and 28-day compressive strengths observed for each mixture over all batches. For some tests, a control mixture was used to provide a baseline for results. This control mixture, also provided in Table 22, was the same as the HR and HS mixtures, simply without the RAP aggregates.

Table 21: Mechanical Properties

Material Property	ASTM Test Method
Compressive Strength	C39
Elastic Modulus	C469
Splitting Tensile Strength	C496
Modulus of Rupture	C78
Shrinkage	C512
Creep	C512

Table 22: Mixes and Average Responses

Property/Response	High RAP (HR)	High Strength (HS)	Control
W/C	0.386	0.386	0.386
Air Dosage Rate (mL/100# of cement)	180.3	180.3	180.3
Paste Content	0.346	0.346	0.346
Fine RAP Replacement Rate (% by volume)	50	25	0
Coarse RAP Replacement Rate (% by volume)	100	50	0
Average Slump (in)	1.12	1.08	3.25
Average Air Content (%)	5.1%	5.5%	7.9%
Average 28-Day Compressive Strength (psi)	2888	4153	5434

6.1 Unconfined Compressive Strength, f'_c

An often cited and important property of hardened concrete is its unconfined compressive strength, which often is also indicative of many other material properties. Figure 26 shows the compressive strength profiles as a function of time for the HR, HS, and Control concretes over one year. These strengths were determined in accordance with ASTM C39, and were calculated as the averages of three 4-by-8 inch test cylinders. As can be seen in the figure, all concretes continued to gain strength over time and the rate of strength gain decreased with time, with all concretes reaching at least 96 percent of their one-year capacity at 182 days. Also, it can be seen that the inclusion of RAP significantly decreases the concrete compressive strength (as expected), with the HR and HS mixes only reaching 53 percent (3,730 vs. 7,031 psi) and 75 percent (5,238 vs. 7,031 psi) of the Control mix strength at one year, respectively.

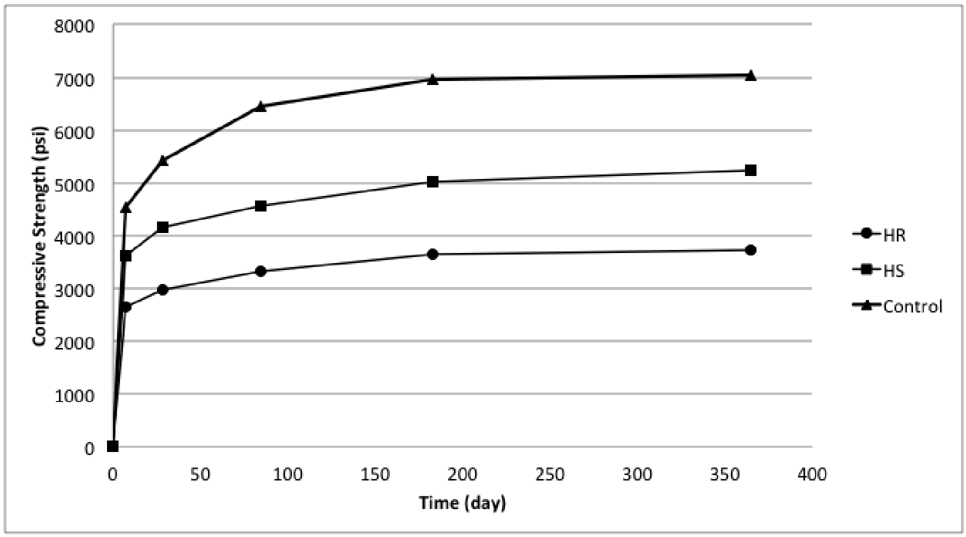


Figure 26: Unconfined Compressive Strength vs. Time for HR, HS, and Control Mixes

6.2 Elastic Modulus, E_c

The elastic modulus of each concrete was determined as the average of three tests on 6-by-12 inch cylinders tested in accordance to ASTM C469. The results for each concrete are provided in Table 23 and Figure 27. Also included in this table, for comparison, are the predicted values of the modulus according to ACI 318: $E_c = w_c{}^{1.5} 33\sqrt{f'_c}$. In this equation, E_c is the elastic modulus in psi, w_c is the unit weight of the concrete in pcf, and f'_c is the compressive strength of the concrete in psi.

Generally speaking, the elastic modulus of each concrete increased with time, as one would expect with increasing compressive strength. It is difficult to make comparisons between the elastic moduli of the different mixtures and hence isolate the effect of increasing RAP replacement rate since their compressive strengths varied significantly. However, the effect of including RAP can be isolated by comparing the measured and predicted moduli for each concrete. The ratio of measured-to-predicted moduli for each concrete is plotted in Figure 28. Referring to Figure 28, the inclusion of RAP clearly affected the elastic moduli of the concrete and the applicability of this ACI prediction. The ratio of measured-to-predicted moduli increased with decreasing replacement rate. For example, on the two extremes, the ACI methodology underestimated the elastic moduli for the Control mix (with no RAP) and significantly overestimated the elastic moduli for the HR mix (with 100 percent coarse replacement and 50 percent fine replacement).

Table 23: Elastic Modulus for HR, HS, and Control Mixes

Mix	Age	$f_c{}'$ (psi)	E_{Meas} (psi)	E_{Pred} (psi)	$\frac{E_{Meas}}{E_{Pred}}$
HR	7 days	2,716	2,231,330	2,774,335	0.80
	28 days	2,753	2,471,322	2,831,951	0.87
	84 days	3,325	2,530,368	3,123,822	0.81
	6 months	3,428	2,501,009	3,175,530	0.79
	1 year	3,493	2,981,765	3,210,472	0.93
HS	7 days	3,931	3,776,387	3,529,470	1.07
	28 days	4,159	3,826,675	3,693,560	1.04
	84 days	4,724	3,906,267	3,948,102	0.99
	6 months	5,167	4,462,776	4,138,397	1.08
	1 year	5,363	4,493,284	4,251,850	1.06
Control	7 days	4,527	4,079,332	3,366,240	1.21
	28 days	5,434	4,620,647	4,044,660	1.14
	84 days	6,443	4,918,332	4,455,103	1.10
	6 months	6,968	5,143,786	4,608,790	1.12
	1 year	7,031	5,331,025	4,618,817	1.15

Control

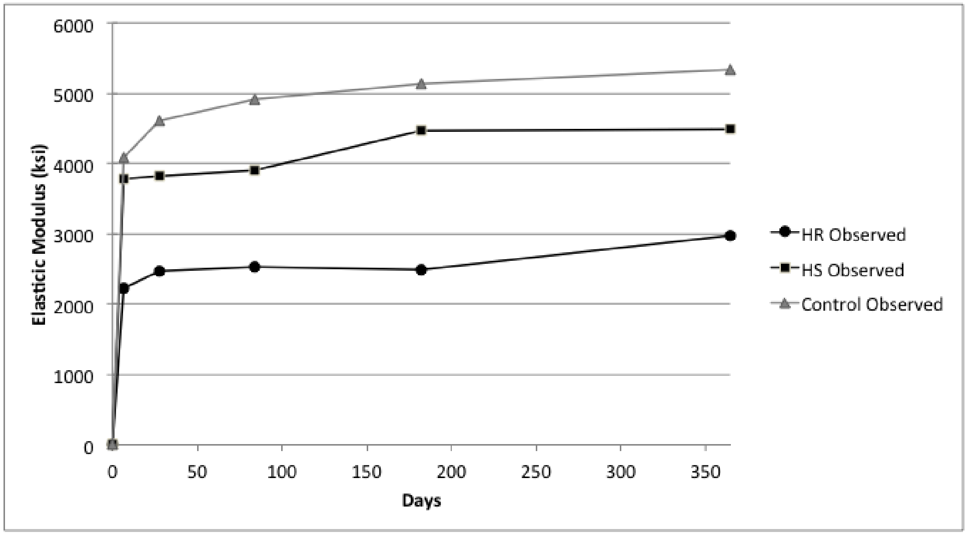


Figure 27: Elastic Modulus for the HR, HS, and Control Mixes

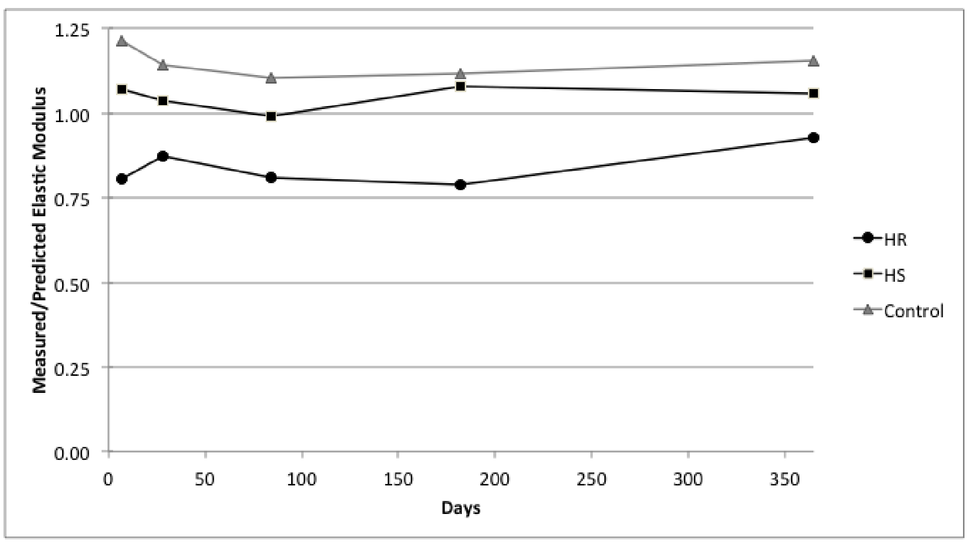


Figure 28: Measured/Predicted Elastic Modulus for HR, HS, and Control Mixes

6.3 Splitting Tensile Strength, f_{ct}

The splitting tensile strengths of the HR and HS mixes were tested by applying a diametral compressive force along the length of 6-by-12 inch concrete cylinders according to ASTM C496. The average compressive and tensile strengths of three cylinders for the two concrete mixtures are provided in Table 24 and Figure 29. As was done for elastic modulus, for comparison, the predicted splitting tensile strength is included in this table. These predicted strengths were calculated according to ACI 318 as $f_{ct} = 6.7\sqrt{f'_c}$ (f_{ct} and f'_c in psi).

Referring to Figure 29, as expected, both concretes continued to gain strength over time, at a decreasing rate. The HS concrete had a higher tensile capacity than the HR mix. In regards to the applicability of the ACI estimate for tensile capacity based on compressive strength, both concretes had tensile strengths significantly less than what is predicted by this ACI equation. To investigate this further, the ratios of measured-to-predicted splitting tensile strengths are plotted versus time in Figure 30. As can be seen in this figure, both mixes had measured-to-predicted ratios less than or equal to 0.75 at all ages. Also, the HR mix had ratios slightly less than the HS mix at all ages, indicating that the increased RAP content in the HR mix is having an increased negative impact on the tensile capacity of the concrete.

Table 24: Splitting Tensile Strength for HR and HS Mixes

Mix	Age	f_c'	f_{ct_Meas}	f_{ct_Pred}	$\frac{f_{ct\_Meas}}{f_{ct\_Pred}}$
HR	7 days	2601	191	342	0.56
	28 days	3196	217	379	0.57
	84 days	3298	262	385	0.68
	6 months	3871	259	417	0.62
	1 year	3966	297	422	0.70
HS	7 days	3293	218	384	0.57
	28 days	4171	284	433	0.66
	84 days	4417	330	445	0.74
	6 months	4858	311	467	0.67
	1 year	5113	363	479	0.76

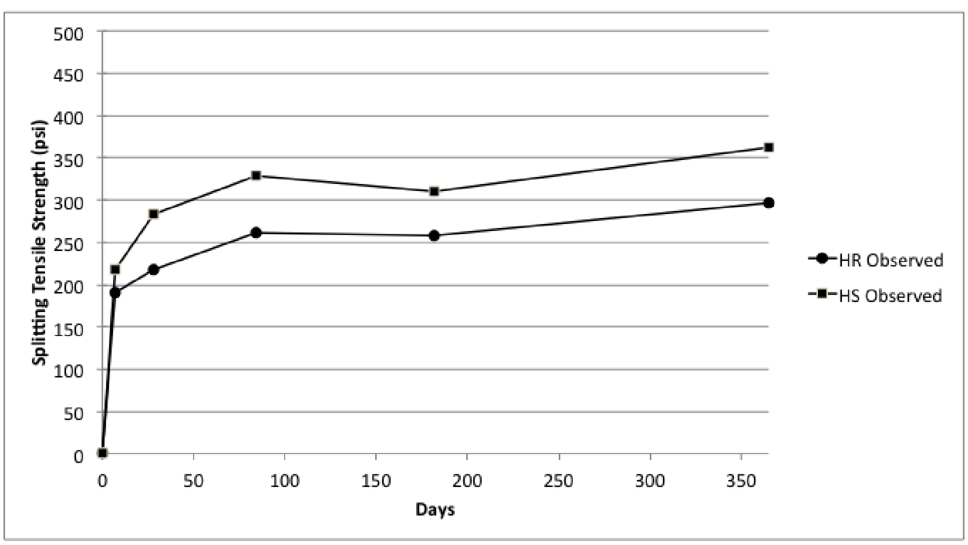


Figure 29: Splitting Tensile Strength for HR and HS Mixes

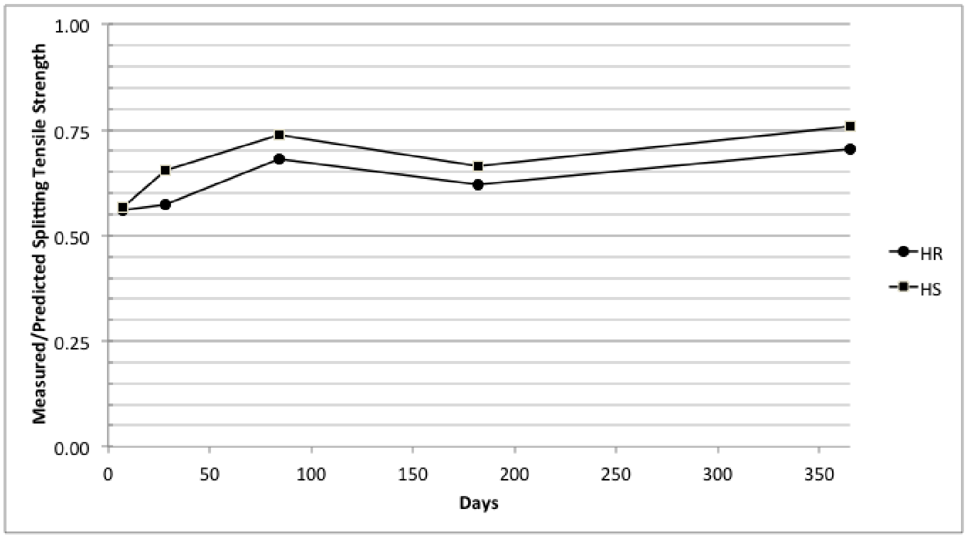


Figure 30: Measured/Predicted Splitting Tensile Strength for HR and HS Mixes

6.4 Modulus of Rupture, f_r

Modulus of rupture was calculated as the average of three 20-by-6-by-6 inch prisms tested according to ASTM C78. The measured data for both concrete mixes is provided in Table 25 and Figure 31. Table 25 also includes the strengths predicted by the ACI equation for modulus of rupture: $f_r = 7.5\sqrt{f'_c}$ (f_r and f'_c in psi). The modulus of rupture was also measured at 28 days for the control specimen, and this result is provided in Table 25.

As can be seen in this data, the HS mix had a higher tensile capacity than the HR mix at every stage. However, this is somewhat expected considering the increased compressive strength of the HS concrete and the strong relationship between compressive and tensile strengths. In comparison to the predicted rupture strengths, both concrete mixtures had rupture strengths greater than the estimated values at every time stage. The ratios of measured-to-predicted rupture strengths are plotted versus time for both concretes in Figure 32. As can be seen in this figure, the ratios of measured-to-predicted values are nearly identical for both concretes at every time stage. Furthermore, at 28 days this ratio is very close for all three concretes: 1.37, 1.34, and 1.44 for the HR, HS, and Control mix, respectively. The fact that this ratio is nearly the same for all mixes indicates that the inclusion of RAP does not significantly affect the tensile capacity of the concrete beyond its effect on compressive strength. The inaccuracy of the empirical predictions may be attributed to the fact that these concrete mixtures do not have typical mixture proportions (e.g., higher paste contents), and this empirical equation was derived for more conventional mixtures.

Table 25: Modulus of Rupture

Mix	Age	f'c	f_{r_Meas}	f_{r_Pred}	$\frac{f_{r\_Meas}}{f_{r\_Pred}}$
HR	7 days	2505	467	375	1.24
	28 days	2620	528	384	1.37
	84 days	3248	648	427	1.52
	6 months	3650	632	453	1.39
	1 year	3449	587	440	1.33
HS	7 days	3598	586	450	1.30
	28 days	4089	643	480	1.34
	84 days	4731	794	516	1.54
	6 months	5373	794	550	1.44
	1 year	5354	714	549	1.30
Control	28 days	5211	779	541	1.44

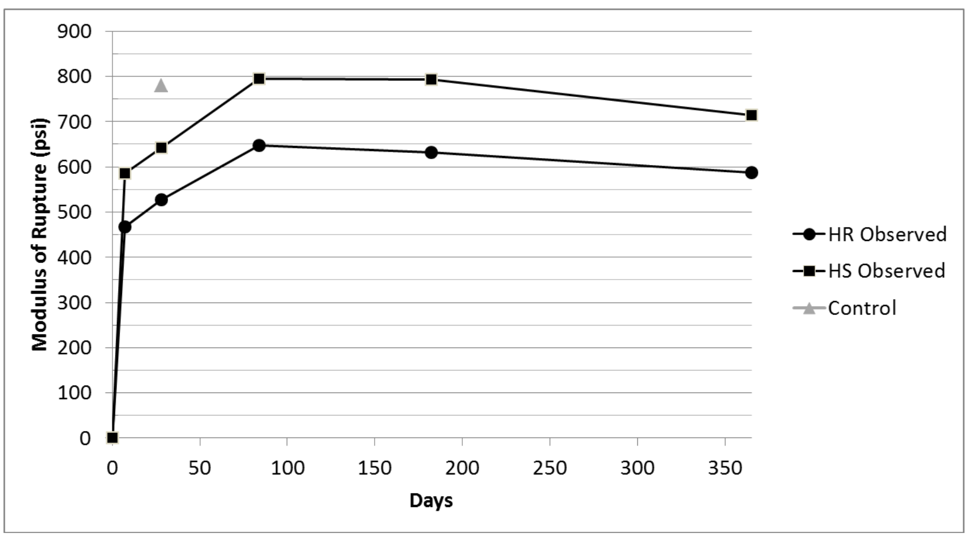


Figure 31: Modulus of Rupture for HR and HS Mixes

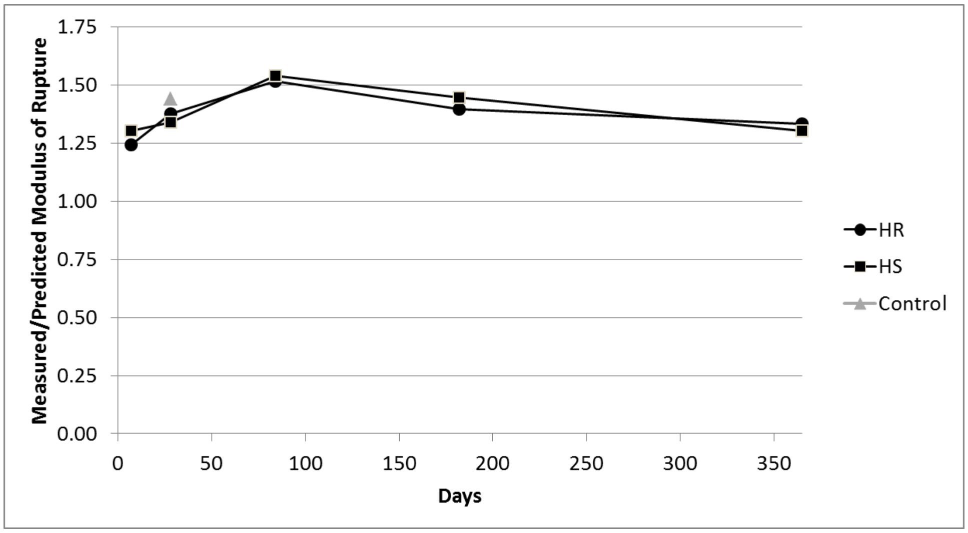


Figure 32: Measured/Predicted Modulus of Rupture for HR and HS Mixes

6.5 Creep and Shrinkage

Creep and shrinkage strains were measured in substantial accordance with the procedures outlined in ASTM C512. Three 6-by-12 inch cylinders were cast from both the HR and HS mix designs. All six cylinders were then moist cured for 28 days. Each cylinder was equipped with two vibrating wire strain gages to monitor deflections (Geokon Model 4000). Once cured, two cylinders from each mix were then placed into the creep frames (Figure 33) and loaded to 30 percent of their unconfined compressive strengths. A full description of the creep frames is provided in Appendix C. The remaining cylinders were placed next to the creep frames and shrinkage strains were monitored on these specimens. The creep strains for each concrete were calculated as the average strains monitored on each of the two cylinders minus the shrinkage strains obtained from the shrinkage specimens.

The measured creep strains and shrinkage strains over one year are provided in Figure 34 and Figure 35, respectively. As can be seen in these figures, the HR mix experienced more creep and had more shrinkage than the HS mix at every time step. In regards to relative magnitude between the creep and shrinkage strains, the creep strains were slightly larger than the shrinkage strains for both concretes at all time steps.

The creep coefficient, defined as the creep strain divided by the initial elastic strain, is often used as a dimensionless parameter for discussing the magnitude of creep response. The average elastic strains were 607 and 596 microstrain for the HR and HS mixes, respectively. This coefficient is plotted as a function of time for both concretes in Figure 36. As was seen for creep strains, the HR mix has a higher creep coefficient than the HS mix at every time step. At one year, the creep coefficients were 2.6 and 2.2 for the HR and HS mixes, respectively.

Figure 33: Creep Frame Loaded with Two Specimens

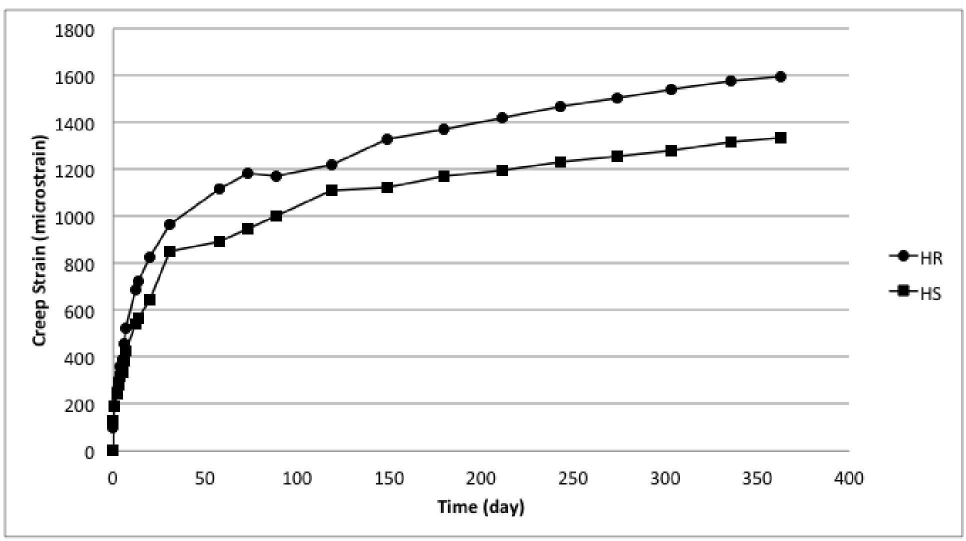


Figure 34: Creep Strain vs. Time for HR and HS Mixes

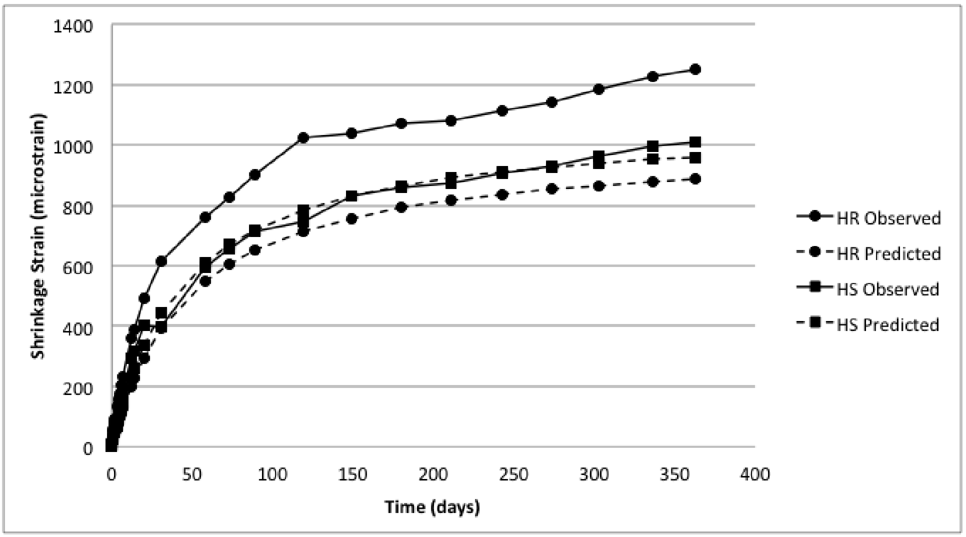


Figure 35: Shrinkage Strains vs. Time for HR and HS Mixes

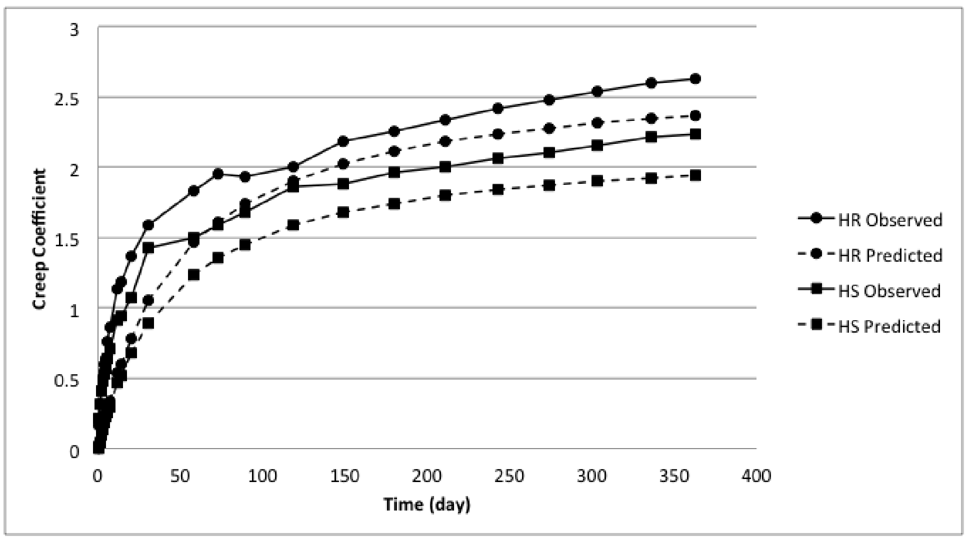


Figure 36: Creep Coefficient vs. Time for HR and HS Mixes

To serve as a point of comparison, the creep coefficient and the shrinkage strain were estimated using the methodology presented in the *AASHTO LRFD Bridge Design Specifications (Section 5.4.2.3)* and included in the figures above. The AASHTO creep coefficient (ψ) was calculated with the following equation.

$$\psi(t, t_i) = 1.9 k_{vs} k_{hc} k_f k_{td} t_i^{-0.118}$$

in which:

t = maturity of concrete (*days*)

t_i = age of concrete at time of load application (days)

k_s= factor for the effect of the volume-to-surface ratio $= 1.45 - 0.13\left(\frac{V}{S}\right) \geq 1.0$

k_{hc}= humidity factor for creep = $1.56 - 0.008H$

k_f = factor for the effect of concrete strength $= \frac{5}{1+f_{ci}'}$

k_{td} = time development factor $= \frac{t}{61-4f_{ci}'+t}$ (f_{ci}' in ksi)

where:

H = relative humidity (%)

f_{ci}' = specified compressive strength at the time of loading (ksi)

V/S is the volume-to-surface ratio (in.)

Similarly, the AASHTO approximation for shrinkage strain (ε_{sh}) was calculated with the following equation.

$$\varepsilon_{sh}(t) = -k_{vs} k_{hs} k_f k_{td} 0.48 * 10^{-3}$$

where:

k_{hs} = humidity factor for shrinkage $= 2.00 - 0.014H$

The relative humidity in the lab was H = 25%.

For comparison, the estimated shrinkage strains and estimated creep coefficients are provided in Figure 35 and Figure 36, respectively. Also, the ratios of measured-to-calculated shrinkage strains and creep coefficients are plotted versus time in Figure 37 and Figure 38, respectively, for both concretes.

The AASHTO methodology predicted the long-term shrinkage strains fairly accurately. The ratio of measured-to-calculated strains decreased from fairly large values the first couple of weeks to values at one year of around 1.41 and 1.05 for the HR and HS mixes, respectively. Shrinkage is a function, in part, of the compressive strength; thus one would expect higher-than-predicted shrinkage from the less resilient RAP mixes. By extension, it is not surprising that the HR mix had larger shrinkage strains than the HS mix and that the measured-to-calculated ratios would be higher for this concrete.

In regards to the estimated and measured creep coefficients, the measured creep coefficients exceeded the estimated coefficients at every time stage for both concretes. However, the predictions were fairly close to the measured coefficients at later stages. As was observed for the shrinkage strains, for both concretes the ratio of measured-to-calculated creep coefficients decreased from fairly large values early on, leveling off at values closer to 1.0 at later stages (~1.15 for both concretes). The fact that the AASHTO method underestimated the amount of creep in the specimens could be partially attributed to the residual asphalt in the RAP aggregates, as asphalt is known to be susceptible to creep. Furthermore, creep is more pronounced in concretes rich in paste, as was the case with both the HR and HS mixtures. The measured-to-calculated ratios for the HR and HS are nearly identical beyond the first week. This finding is somewhat surprising considering that the HR mix had twice the RAP as the HS mix.

With respect to the applicability of the AASHTO methodology for predicting creep and shrinkage, the trends observed in both Figure 37 and Figure 38 indicate that these methodologies are not very accurate at early ages. This finding may be contributed to the possible delay in curing associated with the inclusion of 15 percent fly ash. However, both methods proved to be adequate at predicting long-term creep and shrinkage.

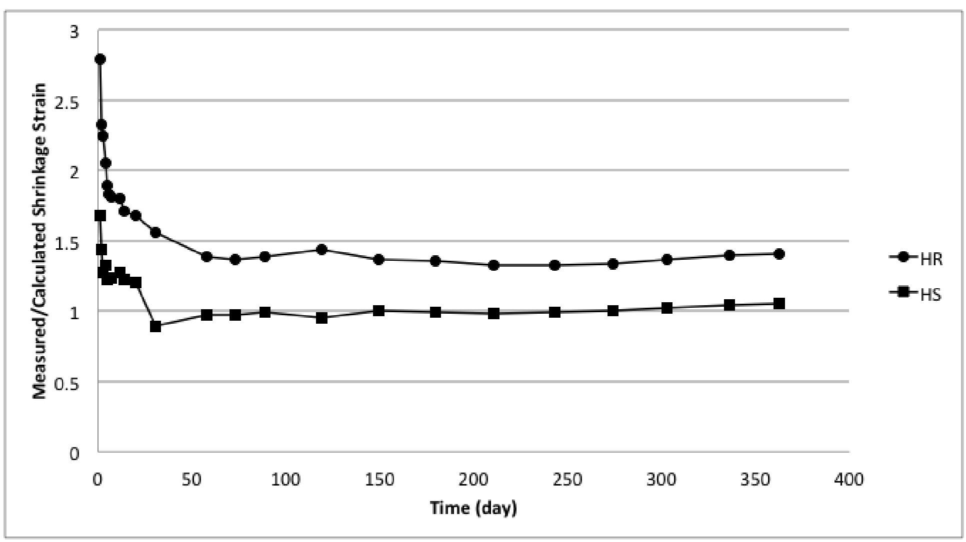


Figure 37: Measured/Calculated Shrinkage Strains for HR and HS Mixes

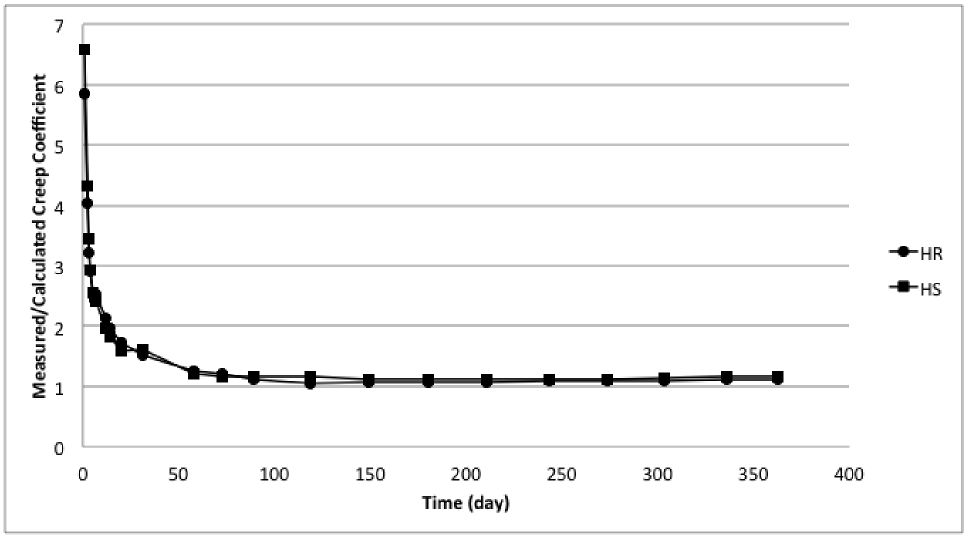


Figure 38: Measured/Calculated Creep Coefficients for HR and HS Mixes

7 DURABILITY OF SELECTED RAP MIXTURES

The durability properties of PCCP are of particular interest in Montana due to the harsh climatic conditions. In this research, several durability properties were evaluated for both the HR and HS mixes to determine the suitability of RAP aggregates in PCCP in Montana. The durability properties that were tested are listed in Table 26. The results of these tests are discussed in this chapter.

Table 26: Durability Properties

Durability Property	ASTM Test Method
Alkali Silica Reactivity	C1260
Absorption	C642
Abrasion	C944
Chloride Permeability	C1202
Freeze-Thaw	C666
Scaling	C672

7.1 Alkali Silica Reactivity

Alkali-silica reactivity of the RAP aggregate concrete was tested according to ASTM C1260. This test method was used because of its short duration and because it has been found to provide reliable and repeatable results. This method monitors the expansion of mortar bars which are submerged in an alkaline solution at 176°F for 14 days. According to this specification, for conventional concretes, expansion of less than 0.10 percent after 14 days of exposure is indicative of innocuous behavior, while expansion of more than 0.20 percent is indicative of potentially deleterious expansions. The HR mix was tested first, which revealed several issues with applying this methodology to concrete with RAP aggregates (discussed below). Because of these issues, the HS mix was not evaluated with this methodology.

The average expansion of three mortar bars constructed with the HR concrete is presented in Figure 39. Expansion exceeded 0.20 percent within the 14-day test period and indicates a need for further investigation. However, some observations made during testing may indicate that ASTM C1260 may be a poor indicator of ASR vulnerability for the RAP aggregates. The elevated temperatures used in this test (176°F) affected the bituminous material on the RAP aggregates. One indicator of this effect can be observed in Figure 40, where the bituminous material was stripped from the exterior of the mortar bars and formed a slick on the top of the solution. This elevated temperature may have also caused the interior RAP aggregates to expand and this expansion could have contributed to the expansion observed in the mortar bars. This finding is consistent with previous research on RAP aggregate concrete; Brand et al. (2012) noted similar issues while investigating ASR in RAP aggregate concrete. ASR effects on Portland cement concretes with RAP aggregates will require further investigation before any conclusive statements can be made.

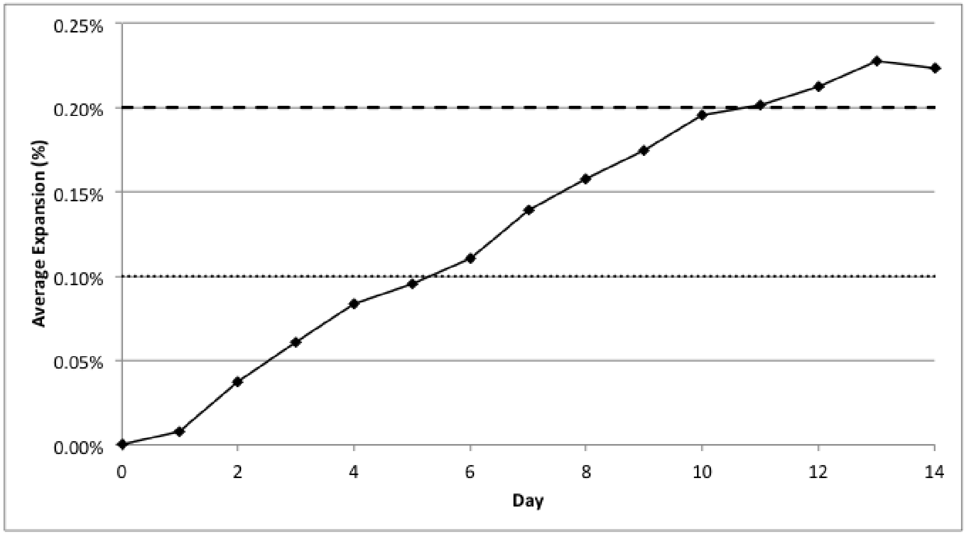


Figure 39: ASR Test Results for HR Mortar Bar

Figure 40: Suspended Asphalt in ASR Test

7.2 Absorption

Absorption is one of several methods used to gauge the permeability of concrete. Permeability can serve as an indicator of performance. For example, concrete with low permeability typically has an increased resistance to freeze-thaw cycles and to infiltration of deleterious substances. For this research, absorption was determined using ASTM C642 which estimates the total void volume of the test samples. Three 6-by-12 inch specimens from both the HR and HS mixes were tested.

The HR concrete was found to have an average void volume of 11.7 percent, while the HS mix had 12.0 percent. Relative to conventional Portland cement concrete pavements, a total void volume less than or equal to 12 percent will typically result in a durable concrete with respect to permeability (Fick, 2008).

7.3 Abrasion

The abrasion properties of the HR and HS mix designs were determined according to ASTM C944. Three samples from each mix were abraded using a 22-pound load applied to a 3¼-inch rotating cutter. The cutter was rotated at approximately 200 rpm for a duration of 2 minutes. The resulting average change in mass for each of the two mix designs are reported in Table 27, and both concretes had wear depths less than 1.0 mm. For reference, concretes with wear depths of less than 1.0 mm meet FHWA standards for Grade 2 high performance structural concrete (Goodspeed, Vanikar, & Cook, 2013). Both sets of samples performed well and warranted a further investigation using a doubled load (44 pounds). Again, there was very little weight loss and wear depth for either sample.

Table 27: Abrasion tests results

Concrete		Weight Loss	
Mix	Strength (psi)	22 Pound (g)	44 Pound (g)
HR	2716	0.3	1.0
HS	4194	0.3	0.9

Abrasion resistance is, in part, a function of compression strength, which in turn is influenced by aggregate toughness and paste content. Even though the fraction of RAP influenced compression strength, the fraction of RAP seemed to have little influence on the abrasion resistance. It is likely that the high paste content and low water-to-cement ratio present in both concretes are responsible for the similarity in their abrasion resistance.

7.4 Chloride Permeability

ASTM C1202 was used to determine the chloride permeability resistance of the RAP concretes. Three specimens were tested from each mix and the average values of chloride ion penetrability are reported in Table 28.

Table 28: Chloride permeability results

Mix	Age at Test (days)	Avg. Adj. Charge Passed (coulombs)	Chloride Ion Penetrability
HR	67	3644	Moderate
HS	62	3328	Moderate

Following ASTM C1202, these results correlate with "Moderate" likelihood of chloride ion penetration issues for both experimental mixes. Note that the average adjusted charge passed was slightly increased for the HR concrete. Thus, larger fractions of RAP seem to indicate a slight increase in the chloride ion penetrability.

7.5 Freeze-Thaw

A primary mechanism of physical deterioration of exposed concrete is prolonged exposure to cycles of freezing and thawing in the presence of moisture. This damage, which can occur at both a microscopic and macroscopic level, accumulates over time, eventually contributing to the failure of the concrete. The freezing-and-thawing resistance of the RAP concrete was quantified according to ASTM C666. This test method consists of subjecting concrete specimens to multiple freezing-and-thawing cycles while fully saturated. Weight loss and change in dynamic modulus are monitored as a function of accumulated freezing-and-thawing cycles. As may be obvious, the degree of damage sustained by the concrete due to microcracking and macrocracking under freezing-and-thawing action is reflected by its attendant loss of weight and stiffness, where material stiffness can be nondestructively measured in terms of dynamic modulus. The relative dynamic moduli were calculated from fundamental transverse frequency measurements (ASTM C215). The durability factor, DF, is used as one of the indicators of performance. The durability factor is defined as: $DF = PN/M$, where P is the relative dynamic modulus, and N and M, in this case, are the total number of cycles at which the exposure is to be terminated (300).

Multiple 3-by-4-by-16 inch rectangular prisms were cast from both the HR and HS mixtures. The specimens were exposed to several freeze-thaw cycles per day results are reported in Table 29. The relative dynamic moduli for both mixes are plotted in Figure 41 as a function of cycles.

Table 29: Freeze-thaw durability results

Mix	Number of Cycles	Avg. Mass Change (%)	Avg. Durability Factor
HR	300	0.90	94
HS	300	-0.25	98

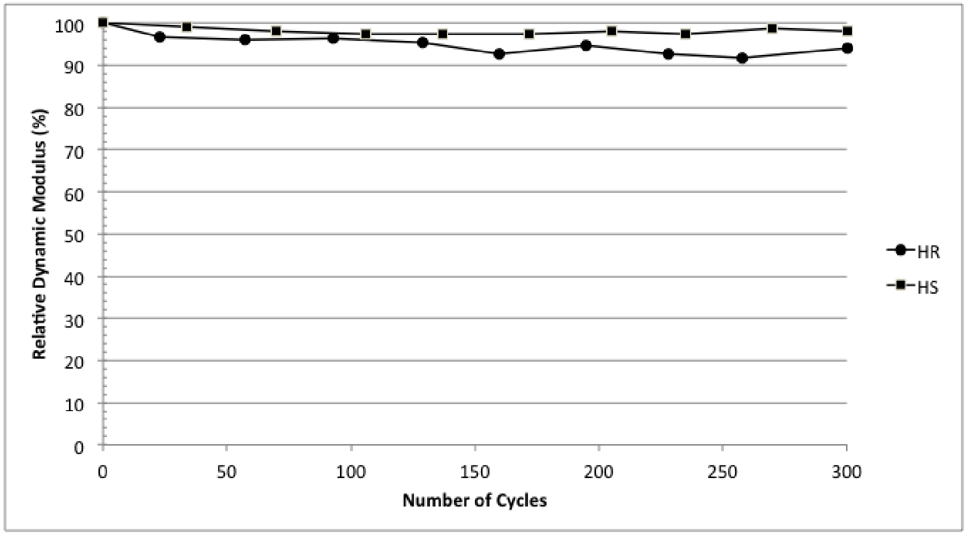


Figure 41: Relative Dynamic Modulus vs. Cycles

For the HR mix, at 300 cycles the average durability factor was 94, while the HS mix maintained an average durability factor of 98. For reference, a value of 100 corresponds to no loss of stiffness, with decreasing values corresponding to increasing deterioration; a relative dynamic modulus of 80% or greater after 300 cycles is often assumed to indicate good freezing-and-thawing resistance. With respect to the average mass change, both samples experienced less than a 1 percent change. The HR mix had a slightly smaller durability factor and a slightly higher mass loss than the HS mix, indicating that the RAP has a slight effect on the freeze-thaw resistance of the concrete.

7.6 Scaling

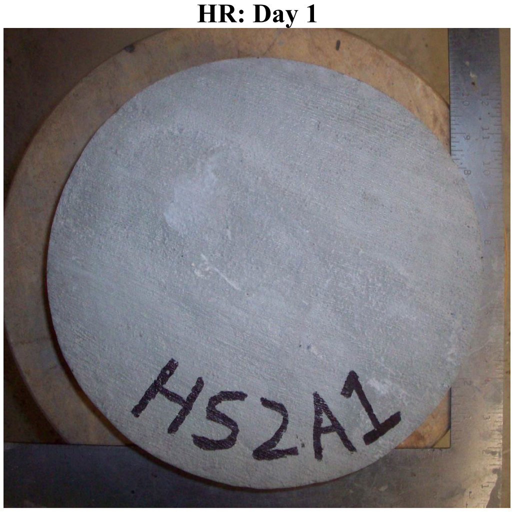
The resistance to scaling resulting from deicing chemicals was determined following the methods outlined in ASTM C672. One 6-by-12 inch cylinder was tested from both HR and HS concretes. The specimens were immersed in a 0.04 g/ml solution of CaCl for 25 freeze-thaw cycles and a visual evaluation of the scaling was conducted every 5 cycles. The numerical rating applied at each evaluation step was taken from ASTM; it ranges from 0, or “no scaling”, up to 5 which corresponds to “severe scaling” (where coarse aggregate is visible over the entire surface). The condition of each specimen is presented in Table 30, while the initial and final conditions of the cylinders are shown in Figure 42.

Table 30: Scaling Surface Condition

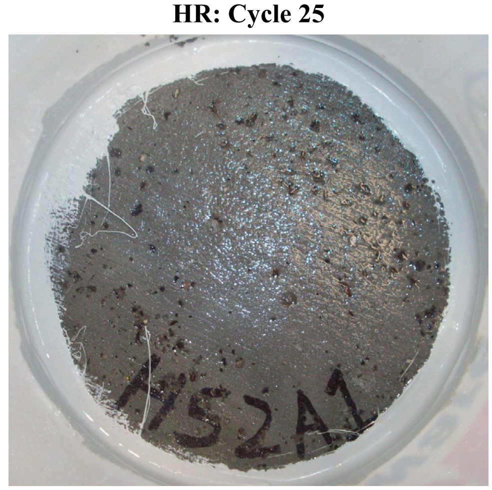
	Surface Condition	
Day	**HR**	**HS**
1	0	0
5	0	0
10	2	1
15	2	1
20	3	2
25	3	2

HR: Day 1

HR: Cycle 25



HS: Day 1



HS: Cycle 25

Figure 42: Scaling Surface Conditions

The HR concrete was “moderately susceptible” to scaling, while the HS mix fared somewhat better at “slightly susceptible.” As with many of the durability properties, the damaging effects of deicers increased with increasing amount of RAP aggregate.

8 SUMMARY AND CONCLUSIONS

This study focused on investigating the feasibility of using reclaimed asphalt pavement (RAP) as aggregate replacement in concrete pavements. In particular, this study considered using minimally processed RAP (i.e., no crushing or washing) in this capacity for roadways in the state of Montana. A statistical experimental design methodology (Response Surface Methodology -- RSM) was used to investigate proportioning concrete mixtures containing RAP aggregates to achieve desired performance characteristics. In the initial RSM investigation, the mix variables consisted of w/c ratio, paste volume, air entraining admixture dosage rate, and fine and coarse RAP replacement rates. Responses of interest were slump, entrained air content, 7- and 28-day compressive strength, and 28-day flexural strength. Target levels for these responses (consistent with MDT performance requirements for PCCP) were a slump of 1.5 inches, entrained air of 6 percent, compressive strengths of 2,000 and 3,000 psi at 7 and 28 days respectively, and flexural strength of 500 psi at 28 days. A series of preliminary trial mixes were performed to establish approximate ranges of interest for each of the mix variables. Notably in this regard, the decision was made to move forward with replacements rates of RAP of 0 to 50 percent for the fine aggregate, and 50 to 100 percent for the coarse aggregate. Thirty trial batches were then made to collect performance data for the initial RSM analysis. This analysis subsequently revealed the basic relationships between the mix variables and responses, and established the general feasibility of using RAP aggregate in PCCP.

The first RSM effort was purposefully broad in the range of variables considered and attendant responses observed, and based on its results, a second more focused RSM study was conducted more closely targeting the desired performance region (notably, a slump of 1.5 inches and air content of 6 percent, with the compromise of allowing compressive strength to simply vary). In this effort, three mix variables were considered, w/c ratio, paste volume, and air entraining admixture dosage rate. Sixteen trial batches were produced across the range of input variables to obtain data for the follow-on RSM analysis.

Two concrete mixtures were subsequently selected for further evaluation based on the RSM model that was developed: a high RAP mix (HR) and a high strength mix (HS). These mixtures were nearly identical with the exception of the RAP replacement rates. The HR mix, as its name implies, was selected to include a relatively large amount of RAP, with 50 percent of the fine and 100 percent of the coarse aggregate replaced with RAP. Similarly, the HS mix was selected to have a relatively high strength, and used half the amount of RAP included in the HR mix – only 25 percent of the fine and 50 percent of the coarse aggregate were replaced with RAP. While attractive relative to RAP use, the HR mix only had a 28-day compressive strength of around 3,000 psi, while the HS mix had a 28-day compressive strength of 4,000 psi. Note that both mixes had similar slumps (HR, 1.0 inches and HS, 0.75 inches) and entrained air contents (both 5.0 percent). Once developed, these two concrete mixtures were evaluated in a comprehensive suite of mechanical and durability tests to assess the potential of using these concretes in Montana roadways. The mechanical tests included: compressive and tensile strength, elastic modulus, shrinkage, and creep. The durability tests included: alkali-silica reactivity, absorption, abrasion, chloride permeability, freeze-thaw resistance, and scaling.

With respect to the mechanical properties, both mixes met all MDT specified requirements for both compressive (2,000 psi at 7 days and 3,000 psi at 28 days) and rupture strengths (500 psi at 28 days), and had adequate elastic moduli. Further, both mixes did not exhibit excessive deformations associated with creep or shrinkage. However, the amount of RAP aggregate included in the mixtures had an obvious impact on the mechanical properties. In terms of strength and stiffness, the control specimens (with no RAP) were significantly stronger and stiffer than the HR and HS mixes, and the HS mix (with half the RAP as the HR mix) was significantly stronger and stiffer than the HR mix. As for creep and shrinkage, the HS mix exhibited less deformation than the HR mix.

Relative to durability, both the HR and HS mixes demonstrated adequate performance for use in concrete pavements in Montana, with the HS mix generally outperforming the HR mix in all tests. Both concretes had void rates less than 12 percent, indicating adequate durability with respect to permeability. For abrasion resistance, the HR and HS mixes lost very little mass and had wear depths less than 1.0 mm. As for chloride permeability, both concretes were rated "Moderate" for likelihood of chloride ion penetration issues. In regards to freeze-thaw resistance, the HR and HS mixes had durability factors of 94 and 98 respectively, where a durability factor of 80 or more is indicative of acceptable freeze-thaw performance. The HR concrete was "moderately susceptible" to scaling, while the HS mix fared somewhat better at "slightly susceptible." As for ASR reactivity, test results indicated that the HR mix might have issues associated with ASR; however, the high temperatures at which this test is conducted could have influenced these results.

Based on the results from this study, the following conclusions can be made:

1) Response surface methodology is a useful and efficient tool for concrete mix development. Both the initial and follow-on experimental designs had resulting response surfaces that fit the data well and adequately characterized the behavior of the mixes. All response surfaces for both studies had R^2 values greater than 0.8, with most responses having R^2 values greater than 0.9. Furthermore, the effects of the independent variables predicted by the response surfaces were consistent with conventional concrete knowledge. In regards to the effectiveness of using RSM for mix optimization, the importance of selecting an appropriate region of interest for the target responses was highlighted by the initial experimental design. In this design, the response surfaces were not suitable for optimization -- for this study -- because the measured responses resulting from the selected region of interest were too far from the target responses. However,

insight on the mixture behavior gained through the initial RSM allowed researchers to select more refined independent variable ranges and perform a second experiment with a lessened scope. The follow-on experimental design with a modified region of interest was successfully used to develop three optimum mixes with varying degrees of performance. When carried out in the lab, these mixes performed as predicted. All measured responses were close to the predicted responses and all were within the respective 95 percent confidence intervals.

2) In regards to the feasibility of using RAP aggregates in concrete pavements, this research showed that both the HR and HS mixes had adequate mechanical properties and durability for use in concrete pavements in the state of Montana, with the HS mixture offering superior performance relative to the HR mixture. As seen in previous research, inclusion of RAP in concrete was found to generally have a negative impact on its mechanical and durability properties. This negative effect was postulated to be due to several aspects of the RAP aggregates. First, the asphalt coating on the aggregates prevented adequate bond between the cement and the aggregates. The fact that the RAP was unwashed may have compounded this issue. Another issue that was suspected to have a significant effect on concrete performance was the conglomerations of asphalt material and smaller aggregates found in the coarse RAP fraction. These conglomerations were much less stiff than the surrounding concrete matrix and, therefore, their effect would be similar to having large voids within the concrete. Furthermore, the inclusion of RAP had an effect on mix proportioning; it was found that the RAP aggregates may have significantly affected the accuracy of traditional techniques for accounting for aggregate moisture content. The moisture content of the RAP aggregates was difficult to determine on the day of mixing due to the high temperatures required in this procedure; this high temperature would melt the asphalt remaining in the RAP. The nature of the RAP aggregates compounded the issues of applying conventional moisture content techniques to RAP aggregate concrete.

This research demonstrated that concretes with up to 50 percent of the fine aggregates and 100 percent of the coarse aggregates replaced with minimally processed RAP were suitable for concrete pavements in the state of Montana. Research is currently being conducted to further develop the concretes discussed herein. Specifically, this follow on research effort is focused on: (1) reducing the cement content of the mixes by including water reducers, (2) studying the effect of including fibers, and (3) investigating constructability issues and field performance via a field demonstration project.

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APPENDIX A: INITIAL EXPERIMENTAL DESIGN AND ANALYSIS

This section presents a summary of the initial mix design development experiment. Although the response surface model produced in this study was not used for determining final concrete mixture proportions, information gained through this initial study was imperative to understanding the alternative concrete in question and developing a successful experiment design in the follow-on study presented in Chapter 4. More details on this initial study can be found in Bermel (2011).

In this initial work, the experimental design had five independent variables and six responses. A total of 32 mixes were carried out in the lab, and all responses were recorded. With this data collected, STATISTICA was used to analyze the data and fit regression surfaces for each response of interest. Analysis of variance (ANOVA) calculations were then used to determine the significant relationships and interactions between the five variables and six responses. With these surfaces defined, desirability functions were then used to optimize the mixture based on defined performance criteria (e.g., given slump, minimum strength). The mix designs resulting from these optimizations were then performed in the lab to evaluate the predictive capabilities of the response surface model. Although the models developed in this work were shown to fit the data well, when tested in the lab, the optimized mixes did not perform as predicted. This shortcoming was attributed the region of interest chosen in this study. The independent variable ranges were selected based off of some general observations of preliminary concrete mixtures containing RAP aggregates and engineering judgment of the research team gained through previous mix design studies. Unfortunately, the chosen region did not encompass and fully describe the behavior of the mixture in relation to the desired response values, resulting in observed responses that were too far from the target responses. For example, the target air content and slump were 6 percent and 1.5 inches, whereas the averaged observed responses in this study were 9.8 percent 4.75 inches. Therefore, the optimized mixes developed in this initial RSM would often be based on extrapolation of the models beyond the region of interest for the designed experiment. As one would expect, mixes based on extrapolation are less reliable than those developed within the region of interest. However, insight from the results of the first experiment allowed the research team to perform a more focused follow-on study with a modified region of interest that resulted in mixture responses that were closer to the targeted values.

While highlights from this study were provided in Chapter 4.3, this section provides more information/details on the study. Following the list of defined independent variables and ranges, the trial batches and their corresponding measured responses are presented. The resulting response surfaces derived from the results of the test batches are presented and evaluated. Finally, the procedure and results of the optimization study are provided.

A.1 Experimental Design

A.1.1 Independent Variables and Ranges

The five independent variables and ranges used in this study are provided in Table 31.

Table 31: Design Points for RAP in PCCP Experiment

Alpha = 2.0	Axial Low	Axial High	Factorial Low	Center	Factorial High
W/C Ratio	0.35	0.45	0.3750	0.4000	0.4250
Paste Volume	0.27	0.40	0.3025	0.3350	0.3675
Fine RAP Replacement	0.00	0.50	0.1250	0.2500	0.3750
Coarse RAP Replacement	0.25	1.00	0.4375	0.6250	0.8125
Air Dosage Rate (mL/100#)	50.0	250.0	100.0	150.0	200.0

A few additional fixed factors were also used to define the remaining unknowns and to characterize all of the mix specifications. These factors were developed based on experiences of the research team and are shown in Table 32.

Table 32: RAP in PCCP Fixed Factors and Values

Fixed Factor	Value
Coarse to Fine Aggregate Ratio	1.36
Mix Volume (ft^3)	2.9
Fly Ash Replacement Fraction	0.15

As mentioned in previous chapters, MDT has a number of specifications regarding the material properties of Portland cement concrete pavement. With the intent of creating a road-worthy product, the research team summarized and evaluated these specifications to determine the responses that would be measured and recorded for the RSM study. The responses of concern and their corresponding MDT specified values are listed in Table 33.

Table 33: RAP in PCCP Responses and Corresponding Specifications

Response	Specification
Slump	1.5±0.75 inches
Air Content	5 to 7 percent
7-Day Compressive Strength	Minimum of 2,000 psi
28-Day Compressive Strength	Minimum of 3,000 psi
28-Day Modulus of Rupture	Minimum of 500 psi
Environmental Factor	Maximize (increased RAP content)

Similar to the "cost" response that was considered in the FHWA study (Simon, 2003), an Environmental Factor was included in the RAP in PCCP experiment design. This Environmental Factor (EF) is a response that was defined to increase in value as the total RAP in the mixture increased. The Environmental Factor is defined by the following equation: *EF = Fine RAP Replacement Fraction + Coarse RAP Replacement Fraction* and ranged from 0.50 to 1.25 for the batch trials that were evaluated in the mixing experiment. Just as past research suggests, the inclusion of RAP in concrete degrades the material strength of the cured product, so when optimizing the RSM model for strength, the analysis would exclude all RAP unless the use of the alternative material was "rewarded" with the Environmental Factor. This mixture optimization process will be described in further detail in the following sections.

A.1.2 Trial Batches

The experiment design included 30 batch trials (see Table 34), consisting of 27 unique mixes and three replicate mixes. The alpha for rotatability was 2.0, and the batch trials and response data were set up as one block. The statistical analysis was conducted using STATISTICA. The five variables chosen to define the mixture were specified for each trial, which combined with the three fixed factors, provided the information necessary to proportion each trial batch. An example of the spreadsheet used to generate each of the mix proportions is provided in Appendix D, along with data collection sheets that were used in the lab. Data for each of the concrete batches had a designated mix ID. The first number in the mix ID identifies the order of the mixes as specified by the central composite design (CCD). The letter "C" designates the center points. The second number in the mix ID gives the order in which the mixes were actually performed. Carrying out the CCD test points in an unselective order reduces the overall effect of uncontrolled factors. For example, if the relative humidity systematically changed in the lab across the duration of the experiment, the overall impact of the relative humidity on the final result would be considered as a contribution to the general variability, rather than being seen as a trend in the data.

Table 34: Experiment Batch Trial Mix Specifications

Mix ID	w/c Ratio	Paste Volume	Fine RAP Replacement	Coarse RAP Replacement	Air Dosage (mL/100#)
17.1	0.350	0.3350	0.250	0.6250	150
18.2	0.450	0.3350	0.250	0.6250	150
30.3 (C)	0.400	0.3350	0.250	0.6250	150
25.4	0.400	0.3350	0.250	0.6250	50
3.5	0.375	0.3025	0.375	0.4375	100
28.6 (C)	0.400	0.3350	0.250	0.6250	150
1.7	0.375	0.3025	0.125	0.4375	200
26.8	0.400	0.3350	0.250	0.6250	250
27.9 (C)	0.400	0.3350	0.250	0.6250	150
8.10	0.375	0.3675	0.375	0.8125	100
22.11	0.400	0.3350	0.500	0.6250	150
11.12	0.425	0.3025	0.375	0.4375	200
2.13	0.375	0.3675	0.125	0.4375	100
19.14	0.400	0.2700	0.250	0.6250	150
12.15	0.425	0.3025	0.375	0.8125	100
4.16	0.375	0.3025	0.375	0.8125	200
15.17	0.425	0.3675	0.375	0.4375	100
29.18 (C)	0.400	0.3350	0.250	0.6250	150
24.19	0.400	0.3350	0.250	1.0000	150
21.20	0.400	0.3350	0.000	0.6250	150
6.21	0.375	0.3675	0.125	0.8125	200
7.22	0.375	0.3675	0.375	0.4375	200
10.23	0.425	0.3025	0.125	0.8125	200
23.24	0.400	0.3350	0.250	0.2500	150
9.25	0.425	0.3025	0.125	0.4375	100
20.26	0.400	0.4000	0.250	0.6250	150
14.27	0.425	0.3675	0.125	0.8125	100
16.28	0.425	0.3675	0.375	0.8125	200
13.29	0.425	0.3675	0.125	0.4375	200
2.30	0.375	0.3025	0.125	0.8125	100

On average, each mix was approximately 2.9-ft^3 in volume and contained about 158-lbs of coarse aggregate, 117-lbs of fine aggregate, 71-lbs of Portland cement, 13-lbs of fly ash, 37-lbs of water, and 107-mL of MicroAir. Examples of the typical material quantities are shown in Figure 43 and Figure 44. Photos of the RAP PCCP in the plastic state are shown in Figure 45 and Figure 46.

Figure 43: Typical Aggregate Quantities

Figure 44: Typical Cementitious Material and Water Quantities

Figure 45: RAP PCCP in Mixer

Figure 46: Typical Mix in Plastic State

A number of techniques and tools were applied to speed up the batch mixing process and complete the sample set of 30 trials in a relatively short period of time. Plastic cylinder molds (shown in Figure 47) were used in-place of the more traditional steel molds to reduce the required mold preparation time. Consolidation of the test specimens by external vibration also accelerated the specimen casting process.

Figure 47: Plastic Cylinder Molds

A.1.3 RAP in PCCP Response Testing

As previously noted, a number of response factors were chosen to characterize the mixture behavior of concrete containing RAP replacement aggregates. Air content and slump tests were performed, and ten 4-by-8-inch cylinders and two 6-by-6-by-20-inch rupture beams were cast. Three cylinders were tested in compression at 1, 7, and 28-days. The rupture beams were tested using the three-point loading method on 28-days. The break data was averaged for each testing day. All specimens were tested using MSU’s Test Mark Compression Testing Machine.

A summary of the test data from the 30 batch trials is presented in Table 35; complete data for each batch trial is presented in Table 36. It should be noted that the 1-day compressive strength of the material was not used in the final analysis, as this value is not an industry standard.

Table 35: Response Statistics for Initial Experimental Design

Response	Observed Range	Observed Average	R^2	Statistically Significant Variables
Slump (inches)	3/16 to 8.5	4.75	0.86	w/c, paste content
Air Content (%)	3.80 to 13.50	9.84	0.90	w/c, paste, air dosage
7-Day Compressive Strength (psi)	1440 to 3559	2131	0.93	w/c, coarse RAP, air dosage
28-Day Compressive Strength (psi)	1722 to 4282	2623	0.92	w/c, fine RAP, coarse RAP, air dosage
28-Day Rupture Strength (psi)	391 to 870	541	0.90	w/c, air dosage

Table 36: Complete Response Data for 30 Batch Trials

Mix ID	Slump (inches)	Air Content (%)	1-Day *fc* (psi)	7-Day *fc* (psi)	28-Day *f'c* (psi)	28-Day MOR (psi)	Estimated 28-Day MOR 7.5√(*f'c*) (psi)	Environmental Factor
17.1	0.1875	3.8	1274	3559	4282	870	491	0.8750
18.2	7.7500	13.0	658	1440	1823	444	320	0.8750
30.3	6.0000	13.0	475	1529	2154	487	348	0.8750
25.4	5.8750	6.8	1239	2609	3246	652	427	0.8750
3.5	2.6250	7.2	934	2524	3193	608	424	0.8125
28.6	4.2500	10.0	605	1986	2585	461	381	0.8750
1.7	1.2500	6.2	770	3268	3660	685	454	0.5625
26.8	4.7500	13.0	518	1562	1927	450	329	0.8750
27.9	5.1250	12.0	485	1940	2339	525	363	0.8750
8.10	4.0625	6.8	1140	2297	2876	564	402	1.1875
22.11	3.7500	8.5	875	1937	2318	450	361	1.1250
11.12	5.0000	12.0	466	1664	1879	424	325	0.8125
2.13	5.3750	9.5	998	2815	3335	639	433	0.5625
19.14	5.3750	9.5	1054	2339	2971	565	409	0.8750
12.15	2.1250	8.0	990	1988	2431	531	370	1.1875
4.16	1.1250	6.6	1218	2283	2639	541	385	1.1875
15.17	8.5000	10.0	730	2130	2362	538	365	0.8125
29.18	5.2500	12.0	922	1843	2213	505	353	0.8750
24.19	5.3750	13.0	782	1480	1795	470	318	1.2500
21.20	4.1250	11.0	749	2020	2579	510	381	0.6250
6.21	6.3750	12.5	949	1798	2178	516	350	0.9375
7.22	6.0000	10.5	1113	2072	2592	533	382	0.8125
10.23	5.1250	12.5	786	1472	1809	391	319	0.9375
23.24	4.5000	10.0	1152	2412	3150	607	421	0.5000
9.25	3.2500	8.0	1298	2578	3209	476	425	0.5625
20.26	7.500	10.0	1338	2252	2833	549	399	0.8750
14.27	7.1250	9.5	891	2130	2555	498	379	0.9375
16.28	7.1250	13.5	678	1516	1722	403	311	1.1875
13.29	8.1250	11.5	858	1722	2622	606	384	0.5625
2.30	0.7500	5.3	883	2772	3420	716	439	0.9375

A.2 Analysis of Response Surfaces

A.2.1 Defining Significant Relationships

The following figures display Pareto charts for each of the measured responses, output by STATISTICA. A key for interpreting the y-axis labels of these Pareto charts is provided in Table 37. In these charts, each of the independent variables, as well as combinations of variables showing potential interactions, are plotted in descending order of statistical significance. As mentioned earlier, ANOVA calculations are used to determine which variables have the largest impact on each response, and these independent variables are determined "significant" if their p-value is less than 0.05. The p-value is a measure of the consistency between the response data that was collected in the laboratory testing phase and the chance that the same data would be randomly generated independently of the tests. The analysis considers both linear and quadratic relationships, and these are denoted in the charts that follow. It should be noted that no statistically significant interaction effects were found between the input variables for any of the six measured responses.

A Pareto chart for the slump response is shown in Figure 48. As can be seen in this figure, a linear relationship exists between slump, the water-cement ratio, and paste volume of the mixture. These main effects, also known as relationships, are generally in line with common concrete knowledge and provide a good "check" for the RSM analysis.

Table 37: Key for Pareto Charts

y-Axis Label	Interpretation
(L)	Implies linear relationship with independent variable listed on y-axis
(Q)	Implies quadratic relationship with independent variable listed on y-axis
(1)	Independent Variable (1) = w/c Ratio
(2)	Independent Variable (2) = Paste Volume
(3)	Independent Variable (3) = Fine RAP Replacement
(4)	Independent Variable (4) = Coarse RAP Replacement
(5)	Independent Variable (5) = Air Dosage Rate (mL/100#)
2Lby3L	Indicates a linear interaction with independent variables (2) and (3)

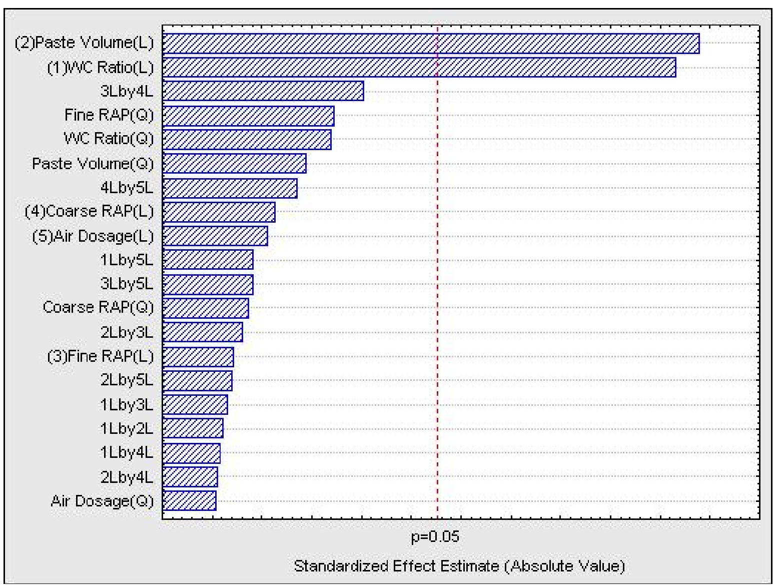


Figure 48: Pareto Chart for Slump Response

The Pareto chart for the measured air content of the RAP in PCCP mixes is provided in Figure 49. As can be seen in this figure, the statistically significant factors include a linear relationship with the water-cement ratio, air-entraining admixture dosage rate, and paste volume; and a quadratic relationship with the water-cement ratio. As previously mentioned, both the linear and quadratic relationships are evaluated, and occasionally the lack of fit test indicates that both the linear and quadratic relationships for a single variable are significant (as seen with the water-cement ratio for the air content response). This result implies that the behavior actually is more complex than can be modeled with either relationship individually, with portions of the relationship matching the linear fit and other regions being best described by the quadratic regression.

The next Pareto chart shown in Figure 50 provides the significant relationships for the 7-day compressive strength of the concrete. As expected, the RAP has a statistically significant effect on the strength of the final product. Other important relationships include water-cement ratio and air-entraining admixture dosage rate.

The Pareto chart for the 28-day compressive strength of the RAP in PCCP material is shown in Figure 51. Similar to the 7-day strength data, the water-cement ratio, air dosage, and coarse RAP replacement rate all have a notable impact on the 28-day strength of the concrete; however it should also be noted that a linear relationship with the fine RAP replacement rate was found to be important as well, whereas this relationship was not present for the 7-day strength. This finding implies that the fine RAP content has implications on the 28-day strength of the material, where this same factor does not impact the early strength as much. This result also confirms some of the behaviors noted during the preliminary mixes that were performed prior to the initial RSM analysis.

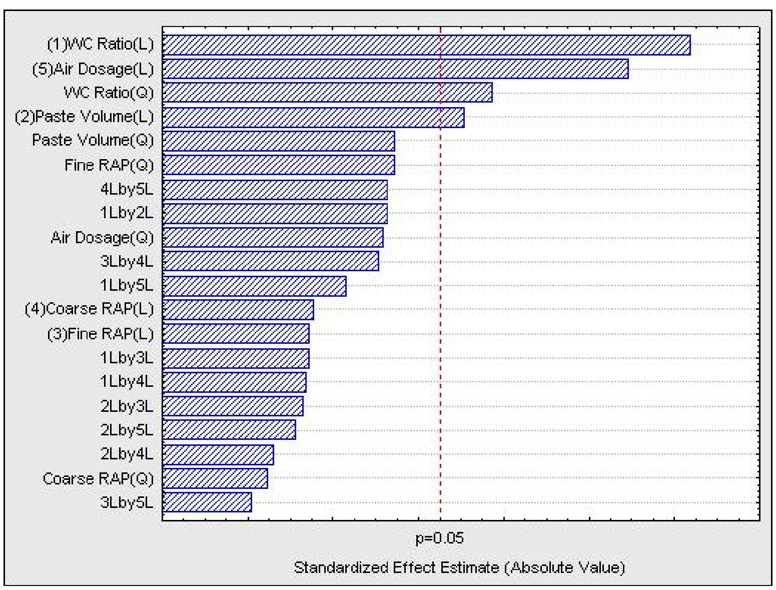


Figure 49: Pareto Chart for Air Content Response

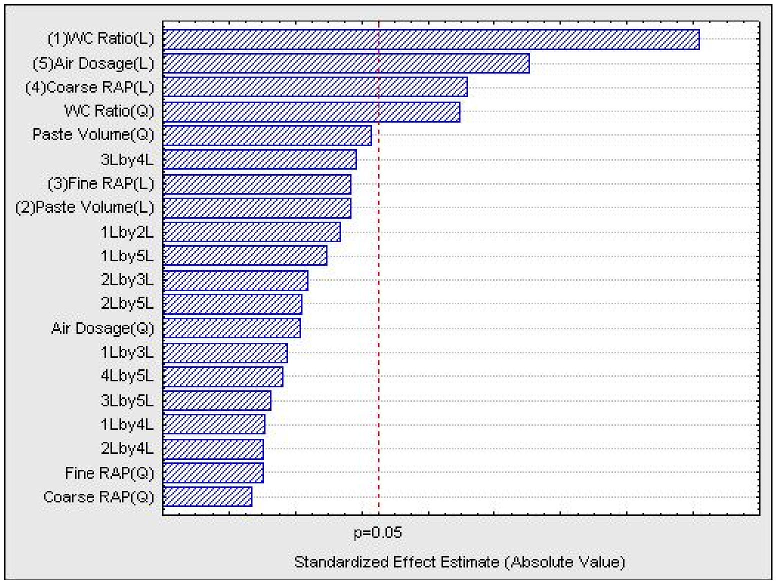


Figure 50: Pareto Chart for 7-Day Compressive Strength Response

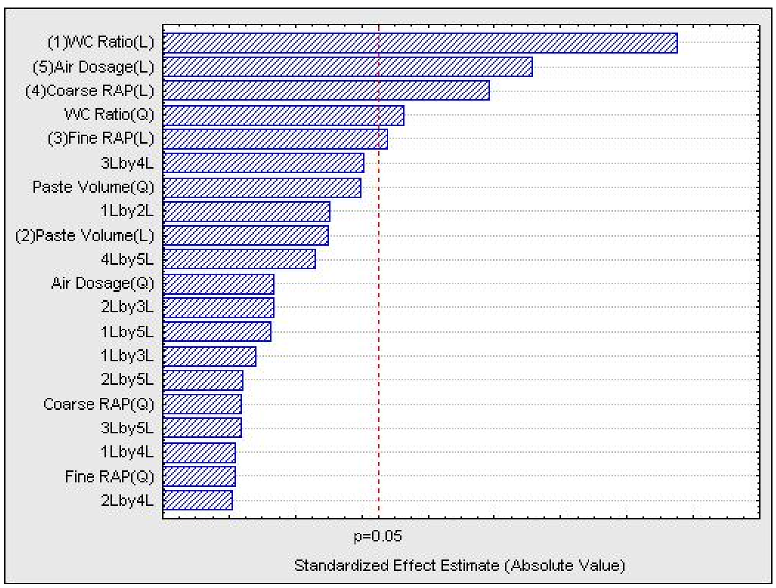


Figure 51: Pareto Chart for 28-Day Compressive Strength Response

The Pareto chart for the 28-day flexural strength (modulus of rupture) of the concrete is shown in Figure 52. Here the significant independent variables are water cement ratio and air dosage. As previously mentioned, the modulus of rupture values for the RAP in PCCP were consistently higher than the values given by the empirical equation $7.5\sqrt{f'c}$ for standard Portland cement concrete. However, despite this observation, the model did not pick up on any significant relationships between the flexural tensile strength and the coarse or fine RAP replacement rates (i.e., it might be expected that flexural strength would increase proportionately with the RAP replacement rates).

This result could imply that the baseline inclusion of RAP alone increases the tensile strength of the material, and that this increase is then relatively insensitive to the specific level of replacement. Note that the minimum RAP replacement rate (coarse plus fine) across each of the batch trials considered herein was 0.5.

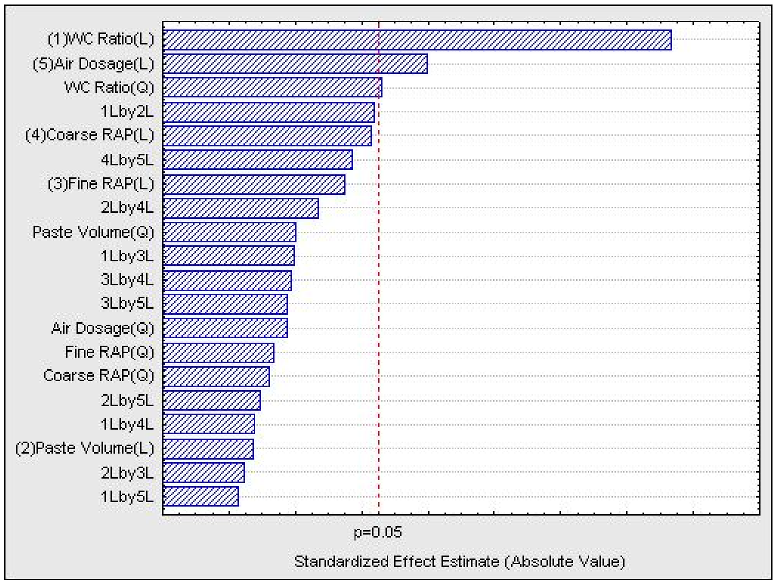


Figure 52: Pareto Chart for 28-Day Rupture Strength Response

A Pareto chart is not provided for the Environmental Factor because, as previously mentioned, this was an arbitrary response input into the model for mix design optimization purposes; thus there is no variability present in the Environmental Factor relationships. The Environmental Factor is based on a linear relationship with the fine and coarse RAP (described in Chapter 6), and the “recorded” values from the mix testing fits the response curve generated through the statistical model perfectly. P-value calculations are based on variability, and in the absence of uncertainty, this data representation is inappropriate. However, the model’s ability to confirm the artificial relationship created for the Environmental Factor proved to be another good verification test for the RSM analysis.

A.2.2 Plots of Response Surfaces

To evaluate the resulting response surfaces and observe the effect of the significant variables, subsets of the surfaces are presented in this section. The response surfaces are nonlinear quadratic functions with 5 independent variables; therefore, they are difficult to visualize. However, subsets of these surfaces can be plotted versus two independent variables if all other variables are held constant. In this section, the response surfaces for each response are plotted versus the two independent variables found to be most significant. In these plots, the other parameters are held constant at the center point of the region of interest. Scatter plots of predicted versus observed responses are also included for each response to evaluate the goodness of fit of the response surfaces.

Figure 53 shows the surface plot for slump, as a function of the two variables that were determined to have the most significant relationship with this response: paste volume and water-cement ratio. As can be seen in the figure, the model predicts that the slump of the concrete mixture will increase with increasing paste volume and water-cement ratio. The presence of these fairly intuitive relationships helps to confirm the validity of the mathematical model. It should also be noted that the surface of this plot is relatively steep, implying that a slight change in water-cement ratio or paste volume could cause a drastic change in the measured slump value.

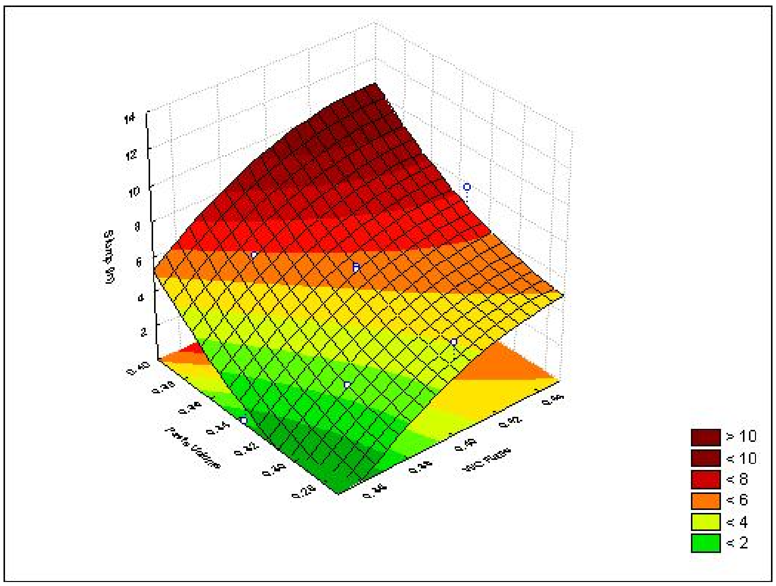


Figure 53: Slump vs. Paste Volume and Water-Cement Ratio

The white dots shown in Figure 53, represent the measured slump values that were recorded from the batch trials (due to the orientation of the surface, not all of the test points are visible in this plot).

Figure 54 shows the predicted slump values for each batch mix versus the observed laboratory test values. Included in this plot is line $y=x$; points above this line indicate the RSM model overestimated the slump, whereas points below this line indicate that the model underestimated the slump. This plot provides a visual representation of the variability (scatter) in the slump predictions. It should be noted that this scatter can be attributed to both inaccuracies in the model (epistemic uncertainty) as well as the scatter in the measured data from which the model was created (aleatory variability). Of the six responses measured, slump had one of the highest levels of variability, resulting in observed slumps for subsequent optimized mixtures that differed significantly from model-predicted values. The normalized root mean square deviation

(NRMSD) for the plot shown is 0.0980 or 9.80 percent. This value is an indication of the residual variance between the predicted and observed data. The lower the residual, the less variance between the data sets. In comparing the six measured responses, slump has the highest NRMSD. When evaluating the variability of the response, it is important to keep in mind the inherent variability of the ASTM slump testing procedure.

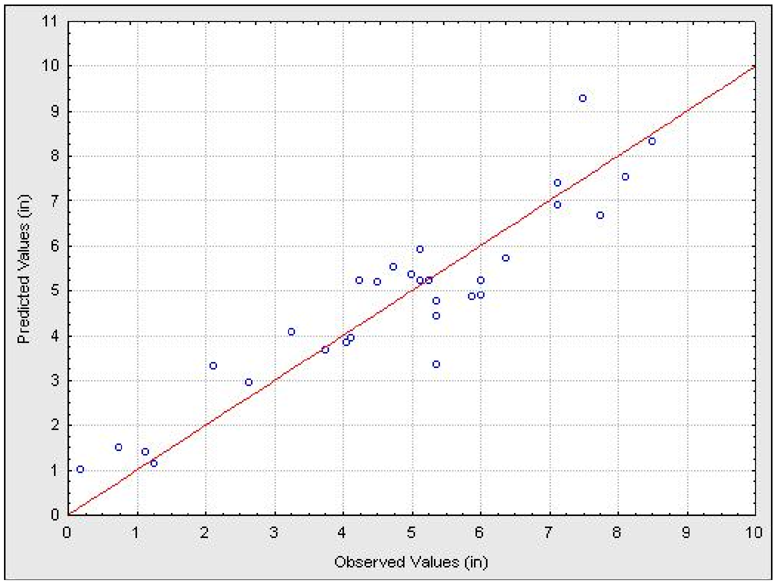


Figure 54: Predicted vs. Observed Values for Slump Response

Figure 55 shows the fitted surface for air content versus water-cement ratio and air dosage rate (the independent variables that were found to have the greatest influence on this response). The graph visibly displays a "plateau" behavior in the air content response. The relatively flat region represented by the dark red color at the high point of the surface plot indicates that the measured air content of PCCP containing RAP levels off at higher air-entraining admixture dosage rates and water-cement ratios. While performing the preliminary mixes prior to executing the designed experiment, it was very difficult to dose the mixture and consistently predict the air content. This observation implied that the air content of the concrete was very sensitive to some or all of the independent mix variables, making it very difficult to even grossly identify an air content relationship in just a few trial mixes. Referring to Figure 55, both the water-cement ratio and the air-entraining admixture dosage rate have a very significant effect on the air content of the final product across approximately the bottom one-half of their tested ranges.

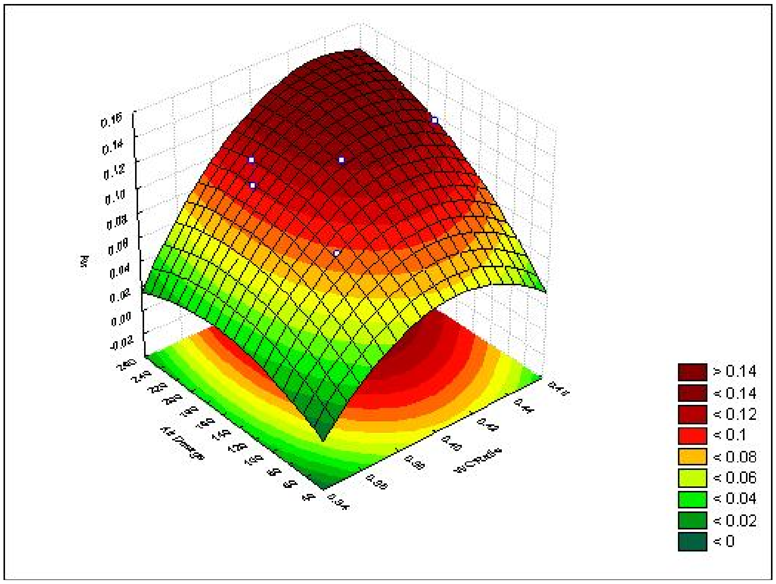


Figure 55: Air Content vs. Air Dosage and Water-Cement Ratio

Figure 56 shows the predicted versus observed values for the air content response. Again this plot provides an indication of how well the model was able to fit the recorded data and the amount of variability that was present in the process. The normalized root mean square deviation for the predicted versus observed air content plot is 0.0863 or 8.63 percent.

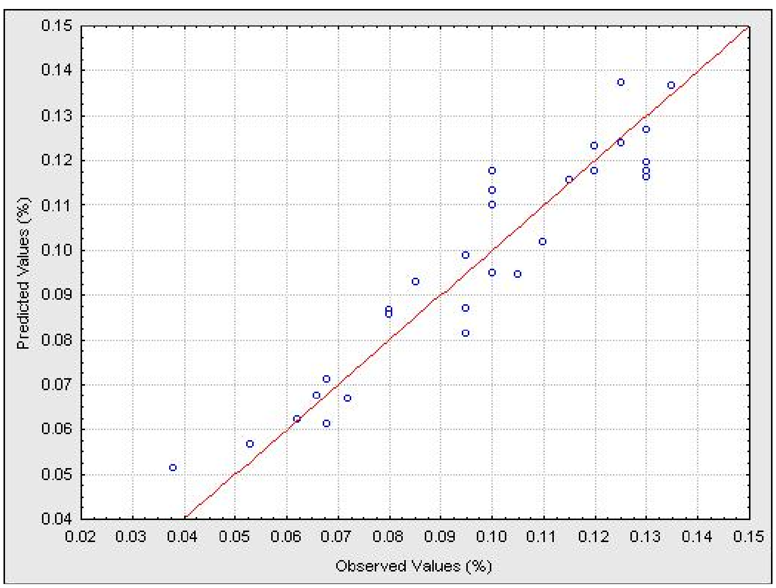


Figure 56: Predicted vs. Observed Values for Air Content Response

Different from the responses of slump and air content, the 7-day compressive strength of the batch trials was significantly related to the RAP content in the mixture. Looking at the Pareto chart for this response (Figure 50), only the relationship with coarse RAP replacement rate was significant, the p-value for the fine RAP to 7-day strength was relatively close to the 0.05 level.

Figure 35 displays the relationship between the early strength of the material and the coarse and fine RAP replacement contents of the mixture. Just as past research has revealed, the plot shows that as the RAP replacement rate increases, the strength of the material decreases. The most notable behavior observed in this plot is the formation of a “saddle” towards the center of the surface. Although the trend of decreasing strength and increasing recycled pavement content is very apparent, the saddle point signifies that the effect of the RAP on the compressive strength of the material is not a uni-directional trend. There is a specific region where further increasing the replacement rate of the coarse or the fine RAP, or both, results in increased strength (although the highest strength reached at the maximum RAP limits used in this study was still only approximately 50 percent of the strength realized when the RAP content was minimized).

The presence of the saddle in the response surface in Figure 57 indicates there is interaction between the coarse and fine RAP aggregate, and the 7-day compressive strength of the concrete. While no significant interactions between input variables were identified in the Pareto charts for any response at the p=0.05 level, slightly below this p level an interaction was seen between the coarse and fine aggregate replacement rates and 7-day compressive strength (Figure 50).

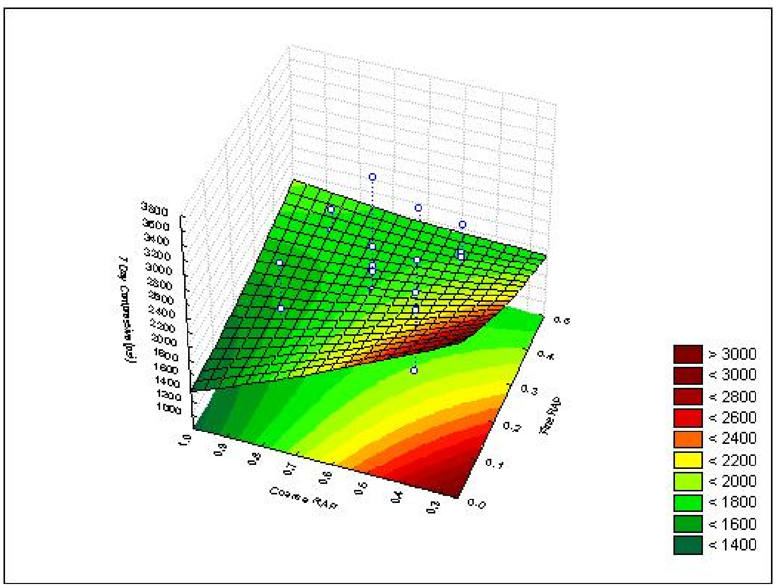


Figure 57: 7-Day Compressive Strength vs. Coarse and Fine RAP Replacement Rates

Figure 58, shows the predicted relationship between the 7-day compressive strength of the concrete and the air-entraining admixture dosage rate and water-cement ratio (two additional variables that correlated significantly with 7-day compressive strength). As would be expected, both an increasing water-cement ratio and air admixture dosage rate are associated with a decreased strength of the material. Once again, while no significant interactions between input variables were identified in the Pareto chart for this response, interaction between air-entraining admixture dosage rate and water-cement ratio was observed in the response’s behavior (Figure

50). This interaction is clearly evident in the response surface in Figure 58, as the slope of the surface is the steepest when both variables increase in magnitude (diagonal transect through surface), as opposed to when either variable is kept constant (transects through the surface parallel to the independent variable axes).

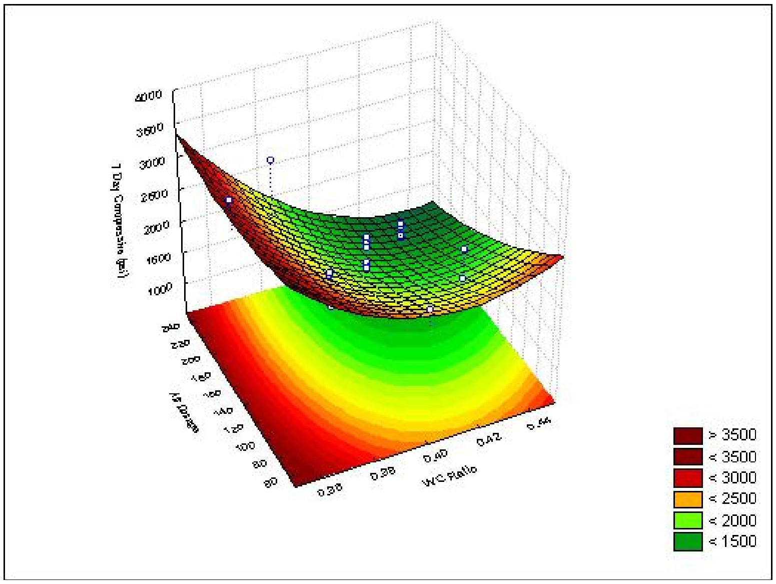


Figure 58: 7-Day Compressive Strength vs. Air-Entraining Admixture Dosage Rate and Water-Cement Ratio

In Figure 59, the model-predicted early compressive strength values are plotted versus the observed values. The trend is similar to the previous responses shown, but it should be noted that the scatter is less pronounced for the strength-measured response. Correspondingly, the normalized root mean square deviation for this data set is 0.0654 or 6.54 percent.

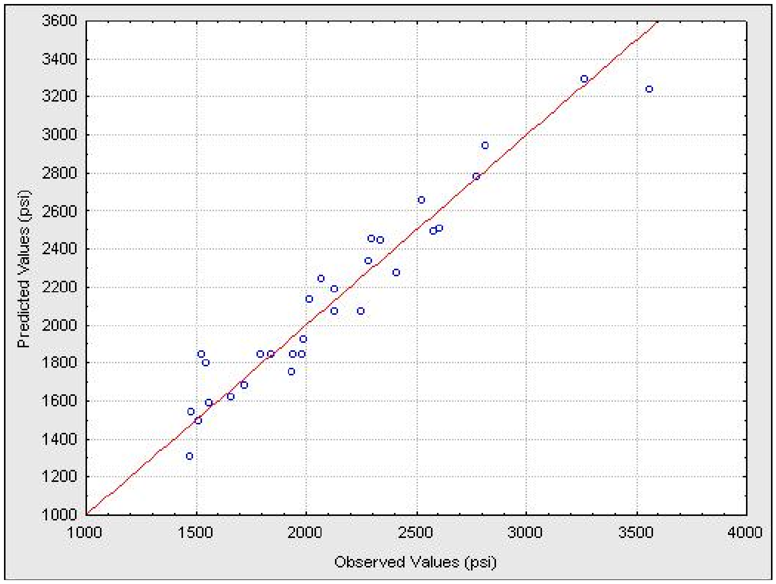


Figure 59: Observed vs. Predicted Values for 7-Day Compressive Strength Response

The 28-day compressive strength response surfaces were very similar to the 7-day compressive strength surfaces. The 28-day strength is plotted as a function of the fine and coarse RAP replacement rates in Figure 60. While the surface is almost identical to that of the plot shown for the 7-day strength, it should be noted that the fine RAP replacement rate was only determined to be significantly related to the long-term strength of the material, and not the 7-day strength. Again, there is a "saddle" region where both coarse and fine RAP replacement rates are at moderate levels and the resulting concrete material has an increased compressive strength (although again, the highest strength reached at the maximum RAP replacement rates used in this study still was only approximately 50 percent of the strength realized when the RAP content was minimized).

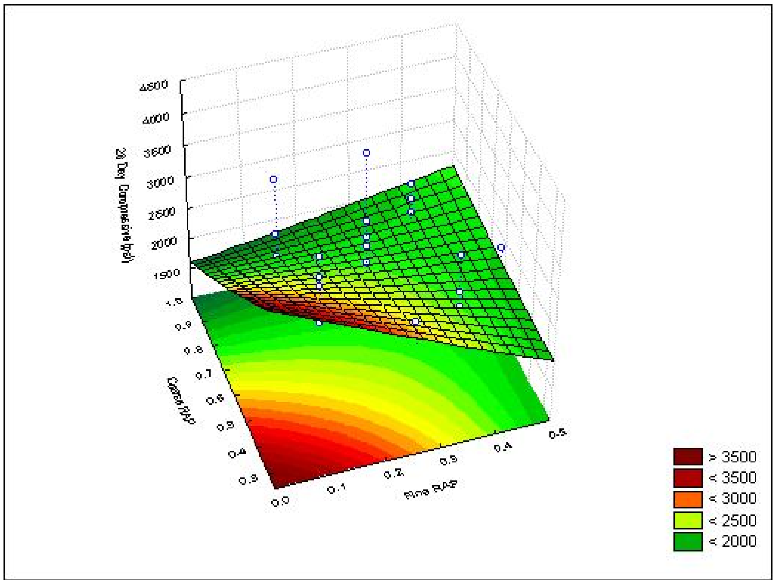


Figure 60: 28-Day Compressive Strength vs. Coarse and Fine RAP Replacement Rates

Figure 61 shows the 28-day compressive strength of the concrete plotted as a function of the two independent variables that affect it the most, the water-cement ratio and air-entraining admixture dosage rate. It is well recognized that an increased water-cement ratio as well as a higher void space in the material will result in a lower strength concrete. These relationships are very evident in this figure; further, it can be seen from the plot that the water-cement ratio appears to have a greater effect on the concrete than the air-entraining admixture dosage rate across the ranges considered for these parameters.

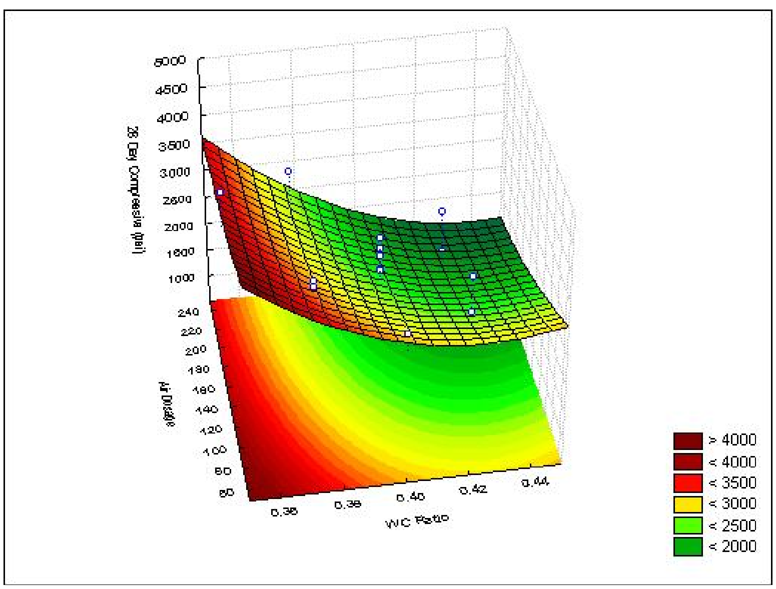


Figure 61: 28-Day Compressive Strength vs. Air-Entraining Admixture Dosage Rate and Water-Cement Ratio

In Figure 62 the model-predicted 28-day compression strengths are plotted versus the observed values. The normalized root mean square deviation for the 28-day data is 0.0661 or 6.61 percent. Again, it can be seen that the scatter is less pronounced for this parameter, relative to earlier results presented for slump and entrained air. Corresponding to this trend, it will be found in the next section that the model is more accurate at predicting the compressive strength responses that have less variability within the data set.

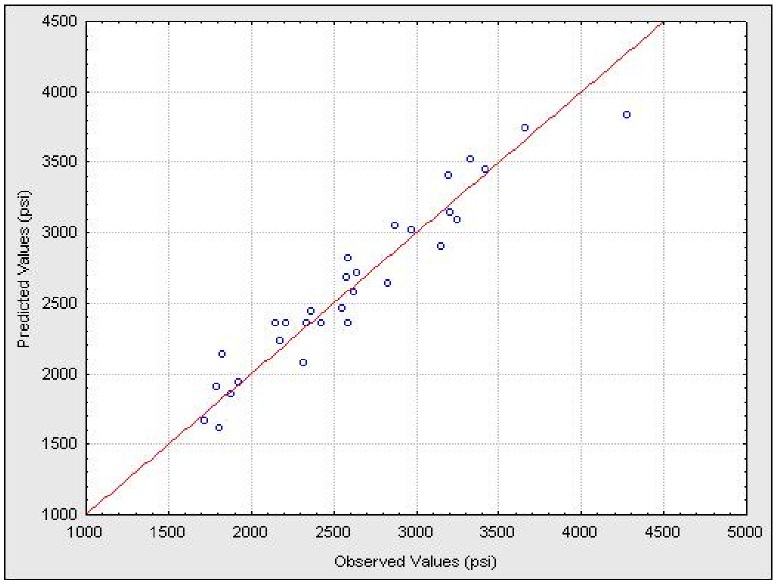


Figure 62: Predicted vs. Observed Values for 28-Day Compressive Strength Response

Figure 63 shows the surface for 28-day modulus of rupture plotted as a function of the fine and coarse RAP replacement rates of the mix. Note neither of the RAP replacement rates were identified as significant factors affecting the rupture capacity of the material, but given the objective of this study it is valuable to examine these relationships. Similar to the compressive strength relationships, the rupture surface also exhibits a “saddle” shape at the point where the RAP replacement rates appear to have a lessened effect on the modulus of rupture.

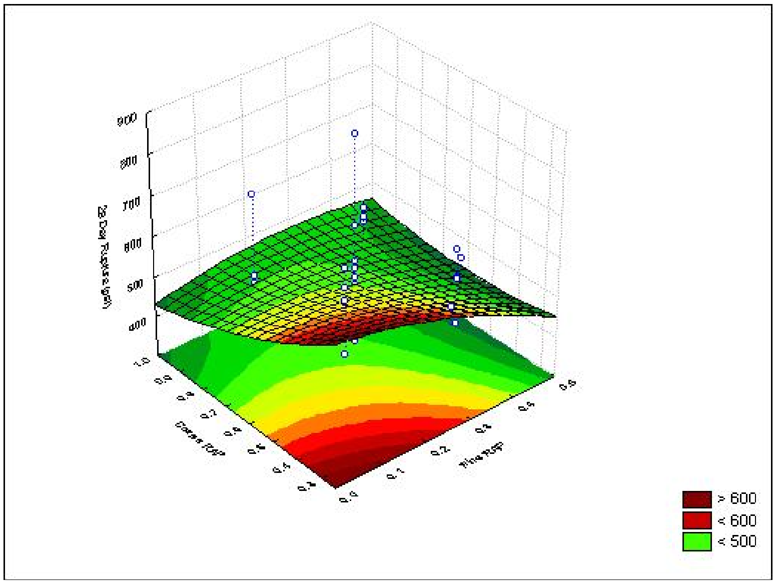


Figure 63: 28-Day Flexural Strength vs. Coarse and Fine RAP Replacement Rates

Figure 64 shows the behavior of the 28-day rupture strength in relation to the water-cement ratio and air admixture dosage rate. These two independent variables proved to be the significant factors for determining the 28-day modulus of rupture for the concrete material, similar to the other strength parameters. In comparison to the other strength versus water-cement ratio and air admixture dosage rate surface plots, it appears that the air content of the mixture has a reduced impact on the rupture strength of the material.

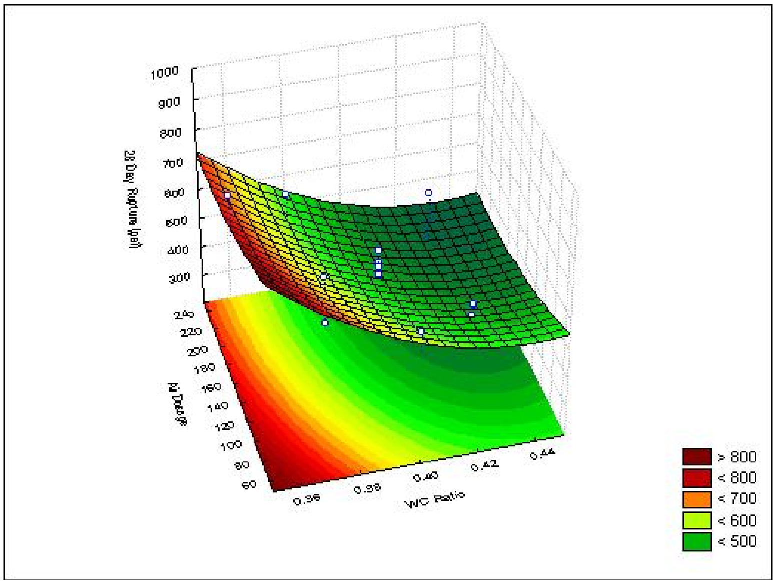


Figure 64: 28-Day Flexural Strength vs. Air-Entraining Admixture Dosage Rate and Water-Cement Ratio

The predicted versus observed plot for the 28-day modulus of rupture can be seen in Figure 65. The normalized root mean square deviation is 0.0648 or 6.48 percent.

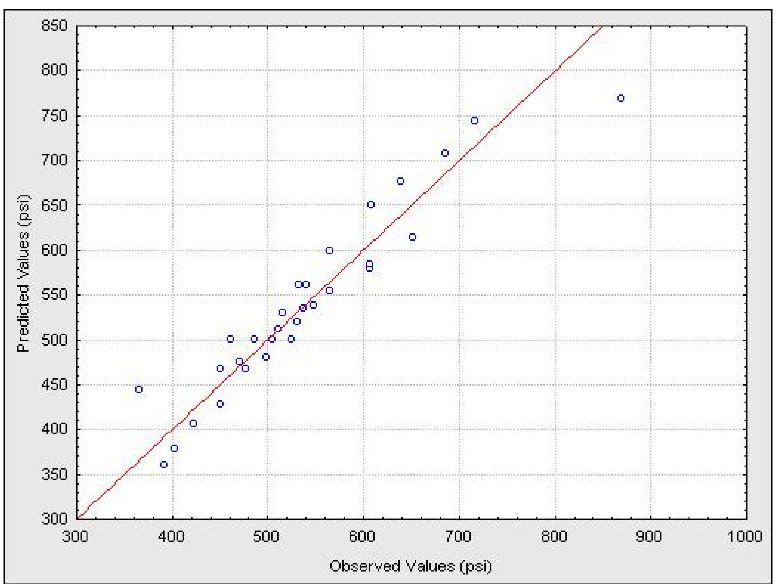


Figure 65: Predicted vs. Observed Values for 28-Day Flexural Strength Response

The last response to be evaluated is the Environmental Factor, which was created as an arbitrary response. As previously mentioned, the Environmental Factor is defined as a linear combination of the coarse and fine RAP replacement rates, and was not an actual measured parameter. Based on the nature of this response, the model shows a “perfect” linear plane when plotted against the coarse and fine RAP replacement rates, as shown in Figure 66. Although seemingly uninteresting when compared to some of the other surface plots, the relationship presented in Figure 66 is a strong validation that the model can correctly pick up on behaviors of the RAP in PCCP mixture.

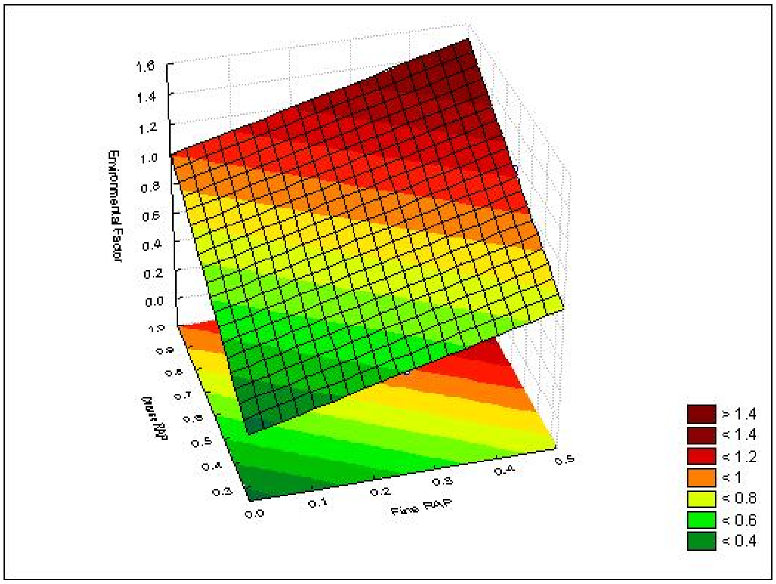


Figure 66: Environmental Impact Factor vs. Coarse and Fine RAP Replacement Rates

Figure 67 shows the observed (calculated) environmental factors plotted against the model-predicted values for the same response. As expected, the test points fall directly on the predicted value trend line, since no variability is present. Again this is a good correlation for confirming the model. As expected, the normalized mean square deviation is 0.00.

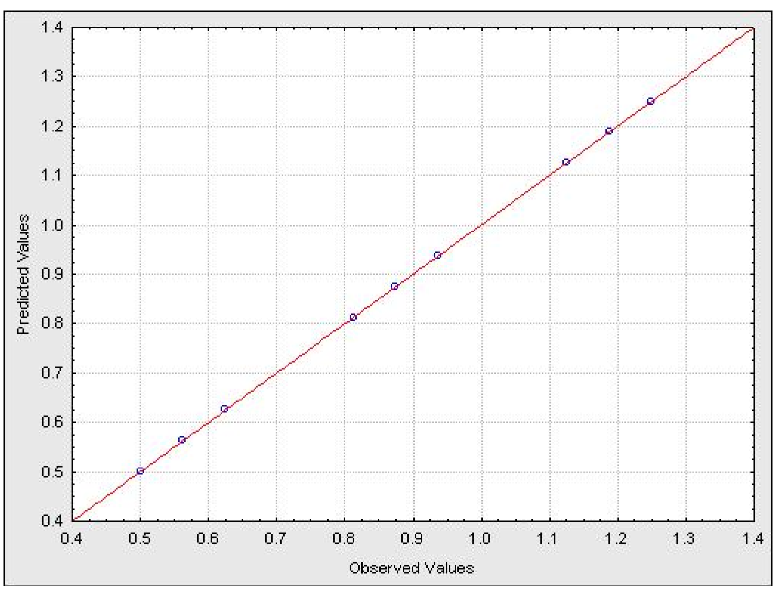


Figure 67: Predicted vs. Observed Values for Environmental Factor Response

A.3 Optimization of Mixes

The statistical model presented in the previous section provides a foundation to develop optimized concrete mixtures to fulfill project specific criteria. This section discusses the optimization strategy used in the initial experiment to develop three concrete mixtures with the desired physical properties. This section also discusses the results of this optimization study.

Response surfaces can be used to obtain a “desirable” result, and often this “desirable” result may be a function of multiple responses. For example, MDT specifies a “desirable” concrete for pavements as having a 1.5-inch slump, air content of 6 percent, and a 28-day compressive strength of at least 3,000 psi. To address this issue of obtaining target results for multiple responses, RSM analyses often use desirability functions, in which the researchers’ priorities on the response values are built into the optimization procedure (Myers & Montgomery, 2002). The optimization procedure involves creating a desirability function for each response, and then using the geometric mean of these desirability functions to generate a single composite response (Myers & Montgomery, 2002). This approach was used in this initial CCD analysis to obtain desirable mixes.

A.3.1 Desirable Mixes

Desirability functions were used to develop three mixes with different performance criteria. First, a mix was developed to meet MDT specifications for PCCP and to include a significant amount of RAP. Two other mixes were then developed: one maximized strength, and the other maximized RAP content. The desirability functions used to obtain these mixes, the resulting mixes, and the subsequent measured responses for these mixes are presented in this subsection.

The first desirable mix (labeled MDT Specs) targeted MDT specifications for slump (1.5 inches), air content (6 percent), minimum 7-day compressive strength (2,000 psi), minimum 28-day compressive strength (3,000 psi), and minimum 28-day modulus of rupture (500 psi). The desirability functions used for this optimization are provided in Figure 68, along with the predicted values and desirability profiles for each response. The desirability functions are set to 1.0 at points considered to be most desirable and are set to 0.0 in regions considered unacceptable. For air content and slump, the desirability functions were input as peaks with values of 1.0 at the target values, and 0.0 outside of the desirable ranges. It should be noted that for air content, the acceptable range was input as 6 to 8 percent; however it was later realized that a reduced air content of 5 to 7 percent would be acceptable for the aggregate size used in the mixing experiment. For the additional mixes, this lower air range was used. The other four responses for this mix had desirability functions where they were simply (and somewhat arbitrarily) maximized from 0.0 to 1.0 over the range of observed values that were gathered throughout the mixing experiment. Relative to RAP use, the objective of this mixture design was to maximize the RAP content, which was implemented by setting the maximum

Environmental Factor to 1.25 (the highest tested value) at a desirability of 1.0, and the minimum desirability value of 0.0 was applied to 0.50 (the lowest tested value).

The optimization results from using these desirability functions are included in Figure 68. In the figure, key relationships between independent variables and responses can also be observed; each response is plotted versus each independent variable while all of the other variables are held at their optimum values. As mentioned previously, the input desirability functions for the responses are shown in the column on the far right of the figure, and the graphs along the bottom represent each of the independent variables' desirability results. The combined desirability of the optimized mixture is 0.643. This value is an indication of how well the model was able to fulfill the specified responses implemented through the desirability functions. The combined desirability can also be seen as the "degree of compromise" involved in proportioning the mix to meet possibly conflicting demands; a value of 1.0 would indicate that all specifications were met to their fullest extent.

The optimized mix proportions for this mix (MDT Specs) are also provided in Table 38, along with the predicted responses and their corresponding 95 percent confidence intervals. This mix was carried out in the lab to verify its performance, and the measured responses are also included in Table 38. The measured responses were all within the specified confidence intervals; however, the confidence intervals were quite large and the responses did not match desired values. The large confidence intervals in the initial experiment are the result of the fact that this mix is near the edge of the region of operability for the response surfaces. The air content, slump, and 28-day compressive strengths were all outside of the limits specified by MDT for their pavements.

A similar procedure was used to develop two additional mixes: one that maximized strength by devaluing RAP content and another that maximized RAP content by devaluing strength. The desirability profiles and the results of the RSM optimization for the high strength and high RAP mixes are shown in Figure 69 and Figure 70, respectively.

For the high strength mix, the desired 28-day compressive strength was set to a minimum of 4,000-psi using a desirability function that transitioned linearly from 0 to 1 between 3,900-psi and 4,282-psi, respectively. Correspondingly, the desired 7-day compressive strength was set to a minimum of 3,200-psi using a desirability function that transitioned linearly from 0 to 1 between 3,100-psi and 3,599-psi, respectively. In light of the known negative impact of RAP content on strength, lower Environmental Factors (and thus RAP content) were treated as acceptable in the mix design by using a desirability function that linearly transitioned from 0 to 1 across Environmental Factors ranging from 0.5 to 0.75. Ultimately, the combined desirability of the high strength design was relatively high at 0.81205, when compared to the value determined for the optimized mixture.

The high RAP desirability functions are in direct contrast to the relationships that were input for the high strength mix. Here, emphasis was placed on a high RAP replacement rate by using a desirability function linearly increasing from 0 to 1 across Environmental Factors of 1.25 to 1.50 (1.5 corresponds to 50 percent fine and 100 percent coarse RAP replacement respectively). For the strength-related responses, the desirability was set from 0 to 0.2 over a low range of strength values. With an Environmental Factor of 1.50, the model must be extrapolated to generate mixture parameters for this high RAP mix (the highest Environmental Factor in the batch trial results was 1.25).

As was done previously for the MDT Spec mix, these mixes were carried out in the laboratory to evaluate their performance. Results from these mixes are provided in Table 38, along with the mixture proportions and their intended responses. As can be seen in this table, there was not a good correlation between the measured and predicted responses. Most of the responses were within the 95 percent confidence intervals, but again these confidence intervals were quite large. Also, none of these mixes met MDT specifications for observed slump and air.

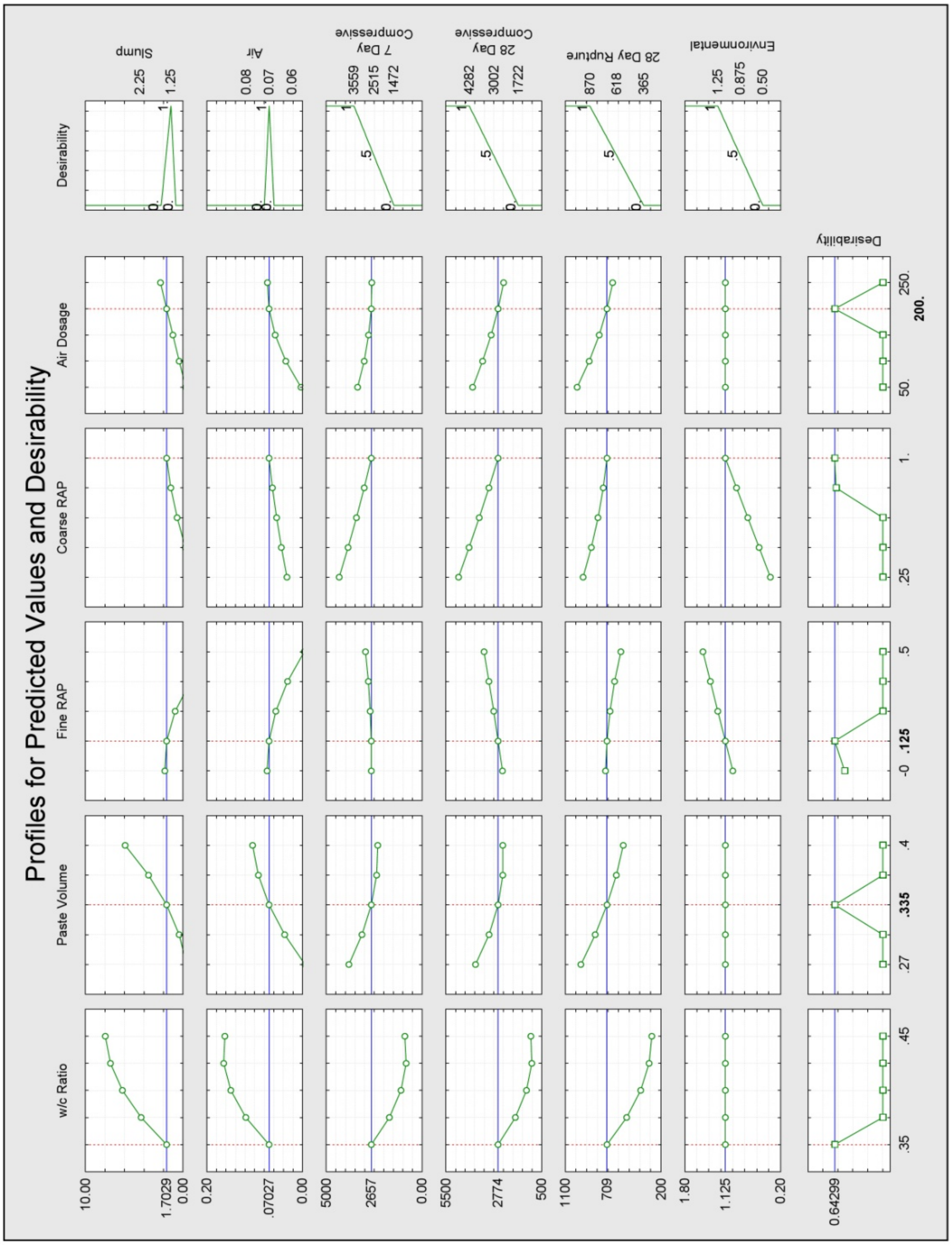


Figure 68: Predicted values and desirability profiles for RAP in PCCP optimized mix

Table 38: Developed Mixes with Predicted and Observed Responses

Variable/Response	MDT Specs		High Strength		High RAP	
w/c Ratio	0.35		0.35		0.41	
Paste Volume	0.335		0.344		0.348	
Fine RAP Replacement Rate (%)	12.5		20		50	
Coarse RAP Replacement Rate (%)	100		45		100	
Air Dosage (mL/100#)	200		136		130	
	Predicted (95% CI)	Observed	Predicted (95% CI)	Observed	Predicted (95% CI)	Observed
Slump (in)	1.7 (-4.5 to 7.9)	3.0	1.4 (-1.9 to 4.6)	2.5	1.38 (-3.9 to 6.6)	8
Air Content (%)	7.0 (0.653 to 13.4)	8.5	5.9 (2.5to 9.2)	7.8	6.9 (1.5 to 12.2)	12.2
7-Day Compressive Strength (psi)	2657 (1617 to 3696)	2228	3534 (2987 to 4081)	2941	2101 (1222 to 2981)	1158
28-Day Compressive Strength (psi)	2774 (1486 to 4062)	2376	4125 (3447 to 4803)	3521	2330 (1240 to 3420)	1363
28-Day Modulus of Rupture (psi)	709 (461 to 958)	615	802 (671 to 933)	661	471 (260 to 681)	354
Environmental Factor	1.125 (no variability)	1.125	0.65 (no variability)	0.65	1.50 (no variability)	1.5

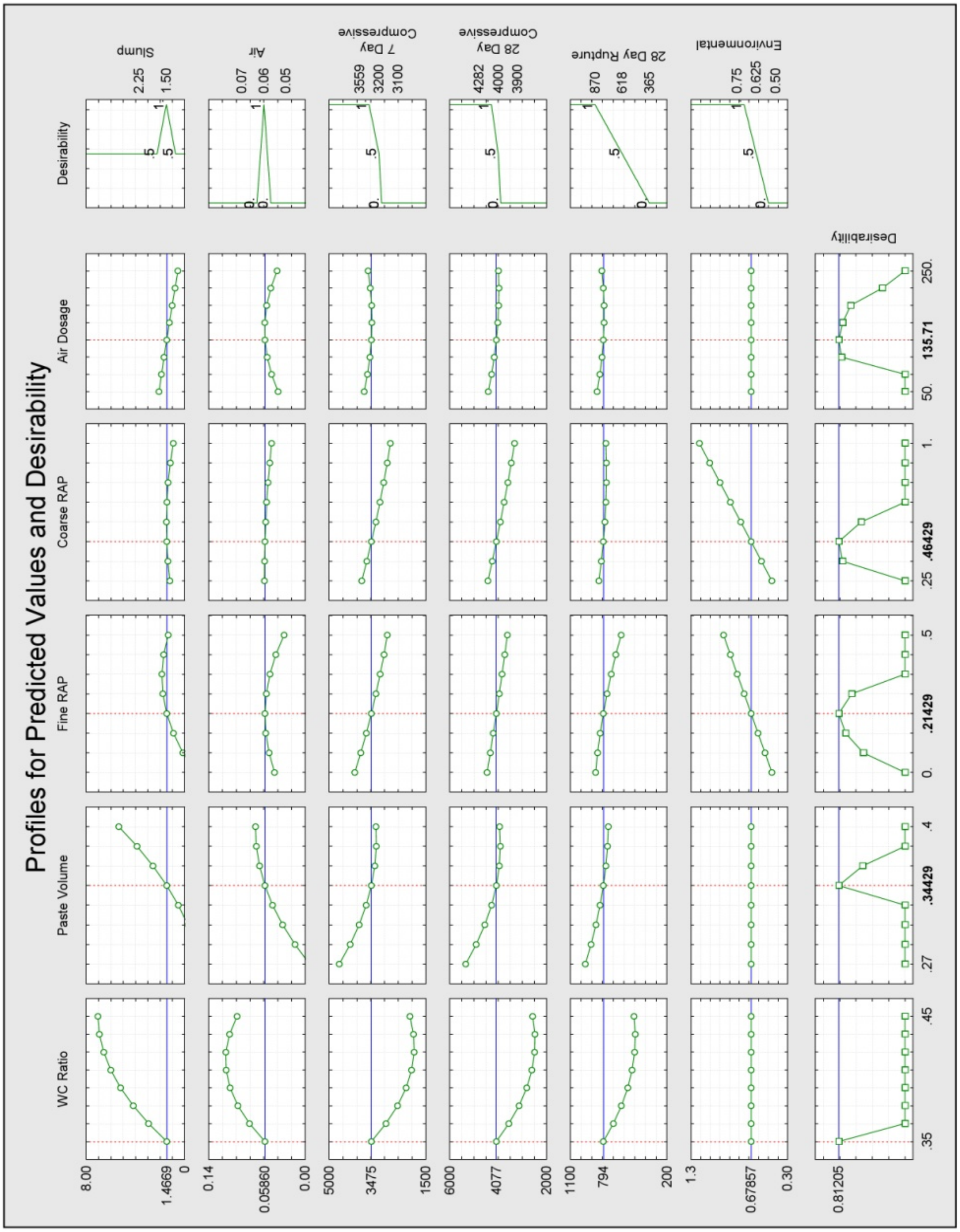


Figure 69: Predicted values and desirability profiles for RAP in PCCP high strength mix

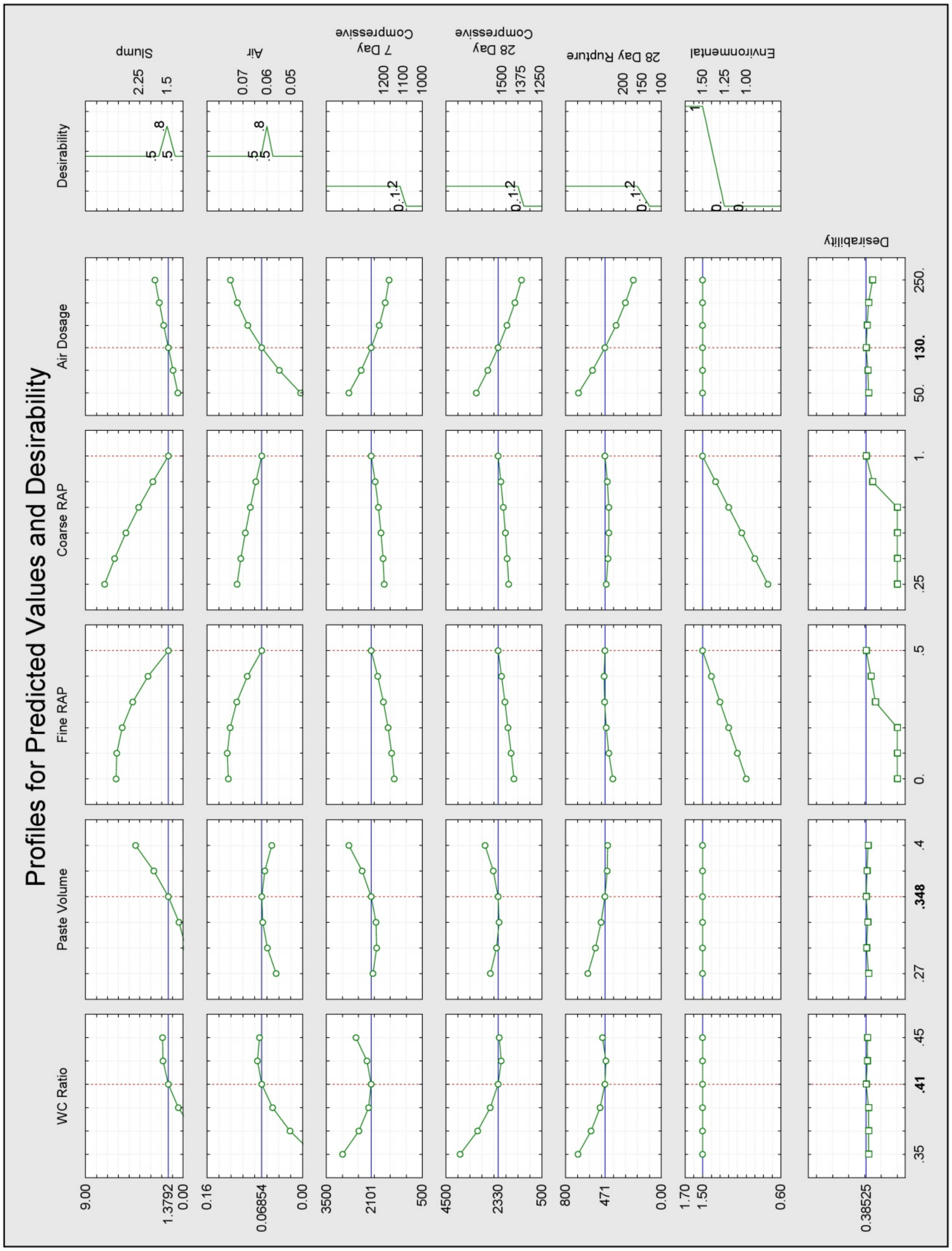


Figure 70: Predicted values and desirability profiles for RAP in PCCP high RAP mix

A.3.2 Potential Sources of Variability

There are several aspects that contribute to the large differences observed between the measured and predicted responses in the initial optimization study. First and foremost, the region of interest chosen in this experimental design resulted in average responses that were too far from the desired responses. For example, the target air content and slump were 6 percent and 1.5 inches, whereas the averaged observed responses in this study were 9.8 percent 4.75 inches. The optimized mixes from the initial response surface model were near or outside of the defined region of interest. As one would expect, the models are less accurate near the perimeter, and even less accurate if they are based on extrapolation.

A second possible source of the discrepancies observed between measured and predicted responses could be the moisture content correction method used in first experiment. Aggregates behave like a sponge during the mixing process, either absorbing water from the mixture if in a dry state (moisture content less than SSD) or contributing water to the mixture if in a wet state (moisture content greater than SSD). In either case, (wet or dry), the water available to react with the cement and the water of convenience contributing to the workability and paste volume are affected by the moisture content of the aggregate. Thus, unless the moisture condition is appropriately accounted for in mix proportioning, the apparent water-cement ratio and paste volume reported for a particular batch trial will not be the same as the effective water-cement ratio and paste volume. In such a situation, when fitting a model to the collected data, observed responses will be paired with inaccurate input values, resulting in a model that is either biased and/or exhibits considerable scatter in predicted versus observed outcomes.

Typically, aggregate moisture condition is addressed in one of two ways: (1) assessment of the absorption characteristic of the aggregate and its moisture content prior to its use, and based on this information, adjustments are made to the amount of mix water, or (2) mix water is withheld or added to the mix as required to achieve the desired slump. The first approach is believed to be more accurate and was used for proportioning each of the 30 batch trials; however, there are still a number of issues associated with this method. Overall, it is difficult to precisely characterize the material properties of aggregates defined by ASTM 127-07 and ASTM 128-07a (notably, absorption capacity). Additionally, it is also hard to define a universal moisture content value for a large stockpile that is continually exposed to a changing environment.

With these complexities in mind, it is believed that the aforementioned traditional aggregate moisture correction method may not be completely accurate in accounting for the available water in a concrete mix. An additional important consideration is the nature of the RAP aggregate itself. This material has not been extensively researched as a replacement aggregate, and how it absorbs and stores water, as well as the applicableness of ASTM standard aggregate tests for the material is relatively unknown. Specifically, presence of bitumen on the surface of aggregates could affect its absorption characteristics. Additionally, existence of this asphalt residual makes it difficult to run traditional moisture-related tests that involve heating the aggregate to elevated temperatures.

The center point mixes from the initial experiment design were used to investigate this further. These mixes were used because they were identical mixes, with the moisture content corrections being the only thing varying between them. If the moisture content correction method was effective for these mixes, the mixes should be identical, and the measured responses should be very close to each other. The only variation between them being the epistemic uncertainty associated with uncontrolled variations in the environment and the testing methods. However, not only was there significant variation between their measured responses, the variation was systematic with the corrected amount of water used in each mix. In Figure 71 through Figure 75 various measured responses are plotted as a function of the water added to each center point mix (the number by each data point is the specific mix designation). The strong relationship between these properties and the water added is obvious in these figures; if the moisture correction was performing its intended function, each property would have been expected to be constant (or vary randomly) across the range of water added. This inadequacy of the aggregate moisture correction method in performing its intended function was effectively interpreted in the RSM as additional (and probably significant) unexplained variability in the process being modeled.

This further examination of the water added phenomenon in the RAP in PCCP mixes allowed the research team to point out and quantify a source of variability that was suspect since the early analysis phase. The data shown above also confirms a few age-old industry practices. Although full-scale professional concrete batch plants always work off of a mix design, the wet concrete is often slump adjusted through the addition or withholding of mix water, or through the use of a water-reducing admixture. These common operational procedures confirm the notion that concrete aggregates do not necessarily follow the ideal behavior and an accurate moisture content of these materials can be hard to quantify.

In the follow-on study, all mixes were conducted within a 1-week period and were not corrected for aggregate moisture content. This enabled the research team to significantly reduce this source of variability. Further research is required to develop an accurate and efficient way to correct for aggregate moisture content in RAP aggregate concrete.

Figure 71: Slump for Center Point Mixes vs. Water Added

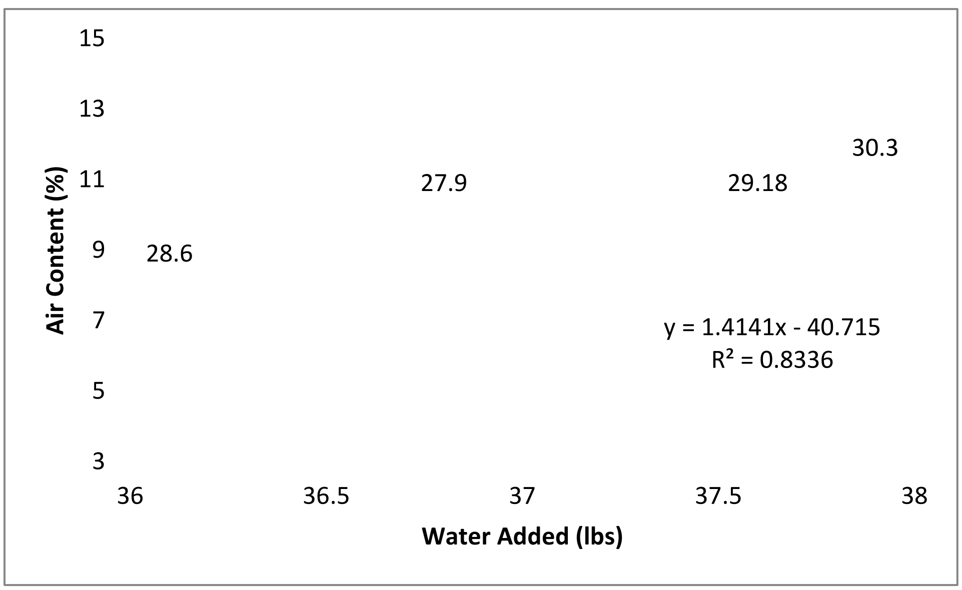


Figure 72: Air Content for Center Point Mixes vs. Water Added

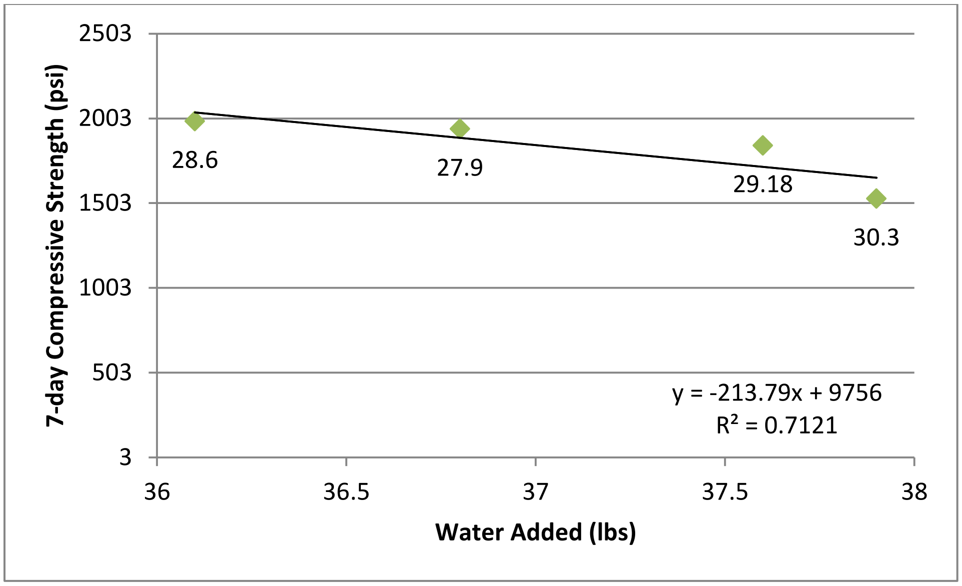


Figure 73: 7-day Compressive Strength for Center Point Mixes vs. Water Added

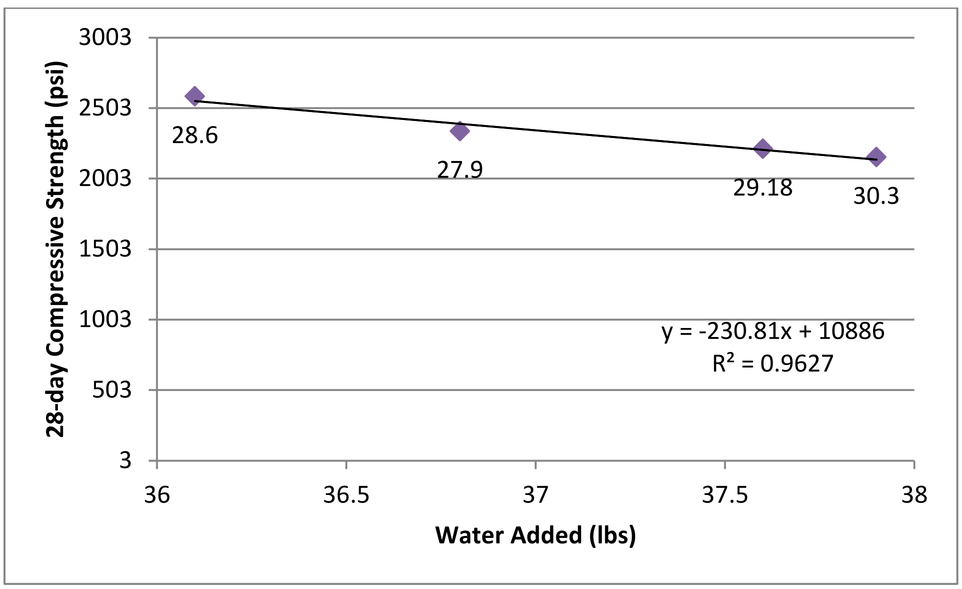


Figure 74: 28-Day Compressive Strength for Center Point Mixes vs. Water Added

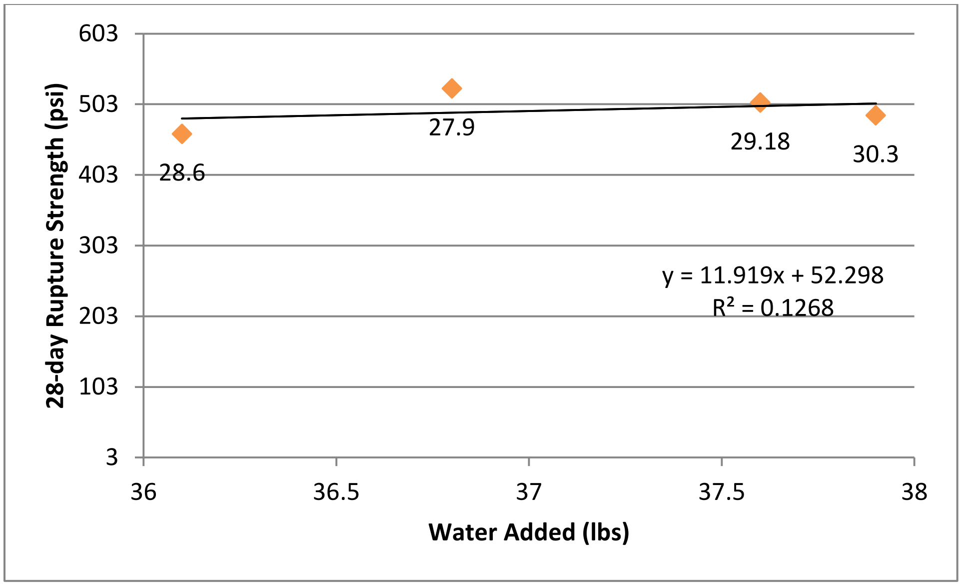


Figure 75: 28-day Tensile Strength for Center Point Mixes vs. Water Added

APPENDIX B: FOLLOW-ON EXPERIMENTAL DESIGN AND ANALYSIS

Upon completion of the initial study, a second central composite design was carried out over a modified region of interest with fixed replacement rates of 0.5 and 1.0 for the fine and coarse aggregates, respectively. Also, in this study, the aggregates were not corrected for moisture content. This follow-on experimental design yielded a response surface that better-evaluated the region of interest and was capable of predicting more accurate optimized mixture proportions and responses. The primary results of this study are presented in the main text. This appendix provides useful graphics that were used to evaluate the resulting response surfaces from this experimental design.

B.1 Pareto Charts

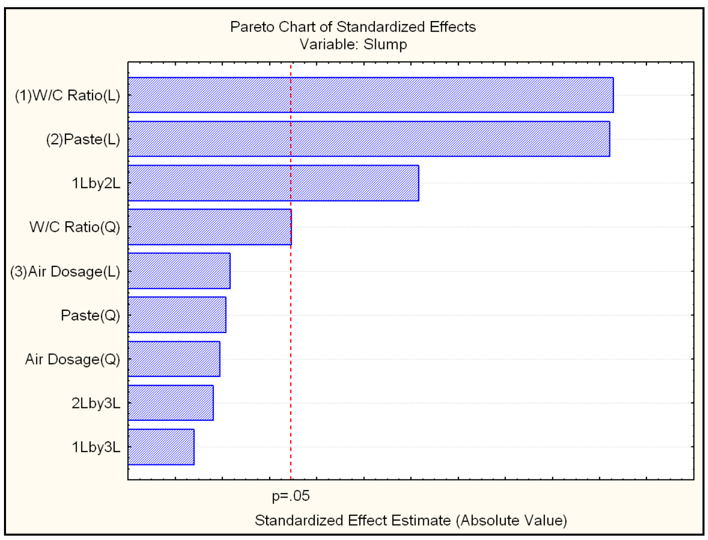


Figure 76: Pareto Chart for Slump Response

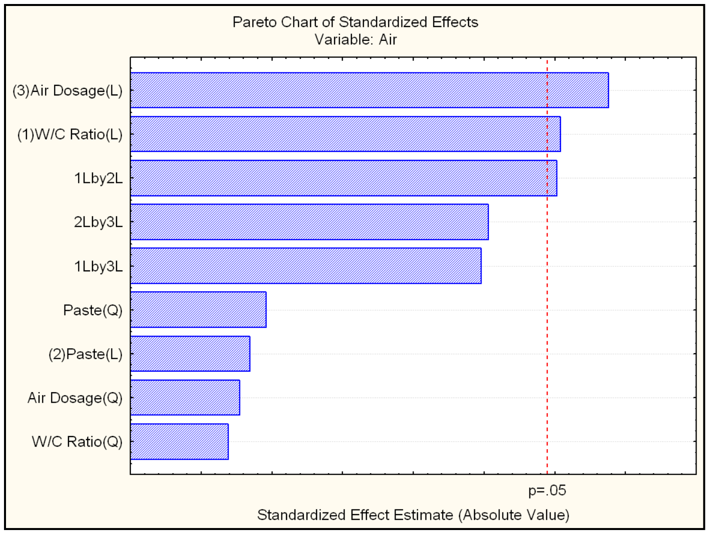


Figure 77: Pareto Chart for Air Content Response

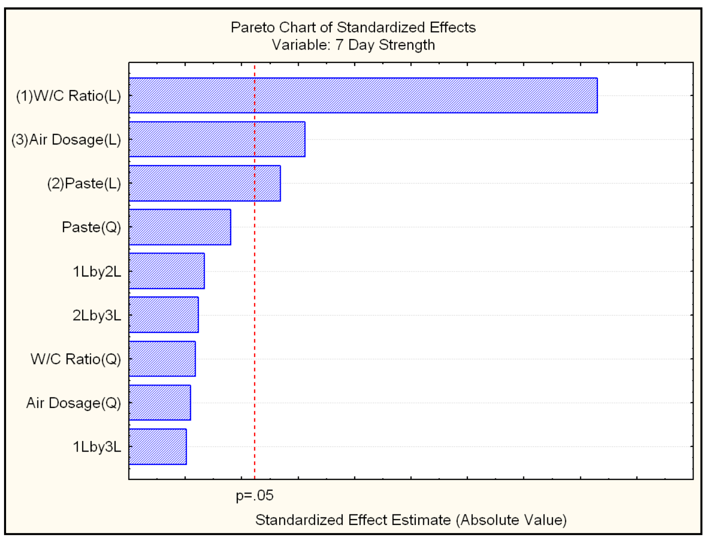


Figure 78: Pareto Chart for 7-Day Compressive Strength Response

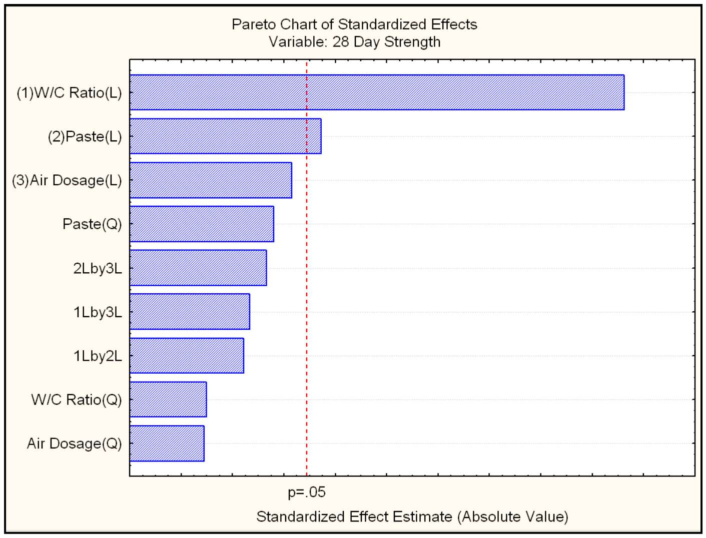


Figure 79: Pareto Chart for 28-Day Compressive Strength Response

B.2 Response Surfaces

The response surfaces resulting from this experimental design are plotted in this section versus the most significant variables for each response. In these plots, the variables in question are varied over the region of interest while all other variables are held at the center point.

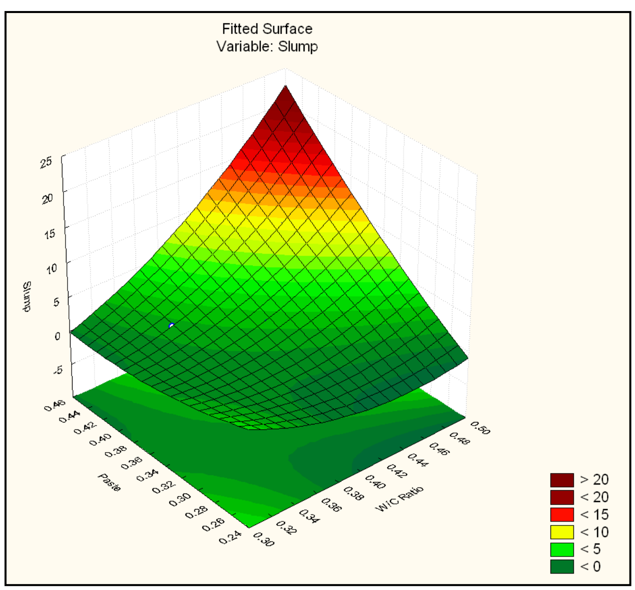


Figure 80: Slump vs. Paste Volume and Water-Cement Ratio

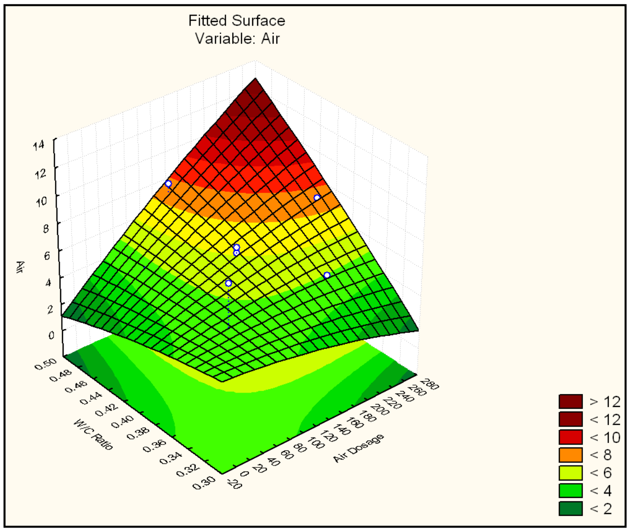


Figure 81: Air Content vs. Water-Cement Ratio and Air Dosage

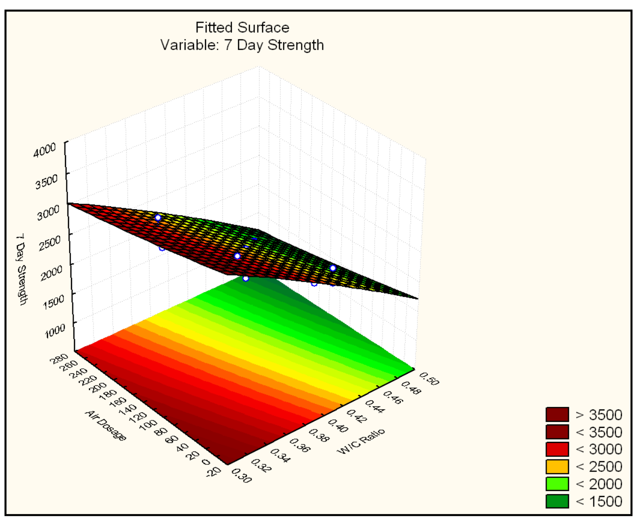


Figure 82: 7-Day Compressive Strength vs. Air Dosage and Water-Cement Ratio

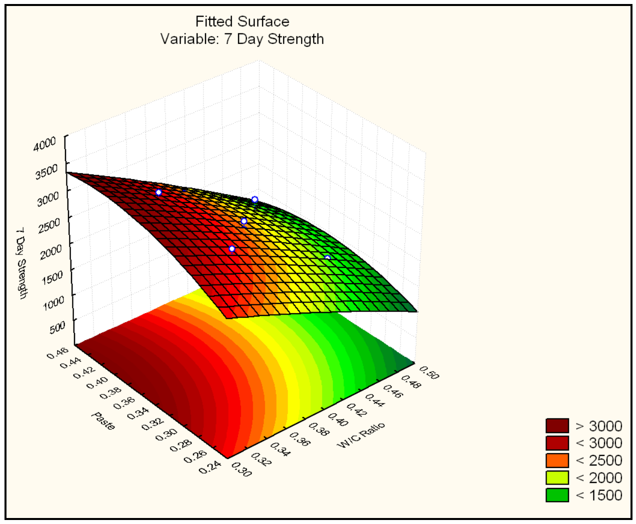


Figure 83: 7-Day Compressive Strength vs. Paste Volume and Water-Cement Ratio

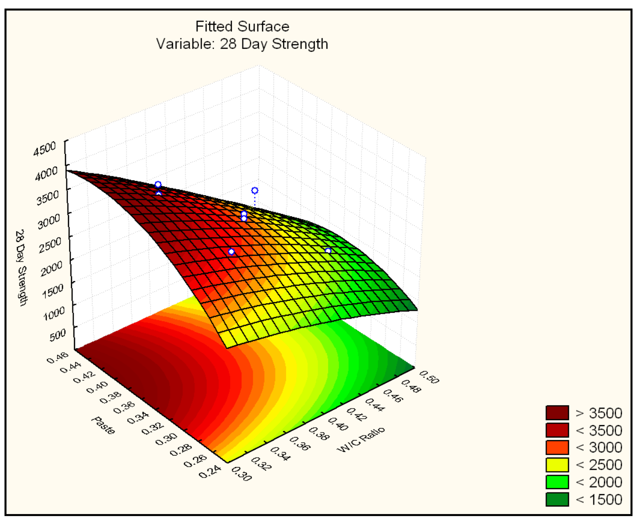


Figure 84: 28-Day Compressive Strength vs. Paste Volume and Water-Cement Ratio

B.3 Predicted vs. Observed Responses

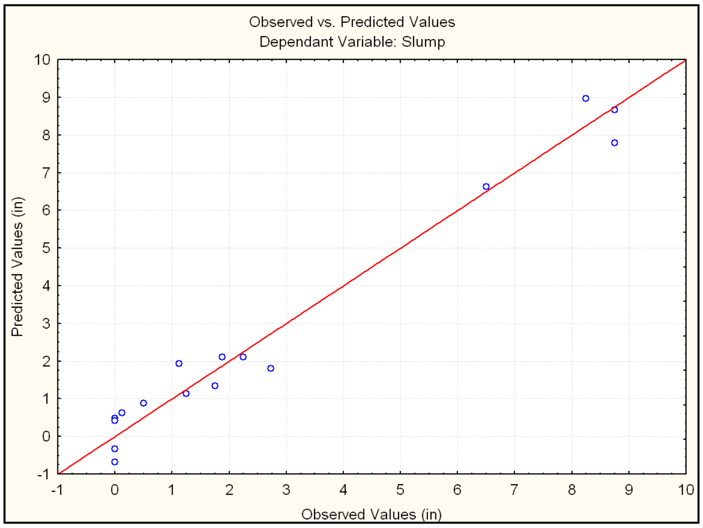


Figure 85: Projected vs. Observed Values for Slump

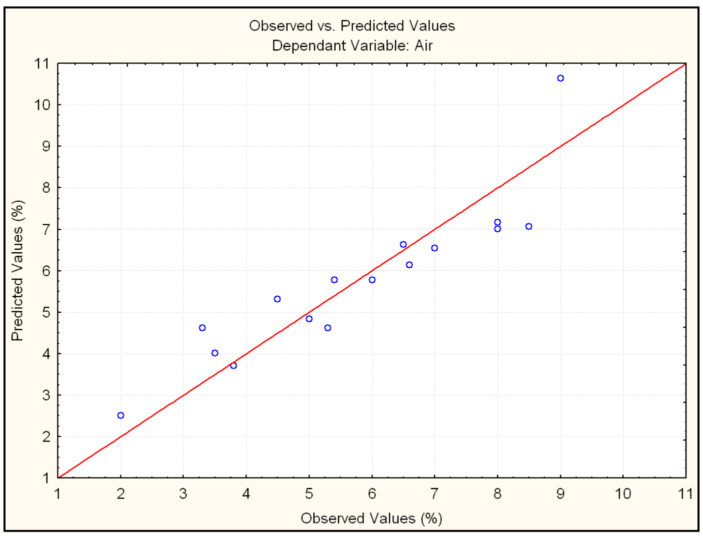


Figure 86: Observed vs. Predicted for Air Content

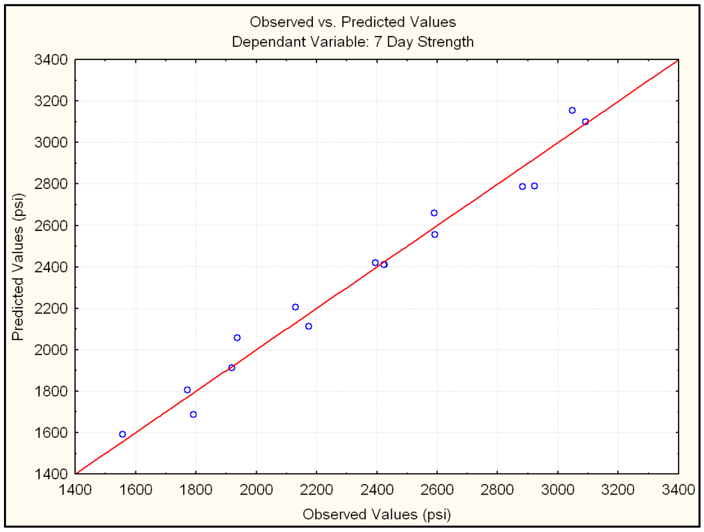


Figure 87: Observed vs. Predicted for 7-Day Compressive Strength

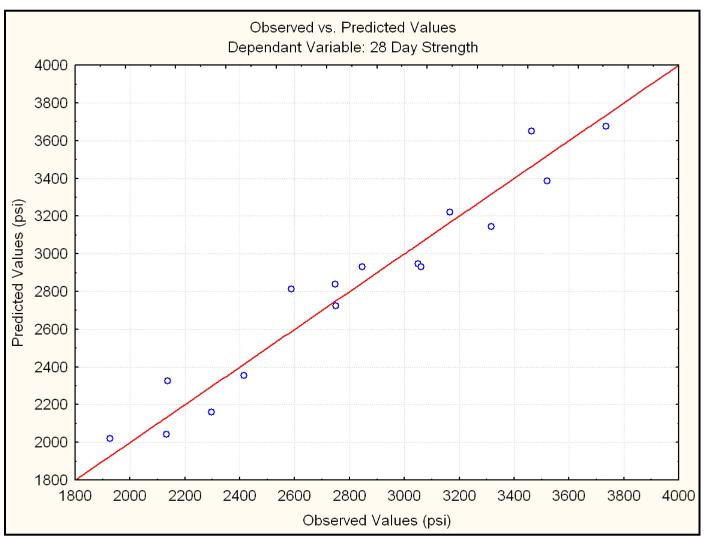


Figure 88: Observed vs. Predicted for 28-Day Compressive Strength

APPENDIX C: CREEP FRAME DESIGN AND CONSTRUCTION

Creep of the concrete was tested according to ASTM C512/C512M. This section describes the load frames used for this test. These load frames consist of four reaction plates that are aligned vertically and held in place with tension rods. The concrete test specimens are placed in the middle of the four plates and a hydraulic jack sits between the top two reaction plates and applies the load to the cylinders. The applied load is maintained by a set of springs that are secured between the bottom two reaction plates. Figure 89 provides a schematic of the frames.

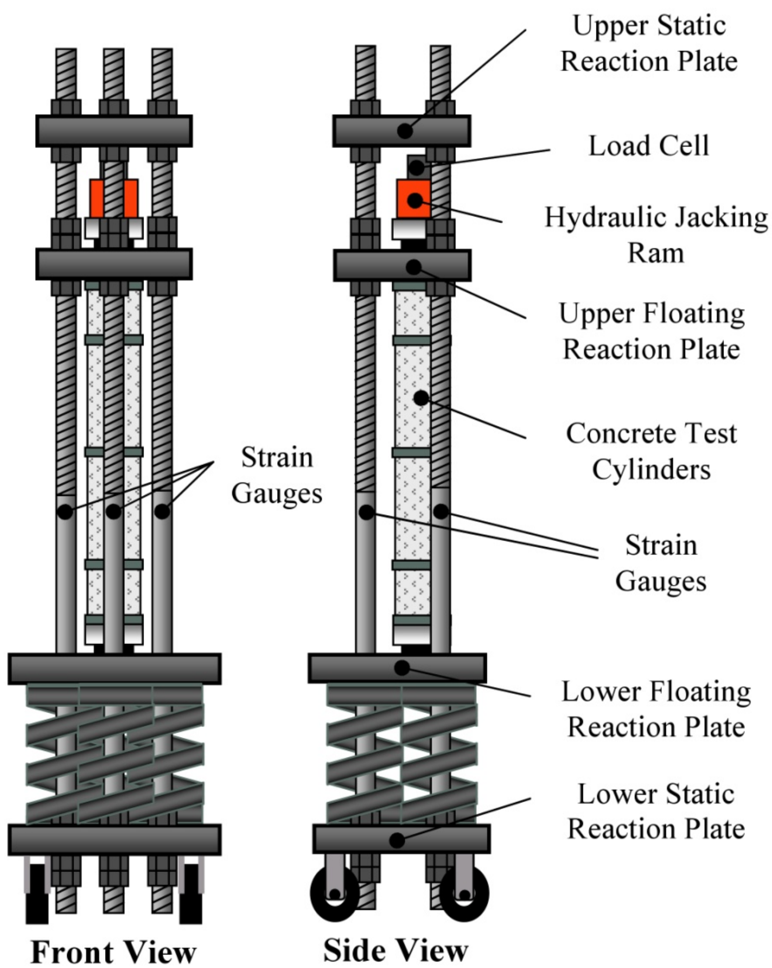


Figure 89: Elevation View of Creep Testing Load Frame
(Kavanaugh, 2008)

These frames were designed to handle concretes with compressive strengths of 10,000-psi. It is also important to note that the ASTM test method requires the application of a load equal to 40 percent of the material's compressive strength, and the frame must maintain this demand throughout the testing phase.

C.1 Compression Spring Design

The compression springs were designed in accordance with standard spring mechanics; a design spreadsheet, implementing these mechanics, is provided in Table 39. The final specified spring dimensions can be found in the top portions of the design table. Photos of the final springs are shown in Figure 90 and Figure 91. The springs were specially manufactured by Duer Carolina Coil in Reidville, South Carolina. Four large springs were installed in each frame. Additionally, one of the compression springs was test-loaded to determine the actual spring constant; load-deflection and strain data from the test was compared to an elastic finite element (FE) model created in ANSYS. The FE model provided a deeper understanding of the strain behavior in the spring as the load on the coil is increased, and information from this modeling process was used to determine how often the load will need to be reapplied.

Figure 90: Compression Spring Coil Diameter

Figure 91: Compression Spring Free Height

Table 39: Compression Spring Design Tables and Equations

Compression Spring Design

Spring Properties				
Demand F=	28275	lbf		input
Outer Diameter D_{out}=	8.5	in		input
Diameter of Wire D_{wire}=	2.1	in		input
Free Length L_{free}=	23	in		input
Deflected Length L_{defl}=	20.64375	in		L_{free}-F/k
Solid Length L_{solid}=	20.428759	in	OK	$D_{wire}*n_t<L_{defl}$
Spring Material	ASTM A313 Grade 220			input
Maximum Tensile Strength τ=	220000	psi		input
Modulus of Elasticity E=	28000000	psi		input
Shear Modulus G=	10000000	psi		input
Calculated Spring Properties				
Spring Constant k=	12000	lbf/in		input
Mean Diameter D_{mean}=	6.4	in		$D_{out}-D_{wire}$
Number of Active Coils n_a=	7.7279806	unitless		$(GD_{wire}^4)/(8KD_{mean}^3)$
Total Coils n_t=	10	unitless		n_a+2
Pitch p=	2	in/n_a		$(L_{free}-2D_{wire})/n_a$
Rise Angle of Coils θ=	6.899	degrees	OK	$\mathrm{atan}(p/(\pi D_{mean}))*(180/\pi)\leq 15^o$
Spring Index C=	3.047619	unitless	OK	D_{mean}/D_{wire}
Wahl Correction Factor K_{w1}=	1.5680759	unitless		(4C-1)/(4C-4)+0.615/C
Wahl Correction Factor K_{w2}=	1.1640625	unitless		1+(0.5/C)
Calculated Maximum Force on Spring				
Maximum Force @ L_{solid}=	30854.889	lbf		$k(L_{free}-L_{solid})$
Torsional Stress Check				
Torsional Stress in Spring @ L_{defl}=	78024.665	psi	OK	$(8FD_{mean})/(\pi D_{wire}^3)$*(greater of K_{w1} and K_{w2})≤0.45τ
Torsional Stress in Spring @ L_{solid}=	85143.849	psi	OK	$(8F_{max}D_{mean})/(\pi D_{wire}^3)$*(greater of K_{w1} and K_{w2})≤0.45τ
Buckling Check				
Length to Diameter Ratio=	3.59375	unitless	OK	$L_{free}/D_{mean}<4$
Deflection to Free Length Ratio=	0.1024457	unitless	OK	$(L_{free}-L_{defl})/L_{free}<0.45$
Load Tolerance Check				
Metric D_{wire}=	53.34	mm		D_{wire}*25.4
Metric D_{mean}=	162.56	mm		D_{mean}*25.4
Metric Spring Index C=	3.047619	unitless		Metric D_{mean}/Metric D_{wire}
Metric Demand F=	125773.42	Newtons		F*4.44822
Factor Af=	12510.517	unitless		65.92(Metric $D_{wire}^{3.3}$/Metric $D_{mean}^{1.6}$)(-0.84(Metric C/10)^3+3.781(Metric C/10)^2-4.244(Metric C/10)+2.274)
Factor Kf=	1.0156213	unitless		$1/(3n_a^2)+8/(5n_a)+0.803$
± Tolerance=	3280.5367	lbf		±(Af)(Kf)+(1.5p)/100
Spreadsheet Check				
K based on Active Turns	12000	OK		$(GD_{wire}^4)/(8n_aD_{mean}^3)=k$
K based on Demand	12000	OK		$F/(L_{free}-L_{defl})=k$
K Based on Fmax	12000	OK		$F_{max}/(L_{free}/L_{solid})=k$

C.2 Tension Rod Design

Four tension rods were designed to align the frame elements and react against the compression forces applied to the concrete specimens. These tension members were design per the AISC Steel Construction Manual. Ultimately, four 12-foot long coarse threaded 1.5-inch diameter rods made of Grade 2 steel were specified to carry the tension load in the frame.

C.3 Reaction Plate Design

The four reaction plates in the frame were analyzed through a finite element model that was produced using Visual Analysis by IES. The upper reaction plates were 15-by-15-inches and the lower reaction plates were specified at 20-by-20-inches. Each of the four plates was 2.5-inches thick and they were cut from standard A36 steel. The following figures show the dimensions and machining elements for each of the reaction plates.

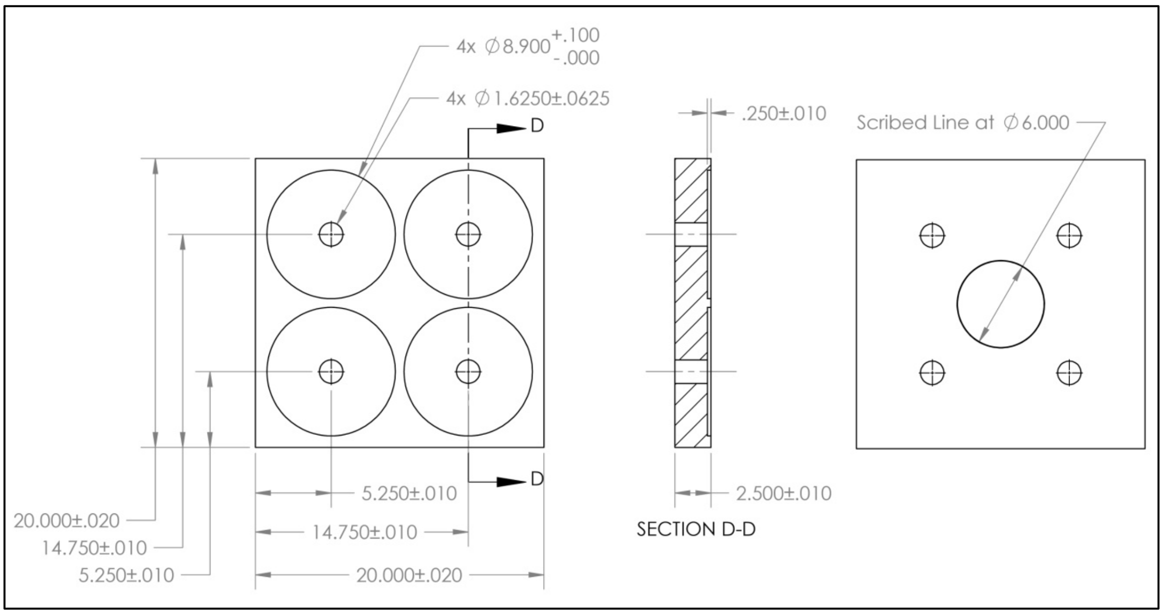


Figure 92: Bottom Lower Reaction Plate

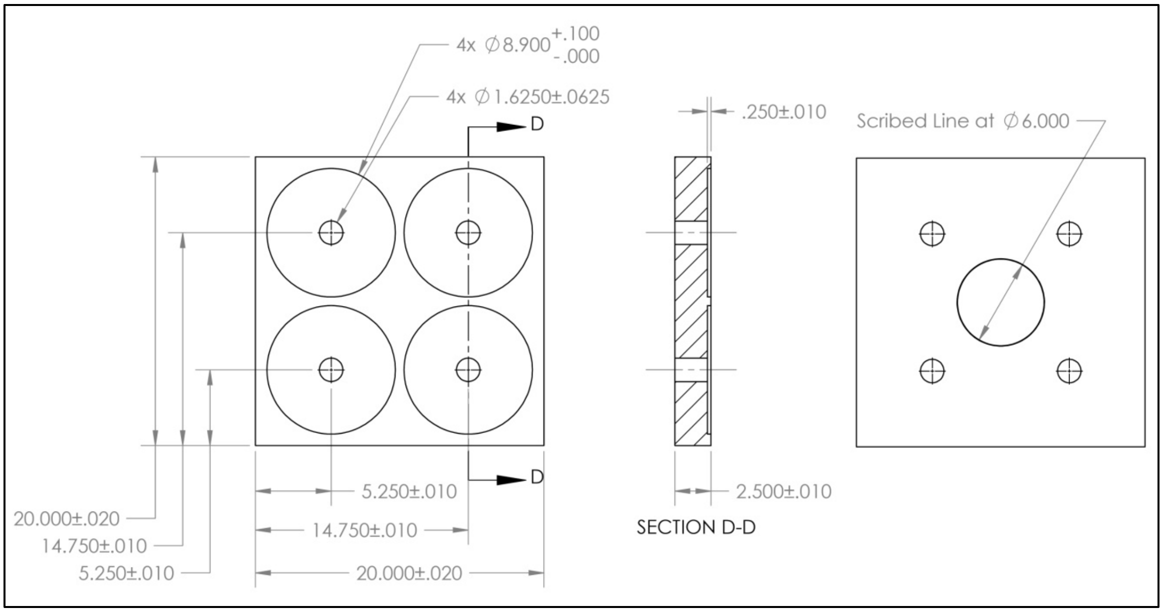


Figure 93: Top Lower Reaction Plate

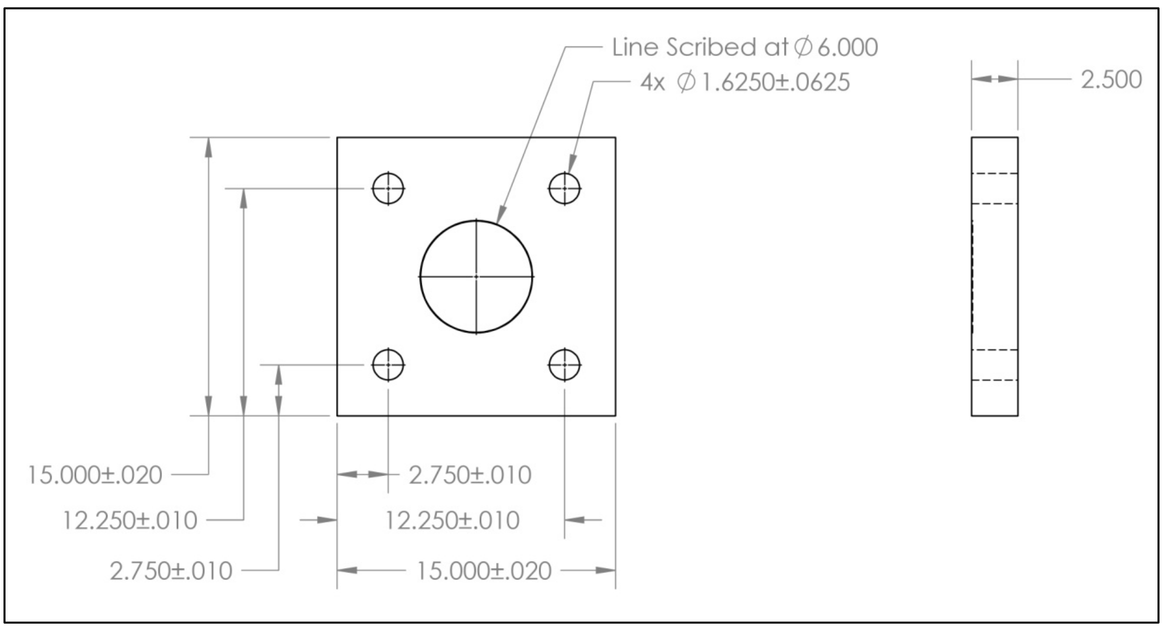


Figure 94: Bottom Upper Reaction Plate

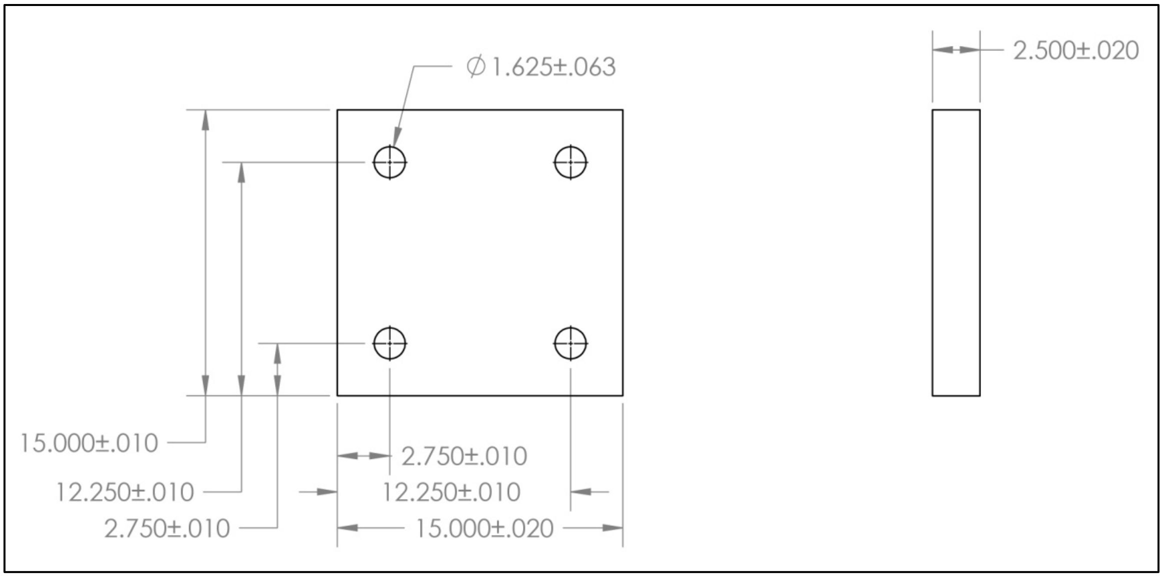


Figure 95: Top Upper Reaction Plate

C.4 Creep Frame Assembly

The concrete creep testing frame plates were pre-machined at a local metal shop in Bozeman, Montana and the apparatuses were assembled using an overhead crane in the MSU Structures Lab. Pictures representing the progressing phases of construction can be seen in the following photographs.

Figure 96: Creep Frame Base Assembly

Figure 97: Creep Frame Upper Reaction Plate Assembly

APPENDIX D: MIX CALCULATOR, PROPORTIONS, AND DATASHEETS FOR INITIAL EXPERIMENTAL DESIGN

Table 40 is an example of the mix design calculator that was developed for this project and used to calculate the material quantities for each of the tested mixes. The following tables provide the mix proportions and datasheets that were used throughout this experimental design.

Table 40: RAP in PCCP Mix Design Calculator

Mix Specifications		
Mix ID:	RAP DOE 17.1	
W/C	0.3500	unitless
Air Dosage Rate	150.0000	mL/100#
Paste Content	0.3350	percent
Fly Ash Replacement Rate	0.1500	fraction by wt
Volume	2.9000	cuft
Coarse to Fine Ratio	1.3600	unitless
Fine RAP Replacement Rate	0.2500	fraction by vol
Coarse RAP Replacement Rate	0.6250	fraction by vol

Air Estimate Calculation		
Target	7.6	percent

Aggregates	
Type	Specific Gravity
Coarse RAP	2.45
Fine RAP	2.30
Coarse Virgin	2.69
Fine Virgin	2.60

Cement	
Type	Specific Gravity
Portland Type I-II	3.15
Fly Ash	2.82
Weighted Average	3.1005

Admixtures		
Type	Percent of Mix	Specific Gravity
Micro Air	7.6	1.01
Dosage Information		
use 0.125 to 1.5 fl oz/cwt of concrete		

Mix Proportions		
Item	Percent	Volume (cuft)
Water + Cementitious	33.50	0.97
Coarse	33.96	0.98
Fine	24.97	0.72
Air	7.57	0.22
Totals	100.0	2.9

Mix Weights				
Item	Fraction of Volume	Volume		Dry Mix Weight (lbs)
Water	0.5204	0.5056	cuft	31.5489
Portland Cement	0.4006	0.3892	cuft	76.4993
Fly Ash	0.0790	0.0767	cuft	13.4999
Coarse Aggregate		0.9848	cuft	
RAP		0.6155	cuft	94.0972
Virgin		0.3693	cuft	61.9889
Fine Aggregate		0.7241	cuft	
RAP		0.1810	cuft	25.9812
Virgin		0.5431	cuft	88.1102

Water Adjustments				
Item	Fine RAP	Coarse RAP	Fine Virgin	Coarse Virgin
Moisture Content (%)	4.66	2.31	1.31	0.31
Absorption Capacity (%)	6.3	3.9	2.1	1.4
Water Adjustment for SSD (lbs)	0.4	1.5	0.7	0.7
Total Additional Water (lbs)	3.3			

	Fine RAP				Coarse RAP				Fine Virgin				Coarse Virgin			
	Wet	Dry	Pan	MC	Wet	Dry	Pan	MC	Wet	Dry	Pan	MC	Wet	Dry	Pan	MC
Sample 1	1268.1	1245.4	315.9	2.442173	1664.9	1639.7	321.6	1.911843	1717.6	1702.5	331.2	1.101145	4200.3	4194.4	2306.2	0.312467
Sample 2	1358.8	1288.4	324.8	7.305936	1027.1	1007.2	121.7	2.247318	967.9	958	231.5	1.362698	3976.9	3970.9	2242.4	0.347122
Sample 3	1159.2	1125.6	328.9	4.217397	1005.3	981.5	127.1	2.785581	3487.3	3469.6	2273.1	1.479315	4241.6	4236.5	2304.5	0.263975
Average Moisture Content				4.655169				2.314914				1.314386				0.307855

Final Mix Design Proportions	
Item	Amount
Water (lbs)	34.8
Portland Cement (lbs)	76.5
Fly Ash (lbs)	13.5
MicroAir (mL)	114.7
Coarse RAP (lbs)	96.3
Coarse Virgin (lbs)	62.2
Fine RAP (lbs)	27.2
Fine Virgin (lbs)	89.3

Table 41: RAP RSM 17.1 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 17.1	
W/C	0.350	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	8/25/2010
Time of Material Prep	1:15 to 1:45 PM
Time of Mix	2:00 PM
Ambient Temperature	80ish, sunny
Technician(s)	Kate, Beth, Lenci

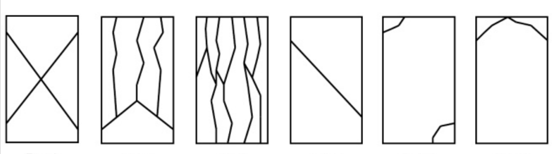
Notes- Moisture content data was highly variable

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	34.8	71.8
Portland Cement	76.5	69.6
Fly Ash	13.5	57.4
MicroAir (mL)	114.7	--
Coarse RAP	96.3	66.2
Coarse Virgin	62.2	66.6
Fine RAP	27.2	65.8
Fine Virgin	89.3	65.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	70.0	Beth
Slump (in)	0.1875	Lenci
Air Content (%)	3.8%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	8/26/2010		9/1/2010		9/22/2010	
	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
Test Data	15870	6	42200	3	55990	5
	15340	3	45720	3	53530	3
	16820	3	46250	3	51890	3
Average Compressive Strength (psi)	1274		3559		4282	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	9/22/2010
Test Data (lbs)	10240
	8550
Tested MOR	870
Empirical MOR	491

Notes-

Table 42: RAP RSM 18.2 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 18.2	
W/C	0.450	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	8/26/2010
Time of Material Prep	12:00 to 12:30 PM
Time of Mix	12:45 PM
Ambient Temperature	high 80s, sunny
Technician(s)	

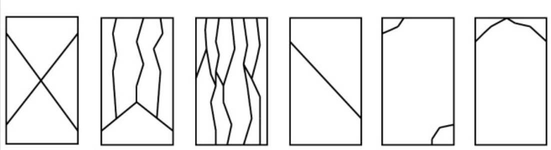
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.6	
Portland Cement	66.6	
Fly Ash	11.8	
MicroAir (mL)	99.9	
Coarse RAP	96.3	
Coarse Virgin	62.2	
Fine RAP	27.2	
Fine Virgin	89.3	

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)		
Slump (in)		
Air Content (%)		

Mix data was lost for this batch, must redo at later date

Compressive Strength Testing Data						
Age	1		7		28	
Date	8/27/2010		9/2/2010		9/23/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	5960	2	17600	6	22990	3
	5980	2	18100	6	22130	3
	5240	2	15790	6	24590	3
Average Compressive Strength (psi)	456		1366		1849	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	9/23/2010
Test Data (lbs)	5050
	4760
Tested MOR	454
Empirical MOR	323

Notes-

Table 43: RAP RSM 18.2 Redo Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 18.2 Redo	
W/C	0.450	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	10/13/2010
Time of Material Prep	2:30 to 3 PM
Time of Mix	3:30 PM
Ambient Temperature	70ish, sunny
Technician(s)	Beth, Keith, Josh

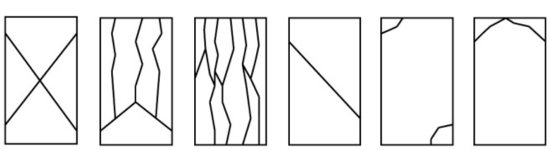
Notes- Material and moisture content from the night before. New cement haluled from Holcim this morning. Had hard time getting consistent temperature reading on cement. Material was significantly warmer than usual, with "pockets" of different temperatures. 9 lbs of coarse RAP taken from bag, not enough in buckets.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.6	51.5
Portland Cement	66.6	89.7
Fly Ash	11.8	62.5
MicroAir (mL)	99.9	--
Coarse RAP	96.3	63.6
Coarse Virgin	62.2	63.2
Fine RAP	27.2	63.7
Fine Virgin	89.3	63.4

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	64.6	Beth
Slump (in)		Josh
Air Content (%)	12.00%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/14/2010		10/20/2010		11/10/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	4010	4	17880	6	24060	6
	3720	2	21070	5	21090	6
	4310	2	19340	5	23790	3
Average Compressive Strength (psi)	319		1546		1829	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	11/10/2010
Test Data (lbs)	3430
	4460
Tested MOR	365
Empirical MOR	321

Notes-

Table 44: RAP RSM 18.2 Redo 2 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 18.2 Redo 2	
W/C	0.450	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	11/3/2010
Time of Material Prep	11:00 to 11:30 AM
Time of Mix	11:30 AM
Ambient Temperature	60s sunny
Technician(s)	Beth and Keith

Notes- Material and moisture content from night before.

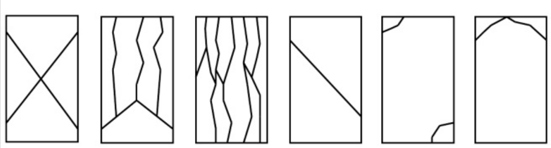
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	39.7	50.5
Portland Cement	66.6	46.3
Fly Ash	11.8	55.7
MicroAir (mL)	99.9	--
Coarse RAP	95.5	72.2
Coarse Virgin	62.4	72.9
Fine RAP	27.1	72.5
Fine Virgin	88.8	72.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	66.0	Beth
Slump (in)	7.75	Keith
Air Content (%)	13.00%	Beth

Notes-

Compressive Strength Testing Data						
Age	1		7		28	
Date	11/4/2010		11/10/2010		12/1/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	7800	3	18970	6	24040	5
	8520	3	18020	3	21630	3
	8500	5	17280	6	23050	3
Average Compressive Strength (psi)	658		1440		1823	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	12/1/2010
Test Data (lbs)	4750
	4830
Tested MOR	444
Empirical MOR	320

Notes-

Table 45: RAP RSM 30.3 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 30.3	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	8/27/2010
Time of Material Prep	12:30 to 1:30 PM
Time of Mix	1:45 PM
Ambient Temperature	75s, sunny
Technician(s)	Beth and Lenci

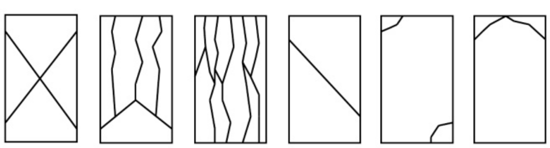
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	37.9	56.8
Portland Cement	71.2	81.0
Fly Ash	12.6	78.4
MicroAir (mL)	106.8	--
Coarse RAP	95.2	67.5
Coarse Virgin	62.3	67.3
Fine RAP	26.6	68.0
Fine Virgin	89.7	67.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	69.1	Beth
Slump (in)	6	Lenci
Air Content (%)	13.00%	Beth

Notes- Wheel barrow full of concrete was spilled on the floor. Beth did second air test with different gauge and got 13% again. Second slump test about 45 min after mix came out at 4.875" by Lenci.

Compressive Strength Testing Data						
Age	1		7		28	
Date	8/28/2010		9/3/2010		9/24/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	6180	4	17170	6	27320	3
	5960	4	19990	6	27650	6
	5760	4	20500	6	26230	3
Average Compressive Strength (psi)	475		1529		2154	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	9/24/2010
Test Data (lbs)	5540
	4970
Tested MOR	487
Empirical MOR	348

Notes - Rupture beam 1 was broke at the load rate of 600 lbf/sec. Could be a false high strength value.

Table 46: RAP RSM 25.4 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 25.4	
W/C	0.400	unitless
Air Dosage Rate	50.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	8/28/2010
Time of Material Prep	10:00 to 10:30 AM
Time of Mix	10:30 AM
Ambient Temperature	60s, partly cloudy
Technician(s)	Beth and Lenci

Notes- All material had a light sprinkling of water when the hose was dropped on the trigger

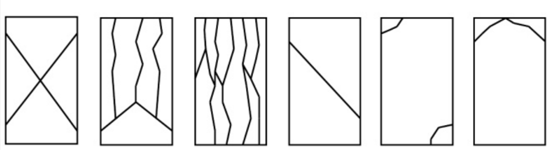
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	38.1	69.1
Portland Cement	71.2	65.8
Fly Ash	12.6	66.7
MicroAir (mL)	35.6	--
Coarse RAP	100.7	68.9
Coarse Virgin	65.9	67.8
Fine RAP	28.2	68.2
Fine Virgin	94.9	67.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	71.1	Lenci
Slump (in)	5.875	Lenci
Air Content (%)	6.80%	Beth

Notes- Second slump by Lenci after mix had sat for about 30 minutes came out at 3.875". Second air test by Beth was 6.2%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	8/29/2010		9/4/2010		9/25/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	14850	2	34580	2	40290	6
	16220	2	32590	4	40820	3
	15630	3	31200	3	41270	3
Average Compressive Strength (psi)	1239		2609		3246	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Notes- & day (9/4) cylinders were broke by Colter

Rupture Strength Testing Data	
Age	28
Date	9/25/2010
Test Data (lbs)	7260
	6820
Tested MOR	652
Empirical MOR	427

Notes- Rupture beams were broke on 9/27 (30 days)

Table 47: RAP RSM 3.5 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 3.5	
W/C	0.375	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	8/30/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	50s, cool, rainy
Technician(s)	Beth and Lenci

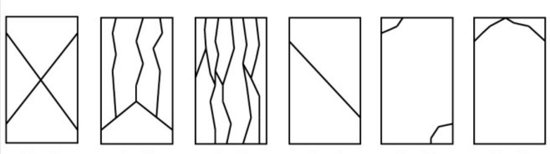
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	34.7	57.9
Portland Cement	66.6	52.5
Fly Ash	11.8	56.1
MicroAir (mL)	66.6	--
Coarse RAP	72.2	66.4
Coarse Virgin	101.3	66.7
Fine RAP	43.3	66.6
Fine Virgin	80.5	67.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	66.9	Beth
Slump (in)	2.625	Lenci
Air Content (%)	7.20%	Beth

Notes- Lenci did second slump test immediately after the first and it came out at 2.75"

Compressive Strength Testing Data						
Age	1		7		28	
Date	8/31/2010		9/6/2010		9/27/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	11380	2	30900	4	37960	4
	11380	2	32380	5	40700	4
	12460	2	31890	3	41710	6
Average Compressive Strength (psi)	934		2524		3193	

ASTM Fracture Type



Notes- 7-day cylinders were broke at 11 PM

Rupture Strength Testing Data	
Age	28
Date	9/27/2010
Test Data (lbs)	7090
	6050
Tested MOR	608
Empirical MOR	424

Notes-

Table 48: RAP RSM 28.6 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 28.6	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	8/31/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	60s, partly cloudy
Technician(s)	Beth and Josh

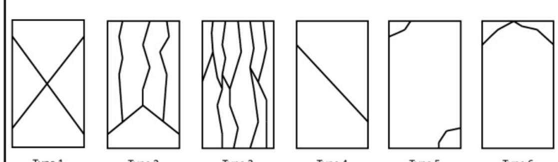
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.1	66.2
Portland Cement	71.2	54.9
Fly Ash	12.6	54.9
MicroAir (mL)	106.8	--
Coarse RAP	96.9	67.5
Coarse Virgin	62.4	64.8
Fine RAP	26.9	64.4
Fine Virgin	89.4	67.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	68.4	Beth
Slump (in)	4.25	Josh
Air Content (%)	10.00%	Beth

Notes- Second slump by Josh came out at 4.125", second air test by Beth was 10%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/1/2010		9/7/2010		9/28/2010	
	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
Test Data	7870	4	26040	5	30790	6
	7500	6	24580	3	33790	6
	7420	6	24260	6	32870	5
Average Compressive Strength (psi)	605		1986		2585	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	9/28/2010
Test Data (lbs)	5790
	4170
Tested MOR	461
Empirical MOR	381

Notes-

Table 49: RAP RSM 1.7 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 1.7	
W/C	0.375	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	9/1/2010
Time of Material Prep	1:00 to 2:00 PM
Time of Mix	3:00 PM
Ambient Temperature	60s, rainy
Technician(s)	Beth, Josh, Lenci

Notes- Material was sealed in buckets prior to mix.

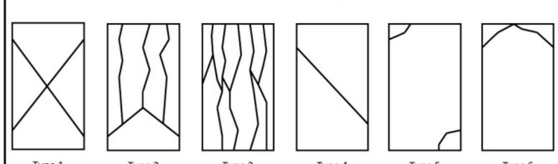
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	31.8	68.0
Portland Cement	66.6	59.0
Fly Ash	11.8	64.0
MicroAir (mL)	133.2	--
Coarse RAP	69.6	65.7
Coarse Virgin	96.0	66.0
Fine RAP	13.8	66.6
Fine Virgin	107.0	66.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	70.0	Beth
Slump (in)	1.25	Josh
Air Content (%)	6.20%	Beth

Notes- Second air test by Beth was 6.4%. Second slump by Josh was 1.25".

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/2/2010		9/8/2010		9/29/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9840	3	42260	4	41190	3
	9920	4	41770	4	49350	4
	9280	6	39180	3	47450	4
Average Compressive Strength (psi)	770		3268		3660	

ASTM Fracture Type



Notes- Machine exceeded allowed stored points on 9/8, thus data was unable to be recorded for the third sample. The extra cylinder was broke to obtain the final data point.

Rupture Strength Testing Data	
Age	28
Date	9/29/2010
Test Data (lbs)	7620
	7180
Tested MOR	685
Empirical MOR	454

Notes-

Table 50: RAP RSM 26.8 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 26.8	
W/C	0.400	unitless
Air Dosage Rate	250.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/7/2010
Time of Material Prep	13:30 to 11:00 AM
Time of Mix	1:45 PM
Ambient Temperature	70s, sunny
Technician(s)	Beth and Josh

Notes- Material was sealed in buckets over the long weekend. After material was weighed out, the buckets sat uncovered from material prep time until mix time.

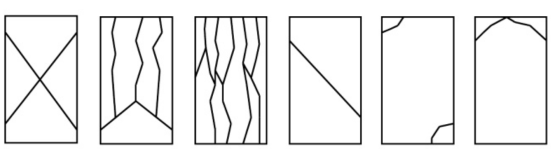
Mix Proportions and Information		
Item	Amount (lbs)	Temp (ºF)
Water	36.7	61.7
Portland Cement	71.2	59.7
Fly Ash	12.6	59.0
MicroAir (mL)	178.0	--
Coarse RAP	90.9	63.9
Coarse Virgin	58.8	64.4
Fine RAP	25.5	63.9
Fine Virgin	84.0	63.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (ºF)	68.4	Beth
Slump (in)	4.75	Josh
Air Content (%)	13.00%	Beth

Notes- Second air test by Beth came out at 13%, second slump by Josh was 5.0 inches.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/8/2010		9/14/2010		10/5/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	6490	3	19520	6	25730	4
	6780	3	19390	6	24440	6
	6260	6	19970	6	22490	6
Average Compressive Strength (psi)	518		1562		1927	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/5/2010
Test Data (lbs)	4750
	4970
Tested MOR	450
Empirical MOR	329

Notes-

Table 51: RAP RSM 27.9 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 27.9	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/8/2010
Time of Material Prep	2:30 to 3:00 PM 9/7
Time of Mix	3:00 PM
Ambient Temperature	60s, cool and rainy
Technician(s)	Josh, Keith, Beth

Notes- Some condensation was noted on the fine RAP bucket lids. Material was sealed in buckets over the long weekend and then used for the mix. The material was weighed out on the afternoon of 9/7, but the mix did not take place till 9/8.

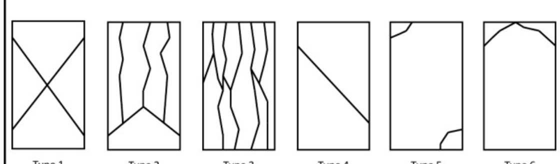
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.8	
Portland Cement	71.2	
Fly Ash	12.6	
MicroAir (mL)	106.8	
Coarse RAP	96.4	
Coarse Virgin	62.3	
Fine RAP	27.0	
Fine Virgin	89.1	

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.1	Beth
Slump (in)	5.125	Josh
Air Content (%)	12.00%	Beth

Notes- Beth, Keith, and Josh were present for mix. Second slump by josh = 4.75". Second air by Beth = 11.5%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/9/2010		9/15/2010		10/6/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	5940	5	22540	3	28600	5
	6360	5	24290	3	30660	6
	5980	5	26320	3	28930	6
Average Compressive Strength (psi)	485		1940		2339	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/6/2010
Test Data (lbs)	6300
	5050
Tested MOR	525
Empirical MOR	363

Notes- First rupture beam was broke at 600 lbf/second. Could be false high rupture strength.

Table 52: RAP RSM 8.10 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 8.10	
W/C	0.375	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	9/9/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	60s, partly cloudy
Technician(s)	Josh, Keith, Beth

Notes- Material and moisture content from the night before.

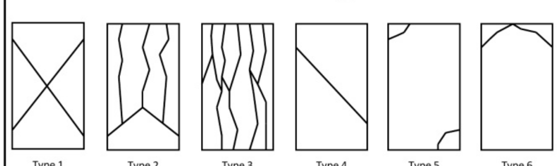
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	38.7	55.0
Portland Cement	80.9	55.9
Fly Ash	14.3	55.8
MicroAir (mL)	80.9	--
Coarse RAP	121.8	63.5
Coarse Virgin	30.3	64.0
Fine RAP	39.8	66.2
Fine Virgin	72.7	64.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	67.6	Beth
Slump (in)	4.0625	Josh
Air Content (%)	6.80%	Beth

Notes- Second slump by Josh = 4.125". Second air by Beth = 6.6%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/10/2010		9/16/2010		10/7/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	14090	3	28480	5	35510	5
	13950	4	28560	3	38430	3
	14950	4	29570	4	34500	4
Average Compressive Strength (psi)	1140		2297		2876	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/7/2010
Test Data (lbs)	6370
	5820
Tested MOR	564
Empirical MOR	402

Notes- The rupture beam molds were not prepared with form oil prior to casting the specimens. Could potentially lead to higher tested rupture strength values.

Table 53: RAP RSM 22.11 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 22.11	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/9/2010
Time of Material Prep	11:45 to 12:15
Time of Mix	12:15 PM
Ambient Temperature	60s, partly cloudy
Technician(s)	Beth, Keith, Josh

Notes- material and moisture content data from night before.

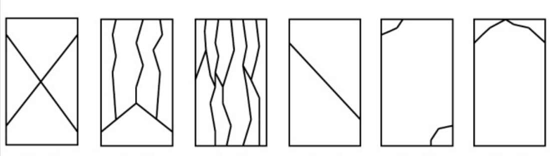
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	36.5	53.4
Portland Cement	71.2	55.4
Fly Ash	12.6	59.0
MicroAir (mL)	106.8	--
Coarse RAP	96.2	64.4
Coarse Virgin	62.3	62.8
Fine RAP	54.5	63.9
Fine Virgin	59.8	63.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	66.0	Beth
Slump (in)	3.75	Josh
Air Content (%)	8.50%	Beth

Notes- Second slump by Josh = 3.375". Second air by Beth = 8.0%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/10/2010		9/16/2010		10/7/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10440	4	24070	6	27380	6
	10740	4	24260	3	30060	5
	11820	4	24700	6	29960	6
Average Compressive Strength (psi)	875		1937		2318	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/7/2010
Test Data (lbs)	4920
	4800
Tested MOR	450
Empirical MOR	361

Notes- The rupture beam molds were not prepared with form oil prior to casting the specimens. Could potentially lead to higher tested rupture strength values.

Table 54: RAP RSM 11.12 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 11.12	
W/C	0.425	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	9/10/2010
Time of Material Prep	2:30 to 3:00 PM
Time of Mix	3:00 PM
Ambient Temperature	hi 50s, rainy
Technician(s)	Beth, Josh, Keith

Notes- Addiotnal cement supply was obtained from Holcim

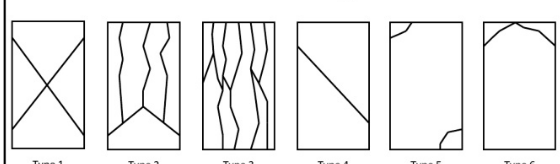
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	35.0	64.4
Portland Cement	62.1	53.2
Fly Ash	11.0	54.0
MicroAir (mL)	124.3	--
Coarse RAP	68.8	66.9
Coarse Virgin	95.9	63.3
Fine RAP	41.7	66.2
Fine Virgin	76.2	64.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	67.5	Beth
Slump (in)	5	Josh
Air Content (%)	12.00%	Beth

Notes- Second slump by Josh = 4.875". Second air by Beth = 12%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/11/2010		9/17/2010		10/8/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	6050	3	20520	6	22580	3
	5830	6	21400	6	23730	6
	5680	3	20810	6	24510	6
Average Compressive Strength (psi)	466		1664		1879	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/8/2010
Test Data (lbs)	4460
	4690
Tested MOR	424
Empirical MOR	325

Notes-

Table 55: RAP RSM 5.13 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 5.13	
W/C	0.375	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

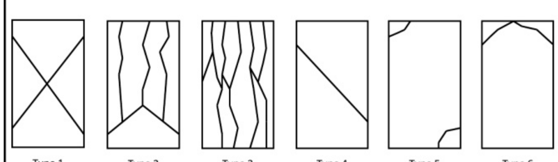
Mix Conditions	
Date	9/13/2010
Time of Material Prep	10:30 to 11:15 AM
Time of Mix	11:30 AM
Ambient Temperature	70s, sunny
Technician(s)	Beth, Keith, Josh
Notes - Material and moisture content prepared over weekend	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.9	54.3
Portland Cement	80.9	56.5
Fly Ash	14.3	60.3
MicroAir (mL)	80.9	--
Coarse RAP	65.4	63.7
Coarse Virgin	91.0	63.9
Fine RAP	13.3	66.2
Fine Virgin	101.2	66.0

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	66.7	Beth
Slump (in)	5.375	Josh
Air Content (%)	9.50%	Beth
Notes - Second slump by Josh = 5.5". Second air by Beth = 9%.		

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/14/2010		9/20/2010		10/11/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	12300	6	33520	3	41760	6
	13770	3	35170	3	42850	6
	11570	3	37440	4	41110	6
Average Compressive Strength (psi)	998		2815		3335	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/11/2010
Test Data (lbs)	7390
	6420
Tested MOR	639
Empirical MOR	433
Notes-	

Table 56: RAP RSM 19.14 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 19.14	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.270	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/14/2010
Time of Material Prep	10:30 to 11:15 AM
Time of Mix	11:30AM
Ambient Temperature	70s, sunny
Technician(s)	Beth, Keith, Josh

Notes- Material and moisture content from over weekend

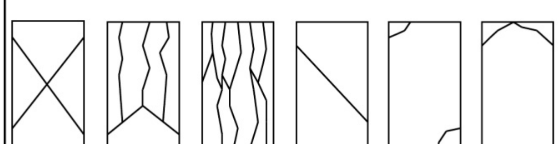
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	31.1	54.3
Portland Cement	57.4	56.5
Fly Ash	10.1	60.3
MicroAir (mL)	86.1	--
Coarse RAP	106.5	63.7
Coarse Virgin	69.2	63.9
Fine RAP	30.2	66.2
Fine Virgin	98.9	66.0

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	66.7	Beth
Slump (in)	5.375	Josh
Air Content (%)	9.50%	Beth

Notes- Second slump by Josh = 5.5". Second air by Beth = 9%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/15/2010		9/21/2010		10/12/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	12840	4	29570	3	37030	6
	13660	4	29530	3	35310	6
	13250	4	29060	3	39660	6
Average Compressive Strength (psi)	1054		2339		2971	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/12/2010
Test Data (lbs)	6390
	5820
Tested MOR	565
Empirical MOR	409

Notes-

Table 57: RAP RSM 12.15 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 12.15	
W/C	0.425	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	9/15/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	70s sunny
Technician(s)	Beth, Keith, Josh

Notes - Material and moisture content from night before.

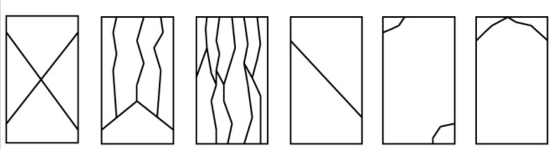
Mix Proportions and Information		
Item	Amount (lbs)	Temp (ºF)
Water	35.0	53.1
Portland Cement	62.1	58.1
Fly Ash	11.0	54.5
MicroAir (mL)	62.1	--
Coarse RAP	135.6	66.6
Coarse Virgin	33.8	65.1
Fine RAP	44.2	66.9
Fine Virgin	80.5	65.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (ºF)	65.8	Beth
Slump (in)	2.125	Josh
Air Content (%)	8.00%	Beth

Notes- Second air by Beth = 7.6%. Second slump by josh = 2.25".

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/16/2010		9/22/2010		10/13/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	12140	6	24670	6	29060	3
	12770	5	26030	4	31190	4
	12420	4	24240	3	31400	4
Average Compressive Strength (psi)	990		1988		2431	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/13/2010
Test Data (lbs)	6430
	5030
Tested MOR	531
Empirical MOR	370

Notes-

Table 58: RAP RSM 4.16 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 4.16	
W/C	0.375	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	9/15/2010
Time of Material Prep	12:00 to 12:30 PM
Time of Mix	12:30 PM
Ambient Temperature	70s sunny
Technician(s)	Beth, Keith, Josh

Notes- Material and moisture content from night before.

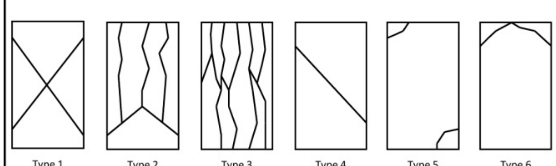
Mix Proportions and Information		
Item	Amount (lbs)	Temp (ºF)
Water	33.1	55.4
Portland Cement	66.6	63.0
Fly Ash	11.8	64.4
MicroAir (mL)	133.2	--
Coarse RAP	128.4	64.0
Coarse Virgin	32.0	64.9
Fine RAP	41.9	66.0
Fine Virgin	76.2	64.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (ºF)	64.9	Beth
Slump (in)	1.125	Josh
Air Content (%)	6.60%	Beth

Notes- A second air and slump test were not run for this mix. Some of the concrete was spilled when poured into the wheel barrow. A portion of the material that landed on the floor was recovered for use in the samples, but only the concrete that was on top of the spill.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/16/2010		9/22/2010		10/13/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	15480	4	28930	6	32500	3
	15210	5	28610	6	32790	3
	15220	5	28540	6	34210	3
Average Compressive Strength (psi)	1218		2283		2639	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/13/2010
Test Data (lbs)	6260
	5420
Tested MOR	541
Empirical MOR	385

Notes- Second beam was loaded once and did not appear to break, however, the machine stored data at 1260 lbs. The beam was reloaded until obvious failure and a load of 5420 lbs was recorded.

Table 59: RAP RSM 15.17 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 15.17	
W/C	0.425	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	9/17/2010
Time of Material Prep	12:00 to 12:45 PM
Time of Mix	1:00 PM
Ambient Temperature	50s, cool and windy
Technician(s)	Beth

Notes- Material and moisture content from Wednesday

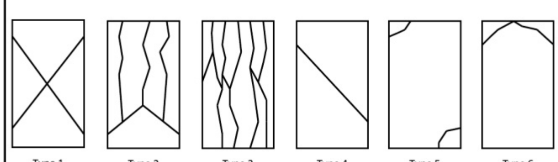
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	41.4	52.9
Portland Cement	75.5	58.1
Fly Ash	13.3	60.3
MicroAir (mL)	75.5	--
Coarse RAP	64.8	68.7
Coarse Virgin	91.0	65.5
Fine RAP	39.6	66.2
Fine Virgin	72.7	68.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	65.8	Beth
Slump (in)	8.5	Beth
Air Content (%)	10.00%	Beth

Notes- A second air and slump test were not performed in order to save time, as Beth was the only person available to do all testing and casting of specimens.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/18/2010		9/24/2010		10/15/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9410	6	26870	6	30350	4
	8780	4	26830	3	27280	6
	9340	4	26590	3	31400	6
Average Compressive Strength (psi)	730		2130		2362	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/15/2010
Test Data (lbs)	5510
	6110
Tested MOR	538
Empirical MOR	364

Notes-

Table 60: RAP RSM 29.18 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 29.18	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/20/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	60s sunny
Technician(s)	Beth, Keith

Notes- Material and moisture content data from last week.

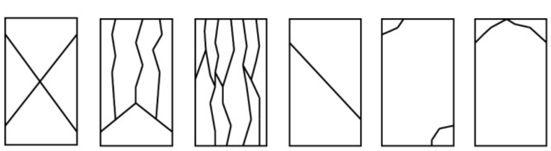
Mix Proportions and Information		
Item	Amount (lbs)	Temp (ºF)
Water	37.6	61.5
Portland Cement	71.2	59.0
Fly Ash	12.6	63.9
MicroAir (mL)	106.8	--
Coarse RAP	95.1	64.4
Coarse Virgin	62.3	66.0
Fine RAP	27.1	64.4
Fine Virgin	89.6	66.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (ºF)	68.7	Beth
Slump (in)	5.25	Keith
Air Content (%)	12.00%	Beth

Notes- Second slump 5.375" by Keith. Second air was 12% by Beth.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/21/2010		9/27/2010		10/18/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	11000	3	23100	6	27580	3
	11630	3	23270	6	27320	6
	12110	3	23100	4	28520	6
Average Compressive Strength (psi)	922		1843		2213	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/18/2010
Test Data (lbs)	4830
	6080
Tested MOR	505
Empirical MOR	353

Notes-

Table 61: RAP RSM 24.19 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 24.19	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

Mix Conditions	
Date	9/21/2010
Time of Material Prep	10:30 to 11:00
Time of Mix	11:00 AM
Ambient Temperature	60s, sunny
Technician(s)	Beth and Keith

Notes- Material and moisture content from night before.

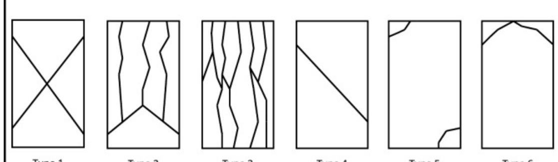
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	38.1	60.8
Portland Cement	71.2	48.4
Fly Ash	12.6	54.8
MicroAir (mL)	106.8	--
Coarse RAP	152.3	63.8
Coarse Virgin	0.0	--
Fine RAP	27.0	63.9
Fine Virgin	90.2	63.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	65.8	Beth
Slump (in)	5.375	Keith
Air Content (%)	13.00%	Beth

Notes- Second slump by Keith = 5.25 in. Second air by Beth = 12.5%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/22/2010		9/28/2010		10/19/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9640	6	19610	6	21410	6
	9590	5	17950	6	22190	6
	10260	6	18250	4	24060	3
Average Compressive Strength (psi)	782		1480		1795	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/19/2010
Test Data (lbs)	5350
	4810
Tested MOR	470
Empirical MOR	318

Notes-

Table 62: RAP RSM 21.20 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 21.20	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.000	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	9/24/2010
Time of Material Prep	3:00 to 3:30 PM
Time of Mix	3:30 PM
Ambient Temperature	60s, sunny
Technician(s)	Josh, Beth, Keith

Notes- One bucket of RAP was taken directly from the bag, as there was not enough material sealed up from the moisture content test.

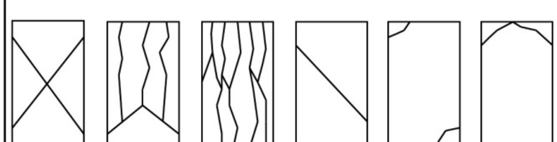
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	36.4	52.8
Portland Cement	71.2	67.7
Fly Ash	12.6	62.7
MicroAir (mL)	106.8	--
Coarse RAP	95.2	55.4
Coarse Virgin	62.3	64.2
Fine RAP	0.0	--
Fine Virgin	120.2	64.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	65.9	Beth
Slump (in)	4.125	Josh
Air Content (%)	11.00%	Beth

Notes- Second air by Beth was 17% (not sure if this values is reasonable, may have been something wrong with pressure meter). Second slump by Josh was 4.25 inches.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/25/2010		10/1/2010		10/22/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10010	4	25420	4	28990	5
	9610	6	25710	4	33350	6
	8620	6	25010	4	34870	6
Average Compressive Strength (psi)	749		2020		2579	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/22/2010
Test Data (lbs)	5530
	5490
Tested MOR	510
Empirical MOR	381

Notes-

Table 63: RAP RSM 6.21 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 6.21	
W/C	0.375	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	9/28/2010
Time of Material Prep	1:00 to 1:30 PM
Time of Mix	1:30 PM
Ambient Temperature	80s, sunny
Technician(s)	Beth, Keith, Josh

Notes- Material and moisture content from the day before

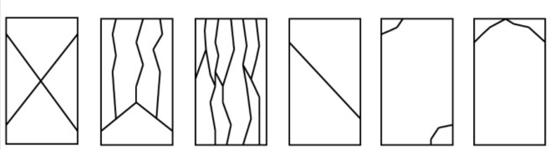
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	41.0	52.9
Portland Cement	80.9	70.5
Fly Ash	14.3	68.2
MicroAir (mL)	161.8	--
Coarse RAP	112.9	69.0
Coarse Virgin	28.5	69.6
Fine RAP	12.4	68.9
Fine Virgin	94.9	69.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	70.0	Beth
Slump (in)	6.375	Josh
Air Content (%)	12.50%	Beth

Notes- Timer was not started at beginning of 3 min mix, tried to adjust, could be off by 30ish seconds. Second slump by Josh was 6.5 inches. Second air by Beth was 13%.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/29/2010		10/5/2010		10/26/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	11930	5	22180	6	26300	3
	12100	5	23500	5	26050	3
	11750	5	22100	4	29760	6
Average Compressive Strength (psi)	949		1798		2178	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/26/2010
Test Data (lbs)	5270
	5880
Tested MOR	516
Empirical MOR	350

Notes-

Table 64: RAP RSM 7.22 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 7.22	
W/C	0.375	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	9/28/2010
Time of Material Prep	2:00 to 2:30 PM
Time of Mix	2:30 PM
Ambient Temperature	70s, sunny
Technician(s)	Beth, Keith

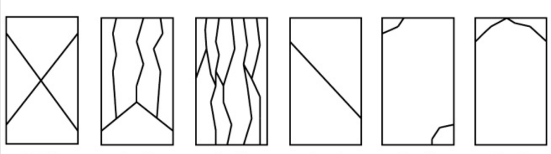
Notes- Moisture content and material from day before.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	40.2	54.2
Portland Cement	80.9	78.6
Fly Ash	14.3	81.2
MicroAir (mL)	161.8	--
Coarse RAP	60.8	69.6
Coarse Virgin	85.6	70.6
Fine RAP	37.1	70.1
Fine Virgin	67.8	69.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	70.0	Beth
Slump (in)	6	Josh
Air Content (%)	10.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/29/2010		10/5/2010		10/26/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	14190	3	26320	6	32180	6
	13370	6	26190	3	33710	6
	14390	5	25590	3	31830	6
Average Compressive Strength (psi)	1113		2072		2592	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	10/26/2010
Test Data (lbs)	5590
	5930
Tested MOR	533
Empirical MOR	382

Notes-

Table 65: RAP RSM 10.23 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 10.23	
W/C	0.425	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	9/29/2010
Time of Material Prep	11:00 to 11:30 PM
Time of Mix	11:30 PM
Ambient Temperature	60s, sunny
Technician(s)	Beth, Josh

Notes- Moisture content and material from night before

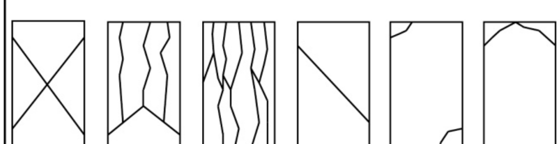
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	35.7	62.6
Portland Cement	62.1	62.6
Fly Ash	11.0	62.8
MicroAir (mL)	124.3	--
Coarse RAP	127.5	70.3
Coarse Virgin	32.1	70.1
Fine RAP	13.9	70.6
Fine Virgin	106.6	70.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	71.7	Beth
Slump (in)	5.125	Josh
Air Content (%)	12.50%	Beth

Notes- Initial mixing was 30 seconds longer than prescribed 3 min mixing.

Compressive Strength Testing Data						
Age	1		7		28	
Date	9/30/2010		10/6/2010		10/27/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9740	5	18740	6	21810	3
	9760	6	17870	6	23470	3
	10150	4	18870	6	22920	3
Average Compressive Strength (psi)	786		1472		1809	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	10/27/2010
Test Data (lbs)	3910
	4540
Tested MOR	391
Empirical MOR	319

Notes-

Table 66: RAP RSM 23.24 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 23.24	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.335	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.250	percent by vol

Mix Conditions	
Date	10/1/2010
Time of Material Prep	10 to 10:30 AM
Time of Mix	10:30 AM
Ambient Temperature	60s sunny
Technician(s)	Beth, Keith

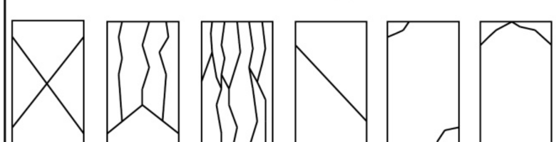
Notes- Material and moisture content from a couple days prior. New coarse aggregate was placed in the bins and used for this mix.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	36.6	53.0
Portland Cement	71.2	57.3
Fly Ash	12.6	58.4
MicroAir (mL)	106.8	--
Coarse RAP	38.2	67.7
Coarse Virgin	125.0	68.1
Fine RAP	27.0	69.3
Fine Virgin	89.0	68.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	66.7	Beth
Slump (in)	4.5	Keith
Air Content (%)	10.00%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/2/2010		10/8/2010		10/29/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	14310	6	29860	6	40260	2
	14800	6	30380	3	39720	2
	14330	5	30690	6	38780	6
Average Compressive Strength (psi)	1152		2412		3150	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Notes-

Rupture Strength Testing Data	
Age	28
Date	10/29/2010
Test Data (lbs)	6140
	6970
Tested MOR	607
Empirical MOR	421

Notes-

Table 67: RAP RSM 9.25 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 9.25	
W/C	0.425	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	10/4/2010
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:15 AM
Ambient Temperature	60s sunny
Technician(s)	Beth, Keith

Notes- Material and moisture content from over the weekend.

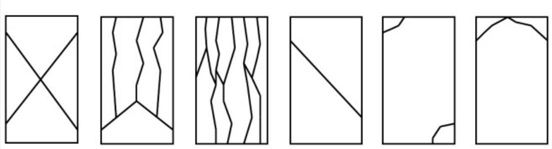
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	31.1	55.2
Portland Cement	62.1	70.3
Fly Ash	11.0	65.1
MicroAir (mL)	62.1	--
Coarse RAP	73.2	70.6
Coarse Virgin	101.5	70.7
Fine RAP	14.7	70.9
Fine Virgin	115.7	70.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	71.2	Beth
Slump (in)	3.25	Keith
Air Content (%)	8.00%	Beth

Notes- Second slump was 3" by Keith.

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/5/2010		10/11/2010		11/1/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	16200	6	29780	6	38770	6
	16080	6	33070	6	41220	6
	16660	3	34350	3	40990	3
Average Compressive Strength (psi)	1298		2578		3209	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Notes- Cure room may have been left off over the weekend 10/8 through 10/10.

Rupture Strength Testing Data	
Age	28
Date	11/1/2010
Test Data (lbs)	4280
	6010
Tested MOR	476
Empirical MOR	425

Notes-

Table 68: RAP RSM 20.26 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 20.26	
W/C	0.400	unitless
Air Dosage Rate	150.000	mL/100#
Paste Content	0.400	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.625	percent by vol

Mix Conditions	
Date	10/4/2010
Time of Material Prep	12 to 12:30 PM
Time of Mix	12:30 PM
Ambient Temperature	60s sunny
Technician(s)	Beth, Keith

Notes- Material and moisture content from over weekend.

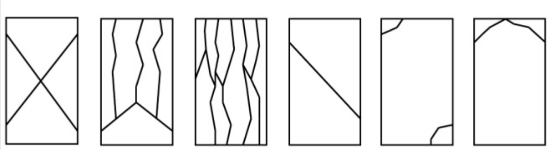
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	40.7	52.7
Portland Cement	85.0	67.6
Fly Ash	15.0	67.6
MicroAir (mL)	127.5	--
Coarse RAP	85.8	70.0
Coarse Virgin	55.6	70.2
Fine RAP	24.1	70.3
Fine Virgin	81.4	68.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.1	Beth
Slump (in)	7.5	Keith
Air Content (%)	10.00%	Beth

Notes- Second slump was 7.125" by Keith.

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/5/2010		10/11/2010		11/1/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	16960	6	26620	5	32600	6
	17140	6	29840	6	38290	3
	16330	6	28420	6	35910	3
Average Compressive Strength (psi)	1338		2252		2833	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	11/1/2010
Test Data (lbs)	6210
	5640
Tested MOR	549
Empirical MOR	399

Notes-

Table 69: RAP RSM 14.27 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 14.27	
W/C	0.425	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

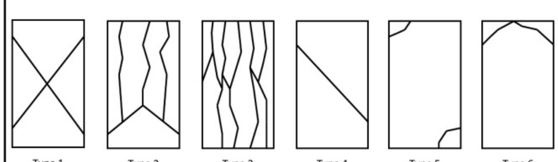
Mix Conditions	
Date	10/6/2010
Time of Material Prep	1:00 to 1:30 PM
Time of Mix	1:30 PM
Ambient Temperature	70s sunny
Technician(s)	Beth, Josh, Tim, Chris

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	39.2	53.6
Portland Cement	75.5	61.9
Fly Ash	13.3	62.6
MicroAir (mL)	75.5	--
Coarse RAP	121.3	67.1
Coarse Virgin	30.3	65.4
Fine RAP	13.3	66.6
Fine Virgin	103.7	65.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	63.9	Beth
Slump (in)	7.125	Josh
Air Content (%)	9.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/7/2010		10/13/2010		11/3/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10600	5	26070	6	29660	3
	11950	5	28130	4	33690	5
	11040	5	26110	6	32960	3
Average Compressive Strength (psi)	891		2130		2555	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	11/3/2010
Test Data (lbs)	5000
	5760
Tested MOR	498
Empirical MOR	379

Notes-

Table 70: RAP RSM 16.28 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 16.28	
W/C	0.425	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.375	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	10/5/2010
Time of Material Prep	2:30 to 3:00 PM
Time of Mix	3:00 PM
Ambient Temperature	60s partly cloudy
Technician(s)	Beth, Keith

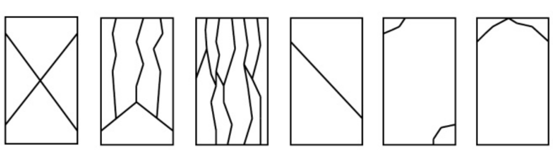
Notes- Material and moisture content from day before

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	39.7	53.9
Portland Cement	75.5	62.8
Fly Ash	13.3	61.3
MicroAir (mL)	151.0	--
Coarse RAP	115.1	67.9
Coarse Virgin	28.5	68.6
Fine RAP	37.0	68.2
Fine Virgin	69.4	68.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	66.6	Beth
Slump (in)	7.125	Keith
Air Content (%)	13.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/6/2010		10/12/2010		11/2/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	8440	3	19510	5	21400	3
	8840	3	18230	6	20330	3
	8290	3	19430	6	23190	3
Average Compressive Strength (psi)	678		1516		1722	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	11/2/2010
Test Data (lbs)	4330
	4380
Tested MOR	403
Empirical MOR	311

Notes-

Table 71: RAP RSM 13.29 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 13.29	
W/C	0.425	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.368	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.438	percent by vol

Mix Conditions	
Date	10/6/2010
Time of Material Prep	12 to 12:30 PM
Time of Mix	12:320 PM
Ambient Temperature	70s sunny
Technician(s)	Beth, Josh

Mnotes- MC and material from night before.

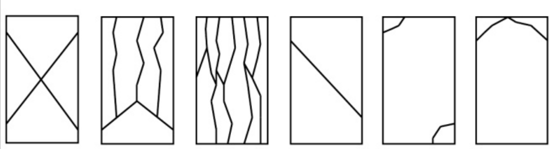
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	38.6	53.4
Portland Cement	75.5	55.5
Fly Ash	13.3	63.0
MicroAir (mL)	151.0	--
Coarse RAP	61.4	68.6
Coarse Virgin	85.6	68.4
Fine RAP	12.5	67.3
Fine Virgin	97.6	67.1

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	66.8	Beth
Slump (in)	8.125	Josh
Air Content (%)	11.50%	Beth

Notes- Second slump test by Josh was 7.625.

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/7/2010		10/13/2010		11/3/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	11060	6	258/00	6	33240	4
	9730	3	18420	3	30960	3
	11550	6	24860	5	34630	3
Average Compressive Strength (psi)	858		1722		2622	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	11/3/2010
Test Data (lbs)	7370
	5730
Tested MOR	606
Empirical MOR	384

Notes-

Table 72: RAP RSM 2.30 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE 2.30	
W/C	0.375	unitless
Air Dosage Rate	100.000	mL/100#
Paste Content	0.303	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.900	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.125	percent by vol
Coarse RAP Replacement Rate	0.813	percent by vol

Mix Conditions	
Date	10/13/2010
Time of Material Prep	2 to 2:30 PM
Time of Mix	2:30 PM
Ambient Temperature	70, sunny
Technician(s)	Beth, Keith, Josh

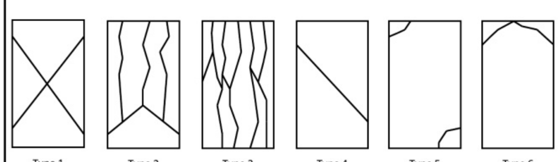
Notes- Material and moisture content from the night before. New cement haluled from Holcim this morning. Had hard time getting consistent temperature reading on cement. Material was significantly warmer than usual, with "pockets" of different temperatures.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	32.4	51.4
Portland Cement	66.6	74.2
Fly Ash	11.8	57.4
MicroAir (mL)	66.6	--
Coarse RAP	135.2	64.4
Coarse Virgin	33.8	64.4
Fine RAP	14.6	64.3
Fine Virgin	113.9	64.0

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	66.0	Beth
Slump (in)	0.75	Josh
Air Content (%)	5.30%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	10/14/2010		10/20/2010		11/10/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10570	5	37210	5	39320	3
	11720	4	33900	3	45730	3
	11010	4	33400	6	43880	4
Average Compressive Strength (psi)	883		2772		3420	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	11/10/2010
Test Data (lbs)	7460
	8010
Tested MOR	716
Empirical MOR	439

Notes-

APPENDIX E: MIX PROPORTIONS AND DATASHEETS FOR FOLLOW-ON EXPERIMENTAL DESIGN

This section provides the mix design datasheets for all mixes in the follow-on experimental design.

Table 73: RAP RSM 2 16 (C).01 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	16 (C).01	
W/C	0.400	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

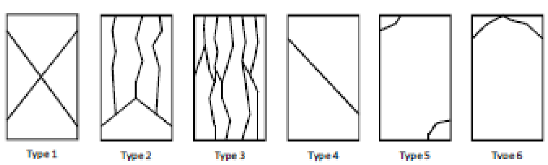
Mix Conditions	
Date	6/28/2011
Time of Material Prep	
Time of Mix	
Ambient Temperature	
Technician(s)	ELH, LW KF
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	18.1	
Portland Cement	38.5	70.4
Fly Ash	6.8	
MicroAir (mL)	48.5	
Coarse RAP	77.0	68.9
Coarse Virgin	0.0	
Fine RAP	26.6	69.5
Fine Virgin	30.7	65.4

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	70.8	elh
Slump (in)	2.25	kf
Air Content (%)	6.0%	kf
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	6/29/2011		7/5/2011		7/26/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	13780	2	32360	5	34340	3
			29750	5,4	37220	4
			29290	5,3	35760	3
Average Compressive Strength (psi)	1097		2424		2847	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 74: RAP RSM 2 2.02 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**2.02**	
W/C	0.350	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.300	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

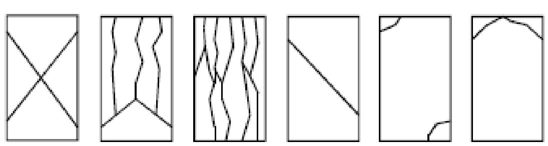
Mix Conditions	
Date	6/28/2011
Time of Material Prep	
Time of Mix	
Ambient Temperature	
Technician(s)	
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
Water	14.5	53.4
Portland Cement	35.4	71.7
Fly Ash	6.3	70.5
MicroAir (mL)	70.9	
Coarse RAP	80.3	69.1
Coarse Virgin	0.0	
Fine RAP	27.7	68.7
Fine Virgin	32.0	66.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^{o}F)	68.7	kf
Slump (in)	0	lw
Air Content (%)	4.5%	lw
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	6/29/2011		7/5/2011		7/26/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	17540	3	33980	3,4	42200	4
			32460	6	41150	4
			31260	3	41650	3
Average Compressive Strength (psi)	1396		2592		3316	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 75: RAP RSM 2 14.03 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**14.03**	
W/C	0.400	unitless
Air Dosage Rate	250.453	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

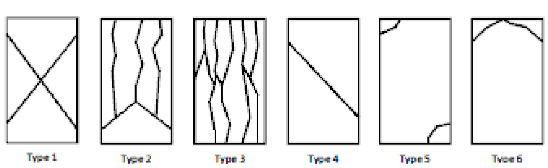
Mix Conditions	
Date	6/28/2011
Time of Material Prep	
Time of Mix	
Ambient Temperature	
Technician(s)	
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	18.1	51.4
Portland Cement	38.5	69.2
Fly Ash	6.8	72.5
MicroAir (mL)	96.4	
Coarse RAP	71.4	69.2
Coarse Virgin	0.0	
Fine RAP	24.6	70.0
Fine Virgin	27.9	68.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	67.9	kf
Slump (in)	2.75	lw
Air Content (%)	8.0%	lw
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	6/29/2011		7/5/2011		7/26/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10810	2	25740	6,3	29480	4
			26520	5,5	34100	4
			28050	5	33940	5
Average Compressive Strength (psi)	860		2130		2587	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 76: RAP RSM 2 7.04 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	7.04	
W/C	0.450	unitless
Air Dosage Rate	52.000	mL/100#
Paste Content	0.400	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

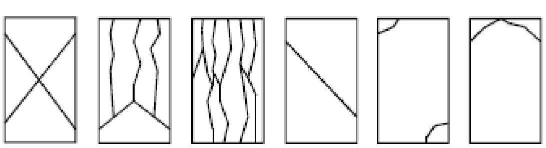
Mix Conditions	
Date	6/28/2011
Time of Material Prep	
Time of Mix	
Ambient Temperature	
Technician(s)	
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	21.7	52.4
Portland Cement	41.1	67.5
Fly Ash	7.3	70.4
MicroAir (mL)	21.4	
Coarse RAP	73.7	68.5
Coarse Virgin	0.0	
Fine RAP	25.4	69.2
Fine Virgin	29.4	68.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	66.4	kf
Slump (in)	8.75	lw
Air Content (%)	5.0%	lw
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	6/29/2011		7/5/2011		7/26/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9890	3	28230	4	32820	6
			27440	4,5	36120	3
			26300	3	34700	5
Average Compressive Strength (psi)	787		2174		2749	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 77: RAP RSM 2 4.05 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	4.05	
W/C	0.350	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.400	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

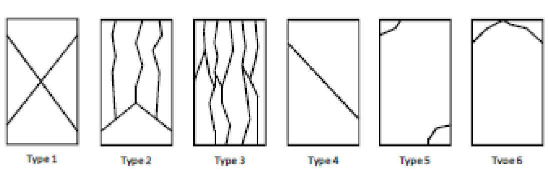
Mix Conditions	
Date	7/6/2011
Time of Material Prep	7/5/2011 10:00
Time of Mix	8:15 AM
Ambient Temperature	72
Technician(s)	elh, lw, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	19.4	61.0
Portland Cement	47.2	71.5
Fly Ash	8.3	70.5
MicroAir (mL)	94.5	
Coarse RAP	67.0	70.0
Coarse Virgin	0.0	
Fine RAP	23.1	69.1
Fine Virgin	26.8	69.4

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	73.1	kf
Slump (in)	1.25	lw
Air Content (%)	5.3%	lw
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/7/2011		7/13/2011		8/3/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	22190	2	35330	4	38270	4
			36790	5	47990	4
			36530	4	46490	5
Average Compressive Strength (psi)	1766		2882		3521	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 78: RAP RSM 2 5.06 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**5.06**	
W/C	0.450	unitless
Air Dosage Rate	52.000	mL/100#
Paste Content	0.300	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

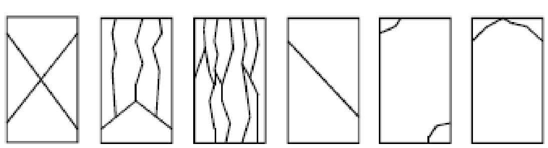
Mix Conditions	
Date	7/6/2011
Time of Material Prep	7/5/2011 10:00
Time of Mix	8:15 AM
Ambient Temperature	72
Technician(s)	elh, lw, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	16.3	59.0
Portland Cement	30.8	71.6
Fly Ash	5.4	70.5
MicroAir (mL)	16.0	
Coarse RAP	86.9	70.6
Coarse Virgin	0.0	
Fine RAP	30.0	70.5
Fine Virgin	34.7	70.0

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	69.9	kf
Slump (in)	0.125	lw
Air Content (%)	3.3%	lw
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/7/2011		7/13/2011		8/3/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	13730	3	24610	58	28500	5
			25880	6	30930	4
			21840	6	31580	5
Average Compressive Strength (psi)	1093		1919		2414	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 79: RAP RSM 2 13.07 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**13.07**	
W/C	0.400	unitless
Air Dosage Rate	1.547	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

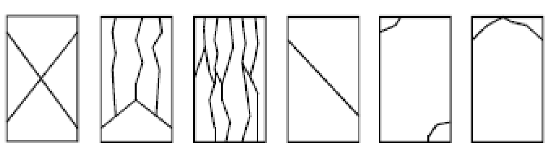
Mix Conditions	
Date	7/6/2011
Time of Material Prep	7/5/2011 10:00
Time of Mix	8:15 AM
Ambient Temperature	72
Technician(s)	elh, lw, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	18.1	58.3
Portland Cement	38.5	72.5
Fly Ash	6.8	71.4
MicroAir (mL)	0.6	
Coarse RAP	82.5	70.7
Coarse Virgin	0.0	
Fine RAP	28.5	70.1
Fine Virgin	32.9	69.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	72.2	kf
Slump (in)	0.5	elh
Air Content (%)	3.8%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/7/2011		7/13/2011		8/3/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	18440	3	31890	6	42530	4
			32890	5	37450	5
			32870	5,3	39370	4
Average Compressive Strength (psi)	1467		2590		3166	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 80: RAP RSM 2 12.08 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**12.08**	
W/C	0.400	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.434	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

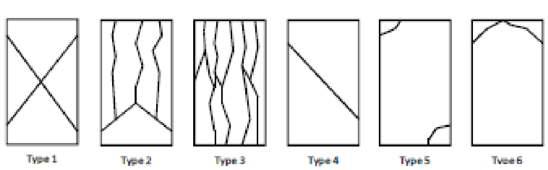
Mix Conditions	
Date	7/6/2011
Time of Material Prep	7/5/2011 10:00
Time of Mix	8:15 AM
Ambient Temperature	72
Technician(s)	elh, lw, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	22.4	57.5
Portland Cement	47.7	72.9
Fly Ash	8.4	72.0
MicroAir (mL)	60.1	
Coarse RAP	65.9	71.0
Coarse Virgin	0.0	
Fine RAP	22.7	71.0
Fine Virgin	26.3	70.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	71.3	kf
Slump (in)	6.5	elh
Air Content (%)	6.6%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/7/2011		7/13/2011		8/3/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	13050	3	30260	6	35920	5
			27470	2	33500	4
			32590	4	34200	4
Average Compressive Strength (psi)	1038		2396		2749	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 81: RAP RSM 2 11.09 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**11.09**	
W/C	0.400	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.266	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

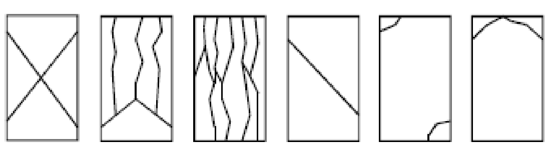
Mix Conditions	
Date	7/7/2011
Time of Material Prep	10:00 AM
Time of Mix	1:30 PM
Ambient Temperature	72
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	13.7	56.2
Portland Cement	29.2	71.8
Fly Ash	5.2	71.4
MicroAir (mL)	36.8	
Coarse RAP	88.1	70.0
Coarse Virgin	0.0	
Fine RAP	30.4	69.2
Fine Virgin	35.2	69.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	70.0	ah
Slump (in)	0	ah
Air Content (%)	7.0%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/8/2011		7/14/2011		8/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	10900	3,4	22340	4	26210	5
			24570	3	27490	4
			26120	4	20860	4
Average Compressive Strength (psi)	867		1937		1978	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	Lots of voids in 28-day cylinders

Table 82: RAP RSM 2 9.10 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	9.10	
W/C	0.316	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

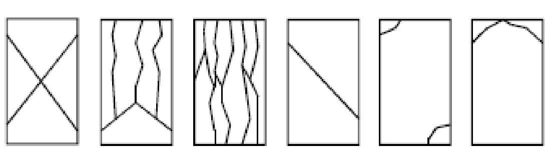
Mix Conditions	
Date	7/7/2011
Time of Material Prep	12:30 PM
Time of Mix	2:00 PM
Ambient Temperature	72
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	16.1	55.4
Portland Cement	43.5	71.2
Fly Ash	7.7	75.4
MicroAir (mL)	54.9	
Coarse RAP	77.0	69.8
Coarse Virgin	0.0	
Fine RAP	26.6	69.2
Fine Virgin	30.7	69.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.0	ah
Slump (in)	0	ah
Air Content (%)	3.5%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/8/2011		7/14/2011		8/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	21400	4,5	41850	5,3	44850	4
			34260	6	42190	5
			38760	3	43550	4
Average Compressive Strength (psi)	1703		3047		3464	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 83: RAP RSM 2 1.11 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**1.11**	
W/C	0.350	unitless
Air Dosage Rate	52.000	mL/100#
Paste Content	0.300	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

Mix Conditions	
Date	7/7/2011
Time of Material Prep	10:00 AM
Time of Mix	2:15 PM
Ambient Temperature	71
Technician(s)	elh, ah, kf
Notes	

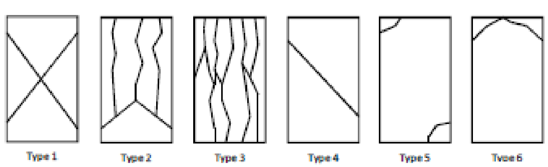
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	14.5	54.6
Portland Cement	35.4	71.0
Fly Ash	6.3	72.9
MicroAir (mL)	18.4	
Coarse RAP	86.9	70.6
Coarse Virgin	0.0	
Fine RAP	30.0	70.5
Fine Virgin	34.7	70.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.1	ah
Slump (in)	0	ah
Air Content (%)	8.0%	elh

Notes Mix not fully hydrated.

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/8/2011		7/14/2011		8/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	15930	5	37180	6	40410	4
			37220	6	34190	6
			35790	4	40400	6
Average Compressive Strength (psi)	1268		2923		3050	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 84: RAP RSM 2 3.12 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	3.12	
W/C	0.350	unitless
Air Dosage Rate	52.000	mL/100#
Paste Content	0.400	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

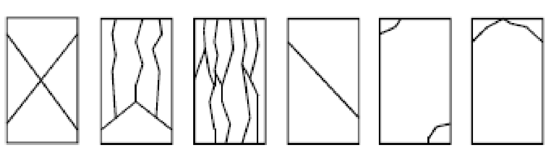
Mix Conditions	
Date	7/7/2011
Time of Material Prep	10:00 AM
Time of Mix	2:45 PM
Ambient Temperature	71
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	19.4	56.7
Portland Cement	47.2	71.4
Fly Ash	8.3	73.2
MicroAir (mL)	24.6	
Coarse RAP	73.7	72.5
Coarse Virgin	0.0	
Fine RAP	25.4	72.1
Fine Virgin	29.4	73.4

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	70.9	ah
Slump (in)	1.75	ah
Air Content (%)	2.0%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/8/2011		7/14/2011		8/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	19950	6	41420	3	45720	6
			36210	5	47470	4
			38920	6	47620	6
Average Compressive Strength (psi)	1588		3092		3735	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 85: RAP RSM 2 6.13 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	6.13	
W/C	0.450	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.300	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

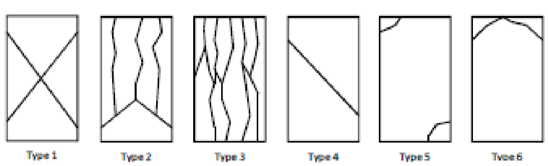
Mix Conditions	
Date	7/11/2011
Time of Material Prep	11:00 AM
Time of Mix	1:00 PM
Ambient Temperature	71
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	16.3	57.4
Portland Cement	30.8	71.1
Fly Ash	5.4	70.9
MicroAir (mL)	61.7	
Coarse RAP	80.3	70.5
Coarse Virgin	0.0	
Fine RAP	27.7	71.2
Fine Virgin	32.0	68.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	71.4	elh
Slump (in)	1.125	ah
Air Content (%)	6.5%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/12/2011		7/18/2011		8/8/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	11420	4	22330	6	29750	5
			21990	4	29270	5
			23260	6	27560	5
Average Compressive Strength (psi)	909		1793		2297	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 86: RAP RSM 2 15(C).15 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	15 (C).14	
W/C	0.400	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

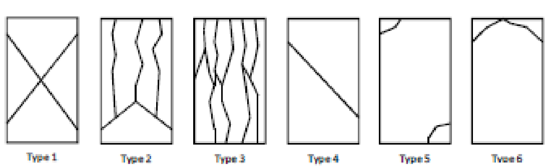
Mix Conditions	
Date	7/11/2011
Time of Material Prep	11:00 AM
Time of Mix	1:45 PM
Ambient Temperature	71
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	18.1	55.5
Portland Cement	38.5	71.2
Fly Ash	6.8	71.2
MicroAir (mL)	48.5	
Coarse RAP	77.0	70.5
Coarse Virgin	0.0	
Fine RAP	26.6	71.6
Fine Virgin	30.7	68.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.3	ah
Slump (in)	1.875	ah
Air Content (%)	5.4%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/12/2011		7/18/2011		8/8/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	16820	4	31460	6	38320	4
			28770	4	39140	4
			31130	6	37920	4
Average Compressive Strength (psi)	1338		2423		3061	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 87: RAP RSM 2 10.15 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**10.15**	
W/C	0.484	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.350	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

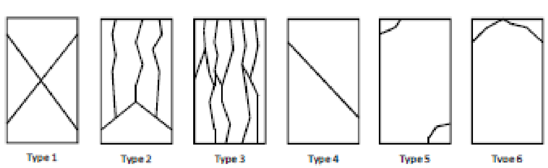
Mix Conditions	
Date	7/11/2011
Time of Material Prep	11:00 AM
Time of Mix	2:10 PM
Ambient Temperature	71
Technician(s)	elh, ah, kf
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^oF)
Water	19.6	54.5
Portland Cement	34.5	71.6
Fly Ash	6.1	71.7
MicroAir (mL)	43.4	
Coarse RAP	77.0	70.6
Coarse Virgin	0.0	
Fine RAP	26.6	71.1
Fine Virgin	30.7	68.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^oF)	68.7	wlh
Slump (in)	7.75	ah
Air Content (%)	8.5%	elh
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/12/2011		7/18/2011		8/8/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	8660	4	18550	5	24290	5
			20010	6	25090	5
			20130	5	23250	5
Average Compressive Strength (psi)	689		1557		1927	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 88: RAP RSM 2 8.16 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**8.16**	
W/C	0.450	unitless
Air Dosage Rate	200.000	mL/100#
Paste Content	0.400	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

Mix Conditions	
Date	7/11/2011
Time of Material Prep	11:00 AM
Time of Mix	2:48 PM
Ambient Temperature	74.3
Technician(s)	elh, ah, kf

Notes

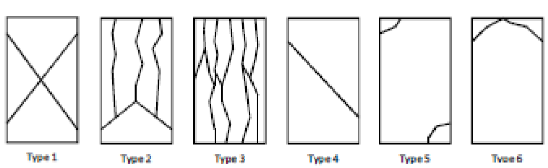
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
Water	21.8	54.7
Portland Cement	41.1	72.0
Fly Ash	7.3	72.1
MicroAir (mL)	82.3	
Coarse RAP	67.0	70.3
Coarse Virgin	0.0	
Fine RAP	23.1	70.8
Fine Virgin	26.8	69.1

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^{o}F)	69.4	ah
Slump (in)	8.25	ah
Air Content (%)	9.0%	elh

Notes

Compressive Strength Testing Data						
Age	1		7		28	
Date	7/12/2011		7/18/2011		8/8/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9720	5	22570	6	26170	4
			21850	6	28590	6
			22400	5	25670	6
Average Compressive Strength (psi)	773		1772		2133	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	

Notes

Table 89: Trial Mix 1 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**Trial Mix 1**	
W/C	0.385	unitless
Air Dosage Rate	182.880	mL/100#
Paste Content	0.347	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

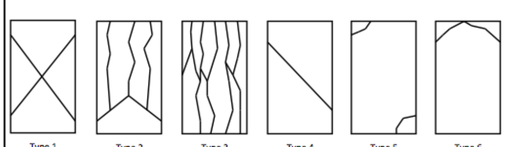
Mix Conditions	
Date	8/1/11
Time of Material Prep	10:00
Time of Mix	1:00 AM
Ambient Temperature	71
Technician(s)	ELH, KF, AH
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	17.7	58.0
Portland Cement	39.0	72.3
Fly Ash	6.9	72.5
MicroAir (mL)	71.3	-
Coarse RAP	74.8	71.5
Coarse Virgin	0.0	-
Fine RAP	25.8	70.0
Fine Virgin	29.2	70.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	71.2	AH
Slump (in)	1"	AH
Air Content (%)	5.0%	EH
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date						
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	18790	4	31150	5	34370	6
			29790	6	38740	4
			32900	4	38050	4
Average Compressive Strength (psi)	1495		2489		2949	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 90: Trial Mix 2 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**Trial Mix 2**	
W/C	0.442	unitless
Air Dosage Rate	126.000	mL/100#
Paste Content	0.308	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

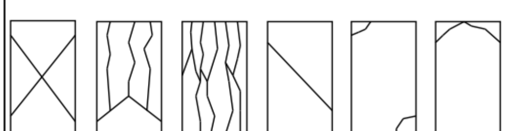
Mix Conditions	
Date	8/1/11
Time of Material Prep	10:00 AM
Time of Mix	1:00 PM
Ambient Temperature	71
Technician(s)	ELH, KF, AH
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	16.7	57.9
Portland Cement	32.0	72.7
Fly Ash	5.6	71.6
MicroAir (mL)	40.3	-
Coarse RAP	82.5	70.5
Coarse Virgin	0.0	-
Fine RAP	28.5	70.1
Fine Virgin	32.2	69.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	69.3	AH
Slump (in)	3/4 "	AH
Air Content (%)	5.4%	ELH
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date						
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	13010	4	23400	5	28520	5
			21520	6	28740	4
			21160	4	28290	4
Average Compressive Strength (psi)	1035		1753		2269	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 91: Trial Mix 3 Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	**Trial Mix 3**	
W/C	0.358	unitless
Air Dosage Rate	250.450	mL/100#
Paste Content	0.392	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	1.500	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.500	percent by vol
Coarse RAP Replacement Rate	1.000	percent by vol

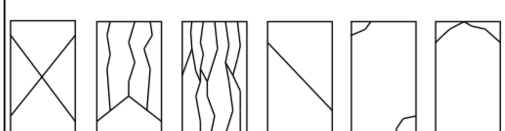
Mix Conditions	
Date	8/1/11
Time of Material Prep	10:00
Time of Mix	1:00 AM
Ambient Temperature	71
Technician(s)	ELH, KF, AH
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	19.3	59.2
Portland Cement	45.8	73.9
Fly Ash	8.1	71.7
MicroAir (mL)	114.6	-
Coarse RAP	65.8	71.5
Coarse Virgin	0.0	-
Fine RAP	22.7	70.1
Fine Virgin	25.7	69.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	71.6	ELH
Slump (in)	2 "	AH
Air Content (%)	5.1%	ELH
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date						
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	19400	4	34330	4	39820	4
			35300	3	41640	4
			35730	3	42170	5
Average Compressive Strength (psi)	1544		2795		3279	

ASTM Fracture Type



Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	
Notes	

Table 92: High Strength (HS) Mix Sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	HS2A-1	
W/C	0.385	unitless
Air Dosage Rate	182.880	mL/100#
Paste Content	0.347	percent
Fly Ash Replacement Rate	0.150	percent by wt
Volume	2.600	cuft
Coarse to Fine Ratio	1.360	unitless
Fine RAP Replacement Rate	0.250	percent by vol
Coarse RAP Replacement Rate	0.500	percent by vol

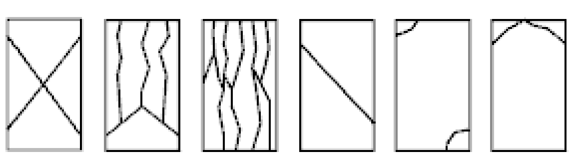
Mix Conditions	
Date	3/13
Time of Material Prep	8:00
Time of Mix	8:30
Ambient Temperature	62
Technician(s)	AH
Notes	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	30.7	60.4
Portland Cement	67.6	65.8
Fly Ash	11.9	66.1
MicroAir (mL)	123.6	-
Coarse RAP	64.8	66.0
Coarse Virgin	71.2	66.7
Fine RAP	22.4	66.7
Fine Virgin	75.9	66.1

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	68.3	AH
Slump (in)	1	AH
Air Content (%)	5.0%	AH
Notes		

Compressive Strength Testing Data						
Age	1		7		28	
Date			3/20		4/10	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
			44840	5, 3	51530	4
			44750	5, 6	54440	4,5
			45680	5	52150	2,5
Average Compressive Strength (psi)			3588		4194	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	
Test Data (lbs)	
Tested MOR	
Empirical MOR	486
Notes	