FEASIBILITY OF RECLAIMED ASPHALT PAVEMENT AS AGGREGATE IN PORTLAND CEMENT CONCRETE PAVEMENT

by

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

of

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in

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ABSTRACT

Each year, the US highway industry produces over 100 million tons of reclaimed asphalt pavement (RAP) through the rehabilitation and construction of the nation's roads. Using RAP as aggregate in Portland cement concrete pavement (PCCP) is one attractive application for a further use of this recyclable material.

Earlier research has demonstrated the feasibility of creating concrete with RAP aggregate; however, prior studies focus on mechanical properties of the material. This research project will further distinguish the properties of this material and draw conclusions on the concrete's aptness for use as a pavement in Montana.

This thesis encompasses the development of candidate RAP in PCCP mixtures that will subsequently move forward for a more thorough evaluation of their material properties. The mixing experiment and preliminary testing phases of this project provided information to draw a number of conclusions about the appropriateness of RAP aggregate in PCCP, including: (1) using conventional practices, PCCP containing RAP aggregate (20 percent fine and 45 percent coarse) can achieve compressive strengths in excess of 3,000-psi; (2) as the RAP replacement rate is increased, the compressive strength of the concrete decreases; (3) fine RAP aggregate appears to have a more detrimental effect on the concrete than coarse aggregate; (4) concretes with a relatively high RAP replacement rate (50 percent fine and 100 percent coarse) may be suitable for transportation applications; (5) at high RAP replacement rates, there appears to be a benefit (relative to concrete strength) in using increased replacements of both fine and coarse RAP, rather than singly replacing just one aggregate gradation; and (6) concrete containing RAP displays increased flexural strengths as compared to traditional PCCP.

This material research was performed using a Design of Experiments (DOE) method. The suitability of this statistical method as a mix design development tool was characterized through several important findings, which include: (1) the DOE method was effective in distinguishing mixture behaviors; (2) mix design optimization is readily accomplished using the statistical model generated from the DOE data; and (3) variability in the concrete mixing and testing processes has a significant effect on the capabilities of the statistical model.

INTRODUCTION

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 reusable product has been employed in some 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 reclaimed plant mix, creating a hybrid pavement that is both efficient and environmentally friendly.

Research Objectives

Preliminary research has demonstrated the feasibility of creating concrete with RAP aggregate; however, these prior studies focus on short-term mechanical properties of the material and do not address long-term durability characteristics of the concrete. It is the intent of this research to further characterize PCCP containing RAP replacement aggregate, by evaluating the material's durability and other long-term properties. Through this study, researchers are also looking to evaluate this alternative Portland cement concrete pavement's potential for use in the State of Montana. The Montana Department of Transportation (MDT) is hoping to use RAP as a replacement aggregate in

PCCP to create a more flexible and more "green" paving material. However, Montana has some unique climate conditions that can have harsh effects on roadway construction materials, and this research will attempt to better characterize the response of PCCP containing RAP to this adverse environment through a series of durability tests.

Research Scope

This research project has been developed with the intent to gain a better understanding on the feasibility of using RAP as aggregate in Portland cement concrete pavement. The directives of this project are set to be accomplished through the following tasks:

- Perform an extensive literature review on the topic and summarize general material behaviors that have been documented in past RAP concrete studies.
- Apply a Design of Experiments (DOE) method to develop a matrix of trial mixtures, the performance of which can be used to mathematically model the interactions and behaviors of the concrete mix ingredients.
- Utilize the results of the DOE analysis to optimize the concrete mixture and select two final optimized mixes for a complete suite of material tests.
- Characterize the long-term durability traits of concrete containing RAP, and evaluate the material's potential for use as a Portland cement concrete pavement.

As mentioned, the main objective of this research project is to quantify the engineering properties and particularly the long-term durability of concrete pavement containing RAP, and a number of material tests will be applied to two selected mixes to gain this more in-depth knowledge of the concrete. Standard material tests to be exercised in this study are shown in Table 1; the durability tests to be conducted are shown in Table 2.

Table 1:
Material properties to be tested

Material Property	ASTM Test Method
Compressive Strength	C39
Elastic Modulus	C469
Tensile Strength	C496 and C78
Shrinkage	C490-00a
Creep	C512

Table 2:
Durability properties to be tested

Durability Property	ASTM Test Method
Alkali Silica Reactivity	C1260 and C1293
Absorption	C642
Abrasion	C944
Chloride Permeability	NA
Freeze-Thaw	C666
Scaling	C672

This thesis only encompasses the development and selection of the two RAP mixtures that will later be subjected to a full suite of material property tests in a follow-on study. Preliminary material properties considered in this work include plastic state properties (slump and entrained air content), compressive strength, and rupture modulus. Chapter 2 of this thesis provides a literature review and summary on past research involving the use of RAP as aggregate in PCCP. Chapter 3 presents the materials used for this study and Chapter 4 describes the testing methods that were used in this research to evaluate the performance of PCCP containing RAP. A design of experiments (DOE) method was chosen for mix design development, and an introduction to this process is presented in detail in Chapter 5. Chapter 6 specifically addresses how the DOE method was applied to the subject RAP in PCCP material, and provides the measured material

properties for the mixes that were tested, including: slump, air content, compressive strength, and flexural strength for the mixes tested. The results of the DOE analysis are then discussed in Chapter 7, along with behavioral descriptions of the concrete mixture. The process used to select the two mix designs that will be carried forward for further testing, as well as the mix designs themselves, are presented and discussed in Chapter 8. Chapter 9 summarizes this thesis and provides key conclusions on the use of RAP in PCCP as well as the use of the DOE method in concrete mixture design.

LITERATURE REVIEW

Several laboratory studies researching the properties of concrete containing reclaimed asphalt pavement have been completed. A few key material tendencies of the concrete with this alternative aggregate have been well-established, and are seen throughout past research results. Test methods, results, and conclusions from the four major studies on concrete containing RAP that were reviewed in this literature study are summarized in this chapter, with an overview on material behaviors presented at the end of this chapter.

Research by Delwar, Fahmy, and Taha

Delwar, Fahmy, and Taha of the University of Washington and Sultan Qaboos University performed one of the first studies on this "green" concrete in 1997. The main goals of their research entailed an investigation on the feasibility of using RAP as aggregate in Portland cement concrete (PCC), and the determination of key material properties and characteristics of the alternative 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-cement (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. The aggregate configurations and water-cement ratios are shown in Table 3 below.

Table 3:
Aggregate configurations
(Delwar, Fahmy, & Taha, 1997)

Mixture Number	Coarse RAP (%)	Coarse Gravel (%)	Fine RAP (%)	Fine Sand (%)
Water Cement Ratios used with each aggregate configuration: 0.40 and 0.50				
1	100	0	100	0
2	75	25	100	0
3	50	50	100	0
4	25	75	100	0
5	0	100	100	0
6	0	100	75	25
7	0	100	50	50
8	0	100	25	75
9	100	0	0	100
10 Control	0	100	0	100

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 any percentage of RAP replacement aggregate, longer curing periods were necessary for achieving higher strengths. One beam made with RAP Concrete Mix 3 (see Table 3) was tested in three-point bending, yielding a modulus of rupture of 685-psi. Researchers commented that with this relatively high flexural capacity of 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 behavior, Delwar and his colleagues (1997) suggested that concrete containing RAP be further evaluated, on its durability properties.

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 in 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.

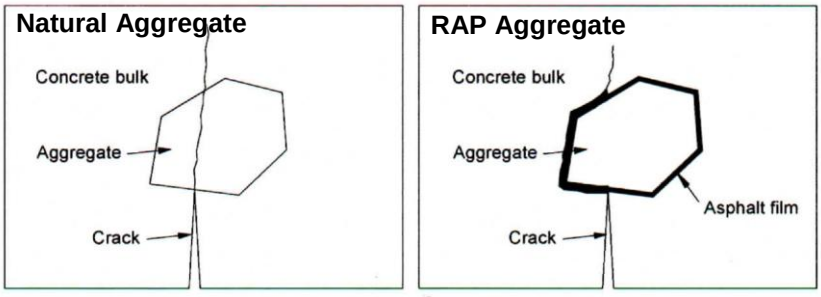


Figure 1:
Crack propagation through natural aggregate and RAP aggregate
(Huang, Shu, & Li, 2005)

In the 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 replacement aggregate. It should also be noted that the researchers chose to manufacture their own RAP material in the laboratory, and did not use pavement that was reclaimed from a roadway. Sufficient asphalt was applied to the virgin aggregate in order to coat the particles with approximately 8-μm of bituminous materials, and 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, and allowed for a more accurate correlation between the control mixes and the concrete mixtures containing the alternative aggregate.

A standard mechanical mixer was used for concrete batching, and ASTM rodding techniques were applied to consolidate the wet concrete. No particular material oddities were noted, and the researchers concluded that concrete containing RAP can 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. However, the material containing RAP had a much lower slump, although 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 their control mix. This decrease in strength was anticipated as asphalt is a much softer material and does not bond as well as the standard cement-natural aggregate combination. Graphs

representing the strength data collected during testing are presented in Figures 2 and 3 below.

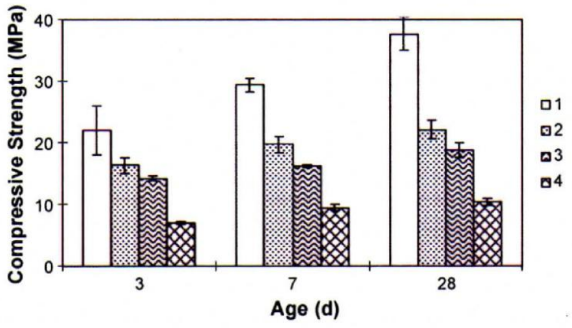


Figure 2:
Compressive strength data
(Huang, Shu, & Li, 2005)

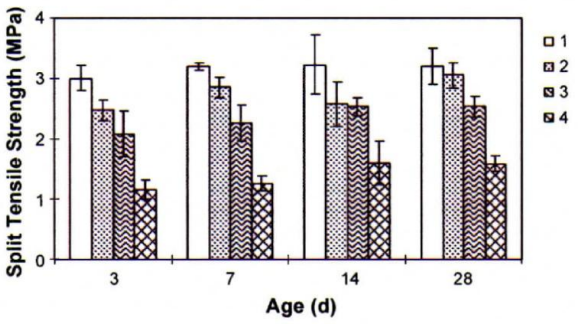


Figure 3:
Split tensile strength data
(Huang, Shu, & Li, 2005)

Further analysis indicated that the RAP concrete had a much higher toughness than the standard mix design (see Figure 4), and the RAP material degraded at a much slower rate after the failure load was applied. Although the inclusion of RAP in the concrete mixture appeared to have a positive effect on the toughness, test data implies

that the coarse RAP had an increased effect on this material parameter as compared to the mix containing only the fine RAP. The authors of the study concluded that the fine RAP had more adverse outcomes on the end product than the coarse recycled material. Note that the toughness index (TI) used in this study was a unitless parameter, based on the tensile strength of the material. This TI was calculated with the following equation: $= \frac{A_\varepsilon - A_p}{\varepsilon - \varepsilon_p}$, where these parameters are defined in the plot shown in Figure 5 (Huang, Shu, & Li, 2005).

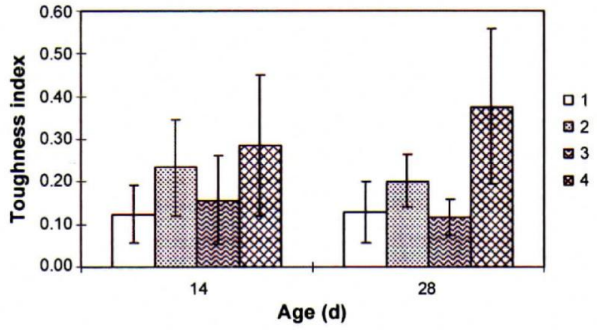


Figure 4:
Toughness index data
(Huang, Shu, & Li, 2005)

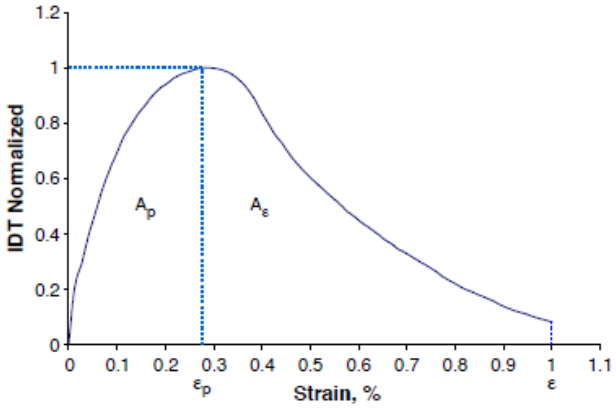


Figure 5:
Typical indirect tensile stress versus strain curve
(Huang, Shu, & Li, 2005)

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, & Li, 2005). Both silica fume and a high-range water reducing agent (HRWRA) were added to help reduce the loss of strength accrued by the use of the RAP aggregate. As in prior studies, several mix designs using different percentages of coarse and/or fine RAP aggregate (10, 30, 50, or 100 percent by weight) were 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 as 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 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 test data for the concrete that included silica fume were identical to those for 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 capabilities to improve the compressive strength, split tensile strength, and elastic modulus of the PCC containing RAP (Huang & Shu, 2005).

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. In their study, four concrete mixtures containing reclaimed asphalt pavement were evaluated in a laboratory setting. The tested material properties were then used to create 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 for the mixing experiment consisted of a porous limestone coarse rock and a standard silica sand fine material. The

mixtures evaluated in the study included mix designs containing 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 were decreased as the RAP content was increased.

The material properties, characterized through the laboratory testing, were then input into a finite element model of a typical Florida roadway constructed of the alternative concrete containing RAP. 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 results of this analysis are presented in Table 4, including a stress ratio defined as the observed stress divided by the flexural strength. For pavement applications, a lower stress ratio is desirable, indicating that the material can withstand more fatigue cycles. The data presented below suggests that RAP concrete

may perform well when employed as a PCCP, since the strength-stress ratio decreases as the RAP content is increased (Hossiney, 2008).

Table 4:
Maximum stresses and strength-stress ratios from FEACONS IV model
(Hossiney, 2008)

% RAP	Elastic Modulus (ksi)	Stress (psi) (+20ºF temp. diff.)	Stress (psi) (-20ºF temp. diff.)	Flexural Strength (psi)	Stress Ratio (+20ºF temp. diff.)	Stress Ratio (-20ºF temp. diff.)	Stress Ratio (-10ºF temp. diff.)
	14-day curing						
0	4,270	438.64	282.92	535	0.81	0.52	0.29
10	4,110	428.11	274.59	558	0.76	0.49	0.26
20	3,310	373.55	231.57	520	0.72	0.45	0.25
40	2,770	333.34	200.11	465	0.72	0.43	0.25
	28-day curing						
0	4,900	477.78	313.95	570	0.84	0.55	0.29
10	4,030	422.67	270.38	534	0.79	0.51	0.27
20	3,450	383.75	239.50	--	--	--	--
40	2,660	324.65	193.40	517	0.63	0.37	0.22

Literature Review Summary and Conclusions

Although the aforementioned researchers all set-out to accomplish very different things through their studies on PCC containing RAP, a few key behaviors of the alternative concrete were defined and verified throughout the range of past studies. Prior test results have demonstrated that several fundamental mechanical properties of concrete all decline with the inclusion of RAP, and these material properties continue to decline as the aggregate replacement rate is increased. These properties include: compressive strength, split-tensile strength, and modulus of rupture (Delwar, Fahmy, & Taha, 1997; Huang & Shu, 2005; Huang, Shu, & Li, 2005; Hossiney, 2008). Experts attribute this

effect to the breakdown of the bond between the aggregate and the cement matrix caused by the residual asphalt covering the RAP replacement aggregate. Reports show that there is about a 75 percent reduction in material compressive strength for mixes with 100 percent RAP replacement, demonstrating the asphalt's significant effect on the mechanical properties of concrete (Delwar, Fahmy, & Taha, 1997; Huang, Shu, & Li, 2005). However, despite low compressive strengths and other adverse effects of RAP, concrete mixtures produced using replacement rates between 40 and 50 percent have proven to be suitable for use in the transportation industry (Hossiney, 2008; Huang, Shu, & Li, 2005).

Although it has been proven that the inclusion of RAP in concrete may produce some unfavorable changes in the mechanical properties of the final concrete product, the effects of using RAP as a replacement aggregate are not always negative; two past studies report improvements in ductility and toughness as the replacement rate was increased (Delwar, Fahmy, & Taha, 1997; Huang, Shu, & Li, 2005). Furthermore, a study completed by researchers at the University of Florida documents that drying shrinkage also decreases with an increasing RAP replacement rate. These aforementioned material property improvements are especially favorable in transportation concretes, as deterioration due to cracking is a major concern with pavements. This past research suggests that the increase of toughness and decrease in shrinkage cracks are due to the adhesive nature of the RAP's residual asphalt content. The University of Florida's study also reports that the coefficient of thermal expansion for concrete containing RAP is nearly unchanged, implying that this material would be appropriate for use in more

extreme weather climates, such as Montana, where pavements are often exposed to a severe freeze-thaw environment. Through a finite element analysis, the same study was also able to demonstrate that the increased flexibility of the concrete containing RAP results in a reduced demand on the pavement, consequently allowing for a decreased strength of the material (Hossiney, 2008).

It should be noted that some additional follow-up studies have investigated the effects of using high-range water reducers and silica fume in concrete mixtures containing RAP. Ultimately, these studies found that the use of HRWRA did indeed improve performance, but the use of silica fume did not positively affect the properties and functionality of the final product (Huang & Shu, 2005).

MATERIALS

In the early phases of this research project, the suitability of various material sources for the RAP, natural aggregates, cement, fly ash, and concrete admixtures to be used in the project were assessed. The research team felt it was imperative to use materials similar to those typically seen on MDT roadway construction sites. The Department of Transportation provided direction on typical properties of PCCP material used on Montana projects, and researchers reviewed sources across the state to find optimum 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.

Reclaimed Asphalt Pavement

An appropriate RAP source proved to be the most difficult item to secure. RAP from far-reaching locations across Montana were evaluated both qualitatively and quantitatively, and throughout this process, much was learned about the production, character, and variability of this material.

Material Characteristics

Several sources suggest that the typical hardened asphalt cement content for RAP ranges from 3 to 7 percent (Federal Highway Administration, 1997), and according to experts at MDT, RAP that is about 5 to 7 percent asphalt is most representative of a Montana pavement (Weber, 2010). MDT also has a number of specifications for

aggregates to be used in Portland cement concrete pavements. Gradation requirements can be found in Tables 5 and 6 (Montana Department of Transportation, 2006).

Table 5:
MDT fine aggregate gradation specifications
(Montana Department of Transportation, 2006)

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 6:
MDT coarse aggregate gradation specifications
(Montana Department of Transportation, 2006)

Percentages By Weight Passing Square Mesh Sieves Designated Sizes				
Sieve Size	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 also be noted that RAP aggregates are hydrophilic and may have moisture contents as high as 5 to 8 percent, depending on where and how long the material has been stockpiled (Federal Highway Administration, 1997). The material's

absorption ability can cause issues and must be evaluated 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. 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 the physical characteristics of the aggregate (Federal Highway Administration, 1997).

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. It is also important to note that RAP tends to have much more aggregate degradation than conventional concrete aggregates. Milling, processing, and stockpiling can all add to the breakdown of the material (Federal Highway Administration, 1997).

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.

Hardy Creek RAP. The first of the materials to be evaluated came from I-15 near the Hardy Creek exit, about 30 miles south of Great Falls, Montana. The pavement was milled on March 29, 2010 and was sampled the same day. In a qualitative comparison to 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. A photo of the material collected from this site can be seen in Figure 6 below.



Figure 6:
Hardy Creek RAP sample

Unprocessed RAP from Lewistown. An additional RAP sample was collected from a stockpile in Lewistown, Montana. The material was milled off of Lewistown's Main Street in the summer of 2008, and a test specimen of the RAP 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 aggregates were evaluated. In a visual comparison to the other RAP samples, the unprocessed Lewistown material was significantly more weathered. 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. Relatively speaking, this value is on the high end of the range normally expected for RAP asphalt content. In visually contrasting this sample to the other 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 extensive period of time. As previously noted, 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, the aggregates were clumped together, requiring that the pile undergo some sort of processing prior to use. It was also suspected that the coarse and fine aggregates of the stockpile became segregated as the material aged. The unprocessed Lewistown material is shown in Figure 7.



Figure 7:
Unprocessed Lewistown RAP sample

Processed RAP from Lewistown. As mentioned, a portion of the material from Lewistown was crushed by 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 up to process the large chunks of material, and the remainder of the smaller aggregate bypassed the equipment and was sent to a separate, unprocessed pile. The majority of the RAP ended up in this pile of material that could not be processed through the given machine set-up, leaving the aggregate unchanged from its original state. Only particles retained on the ¾-inch screen were fractionated out and crushed. The unprocessed pile of aggregate also became very segregated and unevenly graded. The material that did go through the crusher was broken down into particles that ranged from the No. 16 sieve to the No. 4 sieve size. The crushed aggregates were much more angular in comparison to their original state, and the distribution of the asphalt throughout the material was visibly

changed. Prior to the processing, the particles appeared to be evenly coated with a thin layer of oil, 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 the asphalt that was originally added to the pavement. The processed Lewistown material is pictured in Figure 8. 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.

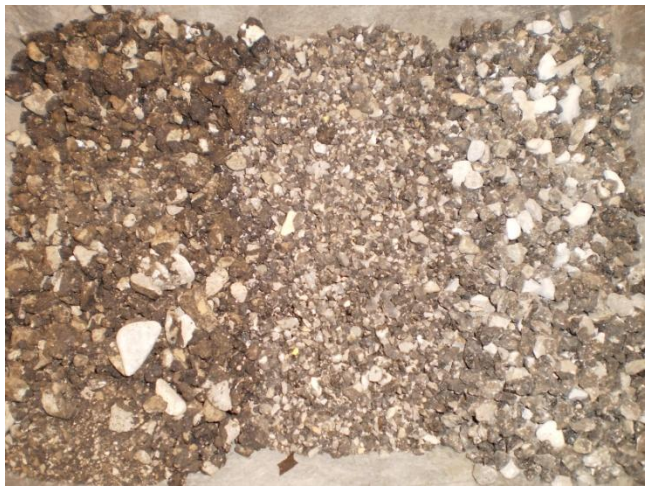


Figure 8:
Processed Lewistown RAP sample

Big Timber RAP. RAP aggregate from I-90 just west of Big Timber, Montana was also evaluated for use in the study. The material was milled on April 21, 2010 and the RAP was sampled by MSU researchers on April 22, 2010. The majority of the material was trucked to nearby county roads and was immediately placed as a gravel driving surface. The remainder of the material was stockpiled at the East Big Timber

exit. The stockpile was very dry and loose, and was not exposed to any sort of precipitation from the time it was milled until it was sampled. A sieve analysis performed on the Big Timber material showed that the pile was relatively 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. See Figure 9 for a photograph of this material.



Figure 9:
Big Timber RAP sample

Harlowton RAP. A final RAP sample was collected from U.S. Highway 191 just south of Harlowton, Montana. A portion of the roadway was milled on April 21, 2010 and the material was sampled on the following day. The pile was loose but did appear to have an increased water content. 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 angularly –faced particles. Like all RAP gradation analyses have shown, the material is slightly coarser than required by MDT's concrete aggregate specification. A sample of the material collected at Harlowton can be seen below in Figure 10.



Figure 10:
Harlowton RAP Sample

Processing

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

With the Department of Transportation's desires to use this material as a wearing surface on extensive and remote sections of Montana roadways, it is ideal to minimize the processing required for its use. Thus, the RAP processing method employed in this

study embodied a minimalistic philosophy. The material was run through large screen shakers to remove all of the particles greater than ¾-inch, and the remaining RAP was then fractionated on No. 8 and No. 16 sieves. This alternating sieve system was found to yield coarse and fine fractions most closely matching MDT gradation specifications (see Tables 5 and 6). The processed RAP was placed in 1-yd^3 sling bags and was covered for future use. As expected, the RAP aggregates continued to degrade after extended periods of storage. After about six months, there was a noticeable difference in the gradation and overall nature of the RAP aggregates. The material was much finer and had begun to harden into large clumps. When using this alternative concrete in a paving application, it is likely that the material will be milled off of an existing roadway and almost immediately incorporated back into a concrete pavement riding surface. Thus, this degradation during stockpiling will most likely not be an issue.

Material Properties of Hardy Creek RAP

The fine and coarse Hardy Creek RAP aggregates were tested for standard material properties, including gradation. This information is shown in the following tables. The asphalt content of the combined RAP was 6.7 percent.

Table 7:
ASTM C127-07 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

Table 8:
ASTM C128-07a 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

Gradation curves for the coarse and fine RAP aggregates are shown in Figures 11 and 12. As previously mentioned, RAP has a tendency to break down 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 material is slightly finer and more poorly-graded than the specifications require. Combining the RAP aggregate with a coarser natural rock could yield a final product that is closer to the specified gradation.

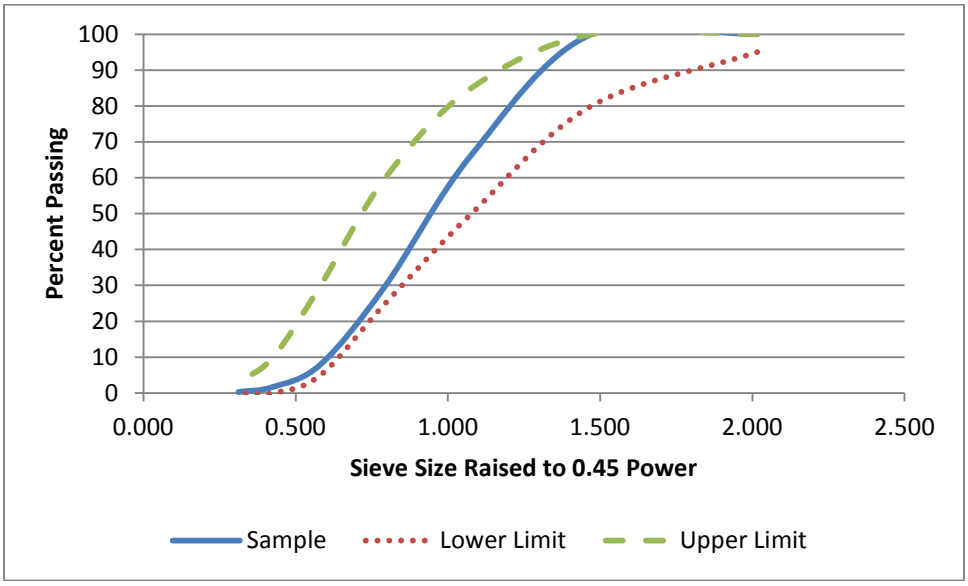


Figure 11:
Fine RAP gradation curve

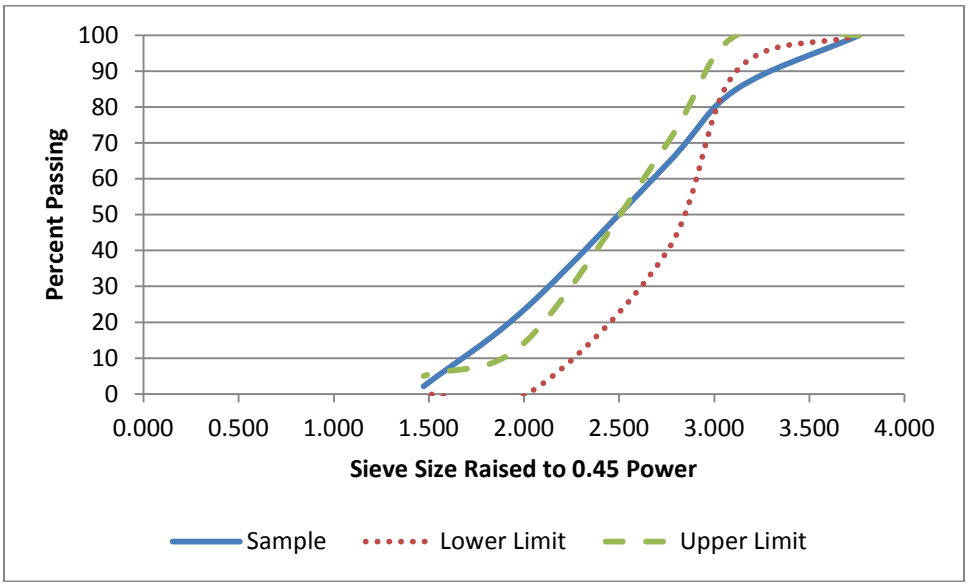


Figure 12:
Coarse RAP gradation curve

Natural Aggregate

Given the findings from past research on the use of reclaimed asphalt pavement as aggregate in concrete, it was decided early on that this study would not consider mixtures made with 100 percent RAP aggregate. As noted in the literature review, the inclusion of RAP has adverse effects on the end concrete product, so in an attempt to produce a better material, reclaimed asphalt aggregates were blended with virgin material for each of the concrete mixtures included in this study. This section describes the source and material properties for the natural aggregates used in this study.

Source

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

Material Properties

The coarse aggregate consists of a standard cracked face rock typical to the Gallatin Valley, and the fine material was ordinary concrete sand. These aggregates were reportedly in accordance with ASTM C33, and the material was not processed by the research team prior to use in the concrete mixtures. The natural aggregates were tested for density, relative density, and absorption per ASTM C127-07 and ASTM C128-07a. Results of these tests are given in Tables 9 and 10. ASTM testing methods (D5821 and C1252-06) for aggregate angularity were also applied to the natural aggregates and it was found that the coarse material is 27.9 percent fractured and the fines' average uncompacted void space is 39.4 percent (ASTM International, 2009).

Table 9:
ASTM C127-07 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

Table 10:
ASTM C128-07a 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

Gradation curves for both fractions of the natural aggregates used in this study are shown in Figures 13 and 14 below. Similar to the RAP material, the fine aggregate was within the bounds given by the specification, while the coarse aggregate was outside of its specified limits across certain particle sizes. In general, the natural coarse material contained more larger particles than the RAP coarse aggregate. See Figure 14.

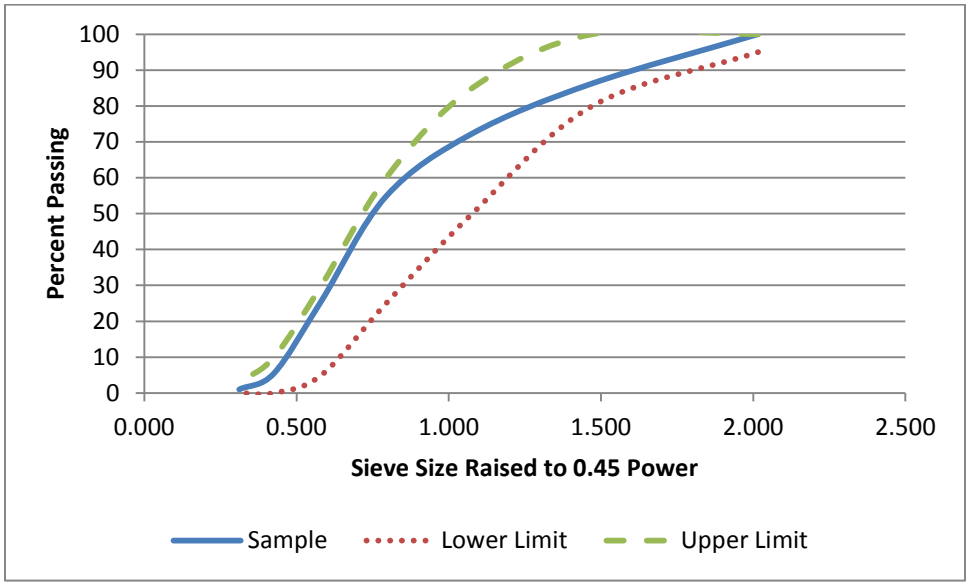


Figure 13:
Fine natural aggregate gradation curve

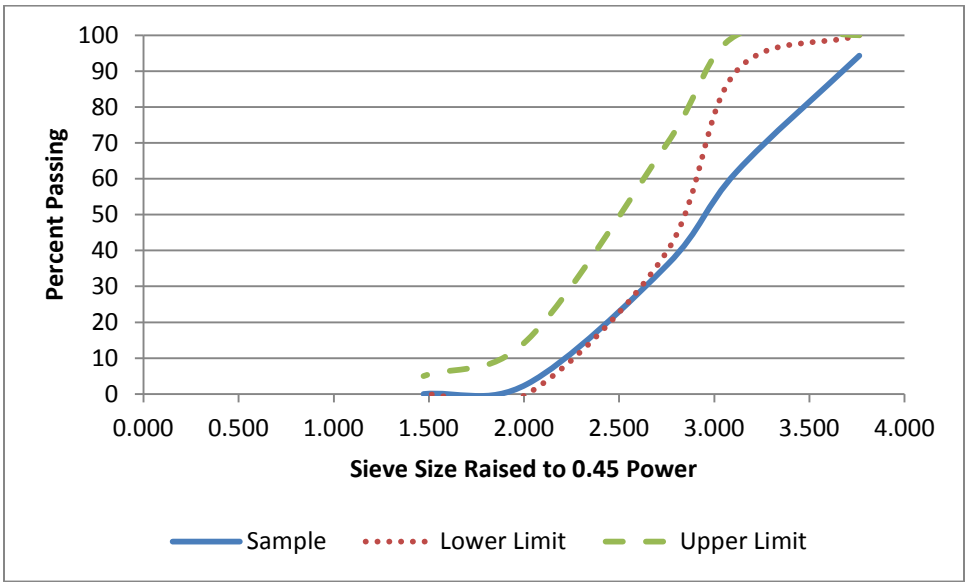


Figure 14:
Coarse natural aggregate gradation curve

Combined Aggregate

As previously mentioned, 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 materials yielded an optimum mixture, falling in the middle of MDT's specified range (see Figure 16), while the coarse material was slightly outside the accepted range (see Figure 17).

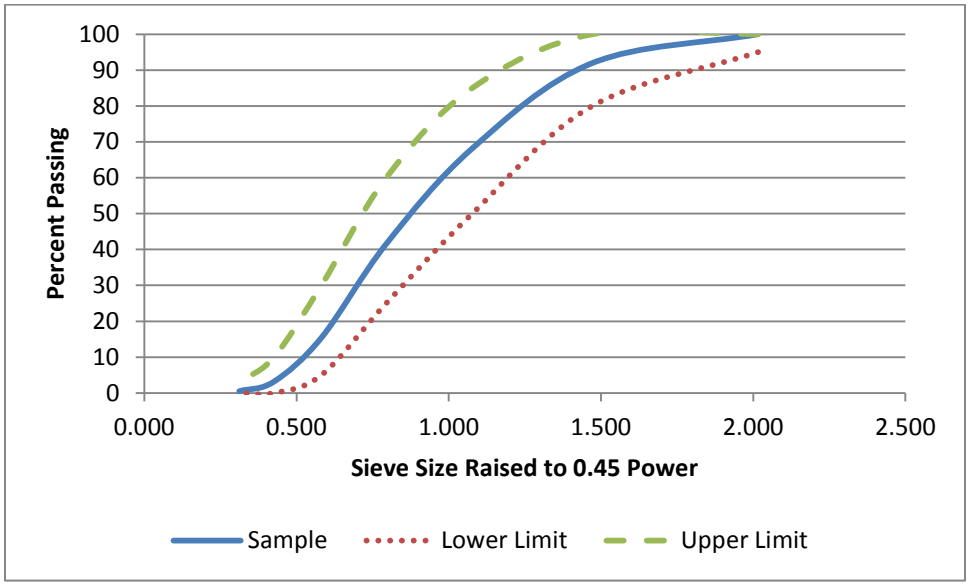


Figure 15:
Combined fine gradation curve

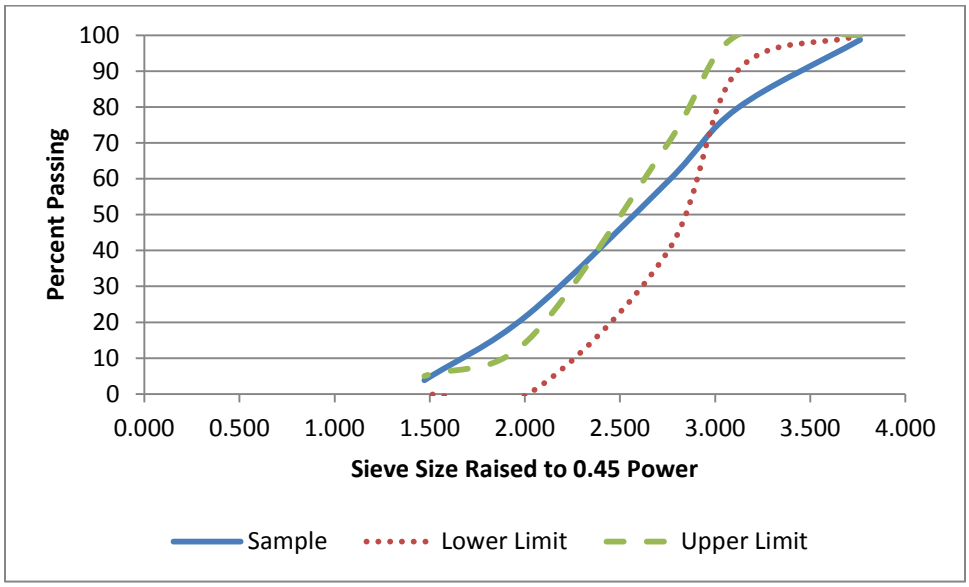


Figure 16:
Combined coarse gradation curve

Portland Cement

Portland cement is widely used and readily available across Montana. Despite its accessibility, the research team wanted to make sure the cement used throughout the mixing experiment was as uniform as possible; thus a sufficient quantity of Portland cement was obtained prior to the commencement of concrete batching.

Source

MDT specifications require the use of type I/II Portland cement for concrete pavement applications (Montana Department of Transportation, 2006). In the research team's effort to meet the Department of Transportation's given conditions, general purpose cement for this study was obtained from the Holcim plant in Trident, Montana.

Material Properties

The cement produced at the Holcim plant in Trident is routinely tested by the manufacturer for conformance with the requirements of ASTM C15. Results from these tests can be found in Table 11.

Table 11:
Cement test data, ASTM C 150 standard requirements
(Holcim (US) Inc., 2010)

Chemical Properties		
Item	Limit	Result
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)

Fly Ash

In keeping with the spirit of "green" building materials, it was decided early on that a baseline replacement of 15 percent fly ash by weight of cement would be incorporated into each mix design for testing. Fly ash is commonly used as a

supplementary cementitious material in mixes developed for MDT projects, and both the research team and the Department of Transportation felt that using an additional recycled byproduct would only add to the desirability of PCCP containing RAP. 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.

Source

A Class C fly ash from the J.E. Corette power plant near Billings, Montana was used throughout this study.

Material Properties

Headwaters Resources, the fly ash supplier that distributes the Corette coal ash, tests the product per ASTM material specification C618-05. Material properties for the Class C fly ash are listed in Table 12. The use of this fly ash 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 12:
Fly Ash test data, ASTM C 618 – 05 standard requirements
(Headwaters Resources, 2010)

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 Alkalies, 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

Air-Entraining Admixture

In order to improve the freeze-thaw performance of the PCCP containing RAP, and to meet standards set by the Montana Department of Transportation, an air-entraining admixture was used. In preliminary test mixes, it was found that the concrete pavement containing reclaimed asphalt pavement had about two percent entrapped air. MICRO AIR by BASF was used to entrain the additional air necessary to reach the five to seven percent of the total volume specified by MDT. 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. The lot number for the MICRO AIR used in this study was 1606886S7.

TESTING METHODS

The experimental regimen for the entire study includes a number of mechanical and durability tests that aim to characterize the performance of Portland cement concrete containing RAP, and in particular its performance as a pavement. The test methods and procedures listed in this section include the set of experiments that are reported on in this thesis. It should be noted that, due to project scheduling and time constraints, this document only encompasses a portion of the mechanical property tests that are to be completed as part of the overall study (Chapter 1). The results from the other tests will be reported at a later date. Although creep results are one of the items that will not be reported in this document, the design and construction of concrete creep testing frames was a significant work item that was included in the research presented in this thesis. A summary of the creep frame design and construction can be found in Appendix A.

Concrete Batching and Test Specimen Preparation

Each of the concrete test batches were mixed according to ASTM C 192/C 192M-07 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. 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. It should also be noted that a 10-ft^3 electric portable mixer was used for the preparation of each concrete batch. The mixing process went as follows:

1. With the mixer off, all of the coarse aggregate, 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 concrete ingredients were mixed for three minutes.
4. The concrete 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.

Slump and air content tests were performed per ASTM specification, and are described in the following paragraphs. 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 humidified cure room until the specified test date. Both unconfined compression and flexural tension tests were performed on the hardened concrete.

Air Content

Air content is an important property of concrete that can be an indication of how well the material will perform when exposed to the elements (freeze-thaw environment). Air voids in the concrete create an open space where moisture can freeze and more freely expand as temperatures cycle throughout the year. An increased air content can imply that a concrete will hold up better through freeze-thaw cycles, ultimately increasing the durability of the material and prolonging the product's service life. Air content was measured for each of the concrete mixtures according to ASTM C231-09 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method (ASTM International, 2009).

Slump

In addition to air content, slump is another crucial plastic state property of concrete. This parameter is an indicator of the workability of wet concrete, and for Portland cement concrete pavements, MDT requires a slump of 1.5±0.75-inches. The material is placed with a Bid-Well paving machine, which lays the material in a slip-forming type process; thus it is very important to have a low slump. Slump was a defining mix constraint in this research effort, and it was measured for each of the trial concrete mixtures per ASTM C 143/C 143M-08 Standard Test Method for Slump of Hydraulic-Cement Concrete (ASTM International, 2009).

Compressive Strength

Compressive strength is perhaps the most informative indicator of overall quality for any concrete mixture, and it is a parameter that is easily obtained through testing. In this study, 4-by-8-inch cylinders were loaded till failure to determine the compressive strength according to ASTM C39 Test Method for Compressive Strength of Cylindrical Concrete Specimens. The concrete cylinders were capped using steel retaining plates lined with elastomer bearing pads. A picture of the loading and testing apparatuses can be seen in Figure 17.



Figure 17:
Cylinder compression test set-up

Tensile Strength

Although concrete's capacity under tension loading is not heavily relied on, the tensile strength of the material can be a very important indicator of a concrete's shear capacity, cracking tendency, anchorage capability, and durability. Further, of the various elements if the infrastructure made with concrete, pavement is one for which flexural tension strength is specified and used in design. As previously noted, past research has demonstrated that concretes containing reclaimed asphalt pavements have an increased tensile strength (relative to a conventional concrete with the same compressive strength), and it was the intent of this study to confirm and characterize this behavior. The tensile strength of the material was tested according to ASTM C78 Test Method for Flexural

Strength of Concrete using 6-by-6-by-20-inch rupture beams. A third-point loading apparatus conforming to ASTM standards was used to test the rupture beams. Pictures of the loading and testing apparatuses can be seen in Figure 18. The collected data was used to calculate the concrete's Modulus of Rupture (MOR). The MOR was then compared to a calculated flexural strength based on the 28-day compressive strength of the material. The equation used in this calculation was empirically derived for standard Portland cement concrete pavement (ASTM International, 2009).



Figure 18:
Rupture beam test set-up

INTRODUCTION TO DESIGN OF EXPERIMENTS

Mix design development is a substantial and imperative aspect of evaluating a new concrete material. For this project, the research team chose to pursue an innovative approach for generating acceptable concrete mixes containing RAP aggregate, by employing a Design of Experiments (DOE) method. This chapter presents an introduction to the DOE process and, how it can be applied to concrete mixture design.

DOE Background

Design of Experiments methods were used in agricultural applications as early as 1918. Since then, the popularity of these statistical procedures has grown tremendously as economies have become more competitive and globalization increases (Pennsylvania State University, 2008). With the DOE method, a set of trial batches encompassing a specified range of mix proportions is developed using proven statistical procedures. These trial batches are then carried out and tested for various specified properties, which in the case of concrete may include compressive strength, slump, and air content. Data from the trial mixes is 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).

Scientific Methods

When examining a given process using any type of scientific experiment it is important to consider all of the elements that affect that process. For the case of RAP in

PCCP, the process under exploration is the concrete mixture itself. The biggest player in this mixture is the input, or concrete ingredients consisting of: cement, water, aggregates, fly ash, and air-entraining admixture. The output of the process is the final concrete product and its properties, including slump, air content, and strength. Although the input and output of a process may be easily seen and understood, there are other less-obvious factors that play an important role in defining a process. Controlled factors are key in reducing variability so the process can be viewed more clearly. For this study, a number of controlled factors were defined; a few examples of these controlled factors are the water-cement ratios and aggregate quantities used in each mix, and the consistent laboratory setting in which the mixes were batched. In contrast to the controlled factors, there are also uncontrolled factors affecting every process. Oftentimes these uncontrolled factors are unknown and unquantifiable, leaving their effects to go undefined in the examination of the process. Perfect examples of uncontrolled factors are weather and temperature. It is entirely possible that climate conditions at the time of batching play an important role in concrete mixture characteristics and properties. Even in a laboratory setting, temperature may increase or decrease by a few degrees, and humidity can vary across days. These climate changes may have an effect on the concrete being produced, but in the true sense of an uncontrolled factor, it is difficult to distinguish what exactly that impact is, making it even harder to control the resulting effect. Figure 19 gives a pictorial representation of a process and the factors that influence it (Pennsylvania State University, 2008).

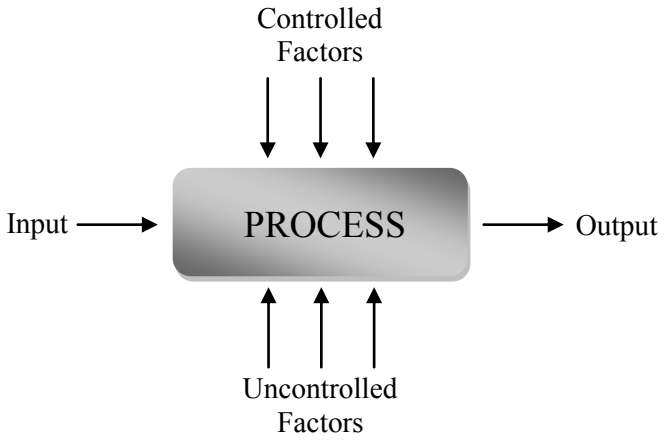


Figure 19:
Factors affecting a process

For any given experiment, a researcher has the option to choose between numerous scientific methods for evaluating the process at hand. A traditional method that is often employed in developing and evaluating concrete mixtures is the "One-Factor-at-a-Time" (OFAT) approach. In applying this approach, a single starting point is chosen and the researcher proceeds through the experiment by changing one variable at a time while keeping all other factors constant, and recording any observations that may be a result of the single variable alteration. In this case, assuming that methods and resources are not available to test every possible combination of mixture ingredients, some would argue that this method requires a certain amount of "luck" to obtain the desired results, and it can be difficult to fully characterize the behavior of the process at hand. Further, when the relationships and interactions between mixture ingredients is not intuitive of is difficult to recognize, a researcher could easily misinterpret test trial results and move the single factor variation in a direction that yields results opposite to the desired end product. Often with the OFAT method there is ultimately no way to tell if an

optimum result has been achieved, or simply a result that is acceptable. The effect of uncontrolled factors also goes unaccounted for if the experiment is systematically (rather than randomly) executed across each individual variable (Czitrom, 1999).

In direct contrast to the "One-Factor-at-a-Time" method, the DOE approach is a more controlled and well-defined experimental procedure that overcomes many of the aforementioned OFAT issues. For this mix design application, the Design of Experiments method is much more advantageous, in that concrete material properties (responses) are defined and described through a study of uncertainty (variables), and the results of this study are considered as a whole, rather than piece-by-piece. The final result can provide a more detailed picture of the global interactions and behaviors that occur in concrete mixtures at a minimum investment of resources and time. There is a learning curve associated with the DOE statistical analysis method and a strong knowledge in objective experimental processes is crucial. Another drawback to the DOE method can be the initial time and money investment required to plan and perform the experiment (Simon, 2003).

Implementation of DOE

Most Design of Experiments techniques are considered Response Surface Methodologies (RSM). The Response Surface Methodology is traditionally defined as a compilation of mathematical and statistical procedures that are commonly used to model and optimize problems that include responses of interest, which are influenced by several variables (Bradley, 2007). In the case of concrete mixtures, a response of interest might be slump, air content, or compressive strength. Variables influencing these responses

could be the water-cement ratio of the mixture, the paste volume incorporated in the concrete, and the coarse-to-fine aggregate ratio.

General Experiment Design. There are numerous viable methods by which an objective DOE may be carried out. For this study, the Central Composite Design (CCD) approach was chosen to model the inclusion of RAP in PCCP mixtures. CCD is an augmented factorial design which is capable of estimating full quadratic models for each of the responses of interest without requiring the completion of a three-level factorial experiment. Thus, a reduced number of batch trials, in comparison to other DOE techniques, is used to obtain the same statistically verified results (Simon, 2003).

An important aspect of any factorial approach is how the variables are presented. Say *n* is a given number of components in a mixture, for factorial designs the number of mixture ingredients is reduced to *n-1* using the ratio of two separate mixture elements to describe one independent variable. Given this clarification, a concrete mixture with its commonly defined water-cement ratio is an obvious application of this approach. Consider a simplified example where a concrete mixture is composed of four mix ingredients: water, cement, coarse aggregate, and fine aggregate. Given these four components, a mixture can be uniquely defined using three independent variables x_i, where x_1 = w/c ratio, x_2 = volume fraction of coarse aggregate, and x_3 = volume fraction of fine aggregate (Simon, 2003).

With the variables describing the mixture defined, reasonable ranges of values are chosen for each of the mix-defining parameters. For example, one may draw on experience and choose to set the range for the water-cement ratio at 0.35 to 0.45. In order

to simplify calculations and reduce computation time, these variable ranges are usually converted into dimensionless coded values. Once the variables of the concrete mixture are fully described, the next step is to identify the important responses. Going back to the concrete mixture example, specifications may require a slump of 1.5-inches, or a 28-day compressive strength of 3,000-psi. These specified concrete properties are considered dependent variables, also known as responses, when considering the overall experiment set-up. These dependent variables will be labeled y_i (Simon, 2003).

After the complete set of experiment parameters is defined, response (dependent variable) data is collected at a set number of strategically chosen variable (independent variable) points. For our same example where there are $j = 3$ independent variables (x_1, x_2, and x_3), the cube schematic shown in Figure 20 displays the graphical location of the strategically chosen test points. There are $2^j = 8$ factorial points and these locations represent all of the possible combinations of coded independent variable (x_i) values. An additional $2j = 6$ axial points are located at a distance of $\pm\alpha$ from the origin. Alpha values determine whether or not the cube of strategic points is rotatable. If a value of α is chosen so that the given design is rotatable, predicted values at equidistances from the origin will have the same variance. Finally, it is necessary to include at least three points at the center of the cube. These replicate points are crucial for defining the variability of the process involved in gathering the desired response data. The cube produced by the three factors is fairly easy to visualize, but this representation gets harder to picture as the number of independent variables increases (Simon, 2003).

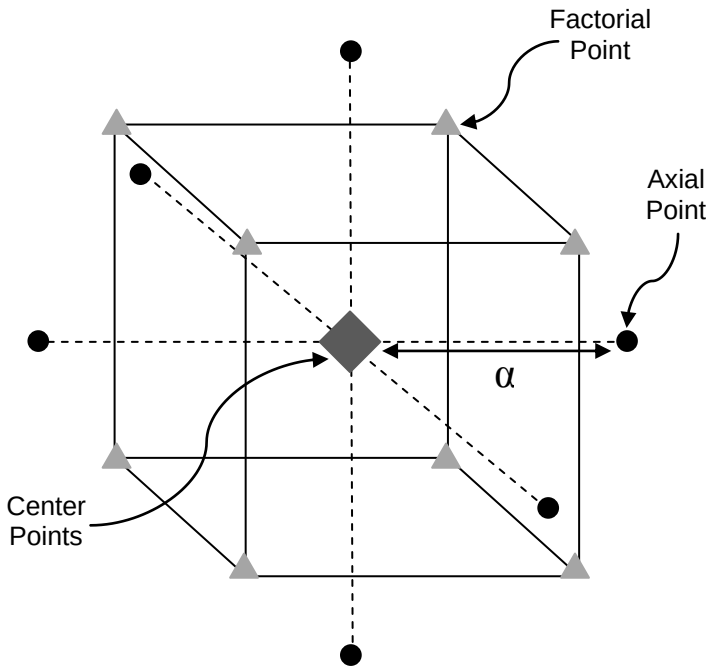


Figure 20:
Location of strategic CCD testing points for $j = 3$
(Pennsylvania State University, 2008)

General Experiment Process and Analysis. As in any laboratory trial, good experimental procedures are necessary to achieve accurate and reliable results. Researchers should be continually mindful of this as they step through the designated batch trial points, collecting response values for each of the trials. With the data set complete, mathematical methods are used to fit a response surface, corresponding all of the variables with the response data. This model can then be used to interpret the mixture behaviors, and the response surface may also be utilized for mixture optimization. Analysis of variance (ANOVA) calculations are used to characterize the variability of the data, and depending on the amount of variability present, the model's capability to predict and optimize accurately can be significantly affected. (Simon, 2003).

A simplified analogy to describe this mathematical procedure can be seen through the examination of a simple two variable scatter plot. For a given set of data, a trend line can be fit to describe the relationship between the *x* and *y* variables, and the regression can be used to predict the values at points that have not been tested. A Design of Experiments analysis follows this same concept, but at a higher mathematical level. Regression equations are still used to describe relationships between variables, except instead of a simple line, more complex multivariable surfaces are utilized to express these relationships.

Federal Highway Administration DOE Study

Although the DOE process has been around for quite some time, it has not been widely applied in civil engineering; however, the Federal Highway Administration (FHWA) has done some research on the statistical procedure's usefulness in developing concrete mixtures. Researchers on the FHWA project set out to apply standard statistical techniques 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 the study, the FHWA team applied the central composite design method and used five independent variables (x_i) to define their concrete mixture. These variables included: w/c ratio, fine aggregate, coarse aggregate, high-range water-reducing admixture (HRWRA), and silica fume (Simon, 2003).

A total of 31 concrete batches, specified by the 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 also conducted. The responses used for

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. Based on this process, the research team was able to successfully optimize the mixture (Simon, 2003).

Upon successful completion of their DOE study, the FHWA went on to develop and sponsor a software program specifically designed to perform the calculations necessary for other users to apply the DOE method for concrete mix design. The software is entitled "COST" and is available online as an interactive website, where the user is required to enter certain parameters pertaining to their experiment. The program uses a Response Surface Methodology for optimization and its 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 (Simon, 2003).

In the COST program, the water-cementitious materials ratio is identified as one of the independent variables and the user is allowed to define up to four additional variable factors, and an unlimited number of fixed factors. The program then enables the use of five response variables (concrete mixture properties) to be evaluated for optimization purposes. With the experiment parameters defined, the underlying code generates the mixture proportions for each of the necessary batch trials. The user must then perform each of the prescribed mixes and enter the response data into the COST

program. The program's statistical tools analyze the data for the user, and several analysis summary tools have been implemented in the program to create a concise summary page. Overall, the program has proven to be very effective for developing concrete mix designs based on statistical methods, and the FHWA hopes to continue to grow its capabilities (Simon, 2003).

RAP IN PCCP EXPERIMENT DESIGN AND RESPONSE INFORMATION

This chapter explains how the Design of Experiments method was implemented in this project to develop and study PCCP concrete mixes containing reclaimed asphalt pavement.

RAP in PCCP Experiment Design

Based on findings and recommendations from the FHWA study on the DOE process applied to concrete mixtures described in Chapter 5, the Central Composite Design method was chosen for the RAP in PCCP DOE. However, the research team was unable to use the COST program developed by the FHWA due to aggregate variable restrictions. Thus, the statistical software program STASTICA by StatSoft was used for the DOE analysis.

Note that prior to applying the DOE method to the RAP in PCCP mixture, the research team performed an extensive proof of concept study. A computer program was created to mathematically generate RAP in PCCP dependent mix responses (e.g., slump, entrained air content, compressive strength, etc.) for a set of batch trials specified by the DOE analysis for a range of input mixture parameters (e.g., water-cement ratio, aggregate proportions, etc.). This "pseudo" data was then analyzed using the DOE method, and it was found that the resulting model relating input mixture parameters to output responses accurately predicted the behaviors hard-coded in the "pseudo" responses. The program used to generate the "pseudo" responses was subsequently altered to include a certain amount of variation in these responses, and through yet another analysis it was

determined that the DOE still reasonably generated the expected model, with a decrease in accuracy commensurate with the amount of variability introduced into the "pseudo" responses.

Variables and Responses

Prior to finalizing and executing the DOE analysis, several "screening" mixes were performed in order to qualitatively observe how the RAP would generally affect the PCCP behavior. Given the aforementioned mix ingredients chosen for this study (Chapter 3), the results of this screening experiment revealed that the PCCP containing RAP had the following tendencies:

- 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.
- Low water-cement ratios as well as low RAP contents could be necessary to achieve desired strengths.
- The inclusion of RAP appeared to increase the tensile strength of the hardened concrete product.

After acquiring a better understanding of the concrete material behavior through the screening mixes, the variables and responses, as well as the variable ranges were selected for the DOE study. To minimize the number of required batch trials, the study was limited to five independent variables, which are listed in Table 13. Additionally, the research team felt that five was the minimum amount of variables that could be used to

effectively define each concrete batch. It should be mentioned that numerous variables related to mix proportioning were qualitatively evaluated for ease of implementation and overall importance in mix design, prior to selection of the final five variables listed in Table 13. Ultimately, the parameters were chosen based on the significance of their impact on the properties of PCCP containing RAP.

Testing ranges for each of these variables, also shown in Table 13, were chosen based on the knowledge and experience of the research team and lessons learned from the screening mixes. The coarse and fine RAP contents in the mixtures were defined as replacement fractions: that is, the alternative RAP material replaced the specified fraction of the natural aggregate.

Table 13:
RAP in PCCP DOE variables and ranges

Variable	Test Range (Alpha Values)
w/c Ratio	0.35 to 0.45
Paste Volume Fraction	0.27 to 0.40
Fine RAP Replacement Fraction	0.00 to 0.50
Coarse RAP Replacement Fraction	0.25 to 1.00
Air-Entraining Admixture Dosage Rate (mL/100#)	50 to 250

The relatively low range chosen for the water-cement ratio was intended to counter-balance the strength-depleting effects of the RAP aggregates. The paste volume range was slightly higher than that specified for typical Portland cement concrete, with the idea that the high paste content would improve the strength and failure mechanism of the final concrete product. The preliminary screening mixes revealed that it was difficult to accurately dose the air-entraining admixture and predict the resulting air content of the

concrete; thus a wide range was set for the dosage rate. It is also important to keep in mind a general DOE philosophy to "be bold." It is imperative to select variable ranges that are large enough to capture the entire behavior, particularly when the variable in question is not well-understood to begin with.

The selected variable ranges are input at the experiment design phase as the "cube" points, defining the region of testing points. See Figure 18 for a pictorial representation of the design "cube." As the figure shows, axial, factorial, and center points define the "cube" of testing points, and given the alpha value, each of the points of interest are calculated from the chosen variable ranges. Table 14 provides the design points for each of the five variables.

Table 14:
Design Points for RAP in PCCP DOE

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 necessary to define the remaining unknowns and to characterize all of the mix specifications. Again, these factors were developed based on experiences of the research team and are shown in Table 15.

Table 15:
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 strict 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 DOE study. Ultimately, these dependent variables were used to optimize the concrete mixture through statistical means. The responses of concern and their corresponding MDT specified values are listed in Table 16.

Table 16:
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, an Environmental Factor was included in the RAP in PCCP DOE. This Environmental Factor (EF) is an arbitrary 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 DOE 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 chapter.

Reducing Variability

As alluded to earlier, the presence of variability in a process can have a significant effect on the resulting DOE model, and if the collected data contains large amounts of variability it can substantially reduce the accuracy of analysis results. With this important factor in mind, the RAP in PCCP research team opted to incorporate a number of additional protocols into the concrete batching process in an attempt to reduce variability due to uncontrolled factors as much as possible. The measures employed for this study are included in the following items.

- Using consistent material sources throughout the batch trails.
- Characterizing the moisture content of the aggregates and then sealing the material off from air prior to preparing each mix.
- Controlling the mixing environment in the laboratory by using the same equipment (electric mixer, shake table, molds, finishing tools, etc.) and procedures (mixing time, consolidation method, cure time, etc.).
- The research team was also very mindful of any uncontrolled factors that may have affected the concrete mixes; noting specific temperature, time of day, and general observations of the concrete and environment during mixing.

- The batch trials were performed in a random order.

Batch Trials

The experiment design included 30 batch trials (see Table 17), 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. Using the strategic method for selecting testing points described in Chapter 5, the mix parameters for the 30 batch trials were determined 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 can be seen in Appendix B, along with data collection sheets that were used in the lab. Data for each of the concrete batches was linked back to the designated mix ID for information storage purposes. The first number in the mix ID the order of the mixes in relation to their location on the design "cube." The letter "C" denotes which mixes are center points in the design. The second number in the mix ID gives the order in which the mixes were actually performed. Carrying out the "cube" test points in an unselective order reduces the overall effect of uncontrolled factors. For example, the relative humidity may have 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 an unexplainable or unidentifiable trend in the data set.

Table 17:
DOE 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 Figures 21 and 22. Photos of the RAP PCCP in the plastic state are shown in Figures 23 and 24.



Figure 21:
Typical aggregate quantities



Figure 22:
Typical cementitious material and water quantities



Figure 23:
RAP PCCP in mixer



Figure 24:
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 25) 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 25:
Plastic cylinder molds

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 18; complete data for each batch trial is presented in Table 19. 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. A more detailed description of the testing methods used is given in Chapter 4.

Table 18:
Summary of response data

Response	Observed Range	Observed Average
Slump (inches)	3/16 to 8-1/2	4-3/4
Air Content (%)	3.80 to 13.50	9.84
1-Day Compressive Strength (psi)	466 to 1338	894
7-Day Compressive Strength (psi)	1440 to 3559	2131
28-Day Compressive Strength (psi)	1722 to 4282	2623
28-Day Rupture Strength (psi)	391 to 870	541
Environmental Factor	0.50 to 1.25	0.88

Table 19:
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 $7.5\sqrt{(f'c)}$ (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

When comparing the laboratory-tested values of the 28-day MOR with the values estimated based on compression strength, it is very apparent that PCCP containing RAP has a significantly higher flexural strength than that of conventional concrete (of similar

compression strength). The average difference between the two data values is 33.5 percent. This finding implies that, as expected, the residual asphalt maintained on the RAP replacement aggregates adds tensile strength to the cured concrete product, which is a desirable property relative to its use as pavement.

RAP IN PCCP DESIGN OF EXPERIMENTS ANALYSIS AND FINDINGS

With the response data collected for the 30 batch trials (as reported in Chapter 5), the research team went back to the statistical software to analyze this data and generate a mixture design model. Using multivariable mathematics, STATISTICA was used to fit a regression surface to the data, creating a model to be reviewed and utilized. Analysis of variance (ANOVA) calculations were then used to determine the significant relationships and interactions between the five variables and six responses.

With the DOE model fully developed, the research team was able to thoroughly analyze the behavior of the concrete mixtures. Ultimately, the model was able to characterize how the mix ingredients interact to yield specified responses. With this understanding of the mixture behavior, the research team was able to use desirability functions to mathematically 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 DOE model. This chapter presents the results from the DOE analysis with respect to goodness of fit of the model as well as significant relationships between the variables and responses. The next chapter discusses the results of several optimization studies performed with the DOE model.

Defining Significant Relationships

The research team reviewed the relationships and interactions between the variables and responses determined by the statistical model. As defined in the STATISTICA manual, a relationship, or main effect, represents the effect of an independent variable on a dependent variable when the independent variable under examination is averaged across the variable ranges of the other independent variables included in the design. Although this definition is somewhat cumbersome, the key point to understand is that the main effect of a variable is measured with consideration of the other independent variables, and the magnitude of this effect is a function of the additional factors being considered. An interaction, or interaction effect, is when the relationship between two or more variables is altered by at least one other variable. In other words, the relationship between two variables is modified as the level of the effecting variable is changed (StatSoft). Given the definition of a relationship and an interaction, the figures below take a closer look at the behaviors of the variables and responses in the RAP in PCCP experiment.

The following figures display Pareto charts for each of the measured responses. A key for interpreting the y-axis labels of the Pareto charts is provided in Table 20. In these charts, each of the independent variables, as well as combinations of variables showing potential interactions, are plotted on the vertical axis in their 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. A p-value less than 0.05 corresponds to a 95 percent confidence interval (Thisted, 1998), which is important when considering the model-predicted values that are discussed in the following chapter. The analysis considers both linear and quadratic relationships, and these are denoted in the charts that follow. It should be noted in looking at these charts, 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 26. 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 DOE analysis.

Table 20:
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)

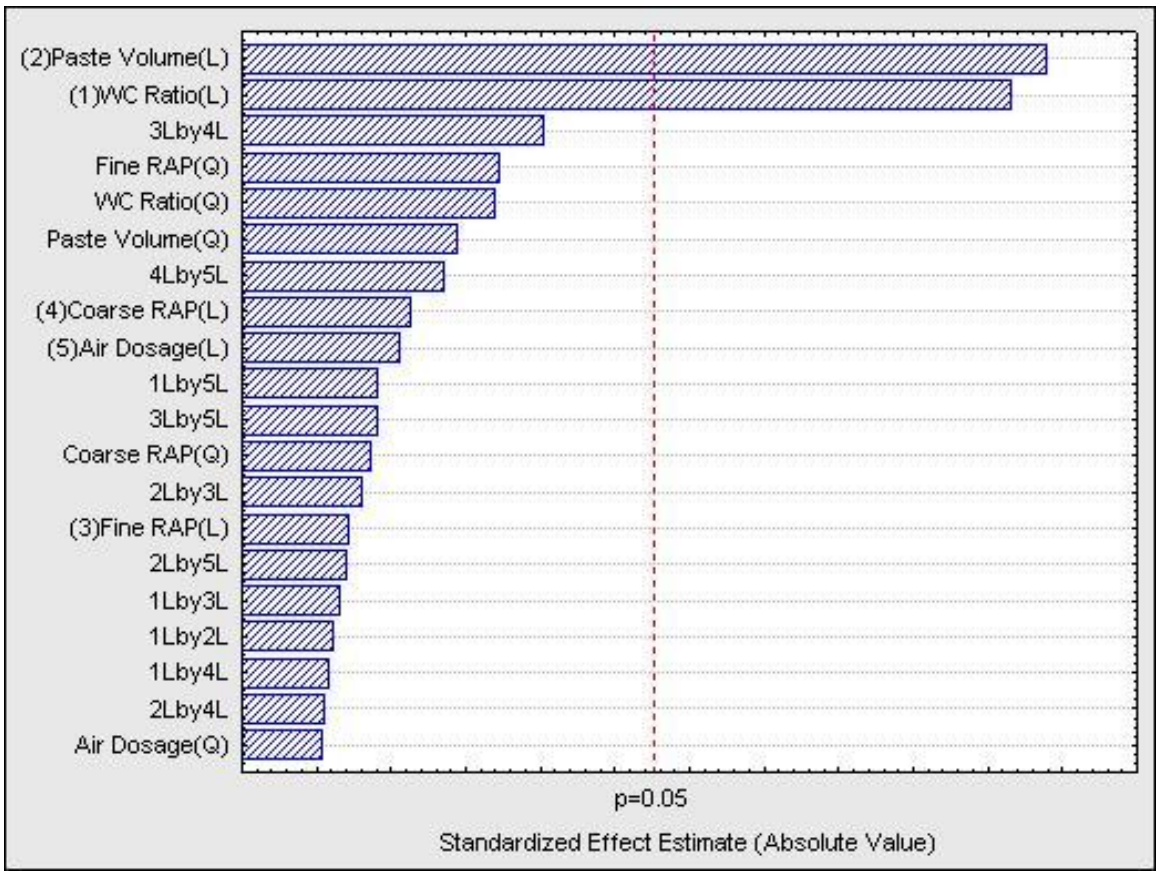


Figure 26:
Pareto chart for slump response

The Pareto chart for the measured air content of the RAP in PCCP mixes is provided in Figure 27. 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.

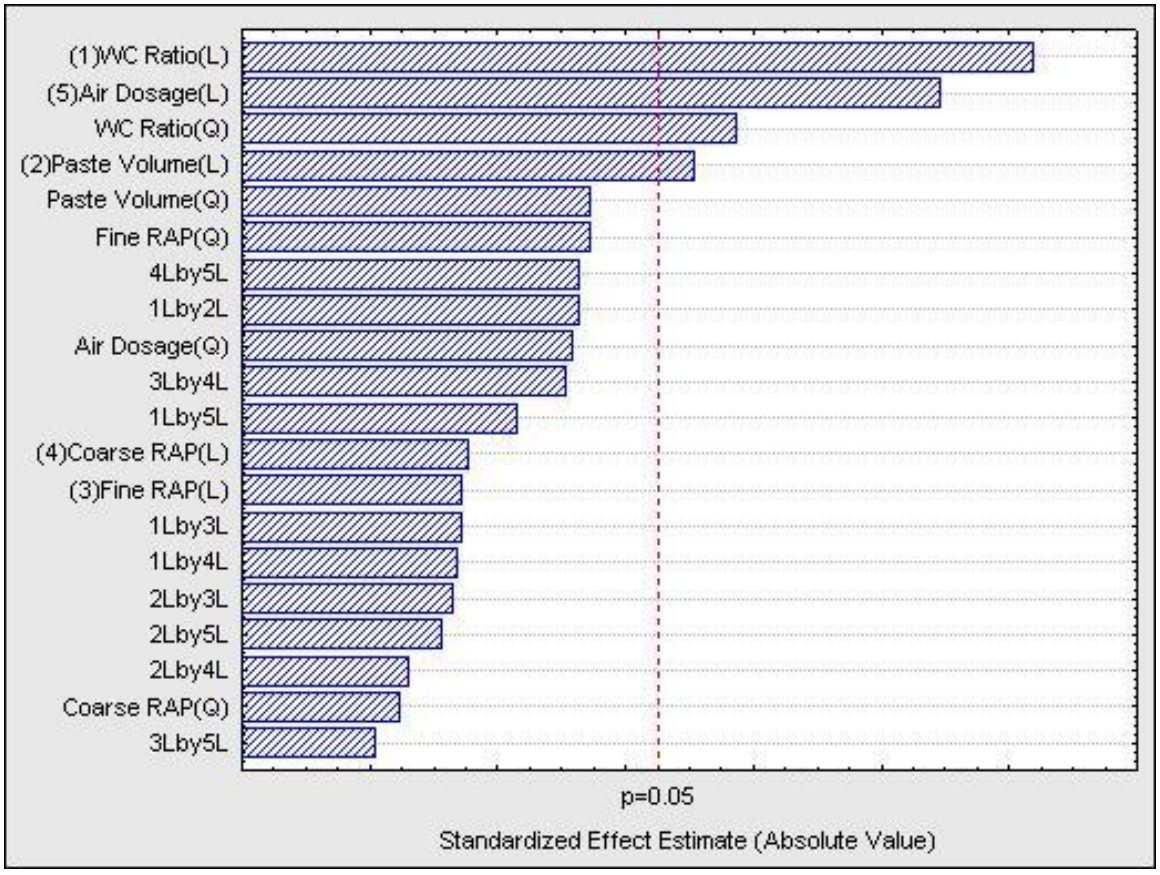


Figure 27:
Pareto chart for air content response

The next Pareto chart shown in Figure 28 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.

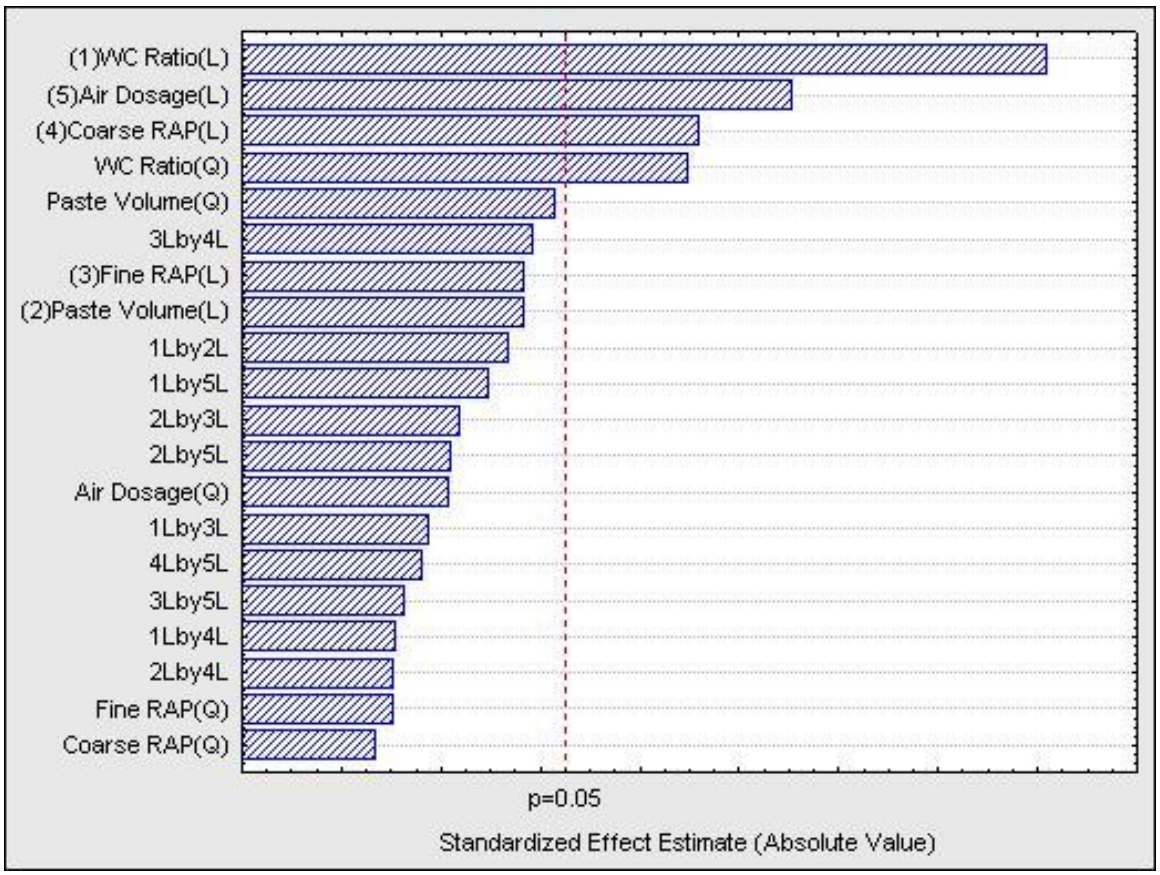


Figure 28:
Pareto chart for 7-day compressive strength response

The Pareto chart for the 28-day compressive strength of the RAP in PCCP material is shown in Figure 29. 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 "screening" mixes that were performed prior to the DOE.

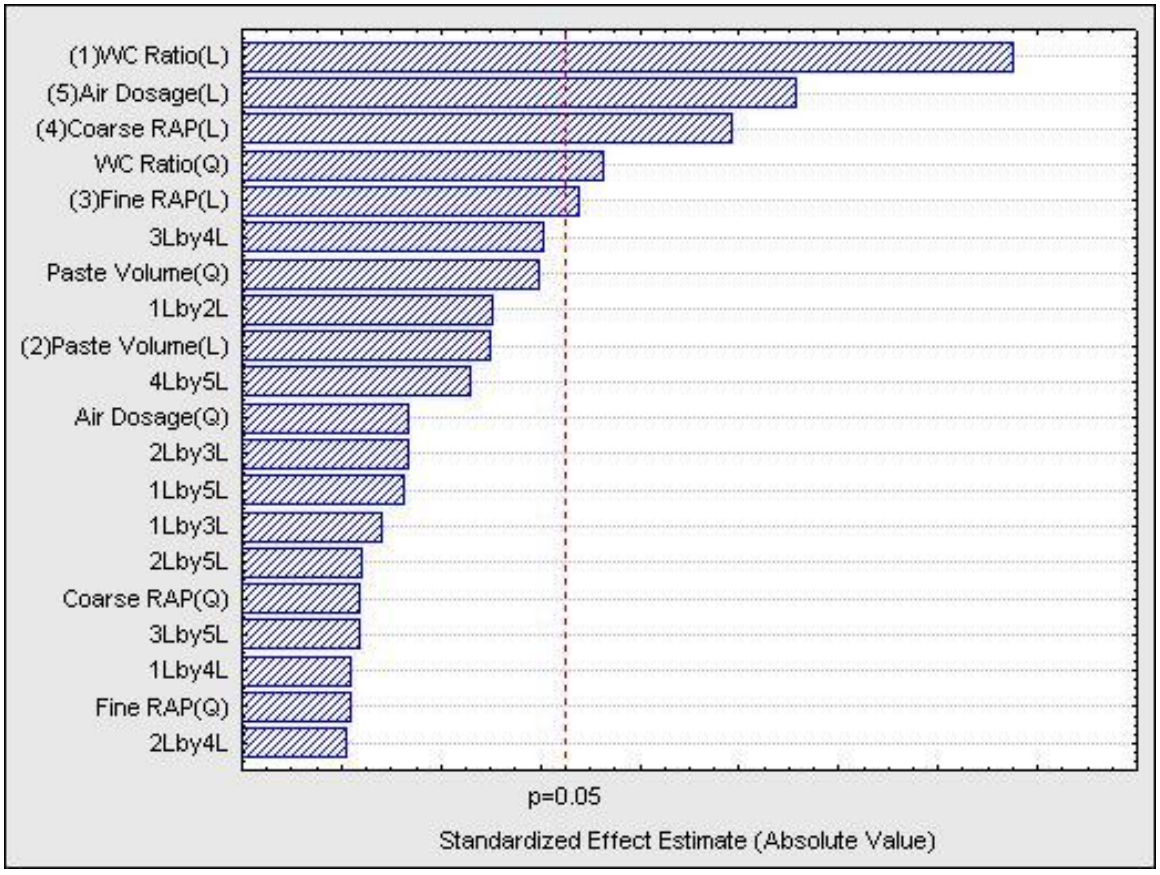


Figure 29:
Pareto chart for 28-day compressive strength response

The Pareto chart for the 28-day flexural strength (modulus of rupture) of the concrete is shown in Figure 30. 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 $\overline{f'c}$ 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 all of the batch trials considered herein was 0.5.

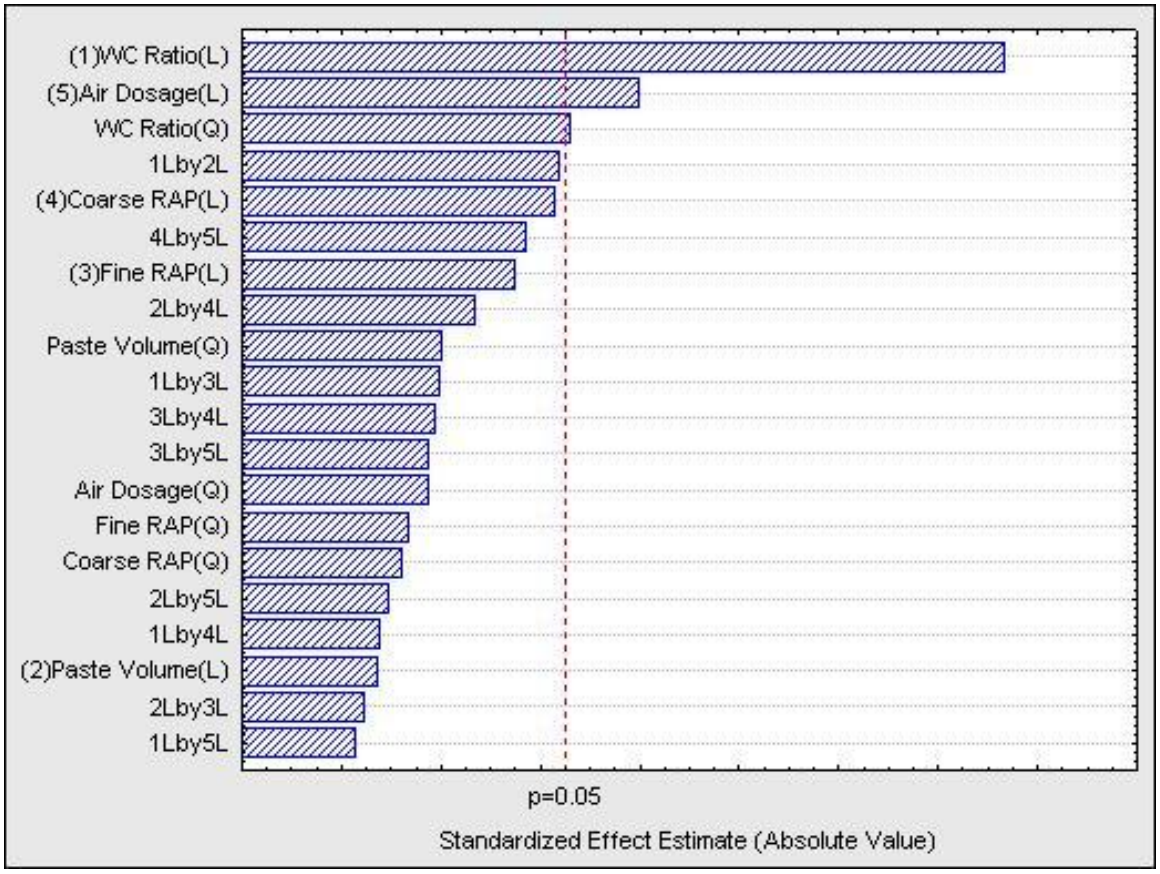


Figure 30:
Pareto chart for 28-day rupture strength response

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 DOE analysis.

Design of Experiments Response Surface Model

After evaluating the significant relationships within the data, STATISTICA was used to develop a regression model that can be used to predict responses from the mix variables. The resulting model for each response is fairly complex and is a function of the five independent variables used in the study. The behavior model for each of the responses can be visualized through 3D surface plots. These surface plots can be created for each response variable as a function of two specified independent variables, while the three remaining independent variables are held at their mean values.

Figure 31 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.

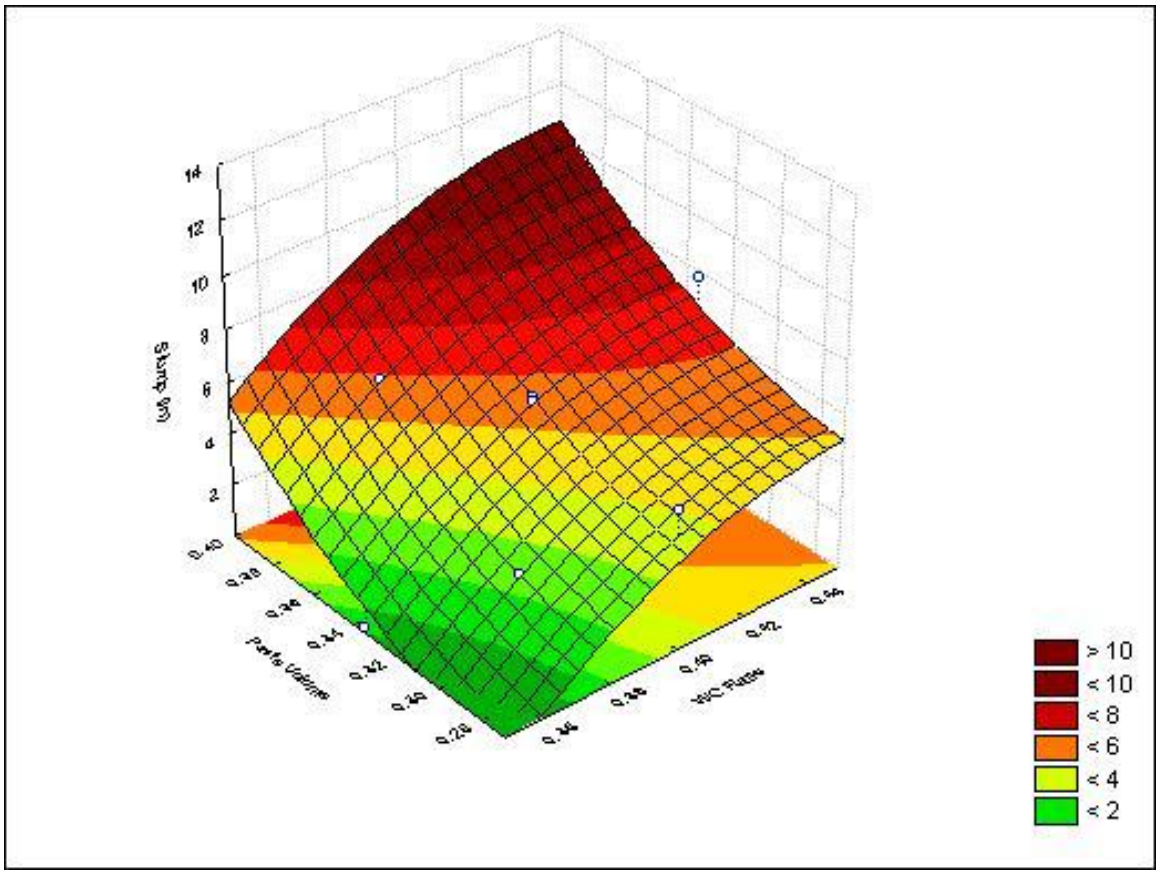


Figure 31:
Slump vs. paste volume and water-cement ratio

The white dots shown in Figure 31, 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 32 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 DOE 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. Slump measurements made on the same batch of concrete can regularly vary up to two inches, due to sampling, testing, and localized material variability (American Concrete Pavement Association, 2011).

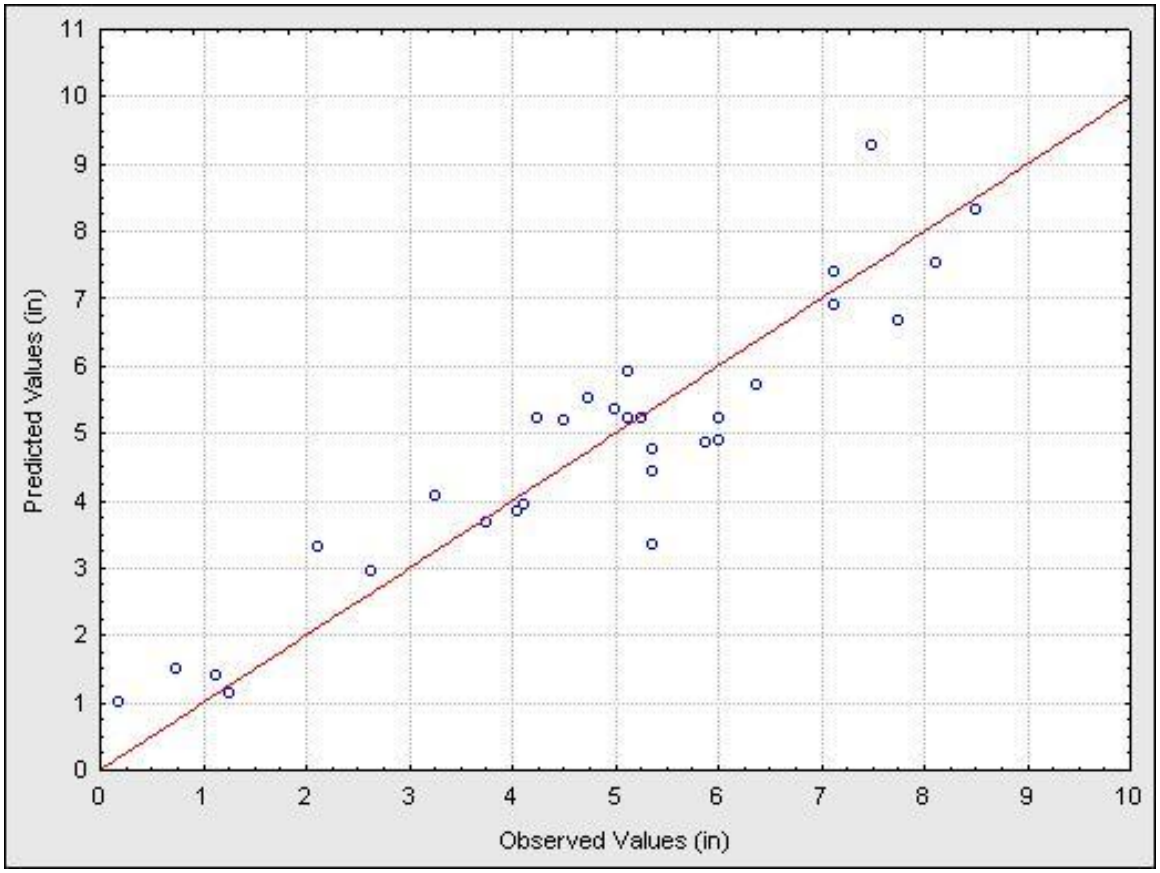


Figure 32:
Predicted vs. observed values for slump response

Figure 33 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 screening mixes prior to executing the DOE, 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 33, 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.

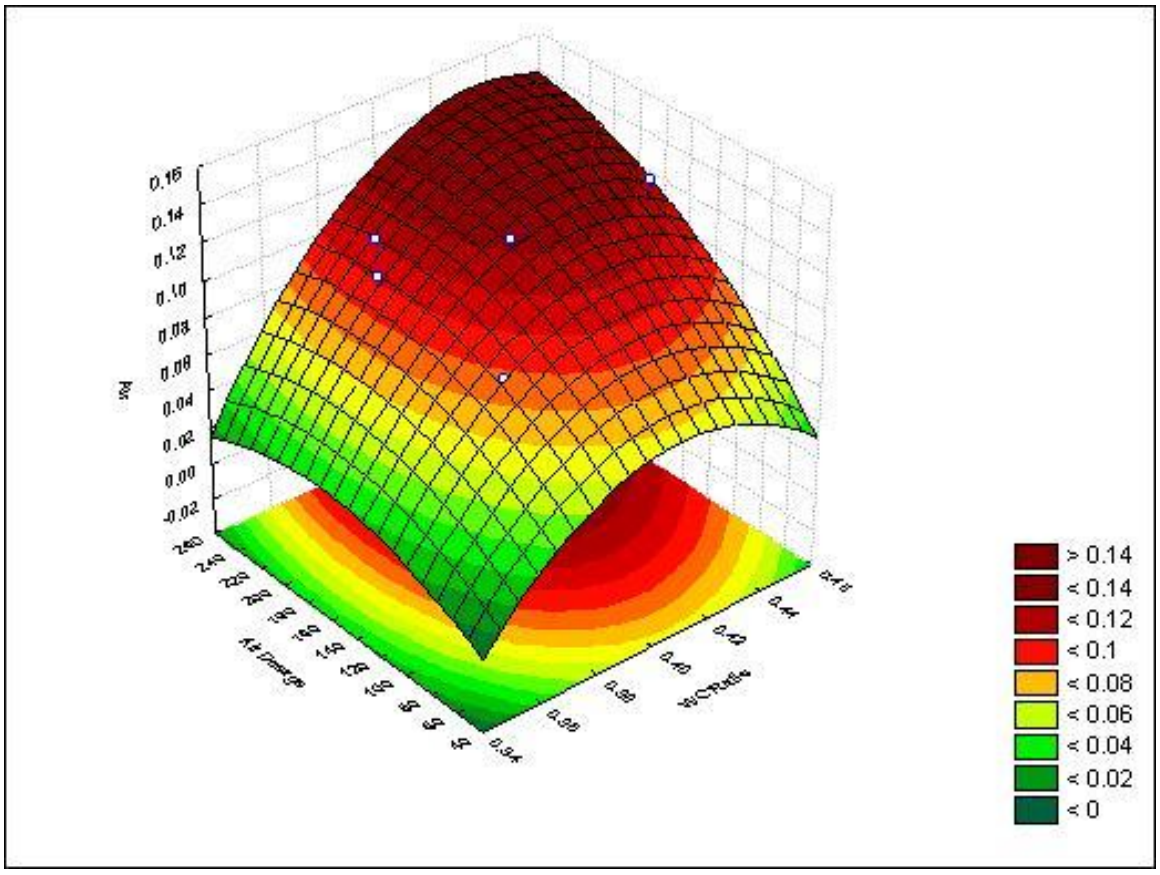


Figure 33:
Air content vs. air dosage and water-cement ratio

Figure 34 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.

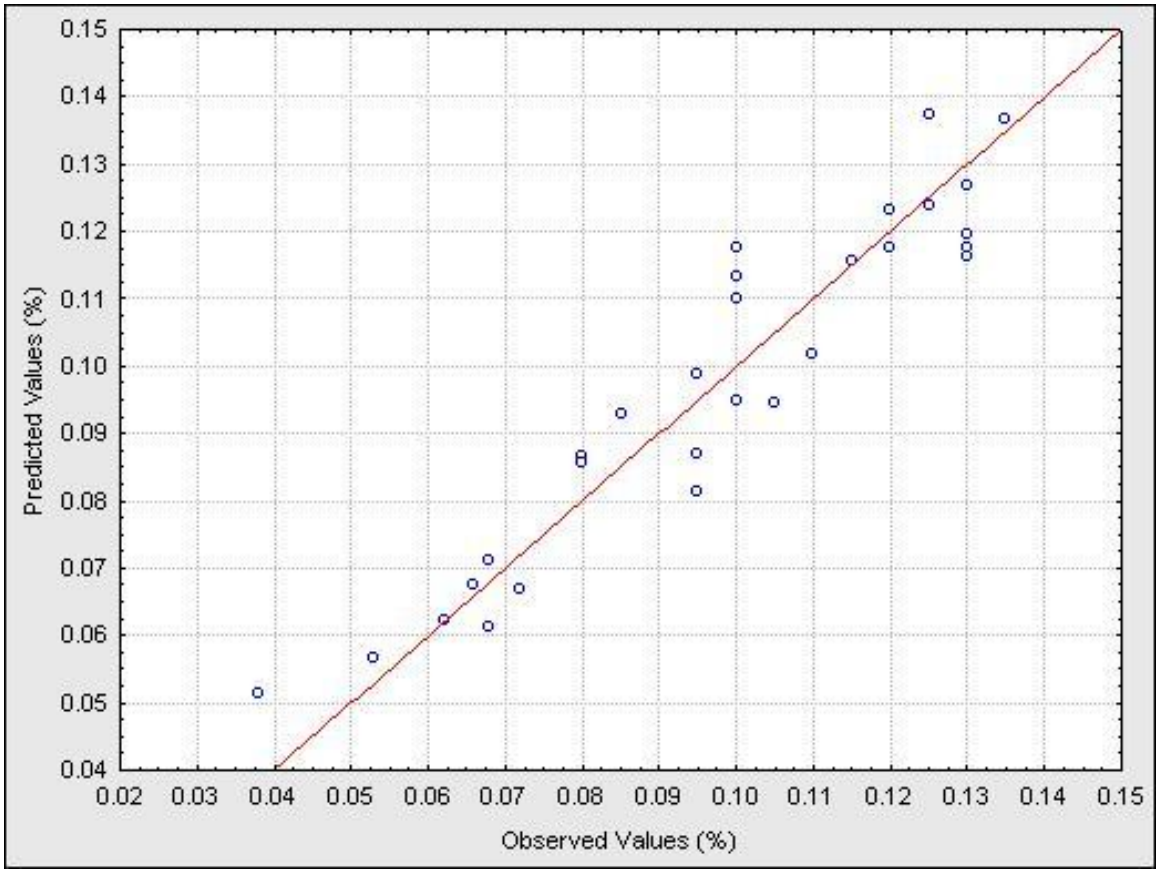


Figure 34:
Predicted vs. observed values for air content response

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 28), 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, 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 35 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 28).

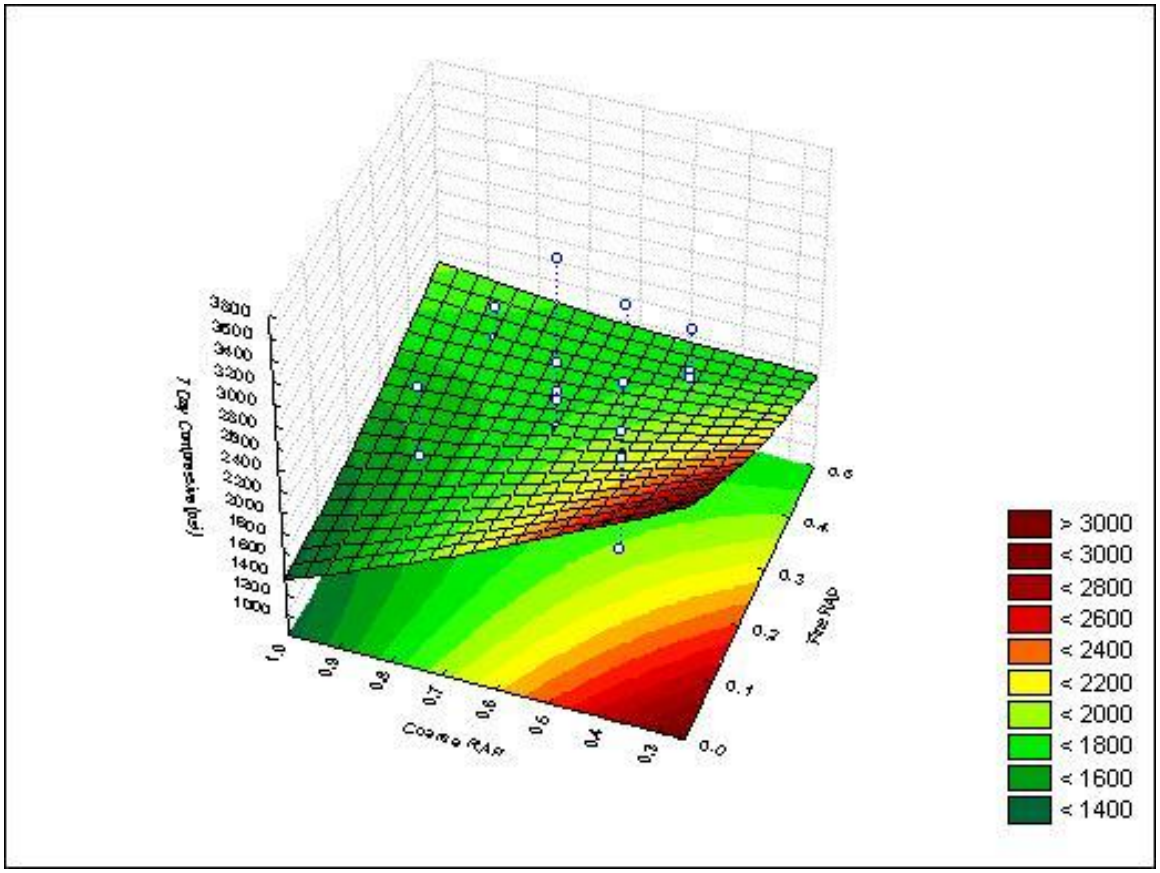


Figure 35:
7-day compressive strength vs. coarse and fine RAP replacement rates

Figure 36, 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 28). This

interaction is clearly evident in the response surface in Figure 36, 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).

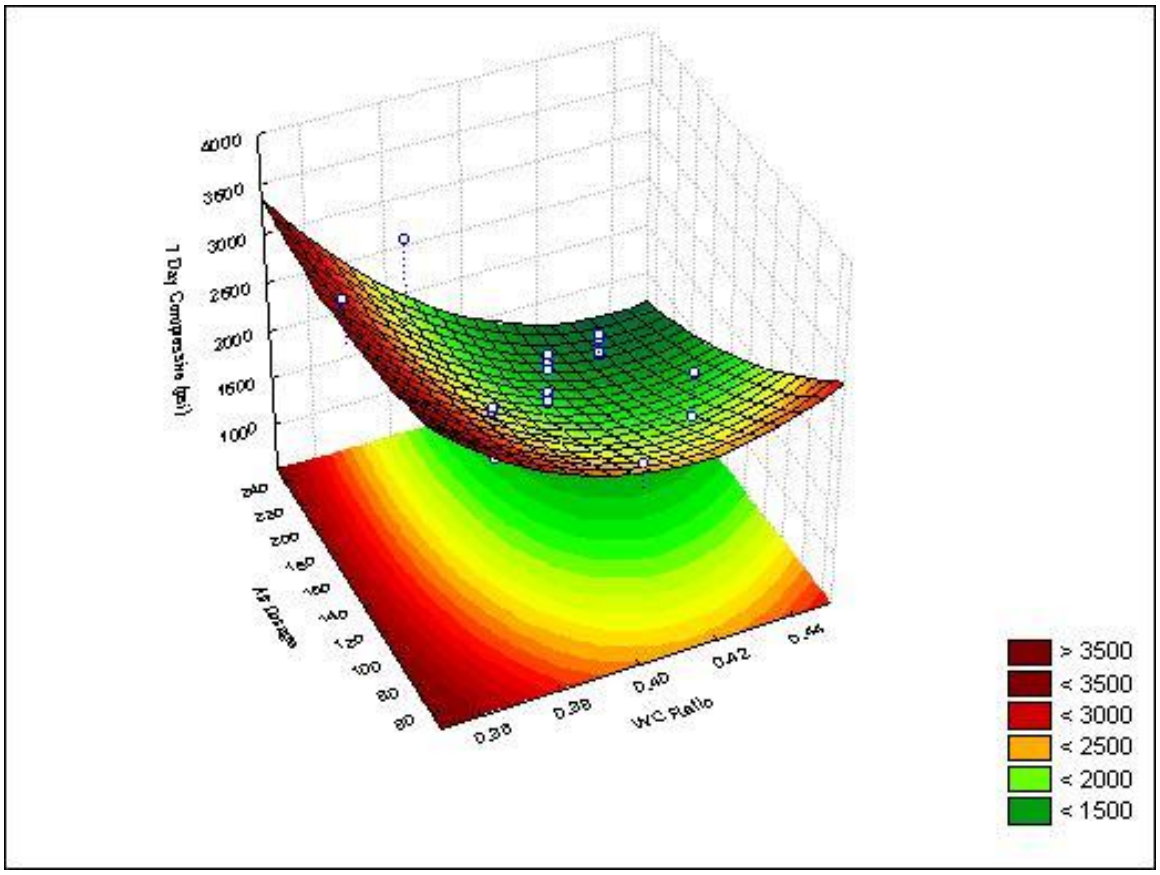


Figure 36:
7-day compressive strength vs. air-entraining admixture dosage rate and water-cement ratio

In Figure 37, 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.

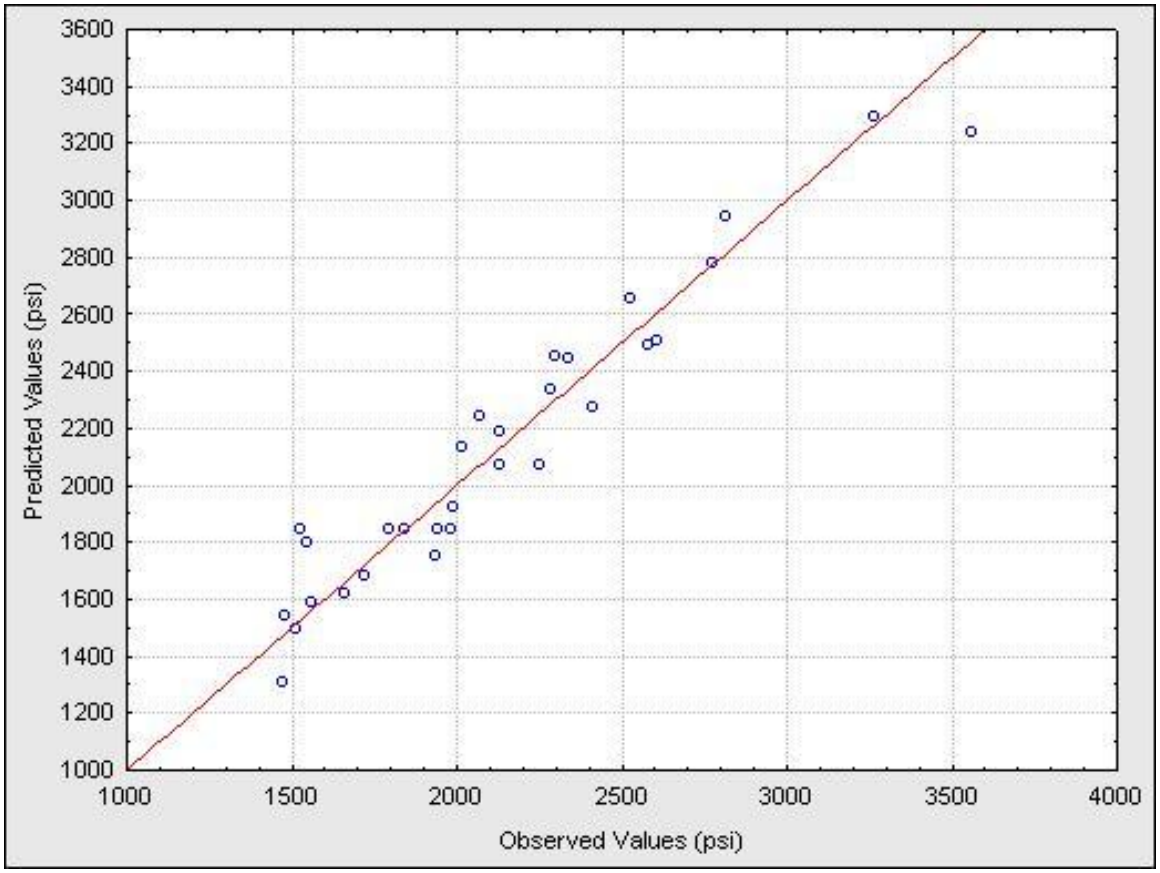


Figure 37:
Observed vs. predicted values for 7-day compressive strength response

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 38. 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 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).

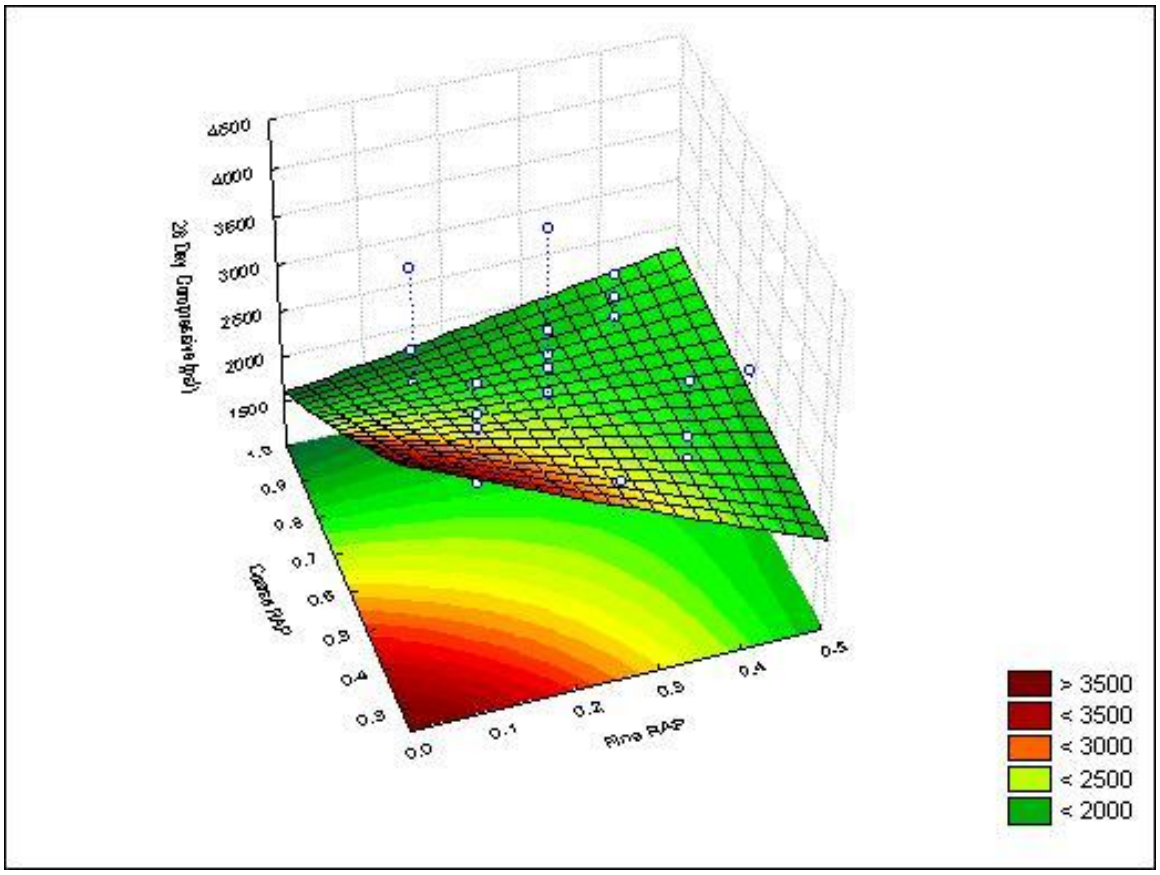


Figure 38:
28-day compressive strength vs. coarse and fine RAP replacement rates

Figure 39 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.

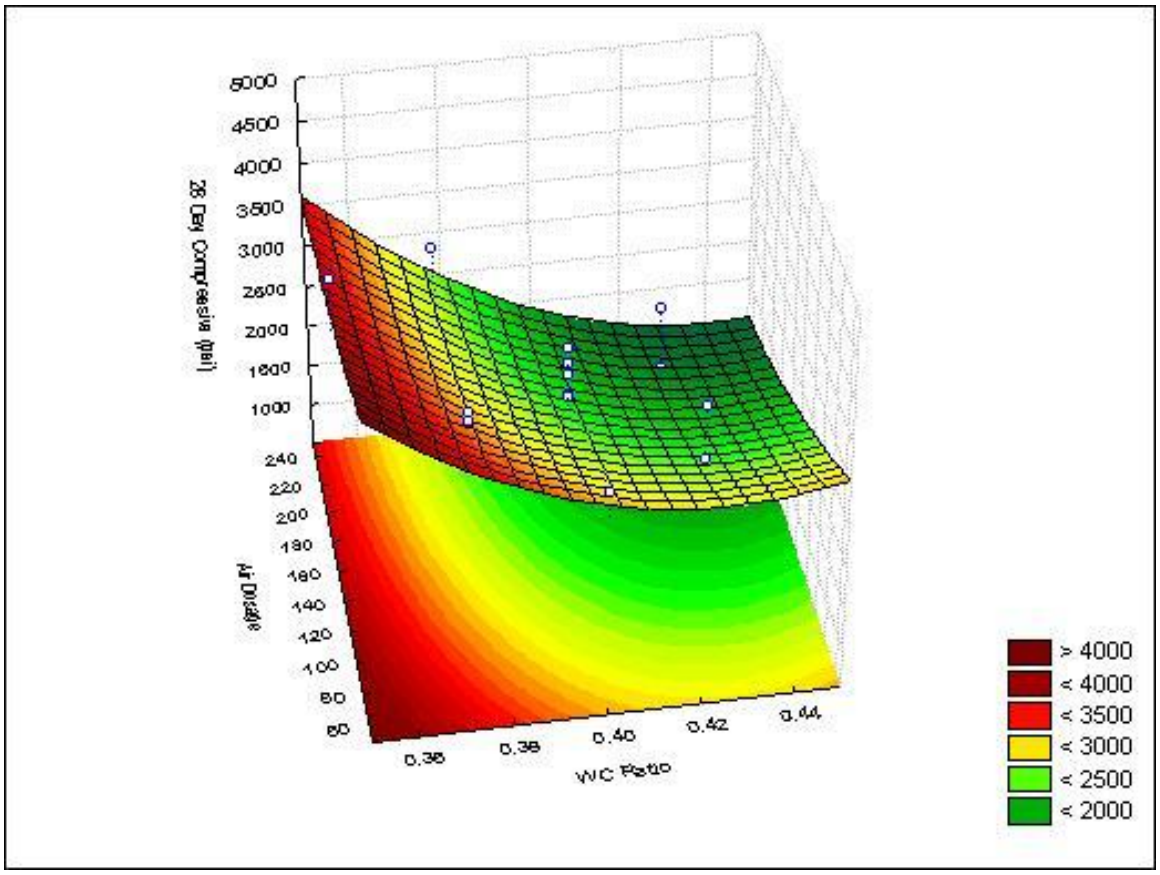


Figure 39:
28-day compressive strength vs. air-entraining admixture dosage rate and water-cement ratio

In Figure 40 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.

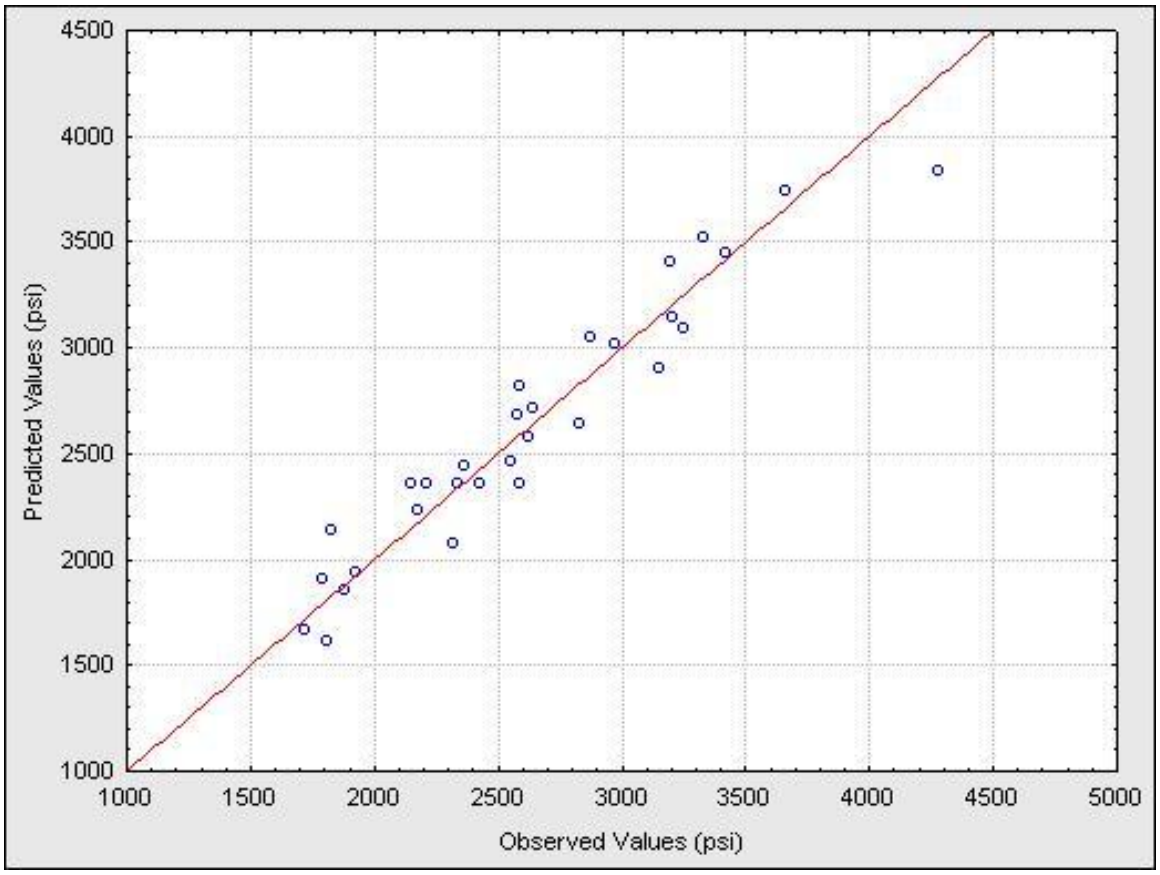


Figure 40:
Predicted vs. observed values for 28-day compressive strength response

Figure 41 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.

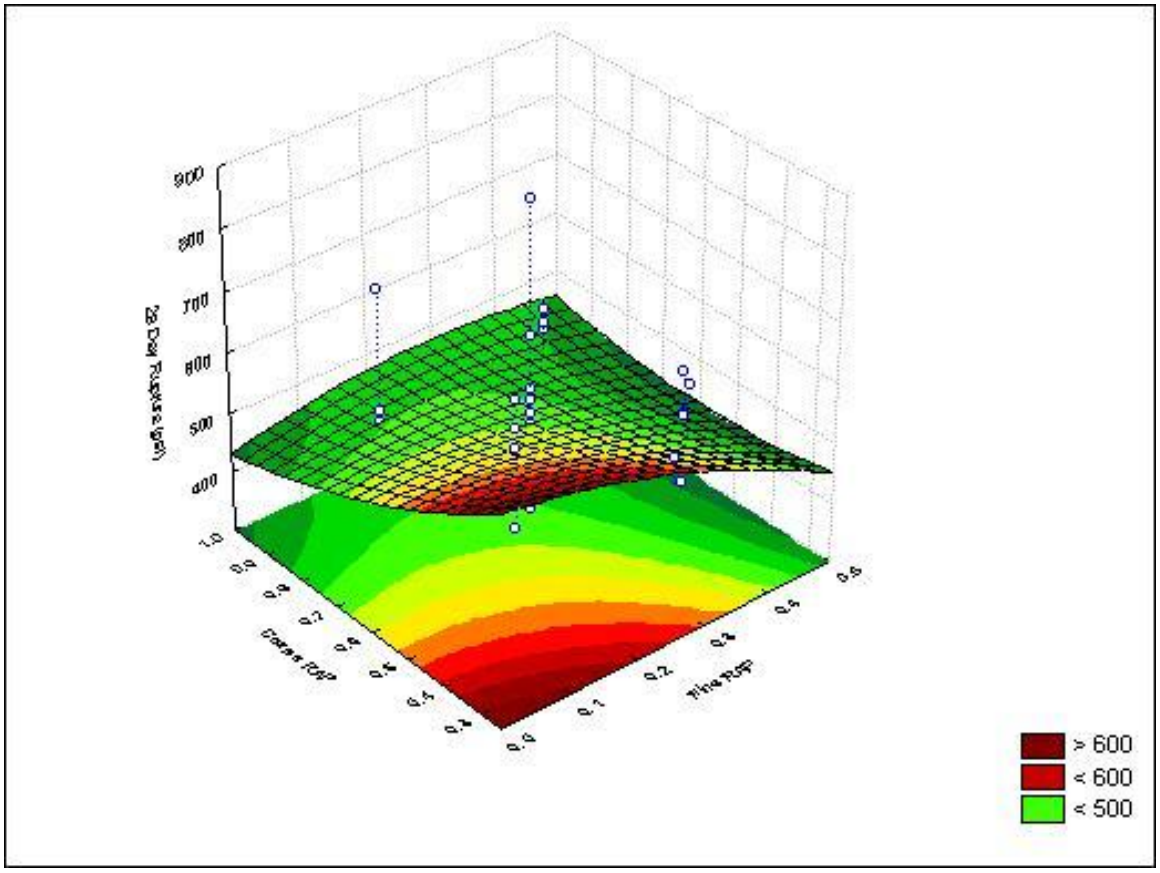


Figure 41:
28-day flexural strength vs. coarse and fine RAP replacement rates

Figure 42 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.

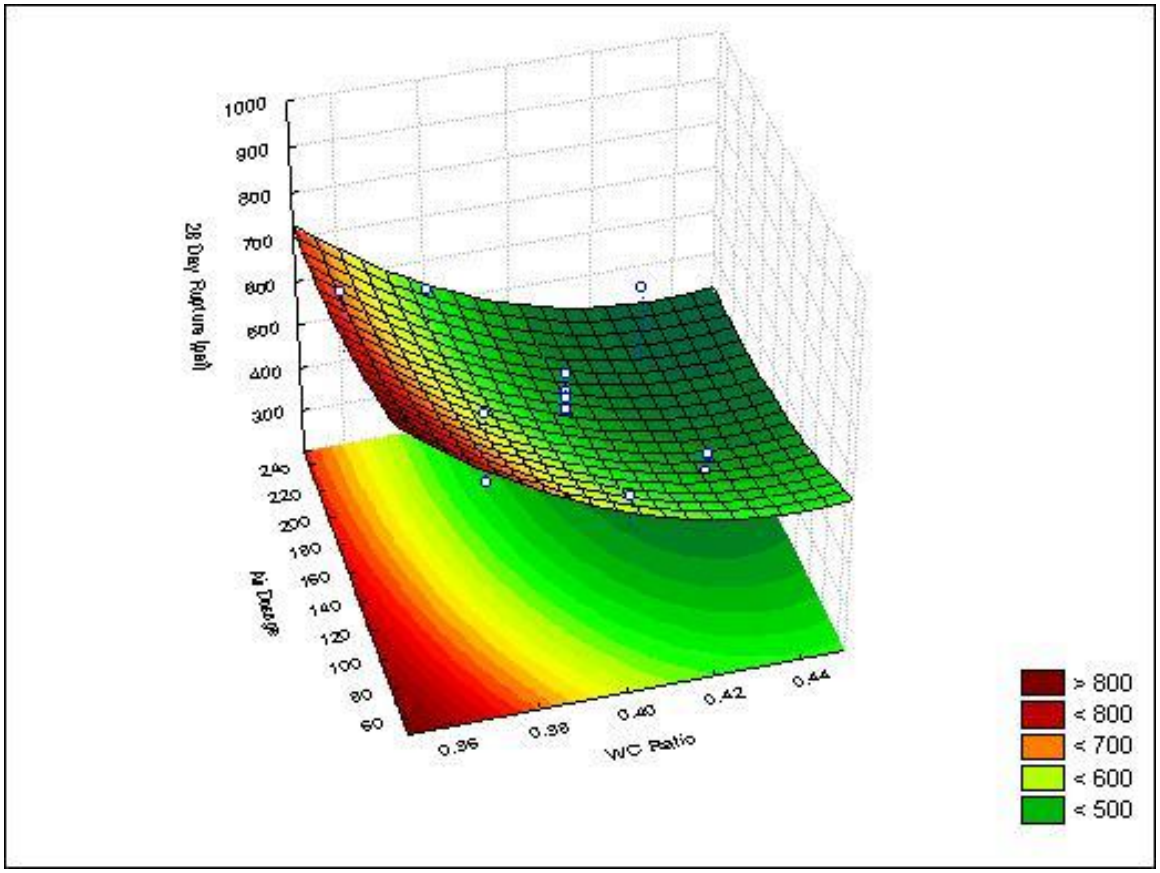


Figure 42:
28-day flexural strength vs. air-entraining admixture dosage rate and water-cement ratio

The predicted versus observed plot for the 28-day modulus of rupture can be seen in Figure 43. The normalized root mean square deviation is 0.0648 or 6.48 percent.

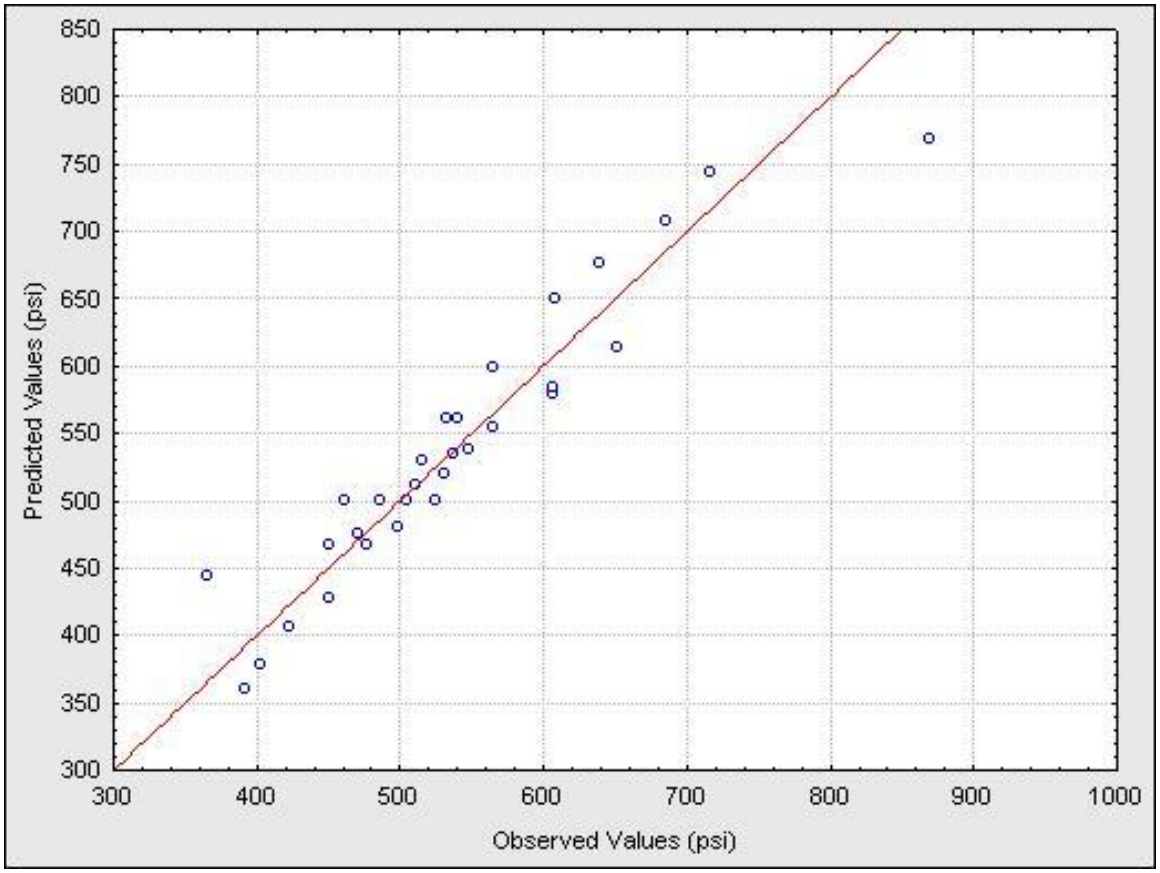


Figure 43:
Predicted vs. observed values for 28-day flexural strength response

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 44. Although seemingly uninteresting when compared to some of the other surface plots, the relationship presented in Figure 44 is a strong validation that the model can correctly pick up on behaviors of the RAP in PCCP mixture.

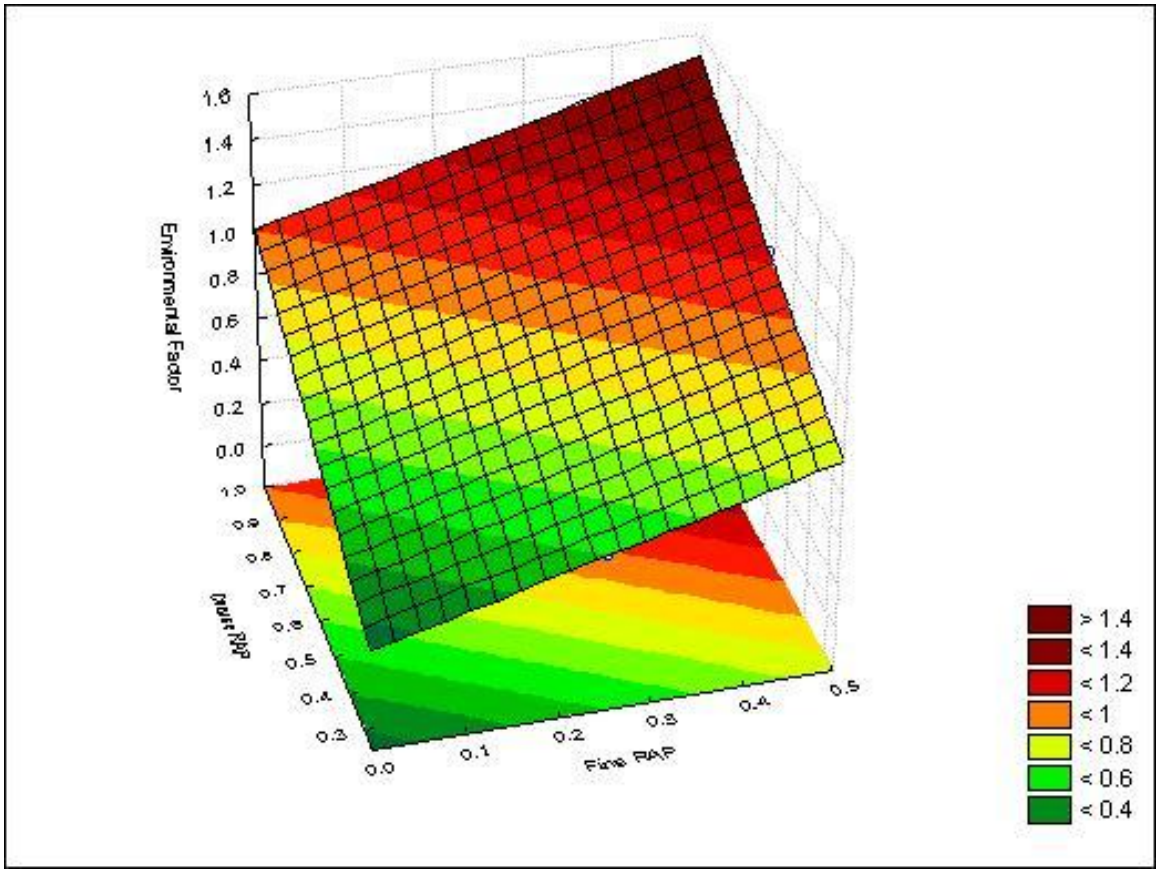


Figure 44:
Environmental impact factor vs. coarse and fine RAP replacement rates

Figure 45 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.

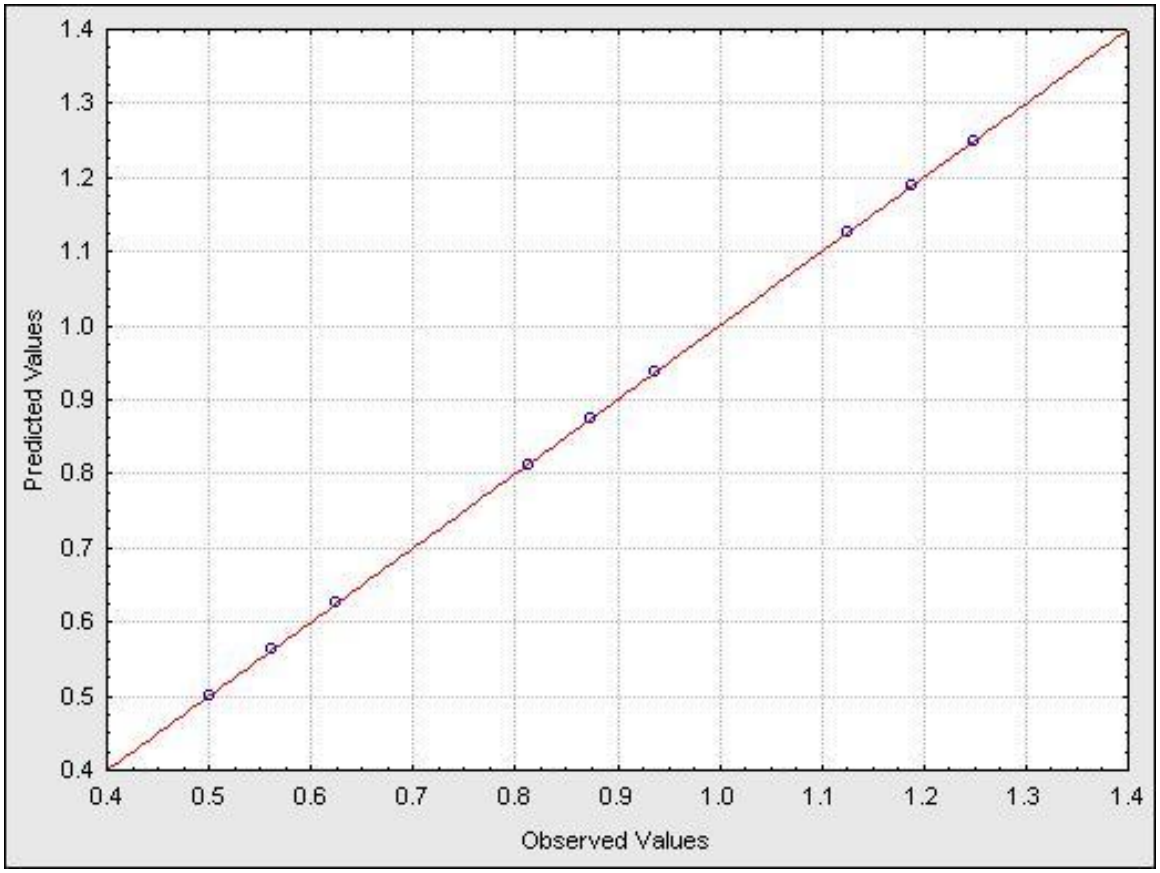


Figure 45:
Predicted vs. observed values for environmental factor response

RAP IN PCCP MIXTURE OPTIMIZATION

The DOE results and statistical model presented in Chapters 6 and 7 provide a foundation to develop optimized concrete mixtures to fulfill project specific criteria. This chapter discusses the optimization strategy used in this research to develop several concrete mixtures to achieve various objectives. Additionally, this chapter presents the results of these optimizations.

Optimizing through Desirability

In order to carry out a mixture optimization, target end-product properties must be defined. With the DOE process, required end specifications are entered into the statistical model through desirability functions for the responses. The statistical model then optimizes towards the desired outcomes and generates independent variable levels that will produce the optimum mix.

Desirability Functions

MDT specifications for Portland cement concrete pavement were used to define the desired material properties for the statistical model, with the exception that the strength requirements were relaxed in order to allow for higher RAP replacements. These MDT specifications are provided in Table 16 and again for convenience in Table 21. The desirability functions input into the statistical software package are piecewise linear relationships where a value of 0.0 is least desirable and 1.0 is most desirable.

Table 21:
MDT specifications for PCCP

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)

The specifications shown in Table 21 were converted to a linear desirability function form, as shown in Figure 46. Both the slump and air specifications give a target value as well as an acceptable range. To capture the essence of this required end result, the desirability function appears as a peak, where the target value is set to the most desirable point at 1.0, and the outside bounds of the acceptable range are set to 0.0 desirability. It should be noted that the desirable air content range for this optimization 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 additional optimization exercises discussed in following sections, this lower air range was used to define the desirability function. The other four responses have very similar desirability functions where they are simply (and somewhat arbitrarily) maximized from 0.0 to 1.0 over the range of observed values that were gathered throughout the mixing experiment (previously reported in Table 17). 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).

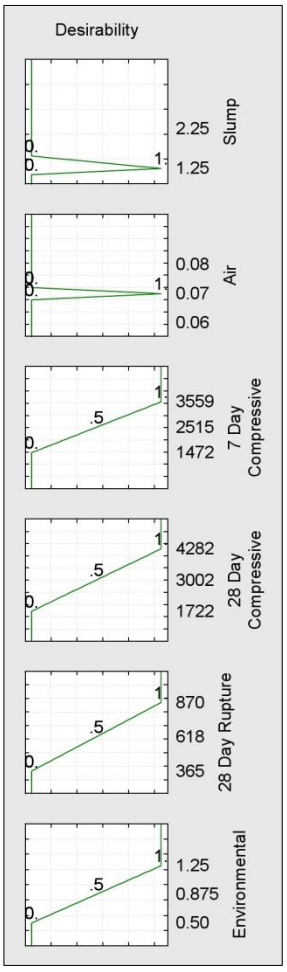


Figure 46:
Desirability functions for optimized mix

Optimization Results

With the desirability functions input into the model, the statistical software program calculated optimum values for the independent variables. These optimum mix specifications are provided in Table 22. Each of the optimized mix parameters is within the range of values considered in developing the DOE. This is an important point as, due to variability and the limited range of tested points; it is difficult for the model to accurately optimize to values that are at or outside the bounds of the defined variable

ranges, or in other words, points that are at or beyond the edges of the design "cube," shown in Figure 18.

Table 22:
Optimum mix parameters for RAP in PCCP

Variable	Predicted Optimum
w/c Ratio	0.35
Paste Volume	0.335
Fine RAP Replacement Rate (%)	12.5
Coarse RAP Replacement Rate (%)	100
Air Dosage (mL/100#)	200

The predicted mix responses as well as their 95 percent confidence intervals are provided in Table 23. Although the predicted responses are fairly close to the desired values, the confidence interval ranges are large. This large spread in the confidence intervals is another indication of the epistemic uncertainty and aleatory variability called out in the previous chapter (Ang & Tang, 2007).

Table 23:
Predicted response values and confidence interval ranges for optimum RAP in PCCP mix

Response	Predicted Value and CI
Slump (in)	1.7029 (-4.5032 to 7.9090)
Air Content (%)	7.027 (0.653 to 13.400)
7-Day Compressive Strength (psi)	2657.0 (1617.2 to 3696.4)
28-Day Compressive Strength (psi)	2774.3 (1486.3 to 4062.3)
28-Day Modulus of Rupture (psi)	709.5 (460.6 to 958.4)
Environmental Factor	1.125 (no variability)

Referring to Table 23, the respective confidence intervals for slump and air content are much larger than those of the strength responses. The trends shown in the

confidence interval ranges are consistent with the nature of the predicted versus observed responses previously presented in Chapter 7.

Key relationships between independent variables and responses are shown in Figure 47, along with the desirability functions and optimization results. In this figure each response is plotted versus each independent variable while all of the other variables are held at their optimum values. 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 specification were met to their fullest extent.

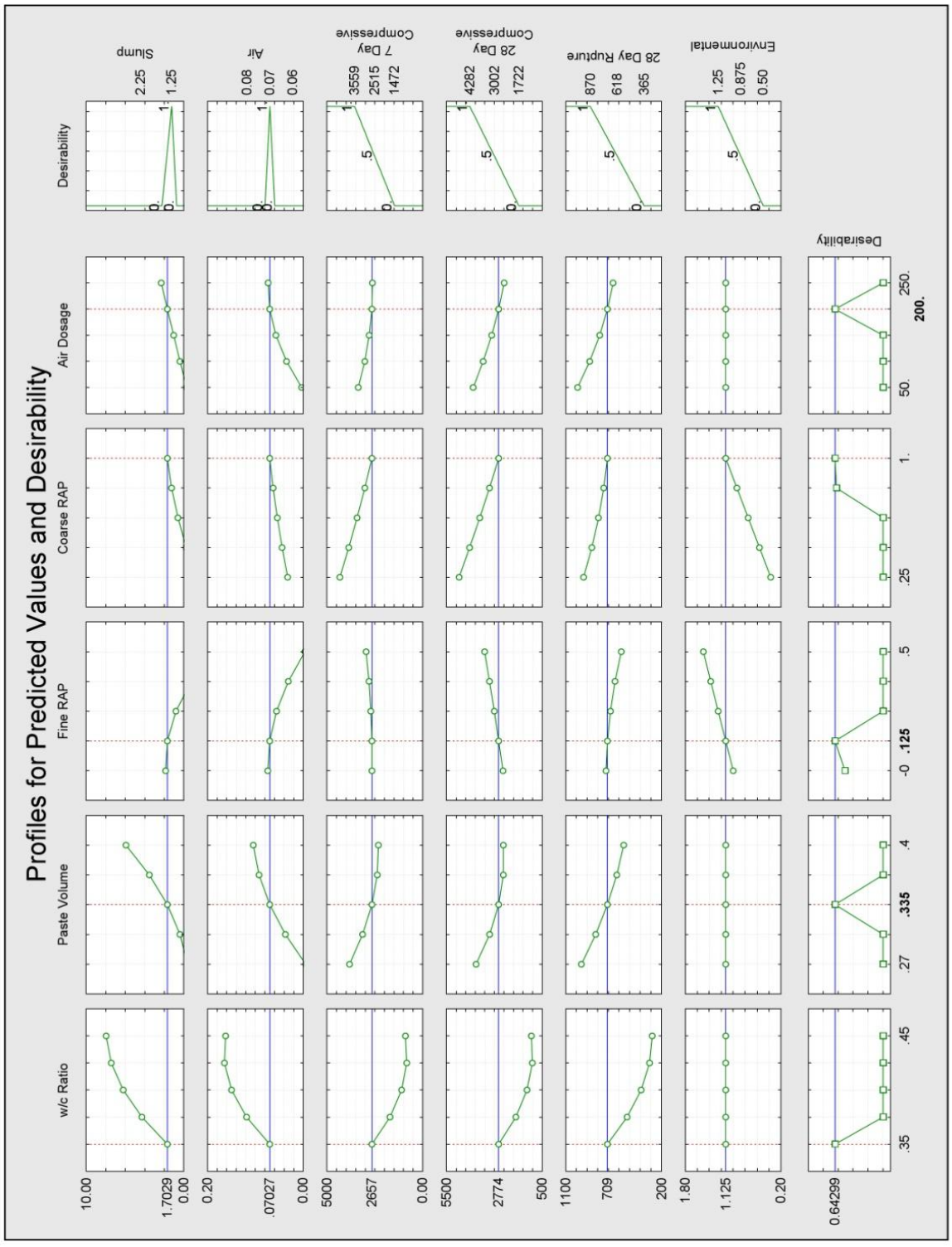


Figure 47:
Predicted values and desirability profiles for RAP in PCCP optimized mix

Verification of MDT Optimized Mix

After reviewing the results of the optimization process, the research team performed the optimized mix design in the laboratory in order to compare the results of the mix design with those predicted through the DOE analysis. The measured mix responses did not exactly match the predicted values (see Table 24), but each response was within the calculated 95 percent confidence intervals (see Table 23).

Table 24:
Comparison of predicted and observed values for optimum mix

Response	Predicted Value	Observed Value
Slump (in)	1.7	3.0
Air Content (%)	7.0	8.5
7-Day Compressive Strength (psi)	2657	2228
28-Day Compressive Strength (psi)	2774	2376
28-Day Modulus of Rupture (psi)	710	615
Environmental Factor	1.125	1.125

Potential Sources of Variability

The differences between the measured and predicted results provided above can be attributed to the epistemic uncertainty of the model and the variability in the recorded data. This subsection discusses two factors that have been identified as potential sources of variability in the data; inherent variability in the slump measurements and inadequacies in the method used for aggregate moisture content corrections.

The subjective nature of the slump test is one of the potential sources of variability. During post-processing of the data, a large amount of variability was observed in the slump data for the center point mixes. In these mixes, all mix proportions were the same (with the exception of aggregate moisture content corrections), and the

slump varied between 4.25 and 6.0 inches. This variability can be attributed, in part, to the subjectivity of the slump test method.

A second possible source of the apparent variability in the DOE data, and the model generated from it is the moisture content correction method used in this research effort. 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.

Turning again particularly to the DOE center point mixes, while the material properties for the aggregate moisture corrected mixes should have been "identical", not only did these properties vary, they varied systematically with the corrected amount of water used in each mix. In Figures 48 through 52, various material properties 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 by the DOE as additional (and probably significant) unexplained variability in the process being modeled. It has been proposed to more fully investigate this phenomenon in greater detail in a follow-up study.

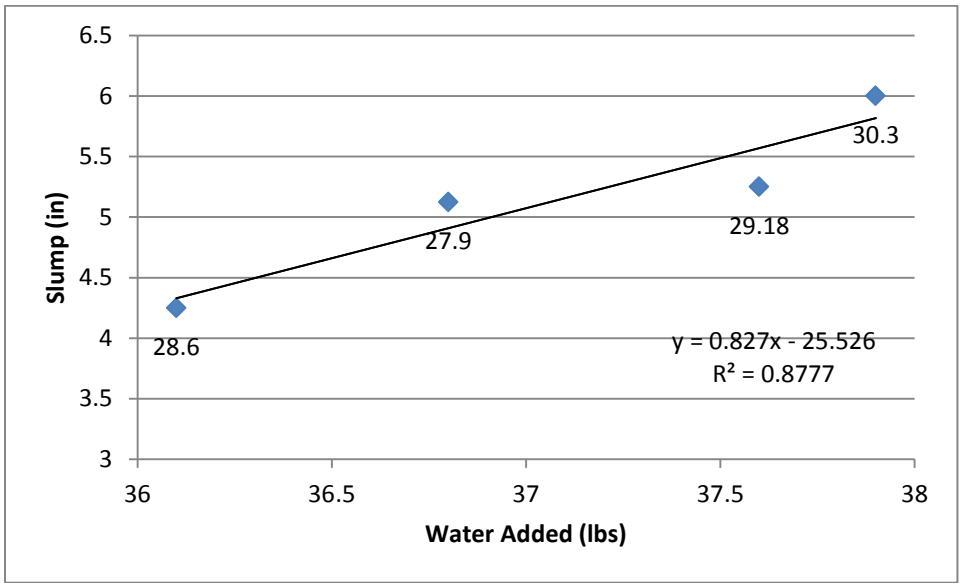


Figure 48:
Water added vs. slump for center point mixes

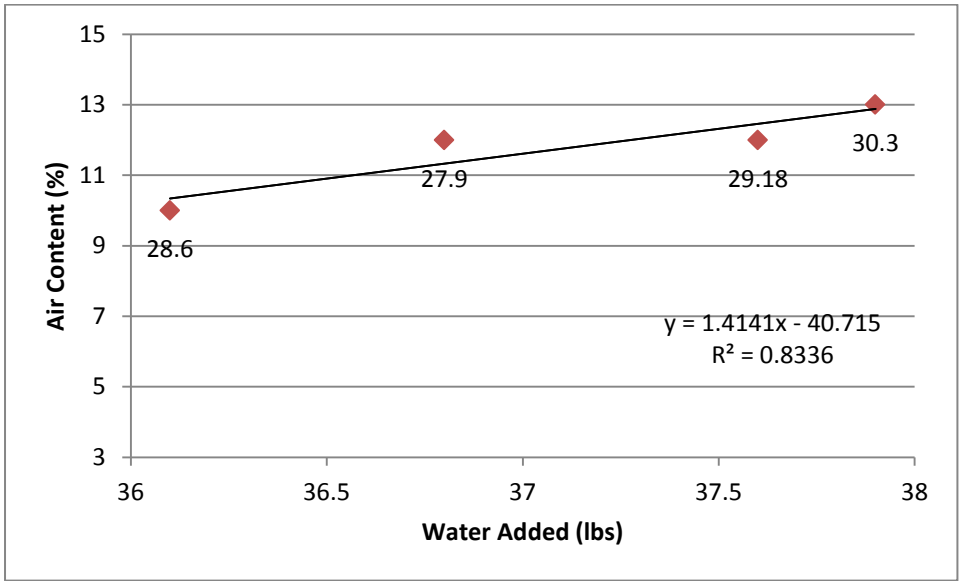


Figure 49:
Water added vs. air content for center point mixes

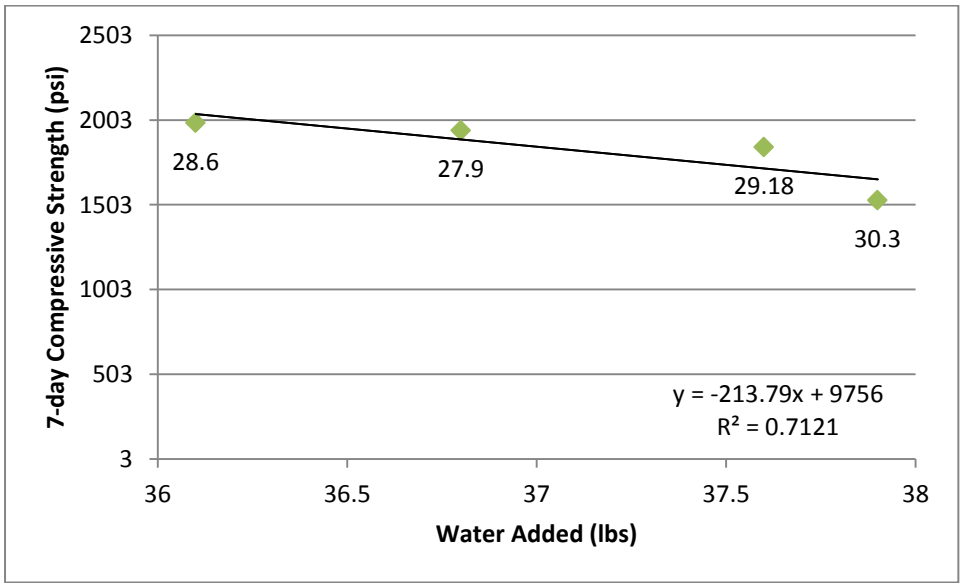


Figure 50:
Water added vs. 7-day compressive strength for center point mixes

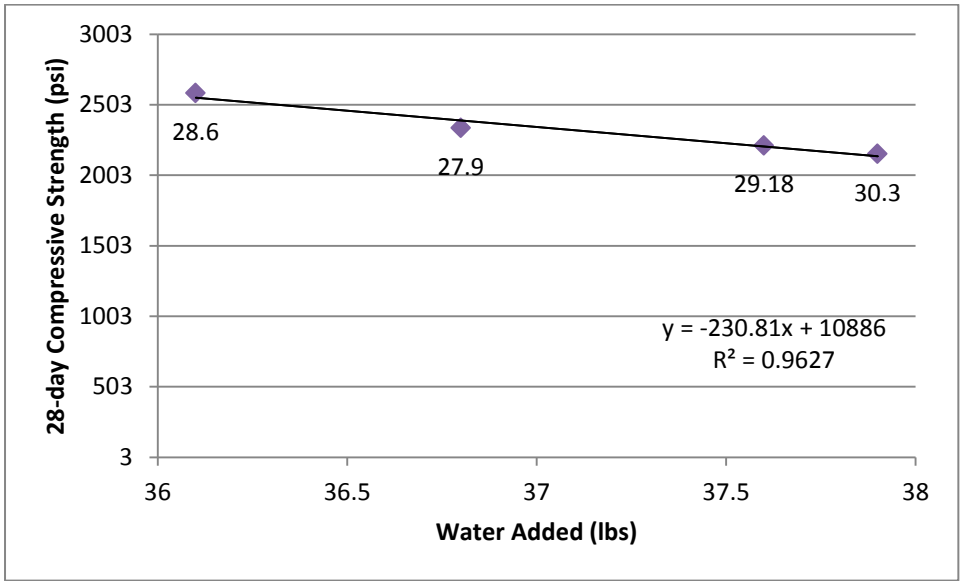


Figure 51:
Water added vs. 28-day compressive strength for center point mixes

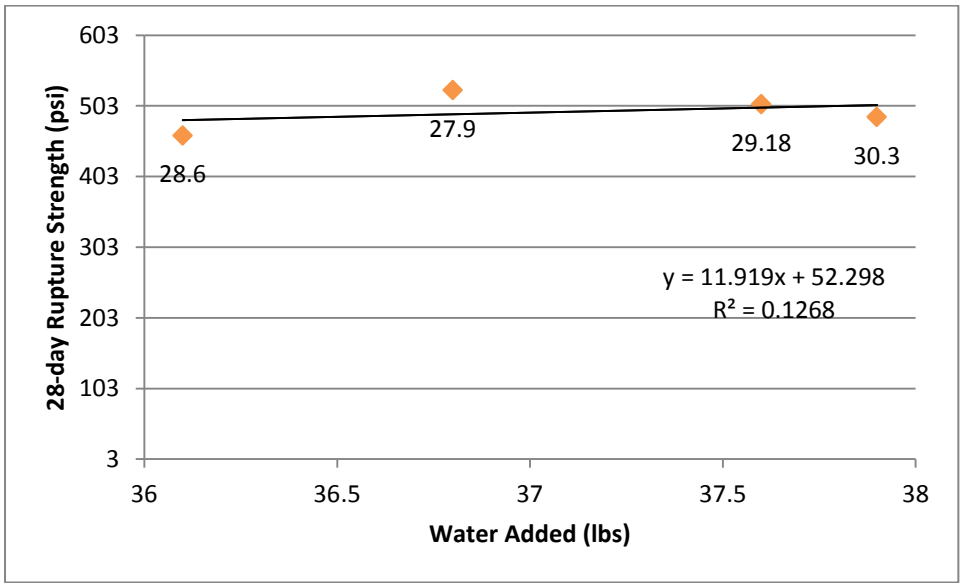


Figure 52:
Water added vs. 28-day tensile strength for center point mixes

The 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.

Selection of the Mixes for Further Testing

An extensive suite of long-term durability and material property tests will be conducted on two mixtures identified by MDT for possible implementation in pavement applications. The two mixture themes chosen by MDT for further evaluation were a high strength mix and a high RAP mix. It was the opinion of MDT and the research team that a high strength mix containing RAP would most likely be implemented in the field, while the high RAP content mix would more specifically explore the material's limitations and boundaries.

High Strength and High RAP Mix Designs

The DOE statistical model was used develop the high strength and high RAP mix designs. Two new sets of desirability functions were created: one set emphasized high strength and devalued RAP content, while the second set of desirability functions encouraged the use of more RAP by devaluing the strength properties. The desirability

functions of the air content and slump for both mixers were targeted towards MDT specified values (as discussed in the previous section).

The desirability profiles and the results of the DOE optimization for the high strength and high RAP mixes are shown in Figures 53 and 54, 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, implying that the material can reasonably achieve this set of desired outcomes.

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. In working with the DOE on this optimization problem that falls outside of the range of tested variables, this desirability function was found to produce usable results. 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).

The designs subsequently generated using the DOE model for the high strength and high RAP mixes are presented in Tables 25 and 26, respectively.

When trying to optimize towards these more extreme outcomes it is important to consider the "cube" analogy presented in Chapter 5, and the manner in which all the possible combinations of the independent variables are represented by the factorial points. Referring to Table 25, which again lists the factorial points originally pointed out in Chapter 6, both mix designs include input parameters outside of the DOE cube of points; therefore, it was difficult to find a solution given this set of desirability functions, and the results may not be accurate. In this regard, for the high RAP mixes in particular, a follow-on DOE study is being conducted to allow for more refined mix optimization.

Table 25:
Design Points for RAP in PCCP DOE

Alpha = 2.0	Axial Low	Axial High	Factorial Low	Center	Factorial Low
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

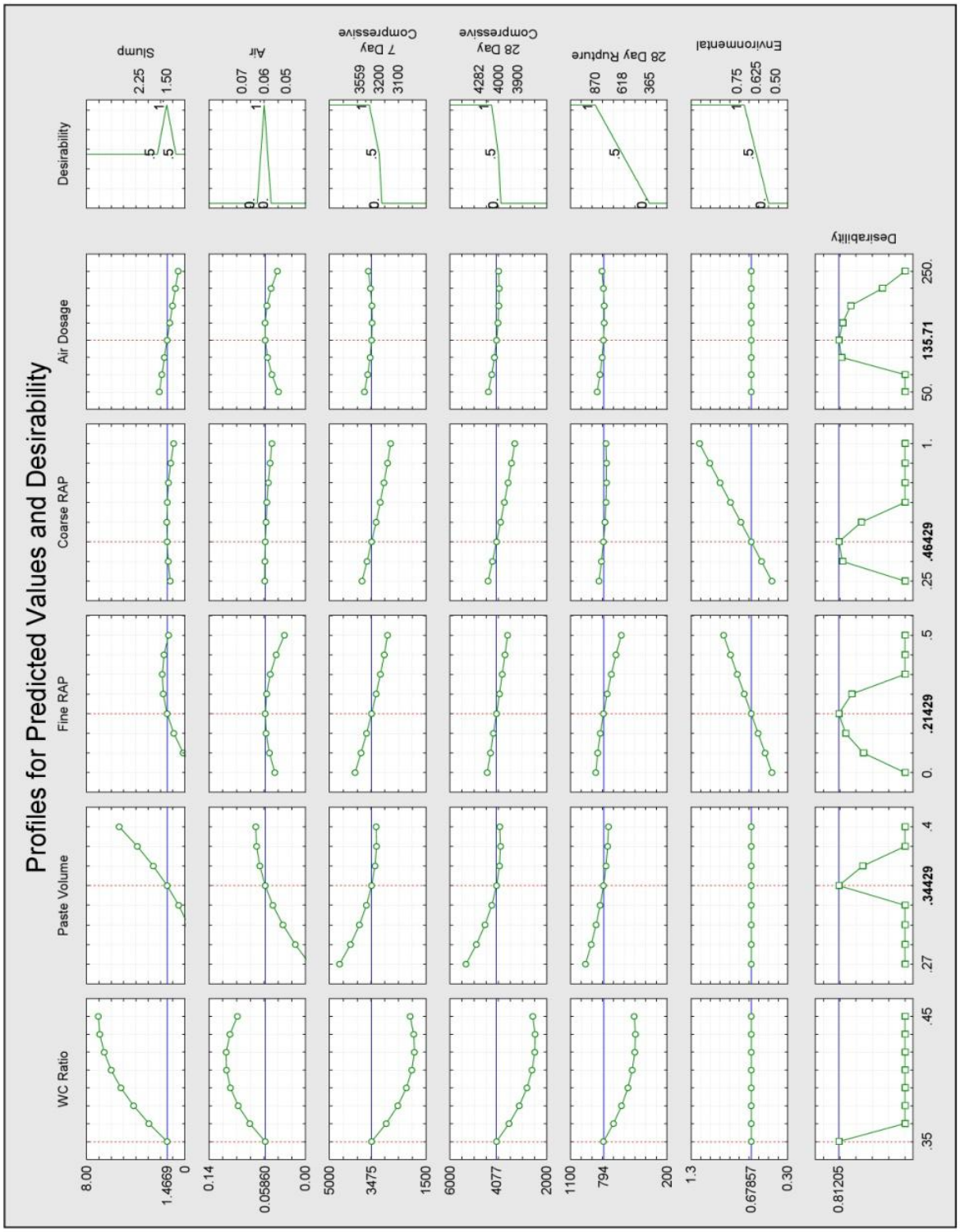


Figure 53:
Predicted values and desirability profiles for RAP in PCCP high strength mix

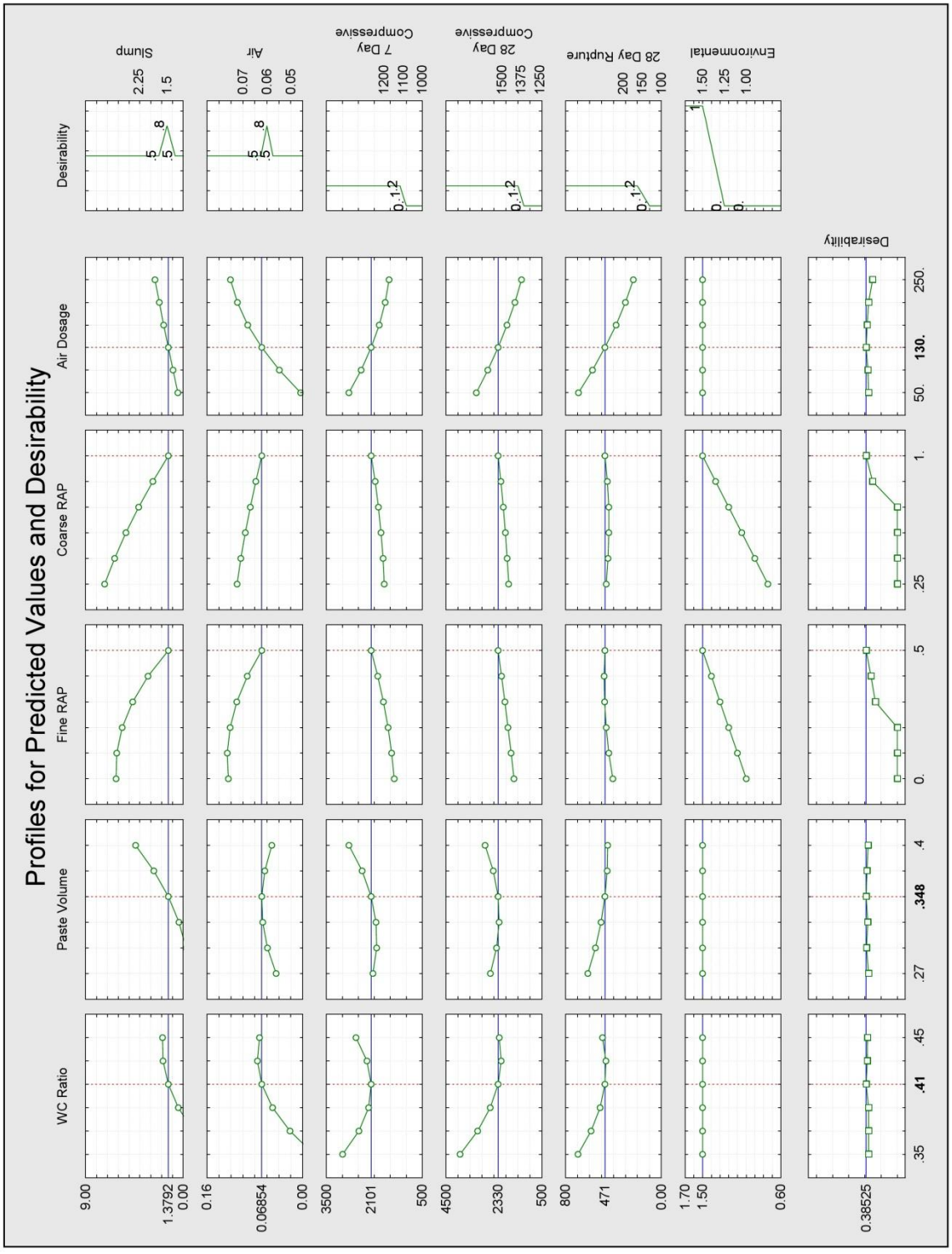


Figure 54:
Predicted values and desirability profiles for RAP in PCCP high RAP mix

Looking more closely at the high strength mix design (see Table 26), as expected, the RAP replacement rate is relatively low, and the water-cement ratio is 0.35, the minimum axial point used in the DOE mixes. It should also be noted that the RAP replacement rates for the high strength mix were rounded for practical purposes, and the predicted response values for this mix were back-calculated with these new rounded replacement rates. Original coarse and fine RAP replacement rates were 21.4 and 46.4 percent, respectively.

Referring to Table 27, in the high RAP mix, the relatively high water-cement ratio of 0.41 and low paste content of 34.8 percent were not expected. Both of these results are somewhat counter-intuitive for mixes with weak aggregate, indicating the possible inaccuracy of the DOE model when applied to ranges outside of the target range (as is done with this mix optimization).

Table 26:
Optimum mix parameters for high strength mix

Variable	Predicted Optimum
w/c Ratio	0.35
Paste Volume	0.34429
Fine RAP Replacement Rate (%)	20
Coarse RAP Replacement Rate (%)	45
Air Dosage (mL/100#)	136

Table 27:
Optimum mix parameters for high RAP mix

Variable	Predicted Optimum
w/c Ratio	0.41
Paste Volume	0.348
Fine RAP Replacement Rate (%)	50
Coarse RAP Replacement Rate (%)	100
Air Dosage (mL/100#)	130

The predicted and observed response values, as well as confidence intervals, for these high strength and high RAP optimized mixes are shown in Table 28 and 29, respectively. The data shown in the "observed" column is the averaged results for three separate high strength batches and two high RAP batches.

Table 28:
Comparison of predicted and observed values for high strength mix

Response	Predicted Value and CI	Observed Value
Slump (in)	1.36 (-1.9038 to 4.6302)	2.46
Air Content (%)	5.87 (2.510 to 9.220)	7.83
7-Day Compressive Strength (psi)	3534 (2987.2 to 4081.5)	2941
28-Day Compressive Strength (psi)	4125 (3447.4 to 4803.4)	3521
28-Day Modulus of Rupture (psi)	802 (671.1 to 933.1)	661
Environmental Factor	0.65 (no variability)	0.65

Table 29:
Comparison of predicted and observed values for high RAP mix

Response	Predicted Value and CI	Observed Value
Slump (in)	1.38 (-3.8732 to 6.6316)	8.00
Air Content (%)	6.85 (1.4600 to 12.249)	12.25
7-Day Compressive Strength (psi)	2101 (1222.0 to 2981.0)	1158
28-Day Compressive Strength (psi)	2330 (1240.0 to 3420.0)	1363
28-Day Modulus of Rupture (psi)	471 (260.2 to 681.5)	354
Environmental Factor	1.50 (no variability)	1.50

The results from the multiple batch trials done for the high strength and high RAP mixes further support the earlier voiced concern that the traditional method for pre-calculating aggregate moisture corrections based on absorption and moisture content are not fully effective with RAP aggregate. Results from two batch trials for the high strength mix (Trials 4 and 5) are reported in Table 30. These mixes were identical, with

the only variation in the proportions resulting from mix water adjustments due to the variation in aggregate moisture content at the time of the trials. While the properties of these concretes therefore should have been "identical", there is a wide disparity in all properties, with this disparity being larger than expected based simply on the variability in the test methods used.

Results from two batch trials for the high RAP mix (trials 3 and 6) are presented in Table 31. In this case, the two mixes again were intended to be identical, but the correction for aggregate moisture was accomplished using "slump adjustment." As previously mentioned, following this approach the assumption is made that independent of the initial moisture condition of the aggregate, when sufficient mix water is added to achieve the desired slump, the necessary water is available to produce the target water-cement ratio and other properties of the paste. The slump adjustment method appears to have worked very well in this case to account for aggregate moisture condition. That is, while a different amount of water was added to each mix (32.6 and 30.7 lbs, respectively, for Trials 3 and 6), the two mixtures subsequently had very similar material properties (see Table 31). These results indicate that adjusting for aggregate moisture content is important, and that the slump adjustment method can be effective.

Table 30:
Slump adjusted data for high strength mixes

Mix Parameter	High Strength 4	High Strength 5
w/c Ratio	0.350	0.350
*Paste Volume	0.367	0.332
Fine RAP Replacement (%)	20	20
Coarse RAP Replacement (%)	45	45
Air Dosage (mL/100#)	135.71	135.71
Water Withheld (%)	0	0
Total Mix Water Added (lbs)	34.7	28.5
Slump (in)	4.0	0.5
Air Content (%)	6.80	3.5
7-Day Compressive Strength (psi)	3035	4327
28-Day Compressive Strength (psi)	3678	5097
28-Day Rupture Strength (psi)	703	906
Environmental Factor	0.65	0.65
*The paste volume was calculated assuming that the aggregates did not absorb or add to the available mix water. The water-cement ratio was taken as the mix water added in pounds divided by the cement plus fly ash content, also in pounds.		

Table 31:
Slump adjusted data for high RAP mixes

Mix Parameter	High RAP 3	High RAP 6
w/c Ratio	0.347	0.320
*Paste Volume	0.343	0.332
Fine RAP Replacement (%)	50	50
Coarse RAP Replacement (%)	100	100
Air Dosage (mL/100#)	130	130
Water Withheld (%)	14.4	20.1
Total Mix Water Added (lbs)	32.6	30.7
Slump (in)	1.0	1.0
Air Content (%)	6.0	5.7
7-Day Compressive Strength (psi)	2251	2219
28-Day Compressive Strength (psi)	2702	2772
28-Day Rupture Strength (psi)	606	693
Environmental Factor	1.50	1.50
*The paste volume was calculated assuming that the aggregates did not absorb or add to the available mix water. The water-cement ratio was taken as the mix water added in pounds divided by the cement plus fly ash content, also in pounds.		

Final Mix Determinations for High RAP and High Strength Mix Designs

Although the research team was able to learn a lot about the relationship between the statistical model and the variability brought on the inherent consistency issues that come along with mixing concrete, it is believed that more research will be necessary to fully understand the effect of different uncontrolled variables. Unfortunately, the additional work required is outside the scope of this thesis project, and should be addressed through a separate study.

High levels of variability identified through the mixing experiment have had a major effect on the outcome of this research. However, through the DOE process the research team was able to gain a much more in-depth understanding of the RAP in PCCP mixture at hand, and the statistical model that was developed through this experiment became a powerful tool for mix design purposes. Although the model was unable to perfectly optimize towards and predict response values, the regression produced mix parameters "in the ball park," and given this information, with some simple laboratory adjustments to compensate for the model's short-comings, it should be possible to create a desirable concrete product for additional material testing.

SUMMARY AND CONCLUSIONS

With the continually increasing pressure to build sustainable and environmentally friendly infrastructure, the state of Montana is exploring the use of reclaimed asphalt pavement as aggregate in Portland cement concrete pavement. The subject study is part of a larger, more encompassing research project to develop and comprehensively evaluate the performance of RAP in PCCP mixtures. The objective of the specific work described herein is more focused, studying the development and initial characterization of mix designs to be used in further testing. An additional goal of this research was to evaluate the effectiveness of using the Design of Experiments method to assist in mix design development. This chapter discusses the conclusions that can be drawn from this research effort, with respect to both of these project objectives.

Findings on PCCP Containing RAP Replacement Aggregates

Through the mixing experiment and preliminary testing phases of this project, a number of conclusions can be drawn about the suitability of PCCP containing RAP as a driving surface in Montana. Findings at this point of the research effort are listed below.

- As the replacement rate of the RAP aggregate is increased, the overall compressive strength of the concrete material decreases. However, this study has revealed that material which is potentially suitable for transportation applications may have replacement rates as high as a 50 percent fine RAP content and 100 percent coarse RAP replacement. Further, at RAP replacement rates of 20 percent fine and 45 percent coarse, a concrete material was produced that exceeded current MDT paving specifications.
- Although the DOE analysis determined that both gradations of RAP aggregate have adverse effects on the strength properties of the final concrete product, the regression model revealed that the fine RAP has a more severe effect on the

material, especially when it comes to the 28-day strength. At high RAP replacement rates, there appears to be a benefit (relative to concrete strength) in using higher replacements of both fine and coarse RAP, rather than singly replacing just one component of the natural aggregate.

- When compared to the traditional empirical formula for the modulus of rupture for conventional concrete of $7.5\ \overline{f'c}$ (psi), PCCP containing RAP showed significantly higher flexural strengths. Although the inclusion of RAP increases the tensile capacity of the material, this strength increase does not appear to be related to the replacement rate of the RAP aggregate. Rather, the baseline inclusion of the RAP aggregate alone increases the MOR. This increased tensile strength could indicate that the material is highly durable. Future creep and durability tests described in Chapter 1 will determine the final adequacy of PCCP containing RAP for pavement application in Montana.

- Finally, conclusions from this study have led to the recommendation that moisture content correction methods be investigated further, especially for RAP aggregates.

Findings on the DOE Method for use in Concrete Mix Design

The DOE method is not widely seen in civil engineering applications, but through the completion of this study, several important findings can be drawn in regards to the method's use as a mix design development tool.

- The DOE method proved to be a very useful tool for characterizing the behavior of the Portland cement concrete pavement containing RAP replacement aggregates.

- Although the application of the Design of Experiments method proved to be effective, both aleatory and epistemic uncertainty had significant effects on the statistical model's accuracy and capability to optimize and predict mixture parameters.

- It is suggested that for future concrete DOE applications a careful variability study be conducted prior to the commencement of the designed experiment. The completion of this more in-depth variance research will hopefully produce additional methods for reducing and characterizing the uncertainty and unpredictability of concrete mixtures.

WORKS CITED

ASTM International. (2009). *Annual Book of ASTM Standards* (Vol. 04.02: Concrete and Aggregates). Baltimore: American Society for Testing and Materials.

Bradley, N. (2007). *The Response Surface Methodology.* Applied Mathematics and Computer Science. South Bend: Indiana University of South Bend.

Czitrom, V. (1999). One-Factor-at-a-Time Versus Designed Experiments. *The American Statistician , 53* (2), 126-131.

Delwar, M., Fahmy, M., & Taha, R. (1997). Use of Reclaimed Asphalt Pavement as an Aggregate in Portland Cement Concrete. *ACI Materials Journal* (May - June 1997), 251-256.

Federal Highway Administration. (1997). *User Guidelines for Waste and Byproduct Materials in Pavement Construction: Reclaimed Asphalt Pavement Material Description.* Retrieved February 8, 2011, from U.S. Department of Transportation Federal Highway Administration: http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap131.cfm

Headwaters Resources. (2010). *ASTM C618-05/AASHTO M 295 Testing of J.E. Corette Plant Fly Ash.* Billings, MT: Headwaters Resources.

Holcim (US) Inc. (2010). *Material Certification Report - Cement.* Trident, MT: Holcim (US) Inc.

Hossiney, N. J. (2008). *Evaluation of Concrete Containing RAP for Use in Concrete Pavement.* Civil Engineering. Gainesville: University of Florida.

Huang, B., & Shu, X. (2005). Experimental Study on Properties of Portland Cement Concrete Containing Recycled Asphalt Pavements. *Innovations for Concrete Pavement: Technology Transfer for the Next Generation* (pp. 485-499). Colorado Springs: Internation Society for Concrete Pavements.

Huang, B., Shu, X., & Li, G. (2005). Laboratory Investigation of Portland Cement Concrete Containing Recycled Asphalt Pavements. *Cement and Concrete Research* , 2008-2013.

Kavanaugh, B. P. (2008). *Creep Behavior of Self-Consolidating Concrete.* Auburn University. Auburn: Auburn University.

Montana Department of Transportation. (2006). Standard Specifications for Road and Bridge Construction. *2006*. Helena, Montana: Montana Department of Transportation and Montana Transportation Commission.

Pennsylvania State University. (2008). *Lesson 1: Introduction to Design of Experiments*. Retrieved March 15, 2011, from Stat 503 Design of Experiments: http://www.stat.psu.edu/online/courses/stat503/01_intro/02_intro_history.html

Simon, M. (2003). *Concrete Mixture Optimization Using Statistical Methods.* FHWA.

StatSoft. (n.d.). STATISTICA Electronic Manual. Tulsa, Oklahoma, United States of America.

Thisted, R. A. (1998, June 8). What is a P-value? Chicago: The University of Chicago.

Weber, B. (2010, February 17). Typical Montana Pavements. (B. Bermel, Interviewer)

APPENDICES

APPENDIX A

CREEP FRAME DESIGN AND CONSTRUCTION

The major intent of studying the feasibility of using RAP as aggregate in PCCP was to characterize the long-term durability characteristics of the material. Given this objective, the material's creep tendency is an obvious and important parameter to test. ASTM C512/C512M gives the standard test method for creep of concrete under compression loading and this specification also gives requirements for the testing frame used to compress the concrete specimens. The load frame consists 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 57 gives a pictorial representation of the frame.

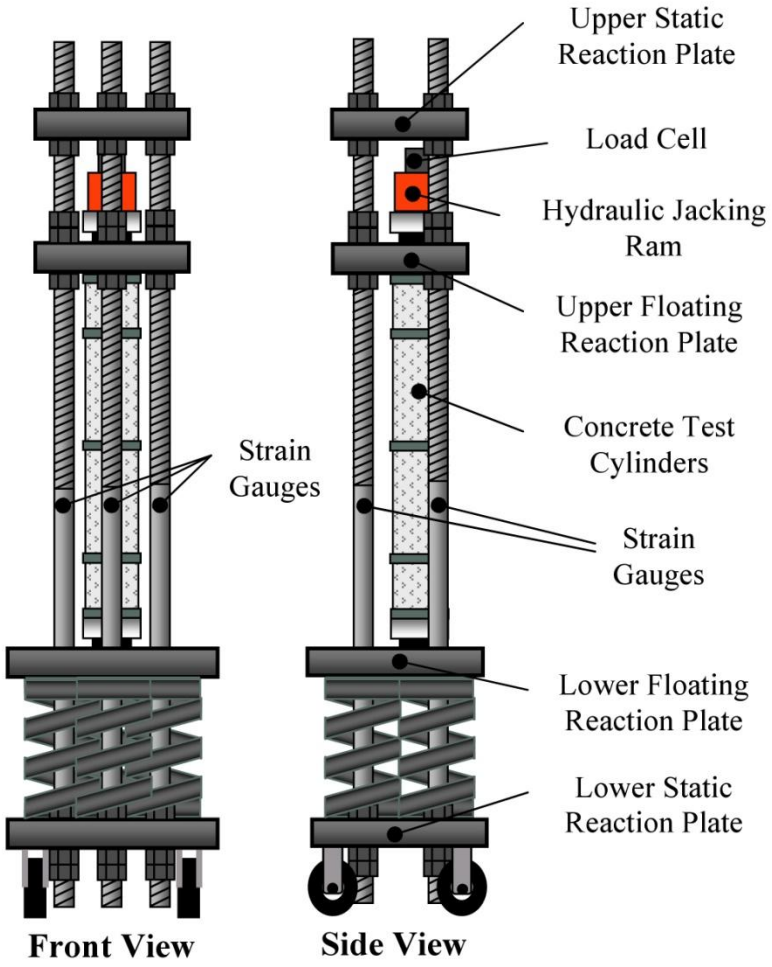


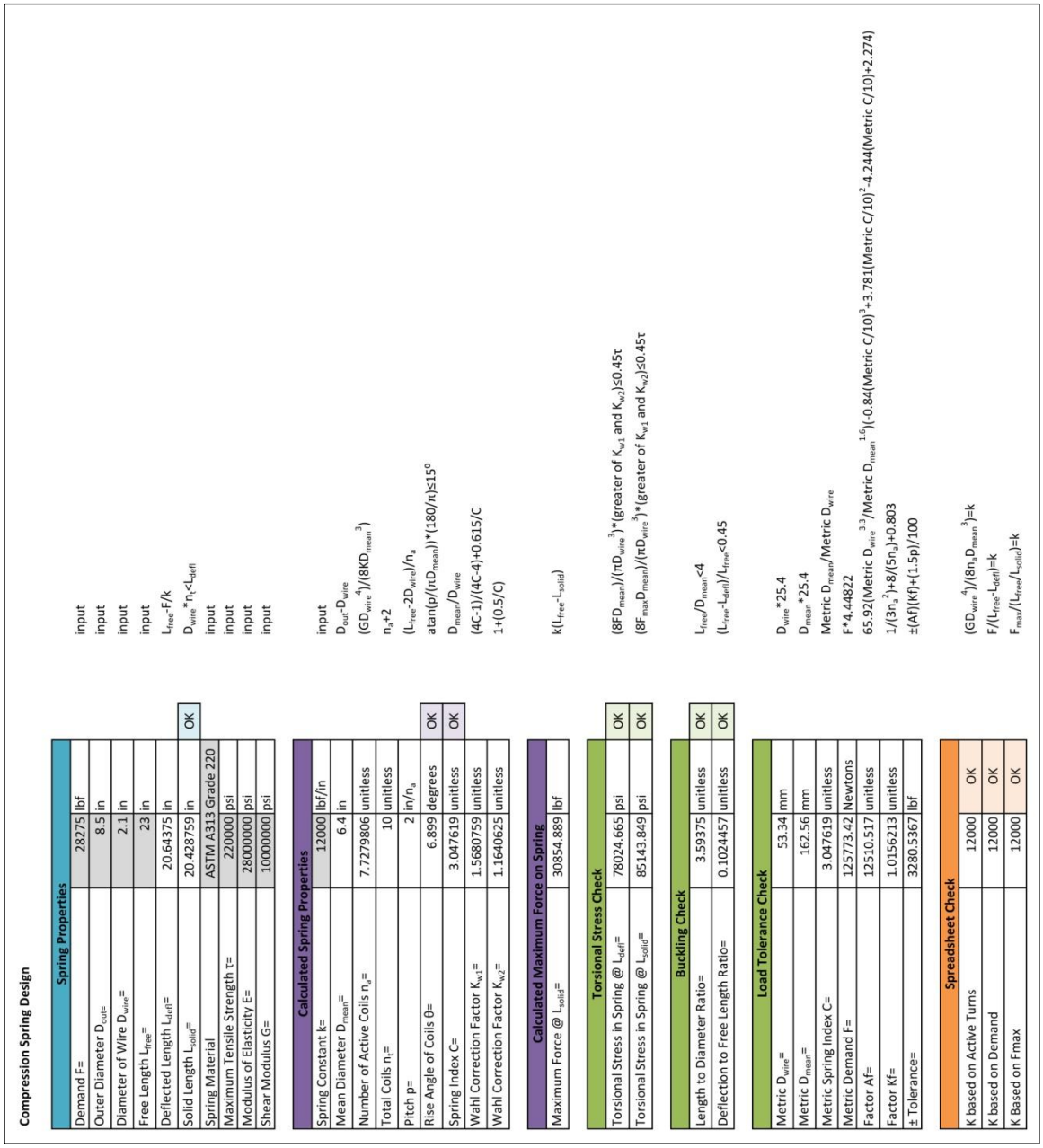
Figure 55:
Elevation view of creep testing load frame
(Kavanaugh, 2008)

The design and construction of two creep testing frames for use in the subject research project was an add-on work item included in the scope of this thesis. The major design elements of the frame included the reaction plates, compression springs, and tension rods. Although the PCCP containing RAP is not expected to achieve overwhelming strengths, the frames were designed to test a concrete with a long-term compressive capacity of 10,000-psi, so as the apparatuses could be used on future

projects. 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.

Compression Spring Design

The compression springs were designed in accordance with standard spring mechanics equations and a spreadsheet showing design calculations and comments can be found in Table 33. The final specified spring dimensions can be found in the top portions of the design table, and as a sort of scale reference see the pictures shown in Figures 58 and 59. 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, and 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 will be used to determine how often the load will need to be reapplied, as the springs relax throughout the year-long testing period.



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	atan(p/(πD_{mean}))*(180/π)≤15°
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

Table 32:
Compression spring design tables and equations



Figure 56:
Compression spring coil diameter



Figure 57:
Compression spring free height

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 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.

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.

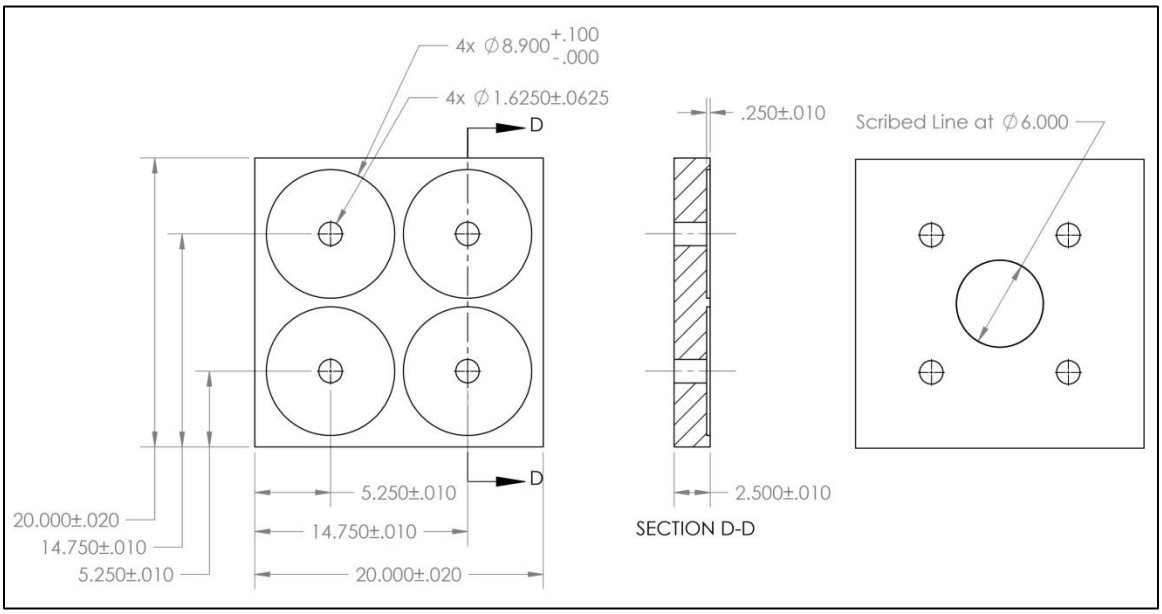


Figure 58:
Bottom lower reaction plate

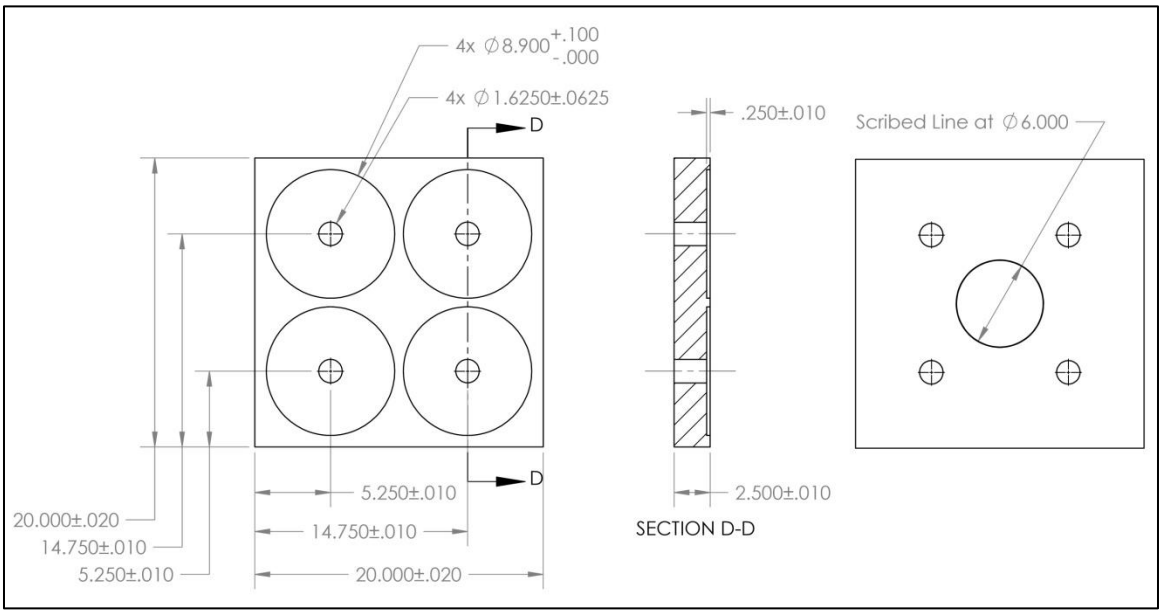


Figure 59:
Top lower reaction plate

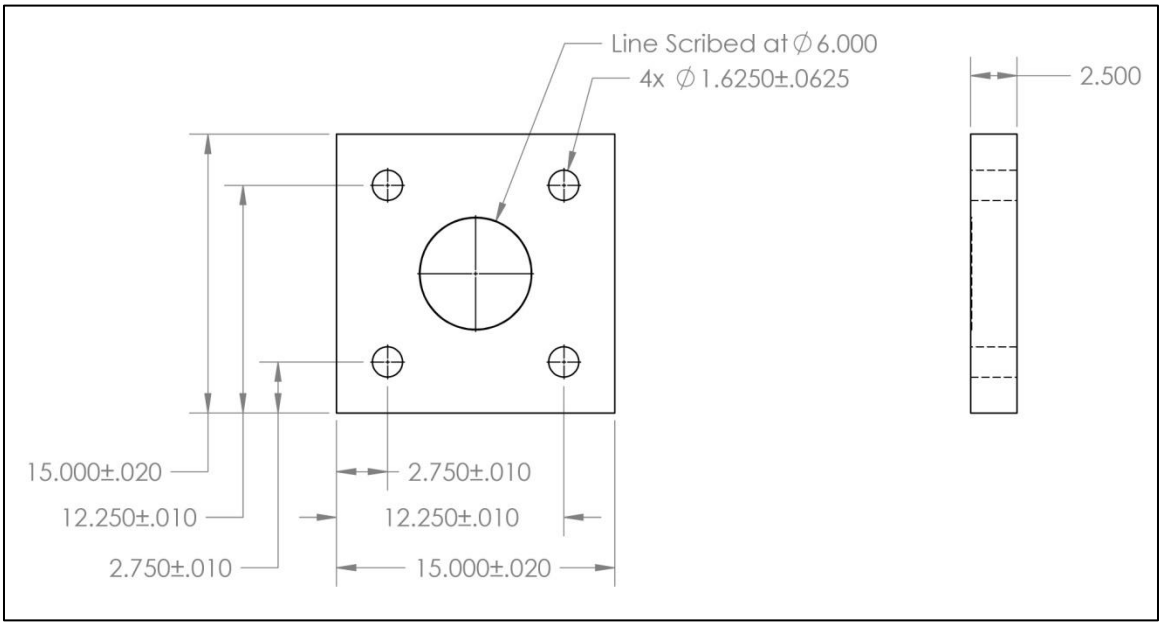


Figure 60:
Bottom upper reaction plate

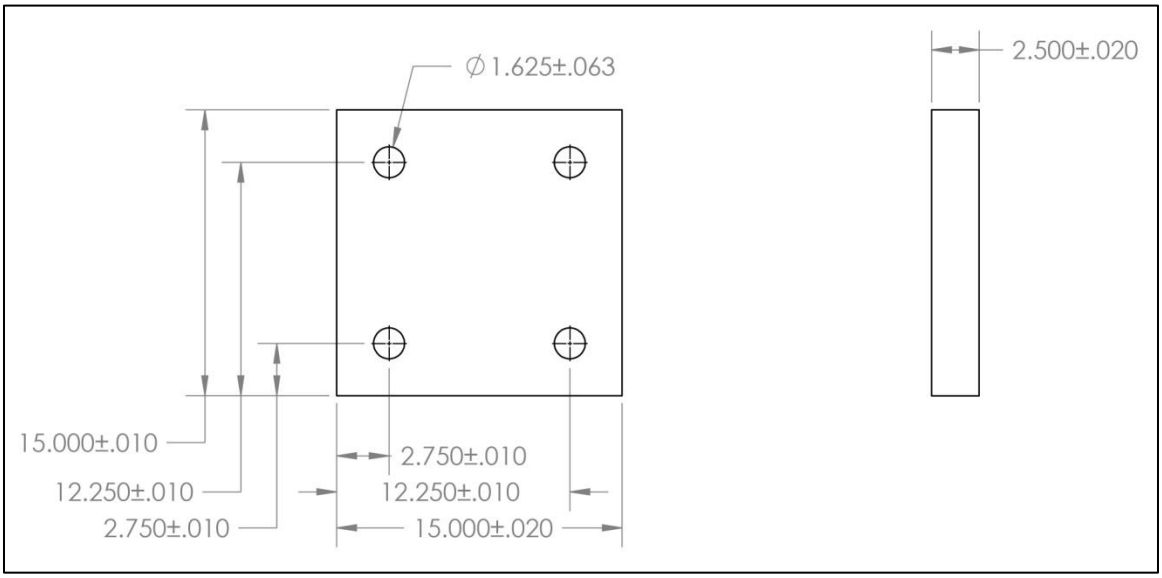


Figure 61:
Top upper reaction plate

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 62:
Creep frame base assembly

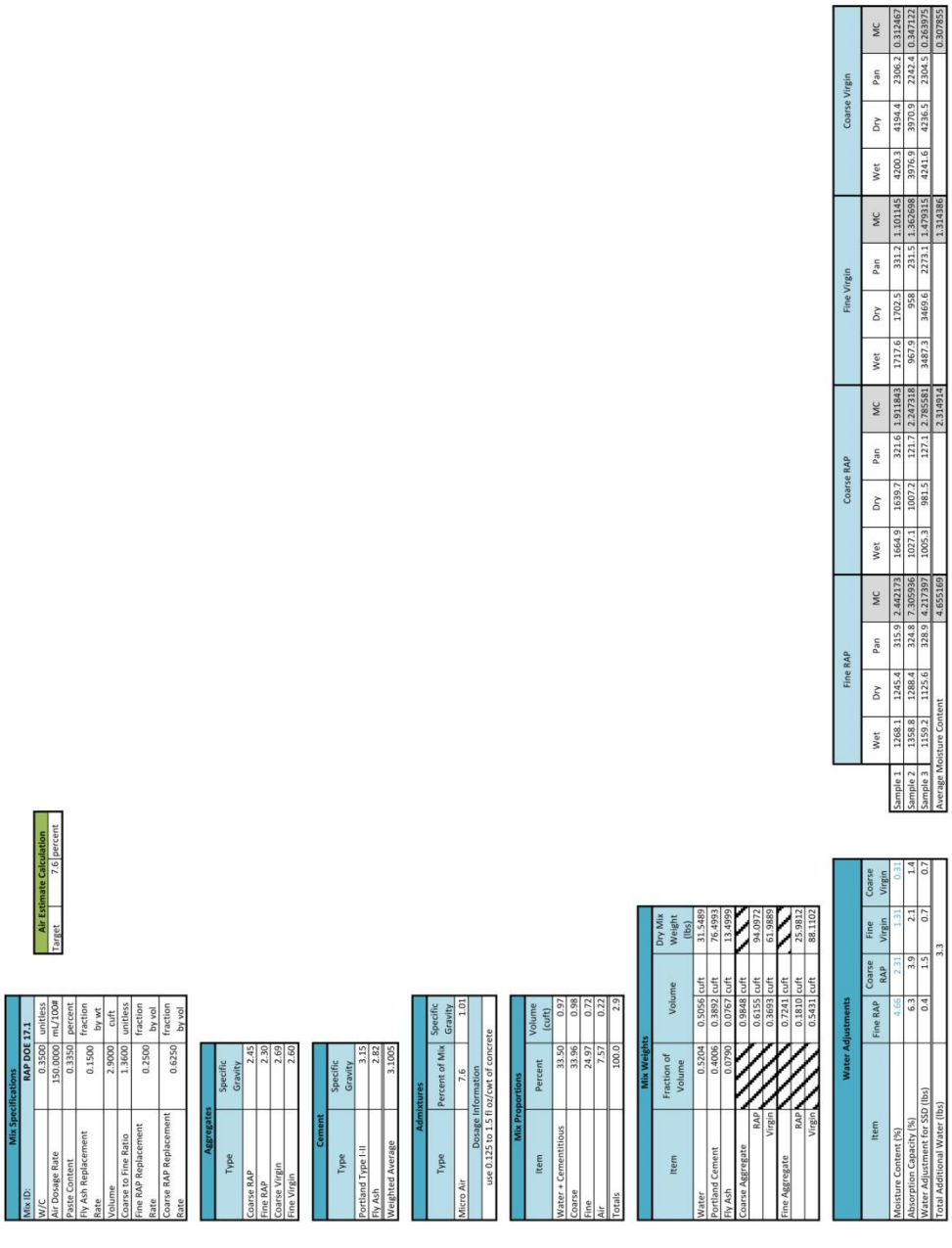


Figure 63:
Creep frame upper reaction plate assembly

APPENDIX B

RAP IN PCCP DOE MIX DESIGN CALCULATOR AND DATASHEETS

Given the large number of mixes that were required to complete the Design of Experiments analysis, a number of spreadsheets were developed for calculation and data storage purposes. The following Table 34 displays an example of the typical mix design calculator that was developed for this project and used to calculate the material quantities for each of the tested mixes. The additional tables give the mix property data for each of the 30 DOE mixes, as well as the additional high strength and high RAP mixes that were tested.



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	94.0972
RAP		0.6155 cuft	61.9889
Virgin		0.3693 cuft	
Fine Aggregate		0.7241 cuft	25.9812
RAP		0.1810 cuft	88.1102
Virgin		0.5431 cuft	

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		

Final Mix Design Proportions	
Item	Amount
Water (lbs)	34.8
Portland Cement (lbs)	76.5
Fly Ash (lbs)	13.5
MicroAir (mL)	1144.7
Coarse RAP (lbs)	96.3
Coarse Virgin (lbs)	62.2
Fine RAP (lbs)	27.2
Fine Virgin (lbs)	89.3

	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	2.765581	3487.3	3469.6	2273.1	1.479315	4241.6	4236.5	2304.5	0.263975
Average Moisture Content				4.655160				2.314914				1.314386				0.307855

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

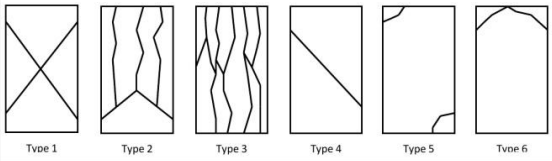
Notes- Moisture content data was highly variable

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	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	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 34:
RAP DOE 17.1 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)	

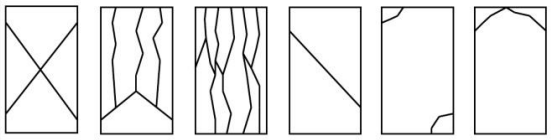
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.6	
Portland Cement	66.6	
Fly Ash	11.8	
MicroAir (mL)	99.9	
Coarse RAP	96.3	
Coarse Virgin	62.2	
Fine RAP	27.2	
Fine Virgin	89.3	

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



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

Notes-

Table 35:
RAP DOE 18.2 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

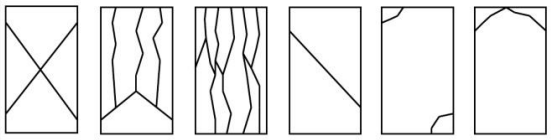
Notes- Material and moisture content from the night before. New cement haluled from Holcim this morning. Had hard time getting consistent temperature reading on cement. Material was significantly warmer than usual, with "pockets" of different temperatures. 9 lbs of coarse RAP taken from bag, not enough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



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

Notes-

Table 36:
RAP DOE 18.2 redo 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.

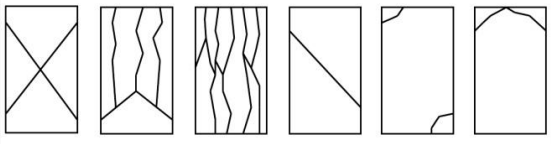
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	39.7	50.5
Portland Cement	66.6	46.3
Fly Ash	11.8	55.7
MicroAir (mL)	99.9	--
Coarse RAP	95.5	72.2
Coarse Virgin	62.4	72.9
Fine RAP	27.1	72.5
Fine Virgin	88.8	72.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 37:
RAP DOE 18.2 redo 2 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

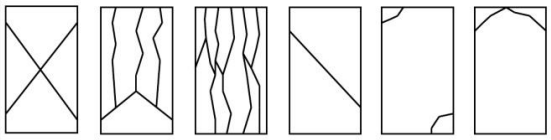
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	37.9	56.8
Portland Cement	71.2	81.0
Fly Ash	12.6	78.4
MicroAir (mL)	106.8	--
Coarse RAP	95.2	67.5
Coarse Virgin	62.3	67.3
Fine RAP	26.6	68.0
Fine Virgin	89.7	67.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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 38:
RAP DOE 30.3 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

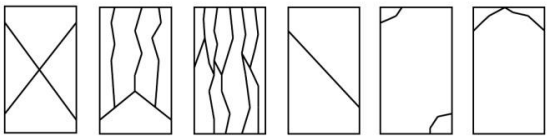
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.1	69.1
Portland Cement	71.2	65.8
Fly Ash	12.6	66.7
MicroAir (mL)	35.6	--
Coarse RAP	100.7	68.9
Coarse Virgin	65.9	67.8
Fine RAP	28.2	68.2
Fine Virgin	94.9	67.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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 39:
RAP DOE 25.4 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

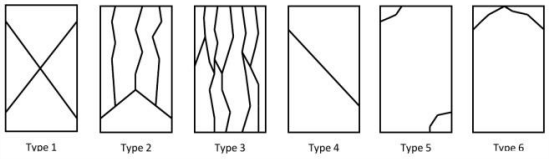
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	34.7	57.9
Portland Cement	66.6	52.5
Fly Ash	11.8	56.1
MicroAir (mL)	66.6	--
Coarse RAP	72.2	66.4
Coarse Virgin	101.3	66.7
Fine RAP	43.3	66.6
Fine Virgin	80.5	67.3

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 40:
RAP DOE 3.5 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

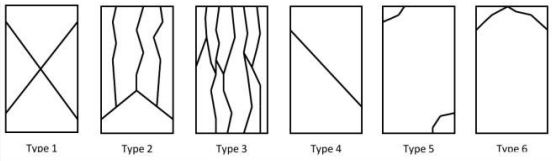
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.1	66.2
Portland Cement	71.2	54.9
Fly Ash	12.6	54.9
MicroAir (mL)	106.8	--
Coarse RAP	96.9	67.5
Coarse Virgin	62.4	64.8
Fine RAP	26.9	64.4
Fine Virgin	89.4	67.3

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	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	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 41:
RAP DOE 28.6 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.

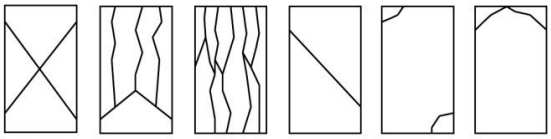
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	31.8	68.0
Portland Cement	66.6	59.0
Fly Ash	11.8	64.0
MicroAir (mL)	133.2	--
Coarse RAP	69.6	65.7
Coarse Virgin	96.0	66.0
Fine RAP	13.8	66.6
Fine Virgin	107.0	66.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 42:
RAP DOE 1.7 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.

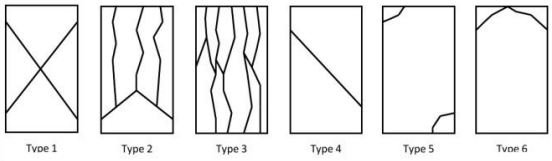
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.7	61.7
Portland Cement	71.2	59.7
Fly Ash	12.6	59.0
MicroAir (mL)	178.0	--
Coarse RAP	90.9	63.9
Coarse Virgin	58.8	64.4
Fine RAP	25.5	63.9
Fine Virgin	84.0	63.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 43:
RAP DOE 26.8 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.

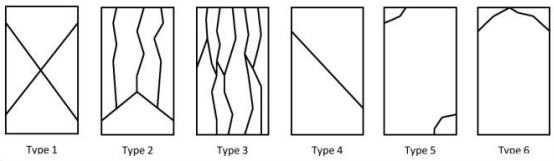
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
Water	36.8	
Portland Cement	71.2	
Fly Ash	12.6	
MicroAir (mL)	106.8	
Coarse RAP	96.4	
Coarse Virgin	62.3	
Fine RAP	27.0	
Fine Virgin	89.1	

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^{o}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 44:
RAP DOE 27.9 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.

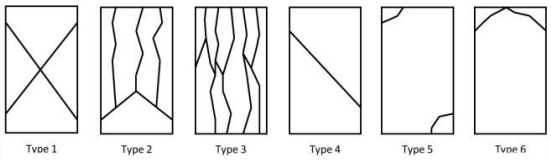
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.7	55.0
Portland Cement	80.9	55.9
Fly Ash	14.3	55.8
MicroAir (mL)	80.9	--
Coarse RAP	121.8	63.5
Coarse Virgin	30.3	64.0
Fine RAP	39.8	66.2
Fine Virgin	72.7	64.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 45:
RAP DOE 8.10 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.

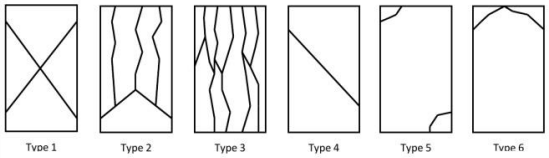
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.5	53.4
Portland Cement	71.2	55.4
Fly Ash	12.6	59.0
MicroAir (mL)	106.8	--
Coarse RAP	96.2	64.4
Coarse Virgin	62.3	62.8
Fine RAP	54.5	63.9
Fine Virgin	59.8	63.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 46:
RAP DOE 22.11 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

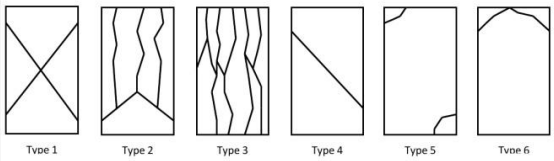
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
Water	35.0	64.4
Portland Cement	62.1	53.2
Fly Ash	11.0	54.0
MicroAir (mL)	124.3	--
Coarse RAP	68.8	66.9
Coarse Virgin	95.9	63.3
Fine RAP	41.7	66.2
Fine Virgin	76.2	64.2

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^{o}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 47:
RAP DOE 11.12 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

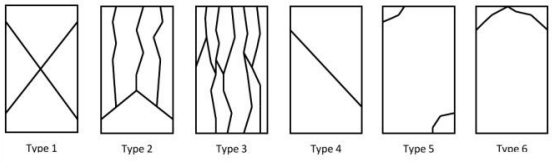
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.9	54.3
Portland Cement	80.9	56.5
Fly Ash	14.3	60.3
MicroAir (mL)	80.9	--
Coarse RAP	65.4	63.7
Coarse Virgin	91.0	63.9
Fine RAP	13.3	66.2
Fine Virgin	101.2	66.0

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 48:
RAP DOE 5.13 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

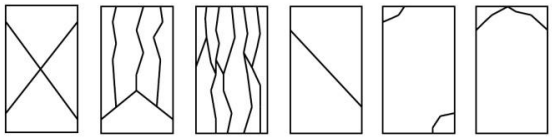
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	31.1	54.3
Portland Cement	57.4	56.5
Fly Ash	10.1	60.3
MicroAir (mL)	86.1	--
Coarse RAP	106.5	63.7
Coarse Virgin	69.2	63.9
Fine RAP	30.2	66.2
Fine Virgin	98.9	66.0

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



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

Notes-

Table 49:
RAP DOE 19.14 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.

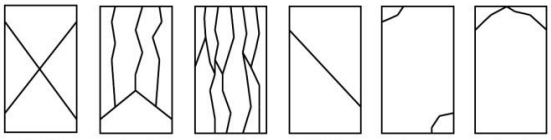
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	35.0	53.1
Portland Cement	62.1	58.1
Fly Ash	11.0	54.5
MicroAir (mL)	62.1	--
Coarse RAP	135.6	66.6
Coarse Virgin	33.8	65.1
Fine RAP	44.2	66.9
Fine Virgin	80.5	65.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 50:
RAP DOE 12.15 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.

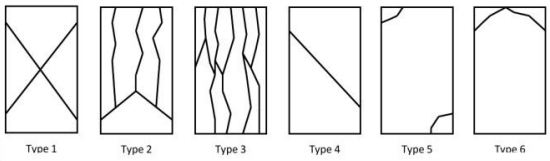
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	33.1	55.4
Portland Cement	66.6	63.0
Fly Ash	11.8	64.4
MicroAir (mL)	133.2	--
Coarse RAP	128.4	64.0
Coarse Virgin	32.0	64.9
Fine RAP	41.9	66.0
Fine Virgin	76.2	64.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 51:
RAP DOE 4.16 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

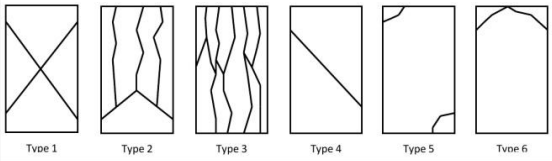
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	41.4	52.9
Portland Cement	75.5	58.1
Fly Ash	13.3	60.3
MicroAir (mL)	75.5	--
Coarse RAP	64.8	68.7
Coarse Virgin	91.0	65.5
Fine RAP	39.6	66.2
Fine Virgin	72.7	68.5

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 52:
RAP DOE 15.17 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.

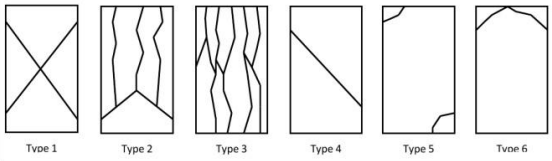
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	37.6	61.5
Portland Cement	71.2	59.0
Fly Ash	12.6	63.9
MicroAir (mL)	106.8	--
Coarse RAP	95.1	64.4
Coarse Virgin	62.3	66.0
Fine RAP	27.1	64.4
Fine Virgin	89.6	66.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 53:
RAP DOE 29.18 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.

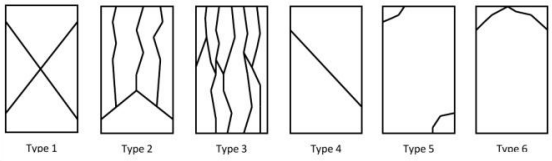
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.1	60.8
Portland Cement	71.2	48.4
Fly Ash	12.6	54.8
MicroAir (mL)	106.8	--
Coarse RAP	152.3	63.8
Coarse Virgin	0.0	--
Fine RAP	27.0	63.9
Fine Virgin	90.2	63.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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 54:
RAP DOE 24.19 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.

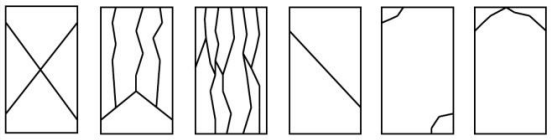
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.4	52.8
Portland Cement	71.2	67.7
Fly Ash	12.6	62.7
MicroAir (mL)	106.8	--
Coarse RAP	95.2	55.4
Coarse Virgin	62.3	64.2
Fine RAP	0.0	--
Fine Virgin	120.2	64.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 55:
RAP DOE 21.20 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

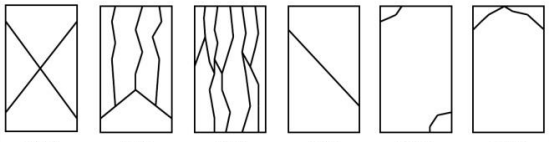
Mix Conditions	
Date	9/28/2010
Time of Material Prep	1:00 to 1:30 PM
Time of Mix	1:30 PM
Ambient Temperature	80s, sunny
Technician(s)	Beth, Keith, Josh
Notes- Material and moisture content from the day before	

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
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 (°F)	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



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

Table 56:
RAP DOE 6.21 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

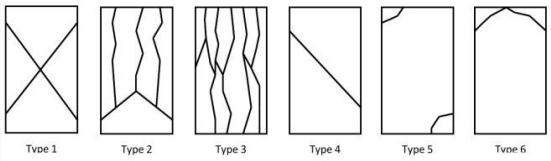
Notes- Moisture content and material from day before.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
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 (°F)	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 57:
RAP DOE 7.22 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

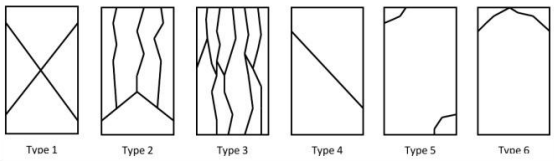
Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
Water	35.7	62.6
Portland Cement	62.1	62.6
Fly Ash	11.0	62.8
MicroAir (mL)	124.3	--
Coarse RAP	127.5	70.3
Coarse Virgin	32.1	70.1
Fine RAP	13.9	70.6
Fine Virgin	106.6	70.8

Elastic State Properties		
Test	Results	Technician
Mix Temperature (^{o}F)	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



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

Notes-

Table 58:
RAP DOE 10.23 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

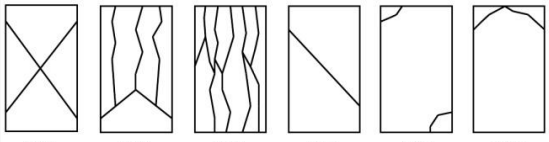
Notes- Material and moisture content from a couple days prior. New coarse aggregate was placed in the bins and used for this mix.

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
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 (°F)	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



Notes-

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

Notes-

Table 59:
RAP DOE 23.24 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.

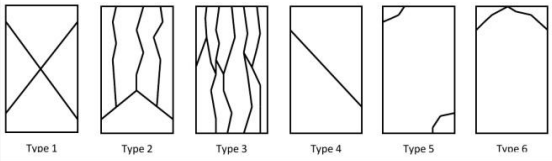
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	31.1	55.2
Portland Cement	62.1	70.3
Fly Ash	11.0	65.1
MicroAir (mL)	62.1	--
Coarse RAP	73.2	70.6
Coarse Virgin	101.5	70.7
Fine RAP	14.7	70.9
Fine Virgin	115.7	70.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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 60:
RAP DOE 9.25 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.

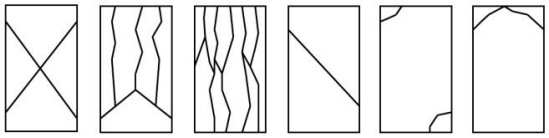
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	40.7	52.7
Portland Cement	85.0	67.6
Fly Ash	15.0	67.6
MicroAir (mL)	127.5	--
Coarse RAP	85.8	70.0
Coarse Virgin	55.6	70.2
Fine RAP	24.1	70.3
Fine Virgin	81.4	68.7

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



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

Notes-

Table 61:
RAP DOE 20.26 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

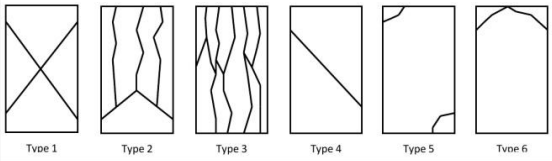
Mix Conditions	
Date	10/6/2010
Time of Material Prep	1:00 to 1:30 PM
Time of Mix	1:30 PM
Ambient Temperature	70s sunny
Technician(s)	Beth, Josh, Tim, Chris

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 62:
RAP DOE 14.27 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

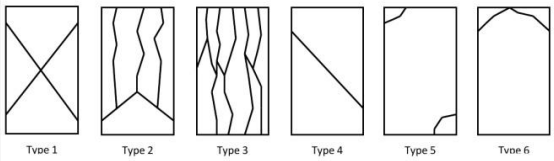
Notes- Material and moisture content from day before

Mix Proportions and Information		
Item	Amount (lbs)	Temp (^{o}F)
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 (^{o}F)	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



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

Notes-

Table 63:
RAP DOE 16.28 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.

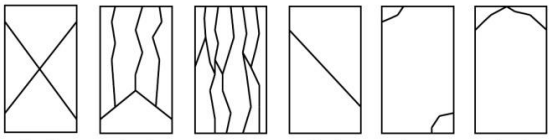
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.6	53.4
Portland Cement	75.5	55.5
Fly Ash	13.3	63.0
MicroAir (mL)	151.0	--
Coarse RAP	61.4	68.6
Coarse Virgin	85.6	68.4
Fine RAP	12.5	67.3
Fine Virgin	97.6	67.1

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	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



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

Notes-

Table 64:
RAP DOE 13.29 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

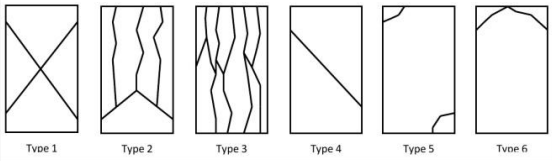
Notes- Material and moisture content from the night before. New cement haluled from Holcim this morning. Had hard time getting consistent temperature reading on cement. Material was significantly warmer than usual, with "pockets" of different temperatures.

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-

Table 65:
RAP DOE 2.30 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 1	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	2/4/2011
Time of Material Prep	8:00 to 8:30 AM
Time of Mix	8:30 AM
Ambient Temperature	30, cloudy
Technician(s)	Beth, Kevin, and Keith

Notes - Moisture content and material from night before

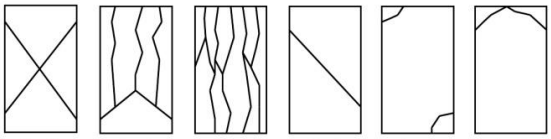
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	37.0	47.7
Portland Cement	78.6	30.7
Fly Ash	13.9	32.0
MicroAir (mL)	106.7	--
Coarse RAP	68.3	61.6
Coarse Virgin	90.6	63.2
Fine RAP	21.0	63.5
Fine Virgin	94.0	64.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	60.1	Keith
Slump (in)	3.5	Keith
Air Content (%)	9.50%	Beth

Notes - May be issues with air content pressure pot. Couldn't get a good seal with lid, may b inaccurate number.

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/5/2011		2/11/2011		3/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	15550	4	34380	6	41070	4
	14910	6	29180	6	35760	6
	15510	6	33540	6	36330	6
Average Compressive Strength (psi)	1219		2576		3002	

ASTM Fracture Type



Notes - High strength mix had much better 24 hour cure. 7-day cylinders were broke on 2/14 - 10-day breaks

Rupture Strength Testing Data	
Age	28
Date	3/4/2011
Test Data (lbs)	7340
	6670
Tested MOR	649
Empirical MOR	411

Notes-

Table 66:
RAP DOE high strength 1 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP 1	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	2/4/2011
Time of Material Prep	9:00 to 9:30 AM
Time of Mix	9:30 AM
Ambient Temperature	30, cloudy
Technician(s)	Beth, Kevin, and Keith

Notes - Moisture content and material from night before

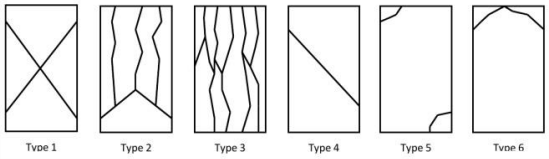
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	41.7	48.4
Portland Cement	73.0	34.0
Fly Ash	12.9	31.5
MicroAir (mL)	94.8	--
Coarse RAP	151.4	60.7
Coarse Virgin	0.0	--
Fine RAP	52.4	61.0
Fine Virgin	58.5	62.0

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	56.1	Beth
Slump (in)	8.5	Keith
Air Content (%)	12.00%	Beth

Notes - May be issues with air content pressure pot. Couldn't get a good seal with lid, may b inaccurate number.

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/5/2011		2/11/2011		3/4/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	5820	6	14830	6	15100	6
	4540	6	14760	6	18820	6
	5830	5	12500	6	17470	6
Average Compressive Strength (psi)	429		1116		1363	

ASTM Fracture Type



Notes - High RAP mix was much more "green" after 24 hour cure and the material appeared to be way softer than the high strength mix. 7-day breaks were on 2/14 - 10-day breaks.

Rupture Strength Testing Data	
Age	28
Date	3/4/2011
Test Data (lbs)	3660
	3980
Tested MOR	354
Empirical MOR	277

Notes-

Table 67:
RAP DOE high RAP 1 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 2	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	2/7/2011
Time of Material Prep	1:45 to 2:00 PM
Time of Mix	2:30 PM
Ambient Temperature	32ish, sunny
Technician(s)	Beth and Keith

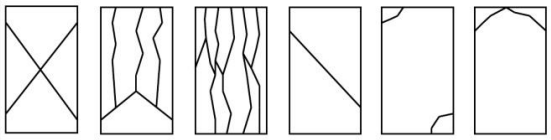
Notes - Material from Friday, moisture content taken on Sunday

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	33.1	40.4
Portland Cement	78.6	63.3
Fly Ash	13.9	31.5
MicroAir (mL)	106.7	--
Coarse RAP	68.9	61.6
Coarse Virgin	90.6	63.7
Fine RAP	21.1	63.6
Fine Virgin	97.2	62.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	59.3	Beth
Slump (in)	1.125	Keith
Air Content (%)	5.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/8/2011		2/14/2011		3/7/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	19650	6	40740	3	51610	6
	21370	5	42930	3	49190	5
	20480	6	43080	4	44380	6
Average Compressive Strength (psi)	1631		3362		3851	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/7/2011
Test Data (lbs)	7580
	7560
Tested MOR	701
Empirical MOR	465

Notes-

Table 68:
RAP DOE high strength 2 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP 2	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	2/7/2011
Time of Material Prep	12:30 to 1:00 PM
Time of Mix	1:15 PM
Ambient Temperature	32ish, sunny
Technician(s)	Beth and Keith

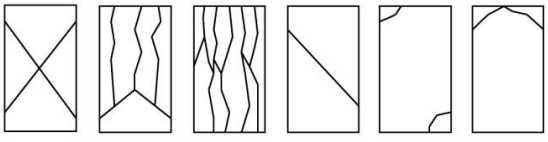
Notes - Material from Friday, moisture content taken on Sunday

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.2	47.1
Portland Cement	73.0	63.2
Fly Ash	12.9	29.3
MicroAir (mL)	94.8	--
Coarse RAP	152.6	62.8
Coarse Virgin	0.0	--
Fine RAP	52.7	65.3
Fine Virgin	60.6	63.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	61.3	Beth
Slump (in)	7.5	Keith
Air Content (%)	12.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/8/2011		2/14/2011		3/7/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	6230	3	15390	4	17880	4
	6320	3	14600	6	17970	6
	6060	3	15210	5	18410	4
Average Compressive Strength (psi)	494		1199		1439	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/7/2011
Test Data (lbs)	3920
	4060
Tested MOR	369
Empirical MOR	285

Notes-

Table 69:
RAP DOE high RAP 2 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 3	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	2/14/2011
Time of Material Prep	1:45 to 2:15 PM
Time of Mix	2:15 PM
Ambient Temperature	40s, sunny
Technician(s)	Beth and Keith

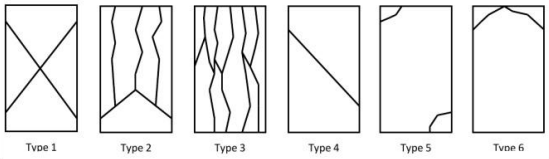
Notes - Material and moisture content were prepared night before

Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	33.8	43.0
Portland Cement	78.6	45.4
Fly Ash	13.9	49.2
MicroAir (mL)	106.7	--
Coarse RAP	69.7	63.1
Coarse Virgin	91.0	61.1
Fine RAP	20.8	64.8
Fine Virgin	95.6	58.6

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	59.4	Beth
Slump (in)	2.75	Keith
Air Content (%)	8.50%	Beth

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/15/2011		2/21/2011		3/14/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	18180	5	34660	4	44270	4
	17940	4	38510	3	46610	3
	18670	2	35570	6	49040	3
Average Compressive Strength (psi)	1453		2884		3711	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/14/2011
Test Data (lbs)	7210
	6440
Tested MOR	632
Empirical MOR	457

Notes-

Table 70:
RAP DOE high strength 3 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	2/14/2011
Time of Material Prep	12:45 to 1:15 PM
Time of Mix	1:15 PM
Ambient Temperature	40s, partly cloudy
Technician(s)	Beth and Keith

Notes - Material and moisture content were prepared the night before

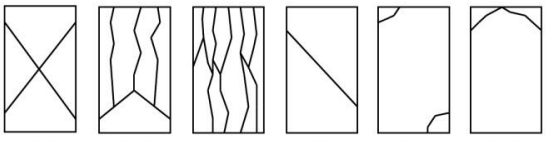
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.1	65.0
Portland Cement	73.0	43.0
Fly Ash	12.9	48.3
MicroAir (mL)	94.8	--
Coarse RAP	154.4	64.3
Coarse Virgin	0.0	--
Fine RAP	51.9	64.9
Fine Virgin	59.5	65.1

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	65.1	Beth
Slump (in)	1	Keith
Air Content (%)	6.00%	Beth

Notes - 32.6 lbs of water were added to mix. Withheld 5.5-lbs (or 14.4%) to reduce slump and air content of the mix to meet MDT specification values.

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/15/2011		2/21/2011		3/14/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	17030	3	28580	4	34640	3
	17430	5	28350	5	33250	5
	16330	4	27920	4	33960	3
Average Compressive Strength (psi)	1347		2251		2702	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/14/2011
Test Data (lbs)	6380
	6710
Tested MOR	606
Empirical MOR	390

Notes-

Table 71:
RAP DOE high RAP 3 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 4	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	2/24/2011
Time of Material Prep	9:00 to 9:30 AM
Time of Mix	9:30 AM
Ambient Temperature	-10 outside, 45 in lab
Technician(s)	Beth and Lenci

Notes - Material and moisture content were prepared night before

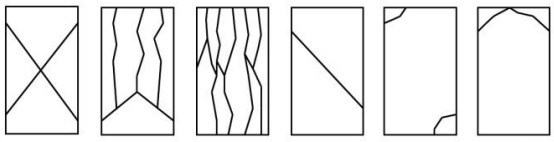
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	34.7	48.8
Portland Cement	78.6	53.2
Fly Ash	13.9	20.5
MicroAir (mL)	106.7	--
Coarse RAP	68.4	49.2
Coarse Virgin	92.4	49.9
Fine RAP	20.9	52.0
Fine Virgin	94.5	48.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	54.6	Lenci
Slump (in)	4	Lenci
Air Content (%)	6.80%	Beth

Notes - Added 2.5 lbs of water at 3:00 min. At 6:40 tested slump at about 1/4". Added remaining 3.5 lbs of water.

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/25/2011		3/3/2011		3/24/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	15240	6	39880	3	45410	4
	16970	4	36310	6	49300	3
	18030	4	38240	6	43940	2
Average Compressive Strength (psi)	1333		3035		3678	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/24/2011
Test Data (lbs)	8150
	7030
Tested MOR	703
Empirical MOR	455

Notes-

Table 72:
RAP DOE high strength 4 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP 4	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	2/24/2010
Time of Material Prep	8:00 to 8:30 AM
Time of Mix	8:30 AM
Ambient Temperature	-10 outside, 45 in lab
Technician(s)	Beth and Lenci

Notes - Material and moisture content were prepared the night before

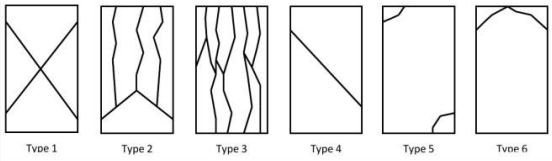
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	41.6	58.0
Portland Cement	73.0	52.9
Fly Ash	12.9	2.7
MicroAir (mL)	94.8	--
Coarse RAP	151.5	48.7
Coarse Virgin	0.0	--
Fine RAP	52.0	53.9
Fine Virgin	58.9	50.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	56.6	Lenci
Slump (in)	4	Lenci
Air Content (%)	9.00%	Beth

Notes - Withheld 6 lbs of water and slump tested during mix came out at 2.875"

Compressive Strength Testing Data						
Age	1		7		28	
Date	2/25/2010		3/3/2010		3/24/2010	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	12220	3	21870	4	28350	5
	12210	6	21730	4	27940	5
	11050	4	23840	4	26110	6
Average Compressive Strength (psi)	941		1789		2186	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/24/2010
Test Data (lbs)	2130
	6380
Tested MOR	591
Empirical MOR	351

Notes-

Table 73:
RAP DOE high RAP 4 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 5	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	2/28/2011
Time of Material Prep	11:00 to 11:30 AM
Time of Mix	11:30 AM
Ambient Temperature	30s, cloudy
Technician(s)	Beth and Lenci

Notes: Water Bucket Weights = Withhold = 5.7 lbs, Micro Air = 5.7 lbs, Mix water = 17.1 lbs. MC and matierial from night before.

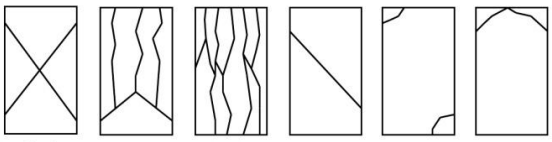
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	28.5	42.6
Portland Cement	78.6	59.8
Fly Ash	13.9	28.6
MicroAir (mL)	106.7	--
Coarse RAP	68.8	60.3
Coarse Virgin	91.7	60.4
Fine RAP	20.9	60.1
Fine Virgin	101.0	59.9

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	59.8	Beth
Slump (in)	0.5	Lenci
Air Content (%)	3.50%	Beth

Notes - Added all of the required 28.5 lbs of mix water.

Compressive Strength Testing Data						
Age	1		7		28	
Date	3/1/2011		3/7/2011		3/28/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	26260	4	54290	5	62770	5
	25610	2	57010	5	64110	5
	24900	4	51810	6	65280	5
Average Compressive Strength (psi)	2036		4327		5097	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/28/2011
Test Data (lbs)	9420
	10160
Tested MOR	906
Empirical MOR	535

Notes-

Table 74:
RAP DOE high strength 5 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP 5	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	2/28/2011
Time of Material Prep	12:00 to 12:30 PM
Time of Mix	12:30 PM
Ambient Temperature	30s, cloudy
Technician(s)	Beth and Lenci

Notes: Water Bucket Weights = Withhold = 7.3 lbs, Micro Air = 7.3 lbs, Mix water = 22.0 lbs. MC and matierial from night before.

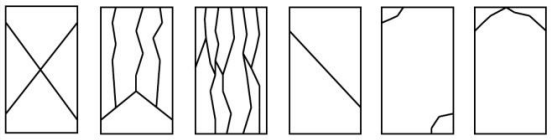
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	36.6	46.0
Portland Cement	73.0	62.4
Fly Ash	12.9	43.7
MicroAir (mL)	94.8	--
Coarse RAP	152.5	60.1
Coarse Virgin	0.0	--
Fine RAP	52.0	60.8
Fine Virgin	62.9	60.7

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	60.8	Beth
Slump (in)	2.5	Lenci
Air Content (%)	6.20%	Beth

Notes - 3/8" slump during mixing. Ultimately withheld4.9 lbs of mix water.

Compressive Strength Testing Data						
Age	1		7		28	
Date	3/1/2011		3/7/2011		3/28/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	9470	4	28110	4	30730	4
	9670	4	25780	5	30200	5
	8860	4	28070	5	29240	3
Average Compressive Strength (psi)	743		2174		2392	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/28/2011
Test Data (lbs)	6180
	6440
Tested MOR	584
Empirical MOR	367

Notes-

Table 75:
RAP DOE high RAP 5 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High Strength 6	
W/C	0.350	unitless
Air Dosage Rate	135.710	mL/100#
Paste Content	0.344	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	0.200	percent by vol
Coarse RAP Replacement Rate	0.450	percent by vol

Mix Conditions	
Date	3/1/2011
Time of Material Prep	9:45 to 10:15 AM
Time of Mix	10:15 AM
Ambient Temperature	35, clear
Technician(s)	Beth, Josh, Jeff

Notes: Water Bucket Weights = Withhold = 6.3 lbs, Micro Air = 6.3 lbs, Mix water = 18.8 lbs. MC and matierial from night before.

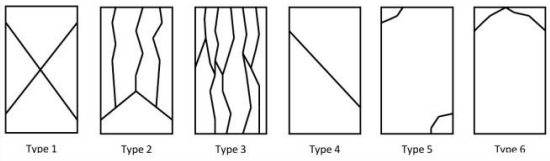
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	31.4	41.9
Portland Cement	78.6	62.0
Fly Ash	13.9	51.3
MicroAir (mL)	106.7	--
Coarse RAP	68.8	62.5
Coarse Virgin	91.8	63.4
Fine RAP	20.9	60.0
Fine Virgin	97.9	63.3

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	62.5	Beth
Slump (in)	1.75	JN and BB
Air Content (%)	4.50%	Beth

Notes - Withheld 1.0 lbs of water.

Compressive Strength Testing Data						
Age	1		7		28	
Date	3/2/2011		3/8/2011		3/29/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	21800	3	44520	3	56480	3
	20870	3	43110	6	50920	4
	20620	3	40340	4	55530	4
Average Compressive Strength (psi)	1679		3395		4322	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/29/2011
Test Data (lbs)	8830
	7850
Tested MOR	772
Empirical MOR	493

Notes-

Table 76:
RAP DOE high strength 6 mix sheet

RAP in PCCP

DOE Mix Reporting Form

Mix Specifications		
Mix ID:	RAP DOE High RAP 6	
W/C	0.410	unitless
Air Dosage Rate	130.000	mL/100#
Paste Content	0.348	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	1.000	percent by vol

Mix Conditions	
Date	3/1/2011
Time of Material Prep	10:30 to 11:00 AM
Time of Mix	11:00 AM
Ambient Temperature	35, clear
Technician(s)	Beth, Josh, Jeff

Notes: Water Bucket Weights = Withhold = 7.7 lbs, Micro Air = 7.7 lbs, Mix water = 23.0 lbs. MC and matierial from night before.

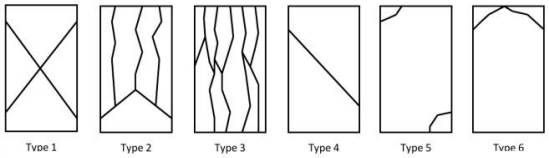
Mix Proportions and Information		
Item	Amount (lbs)	Temp (°F)
Water	38.4	
Portland Cement	73.0	
Fly Ash	12.9	
MicroAir (mL)	94.8	
Coarse RAP	152.5	
Coarse Virgin	0.0	
Fine RAP	52.0	
Fine Virgin	61.0	

Elastic State Properties		
Test	Results	Technician
Mix Temperature (°F)	60.9	Beth
Slump (in)	1	Josh
Air Content (%)	5.70%	Beth

Notes - Withheld 7.7 lbs from mix. Tested slump during mix was 1.5"

Compressive Strength Testing Data						
Age	1		7		28	
Date	3/2/2011		3/8/2011		3/29/2011	
Test Data	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type	Load (lbs)	Fracture Type
	12820	5	26190	6	33210	6
	14020	4	28440	3	34810	3
	12720	4	29020	3	36480	3
Average Compressive Strength (psi)	1049		2219		2772	

ASTM Fracture Type



Rupture Strength Testing Data	
Age	28
Date	3/29/2011
Test Data (lbs)	8220
	6740
Tested MOR	693
Empirical MOR	395

Notes-

Table 77:
RAP DOE high RAP 6 mix sheet