FINAL REPORT

U.F. Project No: P0049221
FDOT Project No: BDV31-977-80

DEVELOPMENT OF MIX DESIGNS FOR RAP CONCRETE FOR FLORIDA CONCRETE TEST ROAD

Mang Tia
Sangyoung Han
Hung-Wen Chung
Thanachart Subgranon
Chaoren Zhu

December 2017

Department of Civil and Coastal Engineering
Engineering School of Sustainable Infrastructure and Environment
College of Engineering
University of Florida
Gainesville, Florida 32611-6580

DISCLAIMER

SI (MODERN METRIC) CONVERSION FACTORS (from FHWA)

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
kip	kilo poundforce	4.45	kilo newtons	kN
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Mix Designs for RAP Concrete for Florida Concrete Test Road		5. Report Date December 2017 6. Performing Organization Code
7. Author(s) Mang Tia, Sangyoung Han, Hung-Wen Chung, Thanachart Subgranon, and Chaoren Zhu		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Coastal Engineering Engineering School of Sustainable Infrastructure & Environment University of Florida 365 Weil Hall – P.O. Box 116580 Gainesville, FL 32611-6580		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDV31-977-80
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report 7/1/17 – 12/31/17 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation and the Federal Highway Administration

16. Abstract

The main objective of this study was to develop mix designs for concrete incorporating Reclaimed Asphalt Pavement (RAP) materials to be used in the Florida Concrete Test Road. Two different FDOT-approved RAP sources were selected and used in this study. Concrete mixtures with 0% to 40% RAP as aggregate replacement, using 0% and 20% fly ash as cement replacement, were designed using optimized aggregate gradation technique. A computer software named OAG Tool for optimizing aggregate gradation in a concrete mix design was developed and used in designing concrete mixes containing RAP. The designed concrete mixes were produced and tested in the laboratory. Critical stress analysis was performed to evaluate the potential performance of a typical concrete pavement in Florida if RAP concretes with the determined properties were used. A cost analysis was also performed to determine the possible saving if RAP materials were used as partial replacement of aggregate in pavement concrete in Florida.

It was demonstrated that the OAG procedure is superior to the ACI procedure in proportioning aggregates to achieve a well-graded aggregate blend and a workable mix. The control mix containing no RAP had a gap-graded aggregate which lacked intermediate-size particles. When 20% or 40% RPA materials were incorporated using the OAG procedure, the aggregate blend became significantly more well-graded and the concrete became more workable.

The results of critical stress analysis indicate that the RAP concrete using 20% fly ash and 20% to 40% RAP with a w/c ratio of 0.50 could have better potential performance than a concrete mix with 0% RAP and using pure cement and the same water-to-cement (w/c). A cost analysis on the replacement of aggregate with RAP indicates that using 20% and 40% RAP in concrete could result in saving in the total cost of aggregate by 10% and 19%, respectively. Four concrete mix designs of concrete incorporating RAP are recommended as feasible mixes to be used in the Florida Concrete Test Road. It is recommended that 20% of RAP can be used as aggregate replacement in pavement concrete.

17. Key Words Reclaimed Asphalt Pavement, Pavement Concrete, Optimum Aggregate Gradation, Critical Stress Analysis, Stress to Strength Ratio, Compressive Strength, Flexural Strength, Cost Analysis	18. Distribution Statement No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	128	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The Florida Department of Transportation (FDOT) is gratefully acknowledged for providing the financial support for this study. A compilation of this nature could not have been completed without the help and support of others. The FDOT Materials Office provided the additional testing equipment, materials, and personnel needed for this investigation. Sincere thanks go to the project manager, Mr. Michael Bergin, for providing his technical coordination and advice throughout the project. Sincere gratitude is extended to Harvey DeFord, Richard DeLorenzo, Patrick Carlton, David Hudson, Richard Davy, Nelson Diaz, and Brandon Sawyer of the FDOT Materials Office for their invaluable expert advice and help on this project. Special thanks are also extended to the student assistants, who are Alex Crossman Alex, Timothy Odom Timothy, Hsu Shao-Chian, Kevin Fisher, and Ryan Molloy for providing their support for this project.

EXECUTIVE SUMMARY

Background

The Florida Department of Transportation will construct a 2.5-mile Florida Concrete Test Road on a northbound segment of US-301 in Clay County. The main purpose for the Florida Concrete Test Road is to evaluate new and innovative techniques and materials for construction, rehabilitation, and maintenance of concrete pavements, as well as to generate data that will be used to locally calibrate the existing mechanistic-empirical pavement design procedure. One of the materials to be evaluated is concrete incorporating Reclaimed Asphalt Pavement (RAP) material as aggregate replacement, which has been found from a previous FDOT-sponsored study to offer the possibility of improving the performance of concrete pavement due to its low modulus of elasticity. The potential benefits for the use of RAP in concrete pavement will include not only the utilization of excess RAP, but also improved performance and cost effectiveness of concrete pavements in Florida.

Objective of Study

The main objective of this research project was to develop the mix designs for the RAP concrete to be used in the Florida Concrete Test Road. The specific objectives included the following:

(1) To develop four optimum mix designs for concrete incorporating RAPs from two different sources, to be used in the Florida Concrete Test Road

(2) To provide language to supplement current FDOT concrete specifications (Section 346) to allow RAP as a component material for pavement concrete.

Scope of Work

Two different FDOT-approved RAP sources were selected and used in this study. Concrete mixtures with 0%, 20%, 30%, and 40% RAP as aggregate replacement, using 0% and 20% fly ash as cement, replacement were designed using optimized aggregate gradation technique. A computer software named OAG Tool for optimizing aggregate gradation in a concrete mix design was developed and used in designing concrete mixes containing RAP. The designed concrete mixes were produced and tested in the laboratory. Emphasis was placed on meeting the requirements for pavement concrete according to FDOT Specifications Section 346. Critical stress analysis was performed to evaluate the potential performance of a typical concrete pavement in Florida if RAP concretes with the determined properties were used. A cost analysis was also performed to determine the possible saving if RAP materials were used as partial replacement of aggregate in pavement concrete in Florida.

Summary of Findings

The main findings from this study are summarized as follows:

<u>Optimized Aggregate Gradation Procedure</u>

(1) An Excel spreadsheet software, named OAG Tool, which was developed to facilitate the use of Optimized Aggregate Gradation (OAG) procedure, was found to be an effective tool to be used for this purpose.

(2) It was demonstrated that the OAG procedure is superior to the ACI procedure in proportioning aggregates to achieve a well-graded aggregate blend and a workable mix.

(3) The OAG procedure was used to proportion the aggregates used in the concrete mixes containing RAP in this study. The control mix containing no RAP had a gap-graded

aggregate which lacked intermediate-size particles. When 20% or 40% RAP materials were incorporated using the OAG procedure, the aggregate blend became significantly more well-graded and the concrete became more workable.

Properties of Concrete Incorporating RAP

(4) All the RAP concrete mixture could be produced to achieve a target slump of 1 to 2 inches and a target air content of 2% to 5% with an appropriate amount of water-reducing admixture. The needed dosage of water-reducing admixture increased as the % RAP increased.

(5) Among the RAP concretes evaluated, the following concrete mixes were able to meet the over-design compressive strength of 4,200 psi at 28 days:

a. Concrete containing 20% RAP and using pure Portland cement, with w/c of 0.43, 0.45, 0.47, and 0.50.

b. Concrete containing 20% RAP and using 20% fly ash, with w/c of 0.43, 0.45, 0.47, and 0.50.

(6) The over-design compressive strength of 4,200 psi could not be achieved by the concrete mixes containing 30% or more RAP.

(7) The compressive strength, modulus of elasticity, and flexural strength decreased as the percentage of RAP increased in the concrete mixture.

(8) The reduction in flexural strength in the concrete containing RAP was 5% to 15% lower than the corresponding reduction in compressive strength of the concrete containing RAP.

(9) The rate of reduction in modulus of elasticity in the concrete containing RAP was slightly lower than the corresponding reduction in compressive strength of the concrete containing RAP.

(10) The Poisson's ratio increased as the percentage of RAP in the concrete increased.

(11) The coefficient of thermal expansion (CTE) of concrete did not clearly show a strong relationship with amount of RAP in the concrete.

Results of Critical Stress Analysis

(12) The results of critical stress analysis indicated that the RAP concrete using 20% fly ash and 20%, 30%, or 40% RAP with a w/c ratio of 0.50 could have better potential performance than a concrete mix with 0% RAP and using pure cement and the same w/c.

Results of Cost Analysis

(13) A cost analysis on the replacement of aggregate with RAP indicates that using 20% and 40% RAP in concrete could result in saving in the total cost of aggregate by 10% and 19%, respectively.

Recommendations

Recommended Mix Designs of Concrete Incorporating RAP

Based on the results of this study, the following four concrete mix designs of concrete incorporating RAP are recommended as feasible mixes to be used in the Florida Concrete Test Road:

(1) Concrete incorporating 20% RAP (Source A0691) with 0% fly ash, with a cement content of 516 lb/yd^3 and w/c of 0.5.

(2) Concrete incorporating 20% RAP (Source A0750) with 0% fly ash, with cement content of 516 lb/yd^3 and w/c of 0.5.

(3) Concrete incorporating 20% RAP (Source A0691) with 20% fly ash, with cementitious material content of 516 lb/yd^3 and w/c of 0.5.

(2) Concrete incorporating 20% RAP (Source A0750) with 20% fly ash, with cementitious material content of 516 lb/yd^3 and w/c of 0.5.

The detailed mix design information for these four concrete mixes is presented in Table 8-1 in the report.

Recommendation for use of RAP as Aggregate in Pavement Concrete

It is recommended that 20% of RAP can be used as aggregate replacement in pavement concrete. All specification requirements for pavement concrete should also apply to concrete containing RAP. The RAP material should be used as-is without pre-soaking prior to mixing in concrete production to avoid degradation of the RAP material due to excessive handling. It is recommended that the OAG procedure be used to proportion the aggregates and RAP materials to ensure a well-graded gradation and a workable concrete mix. The developed OAG Tool software can be used for this purpose.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Background and Research Needs

Reclaimed Asphalt Pavement (RAP) is defined as "removed and/or reprocessed pavement materials containing asphalt and aggregates" by the U.S Department of Transportation (2016). As the idea of using RAP as an aggregate in concrete pavement has become more and more popular in recent years, there have been several comprehensive studies evaluating the mechanical performance of concrete with RAP. The results of a few early studies have revealed that the concrete incorporating RAP exhibits lower compressive strength, modulus of elasticity, splitting tensile strength, and flexural strength as the percentage of RAP increases in the concrete mixture (Delwar et al., 1997; Hassan et al., 2000; Huang et al., 2005; Hossiney et al., 2010; Brand and Roesler, 2015; Berry et al., 2015a; Al-Mufti and Fried, 2017). Recently, concrete pavements containing a high volume of RAP were evaluated through a field demonstration project near Lewistown, Montana. The RAP concrete was batched, placed, and finished using conventional construction methods, and showed satisfactory constructability and serviceability (Berry et al., 2015b). In another analytical study, the beneficial structural behavior of RAP concrete pavement was evaluated using a finite element (FE) model, and the results indicated that the RAP concrete could have potentially better performance, since the computed stress-to-strength ratio of the RAP concrete under critical stress condition decreases as the RAP content of the mix increases (Tia et al., 2012; Kim et al., 2017).

Copeland (2011) reported that more than 100 million tons of RAP are generated by asphalt pavement rehabilitation and reconstruction every year in the United States. However, Hansen and Copeland (2017) reported a recent survey of total estimated amount of RAP in U.S. stockpiles to be 85.1 million tons. The excessive amount of RAP produced every year leads to a need to use up this material effectively. The possibility of using RAP in concrete pavement has not only environmental benefits but also cost saving by replacing the relatively more expensive virgin aggregates with the less expensive RAP. (Tosic et al., 2015).

The Florida Department of Transportation (FDOT) will construct a 2.5-mile Florida Concrete Test Road on a northbound segment of US-301 in Clay County (county segment 71030000, mile marker 0.116 to 3.510). The main purpose for the Florida Concrete Test Road is to evaluate new and innovative techniques and materials for construction, rehabilitation, and maintenance of concrete pavements, as well as to generate data that will be used to locally calibrate the existing mechanistic-empirical pavement design guide. One of the materials to be evaluated is concrete incorporating Reclaimed Asphalt Pavement (RAP) material as aggregate replacement, which has been found from a previous FDOT-sponsored study, to offer the possibility of improving the performance of concrete pavement due to its low modulus of elasticity. The potential benefits for the use of RAP in concrete pavement will include not only the utilization of excess RAP, but also improved performance and cost effectiveness of concrete pavements in Florida.

1.2 Objectives of Research

The main objective of this research project was to develop the mix designs for the RAP concrete to be used in the Florida Concrete Test Road. The specific objectives include the following:

(1) To develop four optimum mix designs for concrete incorporating RAPs from two different sources, to be used in the Florida Concrete Test Road.

(2) To provide language to supplement current FDOT concrete specifications (Section 346) to allow RAP as a component material for pavement concrete.

1.3 Research Approach

The following tasks were performed in order to achieve the main objectives of this study:

(1) Literature Review: Literature review was conducted in the following two areas: 1) Characterization of aggregate gradation in concrete, and 2) Properties of concrete containing RAP.

(2) Selection of RAP material: Two different FDOT approved RAP sources were used for this research project.

(3) Design of concrete mixes contacting RAP: Concrete mixtures with 0%, 20%, 30% and 40% RAP as aggregate replacement, and using 0% and 20% fly ash as cement replacement were designed using optimized aggregate gradation technique.

(4) Development of an Optimized Aggregate Gradation (OAG) tool: A computer software for optimizing aggregate gradation in a concrete mix design was developed and used in designing concrete mixes containing RAP in this study.

(4) Laboratory evaluation of the designed concrete mixes: The designed concrete mixes were produced and tested in the laboratory. The following properties of fresh concrete were evaluated: 1) Slump, 2) Unit weight, 3) Air content, and 4) Temperature. The following properties of the hardened concrete were evaluated: 1) Compressive strength, 2), Modulus of elasticity and Poisson's ratio, 3) Splitting tensile strength, 4) Flexural strength, 5) Drying shrinkage, 6) Coefficient of thermal expansion, and 7) Surface resistivity. Emphasis was placed on meeting the requirements for pavement concrete according to FDOT Specifications Section 346.

(5) Evaluation of potential performance of RAP concrete mixes: Critical stress analysis was performed to evaluate the potential performance of a typical concrete pavement in Florida if RAP concretes with the determined properties were used. Maximum temperature-load induced stresses under the most critical condition were computed, and the maximum stress to flexural strength ratios were used as a mean to evaluate the potential performance of the various RAP concretes which were evaluated. A lower computed stress to strength ratio would mean a higher number of load cycles to fatigue failure and a potentially better performance for the concrete.

CHAPTER 2
LITERATURE REVIEW

2.1 Characterization of Aggregate Gradation in Concrete

2.1.1 Maximum Density Method

Early work by Fuller and Thompson showed the importance of aggregate combined gradation on the workability and strength of concrete. They also developed an ideal shape of the combined gradation curve (Fuller and Thompson, 1907). They concluded that concrete mixtures with densely graded aggregates had the highest strength. But some researchers concluded that concrete produced with aggregate gradation of maximum density would be harsh and difficult to use (Talbot and Richart, 1923). The equation for Fuller's maximum density curve is as follow:

$$P = \left(\frac{d}{D}\right)^{n} \times 100 \qquad (2\text{-}1)$$

Where:

P = percent finer than an aggregate size

d = aggregate size taken for consideration

D = maximum aggregate size

n = parameter that controls fineness and coarseness of the curve (0.5 for maximum particle density)

The use of well graded and well-shaped aggregate with high packing density can significantly reduce the volume of the paste required, thus improving the properties of hardened concrete. Figure 2-1 shows the conceptual representation of aggregate particles in concrete. Apart from the paste required to fill up the voids between the aggregate, additional paste is required to separate the aggregate and make the concrete flowable (Koehler and Fowler, 2007)

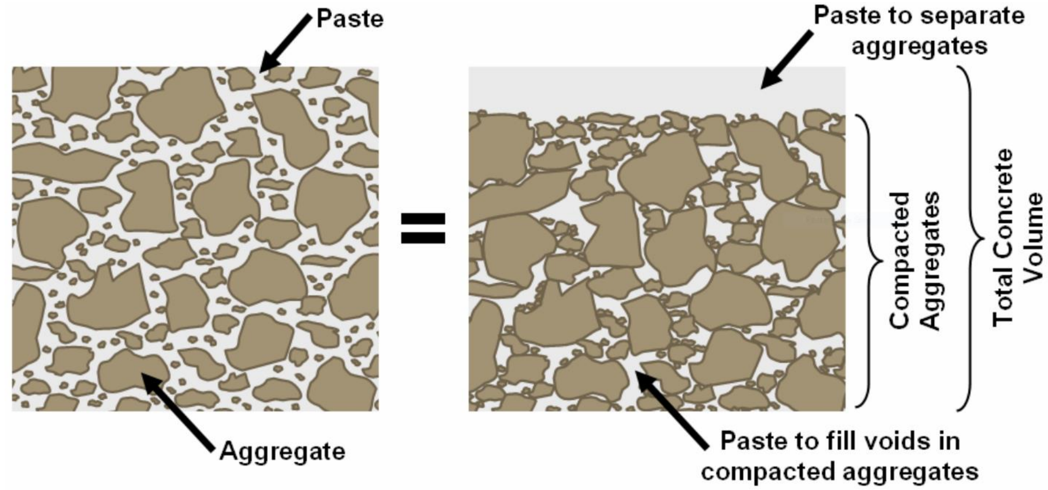


Figure 2-1. Representation of aggregate particles in paste (Koehler and Fowler, 2007)

Figure 2-2. Examples of mixtures with insufficient paste volume (left) and sufficient paste volume (right) for filling ability (Koehler and Fowler, 2007)

2.1.2 Fineness Modulus

Fineness modulus is an index of coarseness or fineness of an aggregate. Fineness modulus can be determined as follows:

$$FM = \frac{Cumulative \cdot percentage \cdot retained}{100} \qquad (2\text{-}2)$$

The sieve selected by Abrams were 11/2", 3/4", 3/8", #4, #8, #14, #28, #48, and #100. The #14, #28, and #48 sieves were later replaced by #16, #30, and #50 sieves. Abrams found that the grading of the mixtures was affected by fineness modulus of the aggregate. He stated that for any concrete mix with aggregate that gives the same fineness modulus, the same quantity of water would be needed to produce a mix of the same plasticity and strength.

2.1.3 Coarseness Factor

Shilstone came up with a concept called coarseness factor chart from the aggregate gradation, which could be used to predict the workability of the concrete mixtures. The coarseness factor chart is a method of analyzing the size and uniformity of the combined aggregate particle distribution, instead of considering the coarse and fine aggregate separately. The equation for coarseness factor is as follows,

$$CF = \left(\frac{Q}{Q + I} \right) \tag{2-4}$$

Where, Q = % Coarse particles which are larger than 3/8", and I = % Coarse particles retained on #4 and #8 sieve. Thus, a coarseness factor (CF) with a value of 100 would represent a gap-graded aggregate blend with no material between 3/8" and #8, while a coarseness factor (CF) of zero would be an aggregate that has no material retained on the 3/8" sieve. Another term on the coarseness factor chart is the workability factor ‘W’. It is the percentage of material passing #8 sieve. Figure 2-3 shows the coarseness factor chart that was proposed by Shilstone. The x-axis of the chart is the coarseness factor (CF) and the y-axis is the workability (W) as discussed above. A trend bar was included in order to use it as a reference and to find the optimal region based on the trial batches performed for different concrete mixtures. In general, the concrete mixtures that fall above the trend bar are considered to be sandy mixtures, and the mixtures below the trend line were considered to be rocky mixtures. The mixtures that fall in the trend bar will require the least amount of water for a given slump, but the concrete can be difficult to pump or even have poor finishability. In a modified coarseness factor chart the entire chart area was divided into five zones which will be used to study the concrete mixtures containing RAP. In the coarseness factor chart, we have five zones with the Roman numerals Ⅰ to Ⅴ as shown in the figure.

Zone Ⅰ, is the condition of a gap-graded mixture and will encounter potential problems of segregation or unnecessary consolidation due to lack of intermediate particles. These mixtures will not be cohesive, and so a clear separation between the coarse particles and the mortar will be observed. Zone Ⅱ, is the condition of an optimum mixture. Mixtures that fall in this zone are well graded and excellent for regular production use. High quality concrete can be produced when the coarseness factor is approximately 60 and the workability is around 35. Zone Ⅱ is also divided into five regions. Depending on the applications, each of these small regions in Zone Ⅱ can be beneficial. Zone Ⅲ is the extension of Zone Ⅱ and is for aggregates with smaller maximum aggregate size (approximately 1/2"). Zone Ⅳ is the condition of excessive fines that can lead to segregation. Mixtures in zone Ⅳ can also cause high permeability, shrinkage, cracking, curling, spalling and scaling. Zone Ⅴ is the condition of very coarse mix with lack of fines making the mixtures nonplastic. Mixtures in this zone will require high amount of fine aggregate to make the mix workable.

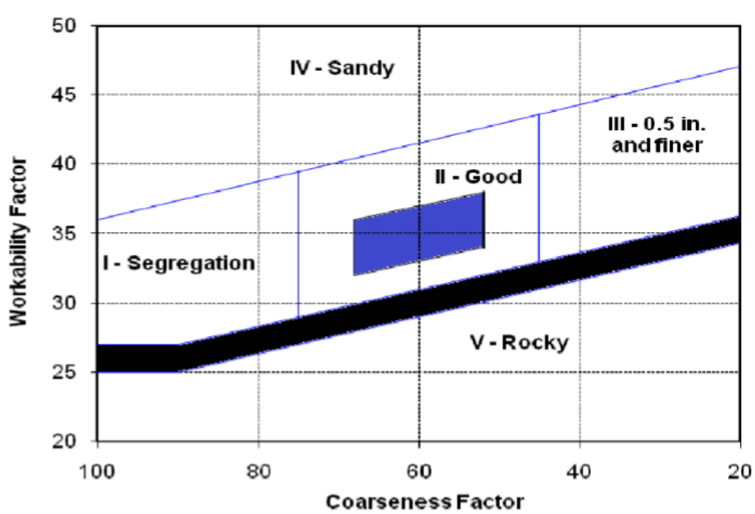


Figure 2-3. Coarseness factor chart proposed by Shilstone

2.1.4 Individual Percent Retained

The individual percent retained chart provides a method for graphing the distribution of different sizes of aggregates in a combined aggregate plot. It helps to reveal the lack of aggregate on specific sieves as gaps on the chart. The “8-18” band on this chart is the region where the ideal aggregate fractions proposed by Shilstone as shown in Figure 2-4. Figure 2-5 shows the ideal individual percentage retained curve that must be achieved. However, with the current ASTM C33 aggregate specification, #57 aggregate and ASTM C33 sand, there is a deficit in particles retained on the #8 and #16 sieves, and excess of particles retained on the #30 and #50 sieves as shown in Figure 2-6. Such kinds of gradation lead to problems like cracking, spalling, deficient sieve sizes.

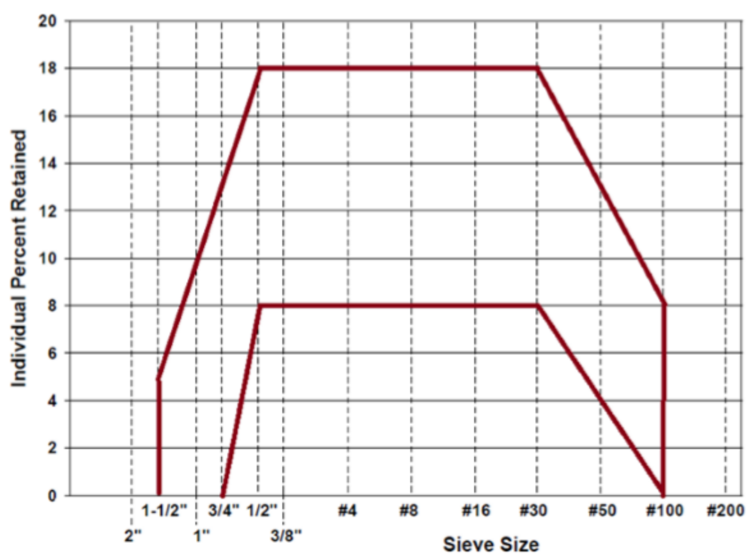


Figure 2-4. Shilstone 8-18 band chart

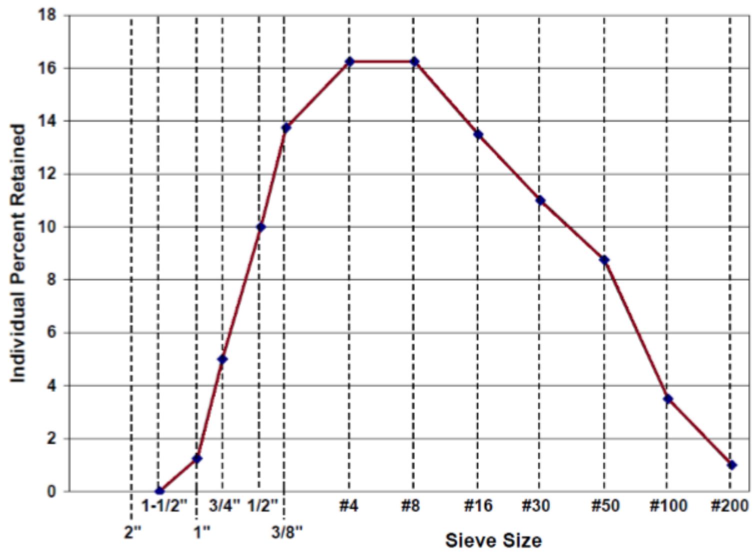


Figure 2-5. Ideal plot on individual percentage retained chart

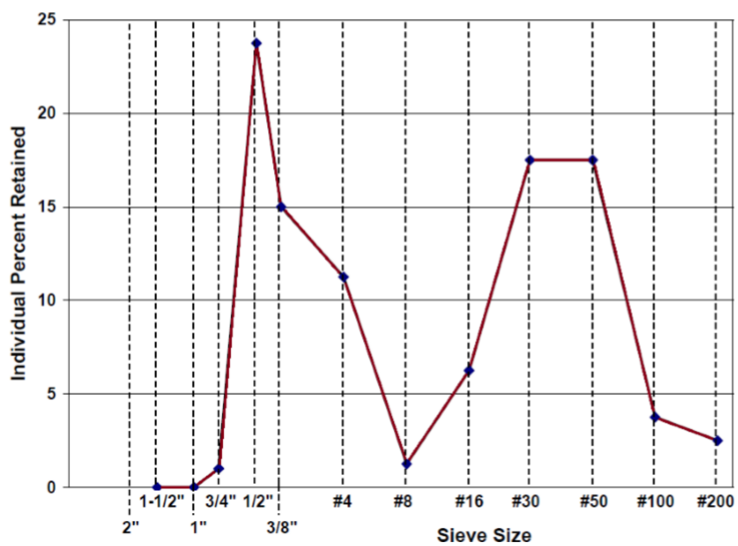


Figure 2-6. Problematic plot on individual percentage retained chart

2.1.5 The 0.45 Power Chart

The 0.45 power chart is similar to semi-log graph, which the exception that the x-axis is the sieve opening plotted on a 0.45 power scale. The 0.45 power chart is widely used in the asphalt industry to reduce the voids of the combined aggregate, and the amount of asphalt in the asphalt mixture design. The optimum line on the 0.45 power chart is the straight line, which will give the least amount of voids and best packing in the combined aggregate. The deviations from the optimum line help to identify the location of grading problems as shown in Figure 2-8. Gradings should be close to the optimum line with very little deviation and zigzag patterns as shown in Figure 2-7. S-shaped curve will usually form in the case of a gap graded mix (ACI.302.1R-04, 2004).

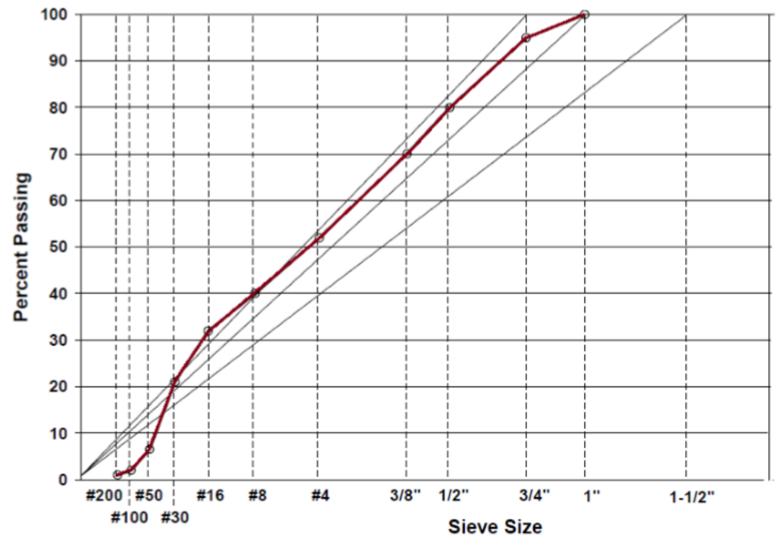


Figure 2-7. 0.45 power chart for a well graded mix

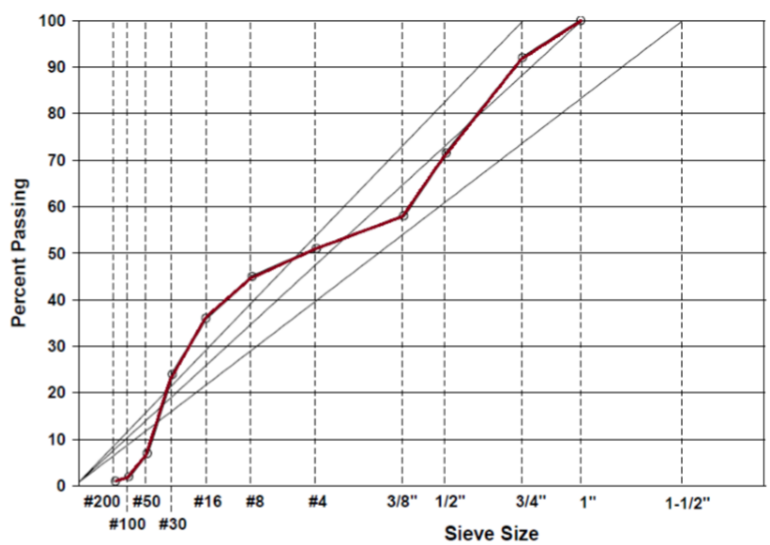


Figure 2-8. 0.45 power chart for a gap-graded mix

2.2 Effect of Aggregate Gradation on Concrete Properties

According to a recent study, optimized aggregate gradation concrete (OAG) provided 9% higher flexural strength than normal aggregate gradation concrete (NAG). There was a reduction in shrinkage and coefficient of thermal expansion when the aggregate gradation was optimized (Kim et al., 2008).

In a report provided by the Innovative Pavement Research Foundation, the authors stated that the use of combined gradation for optimization plays a major role in the performance of concrete pavements at airports. Gap-graded concrete mixtures are not acceptable, according to the proposed specifications, as they may cause segregation and joint spalling, which might affect the long-term performance of concrete pavements. Thus, use of combined gradation and innovative ways of optimizing the mixtures should be performed by the contractors and engineers (Tayabji and Anderson, 2007).

A study performed in Wisconsin showed that the use of optimized total aggregate gradation instead of near-gap-graded gradation in concrete pavement resulted in an increase in the compressive strength by 10% to 20%. A reduction in segregation reduced water demand by up to 15%, and a desirable slump was achieved. Desirable air content was achieved with 20% to 30% reduction in air-entraining agent. In another study, optimized gradation was achieved by increasing the aggregate particles retained on #8 to #16 sieves and decreasing the amount of fines on #50 to #200 sieves. A control mix with 60:40 blend of coarse to fine aggregate and a near-gap-graded aggregate was produced by removing the particles on the #4 to #16 sieves. According to the study, the optimized gradation mixes did not show consistent improvement in performance as compared to the control mixes. The near-gap-graded mixes showed reduced strength and increased shrinkage (Cramer and Carpenter, 1999).

Figure 2-9 through 2-11 show the individual percentage retained chart, 0.45 power chart, and coarseness factor chart for optimized mixtures. This optimized mix resulted in reduction in cracking, increase in air entrainment, increase in strength, and decrease in placement time.

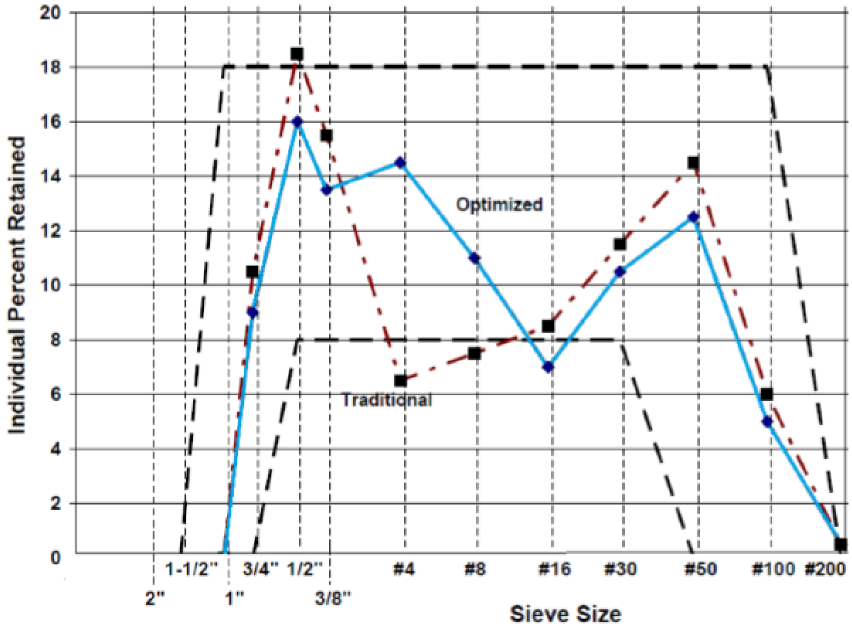


Figure 2-9. Individual percent retained for optimized mix

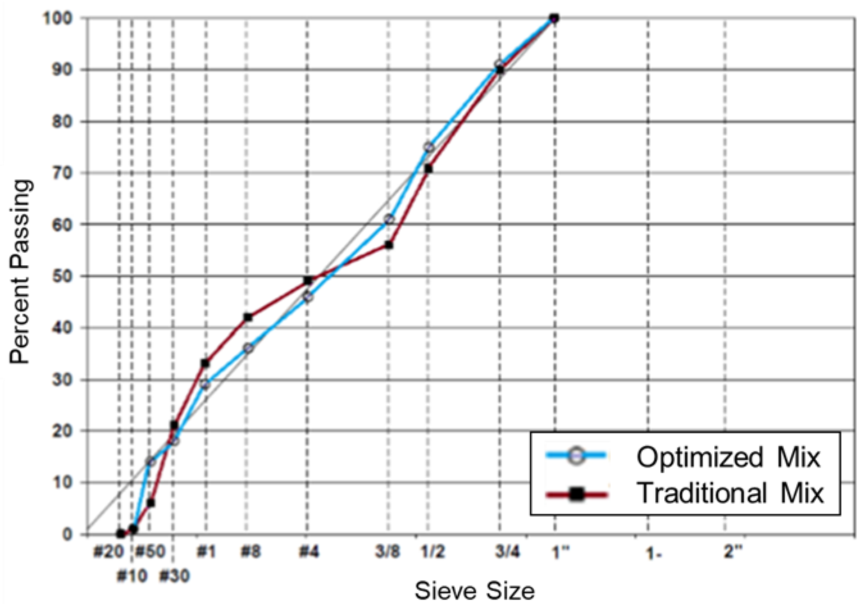


Figure 2-10. 0.45 power chart for optimized mix

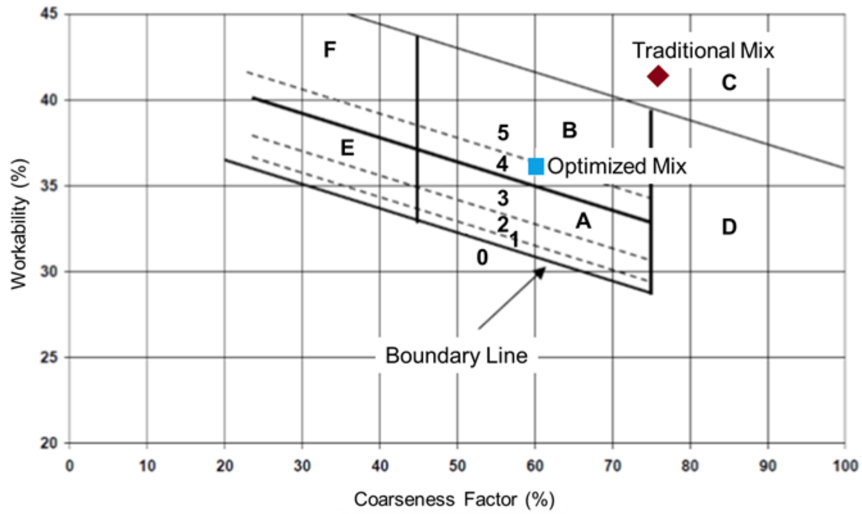


Figure 2-11. Coarseness factor chart for optimized mix

2.3 Properties of Recycled Asphalt Pavement

Reclaimed asphalt pavement (RAP) is bituminous concrete material removed and reprocessed from pavement which have to undergo resurfacing or reconstruction. The reclaiming process involves cold milling a portion of the existing pavement or full depth removal and crushing. The properties of RAP largely depend on the condition of pavement from where it is reclaimed. There can be significant variation in the material due to the type of mix, aggregate quality and size, asphalt mix consistency and asphalt content. RAP is usually finer than its original aggregate constituents, due to processing of the material. Typically, RAP is produced by crushing and screening the material to 1/4" to 1/2" in size (Griffiths and Krstulovich, 2002).

According to Kang et al. 2011, addition of RAP to virgin aggregate increased the proportion of medium to coarse fractions in the mixtures. In the FA-aggregate-RAP mixtures, increase in the proportion of RAP increased the proportions of medium and coarse fraction as shown in the Figure 2-12. Results of the gradation from Huang's study showed that the fine RAP is much coarser than the virgin fine aggregate and coarse RAP is much finer than the virgin coarse aggregate. The proportion of medium fractions in RAP aggregate is much higher, and shown in Figure 2-13.

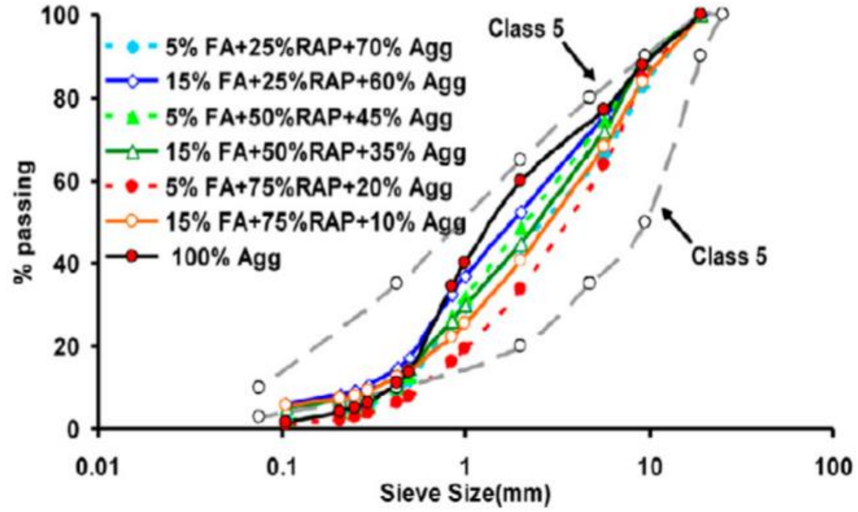


Figure 2-12. Particle size distribution of RAP and virgin aggregates (Kang et al. 2011)

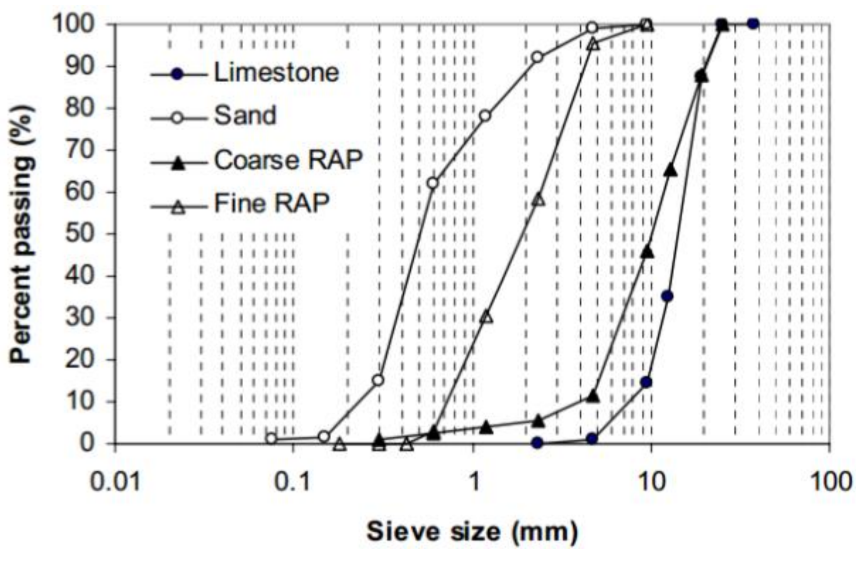


Figure 2-13. Gradation of aggregates and RAP (Huang et al., 2006)

2.4 Properties of Concrete Containing RAP

In concrete incorporating RAP, the asphalt forms a thin film at the interface of cement mortar and aggregate. This asphalt film can be useful in resisting the crack propagation along this interface. Thus, crack develops along the aggregate surface rather than going through it, as shown in Figure 2-14, during which more energy can be dissipated (Huang et al., 2006). Huang also showed that concrete made with only coarse RAP shows a better performance in toughness and has the least reduction in the concrete strength. For concrete with high percentage of RAP, aggregates do not separate after failure but sustain load even after initial failure. It has also been observed that with such a concrete with RAP, there is a systematic reduction in the strength of the concrete. Generally, the strength decreases with increase in the content of RAP (Huang et al., 2005).

Hassan et al. (2000) showed that RAP aggregate reduced the compressive strength of the concrete and the reduction in the strength is proportional to the percentage of RAP used. The author also found that combination of fine RAP and coarse RAP cause more reduction in strength than the combination of coarse RAP and sand. The performance properties of concrete containing RAP improved with the use of fly ash as indicated by the measurements of porosity and permeability. Concrete containing RAP enhances the ductility and strain capacity of the concrete. This improvement in property can be useful for applications such as rigid pavements, road bases and subbases.

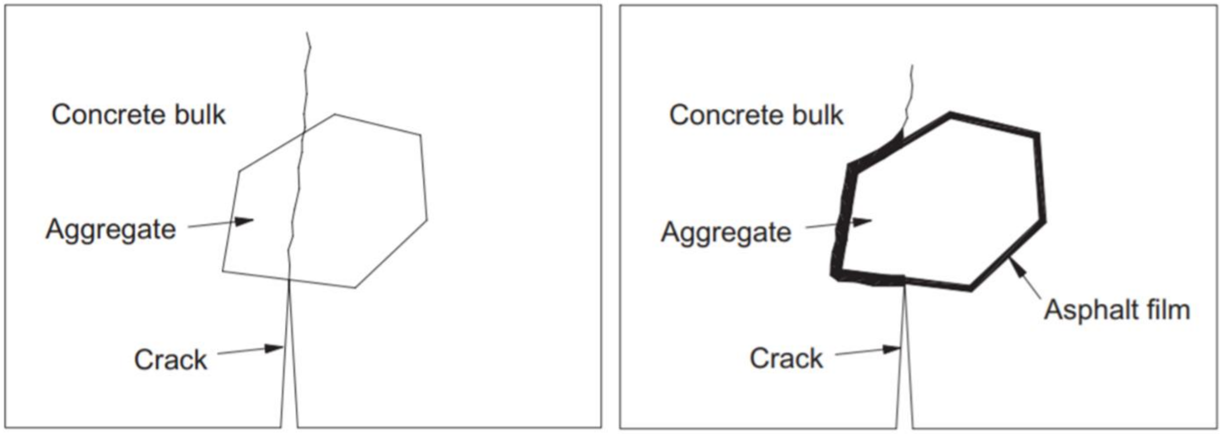


Figure 2-14. Propagation of crack through aggregate with and without asphalt film (Huang et al., 2006)

Al-Oraimi et al. (2009), found that the general trend of strength development for RAP concrete and the relations between compressive strength, elastic modulus, and flexural strength for concrete mixtures with RAP agreed well with the normal concrete. Reduction in slump with increasing RAP content was observed. According to the authors, RAP can be used as aggregate in non-structural applications but the percentage of RAP should be limited to achieve the required performance for the desired application. Figure 2-15 shows the reduction of compressive strength with increase in percentage of RAP, and Figure 2-16 shows the percent reduction in compressive strength for different percentage of RAP replacement.

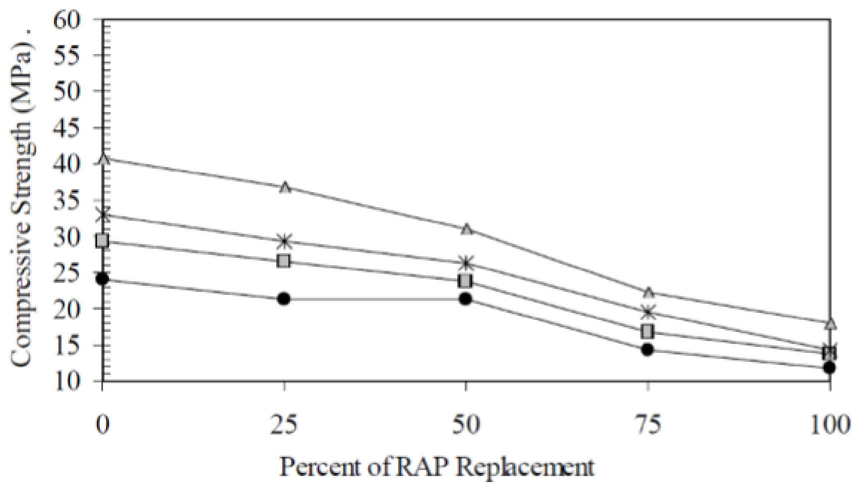


Figure 2-15. Compressive strength of concrete containing RAP (Al-Oraimi et al. 2009)

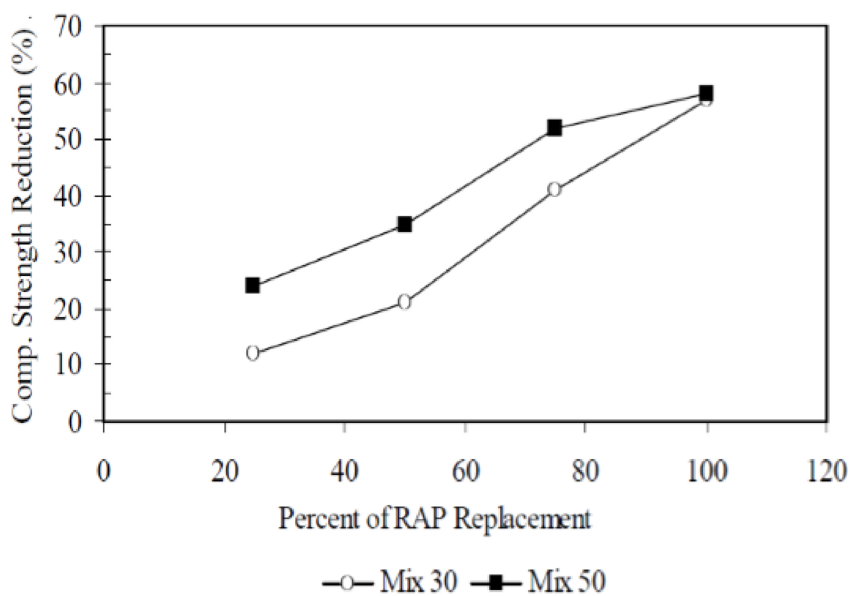


Figure 2-16. Reduction in compressive strength of concrete containing RAP (Al-Oraimi et al., 2009)

Delwar et al. (1997) investigated varying percent of replacements for coarse and fine RAP (0, 25, 50, 75, and 100), with two different water-to-cement ratios (0.45 and 0.50). They concluded that in general concrete containing RAP increased the amount of entrapped air, decreased the unit weight and decreased the slump of the concrete. Reduction in modulus of elasticity and compressive strength was also observed with the increase in the percentage of RAP. Delwar concluded that concrete containing high percentage of RAP should be used for non-pavement applications like sidewalks, gutters and barriers.

Sommer (1994) performed a study with RAP replacement of 0, 25, 50, 75, and 100% in concrete. They found reduction in compressive strength, splitting tensile strength, flexural strength, and elastic modulus with increasing percentage of RAP. They also stated that it would be acceptable to add 50% coarse RAP into the concrete mixtures and strength of RAP concrete could be improved by reducing the water-to-cement ratio.

Mathias (2004) studied concrete using five different total RAP contents (0, 12.5, 26, 51, and 90%). Compressive strength, splitting tensile strength and elastic modulus tests were performed at three different temperatures of 2, 20, and 40 ℃. Results showed that compressive strength, splitting tensile strength, and elastic modulus decreased with increasing RAP content, and that as the amount of RAP in concrete increased, the concrete properties became more sensitive to temperature. They also performed fatigue testing and concluded that for concrete mixture with 90% RAP, the fatigue failure stress was approximately 10% lower to achieve at least one million cycles to fatigue failure.

Okafor (2010) found that RAP aggregate may be able to absorb more impact load than virgin aggregate after performing impact crushing test. His study also found that concrete mixtures with RAP had reduced slump but the mixtures were still workable. Reduction in the strength of the concrete at different curing times and water-cement-ratios was also observed. He also stated that the failure in compression often resulted as the failure between RAP-mortar interface with little aggregate crushing, while the virgin aggregate often fails by crushing of the aggregate.

Katsakou and Kolias (2007) replaced 10, 25, 50, 75, and 100% of aggregate with RAP for a cement treated mixture. They found the compressive strength decreased with increasing percentage of RAP content. However, the flexural strength of the material was unchanged up to 50% RAP replacements. The rate of strength loss in tension was lower than in compression with increasing RAP content. They also found that the rate of decrease in the modulus of elasticity was greater than the rate at which the strength decreased.

Topcu and Isikdag (2009) studied the use of fine RAP as a replacement to natural fine aggregate in mortars with replacements of 0, 25, 50, 75, and 100%. They found the compressive strength, modulus of elasticity, flexural strength, and unit weight of concrete decreased as the percentage of RAP replacement increased. The amount of free shrinkage increased for the mixtures with RAP.

Researchers have also studied the use of RAP and aggregate freshly coated with asphalt in concrete for subbase applications. In general, they found reduction in compressive strength, modulus of elasticity, and flexural strength for concrete mixtures containing RAP and asphalt coated aggregates. They also found the drying shrinkage to increase for concrete mixtures containing RAP and asphalt coated aggregate (Dumitru et al., 1999, Patankar and Williams, 1970).

Li et al. (1998) studied the use of coarse aggregate coated with asphalt emulsion in cement mortar for the application of base layer as a lean concrete. They showed that cement-asphalt emulsion concrete had a more ductile fatigue failure with a longer period of crack propagation as compared with the control mixtures. It also resulted in a better fatigue performance at the same stress strength ratio relative to the control mixture. They studied the stress strain behavior and found that at higher temperatures, the stress peak is lower and the postpeak strain is significantly extended, enhancing the strain capability of the material. However, at lower temperatures, the stress-strain behavior was found to be similar to that of plain concrete.

In Austria, a section of concrete pavement was reconstructed using the crushed concrete from the existing highway and RAP from the preexisting asphalt overlay. The contractors also placed a 20-year guarantee for that pavement section subjected to skid resistance, joint seal performance, and other measures. Till today the roadway has not reported any problems (Tompkins et al., 2009).

CHAPTER 3
MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter presents the materials and properties of the materials used for this study. The concrete mix proportions used are also presented.

3.2 Selection of Materials

All the materials selected were approved by the FDOT materials office at Gainesville, Florida. Type Ⅰ/Ⅱ cement donated by Florida Argos USA was selected for this study. The fine aggregate used was a silica sand and the coarse aggregates used was a Florida limestone #57. Recycled asphalt pavement (RAP) materials were selected from two different sources in Florida, and were from FDOT-approved sources as shown in Table 3-1. The details of the properties of the RAPs are presented in the section on material properties.

Table 3-1. Details of the selected RAP materials for this research study

Plant No.	Location	Plant Name	F.M
A0691	Lake City, FL	Anderson Columbia Company, Inc.	5.91
A0750	Jacksonville, FL	Hubbard Construction Company	6.03

3.3 Material Properties

3.3.1 Cement

Type Ⅰ/Ⅱ cement was used for all the concrete productions in this study. The physical and chemical properties for the cement were provided by FDOT and are shown in Table 3-2. The results are compared with ASTM specifications.

Table 3-2. Physical and chemical properties of Portland cement

Test	Standard Specification	Cement Property	AASHTO 85 for Type Ⅰ/Ⅱ
Loss on Ignition	ASTM C114	2.7%	≤ 3.5%
SO_3 in Cement	ASTM C114	3.1%	≤ 3.6%
Insoluble Residue	ASTM C114	0.24%	≤ 1.5%
Compressive Strength Cubes at 3 days	ASTM C109	3,780 psi	≥ 1,450
Compressive Strength Cubes at 7 days	ASTM C109	4,760 psi	≥ 2,470
Autoclave Expansion	ASTM C151	0.01%	0.80%
Fineness by Air permeability	ASTM C204	417 kg/m^2	≥ 260 and ≤ 430 kg/m^2

3.3.2 Virgin Fine Aggregate

The virgin fine aggregate is a silica sand, mined from plant #76-349. The properties of fine aggregate were provided by FDOT and are shown in Tables 3-3 through 3-4. Due to the limitation of the size of fine aggregate stock pile, two different fine aggregates were used for this study. Fine aggregate-1 was used for trial batches, and fine aggregate-2 was used for production batches. Table 3-3 shows the specific gravity and water absorption of the fine aggregates and Table 3-4 shows the gradation of the fine aggregates, used as compared to the FDOT specifications. Both of the fine aggregates had similar specific gravity and water absorption. Figure 3-1 shows the gradation chart of the fine aggregates. It can be seen that the fine aggregate is very fine, but its gradation falls within the specification limits of the FDOT standards.

Table 3-3. Specific gravity and water absorption of fine aggregates

Property	Unit	Fine Aggregate-1	Fine Aggregate-2
Bulk Specific Gravity (SSD)	−	2.641	2.645
Bulk Specific Gravity (Dry)	−	2.634	2.638
Apparent Specific Gravity (Dry)	−	2.654	2.657
Absorption	%	0.3	0.3

Table 3-4. Gradation of fine aggregates

Sieve Size	Fine Aggregate-1		Fine Aggregate-2		Grading Limits (FDOT)	
	Cumulative Retained (%)	Passing (%)	Cumulative Retained (%)	Passing (%)	Max Passing (%)	Min Passing (%)
#4	0.3	99.7	0.5	99.5	100.0	95
#8	3.5	96.5	3.6	96.4	100.0	85
#16	13.8	86.2	12.4	87.6	97.0	65
#30	37.1	62.9	30.9	69.1	70.0	25
#50	79.1	20.9	76.3	23.7	35.0	5
#100	97.7	2.3	98.5	1.5	7.0	0
#200	99.8	0.2	99.9	0.1	4.0	0
F.M	2.32		2.22			

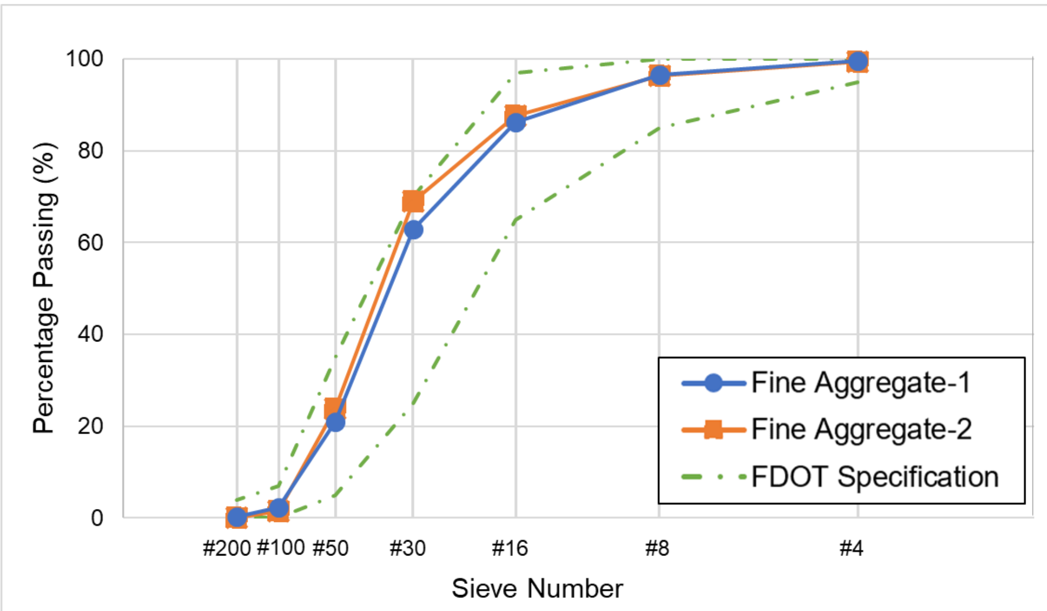


Figure 3-1. Gradation chart for virgin fine aggregates

3.3.3 Virgin Coarse Aggregate

The virgin coarse aggregate used for this study was a Florida limestone, mined from plant number #87-090. The properties of the coarse aggregate were provided by FDOT and are shown in Tables 3-5 through 3-6. Only one coarse aggregate was used for both the trial and production batches. Table 3-5 shows the specific gravity and water absorption of the coarse aggregate and Table 3-6 shows the gradation of coarse aggregate, which meets the FDOT specification.

Table 3-5. Specific gravity and water absorption of coarse aggregate (Florida limestone)

Property	Unit	Coarse Aggregate
Bulk Specific Gravity (SSD)	−	2.449
Bulk Specific Gravity (Dry)	−	2.361
Apparent Specific Gravity (Dry)	−	2.589
Absorption	%	3.7

Table 3-6. Gradation of coarse aggregate

Sieve Size	Coarse Aggregate		Grading Limits (FDOT)	
	Cumulative Retained (%)	Passing (%)	Max Passing (%)	Min Passing (%)
1½"	0.0	100.0	100.0	100.0
1"	0.3	99.7	100.0	95.0
1/2"	56.1	43.9	60.0	25.0
#4	93.4	6.6	10.0	0.0
#8	94.9	5.1	5.0	0.0

3.3.4 Recycled Asphalt Pavement (RAP)

In order to simulate how RAP will be used in the practical production of RAP concrete, the RAP was not separated into coarse and fine portions, and the RAP with its unaltered gradation was used. Initially, RAPs from six different sources were considered, and RAPs from two sources were selected out of these six sources. The two RAP sources were selected based on how well they would blend with the virgin coarse and fine aggregates to achieve optimal gradation in the blended aggregated if 20% RAP were used as aggregate replacement. The determination of optimum gradation was based on evaluation of coarseness factor and workability factor of the combined aggregated. An optimum gradation would have its workability versus coarseness factors plotted within Zone Ⅱ on the coarseness factor chart as shown in Figure 3-2. It would also have a plot of % retained close to the ideal plot on the percent retained chart as shown in Figure 3-3, and a plot of % passing close to the 0.45 power line on a gradation chart as shown in Figure 3-4. Based on this analysis, two RAP sources (A0691 and A0750) were selected to be used.

Table 3-7 presents the results of such gradation analysis of computationally blending 20% RAP from six different sources with the virgin coarse and virgin fine aggregates. The results of the analysis are presented in terms of standard deviation from the 0.45 power line, coarseness factor, workability factor, and standard deviation from the ideal % retained plot.

Figure 3-2 shows the coarseness factor chart of the blended aggregates with 20% of the selected RAP. Figure 3-3 and 3-4 show the percentage retained chart and the 0.45 power gradation chart, respectively, of the blended aggregates with 20% of the selected RAP. Tables 3-8 shows the specific gravity and water absorption of the two RAPs. The specific gravity and absorption for the two RAPs are very close to one another. Table 3-9 presents the gradation of the selected RAPs. The comparison of the gradations of the two selected RAP and the coarse and fine virgin aggregate is shown in Figure 3-5. It can be seen that the RAPs contain intermediate sizes while the virgin coarse and fine aggregate lack intermediate sizes. Table 3-8 presents the specific gravity and water absorption of the two selected RAPs. Table 3-9 presents the gradation of these two selected RAPs.

Table 3-7. Results of gradation analysis of blended aggregate containing 20% RAP

Plant No.	0.45 Power* (SD)	Coarseness[#] Factor (%)	Workability[#] Factor (%)	% Retained* (SD)	Remarks
A0691	5.2	56.1	36.0	4.2	Selected
A0750	5.2	56.1	36.5	4.1	Selected
A0200_1	5.4	55.5	35.5	4.4	
A0200_2	5.7	54.8	34.7	4.1	
A0712_1	5.4	56.9	35.6	4.5	
A0712_2	5.8	58.9	35.2	4.9	

Note: *the value was the standard deviation (SD) of the differences between actual and ideal percentage on each sieve. Thus, the lower value indicates the closeness of ideal percentage on each sieve.
[#]Coarseness and workability are related to the packing optimization. Best range of coarseness factor is between 52% and 68%, and best range of workability factor is between 32% and 38%.

Table 3-8. Specific gravity and water absorption of the selected RAPs

Property	Unit	RAP-A0691	RAP-A0750
Bulk Specific Gravity (SSD)	–	2.412	2.352
Bulk Specific Gravity (Dry)	–	2.391	2.326
Apparent Specific Gravity (Dry)	–	2.442	2.388
Absorption	%	0.84	1.10

Table 3-9. Gradation of the selected RAPs

Sieve Size	RAP-A0691		RAP-A0750	
	Cumulative Retained (%)	Passing (%)	Cumulative Retained (%)	Passing (%)
1½"	0.0	100.0	0.0	100.0
1"	0.2	100.0	0.2	100.0
3/4"	20.1	100.0	19.8	100.0
1/2"	31.4	94.7	30.6	95.9
3/8"	42.3	84.4	42.1	82.0
#4	59.2	56.4	59.5	50.3
#8	65.1	35.5	64.9	31.7
#16	73.5	20.3	72.7	20.2
#30	81.8	9.0	80.7	11.6
#50	94.1	2.5	93.5	4.4
#100	99.3	0.7	99.2	1.1
#200	99.9	0.2	99.9	0.1

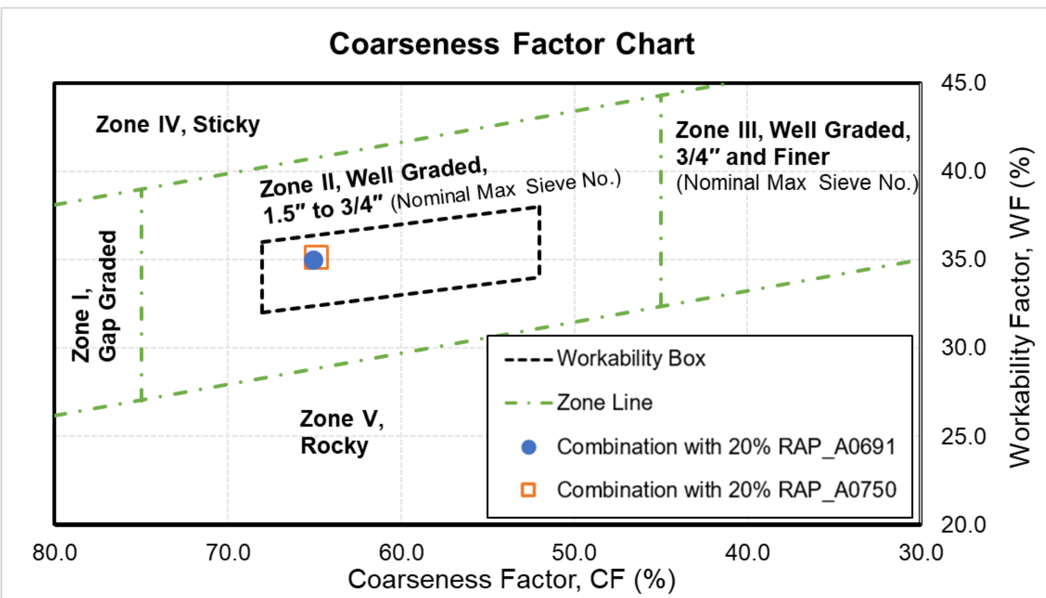


Figure 3-2. Coarseness factor chart of blended aggregates with 20% RAP

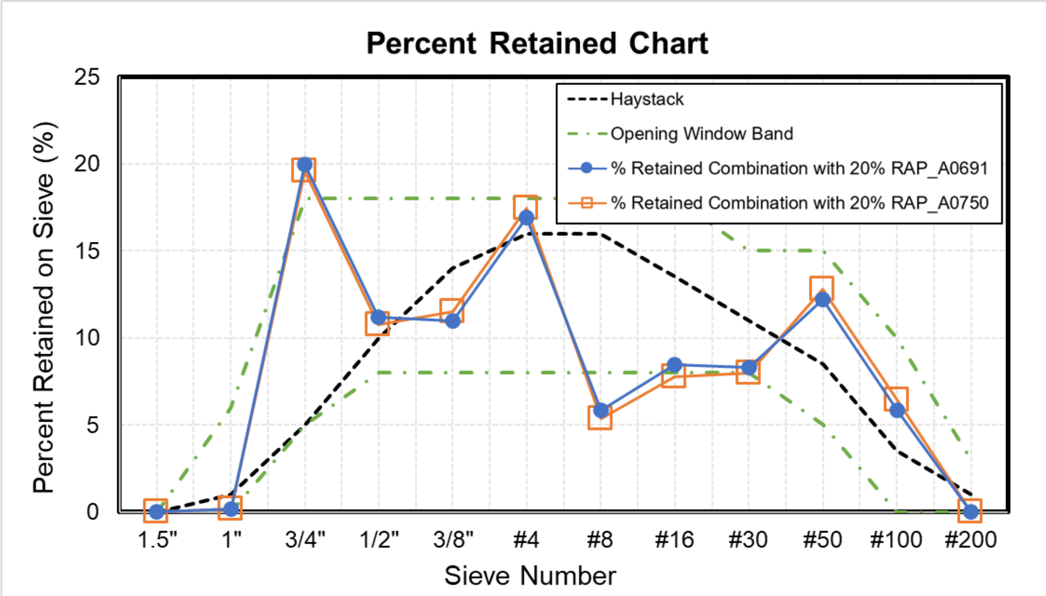


Figure 3-3. Percentage retained chart of blended aggregates with 20% RAP

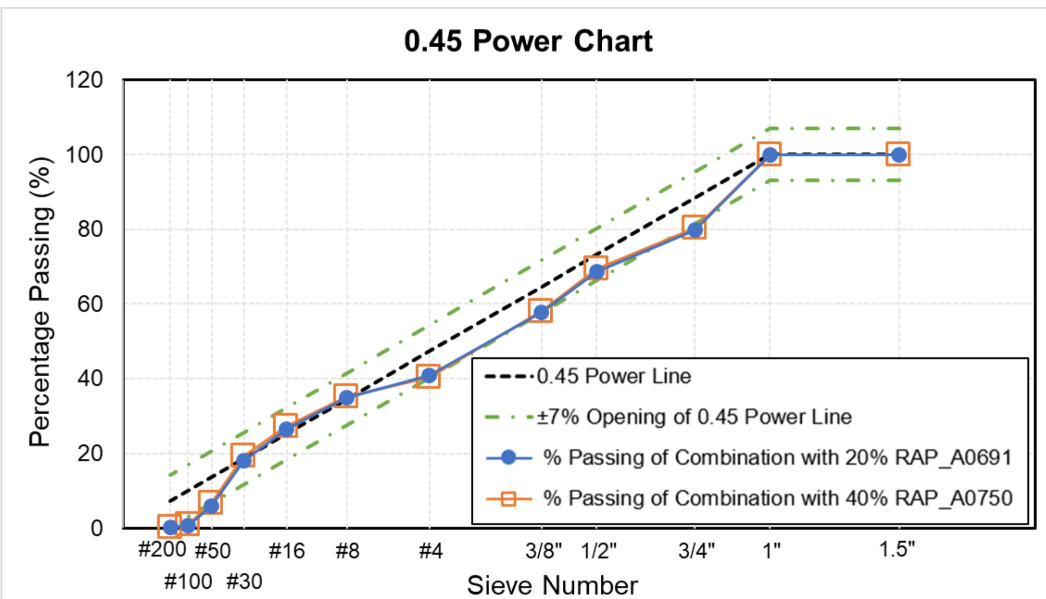


Figure 3-4. 0.45 power gradation chart of blended aggregates with 20% RAP

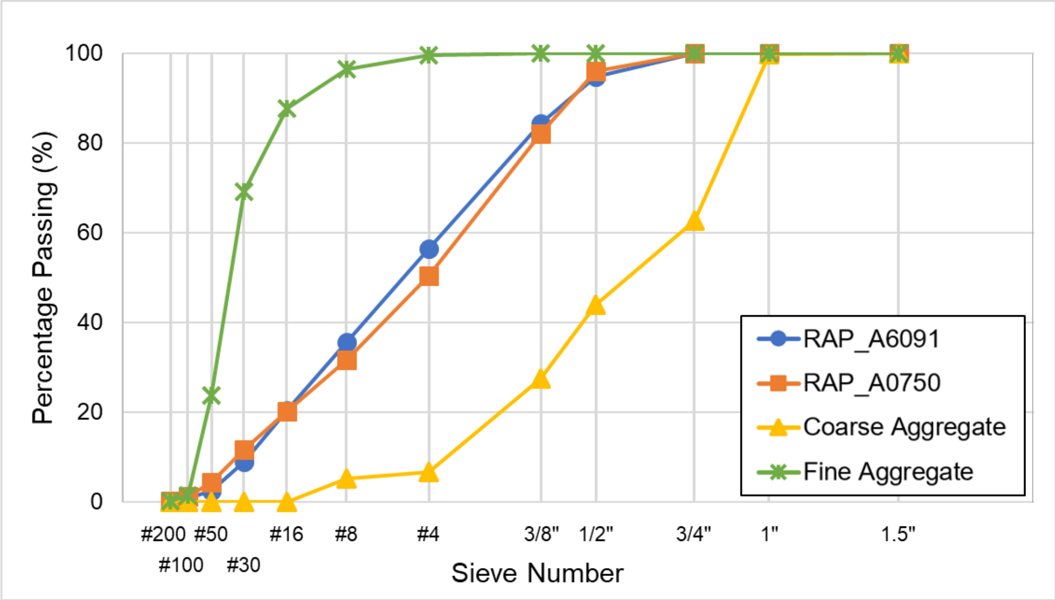


Figure 3-5. Gradation chart for selected RAPs versus virgin aggregates

3.4 Concrete Mix Proportions

3.4.1 Requirements for Fresh and Hardened Concrete

The main objective of this study was to develop four recommended mix designs incorporating RAP which could be used in the Florida Concrete Test Road. These developed concrete mixes must meet the required fresh and hardened properties for pavement concrete as specified in FDOT specifications Section 346. Table 3-10 presents the required fresh and hardened concrete properties for pavement concrete according to FDOT specifications.

Table 3-10. Required fresh and hardened concrete properties for pavement concrete according to FDOT specifications

Items		Specification
Cement Content	(lb/yd^3)	470
Fly ash Content	(% replacement by weight)	18 ~ 30
Slump	(in.)	0.5 ~ 3.5
Air Content	(%)	1.0 ~ 6.0
w/c	(ratio)	0.5 (Max.)
Compressive Strength	(psi)	3,000 (Regular design) 4,200 (Over-design)

The laboratory testing program was conducted in two phases. Phase 1 involves testing of twenty-four (24) trial mixes to identify feasible mixes which could meet the FDOT specification requirements for pavement concrete. Based on the preliminary test results from the trial mixes, ten (10) production mixes were identified and evaluated more extensively in Phase 2 to establish four optimum concrete mixes incorporating RAP to be recommended. The following sections present the mix proportions of the trial and production mixes which were evaluated.

3.4.2 Mix Proportions of Trial Mixes

Table 3-11 presents the mix parameters which were incorporated in the 24 trial mixes evaluated. The following mix parameters were incorporated:

1) Two RAP sources
2) Two RAP contents – 20% and 40%
3) Four w/c ratios – 0.43, 0.45, 0.47, and 0.50
4) Two fly ash contents – 0% and 20%

Table. 3-11 Mix parameters for the 24 trial mixes incorporating RAP

Mix Types	RAP1 (A0691) w/c				RAP2 (A0750) w/c			
	0.50	0.47	0.45	0.43	0.50	0.47	0.45	0.43
20% RAP + 0% Fly ash	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
20% RAP + 20% Flay ash	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
40% RAP + 20% Fly ahs	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

The mix proportions used for the 24 trial mixes are presented in Table 3-12. Appropriate amounts of Type D (water-reducing) admixture was added to each mix to achieve a target slump of 2 ± 1.5 inches for the fresh concrete.

Table 3-12. Mix proportions of trial concrete mixtures used in this research study

Mix No.	Cement (lb/yd^3)	Fly ash (lb/yd^3)	Cementitious (lb/yd^3)	Water (lb/yd^3)	Fine (lb/yd^3)	RAP (lb/yd^3)	Coarse (lb/yd^3)	Type D (oz)
M01-T	563	0	563	242	785	604	1,632	60
M02-T	439	109	548	236	785	604	1,632	80
M03-T	439	109	548	236	599	1,199	1,199	80
M04-T	563	0	563	242	812	601	1,594	80
M05-T	439	109	548	236	812	601	1,594	80
M06-T	439	109	548	236	623	1,187	1,157	100
M07-T	549	0	549	247	785	604	1,631	40
M08-T	428	107	535	241	785	604	1,631	40
M09-T	428	107	535	241	599	1,198	1,198	60
M10-T	549	0	549	247	811	601	1,593	40
M11-T	428	107	535	241	811	601	1,593	60
M12-T	428	107	535	241	623	1,187	1,157	60
M13-T	536	0	536	252	784	603	1,630	40
M14-T	416	104	520	245	785	604	1,632	40
M15-T	416	104	520	245	600	1,200	1,200	60
M16-T	536	0	536	252	811	600	1,592	40
M17-T	416	104	520	245	812	601	1,594	40
M18-T	416	104	520	245	623	1,188	1,158	60
M19-T	516	0	516	258	784	603	1,630	40
M20-T	403	100	503	252	784	603	1,630	40
M21-T	403	100	503	252	599	1,198	1,198	40
M22-T	516	0	516	258	811	601	1,593	40
M23-T	403	100	503	252	811	601	1,593	40
M24-T	403	100	503	252	623	1,186	1,157	40

3.4.3 Mix Proportions of Production Mixes

Based on the results of the trial mixes, four feasible mixes were selected for further extensive testing. These four selected mixes were concrete mixes containing 0% and 20% fly ash with 20% RAP, using RAP1 and RAP2. For comparison purpose, six additional mixes were also tested. These additional mixes to be evaluated include the following:

1) Two control mixes with no RAP, using 0% and 20% fly ash
2) Two mixes with 30% RAP and 20% fly ash, using RAP1 and RAP2
3) Two mixes with 40% RAP and 20% fly ash, using RAP1 and RAP2

The mix parameters for these ten production mixes are shown in Table 3-13.

Table 3-13. Mix parameters for the ten production mixes evaluated

	RAP1 (A0691)	RAP2 (A0750)	Virgin Aggregate
20% RAP + 0% Fly ash	**X**	**X**	
20% RAP + 20% Fly ash	**X**	**X**	
30% RAP + 20% Fly ash	**X**	**X**	
40% RAP + 20% Fly ash	**X**	**X**	
0% RAP + 0% Fly ash (Control mix)			**X**
0% RAP + 20% Fly ash (Control mix)			**X**

Note: w/c = 0.5 for all mixes.

The mix proportions used for the ten production mixes are presented in Table 3-14. Similarly, appropriate amounts of Type D (water-reducing) admixture was added to each mix to achieve a target slump of 2 ± 1.5 inches for the fresh concrete.

Table 3-14. Mix proportions of production concrete mixtures used

Mix No.	Cement (lb/yd^3)	Fly ash (lb/yd^3)	Cementitious (lb/yd^3)	Water (lb/yd^3)	Fine (lb/yd^3)	RAP (lb/yd^3)	Coarse (lb/yd^3)	Type D (oz)
M01-P	516.0	0	516.0	258.0	1,034.4	0.0	2,005.0	40
M02-P	403.2	100.8	504.0	252.0	1,034.4	0.0	2,005.0	40
M03-P	516.0	0	516.0	258.0	814.6	603.4*	1,599.0	40
M04-P	516.0	0	516.0	258.0	841.1	600.8#	1,562.0	40
M05-P	403.2	100.8	504.0	252.0	814.6	603.4*	1,599.0	40
M06-P	403.2	100.8	504.0	252.0	841.1	600.8#	1,562.0	40
M07-P	403.2	100.8	504.0	252.0	721.3	901.6*	1,382.5	40
M08-P	403.2	100.8	504.0	252.0	745.8	895.0#	1,342.5	40
M09-P	403.2	100.8	504.0	252.0	628.7	1,197.4*	1,167.5	40
M10-P	403.2	100.8	504.0	252.0	682.5	1,187.0#	1,098.0	40

***RAP1 and #RAP2**

CHAPTER 4
DESIGNING CONCRETE MIXES CONTAINING RAP

4.1 Introduction

The mix proportions of the concrete mixes containing various percentages of RAP and which were evaluated in this study have been presented in Chapter 3. This chapter presents the procedures used in proportioning the ingredients for these concrete mixes.

4.2 Proportioning of Mix Ingredients Using Optimized Aggregate Gradation Technique

4.2.1 Coarseness Factor Chart

In this study, the modified coarseness factor chart as proposed by Lindquist et al. (2015) was used to proportion the virgin coarse aggregate, virgin fine aggregate, and RAP materials to produce the concrete mixes to be evaluated. The coarse factor chart is a plot of coarseness factor (CF) versus workability factor (WF) as shown in Figure 4-1.

The CF of an aggregate blend can be calculated as follows:

$$CF = \frac{Q}{Q+I} \times 100 \tag{4-1}$$

Where,

Q = 1½ in. + 1 in. + ¾ in. + ½ in. + ⅜ in. (Sieve Size No.)

I = No.4 + No.8 (Sieve Size No.)

The WF of a concrete mix can be calculated as follows:

$$WF = \frac{W}{Q+I+W} \times 100 + CCF \tag{4-2}$$

Where,

W = No.16 + No.30 + No.50 + No.100 + No.200 + Pan (Sieve Size No.)

CCF = 2.5(C – 564)/94 (C is the amount of cementitious)

The CF and WF of a concrete mix can be plotted on the coarseness factor chart to determine the workability of the concrete mix. A concrete mix with optimum aggregate gradation should be plotted within the workability box. The workability box is defined by the corners coordinates as shown in Table 4-1. The proper combination of CF and WF which plots inside the workability box would be desirable and would most likely produce a workable concrete mixture which can be placed and finished easily and will have good long-term performance.

Table 4-1. Corners coordinates of workability box

CF (%)	68	68	52	52
WF (%)	32	36	38	34

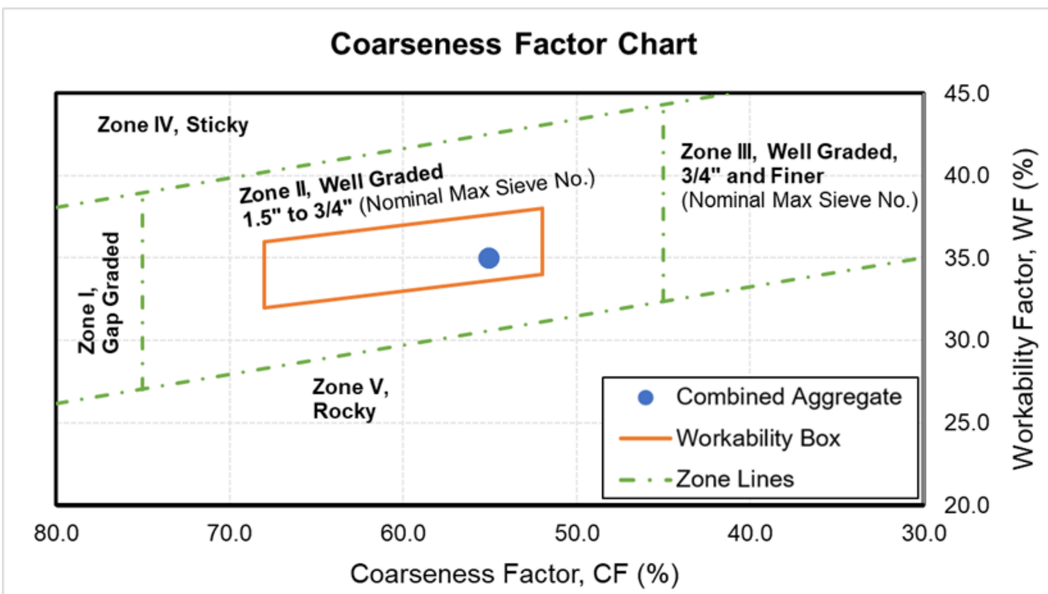


Figure 4-1. Example of coarseness factor chart

4.2.2 Percent Retained Chart

The percent retained chart is a plot of the percentage of combined aggregate retained on each individual sieve. The chart can be used to evaluate the gradation of an aggregate blend and to identify the lack or excess of certain-size aggregate. The desirable percent retained (i.e., model of Haystack) and allowable band on each sieve are presented in Figure 4-2.

In this study, the difference between the Haystack line and actual retained aggregate percentage plot is quantified calculating the standard deviation as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \tag{4-3}$$

Where,

N = Number of sieve

x = % retained aggregate of Haystack line

y = % retained aggregate of an actual combined aggregate

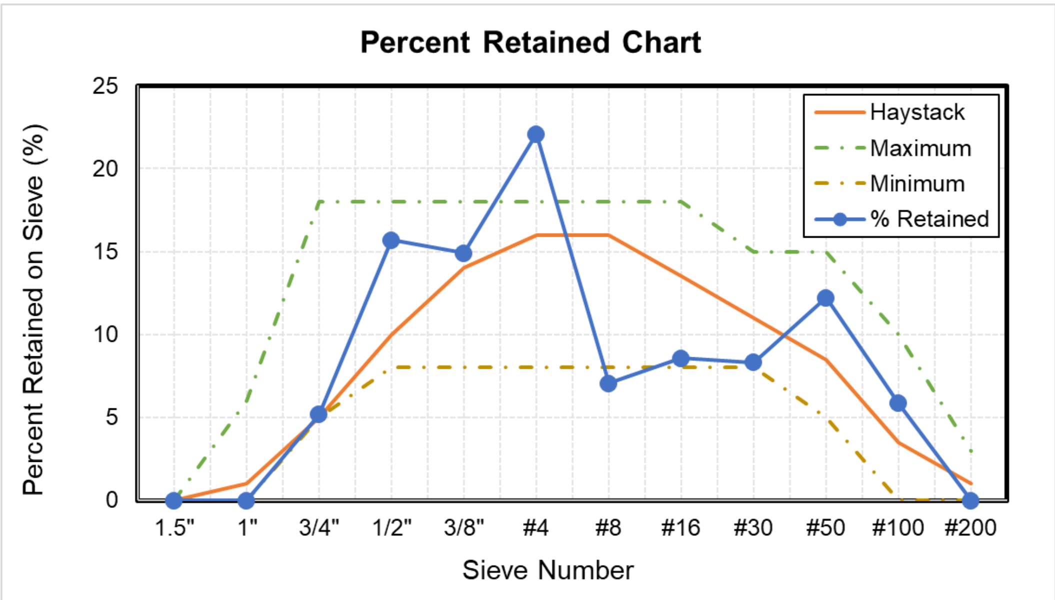


Figure 4-2. Example of percent retained chart

4.2.3 0.45 Power Chart

The evaluation of the gradation of the aggregate blend can also be done by the plot of the gradation on the 0.45 power chart. Figure 4-3 shows an example of a plot of gradation on the 0.45 Power chart. The gradation of a well-graded aggregate with maximum density will plot along the 0.45 Power line and will have cumulative % passing according to the following equation:

$$\%Pass = \left(\frac{d}{D}\right)^{0.45} \times 100 \tag{4-4}$$

Where,

d = Square opening of the sieve size being considered

D = Square opening of the nominal sieve size

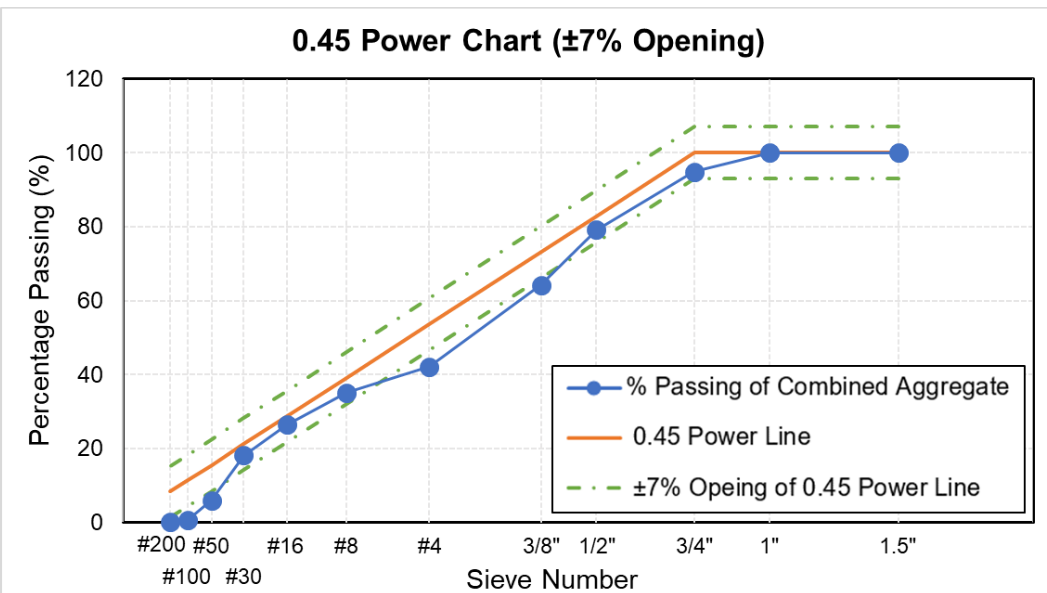


Figure 4-3. Example of 0.45 power chart

The deviation from the ideal 0.45 Power line can be quantified by calculating the standard deviation as follows:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \qquad (4\text{-}5)$$

Where,

N = Number of sieves

x = % passing according to the 0.45 power line

y = % passing of the aggregate blend

4.2.4 Proportioning of Aggregates Using the OAG Technique

In this study, various percentages of RAP were used as replacement of aggregates in the concrete mixes to be evaluated. In designing a concrete mix containing a specified percentage of RAP, the determination of the proportioning of the coarse aggregate and fine aggregate was made using the OAG technique. The following procedures were followed:

(1) Choose some initial estimated percentages of coarse and fine aggregates to be used along with the incorporated RAP. For example, if 20% RAP is to be incorporated, the initial estimated percentages of coarse aggregate and fine aggregate can be 50% and 30%. The total sum of the percentages of RAP, coarse aggregate, and fine aggregate should add up to 100%.

(2) Calculate the gradation of the blended aggregate using the gradations of the coarse aggregate, fine aggregate, and the RAP material, and the percentages of these aggregates and RAP.

(3) Using the calculated gradation of the blended aggregate, calculate the coarseness factor (CF) and the workability factor (WF) according to Equations 4-1 and 4-2. The

cementitious materials content of the concrete mix needs to be provided in order to calculate the workability factor.

(4) Plot the calculated CF and WF on the coarseness factor chart. If the combination of CF and WF plots within the workability box as shown in Figure 4-1, the chosen percentages of coarse and fine aggregate would be considered the optimum percentages to be used.

(5) If the combination of calculated CF and WF does not plot within the workability box, adjust the percentages of the coarse and fine aggregate by a trial-and-error process to try to move the plot of CF and WF to go within the workability box or to get close to it. The percentages of coarse and fine aggregates which enable the CF and WF to be plotted within the workability box or closest to it are considered the optimum percentages to be used.

4.2.5 A Developed Software for Proportioning Aggregates According to OAG Procedure

In order to facilitate the proportioning of aggregate using the OAG technique, an Excel spreadsheet software, named OAG Tool was developed. Figure 4-4 shows the screen display of the OAG Tool. Basically, the OAG Tool automates the procedure as described in Section 4.2.4. To use this software, the user inputs the gradations of the coarse aggregate, the fine aggregate, and the RAP material to be used, the percentage of RAP to be used, and the cementitious materials content of the concrete mixture to be designed. The user also enters an initial percentage of coarse aggregate to be used. It is to be noted that the percentage of fine aggregate does not need to be entered as the percentages of coarse aggregate, fine aggregate, and RAP materials add up to 100%. With the entered information, the OAG Tool then calculates the CF and WF values and plots them on a coarseness factor chart. If the CF and WF values do not plot within the workability box, the user can adjust the percentage of coarse aggregate to be tried, and the OAG will instantaneously recalculate the new CF and WF values and re-plot them on the coarseness factor chart. This process can be repeated until the optimum percentage of coarse aggregate is obtained.

In addition to the display of a plot of CF and WF on the coarseness factor chart, the OAG Tool also displays the plot of percent retained and the calculated standard deviation as described in Section 4.2.2, and the gradation plot on the 0.45 power chart and the calculated standard as described in Section 4.2.3.

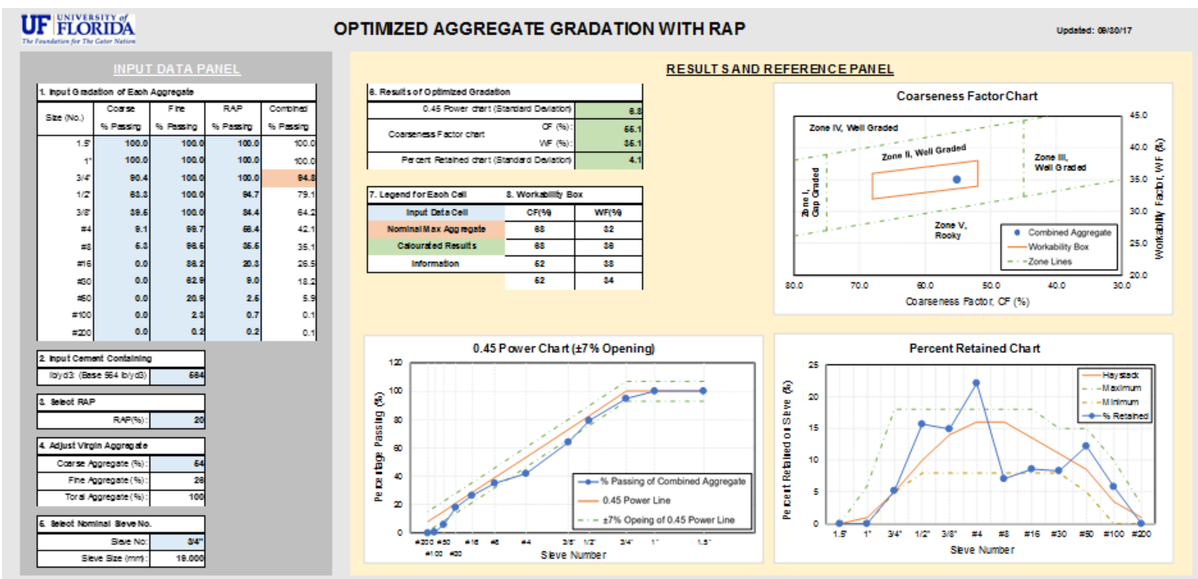


Figure 4-4. Screen display of OAG tool

4.3 Gradation of the Aggregate Blend Used in the Concrete Mixes Evaluated

4.3.1 Optimized Gradations of the Aggregate Blends by the OAG Procedure

Using the OAG procedure and aided by the OAG Tool software, optimized proportions of coarse and fine aggregate were determined for the various concrete mixes with various percentages of RAP, which were to be evaluated in this study. Tables 4-2 and 4-3 present the gradations of the blended aggregates of the concrete using 0%, 20%, and 40% RAP of sources A0691 and A0750, respectively. The optimized percentages of coarse and fine aggregates to be used are also shown on these tables. It is to be noted that the RAP materials from these two sources are very similar in gradation and thus the gradations of their resulting aggregate blends are very similar. Thus, only the gradation of the blended aggregate using one RAP source will be presented in the following sections.

Table 4-2. Gradations of blended aggregates of concrete using RAP-A0691

% Passing Sieve	RAP 0%			RAP 20%			RAP 40%		
	Coarse 68%	Fine 32%	Combine 100%	Coarse 54%	Fine 26%	Combine 100%	Coarse 40%	Fine 20%	Combine 100%
1½"	100.0	100.0	**100.0**	100.0	100.0	**100.0**	100.0	100.0	**100.0**
1"	99.7	100.0	**99.8**	99.7	100.0	**99.8**	99.7	100.0	**99.9**
3/4"	62.7	100.0	**74.6**	62.7	100.0	**79.9**	62.7	100.0	**85.1**
1/2"	43.9	100.0	**61.9**	43.9	100.0	**68.6**	43.9	100.0	**75.4**
3/8"	27.4	100.0	**50.6**	27.4	100.0	**57.7**	27.4	100.0	**64.7**
#4	6.6	99.7	**36.4**	6.6	99.7	**40.8**	6.6	99.7	**45.1**
#8	5.1	96.5	**34.3**	5.1	96.5	**34.9**	5.1	96.5	**35.5**
#16	0.0	86.2	**27.6**	0.0	86.2	**26.5**	0.0	86.2	**25.4**
#30	0.0	62.9	**20.1**	0.0	62.9	**18.2**	0.0	62.9	**16.2**
#50	0.0	20.9	**6.7**	0.0	20.9	**5.9**	0.0	20.9	**5.2**
#100	0.0	2.3	**0.7**	0.0	2.3	**0.7**	0.0	2.3	**0.7**
#200	0.0	0.2	**0.1**	0.0	0.2	**0.1**	0.0	0.2	**0.1**

Table 4-3. Gradations of blended aggregates of concrete using RAP-A0750

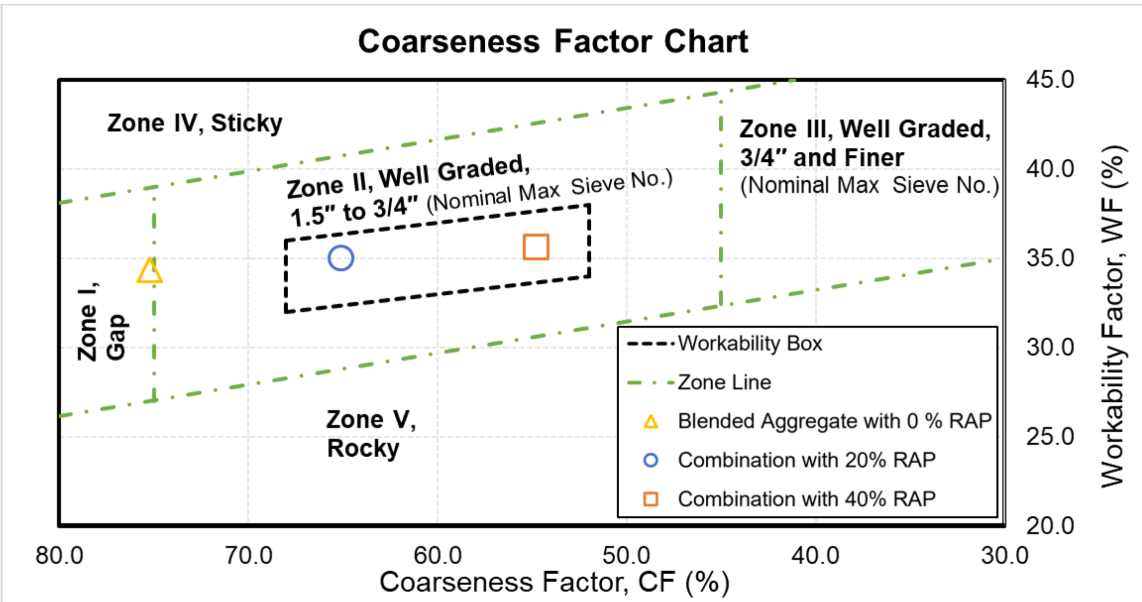
% Passing Sieve	RAP 0%			RAP 20%			RAP 40%		
	Coarse 68%	Fine 32%	Combine 100%	Coarse 53%	Fine 27%	Combine 100%	Coarse 39%	Fine 21%	Combine 100%
1½"	100.0	100.0	**100.0**	100.0	100.0	**100.0**	100.0	100.0	**100.0**
1"	99.7	100.0	**99.8**	99.7	100.0	**99.8**	99.7	100.0	**99.9**
3/4"	62.7	100.0	**74.6**	62.7	100.0	**80.2**	62.7	100.0	**85.5**
1/2"	43.9	100.0	**61.9**	43.9	100.0	**69.4**	43.9	100.0	**76.5**
3/8"	27.4	100.0	**50.6**	27.4	100.0	**57.9**	27.4	100.0	**64.5**
#4	6.6	99.7	**36.4**	6.6	99.7	**40.5**	6.6	99.7	**43.6**
#8	5.1	96.5	**34.3**	5.1	96.5	**35.1**	5.1	96.5	**34.9**
#16	0.0	86.2	**27.6**	0.0	86.2	**27.3**	0.0	86.2	**26.2**
#30	0.0	62.9	**20.1**	0.0	62.9	**19.3**	0.0	62.9	**17.8**
#50	0.0	20.9	**6.7**	0.0	20.9	**6.5**	0.0	20.9	**6.1**
#100	0.0	2.3	**0.7**	0.0	2.3	**0.8**	0.0	2.3	**0.9**
#200	0.0	0.2	**0.1**	0.0	0.2	**0.1**	0.0	0.2	**0.1**

4.3.2 Evaluation of Aggregate Gradation of Concrete Incorporating RAP

Figure 4-5 presents the plots of CF and WF on the coarseness factor chart for the aggregate blend of the concrete containing 0%, 20%, and 40% RAP. It can be seen that the aggregated blend of the control concrete without incorporation of RAP are gap-graded, and plots outside of the workability box in the coarseness factor chart. However, with the incorporation of 20% or 40% RAP, the aggregate blend becomes well-graded and plots within the workability box.

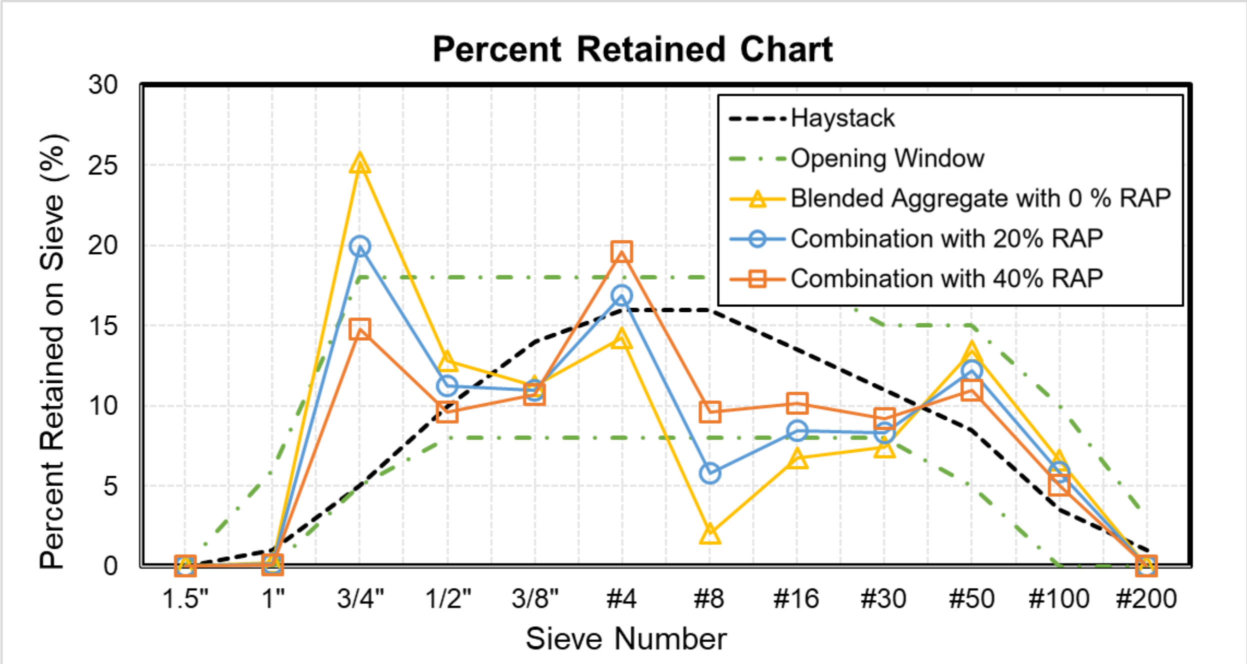
Figure 4-6 shows the plots of percent retained for the blends of aggregate for the concrete containing 0%, 20%, and 40% RAP. For the concrete mix with no RAP, there is clearly a lack of intermediate-size materials (#8, #16, and #30 sieves). This deficiency is reduced as the percentage RAP increases.

Figure 4-7 shows the plot of the aggregate gradations of the concrete containing 0%, 20%, and 40% RAP. It can be seen that the aggregate blend of the concrete mix with no RAP is gap graded, and plots for away from the ideal 0.45 Power line. However, with the incorporation of 20% or 40% RAP, the aggregate blend becomes more well-graded and plots closer to the 0.45 Power line.



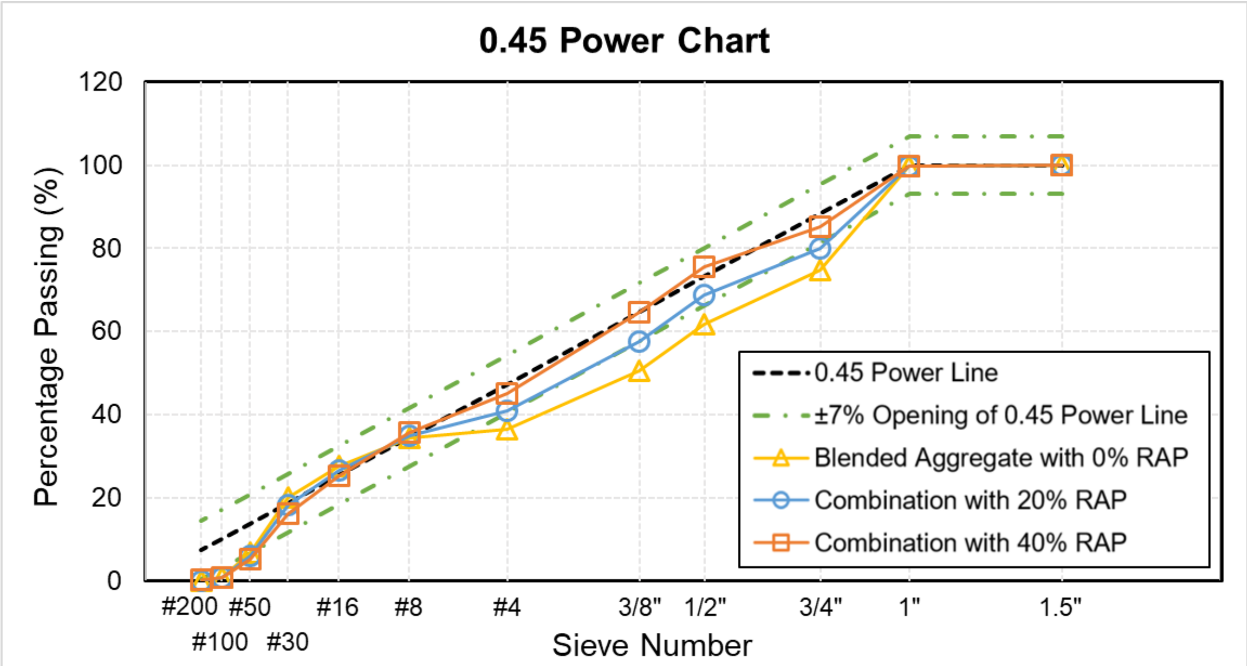
Note: Results of two RAPs were very similar to each other.

Figure 4-5. Coarseness factor chart for concrete mixtures containing RAP



Note: Results of two RAPs were very similar to each other.

Figure 4-6. Percent retained chart for concrete mixtures containing RAP



Note: Results of two RAPs were very similar to each other.

Figure 4-7. 0.45 power chart for aggregate gradation of concrete mixtures containing RAP

4.3.3 Comparison of OAG with ACI Procedure

Investigation was also made to see if the ACI 211.1 (2009) method of proportioning coarse and fine aggregates could be used in the design of concrete mixes containing RAP. According to the ACI procedure, the values of the coarse aggregates to be used are based on the nominal maximum size of the coarse aggregate and the fineness modulus of the fine aggregate and the table provided by ACI. The volume of the fine aggregate is then determined by the absolute volume method. In using the ACI method, when a certain percentage of aggregate was to be replaced by RAP, the amounts of coarse and fine aggregate were then reduced proportionally according to their original proportions without RAP.

When the ACI method was used to proportion the coarse and fine aggregate, it was difficult to produce a well-graded aggregate blend and a workable mix. Figure 4-8 compares the plots of CF and WF values on the Coarseness Factor Chart for aggregate blends from the OAG versus the ACI procedures. It can be clearly seen that the OAG procedure is superior to the ACI procedure in achieving a well-graded aggregate blend and workable mix.

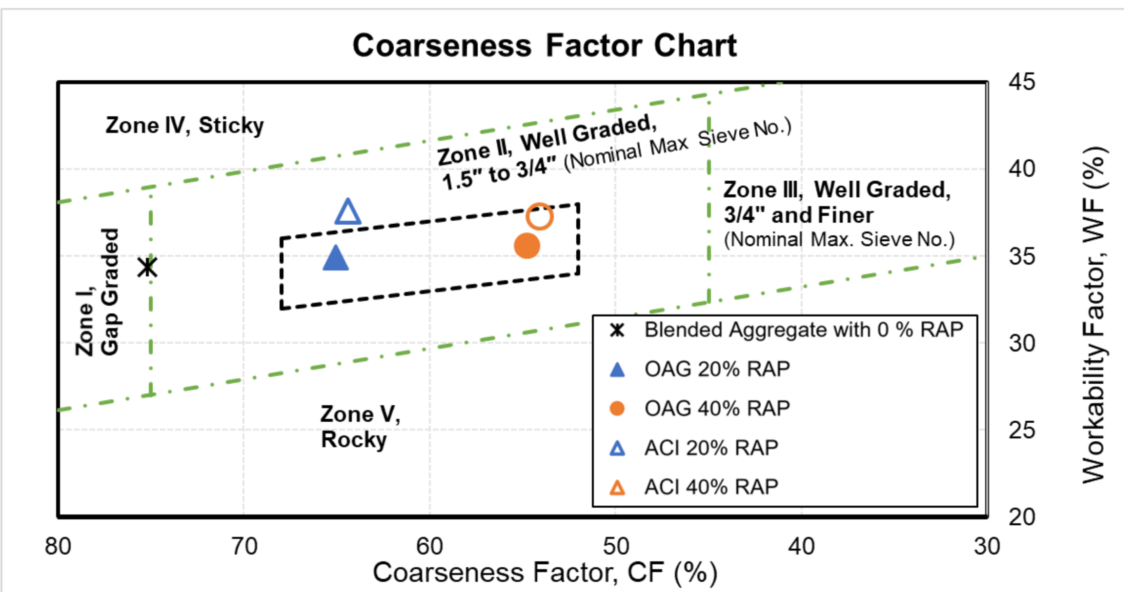


Figure 4-8. Coarseness factor chart of aggregate blends using OAG versus ACI procedure

4.4 Summary of Findings

This chapter presents an Optimized Aggregate Gradation (OAG) for proportioning aggregates to achieve a well-graded aggregate blend and a workable concrete mix. An Excel spreadsheet software, named OAG Tool, was developed to facilitate the use of this procedure. It was also demonstrated that the OAG procedure is superior to the ACI procedure in achieving a well-graded aggregate blend and a workable mix.

The OAG procedure was used to proportion the aggregates used in the concrete mixes containing RAP in this study. The control mix containing no RAP had a gap-graded aggregate which lacked intermediate-size particles. When 20% or 40% RAP materials were incorporated using the OAG procedure, the aggregate blend became significantly more well-graded and the concrete became more workable according to the prediction from the coarseness factor chart.

CHAPTER 5
CONCRETE PRODUCTION AND TEST METHODS

5.1 Introduction

This chapter presents the details of the procedures for the preparation of concrete in laboratory, specimen preparation and curing. Table 5-1 shows all the standard tests performed on the fresh and hardened concrete. The details of these tests are also presented in this chapter.

Table 5-1. Standard tests on fresh and hardened concrete

Concrete Test	Standard	
Slump	ASTM C143	Standard Test Method for Slump of Hydraulic-Cement Concrete
Unit Weight	ASTM C138	Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
Air Content	ASTM C173	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
Fresh Concrete Temperature	ASTM C1064	Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete
Setting Time	ASTM C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
Bleeding	ASTM C232	Standard Test Method for Bleeding of Concrete
Compressive Strength	ASTM C39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
Young's Modulus	ASTM C469	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Poisson's Ratio	ASTM C469	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
Splitting Tensile Strength	ASTM C496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
Flexural Strength	ASTM C78	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
Drying Shrinkage	ASTM C157	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
Surface Resistance	AASHTO T358	Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration
Coefficient of Thermal Expansion	AASHTO T336	Coefficient of Thermal Expansion of Hydraulic Cement Concrete

5.2 Fabrication and Curing of Concrete Specimens

Concrete mixtures were produced at the FDOT materials concrete laboratory in Gainesville, Florida. All tests were conducted with the provided FDOT equipment. Trial batches were produced before the production batch not only to ensure the slump, air content, and workability of the concrete mixes but also to select the desirable w/c ratio to be used. Table 5-2 and Table 5-3 show the number of specimens and volume of the concrete produced per trial and production batches.

Table 5-2. Fresh and hardened concrete tests performed per trial batch of concrete

Test Name	Sample Size	Curing Age (days)	Number of Samples per Mix
Compressive Strength	4" x 8"	7 and 28	6
Modulus of Elasticity	4" x 8"	28	3
Splitting Tensile Strength	4" x 8"	28	3
Slump	–	–	–
Unit Weight of Fresh Concrete	–	–	–
Air Content	–	–	–
Mix Temperature	–	–	–

Table 5-3. Fresh and hardened concrete tests performed per production batch of concrete

Test Name	Sample Size	Curing Age (days)	Number of Samples per Mix
Compressive Strength	4" x 8"	7, 14, 28, 56, and 90	15
Modulus of Elasticity	4" x 8"	28, 56, and 90	9
Splitting Tensile Strength	4" x 8"	7, 14, 28, 56, and 90	15
Flexural Strength	4" x 4" x 14"	28 and 90	6
Drying Shrinkage	4" x 8"	1, 7, 14, 28, 56 and 90	3
Coefficient of Thermal Expansion	4" x 4" x 14"	28 and 90	6
Surface Resistance	4" x 8"	28, 56, and 90	3
Slump	–	–	–
Unit Weight of Fresh Concrete	–	–	–
Air Content	–	–	–
Mix Temperature	–	–	–
Bleeding	–	–	–
Setting Time	–	–	–

5.2.1 Concrete Preparation

The following steps were followed to produce concrete in the laboratory:

- Fill the cloth bags with coarse and fine aggregates required for mix.
- Dry the fine aggregate for at least 24 hours in the oven at 230°F, and let it cool for another 24 hours inside the lab.
- Soak the coarse aggregate for 48 hours, as shown in Figure 5-1 and let it sit outside the tank for 1 hour and 30 minutes before weighing.
- The stockpile of RAP was covered with plastic sheets in order to keep its gradation from changing due to rain as shown in Figure 5-2. Store all the RAP material inside the lab in cloth bags as shown in Figure 5-3 and weigh it as-is for mixing.
- Use the weighing scale to weigh all the materials to be used in concrete production for mixing as shown in Figure 5-4.
- Place all the aggregate in the drum mixer as shown in Figure 5-5.
- Mix it for 3 minutes with one third of the water added to break loose the RAP pieces which may be stuck together.
- Place cementitious material into the mixer and add the remaining mixing water with the water-reducing admixture mix it for 3 minutes, followed by a 2-minute rest, followed by 3-minute mixing as shown in Figure 5-6.
- Perform fresh concrete property tests to obtain the slump and air content as shown in Figure 5-7.
- If workability is not achieved, add more water-reducing admixture to the mix until the target slump between 1 and 3 in. is reached.

Figure 5-1. Pre-soaked coarse aggregate

Figure 5-2. Stockpile of RAP covered by plastic sheets

Figure 5-3. Bags of RAP kept in the laboratory

Figure 5-4. Weighted materials in buckets to be used for concrete production

Figure 5-5. Mixing aggregates for 3 minutes to separate the RAP pieces

Figure 5-6. Finished concrete mixture incorporating RAP

Figure 5-7. Testing of fresh concrete

5.2.2 Specimen Preparation

After the concrete was mixed, a portion of the fresh concrete was immediately used to perform tests to determine fresh concrete properties. The remaining concrete was used to fabricate different concrete specimens as follows:

- Cylinders, beams, and prisms were casted.
- Molds were filled with concrete in three layers and each layer was vibrated for almost 45 seconds. If the concrete is not workable, vibrate it for some additional time in order to ensure proper consolidation.
- A vibrating table was used to consolidate all the specimens.
- The concrete specimens were covered with polyethylene sheets to prevent loss of moisture as shown in Figure 5-8.
- Specimens were removed from the molds after one day and placed in a moist curing room as shown in Figure 5-9.
- Figure 5-10 shows the surface of the hardened concrete mixtures containing different percentages of RAP.

(a)

(b)

Figure 5-8. Fabricated specimens: a) cylinder samples and b) beam and prism samples

Figure 5-9. Samples in the moist room during curing

Figure 5-10. Hardened surface of concrete containing RAP

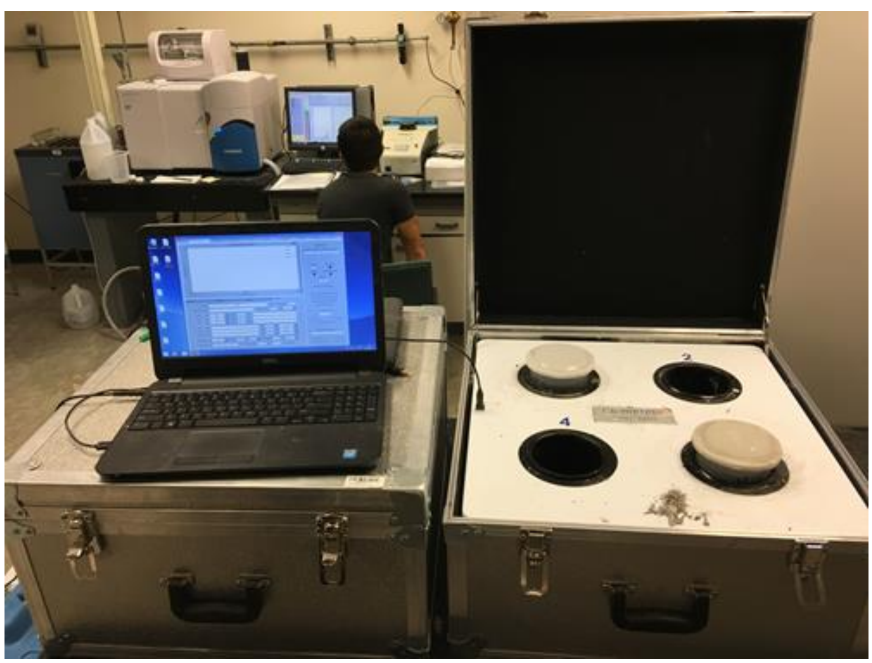
5.3 Tests on Fresh Concrete

Slump test was immediately performed after the concrete was produced in order to ensure the workability of the mix. If the right workability was not achieved, then a water-reducing admixture was added to make the concrete more workable. When the target slump was achieved, the remaining tests on the fresh concrete were performed in accordance to the ASTM standards as described below. The results of the fresh concrete tests are discussed in chapter 6.

The following fresh concrete tests were performed:

- Slump: The slump test was performed in accordance with ASTM C143 standard. The slump value was used to evaluate the consistency of fresh concrete.
- Unit weight test: This test was used to verify the density of concrete mixture for quality control in accordance with the ASTM C138 standard.
- Air content test: The volumetric method was used to determine the air content in accordance with ASTM C173 standard.
- Temperature test: This test was used to ensure the temperature of fresh concrete was within the normal range, and that there was no unexpected condition in the fresh concrete. Temperature of the fresh concrete was determined in accordance with ASTM C1064 standard.
- Bleeding test: This test was used to measure the relative quantity of mixing water that will bleed on the surface of fresh concrete mixture. Amount of bleeding water was determined in accordance with ASTM C232/C232M standard.
- Setting Time test: The initial and final setting times of fresh concrete were determined by penetration resistance test in accordance with ASTM C403/C403M as shown in Figure 5-11(a). However, the use of a water-reducing admixture increased the setting time of mortar sample. It is impossible to observe the setting time during the facility operation hours. Instead, semi-adiabatic calorimetry testing as shown in Figure 5-11(b) was utilized to measure the setting time by inferencing from the plot of heat of hydration.

(a)



(b)

Figure 5-11. Measuring the setting time: a) penetration resistance test and b) semi-adiabatic calorimetry

5.4 Tests on Hardened concrete

5.4.1 Compressive Strength Test

The compressive strength test was performed on 4” x 8” concrete cylinder specimens in accordance with ASTM C39 standard test method (Figure 5-13). Three replicate specimens were tested at each of the different curing times of 7 and 28 days for the trial mixes, and 7, 14, 28, 56, and 90 days for the production mixes. Prior to the test, both the ends of the specimen were ground in order to ensure uniform load during testing as shown in Figure 5-12. The load was applied continuously without stopping or shocking at the stress rate of 35 ± 7 psi/s. Since the ends of the specimen had been ground, no capping compound or rubber pads were applied.

The compressive strength of the specimen is calculated by dividing the maximum load carried by the specimen during the test by the average cross-sectional area determined as shown in the following equation.

$$\sigma = P/A \tag{5-1}$$

Where,

σ = ultimate compressive strength of cylinder

P = ultimate compressive axial load applied to cylinder

A = cross-sectional area of the cylinder

There are five types of fracture in concrete cylinder according to the ASTM standard. These fractures are cone fracture, cone and split fracture, cone and shear fracture, shear fracture, and columnar fracture. Majority of the specimens encountered shear fracture in this study.

Figure 5-12. Grinding both ends of cylinder samples

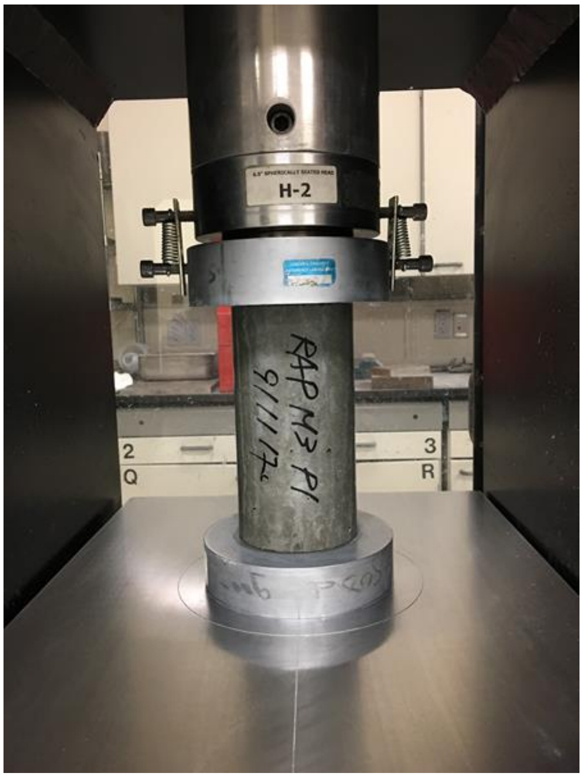


Figure 5-13. Compressive strength test equipment

5.4.2 Young's Modulus and Poisson's Ratio Test

The Young's modulus or modulus of elasticity and Poisson's ratio test was performed on 4" x 8" concrete cylinder specimens in accordance with ASTM C469 standard test method as shown in Figure 5-14. Three replicate specimens were tested at each of the different curing times of 28, 56, and 90 days. Compressive load was applied to the concrete cylinder in the longitudinal direction. The test was carried out on a compressive testing machine which had connections to the strain gauges along with the longitudinal and transverse directions. Prior to the Young's modulus test, the compressive strength test was performed on three specimens in accordance with ASTM C39 standard. The 40% of the ultimate compressive strength was determined from three samples and averaged. Then 40% of the average ultimate compressive strength was used to perform the elastic modulus test. For each specimen four repetitions were performed and the average of the last three was recorded as the elastic modulus of that specimen. The equation used to measure the elastic modulus is as follows:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{5-2}$$

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.000050} \tag{5-3}$$

Where,

E = chord modulus of elasticity

σ_1 = stress corresponding to a longitudinal strain of 50 millionths

σ_2 = stress corresponding to 40% of ultimate load

ε_1 = 50 millionths

ε_2 = longitudinal strain generated by stress σ_2

Poisson's ratio was measured using the horizontal gauge. The Poisson's ratio was calculated using the following equation.

$$\mu = \frac{\varepsilon t_2 - \varepsilon t_1}{\varepsilon_2 - 0.000050} \tag{5-4}$$

Where,

μ = Poisson's ratio

εt_1 = transverse strain at specimen mid height due to stress of σ_1

εt_2 = transverse strain at specimen mid height due to stress of σ_2

ε_1 = 50 millionths

ε_2 = longitudinal strain due to the stress of σ_2

Young's modulus and Poisson's ratio test were non-destructive with maximum applied load of 40% of the average ultimate compressive strength.

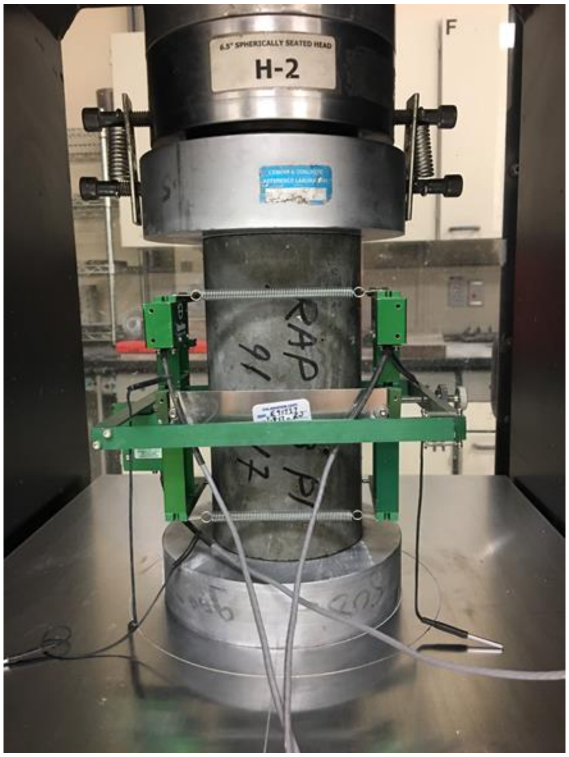


Figure 5-14. Modulus of elasticity and Poisson's ratio test equipment

5.4.3 Splitting Tensile Strength Test

The splitting tensile strength test was performed on 4” x 8” concrete cylinder specimens in accordance with ASTM C496 standard test method as shown in Figure 5-15. Three replicate specimens were tested at each of the different curing times of 7, 14, 28, 56, and 90 days. The specimens were marked along the center line using a permanent marker prior to the test. The specimen was placed in a jig which helps it to be clamped and aligned properly during the test. Load is applied to the specimen through thin strips of plywood placed on the top and bottom sides of the specimen. The load is increased until failure occurs by indirect tension in the form of splitting along vertical diameter as shown in Figure 5-16. The splitting tensile strength is calculated using the flowing equation.

$$T_i = \frac{2P_i}{\pi LD} \tag{5-5}$$

Where,

Ti = splitting tensile strength of cylinder

Pi = maximum applied load to break the cylinder

L = length of cylinder

D = diameter of cylinder

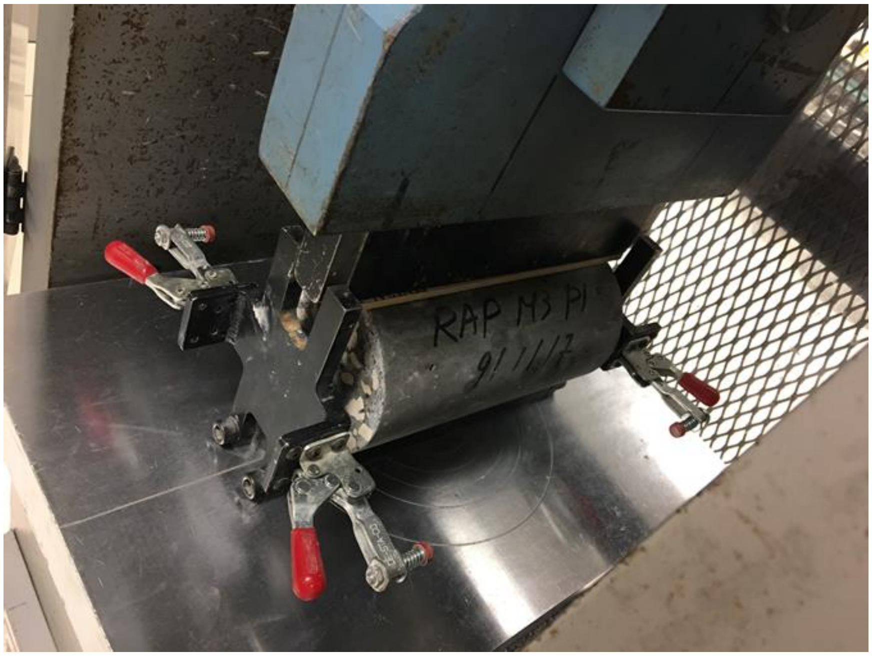


Figure 5-15. Splitting tensile strength test equipment

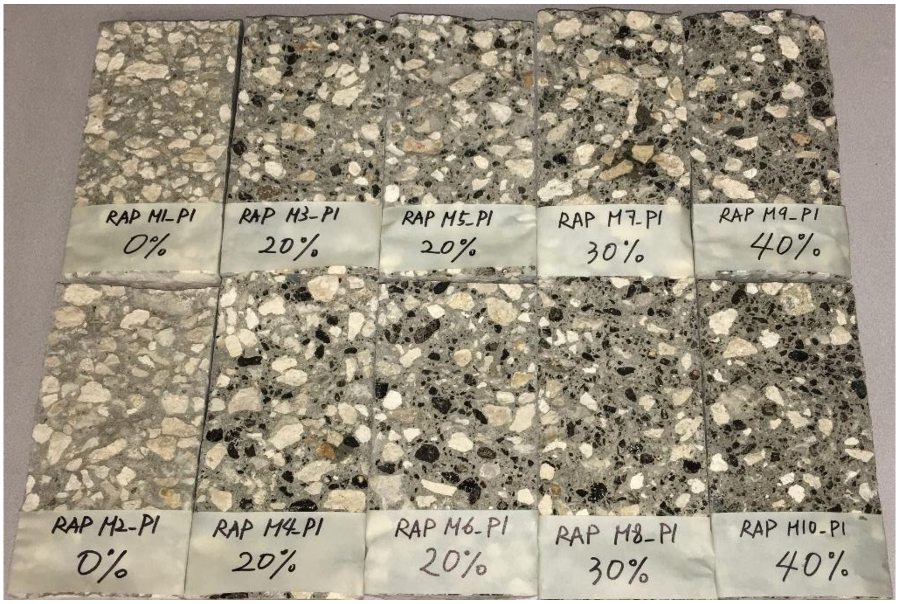


Figure 5-16. Concrete specimens after splitting tensile strength test

5.4.4 Flexural Strength Test.

The flexural strength test was performed on 4” x 4” x 14” concrete beam specimens in accordance with the ASTM C78 standard test method. Three replicate specimens were tested at each of the different curing times of 28 and 90 days. Before testing, the loading surface and the edges of the beams were ground evenly by using a grinding stone. The grinding ensured that the applied load was uniform. The flexural strength was determined according to the type of failure or fracture in the beam.

If the fracture initiates in the tension surface within the middle third of the span length, calculate the modulus of rupture using the following equation.

$$R = \frac{PL}{bd^2} \tag{5-6}$$

Where,

R = modulus of rupture of the specimen

P = maximum applied load on the specimen as indicated by the machine

L = span length

b = average depth of the specimen measured near the fracture

d = average depth of the specimen measured near the fracture

If the fracture occurs in the tension surface outside of the middle third of the span length by not more than 5% of the span length, calculate the modulus of rupture as follows:

$$R = \frac{3Pa}{bd^2} \tag{5-7}$$

Where,

a = average distance between line of fracture and the nearest support measured on the tension surface of the beam

If the fracture occurs in the tension surface outside of the middle third of the span length by more than 5% of the span length, discard the results of the tests.

The following steps were followed to determine the flexural strength test with beam samples:

- The test was run using a Tinius Olsen testing machine as shown in Figure 5-17.
- The tension surface which is the bottom side of the beam was smoothened with sand paper and cleaned with acetone.
- Mark the center point, on third point and support point of the beam with a permanent marker.
- Place the beams properly centered on the loading frame such that the one-third mark accurately aligns with the loading platens.
- Run the testing machine at a rate of 13.33 lbs/s, while acquiring both voltage data and the load cell data.
- Load the beam to failure.
- Figure 5-18 shows the fracture surfaces of beams containing RAP.

Figure 5-17. Flexural strength test set-up

Figure 5-18. Concrete specimens tested in flexural strength

5.4.5 Drying Shrinkage Test

Drying shrinkage test was performed on 3" x 3" x 11.25" concrete prism specimens in accordance with ASTM C157 standard test method. The specimens were removed from the molds after 24 hours of curing in the mold and then an initial reading was immediately taken as shown in Figure 5-19. Three specimens were placed in the moisture room up to 28 days, then allowed to dry at ambient condition in the laboratory during the rest of days. Length measurement on the specimen was taken at 1, 7, 14, 28, 56, and 90 days of curing time. The length change of a specimen at any age after the initial comparator reading was calculated as follows:

$$\Delta L_x = \frac{InitialCRD - FinalCRD}{G} \tag{5-8}$$

Where,

ΔL_x = length change of specimen at any age

CRD = comparator reading of between the specimen and the bar

G = gauge length

Figure 5-19. Drying shrinkage test set-up

5.4.6 Coefficient of Thermal Expansion Test

The coefficient of thermal expansion was performed on 4" x 8" concrete cylinder specimens in accordance with AASHTO TP 60 (2000) standard test method. Three replicate specimens were tested at each of the different curing times of 28 and 90 days. This test measures the coefficient of thermal expansion of concrete specimen, maintained in a saturated condition, by measuring the length change of the specimen due to specified temperature changes. The measured length change is corrected for any change in length of the measuring apparatus, and the coefficient of thermal expansion is then calculated by dividing the corrected length change by the temperature change and the specimen length. The coefficient of thermal expansion of one expansion or contraction test segment of a concrete specimen is calculated as follows:

$$CTE = \left(\frac{\Delta L_a}{L_o}\right) \times \Delta T \tag{5-9}$$

Where,
CTE = coefficient of thermal expansion
ΔL_a = actual length change of specimen during temperature change
L_o = measured length of specimen at room temperature
ΔT = measured temperature change

$$\Delta L_a = \Delta L_m + \Delta L_f \tag{5-10}$$

Where,
ΔL_m = measured length change of specimen during temp. change
ΔL_f = length change of the measuring apparatus during temp. change

$$\Delta L_f = C_f \times L_o \times \Delta T \tag{5-11}$$

Where,
C_f = correction factor accounting for the change in length of the measurement apparatus with temperature

The CTE is determined from the average of the CTE value in expansion and the CTE value in contraction as follows:

$$CTE = \frac{CTEexpansion + CTEcontraction}{2} \tag{5-12}$$

The cylinders were sawed and ground to the length of 7.0 ± 0.1 in., and then lengths were measured to the nearest 0.004 in. After measuring the length, specimens were submersed in the controlled temperature bath. The lower end of the specimen was firmly seated against the support button, and the LVDT tip was seated against the upper end of the specimen. The initial temperature of the bath was set to 50°F ± 1.8°F. After reaching the temperature, the bath was allowed to remain at this temperature until thermal equilibrium of the specimen had been reached, as measured by the LVDT to the nearest 0.00001 in. Then temperature of the bath was changed to 122°F ± 1.8°F to get the second reading of the LVDT. The temperature was again changed to 50°F ± 1.8°F to get the final reading of the LVDT. The average value from the three specimens was used to measure the coefficient of the thermal expansion of the concrete mix. The test set-up for the coefficient of thermal expansion test is shown in Figure 5-20.

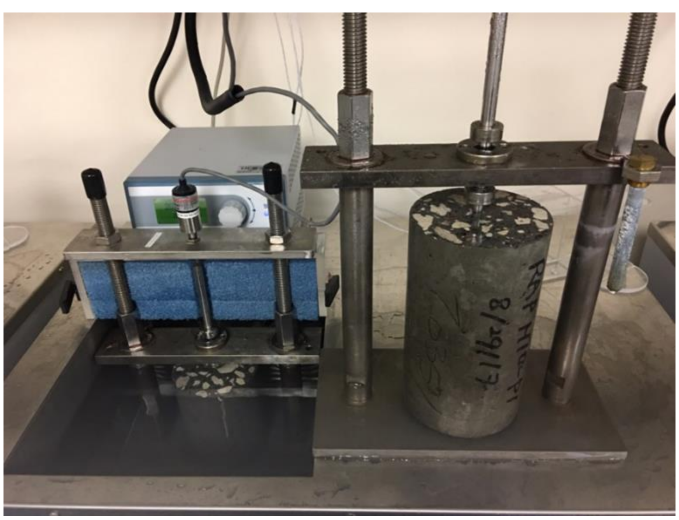


Figure 5-20. Coefficient of thermal expansion test

5.4.7 Surface Resistivity Test

The surface resistivity (SR) test was run on the hardened concrete specimens in accordance with AASHTO T358. The measurement of SR was carried out using the Resipod testing equipment manufactured by Proceq that operates with the Wenner four-electrode probe as shown in Figure 5-21 and 5-22. When the four equally spaced electrodes contact with the surface of concrete sample, an alternating current is applied to the outmost electrodes and the middle of two electrodes is used to measure the resistance of concrete sample. The resistivity of concrete sample is computed using the following equation.

$$\rho = 2\pi aV/I \tag{5-13}$$

Where,

ρ = Resistivity

a = distance between electrodes

V = voltage

I = electrical intensity

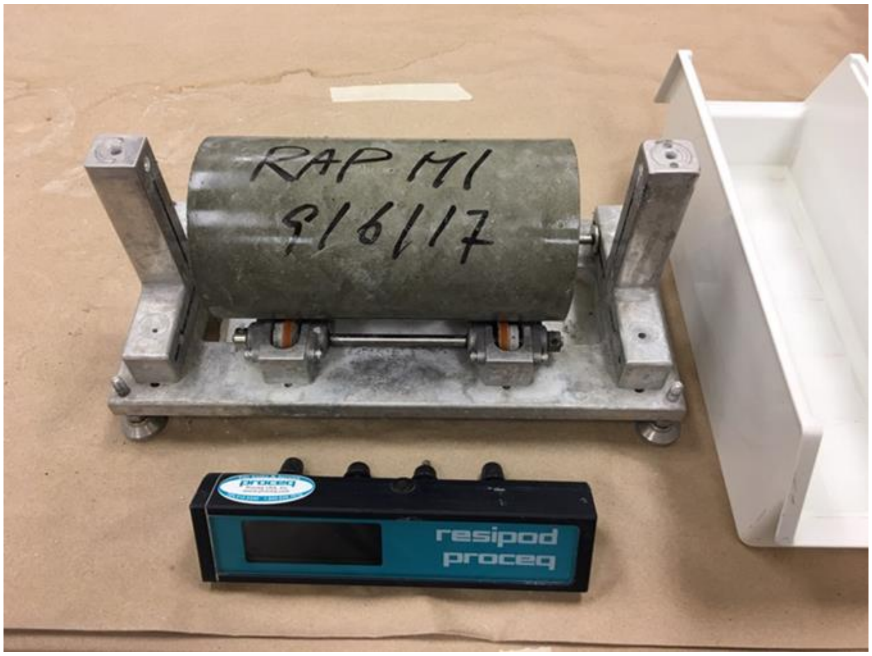


Figure 5-21. Surface resistivity test apparatus

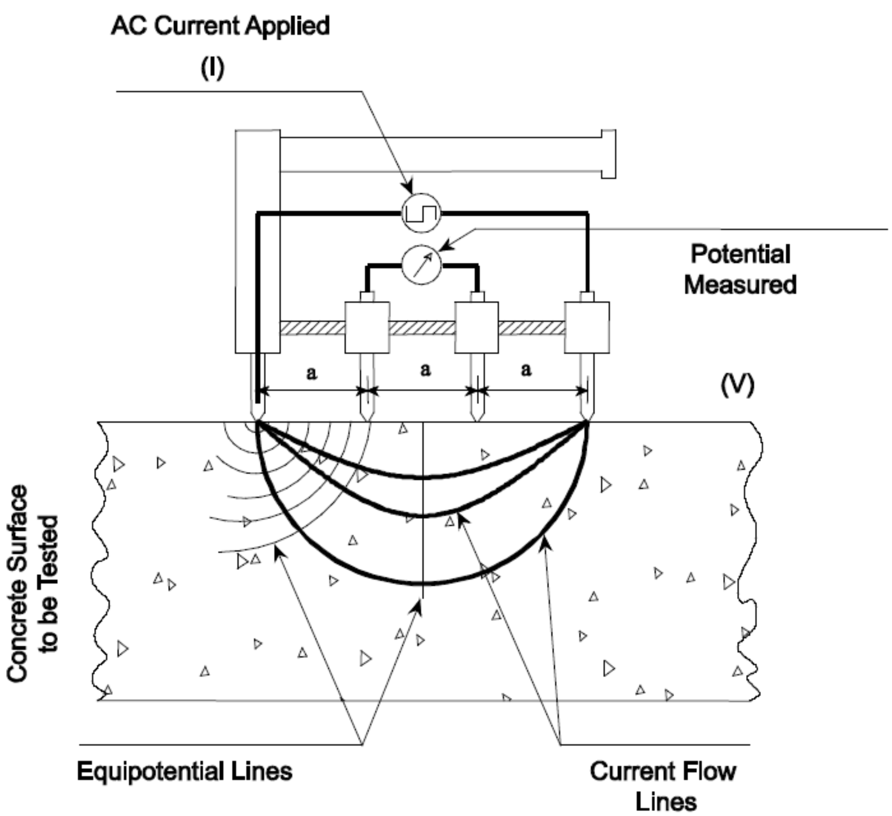


Figure 5-22. Four-point Wenner array probe set-up

CHAPTER 6
CONCRETE TEST RESULTS AND ANALYSIS

6.1 Results of Fresh Concrete Properties

This results of fresh concrete properties evaluated for all the concrete mixtures are shown in Table 6-1. All mixture used the needed amounts of water-reducing admixture to achieve the target slump between 1 to 3 in. All concrete mixtures exhibit slump between 1 to 2 in. for RAP mixture and showed good workability without the segregation problem. The needed dosage of water-reducing admixture increased as the percentage of RAP replacement increased in the mix. This means that the use of RAP decreases the slump of the fresh concrete. The percentage air of the mixture did not exhibit a relationship between the percentage of RAP and air content. The percentage air was within the targeted range of 2% to 5%. The unit weight of the concrete mixtures decreased as the percentage of RAP replacement increased in the Production mixes. The unit weight of the concrete mixtures without RAP was 143 lb/ft^3 and the unit weight was between 137 lb/ft^3 and 142 lb/ft^3 for concrete mixtures with 20%, 30%, and 40% RAP. The temperature of concrete for all the mixtures was between 68°F and 72°F. The mixture with RAP produced relatively lower amount of bleeding water as compared with the control mixes without RAP.

Table 6-1. Fresh concrete properties of the mixtures evaluated

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Slump (in.)	Unit Weight (lb/ft^3)	Air Content (%)	Temp. (°F)	Bleeding (oz)	Initial Setting Time (hr)	Final Setting Time (hr)
Trial Mixtures with w/c Ratios of 0.50 through 0.43										
M01-T	0	20*	0.50	1.00	141.8	3.00	68	–	–	–
M02-T	20	20*	0.50	1.00	143.6	2.75	71	–	–	–
M03-T	20	40*	0.50	1.00	140.7	3.25	70	–	–	–
M04-T	0	20#	0.50	1.50	143.3	3.00	71	–	–	–
M05-T	20	20#	0.50	1.25	142.1	2.50	71	–	–	–
M06-T	20	40#	0.50	1.00	139.7	2.50	71	–	–	–
M07-T	0	20*	0.47	1.25	141.9	2.25	71	–	–	–
M08-T	20	20*	0.47	2.00	141.4	2.50	71	–	–	–
M09-T	20	40*	0.47	1.00	140.0	3.25	70	–	–	–
M10-T	0	20#	0.47	1.25	142.6	1.75	71	–	–	–
M11-T	20	20#	0.47	1.25	142.1	2.25	72	–	–	–
M12-T	20	40#	0.47	1.25	140.7	2.75	71	–	–	–
M13-T	0	20*	0.45	1.25	141.4	2.50	70	–	–	–
M14-T	20	20*	0.45	1.75	141.5	2.25	71	–	–	–
M15-T	20	40*	0.45	1.25	140.8	3.00	70	–	–	–
M16-T	0	20#	0.45	1.00	142.4	2.50	72	–	–	–
M17-T	20	20#	0.45	1.50	142.7	2.50	71	–	–	–
M18-T	20	40#	0.45	1.75	141.7	2.75	70	–	–	–
M19-T	0	20*	0.43	1.25	143.9	1.75	71	–	–	–
M20-T	20	20*	0.43	1.00	142.2	2.50	72	–	–	–
M21-T	20	40*	0.43	1.25	139.4	3.50	72	–	–	–
M22-T	0	20#	0.43	1.00	143.7	3.25	69	–	–	–
M23-T	20	20#	0.43	1.00	140.9	3.00	70	–	–	–
M24-T	20	40#	0.43	1.00	139.5	3.75	70	–	–	–
Production Mixtures with the Fixed w/c Ratio of 0.50										
M01-P	0	0	0.50	2.00	142.5	3.25	71	2.3	6	14
M02-P	20	0	0.50	3.50	142.5	2.00	71	3.0	7	16
M03-P	0	20*	0.50	1.75	140.6	3.50	71	1.0	6	13
M04-P	0	20#	0.50	1.00	140.0	4.00	71	1.1	7	15
M05-P	20	20*	0.50	1.50	140.3	3.25	72	1.2	7	15
M06-P	20	20#	0.50	1.50	141.8	2.75	71	1.4	8	17
M07-P	20	30*	0.50	1.25	139.2	4.00	71	1.1	8	16
M08-P	20	30#	0.50	1.00	140.3	3.25	70	1.2	8	17
M09-P	20	40*	0.50	1.50	139.4	4.00	72	1.2	8	15
M10-P	20	40#	0.50	1.25	136.6	3.50	70	1.0	8	15

Note: *RAP source is the plant number of A0691
#RAP source is the plant number of A0750

The term of setting is used to describe the solidification of the fresh concrete mix. The initial setting time is the beginning of solidification and the final setting time is when the fresh concrete solidifies completely. In general, the initial and final setting times of fresh concrete are determined by the penetration resistance test in accordance with ASTM C403/C403M (2016). However, the use of a water-reducing admixture increased the setting time of the mortar sample. It was not possible to observe the setting times during the facility operation hours.

Instead, the total amount of heat of hydration was used for determining the initial and final setting times since the reaction of hydration in cement past is related to the solidifying of concrete (i.e., the heat of formation of ettringite). Therefore, in this study, semi-adiabatic calorimetry testing was utilized to measure the setting time by inferencing from the plot of heat of hydration as shown in Figure 6-1.

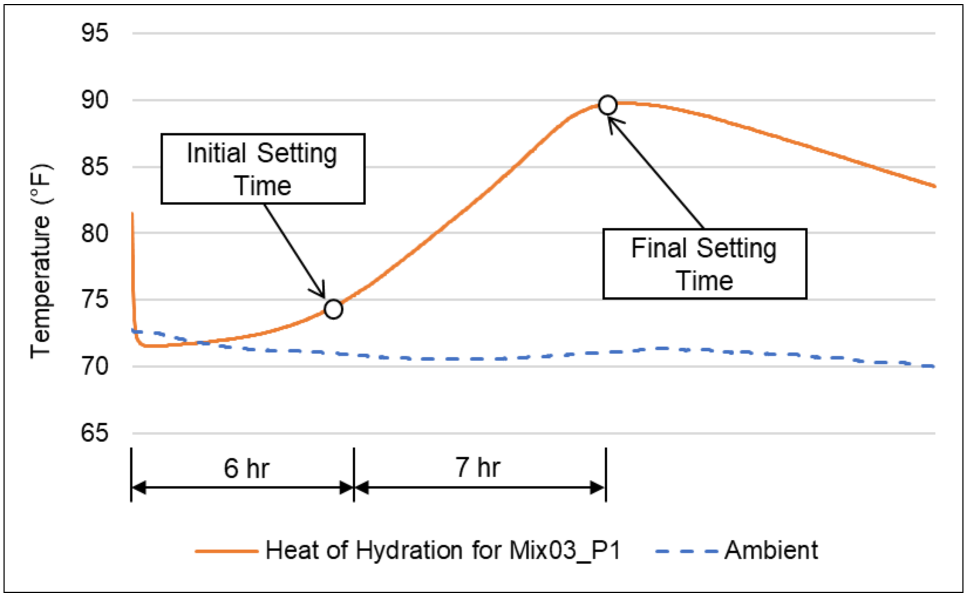


Figure 6-1. Heat of hydration of M03_P1 for measuring the initial and final setting time

6.2 Analysis of Strength Test Results

6.2.1 Compressive Strength Test Results

Early study revealed that a reduction of compressive strength in RAP concrete mixture increase as the proportion of RAP replaced virgin aggregate increase (Delwar et al., 1997; Dumitru et al., 1999; Hassan et al., 2000; Huang et al., 2005; Hossiney et al., 2010; Al-Oraimi et al., 2009). FDOT specifications for pavement concrete require a minimum compressive strength of 3,000 psi at 28 days and an over-design strength of 4,200 psi (FDOT, 2017). AASHTO recommends a minimum concrete compressive strength of 3,500 psi at 28 days (AASHTO PP 84, 2017). Table 6-2 summarizes the average compressive strength of all the concrete mixtures evaluated in this research. For all the concrete mixtures, there is a reduction in compressive strength with increase in the percentage of RAP in the concrete mixtures.

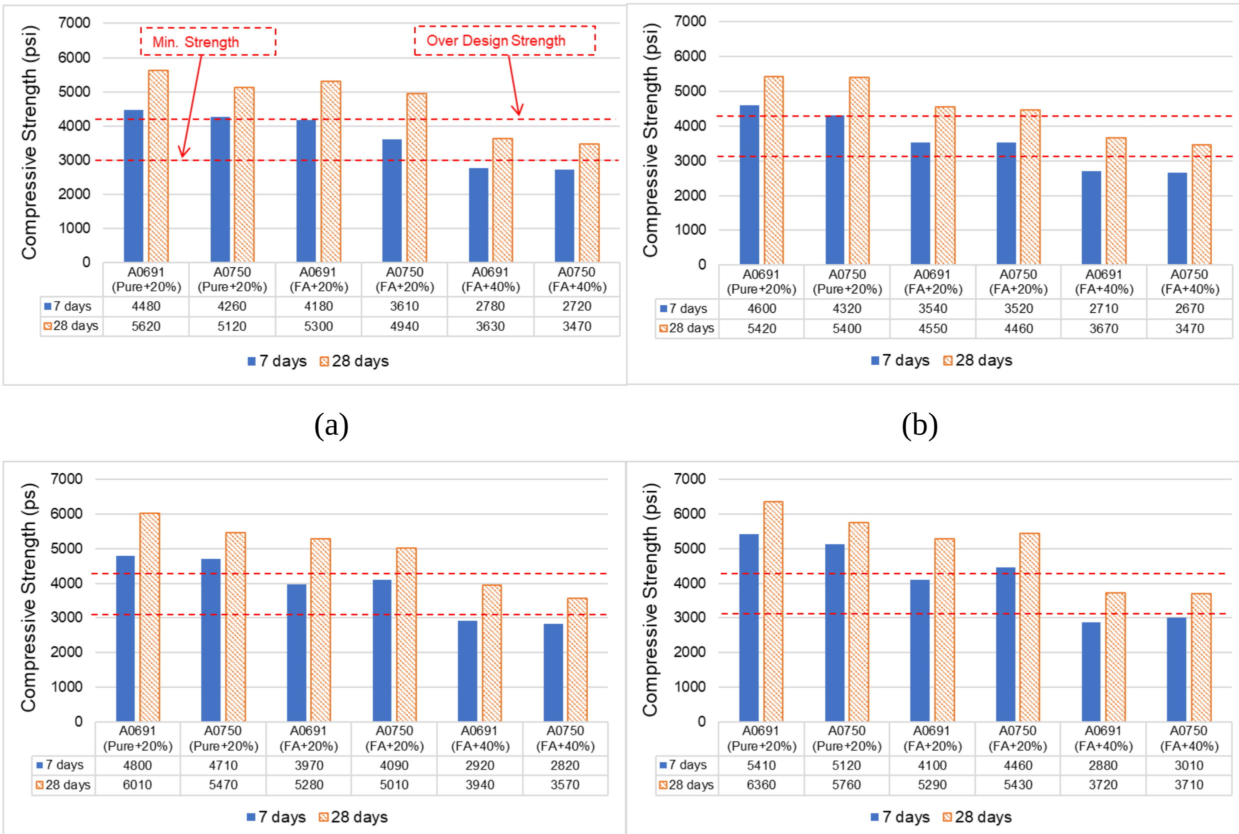
Figure 6-2 shows the average compressive strength of the trial mixes at 7 and 28 days with two different sources of RAPs. The mixtures incorporating two different RAPs produced similar compressive strength development. Figure 6-3 shows plots of 28-day compressive strength of the trial mixtures versus w/c ratio. For all mixtures with w/c ratio of 0.50, 0.47, 0.45, and 0.43, the compressive strength minimum required 28-day of 3,000 psi set by FDOT and 3,500 psi set by AASHTO are met. However, for the mix with 40% RAP regardless of w/c ratio, the 28-day compressive strength could not reach the over-design strength of 4,200 psi. With 40% RAP, using a lower w/c ratio did not help to increase its strength sufficiently.

Figure 6-4 shows the development of compressive strength with curing time. For the pure cement mixtures without RAP, the strength development was much higher than any other mixtures, especially for the 40% RAP mixtures. For the 20% fly ash mixtures without RAP, the development of strength was slower at early days. For the mix with 30% and 40% RAP, the developed strength did not reach the required over-design strength of 4,200 psi. Figure 6-5 shows the ratio of compressive strength of concrete mixtures containing RAP at different curing time, relative to the strength of the control mixtures (e.g., pure cement mixture without RAP and 20% fly ash mixture without RAP). For concrete mixtures with 40% RAP, there is almost 45% reduction in compressive strength at 28 days, when compared with the control mix. For concrete mixtures with 20% RAP, there is almost 20% reduction in compressive strength at 28 days, when compared with the control mix. There was slightly higher % reduction in compressive strength for concrete mixture with 30% and 40% RAP, and the concrete mixtures with 20% RAP showed the least reduction in compressive strength.

Table 6-2. Compressive strength of concrete mixtures evaluated

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average Compressive Strength of RAP mixtures (psi)				
				Curing Time (days)				
				7	14	28	56	90
Trial Mixtures with w/c Ratios of 0.50 through 0.43								
M01-T	0	20*	0.50	4,480	–	5,620	–	–
M02-T	20	20*	0.50	4,180	–	5,300	–	–
M03-T	20	40*	0.50	2,780	–	3,630	–	–
M04-T	0	20#	0.50	4,260	–	5,120	–	–
M05-T	20	20#	0.50	3,610	–	4,940	–	–
M06-T	20	40#	0.50	2,720	–	3,470	–	–
M07-T	0	20*	0.47	4,600	–	5,420	–	–
M08-T	20	20*	0.47	3,540	–	4,550	–	–
M09-T	20	40*	0.47	2,710	–	3,670	–	–
M10-T	0	20#	0.47	4,320	–	5,400	–	–
M11-T	20	20#	0.47	3,520	–	4,460	–	–
M12-T	20	40#	0.47	2,670	–	3,470	–	–
M13-T	0	20*	0.45	4,800	–	6,010	–	–
M14-T	20	20*	0.45	3,970	–	5,280	–	–
M15-T	20	40*	0.45	2,920	–	3,940	–	–
M16-T	0	20#	0.45	4,710	–	5,470	–	–
M17-T	20	20#	0.45	4,090	–	5,010	–	–
M18-T	20	40#	0.45	2,820	–	3,570	–	–
M19-T	0	20*	0.43	5,410	–	6,360	–	–
M20-T	20	20*	0.43	4,100	–	5,290	–	–
M21-T	20	40*	0.43	2,880	–	3,720	–	–
M22-T	0	20#	0.43	5,120	–	5,760	–	–
M23-T	20	20#	0.43	4,460	–	5,430	–	–
M24-T	20	40#	0.43	3,010	–	3,710	–	–
Production Mixtures with the Fixed w/c Ratio of 0.50								
M01-P	0	0	0.50	5,380	6,440	6,670	7,870	7,520
M02-P	20	0	0.50	4,400	5,490	5,390	6,410	6,060
M03-P	0	20*	0.50	4,480	4,860	5,250	5,470	5,650
M04-P	0	20#	0.50	4,280	4,650	4,920	5,510	5,660
M05-P	20	20*	0.50	3,420	3,810	4,440	5,040	5,350
M06-P	20	20#	0.50	3,260	3,900	4,280	5,140	5,190
M07-P	20	30*	0.50	2,920	3,290	3,720	4,240	4,440
M08-P	20	30#	0.50	2,720	3,150	3,470	3,970	4,100
M09-P	20	40*	0.50	2,520	3,060	3,240	3,820	3,910
M10-P	20	40#	0.50	2,510	2,850	3,010	3,470	3,520

Note: *RAP source is the plant number of A0691
#RAP source is the plant number of A0750



(a) (b)

(c) (d)

Figure 6-2. Compressive strength of trial mixtures containing RAP: a) w/c ratio of 0.50, b) w/c ratio of 0.47, c) w/c ratio of 0.45, and d) w/c ratio of 0.43

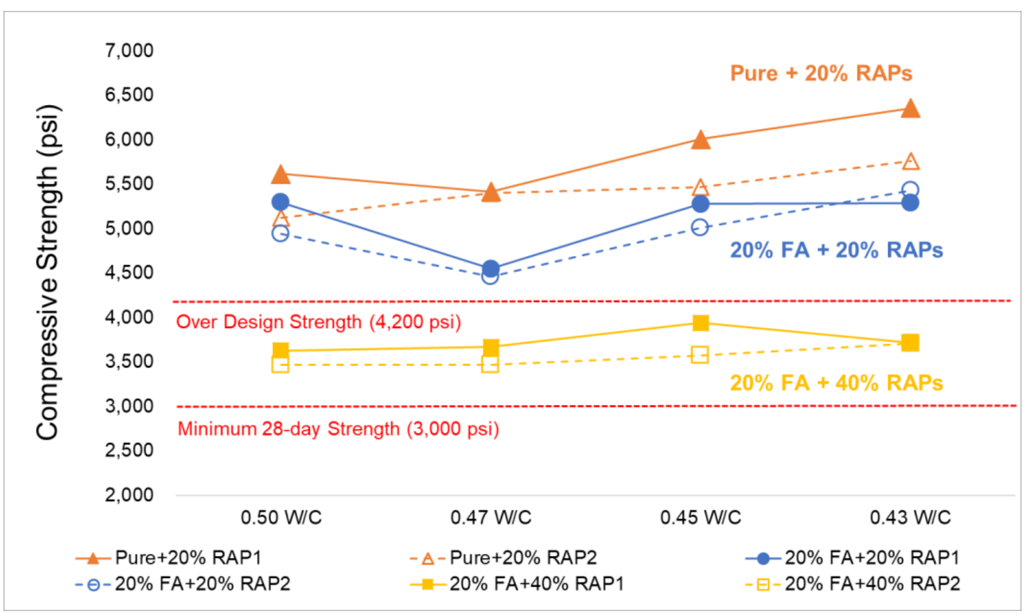


Figure 6-3. Compressive strength versus w/c of trial mixtures containing RAPs

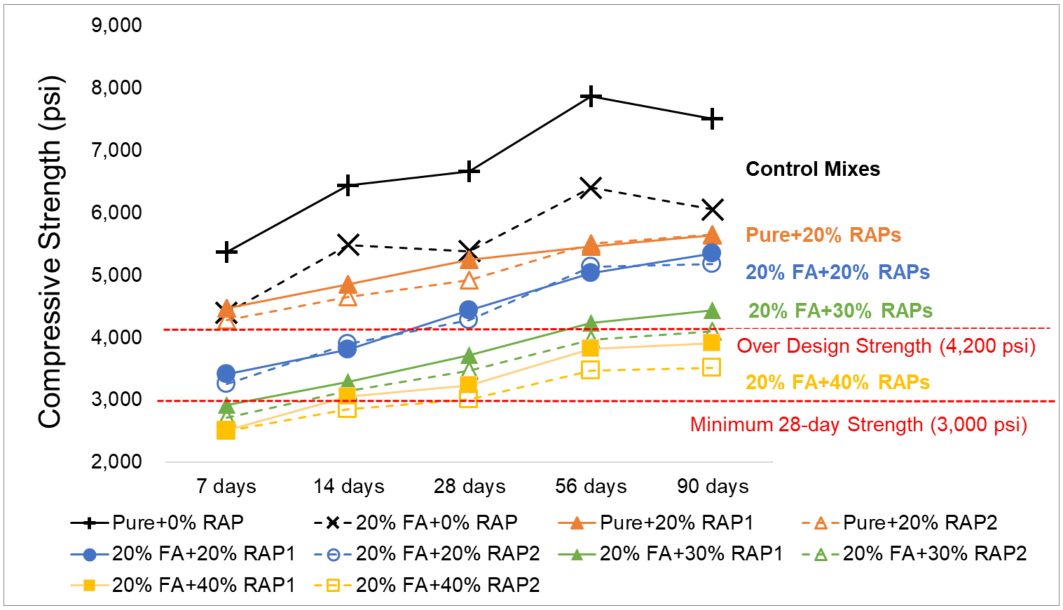


Figure 6-4. Development of compressive strength with curing time in production mixtures

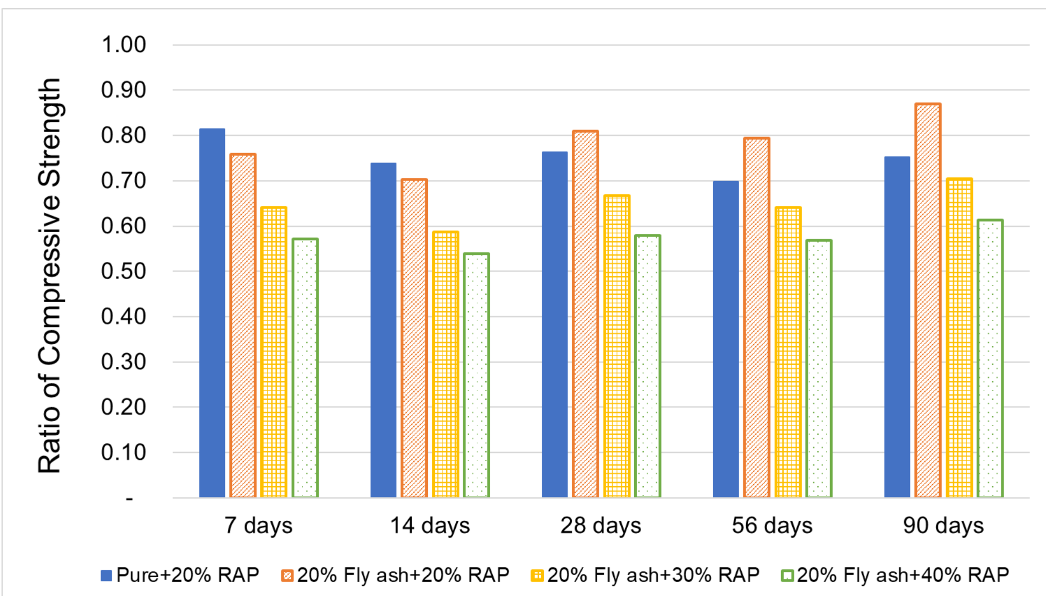


Figure 6-5. Ratios of compressive strength of RAP concrete relative to the control mix

6.2.2 Modulus of Elasticity Test Results

Early study revealed that a reduction of modulus of elasticity (MOE) in RAP concrete mixture increased as the proportion of RAP increased (Delwar et al., 1997; Dumitru et al., 1999; Huang et al., 2006; Hossiney et al., 2010). There is not any requirement of MOE provided by FDOT or AASHTO for the rigid pavement. However, the MOE plays a pivotal role in developing stresses in concrete slabs. A reduced MOE of RAP concrete mixture will result in lower stresses in the concrete slabs (Hossiney et al., 2010). Table 6-3 summarizes the average modulus of elasticity of all the concrete mixtures evaluated in this research study. For all the concrete mixtures, there is a reduction in MOE with increase in the percentage of RAP used.

Figure 6-6 shows the MOE of the trial mixtures as a function of w/c ratio at 28-day curing time. The concrete mixtures with RAP showed development in modulus of elasticity with respect to time. Figure 6-7 shows the development of MOE of production mixtures as a function of curing time. The concrete mixture without RAP indicated the highest values. The concrete mixture with 40% RAP indicated the lowest values. The results of production mixtures were very similar to the trial mixtures with respect to MOE at 28 days.

Figure 6-8 shows the ratio of modulus of elasticity of concrete mixtures containing RAP at 90 days of curing time, relative to that of the normal concrete. The reduction in modulus of elasticity for concrete mixtures with RAP was slightly lower to that of the compressive strength reductions. There was not much difference in the reduction of modulus of elasticity between different RAP types.

Table 6-3. Modulus of elasticity of concrete mixtures evaluated

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average MOE of RAP mixtures (psi) Curing Time (days) 28	56	90
Trial Mixtures with W/C Ratios of 0.50 through 0.43						
M01-T	0	20*	0.50	4,300,000	–	–
M02-T	20	20*	0.50	4,100,000	–	–
M03-T	20	40*	0.50	2,800,000	–	–
M04-T	0	20#	0.50	4,075,000	–	–
M05-T	20	20#	0.50	4,050,000	–	–
M06-T	20	40#	0.50	3,125,000	–	–
M07-T	0	20*	0.47	4,125,000	–	–
M08-T	20	20*	0.47	3,850,000	–	–
M09-T	20	40*	0.47	3,050,000	–	–
M10-T	0	20#	0.47	3,900,000	–	–
M11-T	20	20#	0.47	3,700,000	–	–
M12-T	20	40#	0.47	3,000,000	–	–
M13-T	0	20*	0.45	4,125,000	–	–
M14-T	20	20*	0.45	4,000,000	–	–
M15-T	20	40*	0.45	3,125,000	–	–
M16-T	0	20#	0.45	4,100,000	–	–
M17-T	20	20#	0.45	4,025,000	–	–
M18-T	20	40#	0.45	3,100,000	–	–
M19-T	0	20*	0.43	4,350,000	–	–
M20-T	20	20*	0.43	3,900,000	–	–
M21-T	20	40*	0.43	3,100,000	–	–
M22-T	0	20#	0.43	4,350,000	–	–
M23-T	20	20#	0.43	4,100,000	–	–
M24-T	20	40#	0.43	3,075,000	–	–
Production Mixtures with the Fixed W/C Ratio of 0.50						
M01-P	0	0	0.50	5,100,000	5,100,000	5,550,000
M02-P	20	0	0.50	4,650,000	5,200,000	5,150,000
M03-P	0	20*	0.50	4,150,000	3,950,000	4,050,000
M04-P	0	20#	0.50	4,100,000	4,200,000	4,250,000
M05-P	20	20*	0.50	4,000,000	3,950,000	4,050,000
M06-P	20	20#	0.50	3,850,000	3,700,000	4,100,000
M07-P	20	30*	0.50	3,200,000	3,400,000	3,500,000
M08-P	20	30#	0.50	3,350,000	3,250,000	3,500,000
M09-P	20	40*	0.50	3,000,000	3,200,000	3,300,000
M10-P	20	40#	0.50	2,850,000	2,900,000	3,000,000

Note: *RAP source is the plant number of A0691
#RAP source is the plant number of A0750

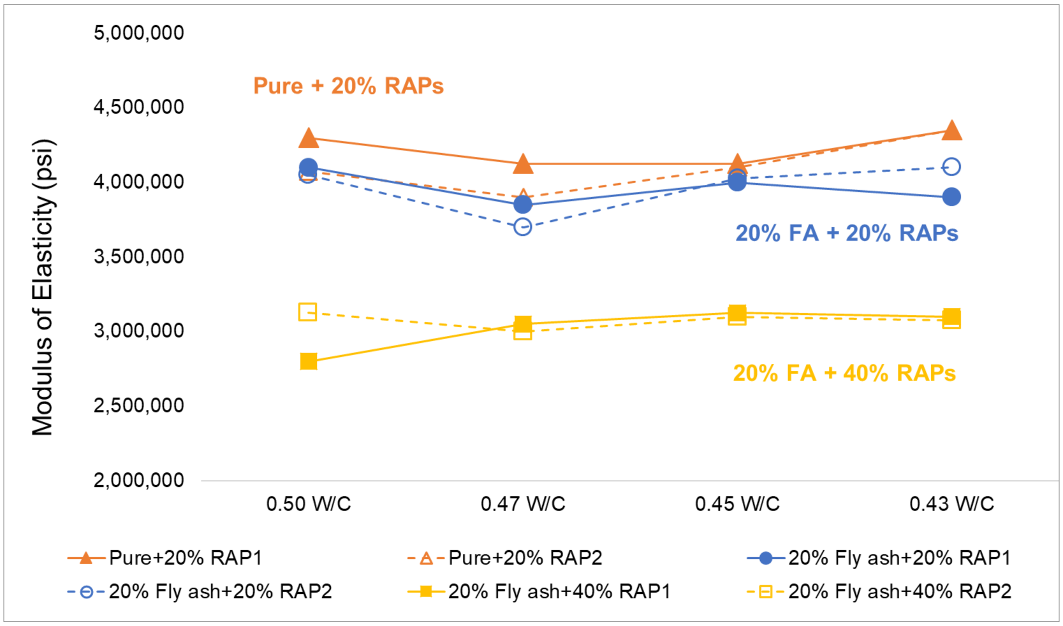


Figure 6-6. MOE versus w/c of concrete mixtures containing RAPs

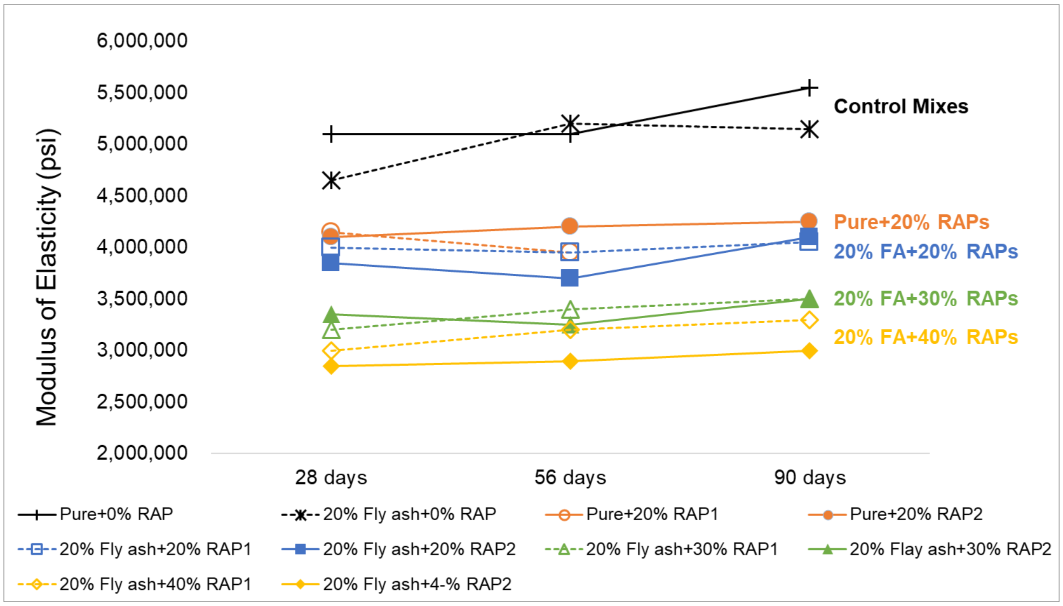


Figure 6-7. Development of modulus of elasticity at different curing times

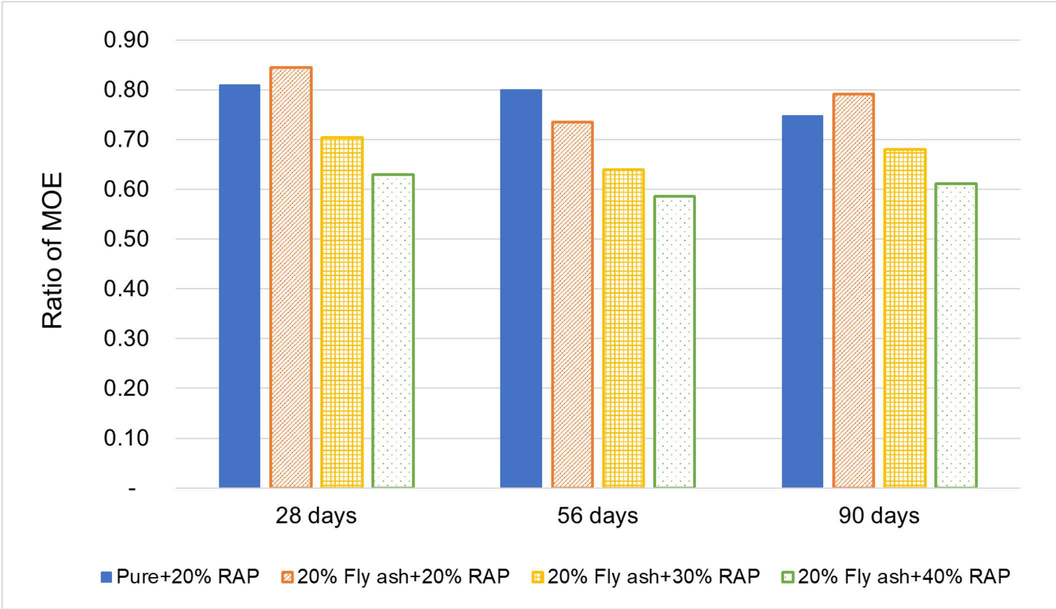


Figure 6-8. Ratios of modulus of elasticity at different curing times relative to the elastic modulus of the reference concrete

6.2.3 Poisson's Ratio Test Results

Table 6-4 summarizes the average Poisson's ratios of all the concrete mixtures evaluated in this research study. For all the concrete mixtures, the numerical value of Poisson's ratio was between 0.21 and 0.26. The concrete mixtures without RAP exhibited low values of Poisson's ratio. In general, the Poisson's ratio increased as the percentage of the RAP increased in the concrete mixtures.

Table 6-4. Poisson's ratio of concrete mixtures evaluated

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average Poisson's Ratio of RAP mixtures (psi)		
				Curing Time (days)		
				28	56	90
M01-P	0	0	0.50	0.22	0.22	0.23
M02-P	20	0	0.50	0.21	0.23	0.22
M03-P	0	20*	0.50	0.22	0.24	0.22
M04-P	0	20#	0.50	0.22	0.22	0.23
M05-P	20	20*	0.50	0.21	0.25	0.23
M06-P	20	20#	0.50	0.23	0.21	0.23
M07-P	20	30*	0.50	0.24	0.22	0.23
M08-P	20	30#	0.50	0.26	0.22	0.24
M09-P	20	40*	0.50	0.23	0.24	0.23
M10-P	20	40#	0.50	0.25	0.21	0.26

Note: *RAP source is plant number A0691
#RAP source is plant number A0750

6.2.4 Splitting Tensile Strength Test Results

Table 6-5 summarizes the average splitting tensile strengths of all the concrete mixtures evaluated in this study. Figure 6-9 presents the splitting tensile strengths of the trial mixtures as a function of w/c ratio at 28-day curing. Figure 6-10 presents the development of splitting tensile strength of the production mixes as a function of curing time. Figure 6-11 presents the ratios of splitting tensile strength relative to that of the control mix.

Table 6-5. Splitting tensile strength of concrete containing RAP

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average Splitting Tensile Strength of RAP mixtures (psi)				
				Curing Time (days)				
				7	14	28	56	90
Trial Mixtures with W/C Ratios of 0.50 through 0.43								
M01-T	0	20*	0.50	–	–	525	–	–
M02-T	20	20*	0.50	–	–	455	–	–
M03-T	20	40*	0.50	–	–	375	–	–
M04-T	0	20#	0.50	–	–	480	–	–
M05-T	20	20#	0.50	–	–	410	–	–
M06-T	20	40#	0.50	–	–	315	–	–
M07-T	0	20*	0.47	–	–	455	–	–
M08-T	20	20*	0.47	–	–	425	–	–
M09-T	20	40*	0.47	–	–	370	–	–
M10-T	0	20#	0.47	–	–	490	–	–
M11-T	20	20#	0.47	–	–	405	–	–
M12-T	20	40#	0.47	–	–	390	–	–
M13-T	0	20*	0.45	–	–	565	–	–
M14-T	20	20*	0.45	–	–	470	–	–
M15-T	20	40*	0.45	–	–	370	–	–
M16-T	0	20#	0.45	–	–	465	–	–
M17-T	20	20#	0.45	–	–	430	–	–
M18-T	20	40#	0.45	–	–	390	–	–
M19-T	0	20*	0.43	–	–	560	–	–
M20-T	20	20*	0.43	–	–	490	–	–
M21-T	20	40*	0.43	–	–	375	–	–
M22-T	0	20#	0.43	–	–	525	–	–
M23-T	20	20#	0.43	–	–	455	–	–
M24-T	20	40#	0.43	–	–	345	–	–
Production Mixtures with the Fixed W/C Ratio of 0.50								
M01-P	0	0	0.50	515	415	395	420	557
M02-P	20	0	0.50	380	400	395	395	523
M03-P	0	20*	0.50	340	460	405	385	430
M04-P	0	20#	0.50	330	475	380	405	445
M05-P	20	20*	0.50	340	385	345	365	345
M06-P	20	20#	0.50	365	415	330	355	380
M07-P	20	30*	0.50	335	365	360	350	390
M08-P	20	30#	0.50	310	345	330	310	365
M09-P	20	40*	0.50	285	335	315	300	390
M10-P	20	40#	0.50	305	315	275	305	385

Note: *RAP source is the plant number of A0691
#RAP source is the plant number of A0750

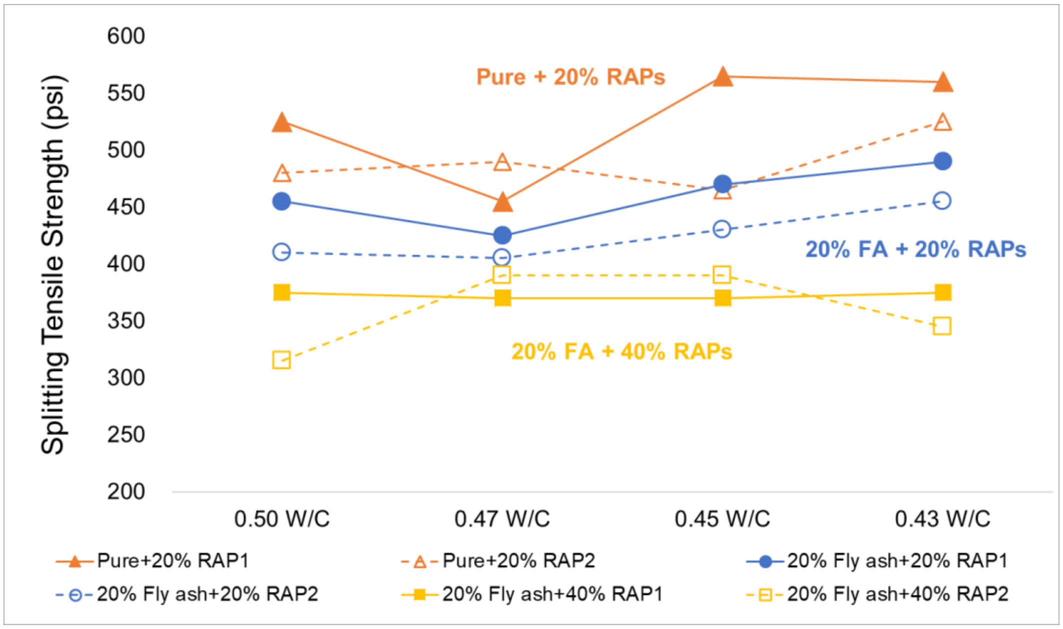


Figure 6-9. Splitting tensile strength versus w/c of trial mixtures containing RAPs

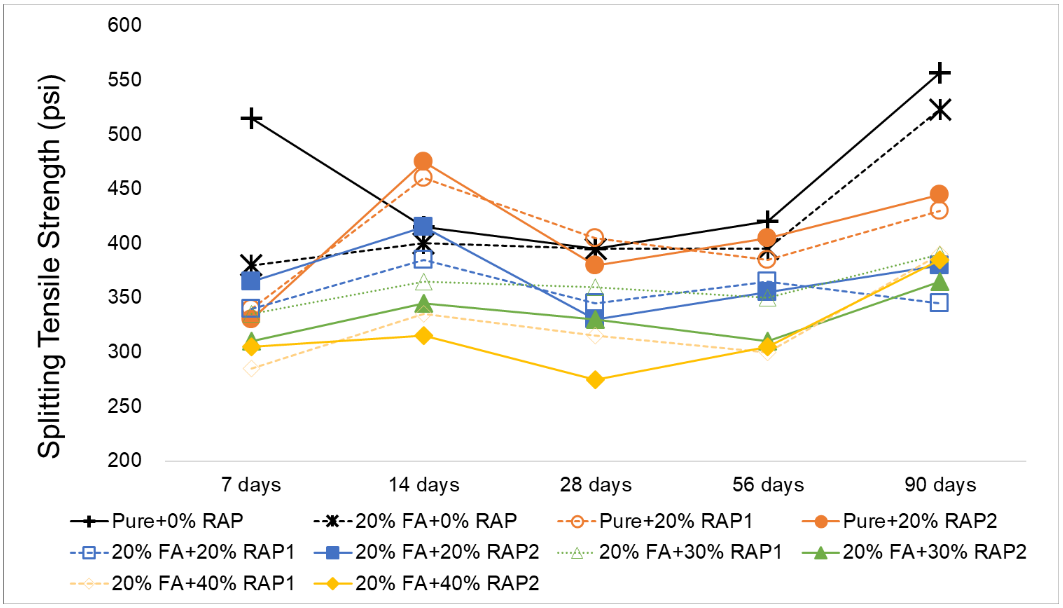


Figure 6-10. Development of splitting tensile strength in production mixtures at different curing times

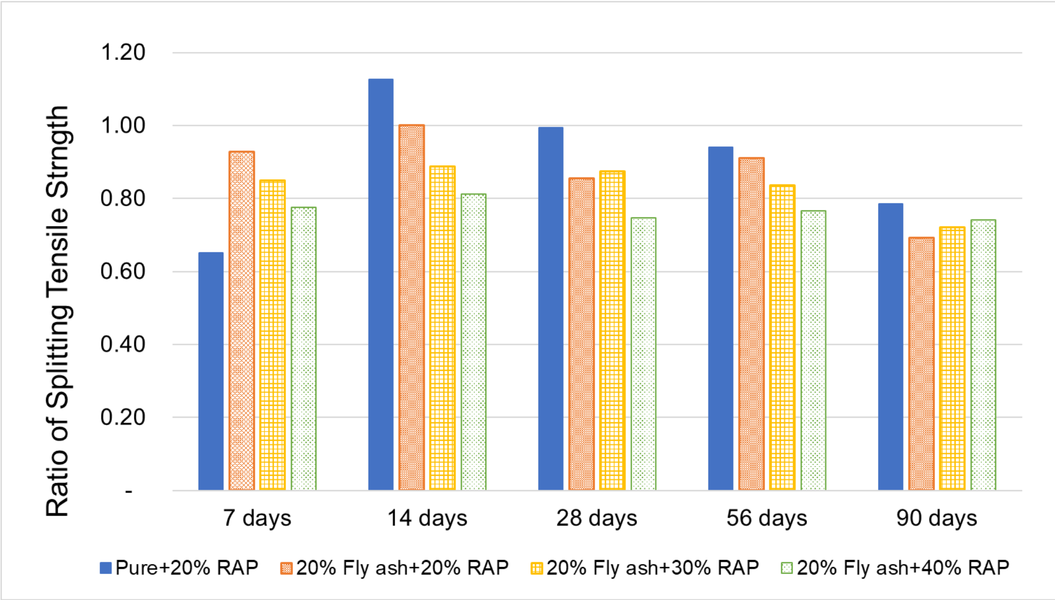


Figure 6-11. Ratios of splitting tensile strength of production mixtures relative to the control mix

6.2.5 Flexural Strength Test Results

Past study has shown that the flexural strength decreases as the proportion of RAP in the concrete mixture increases (Dumitru et al., 1999; Hassan et al., 2000; Katsakou et al., 2007; Hossiney et al., 2010; Al-Oraimi et al., 2009). Table 6-6 summarizes the average flexural strength of all the concrete mixtures evaluated in this research study. For all the concrete mixtures, there is a reduction in flexural strength with increase in the percentage of RAP in the mix. Figure 6-12 presents the flexural strength of the production mixes at different curing times.

Figure 6-13 shows the ratio of flexural strength of concrete mixtures containing RAP, relative to the flexural strength of the normal concrete. The maximum reduction in flexural strength was 33%, 22%, and 15% for the concrete mixtures with 40%, 30% and 20% RAP, respectively.

Table 6-6. Flexural strength of concrete mixtures evaluated

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average Flexural Strength of RAP mixtures (psi)	
				Curing Time (days)	
				28	90
M01-P	0	0	0.50	760	821
M02-P	20	0	0.50	727	796
M03-P	0	20*	0.50	680	708
M04-P	0	20#	0.50	650	682
M05-P	20	20*	0.50	600	720
M06-P	20	20#	0.50	615	678
M07-P	20	30*	0.50	568	655
M08-P	20	30#	0.50	560	588
M09-P	20	40*	0.50	535	598
M10-P	20	40#	0.50	500	565

Note: *RAP source is plant number A0691
#RAP source is plant number A0750

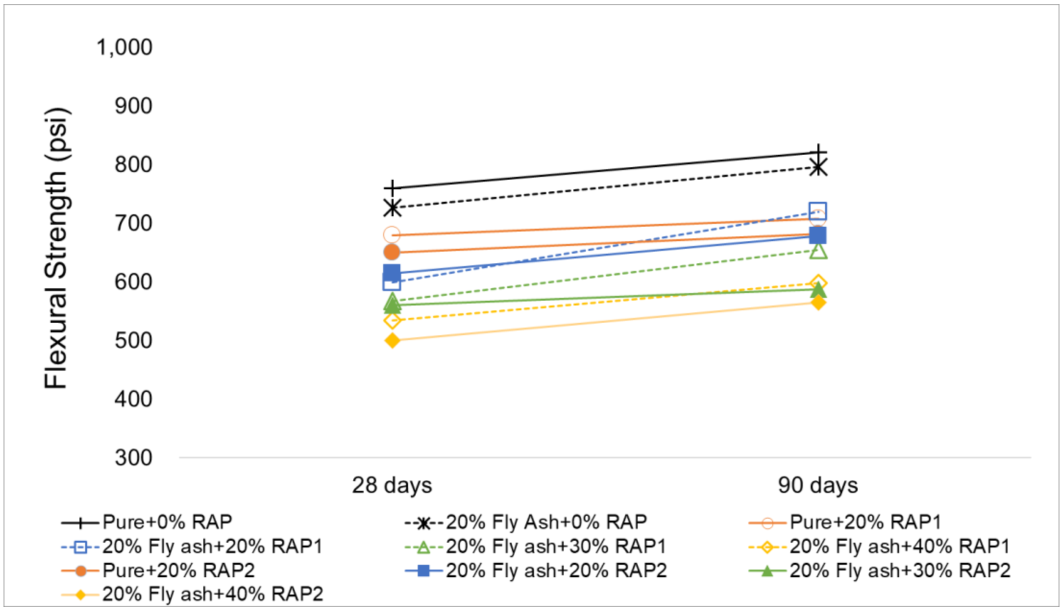


Figure 6-12. Flexural strength of production mixtures at different curing times

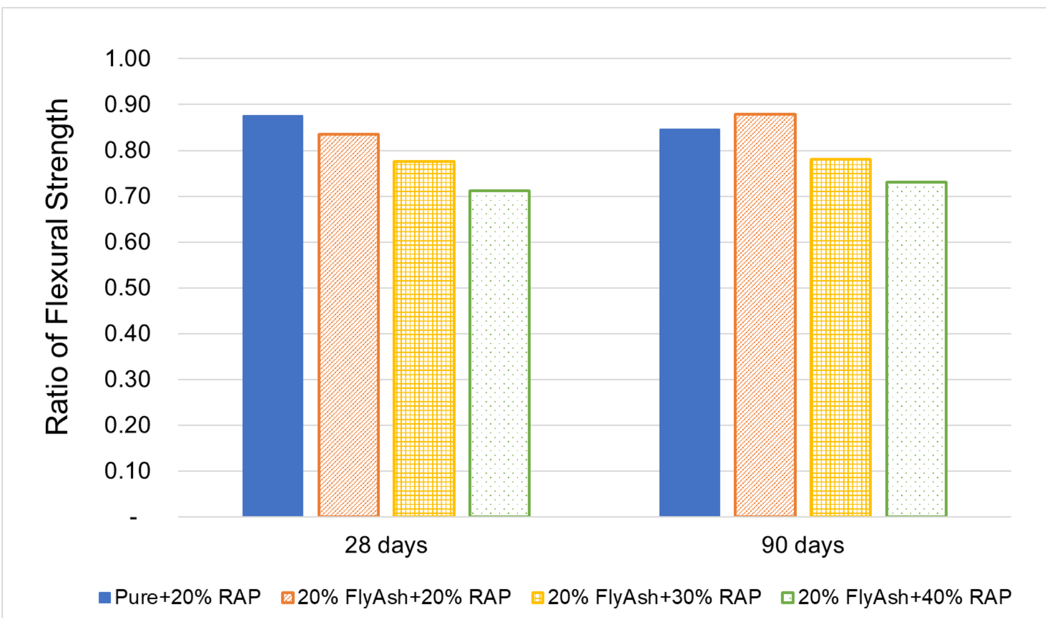


Figure 6-13. Ratio of flexural strength of production mixtures relative to the control mix

6.2.6 Drying Shrinkage Test Results

Early study revealed that there is no strong correlation between proportioning RAP in concrete mixture and free drying shrinkage (Dumitru et al., 1999; Sommer, 1994). Table 6-7 summarizes the average drying shrinkage strain values for all the concrete mixtures evaluated in this research study. The percentage length change was determined by multiplying the actual shrinkage strain reading by 100. The positive value for length change indicates that the concrete specimen has shrunk, and the negative value indicates that the concrete specimen has expanded.

Table 6-7. Drying shrinkage strain of concrete containing RAP

Mix No.	Fly Ash (%)	RAP (%)	w/c Ratio	Average Shrinkage Strain of RAP mixtures (10^{-6})				
				Curing Time (days)				
				7	14	28	56	90
M01-P	0	0	0.50	–	-30	-3	29	25
M02-P	20	0	0.50	–	-27	7	32	29
M03-P	0	20*	0.50	–	-60	-57	18	27
M04-P	0	20#	0.50	–	-30	-40	14	22
M05-P	20	20*	0.50	-80	-73	-40	22	29
M06-P	20	20#	0.50	-73	-33	-73	15	21
M07-P	20	30*	0.50	-53	-53	-70	22	27
M08-P	20	30#	0.50	-37	-40	-43	27	31
M09-P	20	40*	0.50	-37	-30	-27	32	36
M10-P	20	40#	0.50	-73	-87	-83	27	29

Note: *RAP source is plant number A0691
#RAP source is plant number A0750

6.2.7 Coefficient of Thermal Expansion Test Results

Coefficient of thermal expansion (CTE) determines the tendency of matter to length change as a function of temperature, which can be used in the analysis of a concrete pavement structure subject to temperature effects. The CTE is one of the significant factors to be considered in the design of concrete pavement. During FE analysis, accurate values of the CTE are needed to predict potential behavior of the concrete pavement. Table 6-8 summarizes the CTE of all the concrete mixtures evaluated in this research study. Average CTE values at 28-day and 90-day curing times are presented. A grand-average CTE value of 4.34 x 10^{-6}/°F was obtained. This value compared well to the CTE value from an early study using limestone aggregate (Hall and Tayabji, 2011). There was no strong correlation between the amount of RAP and CTE.

Table 6-8. CTE of concrete mixtures evaluated

Mix No.	Fly ash (%)	RAP (%)	w/c Ratio	Average CTE of RAP mixtures (10^{-6}/°F) Curing Time (days)	
				28	90
M01-P	0	0	0.50	4.42	4.16
M02-P	20	0	0.50	4.49	4.23
M03-P	0	20*	0.50	4.12	4.28
M04-P	0	20#	0.50	4.13	4.21
M05-P	20	20*	0.50	4.33	4.34
M06-P	20	20#	0.50	4.41	4.71
M07-P	20	30*	0.50	4.21	4.39
M08-P	20	30#	0.50	4.25	4.12
M09-P	20	40*	0.50	4.21	4.37
M10-P	20	40#	0.50	4.54	4.63

Note: *RAP source is plant number A0691
#RAP source is plant number A0750

6.2.8 Surface Resistivity Test Results

The chloride ion penetrability of a concrete mixture is one of the important factors affecting concrete structure durability. AASHTO T358 was used to determine the chloride ion penetrability of the concrete mixtures incorporating 0%, 20%, 30%, and 40% RAP. AASHTO PP 84 provides the level of surface resistivity for likelihood of chloride ion permeability (2017), as shown in Table 6-9. The results of the surface resistivity tests are presented in Table 6-10. According to the AASHTO specification of chloride ion penetrability, both the control and RAP concrete mixtures were rated as "Moderate" for possibility of chloride ion penetration issues at 28 days. These concrete mixtures have normal chloride ion penetration performance. Also, the results of surface resistivity showed that the surface resistivity increased as the curing time increased.

Table 6-9. Specification of surface resistivity

Chloride Ion Penetrability (KΩ·in.)	High	Moderate	Low	Very Low	Negligible
Greatest Resistivity	2.0	3.9	7.9	78.7	~
Lowest Resistivity	~	2.0	3.9	7.9	78.7

Table 6-10. Surface resistivity of concrete mixtures evaluated

Mix No.	Fly ash (%)	RAP (%)	w/c Ratio	Average Surface Resistivity of RAP mixtures (KΩ·in.) Curing Time (days) 28	56	90
M01-P	0	0	0.50	2.9	3.1	3.5
M02-P	20	0	0.50	2.8	4.1	5.5
M03-P	0	20*	0.50	2.8	3.1	3.4
M04-P	0	20#	0.50	2.9	3.2	3.5
M05-P	20	20*	0.50	2.9	4.1	8.4
M06-P	20	20#	0.50	3.2	4.8	6.9
M07-P	20	30*	0.50	2.8	4.6	6.5
M08-P	20	30#	0.50	2.8	4.3	6.2
M09-P	20	40*	0.50	3.2	5.0	6.8
M10-P	20	40#	0.50	3.5	5.6	7.5

Note: *RAP source is plant number A0691
#RAP source is plant number A0750

6.3 Fracture Mechanism

It is clearly observed that the RAP concrete mixture of strength was decreased and toughness was increased as the percentage of RAP increased when compared with the normal concrete mixture. The early study revealed that the asphalt coated around the surface of aggregate typically forms a film with a thickness ranging from six to nine microns. For concrete mixture incorporating RAP, a thin asphalt film is located between cement mortar and aggregate in the interface zone, which can capture crack propagation as shown in Figure 6-14. In other word, cracking propagation develops around the aggregate along the asphalt film (Huang et al., 2006). This failure behavior was also observed in the RAP concrete mixture in this study as shown in Figure 6-15.

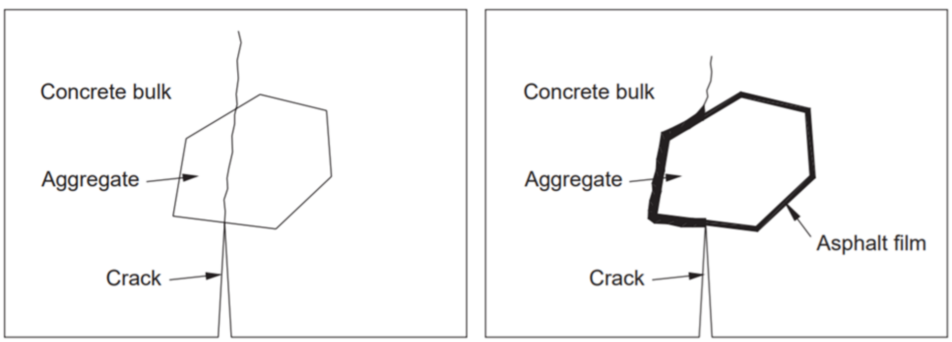


Figure 6-14. Propagation of crack through aggregate with and without asphalt film (Huang et al., 2006)

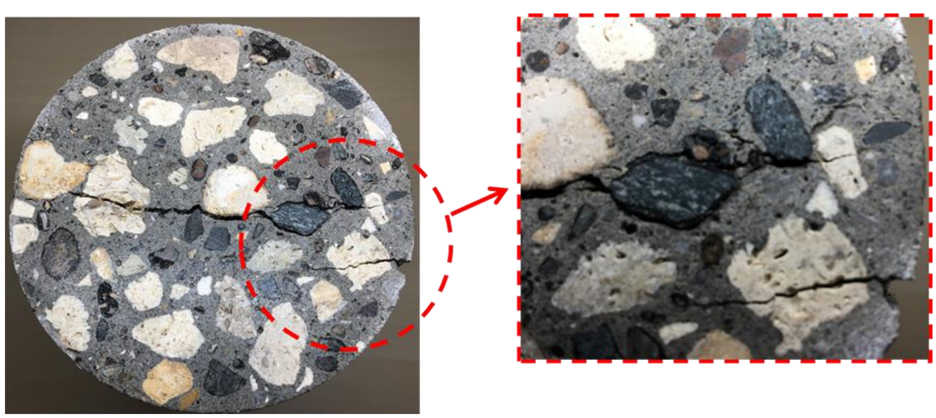


Figure 6-15. Observed crack propagation through the RAP concrete in splitting tensile strength test

6.4 Summary of Findings

- All the RAP concrete mixture could be produced to achieve a target slump of 1 to 2 inches and a target air content of 2% to 5% with an appropriate amount of water-reducing admixture. The needed dosage of water-reducing admixture increased as the percentage RAP increased.

- Among the RAP concretes evaluated, the following concrete mixes were able to meet the over-design compressive strength of 4,200 psi at 28 days:

    (1) Concrete containing 20% RAP and using pure Portland cement, with w/c of 0.43, 0.45, 0.47, and 0.50.

    (2) Concrete containing 20% RAP and using 20% fly ash, with w/c of 0.43, 0.45, 0.47, and 0.50.

- The over-design compressive strength of 4,200 psi could not be achieved by the concrete mixes containing 30% or more RAP.

- The compressive strength, modulus of elasticity, and flexural strength decreased as the percentage of RAP increased in the concrete mixture.

- The reduction in flexural strength in the concrete containing RAP was 5% to 15% lower than the corresponding reduction in compressive strength of the concrete containing RAP.

- The rate of reduction in modulus of elasticity in the concrete containing RAP was slightly lower than the corresponding reduction in compressive strength of the concrete containing RAP.

- The Poisson's ratio increased as the percentage of RAP in the concrete increased.

- The CTE of concrete does not clearly show a strong relationship with the amount of RAP in the concrete.

CHAPTER 7
EVALUATION OF POTENTIAL PERFORMANCE OF RAP CONCRETE IN CONCRETE PAVEMENT SLABS

7.1 Introduction

Using the measured properties of concrete mixtures containing RAP to determine how each of the concrete mixtures would perform if it were used in a typical concrete pavement in Florida. A cost analysis was also made to determine the possible cost savings if RAP were to be used as aggregate replacement in concrete mixtures. This chapter presents the results of these analyses.

7.2 Critical Stress Analysis

Using the measured elastic modulus and the coefficient of thermal expansion to model the concrete, analysis was performed to determine the maximum stresses in a typical concrete pavement slab if it were under a critical combination of load and temperature condition. Prior study has shown that a 22-kip axle load applied at the middle of the slab edge, when there was a temperature differential of +20°F in the concrete slab, represents a critical loading condition in Florida. Thus, this loading condition was used in the analysis.

The 3-D Finite Element model for Jointed Concrete Pavement which was developed in a prior FDOT-sponsored research study (Contract BDV 31-977-30) was used to perform the stress analysis. Figure 7-1 shows the 3-D FE model used to model the pavement slab. The following parameters were used to model the concrete pavement: Slab thickness = 9 in.; slab length = 16 ft; slab width = 12 ft; elastic modulus of subgrade = 80 ksi.

Critical stress analyses were performed using the properties of the concrete from the production mixes (all with w/c of 0.50) at 28-day curing. Since the properties of the RAP concrete using the two different RAP sources were very similar to one another, only the RAP concretes using RAP source #1 were used in the analysis. The maximum stress in the concrete slab under the critical condition was first computed. The maximum computed stress was then divided by the flexural strength of the concrete to obtain the stress to flexural strength ratio, which can indicate the potential performance of the concrete in service. According to fatigue theory, a low stress to strength ratio would indicate a higher number of load repetitions to failure and potentially better performance for concrete pavements in the field. The results of this stress analysis are summarized in Table 7-1.

Table 7-1. Computed maximum stresses and stress-to-strength ratios

Mix	28-Day Curing			Computed Stress, psi (*Stress-to-Strength Ratio*)
	CTE ($x10^{-6}$/°F)	MOE (ksi)	Flexural Strength (psi)	
M01-P	4.42	5,100	760	**405.4 (*0.53*)**
M02-P	4.49	4,650	727	**366.7 (*0.50*)**
M03-P	4.12	4,150	680	**310.9 (*0.46*)**
M05-P	4.33	4,000	600	**306.2 (*0.51*)**
M07-P	4.21	3,200	568	**260.0 (*0.46*)**
M09-P	4.21	3,000	535	**237.8 (*0.42*)**

Note: Only RAP1 was used for this FE analysis due to the similar properties between RAP1 and RAP2.
Temperature differential in the concrete slab: +20°F.
Applied load: 22-kip axial load at mid edge of slab.

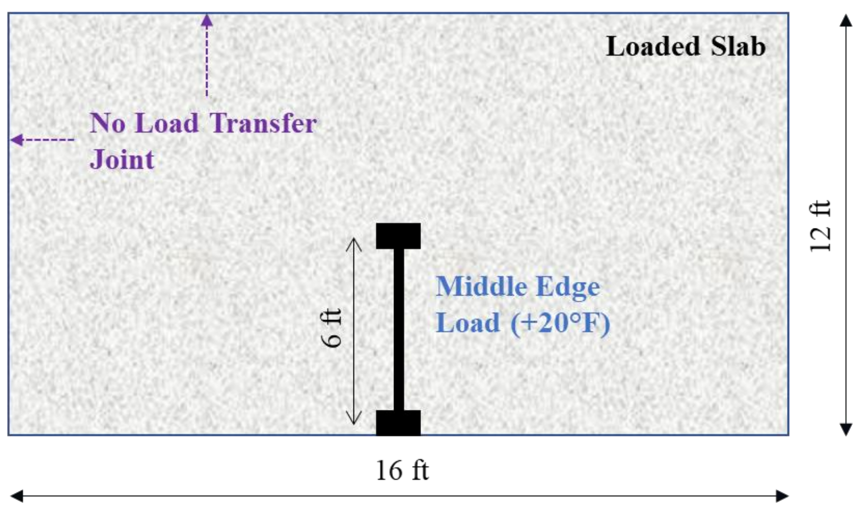


Figure 7-1. 3-D finite-element model for analysis of jointed plain concrete pavement under critical loading condition

From the results presented in Table 7-1, it can be seen that at the critical loading condition, the computed stress-to-strength ratios for Mix 1 (control mix of pure cement), Mix 2 (Control mix with 20% fly ash), Mix 3, Mix 5, Mix 7, and Mix 9 are 0.53, 0.50, 0.46, 0.51, 0.46 and 0.42, respectively.

Though the two control concretes with 0% RAP had higher flexural strengths than the RAP concrete, the concrete mix with 40% RAP and using pure cement (Mix 9) had the lowest stress-to-strength ratio of 0.42. The RAP concrete using 20% fly ash and 20%, 30%, and 40% RAP show stress-to-strength ratios which are lower than those for the control mixes with 0 % RAP.

7.3 Cost Analysis

A cost analysis was made to determine the possible cost savings if RAP were to be used as aggregate replacement in concrete mixtures. Table 7-2 presents the estimated total cost of aggregate in a concrete mixture if 20% and 40% RAP are to be used. The cost figures for a #57 limestone, silica sand, and RAP material in Florida were used in this analysis. It can be noted that the total estimated cost of aggregates was $43.3, $39.2, and $35.2 per cubic yard of concrete incorporating 0%, 20%, and 40% RAP, respectively. The saving in aggregate cost is estimated to be 10% and 19% for incorporating 20% and 40% RAP, respectively.

Table 7-2. Estimated total cost of aggregate in concrete mixes containing different percentages of RAP

	#57 Limestone		Silica Sand		RAP		Total	
Local Price ($/1,000lb)	13.6		15.5		8.0		12.4	
0% RAP Mix ($/yd^3)	27.3	66%	16.0	34%	0.0	0%	43.3	Control
20% RAP Mix ($/yd^3)	21.7	53%	12.6	27%	4.8	20%	39.2	-10%
40% RAP Mix ($/yd^3)	15.9	39%	9.7	21%	9.6	40%	35.2	-19%

7.4 Summary of Findings

The results of critical stress analysis indicate that the RAP concrete using 20 % fly ash and 20 %, 30 %, or 40% RAP with a w/c ratio of 0.50 could have better potential performance than a concrete mix with 0% RAP and using pure cement and the same w/c. A cost analysis on the replacement of aggregate with RAP indicates that using 20% and 40% RAP in concrete could result in saving in the total cost of aggregate by 10% and 19%, respectively.

CHAPTER 8
SUMMARY OF FINDINGS AND CONCLUSIONS

8.1 Summary of Findings

The main objective of this research project was to develop the mix designs for concrete mixtures incorporating RAP to be used in the Florida Concrete Test Road. Two different FDOT approved RAP sources were selected and used. Concrete mixtures with 0%, 20%, 30% and 40% RAP as aggregate replacement, and using 0% and 20% fly ash as cement replacement were designed using optimized aggregate gradation technique. A computer software named OAG Tool for optimizing aggregate gradation in a concrete mix design was developed and used in designing concrete mixes containing RAP. The designed concrete mixes were produced and tested in the laboratory. Emphasis was placed on meeting the requirements for pavement concrete according to FDOT Specifications Section 346. Critical stress analysis was performed to evaluate the potential performance of a typical concrete pavement in Florida if RAP concretes with the determined properties were used. A cost analysis was also performed to determine the possible saving if RAP materials were used as partial replacement of aggregate in pavement concrete in Florida. The main findings from this study are summarized as follows:

<u>Optimized Aggregate Gradation Procedure</u>

(1) An Excel spreadsheet software, named OAG Tool, which was developed to facilitate the use of Optimized Aggregate Gradation (OAG) procedure was found to be an effective tool to be used for this purpose.

(2) It was demonstrated that the OAG procedure is superior to the ACI procedure in proportioning aggregates to achieve a well-graded aggregate blend and a workable mix.

(3) The OAG procedure was used to proportion the aggregates used in the concrete mixes containing RAP in this study. The control mix containing no RAP had a gap-graded aggregate which lacked intermediate-size particles. When 20% or 40% RAP materials were incorporated using the OAG procedure, the aggregate blend became significantly more well-graded and the concrete became more workable.

Properties of Concrete Incorporating RAP

(4) All the RAP concrete mixture could be produced to achieve a target slump of 1 to 2 inches and a target air content of 2% to 5% with an appropriate amount of water-reducing admixture. The needed dosage of water-reducing admixture increased as the percentage RAP increased.

(5) Among the RAP concretes evaluated, the following concrete mixes were able to meet the over-design compressive strength of 4,200 psi at 28 days:

a. Concrete containing 20% RAP and using pure Portland cement, with w/c of 0.43, 0.45, 0.47, and 0.50.

b. Concrete containing 20% RAP and using 20% fly ash, with w/c of 0.43, 0.45, 0.47, and 0.50.

(6) The over-design compressive strength of 4,200 psi could not be achieved by the concrete mixes containing 30% or more RAP.

(7) The compressive strength, modulus of elasticity, and flexural strength decreased as the percentage of RAP increased in the concrete mixture.

(8) The reduction in flexural strength in the concrete containing RAP was 5% to 15% lower than the corresponding reduction in compressive strength of the concrete containing RAP.

(9) The rate of reduction in modulus of elasticity in the concrete containing RAP was slightly lower than the corresponding reduction in compressive strength of the concrete containing RAP.

(10) The Poisson's ratio increased as the percentage of RAP in the concrete increased.

(11) The CTE of concrete does not clearly show a strong relationship with the amount of RAP.

Results of Critical Stress Analysis

(12) The results of critical stress analysis indicate that the RAP concrete using 20% fly ash and 20%, 30%, or 40% RAP with a w/c ratio of 0.50 could have better potential performance than a concrete mix with 0% RAP and using pure cement and the same w/c.

Results of Cost Analysis

(13) A cost analysis on the replacement of aggregate with RAP indicates that using 20% and 40% RAP in concrete could result in saving in the total cost of aggregate by 10% and 19%, respectively.

8.2 Recommendations

Recommended Mix Designs of Concrete Incorporating RAP

Based on the results of this study, the following four concrete mix designs of concrete incorporating RAP are recommended as feasible mixes to be used in the Florida Concrete Test Road:

(1) Concrete incorporating 20% RAP (Source A0691) with 0% fly ash, with cement content of 516 lb/yd^3 and w/c of 0.5.

(2) Concrete incorporating 20% RAP (Source A0750) with 0% fly ash, with cement content of 516 lb/yd^3 and w/c of 0.5.

(3) Concrete incorporating 20% RAP (Source A0691) with 20% fly ash, with cementitious material content of 516 lb/yd^3 and w/c of 0.5.

(4) Concrete incorporating 20% RAP (Source A0750) with 20% fly ash, with cementitious material content of 516 lb/yd^3 and w/c of 0.5.

The detailed mix design information for these four concrete mixes are presented in Table 8-1.

Table 8-1. Four recommended mix designs for concrete containing RAP

	20% RAP + 0% Fly Ash		20% RAP + 20% Fly Ash	
	RAP 1	RAP 2	RAP 1	RAP 2
Cement – Type I/II	516	516	403	403
Fly Ash – Class F (lb/yd^3)	0	0	100	100
Water (lb/yd^3)	258	258	252	252
w/c Ratio	0.50	0.50	0.50	0.50
Paste Volume Ratio	0.25	0.25	0.25	0.25
RAP (lb/yd^3)	603 (20%)	600 (20%)	603 (20%)	600 (20%)
Coarse Aggregate #57 (lb/yd^3)	1,599 (53%)	1,562 (52%)	1,599 (53%)	1,562 (52%)
Fine Aggregate (lb/yd^3)	814 (27%)	841 (28%)	814 (27%)	841 (28%)
Water-Reducing – Type D (oz/yd^3)	40	40	40	40

Recommendation for use of RAP as Aggregate in Pavement Concrete

It is recommended that 20% of RAP can be used as aggregate replacement in pavement concrete. All specification requirements for pavement concrete should also apply to concrete containing RAP. The RAP material should be used as-is without pre-soaking prior to mixing in concrete production to avoid degradation of the RAP material due to excessive handling. It is recommended that the OAG procedure be used to proportion the aggregates and RAP materials to ensure a well-graded gradation and a workable concrete mix. The developed OAG Tool software can be used for this purpose.

LIST OF REFERENCES

AASHTO C336. (2015). *Standard method of test for coefficient of thermal expansion of hydraulic Cement Concrete*. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO C358. (2017). *Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration*. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO PP 84. (2017). *Standard practice for developing performance engineered concrete pavement mixtures*. American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO TP 60. (2010). *Standard method of test for coefficient of thermal expansion of hydraulic cement concrete*. American Association of State Highway and Transportation Officials, Washington, D.C.

ACI 211.1-91. (2009). *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*. Farmington Hills, MI.

ACI 302.1R. (2015). *Guide for Concrete Floor and Slab Construction*. American Concrete Institute. Farmington Hills, MI.

Al-Mufti, R. L., and Fried, A. N. (2017). "Improving the strength properties of recycled asphalt aggregate concrete." *Construction and Building Materials*, 149, 45-52.

Al-Oraimi, S., Hassan, H. F., and Hago, A. (2009). "Recycling of Reclaimed Asphalt Pavement in Portland Cement Concrete." *The Journal of Engineering Research*, 6(1), 37-45.

ASTM C39/C39M. (2017). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA.

ASTM C78 / C78M. (2015). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).* ASTM International, West Conshohocken, PA.

ASTM C138/C138M. (2017). *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*. ASTM International, West Conshohocken, PA.

ASTM C143/C143M. (2015). *Standard Test Method for Slump of Hydraulic-Cement Concrete*. ASTM International, West Conshohocken, PA.

ASTM C157/C157M. (2008). *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. ASTM International, West Conshohocken, PA.

ASTM C173/C173M. (2016). *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*. ASTM International, West Conshohocken, PA.

ASTM C232/C232M. (2014) *Standard Test Method for Bleeding of Concrete*. ASTM International, West Conshohocken, PA.

ASTM C403/C403M. (2016). *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. ASTM International, West Conshohocken, PA.

ASTM C469 / C469M. (2010). *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. ASTM International, West Conshohocken, PA.

ASTM C496 / C496M. (2004). *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM International, West Conshohocken, PA.

ASTM C1064/C1064M. (2012). *Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete*. ASTM International, West Conshohocken, PA.

Berry, M., Dalton, K., and Murray, F. (2015b). *Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete Pavements Phase II: Field Demonstration*. Research Report, Montana State University, Bozeman, MT.

Berry, M., Kappes, B., and Kappes, L. (2015a). "Optimization of Concrete Mixtures Containing Reclaimed Asphalt Pavement." *ACI Materials Journal*, 112(6).

Brand, A. S., and Roesler, J. R. (2015). "Ternary Concrete with Fractionated Reclaimed Asphalt Pavement." *ACI Materials Journal*, 112(1).

Copeland, A. (2011). *Reclaimed asphalt pavement in asphalt mixtures: State of the practice (No. FHWA-HRT-11-021).* Federal Highway Administration, Mclean, VA.

CDOT. (2012). *Optimized Portland cement concrete pavement mix. Specification Section No. 601*. Colorado Department of Transportation, Denver, CO.

Cramer, S. M., Hall, M., and Parry, J. (1995). "Effect of optimized total aggregate gradation on Portland cement concrete for Wisconsin pavements." *Transportation Research Record*, 1478, 100−106.

Cramer, S. M., and Carpenter, A. J. (1999). "Influence of Total Aggregate Gradation on Freeze-Thaw and Other Performance Measures of Paving Concrete." *Transportation Research Board*, 1668, 1-8.

Darwin, D., Browning, J., McLeod, H., Lindquist, W., and Yuan, J. (2012). *Implementing lessons learned from twenty years of bridge-deck crack surveys*. American Concrete Institute, Farmington Hills, MI.

Delwar, M., Fahmy, M., and Taha, R. (1997). "Use of reclaimed asphalt pavement as an aggregate in Portland cement concrete." *ACI Materials Journal*, 94(3), 251-256.

Dumitru, I., Smorchevshy, G., and Caprar, V., (1999). “Trends in the Utilization of Recycled Materials and By-Products in Concrete Industry in Australia.” In D. Baweja, ed., *Concrete 99-Our Concrete Environment: Proceedings of the Concrete Institute of Australia 19th Biennial Conference, 5-7 May 1999, Sydney, Australia*. Sydney, Australia: Concrete Institute of Australia. PP. 289-301.

Federal Highway Administration Research and Innovative Technology. (2016). *User Guidelines for Waste and Byproduct Materials in Pavement Construction*. Available from: https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap131.cfm (accessed Sep. 9. 2017).

FDOT. (2017). *Standard Specifications for Road and Bridge Construction*. Florida Department of Transportation, Tallahassee, FL.

Fuller, W. B., and Thompson, S. E. (1907), “The Laws of Proportioning Concrete” *ASCE Journal*, 59(2), 67-113.

Glavind, M, Olsen, G. S., and Munch-Peterson, C. (1993). “Packing calculations and concrete mix design.” *Nordic Concrete Research*, 13.

Griffiths, C. T., and Krstulovich, J. M. (2002). *Utilization of Recycled Materials in Illinois Highway Construction* (Research Report No.142). Illinois DOT, Chicago, Illinois.

Hall, K., and Tayabji, S. (2011). Coefficient of thermal expansion in concrete pavement design (FHWA-HIF-09-015). Federal Highway Administration, Mclean, VA.

Hansen, K. R., and Copeland, A. (2017). *Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage:* (Information Series 138). NAPA, Lanham, MD.

Hassan, K. E., Brooks, J. J., and Erdman, M. (2000). “The use of reclaimed asphalt pavement (RAP) aggregates in concrete.” *Waste Management Series*, 1, 121-128.

Hossiney, N., Tia, M., and Bergin, M. J. (2010). “Concrete containing RAP for use in concrete pavement.” *International Journal of Pavement Research and Technology*, 3(5), 251-258.

Huang, B., Shu, X., and Li, G. (2005). “Laboratory investigation of portland cement concrete containing recycled asphalt pavements.” *Cement and Concrete Research*, 35(10), 2008-2013.

Huang, B., Shu, X., and Burdette, E. G. (2006). “Mechanical Properties of Concrete Containing Recycled Asphalt Pavements.” *Magazine of Concrete Research*, 58(5), 313-320.

Johansson, L. (1979). *Effect of aggregate grading and mix proportions on the workability for concrete made with entirely crushed aggregate, studies on concrete technology*. Swedish Cement and Concrete Research Institute, Stockholm, Sweden.

Johansen, V., and Anderson, P. J. (1989). *Particle packing and concrete properties*. Material science of concrete II, Westerville, OH.

Kang, D. H., Gupta, S. C., and Ranaivoson, A. Z. (2011). “Recycled Materials as Substitutes for Virgin Aggregates in Road Construction: 1-Hydraulic and Mechanical Characteristics.” *Soil Science Society of America*, 75(4), 1265-1275.

Katsakou, M., and Kolias, S. (2007). “Mechanical Properties of Cement-Bound Recycled Pavements.” *Proceeding of the Institution of Civil Engineers-Construction Materials,* 160(4), 171-179.

Kim, D. H., and Won, M. (2008). *Pilot Implementation of Optimized Aggregate Gradation for Concrete Paving*. Research Report, Texas DOT, Texas.

Kim, K., Chun, S., Park, B., and Tia, M. (2017). “Effects of the Non-linear Stress-Strain Behavior of RAP Concrete on Structural Responses for Rigid Pavement Application.” *International Journal of Highway Engineering*, 19(1), 37-44.

Koehler, E. P., and Fowler, D. W. (2007). *Aggregate in Self-Consolidating Concrete*. International Center for Aggregate, Research Report No.108-2F, Austin, Texas

Li, G., Zhoa, Y., Pang, S. S., and Huang, W. (1998). “Experimental Study of Cement-Asphalt Emulsion Composite.” *Cement and Concrete Research*, 28(5), 635-641.

Lindquist, W., Darwin, D., Browning, J., McLeod, H. A., Yuan, J., and Reynolds, D. (2015). “Implementation of concrete aggregate optimization.” *Construction and Building Materials*, 74, 49-56.

Mathias, V., Sedran, T., and De Larrard, F. (2004). “Recycling Reclaimed Asphalt Pavement in Concrete Roads.” *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures*, 10.

Montana department of transportation. (2016). Concrete aggregate combined gradation example. http://www.mdt.mt.gov/other/const/external/temp_drawings_calc_ex/combined_gradation_example.pdf (accessed Sep. 9. 2017).

Okafor, F. O. (2010). “Performance of Recycled Asphalt Pavement as Coarse Aggregate in Concrete.” *Leonardo Electronic Journal of Practices and Technologies*, 17, 47-58.

ODOT. (2006). *Aggregate proportioning guide for optimized gradation concrete mix designs*. Oklahoma Department of Transportation, Oklahoma City, OK.

Patankar, V. D., and Williams, R. I. T. (1970). “Bitumen in Dry Lean Concrete.” *Highways and Traffic Engineering*, 38(1721), 32-35.

Proceq. (2017). *Operating Instructions-Concrete Durability Testing*. Schwerzenbach, Switzerland.

Shilstone, J. H. (1990). “Concrete Mixture Optimization.” *ACI Concrete International*, 12(6), 33-39.

Sommer, H. (1994). "Recycling of Concrete for the Reconstruction of the Concrete Pavement of the Motorway Vienna-Salzburg," *7th International Concrete Roads Symposium*, Vienna, Austria.

Talbot, A. N., and Richart, F. E. (1923). "The Strength of Concrete," Bulletin No.137, *Engineering Experiment Station*, University of Illinois, Urbana-Champaign, IL.

Tayabji, S., and Anderson, J. (2007). Supplemental Report for Proposed Specification for Construction of Concrete Airfield Pavements. Innovative Pavement Research Foundation Report, Rosemont, IL.

TxDOT. (2017) *Optimized aggregate gradation for hydraulic cement concrete mix designs*. Texas department of transportation, Austin, TX.

Tia, M., Hossiney, N., Su, Y.-M., Chen, Y., and Do, T. A. (2012). *Use of Reclaimed Asphalt Pavement in Concrete Pavement Slabs.* Research Report, Florida Department of Transportation, Tallahassee, FL.

Tia, M., Kim, K., and Han, S. (2017). *Improved Analysis Tool for Concrete Pavement*. Research Report, Florida Department of Transportation, Tallahassee, FL.

Tompkins, D., Khazanovich, L., Darter, M.I., and Walter, F. (2009). "Design and Construction of Sustainable Pavements." *Transportation Research Board*, Record No. 2098, 75-85.

Topcu, I. B., and Isikdag, B. (2009). "Effects of Crushed RAP on Free and Restrained Shrinkage of Mortars." *International Journal of Concrete Structures and Materials*, 3(2), 91-95.

Tošić, N., Marinković, S., Dašić, T., and Stanić, M. (2015). "Multicriteria optimization of natural and recycled aggregate concrete for structural use." *Journal of Cleaner Production*, 87, 766-776.

U.S. Department of Transportation (2016). *User guidelines for waste and by-product materials in pavement construction* (FHWA-RD-97-148). Federal Highway Administration, Mclean, VA. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap131.cfm, 2016 (accessed Sep. 9. 2017).