FINAL REPORT

U.F. Project No. 00059678
RPWO#: 67
Contract No: BD545

MODULUS OF ELASTICITY, CREEP AND SHRINKAGE OF CONCRETE – PHASE II

PART 2 – LOW MODULUS CONCRETE

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October 2009

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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	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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
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)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}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. 00059678	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Modulus of Elasticity, Creep and Shrinkage of Concrete – PHASE II: Part 2– Low Modulus Concrete	5. Report Date October 2009
	6. Performing Organization Code
7. Author(s) Mang Tia, Nabil Hossiney, and Patrick Bekoe	8. Performing Organization Report No. 00059678
9. Performing Organization Name and Address Department of Civil and Coastal Engineering 365 Weil Hall – P.O. Box 116580 University of Florida Gainesville, FL 32611-6580	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. BD-545 #67
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 02/10/06 - 10/31/09
	14. Sponsoring Agency Code

15. Supplementary Notes

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

16. Abstract

This study evaluated the feasibility of use of Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregate (RCA) as aggregate in concrete when used in a typical concrete pavement in Florida.

Concrete containing 0%, 10%, 20%, and 40% of RAP were evaluated for their properties that are relevant to performance of concrete pavements. The compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the concrete decreased as the percentage of RAP increased. The coefficient of thermal expansion appeared to increase slightly when the first RAP was incorporated, and to decrease slightly when a second RAP was used. When a finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the resulting maximum stress to flexural strength ratio for the concrete was reduced as compared with that of a reference concrete with no RAP. This indicates that using a concrete containing RAP could possibly result in improvement in the performance of concrete pavements.

Concrete containing 0%, 25%, and 50% of RCA were evaluated in a similar fashion. The compressive strength and elastic modulus decreased slightly as the percentage of RCA increased. The splitting tensile strength, flexural strength, and coefficient of thermal expansion were about the same for the control mix and the concrete containing RCA. When a similar analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses to strength ratios in the pavement were found to be about the same for the control mix and concrete containing RCA. Thus, a concrete using RCA will likely have the same performance as a conventional concrete using virgin aggregates.

17. Key Words Concrete Pavement, Reclaimed Asphalt Pavement (RAP), Recycled Concrete Aggregate (RCA), Elastic Modulus, Flexural Strength, Coefficient of Thermal Expansion, Critical Stress Analysis	18. Distribution Statement No restrictions.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 172	22. Price

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. 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 the FDOT Materials Office personnel, particularly to Messrs. Charles Ishee, Richard DeLorenzo, Craig Roberts, and Luke Goolsby for their invaluable help on this project. Sincere thanks also go to the support of the staff at the Department of Civil and Coastal Engineering at the University of Florida, particularly to Messrs. George Lopp and Chuck Broward for their technical support in the lab, and to Ms. Candace Leggett for her expert editing of this report.

EXECUTIVE SUMMARY

Research Objectives

Every year in the United States, more than 100 million tons of reclaimed asphalt pavement (RAP) are generated by asphalt pavement (AC) rehabilitation and reconstruction. Some have been recycled into new asphalt mixtures; some have been used as pavement base materials. However, a large quantity of RAP still remains unutilized and needs to be put to good use. An alternative use of RAP is to use it as an aggregate in Portland cement concrete (PCC).

Another waste product of great abundance from the highway and building industry is recycled concrete aggregate (RCA). RCA has been used as a base material in flexible pavement construction, but its use in a new concrete pavement has not been fully exploited. Past research supported by the Florida Department of Transportation (FDOT) has also been focused on the use of recycled concrete as a base material for concrete and asphalt pavement.

With the increasing volume of waste or by-product materials from industry, domestic, and mining sources, decreasing availability of landfill space for disposal and depletion of virgin aggregates, there is a need to assess the feasibility of using RAP and RCA as aggregates in concrete for use in concrete pavements.

The main research objectives of this study are as follows:

1) To evaluate the potential use of RAP and RCA in concrete and its effects on the mechanical and thermal properties of concrete; and
2) To determine the performance of concretes containing different amounts of RAP and RCA when used in a typical concrete pavement in Florida.

Findings from the Evaluation of Concrete Containing RAP

The feasibility of using concrete containing recycled asphalt pavement (RAP) in concrete pavement applications was evaluated. Concrete containing 0%, 10%, 20%, and 40% of RAP were produced in the laboratory, and evaluated for their properties that are relevant to performance of concrete pavements. Results of the laboratory testing program indicate that compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the concrete decreased as the percentage of RAP increased. The coefficient of thermal expansion appeared to increase slightly when the first RAP was incorporated, and to decrease slightly when a second RAP was used. The drying shrinkage appeared to increase slightly with the use of RAP in concrete. When a finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses in the pavement were found to decrease as the RAP content of the content increased, due to a decrease in the elastic modulus of the concrete. Though the flexural strength of the concrete decreased as RAP was incorporated in the concrete, the resulting maximum stress to flexural strength ratio for the concrete was reduced as compared with that of a reference concrete with no RAP. This indicates that using a concrete containing RAP could possibly result in improvement in the performance of concrete pavements.

Findings from the Evaluation of Concrete Containing RCA

The feasibility of using concrete containing recycled concrete aggregate (RCA) in concrete pavement applications was evaluated. Concrete containing 0%, 25%, and 50% of RCA were produced in the laboratory and evaluated for their properties that are relevant to performance of concrete pavements. Results of the laboratory testing program indicate that compressive strength and elastic modulus decreased slightly as the percentage of RCA increased. The splitting tensile strength, flexural strength, and coefficient of thermal expansion were about the same for the control mix and the concrete containing RCA. The drying shrinkage decreased slightly as the percentage of RCA increased. When a finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses to strength ratios in the pavement were found to be about the same for the control mix and concrete containing RCA. Thus, a concrete using RCA will likely have the same performance as a conventional concrete using virgin aggregates. With the use of RCA up to about 50%, there will likely not be much difference in its performance compared with concrete containing virgin aggregate. Thus, the main advantages for the use of the RCA would be the economical and environmental benefits.

Recommendations on Concrete Containing RAP

The results of a laboratory testing program and finite element analysis indicate that the use of RAP as aggregate replacement in pavement concrete appears to be not only feasible but also offer the possibility of improving the performance of concrete pavement. It is thus recommended that further research be conducted in this area to further substantiate this finding. It is recommended that further research work be done in the following areas:

1) To conduct a full factorial experiment to investigate the properties of concrete containing RAP as affected by: a) the mechanical properties of the RAP; b) the gradation of the RAP; c) properties of the virgin aggregate; d) w/c of the concrete; and e) mineral admixtures such as fly ash and ground blast-furnace slag;
2) To evaluate the potential performance of the various concrete mixes tested in the factorial experiment using finite element analysis where the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions would be determined

using the measured properties–the results of these analyses can then be used to develop a method for optimizing a concrete mix design incorporating RAP; and

3) To conduct accelerated pavement testing on concrete pavement slabs made with concrete containing RAP to evaluate the actual field performance of these concrete mixes.

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CHAPTER 1
INTRODUCTION

1.1 Background and Research Needs

The modulus of elasticity of concrete is known to have a major effect on the performance of concrete pavements. Modulus of elasticity of concrete is an important input parameter to the American Association of State Highway Transportation Officials (AASHTO) Mechanistic Empirical Pavement Design Guide. Concrete pavements using concrete with a lower modulus of elasticity would have a lower stress due to the same applied load and thus could have a lower chance of cracking. In an investigation of the performance of Interstate 75 (I-75) concrete pavements in Sarasota and Manatee counties [Tia et al., 1989], it was reported that the percent cracked slabs increased with an increase in modulus of elasticity of the concrete. In another research study on pavement concrete, it was reported that the optimal concrete mixture for concrete pavement was not necessarily a concrete with a high flexural strength, but a concrete with a proper combination of low modulus of elasticity, low coefficient of thermal expansion, and adequate flexural strength [Tia et al., 1991].

Every year in the United States, more than 100 million tons of reclaimed asphalt pavement (RAP) are generated by asphalt pavement (AC) rehabilitation and reconstruction [Collins and Ciesielski, 1994]. Some have been recycled into new asphalt mixtures; some have been used as pavement base materials. However, a large quantity of RAP still remains unutilized and needs to be put to good use. An alternative use of RAP is to use it as an aggregate in Portland cement concrete (PCC). RAP has been experimented with as an aggregate in Portland cement concrete (PCC) to improve the toughness and ductility of the PCC. According to studies by Huang et al. [2006], RAP aggregate coated with asphalt forms a film with a thickness of about 6 to 9 μm. This asphalt film acts as an asphalt interface layer between the aggregate and cement mortar, which can blunt or even arrest the micro-cracking and delay the widening and propagating of the micro-cracking. Delwar et al. [1997] examined the stress-strain behavior of PCC containing RAP and found that PCC containing a higher amount of RAP fails at a higher strain level indicating that RAP may contribute to the ductility of PCC.

Another waste product of great abundance from the highway and building industry is recycled concrete aggregate (RCA). RCA has been used as a base material in flexible pavement construction, but its use in a new concrete pavement has not been fully exploited. Past research supported by the Florida Department of Transportation (FDOT) has also been focused on the use of recycled concrete as a base material for concrete and asphalt pavement. One of the reasons why RCA has not been used in pavement concrete in the past is the concern for its relatively lower strength as compared with concrete made with virgin aggregates. However, research results have indicated that concrete made with RCA had a reduction in elastic modulus [BCS of Japan, 1978]. Since using concrete with a lower modulus of elasticity would result in lower load-induced stresses in a concrete pavement, it could possibly result in an equal or even better pavement performance in service.

With the increasing volume of waste or by-product materials from industry, domestic and mining sources, decreasing availability of landfill space for disposal and depletion of virgin aggregates, there is a need to assess the feasibility of using RAP and RCA as aggregates in concrete for use in concrete pavements.

1.2 Research Objectives

The main research objectives of this study are as follows:

1) To evaluate the potential use of RAP and RCA in concrete and its effects on the mechanical and thermal properties of concrete; and

2) To determine the performance of concretes containing different amounts of RAP and RCA when used in a typical concrete pavement in Florida.

1.3 Research Approach

The following approaches were used in this research:

1) Performed a literature review on past and present studies on the use of RAP and RCA in concrete;
2) Prepared concrete mixtures containing natural aggregates, RAP, and RCA with varying proportions;
3) Evaluated the properties of concrete containing different amounts of RAP and RCA in the laboratory; and
4) Performed stress analyses on hypothetical concrete pavements under critical load and temperature conditions in Florida, if these pavements had been made with these concretes containing different amounts of RAP and RCA; and evaluated the potential performance of these hypothetical pavements based on the ratio of computed maximum stress to the flexural strength of the concrete.

CHAPTER 2
LITERATURE REVIEW

2.1 Properties of Concrete Containing RAP

RAP (reclaimed asphalt pavement) is a combination of both aged asphalt and aggregate, which is removed from existing distressed asphalt pavements. Experiments using RAP as an aggregate in concrete have been conducted by Huang et al. [2006]. It was found that the toughness and crack resistance of the concrete could be improved by the addition of RAP into concrete. In concrete made with RAP, asphalt forms a thin film at the interface of the cement mortar and aggregate as shown in Figure 2-1. This thin film can be useful in resisting the crack propagation going along that direction. Thus, a crack would propagate around the aggregate rather than going through it, during which more energy can be dissipated [Huang et al., 2006]. Generally, for a concrete with a high percentage of RAP, the concrete does not separate after failure but tries to sustain load even after initial failure.

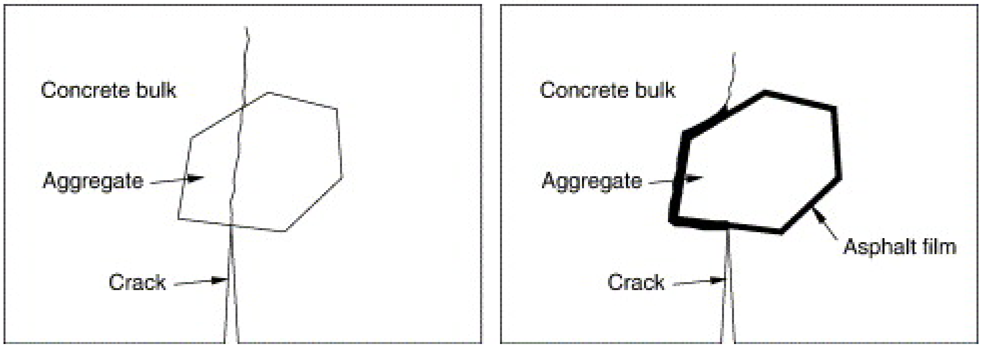

Figure 2-1. Propagation of crack through aggregate with and without asphalt film [Huang et al., 2006].

2.1.1 Strength of Concrete Containing RAP

It has been observed that, for a concrete incorporating RAP, the strength generally decreases with an increase in the content of RAP [Huang et al., 2006]. Figures 2-2 and 2-3 present the compressive strength and splitting tensile strength of concrete with a varying percent of RAP. Numbers 1 through 4 represent the concrete mixes with different RAP composition. Number 1 was the control mix and number 4 was a mix with the maximum percentage of RAP used [Huang et al., 2006]. Results from a study by Delwar et al. [1997] showed similar trends.

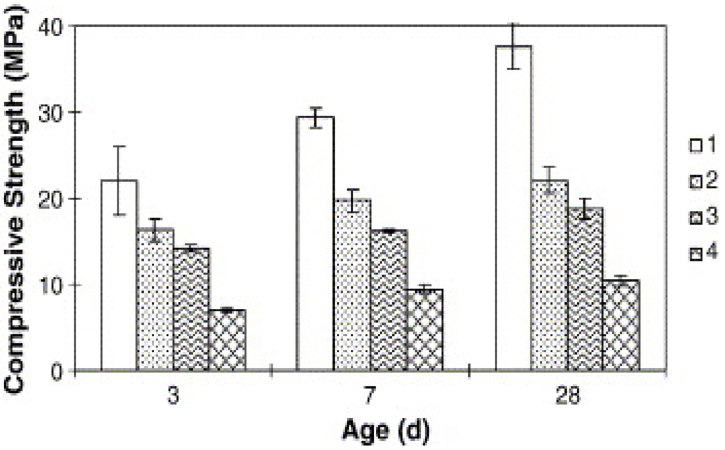

Figure 2-2. Compressive strength of concrete with a varying percent of RAP [Huang et al., 2006].

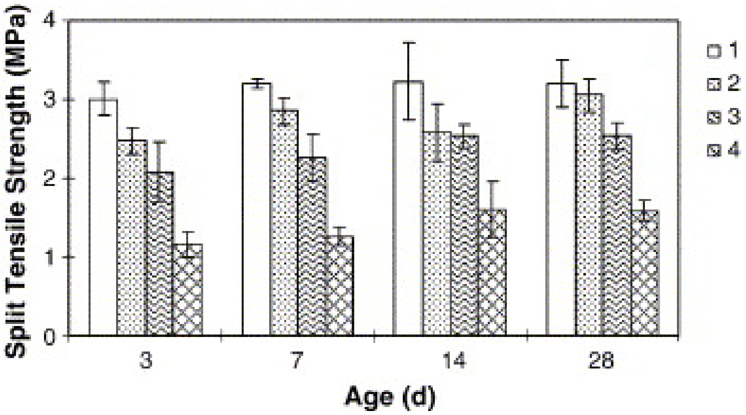

Figure 2-3. Splitting tensile strength of concrete with a varying percent of RAP [Huang et al., 2006].

Table 2-1 presents the compressive strength of concrete containing RAP from this study. Concrete made with natural aggregates yielded the highest compressive strength. At 28 days of curing, a compressive strength of 3180 psi was obtained for a mixture that contained 100% gravel and 100% RAP fines, as compared with a compressive strength of 5300 psi for a control mix [Delwar et al., 1997]. For a beam with 50% gravel, 50% coarse RAP, 100% fine RAP and 0.40 water-to-cement (w/c) ratio, the modulus of rupture was about 685 psi. [Delwar et al., 1997].

Table 2-1. Compressive Strength of Concrete Containing RAP [Delwar et al., 1997]

Aggregate Composition-Percent	Compressive Strength Range	
	w/c = 0.5 (psi)	w/c = 0.4 (psi)
Fine RAP-100 Coarse RAP-100	750	1600
Fine RAP-50 Sand-50 Coarse RAP-100	1300	1800
Fine RAP-25 Sand-75 Coarse RAP-100	1600	2000
Sand-100 Coarse RAP-100	1700	2300
Fine RAP-100 Coarse RAP-100	900	1700
Fine RAP-100 Gravel-50 Coarse RAP-50	1800	1900
Fine RAP-100 Gravel-75 Coarse RAP-25	2100	2600
Fine RAP-100 Gravel-100	2700	3200
Gravel-100 Sand-100	3800	5300

Note: Above strengths are not the exact values obtained by the authors, they have been rounded to nearest upper or lower whole digit number.

2.1.2 Secant Modulus of Concrete Containing RAP

Table 2-2 presents the secant modulus values of concrete with different percentages of RAP from a study by Delwar et al. [1997]. For a concrete made with 100% fine and 100% coarse RAP, the secant modulus was 1.39×10^6 psi, while for a concrete with 100% sand and 100% gravel, the secant modulus was 3.56×10^6 psi with the same w/c ratio of 0.5. The secant modulus for concrete made with 100% coarse and fine RAP was 1.18×10^6 psi, while for concrete with 100% sand and gravel it was 4.24×10^6 with 0.4 w/c ratio. Therefore, secant modulus increases with a decrease in w/c ratio for both the concretes with and without RAP.

Table 2-2. Secant Modulus of Concrete Containing RAP [Delwar et al., 1997]

Aggregate Composition-Percent	Secant Modulus	
	w/c = 0.5 (psi)	w/c = 0.4 (psi)
Coarse RAP-100 Fine RAP-100	1,392,000	1,185,455
Coarse RAP-50 Gravel-50 Fine RAP-100	1,555,555	1,536,000
Gravel-100 Fine RAP-100	2,846,753	2,958,140
Coarse RAP-100 Sand-50 Fine RAP-50	1,266,666	1,453,763
Coarse RAP-100 Sand-100	1,710,000	2,340,000
Gravel-100 Sand-100	3,568,421	4,240,000

2.2 Historical Overview of Concrete Recycling

Recycling in the construction industry dates back several centuries. The Romans are thought to be the first to develop recycling technology more than 1900 years ago. They built walls, roads, and aqueducts with concrete using rock, and sometimes crushed burnt clay brick, as an aggregate [Schulz, 1988]. Recycling of concrete on a large scale began within Europe after the widespread destruction brought about by World War II. In Germany, recycling became an important way of using debris created during war. Since rebuilding the transportation infrastructure was a top priority, Germany developed an early lead in the recycling of rubble into new highway construction products. For example, by 1987 some 100 million tons of debris had been processed into aggregate and other products in Berlin alone [Von Stein, 1993]. The first modern recorded use of concrete recycling occurred in the U.S. in 1942 [Richardson and Jordan, 1994]. It was performed by the Portland Cement Association and was used in the rehabilitation of failed road pavement in Kansas. The use of the recycled concrete became more common in the 1970's when the U.S. Army utilized it for runway construction. The Federal Highway Administration (FWHA) also began programs in recycling since the early 1970's.

2.3 Current Development in Concrete Recycling

Since the year 2000, there has been a renewed interest in recycling, spurred by an increasing volume of waste or by-product materials from industry, domestic and mining sources and a decreasing availability of landfill space for disposal [Simon et al., 2000]. In 2003, the FHWA undertook a national review of use of recycled concrete aggregate, and the results were published in September 2004. Its purpose was to capture, for technology transfer, the most advanced uses of recycled concrete aggregate by state highway agencies. The FHWA found that concrete routinely is being recycled into the highways of the United States, and its principal application has been as base material [Kuennen, 2008].

The Construction Materials Recycling Association maintains that 140 million tons of concrete are recycled per year in the United States. However, many economic factors impact the supply including equipment costs, transportation costs, and external landfill tipping fees. A major obstacle is the cost of crushing, grading, controlling dust, and separating out undesirable constituents when using building rubble as aggregate for concrete. RCA from crushed concrete pavement and massive structures can prove to be an economical source of aggregate where good quality aggregates are scarce and when the cost of waste disposal of concrete rubble is high [Mehta and Monteiro, 2006]. Aggregate producers need to contend with these factors before making a decision to enter the recycle market. In 2005, the United States Geological Survey (USGS) reported the average U.S. price of RCA as $7.62 per metric ton, which compares well with virgin stone of an average of $7.16 per metric ton. The degree of penetration of RCA into a local market will depend on availability of demolition materials, its quality after processing, local labor costs and local landfill tipping fees [Kuennen, 2007a]. The March 2007 issue of *Rock Products* reported on a Transportation Research Board paper that supported higher substitution of RCA for virgin aggregates in large airfield applications [Kuennen 2007a]. Saeed et al. [2007] of Applied Research Association Inc., reported in their paper, "Comprehensive Evaluation, Design, and Construction Techniques for Airfield Recycled Concrete Aggregate as Unbound Base," that a small increase in the amount of recycled concrete aggregate to replace the virgin aggregate in pavement construction will have large economic and environmental benefits while extending the supply of traditional construction materials.

A survey conducted of many highway agencies in the United States depicts a great potential for the use of recycled aggregates in new pavement construction. There are sufficient published data currently available to demonstrate that RCA is a viable alternative to virgin aggregate for unbound base course construction. In the State of Florida, it is estimated that about 10% of the current aggregate requirement is produced from recycling. In 2001, FDOT undertook a study on the "Use of Recycled Concrete Made with Florida Limestone Aggregate for a Base Course in Flexible Pavement," and the report submitted by Kuo et al. [2001], supported the hypothesis that RCA can be used effectively as a base course when appropriate quality control techniques are utilized. Thus, RCA from demolished materials is broadly accepted as a base material, but its use as an aggregate in concrete itself has not been fully accepted.

In 1983, deteriorated concrete from a 9-km (6-mi) long freeway pavement in Michigan was crushed, and the rubble was used as aggregate for concrete that was needed for the construction of the new pavement [Mehta and Monteiro, 2006]. In 1986, the Illinois Department of Transportation (IDOT) undertook a demonstration project to monitor the construction and performance of two separate concrete pavements constructed from an old recycled PCCP. On one project, an old, badly faulted, jointed reinforced concrete (JRC) pavement containing high quality aggregates was recycled into a new continuously reinforced concrete (CRC) inlay. On the second project, a deteriorated CRC pavement containing D-cracking susceptible aggregates was recycled into a full-depth asphalt concrete (AC) inlay. Inlays were constructed because the existing shoulders were in good condition. The construction of both projects was monitored. Performance monitoring of the recycled pavement began in 1987 and included friction testing, ride quality testing, visual distress surveys, and deflection testing with a Falling Weight Deflectometer. After five to six years in service, no major maintenance has been required and both pavements have been performing well. RCA is not used in higher-quality applications often because of long-term performance considerations and because most professionals are hesitant to use a relatively untested material with no developed guidelines or specifications for its use [Wilburn and Goonan, 1998]. Moreover, the reuse of crushed concrete as aggregate in high-grade concrete has up to now been restricted by a lack of standards, experience, and knowledge.

It would require extensive screening and testing of the recycled material to produce recycled coarse aggregate that would potentially meet the technical specifications and performance expectations for structural Portland cement concrete. However, laboratory research and experience at several recent projects have proven that it is feasible to use recycled concrete as aggregate for new concrete mixtures. The use of recycled fine aggregate is, however, mostly unsuitable due to the large amount of hydrated cement and gypsum. Specifications often vary considerably by local climatic conditions and product availability because the quality of the recycled materials varies from location to location and is fairly difficult to control. The above studies suggest that there is technical feasibility in the use of recycled old PCCP as aggregates for new PCCP.

2.4 General Properties of Recycled Concrete Aggregates (RCA) from Concrete Pavement

2.4.1 Production of RCA

Recycled Concrete Aggregates (RCA) from existing concrete pavements or other concrete structures involves the demolition of the existing structure, removal and transporting of broken concrete to the crusher, removal of steel, if any, then crushing, sizing, and stockpiling of the aggregates. The breaking up procedure used depends on a number of factors, key amongst them are the location, the condition of the existing pavement, and traffic. This is done to reduce the concrete into smaller sizes in order for it to be easily transported. Most commonly used demolishing equipment includes hand-operated power tools, vehicle-mounted equipment, and hydro demolition equipment. The removal and transporting of the broken concrete to the crusher involves the use of various equipment key amongst them are backhoes/hydraulic excavators, loaders/front-end loaders and trucks/dump trucks. Crushing is usually performed in two steps: a primary crusher reduces the larger incoming debris, and a secondary crusher further reduces the material to the desired particle size. Magnetic ferrous metal recovery can take place after both stages. The two main types of equipment are jaw and impact crushers. Jaw crushers are best suited to quickly reduce large or odd-shaped debris from construction and demolished projects to a manageable size. Impact crushers are more effective than jaw crushers at freeing rebar encased in rubble. At the crushing plant, all steel reinforcement or wire mesh is removed and the aggregate is sized to the desired dimension and stockpiled. The processed RCA typically consists of 60% to 75% high-quality, well-graded aggregate that is held together by the hardened cement paste [Kuo et al., 2001]. The amount of cement paste that remains attached to aggregate particles in RCP after processing depends on the process used to manufacture RCP and properties of the original concrete. Cement paste attached to aggregate particles in RCP makes RCP less heavy than conventional aggregate [Saeed et al., 2007].

2.4.2 Physical and Mechanical Properties of Coarse Recycled Aggregates

Recycled coarse aggregates have attached mortar which influences its physical and mechanical properties in both fresh and hardened concrete. The physical properties of recycled aggregates depend on both the adhered mortar quality and the amount of adhered mortar. The crushing procedure and the dimension of the recycled aggregate have an influence on the amount of adhered mortar [Hansen, 1986]. The adhered mortar is a porous material; its porosity depends upon the w/c ratio of the recycled concrete employed [Nagataki et al., 2000]. The absorption capacity is one of the most significant properties which distinguish recycled aggregate from raw aggregates, and it can have an influence both on fresh and hardened concrete properties.

Compared with virgin coarse aggregates, recycled coarse aggregates are highly angular in shape and have a rougher surface texture, lower specific gravity, and higher water absorption. Furthermore, recycled aggregates are more permeable than most natural sands, crushed limestone and gravel [Chesner et al., 1998]. Generally, up to 30% of the conventional aggregate in concrete may be replaced by recycled aggregate without significantly affecting the mechanical properties of the new concrete. This may be the simplest, most economical, and least controversial way of getting wider use of recycled aggregates in new concrete [ECCO, 2003].

2.4.3 Gradation

The gradation of aggregates refers to the particle size distribution. The gradation mainly influences the workability and the cost of the concrete. Specifications for the gradation are normally based on the gradation limits and the maximum aggregate size. As any aggregate used for concrete, RCA must meet the gradation requirements, it must be strong, possess good dimensional stability and provide acceptable workability. Moreover, RCA must be inert and free from potential harmful impurities that affect the environment. Most research into recycled coarse aggregates shows that the aggregates meet ASTM C 33 specifications for coarse aggregates.

2.4.4 Particle Shape and Texture

The shape and texture of aggregate particles mainly influences the properties of fresh concrete more than hardened concrete. Compared to smooth and rounded particles, rough-textured, angular and elongated particles require more cement paste to produce workable concrete mixtures. Surface texture refers to the degree to which the surface of the aggregates is smooth or rough and is based on visual judgment [Mehta and Monteiro, 2006, p. 276]. Surface texture depends on the hardness, grain size, and porosity of the parent rock and its subsequent exposure to forces of attrition. Demolished plain and reinforced concrete can be crushed in various types of crushers to provide recycled aggregate with an acceptable particle shape, but the type of crushing equipment influences the gradation and other characteristics of crushed concrete fines. Compared with natural aggregates, the surface texture and shape of recycled aggregates are generally rough, porous and highly angular. This is attributed to the presence of the old mortar. Typically, 30% to 60% by volume of old mortar is adhered to recycled coarse aggregate particles, depending on the aggregate size. More old mortar is attached to the smaller size fractions of coarse aggregate [ECCO, 2003].

2.4.5 Specific Gravity

Due to the large amount of old mortar and cement paste adhered to recycled aggregates, their specific gravity (relative density) is 5% to 10% lower than that of the virgin aggregates in old concrete. Typical values of specific gravity of recycled aggregates range between 2.2 and 2.5 in the saturated surface dry condition [ECCO, 2003; Saeed et al., 2007].

2.4.6 Density

In general, recycled aggregates have densities slightly lower than virgin aggregates. Hansen [1986] and BCS of Japan [1978] attributed this to the low density of cement mortar attached to the aggregates. Variations in w/c ratios of the concrete did not significantly affect the densities [Hansen, 1986].

2.4.7 Water Absorption

Water absorption of recycled aggregates happens to be one of the major property differences between recycled and virgin aggregates. BCS of Japan [1978] and Hansen [1986] concluded that the higher water absorption of the coarse aggregates is a result of the absorption of the old cement mortar attached to the aggregate particles. NCHRP Report 598 [2008] gave typical water absorption of recycled coarse aggregates in the United States to be between 2% and 6%. Absorption rates for crushed concrete fines range from 4% to 8%. Pre-soaking of recycled aggregates is sometimes recommended to help maintain uniformity.

2.4.8 Los Angeles Abrasion Loss

The abrasion resistance of aggregates is very important in concrete pavements. ASTM C 33 indicates that aggregates for use in concrete construction should have abrasion loss of less than 50% for general construction and for crushed stone used under pavements losses should be less than 40%. Hansen [1986] concluded, based on available data, that recycled concrete aggregates produced from all but the poorest quality recycled concrete can be expected to pass ASTM requirements for concrete aggregates. NCHRP Report 598 [2008] reported typical LA abrasion loss for recycled coarse aggregates in the United States to be between 20% and 45%.

2.4.9 Sulfate Soundness

Sulfate soundness tests (ASTM C 88) are required by ASTM C 33, and recycled concrete fine and coarse aggregates may be tested by ASTM C 88 to ensure appropriate resistance to freezing and thawing of the recycled aggregates. NCHRP Report 598 [2008] reported typical magnesium sulfate loss for recycled coarse aggregates in the United States to be less than 9%.

2.5 Properties of Concrete Made from RCA

2.5.1 Fresh Concrete

2.5.1.1 Mix design

The principles used to design concrete mixtures with conventional aggregates apply to using recycled aggregates with additional care. Trial mixtures are required to determine proper proportions and to check the quality of new concrete. Hansen [1986] recommended that all recycled concrete aggregates be pre-soaked to offset the high absorption before mixing.

2.5.1.2 Water-to-cement (w/c) ratio

Selection of the water-to-cement (w/c) ratio is the most critical part of controlling the strength of the concrete. There is excellent correlation between the w/c ratio and compressive and flexural strength. Hansen concluded that the w/c ratio is as valid for recycled aggregate concrete as it is for concrete made with virgin materials, but the level of strength development would be reduced [Hansen 1986]. To produce a similar workability, Mukai and Koizumi [1979] found that 5% more water was required for a recycled coarse aggregate concrete. Buck [1976] has found that approximately 15% more water was needed to produce the same workability for both fine and coarse recycled aggregate concrete. Mukai and Koizumi [1979] and Hansen and Narud [1983] found bleeding from recycled aggregate concrete to be slightly less than from concrete using virgin aggregates.

2.5.1.2 Unit weight and air content

Mukai and Koizumi [1979] and Hansen and Narud [1983] concluded that unit weights of concrete made using recycled concrete as aggregate were within 85% to 95% and 95% of the original concrete mixture, respectively. Mukai and Koizumi [1979] found that air content of freshly recycled concrete was higher and varied more than air content of fresh control mixtures. Hansen and Narud [1983] found that air content of recycled aggregate concrete was up to 0.6% higher. Hansen [1986] concluded that the air content of recycled aggregate concrete was slightly higher and that densities could be 5% to 15% lower.

2.5.1.3 Fine-to-coarse aggregate ratio

From the point of view of both economy and cohesion of fresh concrete, BCS of Japan [1978] found that the optimum ratio of fine-to-coarse aggregate is the same for recycled aggregate concrete as it is for concrete made from virgin materials [Hansen, 1986]. Studies by Kasai [1985] indicate that the fineness of recycled concrete aggregates decreases with time of mixing. This is most likely a result of mechanical removal of cement paste from the recycled coarse aggregates.

2.5.2 Hardened Concrete

2.5.2.1 Compressive strength

A number of studies have investigated the strengths of concrete made with recycled aggregates. Most found reductions in strengths from approximately 5% to 24% using recycled aggregates [Hansen, 1986]. Hansen and Narud [1983] found that recycled aggregate concrete obtained approximately the same strengths as the original concrete from which they were made. Bernier et al. [1978] found similar results, except that, in the case of high-strength concrete produced from low-strength recycled coarse aggregates, they found that the compressive strength was 39% lower than the high-strength concrete produced from high-strength recycled aggregates. Hansen and Narud [1983] concluded that the compressive strength of recycled concrete depends on the strength of the original concrete and it is largely controlled by a combination of the w/c ratio of the original concrete and the w/c ratio of the recycled concrete. Reports by Hansen and Narud [1983] and Buck [1976] concluded that higher strength concrete could be made with recycled aggregates from lower-strength concrete.

Concrete manufactured from both coarse and fine recycled aggregates has been investigated. The majority of researchers found that the compressive strength for concrete manufactured from recycled coarse and fine aggregates was lower by 15% to 40% of the strength of concrete made with all naturally occurring materials. Rasheeduzzafar [1984] found that the low strength and corresponding high water absorption for recycled concrete could be offset by lowering the w/c ratio of the recycled concrete by 0.05 to 0.10.

Blends of 50% natural and 50% recycled sands produced strengths 10% to 20% less than recycled concrete made with all natural sands. Further examination reveals that certain portions of the fine recycled aggregates appear to inhibit recycled concrete performance. Studies indicate that the majority of strength loss is brought about by that portion of the recycled aggregate smaller than 2 mm. Therefore, the use of any recycled fines in concrete production may be prohibited [Hansen, 1986].

2.5.2.2 Tensile and flexural strength

Various researchers have investigated the effect of recycled aggregates on flexural and tensile strengths. The majority of findings indicate that concrete made from recycled coarse aggregates and natural fine aggregates has generally the same or, at most, a 10% reduction in tensile strength. Generally, concrete made from recycled coarse and fine aggregates has reductions in tensile strength of less than 10% and a maximum of 20% reduction for the worst case [Hansen, 1986].

2.5.2.3 Elastic modulus

BCS of Japan [1978] investigated the change in modulus of elasticity of concrete made using recycled concrete aggregates. They reported that the reductions in modulus of elasticity made with recycled coarse and fine aggregates varied from 25% to 40%. They also reported that the reductions in modulus of concrete made with recycled coarse aggregates varied only from 10% to 33%.

2.5.2.4 Drying shrinkage

Concrete made with recycled coarse aggregates and natural sands produced shrinkages of 20% to 50% greater than concrete made with all natural aggregates [BCS of Japan, 1978]. Concrete made with recycled coarse and fine aggregates produced shrinkages that are 70% to 100% greater than that of corresponding natural aggregates [BCS of Japan, 1978]. Hansen [1986] found that shrinkages were greater for higher-strength concrete than for lower strength concrete. The increase in the drying shrinkage may be due to the combined effects of lower modulus of elasticity of the aggregates and additional shrinkage caused by mortar adhering to aggregates [Sri Ravindrarajah and Tam, 1985]. Thus, from the point of view of shrinkage, the use of recycled aggregates is undesirable. However, it is possible to reduce the shrinkage by making modifications to the mix design.

2.5.2.5 Coefficient of thermal expansion

Coefficient of thermal expansion (CTE) is a key property of concrete that controls the amount of expansion/contraction due to changes in temperature. The coefficient of thermal expansion of a mix mainly depends on the aggregate type and the amount of aggregate in a mix. Limestone is known to have the lowest coefficients of thermal expansion compared with rocks such as sandstone and granite. In research by Smith and Tighe [2009] on concrete containing 0%, 15%, 30% and 50% of coarse RCA showed that as the coarse RCA content increased, the CTE decreased.

2.5.2.6 Creep

Hansen [1986] found creep for concrete manufactured from recycled aggregates to be 30% to 60% greater than for concrete manufactured from virgin materials. These results are not surprising because concrete containing recycled aggregates has up to 50% more paste volume, and creep of concrete is proportional to the content of paste or mortar in the concrete [Lamond et al., 2001].

2.5.2.7 Permeability

Concrete made from recycled aggregates with a w/c ratio of 0.5 to 0.7 has permeability two to five times that of concrete made with natural aggregates [Hansen, 1986].

2.5.2.8 Freezing and thawing resistance

Many studies of freezing-and-thawing resistance indicate that there is almost no difference between that of concrete made with virgin aggregates and that made with recycled aggregates [Hansen, 1986]. A report by BCS of Japan [1978], however, indicated that concrete made from recycled coarse and fine aggregates had significantly reduced resistance to freezing-and-thawing damage. They also found that if the fine aggregates were replaced with virgin materials, the freezing-and-thawing resistance was comparable to the original concrete. Another Japanese study indicated that air entrained concrete made with recycled aggregates had less freezing-and-thawing resistance than the concrete made with virgin materials [Hasaba et al., 1981].

2.5.2.9 Carbonation, chloride penetration, and reinforcement corrosion

BCS of Japan [1978] concluded that the rate of carbonation of a recycled aggregate concrete made with concrete that had already suffered carbonation was 65% higher than the control concrete made with conventional aggregates. BCS also concluded that reinforcement in recycled concrete may corrode faster than in conventional concrete. This accelerated corrosion, however, could be offset by reducing the w/c ratio of the recycled concrete. Additional studies by Rasheeduzzafar [1984] confirmed these conclusions. Hansen [1986] also concluded that a reduction in w/c ratio reduces the corrosion potential of recycled concrete.

CHAPTER 3
TESTING PROGRAM TO EVALUATE CONCRETE CONTAINING RAP

3.1 Introduction

This chapter describes the laboratory testing program utilized to evaluate the use of reclaimed asphalt pavement (RAP) material in concrete. It provides the mix proportion and mix ingredients used for the concrete mixture in this testing program, and also explains the standard method of preparation of the concrete mixture in laboratory, fabrication procedure, and standard ASTM testing methods performed in this testing program.

3.2 Concrete Mix Proportions

Two different RAP materials were used in this study. The percentages of RAP incorporated in different concrete mixtures evaluated are shown in Tables 3-1 and 3-2. The mix proportions for these different mixtures are shown in Tables 3-3 and 3-4.

3.3 Mix Ingredient Properties

The properties of the mix ingredients are described in this section.

3.3.1 Water

Normal tap water supplied locally by the city water supply system was used. Clean water was used without allowing any unwanted impurities to get into it.

3.3.2 Cement

Portland cement Type I/II supplied by Florida Rock Industry was used. Tables 3-5 and 3-6 show the physical and chemical properties of the cement as determined by Florida Department of Transportation personnel.

Table 3-1. Concrete Mixes Containing RAP-1 to be Evaluated

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Coarse Aggregate (% of total coarse aggregate)		Fine Aggregate (% of total fine aggregate)		Total RAP (% of total aggregate)
				Virgin	RAP	Virgin	RAP	
Set-1 RAP-1	1	0.53	508	100	0	100	0	0
	2	0.53	508	90	10	90	10	10
	3	0.53	508	80	20	80	20	20
	4	0.53	508	60	40	60	40	40
Set-2 RAP-1	1	0.53	508	100	0	100	0	0
	2	0.53	508	90	10	90	10	10
	3	0.53	508	80	20	80	20	20
	4	0.53	508	60	40	60	40	40
Set-3 RAP-1	1	0.53	508	100	0	100	0	0
	2	0.51	508	90	10	90	10	10
	3	0.48	508	80	20	80	20	20
	4	0.43	508	60	40	60	40	40

Table 3-2. Concrete Mixes Containing RAP-2 to be Evaluated

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Coarse Aggregate (% of total coarse aggregate)		Fine Aggregate (% of total fine aggregate)		Total RAP (% of total aggregate)
				Virgin	RAP	Virgin	RAP	
Set-1 RAP-2	1	0.53	508	100	0	100	0	0
	2	0.53	508	90	10	90	10	10
	3	0.53	508	80	20	80	20	20
	4	0.53	508	60	40	60	40	40
Set-2 RAP-2	1	0.48	562	182	18	77	23	20
	2	0.48	562	66	34	47	53	40
	3	0.43	628	82	18	76	24	20
	4	0.43	628	67	33	44	56	40
Set-3 RAP-2	1	0.43	508	100	0	100	0	0
	2	0.43	562	82	18	76	24	20
	3	0.43	562	67	33	44	56	40
	4	0.43	562	67	33	44	56	40
	1	0.48	508	100	0	100	0	0
	2	0.48	562	82	18	77	23	20
	3	0.48	562	66	34	47	53	40
	1	0.53	508	100	0	100	0	0
	2	0.53	562	82	18	77	23	20
	3	0.53	562	66	34	47	53	40

Table 3-3. Mix Proportions for Concrete Containing RAP-1

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Coarse Aggregate (lb/cy)		Fine Aggregate (lb/cy)		Air Entrainer WR Grace Daravair 1000 (oz)	Admixture WR Grace WRDA 60 (oz)
					Virgin	RAP	Virgin	RAP		
Set-1 RAP-1	1	0.53	508	270	1782	0	1239	0	/	/
	2	0.53	508	270	1604	167	1115	103	/	/
	3	0.53	508	270	1426	335	991	205	/	/
	4	0.53	508	270	1069	670	743	410	/	/
Set-2 RAP-1	1	0.53	508	270	1782	0	1239	0	/	/
	2	0.53	508	270	1604	167	1115	103	/	/
	3	0.53	508	270	1426	335	991	205	/	/
	4	0.53	508	270	1069	670	743	410	/	/
Set-3 RAP-1	1	0.53	508	270	1782	0	1239	0	/	/
	2	0.51	508	260	1604	167	1115	103	/	/
	3	0.48	508	245	1426	335	991	205	/	/
	4	0.43	508	215	1069	670	743	410	/	/

Table 3-4. Mix Proportions for Concrete Containing RAP-2

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Coarse Aggregate (lb/cy)		Fine Aggregate (lb/cy)		Air Entrainer WR Grace Daravair 1000 (oz)	Admixture WR Grace WRDA 60 (oz)
					Virgin	RAP	Virgin	RAP		
Set-1 RAP-2	1	0.53	508	270	1782	0	1239	0	/	/
	2	0.53	508	270	1604	167	1115	103	/	/
	3	0.53	508	270	1426	335	991	205	/	/
	4	0.53	508	270	1069	670	743	410	/	/
Set-2 RAP-2	1	0.48	562	270	1563	221	833	337	/	/
	2	0.48	562	270	1304	445	452	673	/	/
	3	0.43	628	270	1544	219	776	331	/	/
	4	0.43	628	270	1351	438	385	664	/	/
Set-3 RAP-2	1	0.43	628	270	1736	0	1187	0	/	18
	2	0.43	628	270	1544	219	776	331	6.6	/
	3	0.43	628	270	1351	438	385	664	6.6	/
	4	0.43	628	270	1351	438	385	664	/	/
	1	0.48	562	270	1760	0	1214	0	/	18
	2	0.48	562	270	1563	221	833	337	/	/
	3	0.48	562	270	1304	445	452	673	/	18
	1	0.53	508	270	1782	0	1239	0	/	/
	2	0.53	508	270	1561	226	850	342	/	/
	3	0.53	508	270	1426	335	991	205	/	/

Table 3-5. Physical Properties of Portland Cement [FDOT, 2007]

Test	Standard Specification	Cement
Loss of ignition	ASTM C114	0.30%
Autoclave expansion	ASTM C151	0.04%
Time of setting (initial)	ASTM C266	190 min
Time of setting (final)	ASTM C266	290 min

Table 3-6. Chemical Properties of Portland Cement [FDOT, 2007]

Constituents	Percent
Silicon dioxide	20.5%
Aluminum oxide	5.20%
Ferric oxide	3.80%
Magnesium oxide	0.60%
Sulfur trioxide	2.80%
Tricalcium aluminate	7%
Tricalcium silicate	54%
Total alkali as Na_2O	0.25%

3.3.3 Virgin Aggregate

Silica sand from Goldhead of Florida was used as fine aggregate, and Number 57 Miami Oolite limestone was used as coarse aggregate. Physical properties of this aggregate were obtained by FDOT personnel. The properties of the fine and coarse aggregate are shown in Tables 3-7 and 3-8. Figure 3-1 shows the gradation chart for the fine and coarse aggregates.

Table 3-7. Specific Gravity and Water Absorption of Virgin Aggregates [FDOT, 2007]

Property	Coarse Aggregate	Fine Aggregate
SSD specific gravity	2.37	2.64
Dry bulk specific gravity	2.28	2.63
Dry apparent specific gravity	2.52	2.65
Absorption	4.31%	0.30%

Table 3-8. Results of Sieve Analysis on the Virgin Aggregates

Sieve Size		Percent Passing	
(inches or number)	(mm)	Coarse Aggregate	Fine Aggregate
1″	25.0	100%	/
1/2″	12.5	50%	/
#4	4.75	8%	100%
#8	2.36	5%	97%
#16	1.18	/	85%
#30	0.60	/	57%
#50	0.30	/	18%
#100	0.15	/	1%
#200	0.075	/	/
Fineness modulus			2.41

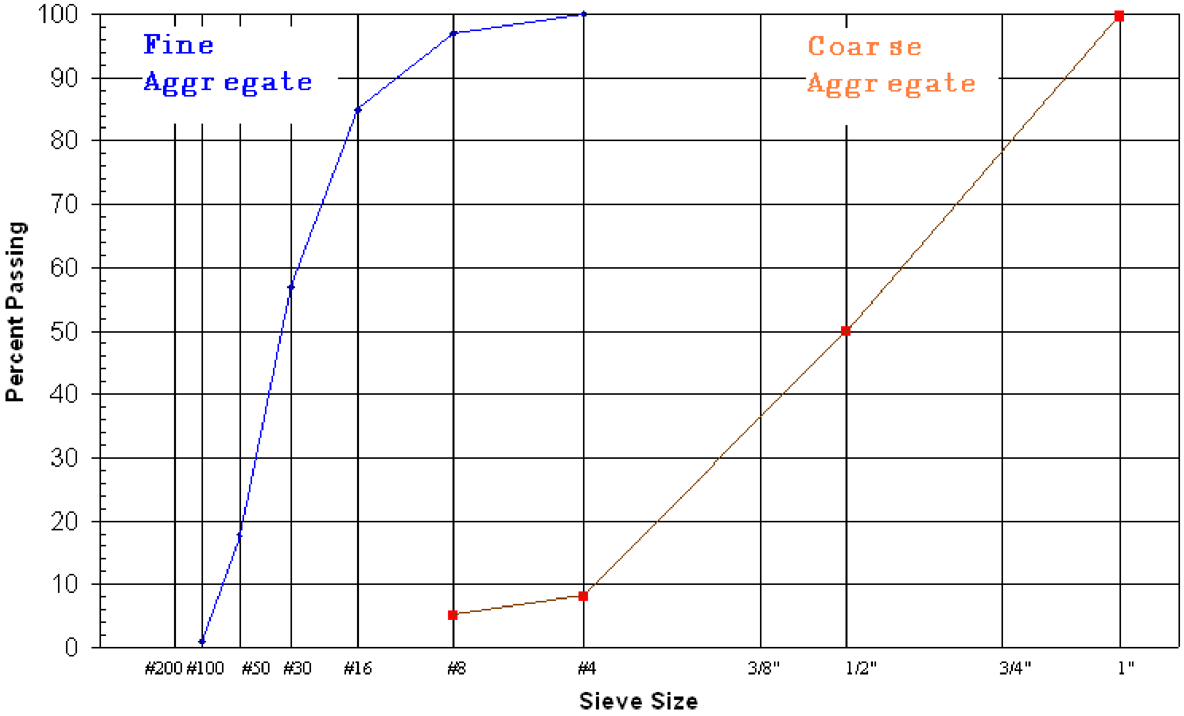

Figure 3-1. Gradation plot for the virgin aggregate used.

3.3.4 Recycled Asphalt Pavement (RAP)

RAP was obtained from a RAP stockpile at an asphalt plant owned by Whitehurst and Sons, Inc., in Gainesville. The RAP material was separated into a coarse portion and a fine portion using a #4 sieve. Tests were run on the RAP to determine their specific gravity, water absorption and gradation. Two different RAP materials obtained from the same plant at two different times were used. The specific gravity and water absorption of the RAP materials are shown in Table 3-9. The results of sieve analysis on the RAP material are shown in Tables 3-10 and 3-11. Gradation plots for the different RAP materials are shown in Figures 3-2 and 3-3.

Table 3-9. Specific Gravity and Water Absorption of the RAP Materials Used

Property	Coarse RAP-1	Fine RAP-1	Coarse RAP-2	Fine RAP-2
SSD specific gravity	2.231	2.185	2.309	2.325
BSG specific gravity	2.186	2.125	2.259	2.283
ASG specific gravity	2.290	2.261	2.377	2.383
Absorption	2.08%	2.84%	2.20%	1.77%

Table 3-10. Results of Sieve Analysis on RAP-1

Sieve Size		Percent Passing		Recovered Aggregate
(inches or number)	(mm)	Coarse RAP	Fine RAP	
2"	50.0	100.00	/	/
3/2"	37.5	98.30	/	/
1"	25.0	97.07	/	/
3/4"	19.0	87.47	/	/
1/2"	12.5	67.40	/	100
3/8"	9.5	50.97	/	98
#4	4.75	0.00	100	76
#8	2.36	/	80.95	60
#16	1.18	/	60.71	51
#30	0.60	/	37.5	40
#50	0.30	/	12.1	24
#100	0.15	/	1.98	9
#200	0.075	/	0	5.2
Fineness modulus			3.07	
Asphalt content				6.30%

Table 3-11. Results of Sieve Analysis on RAP-2

Sieve Size		Percent Passing		Recovered Aggregate
(inches or number)	(mm)	Coarse RAP	Fine RAP	
2"	50.0	100.00	/	/
3/2"	37.5	100.00	/	/
1"	25.0	100.00	/	/
3/4"	19.0	96.00	/	100
1/2"	12.5	80.00	/	92.74
3/8"	9.5	60.00	/	79.58
#4	4.75	14.00	100	43.79
#8	2.36	8.00	81	34.31
#16	1.18	/	61	29.51
#30	0.60	/	40	25.24
#50	0.30	/	20	19.42
#100	0.15	/	5	11.33
#200	0.075	/	1	6.53
Fineness modulus			3.92	
Asphalt content				5.40%

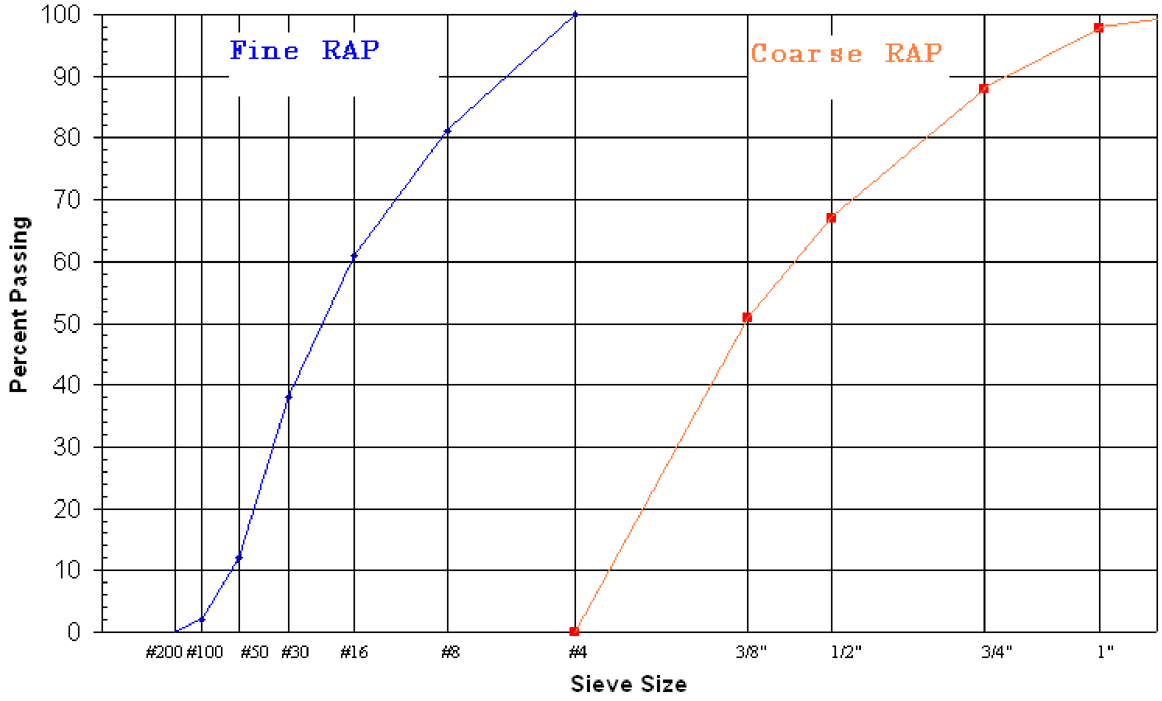

Figure 3-2. Gradation plot for RAP-1 material.

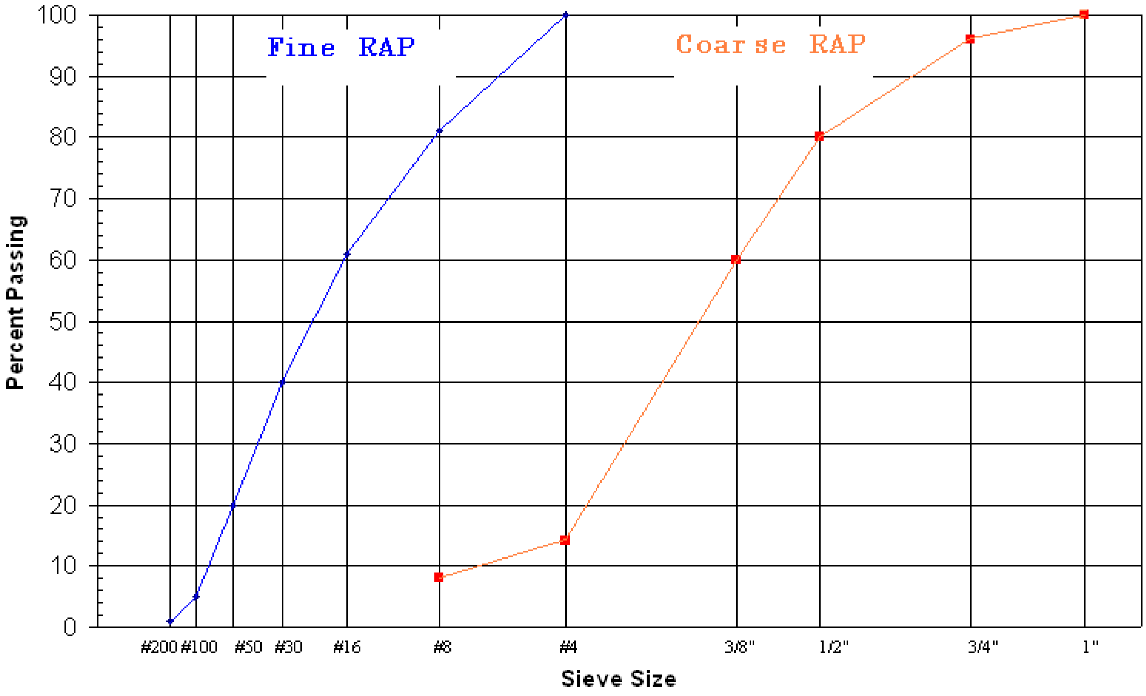

Figure 3-3. Gradation plot for RAP-2 material.

3.3.5 Combined Gradation Plots

Figures 3-4 through 3-7 show the combined gradation plots for concrete mixtures containing different percentages of RAP. The combined gradation plots show the differences in the gradation of RAP-1, RAP-2, and virgin aggregate when incorporated in a concrete mixture. It shows that mixtures containing RAP are more dense-graded as compared with the mixtures without RAP.

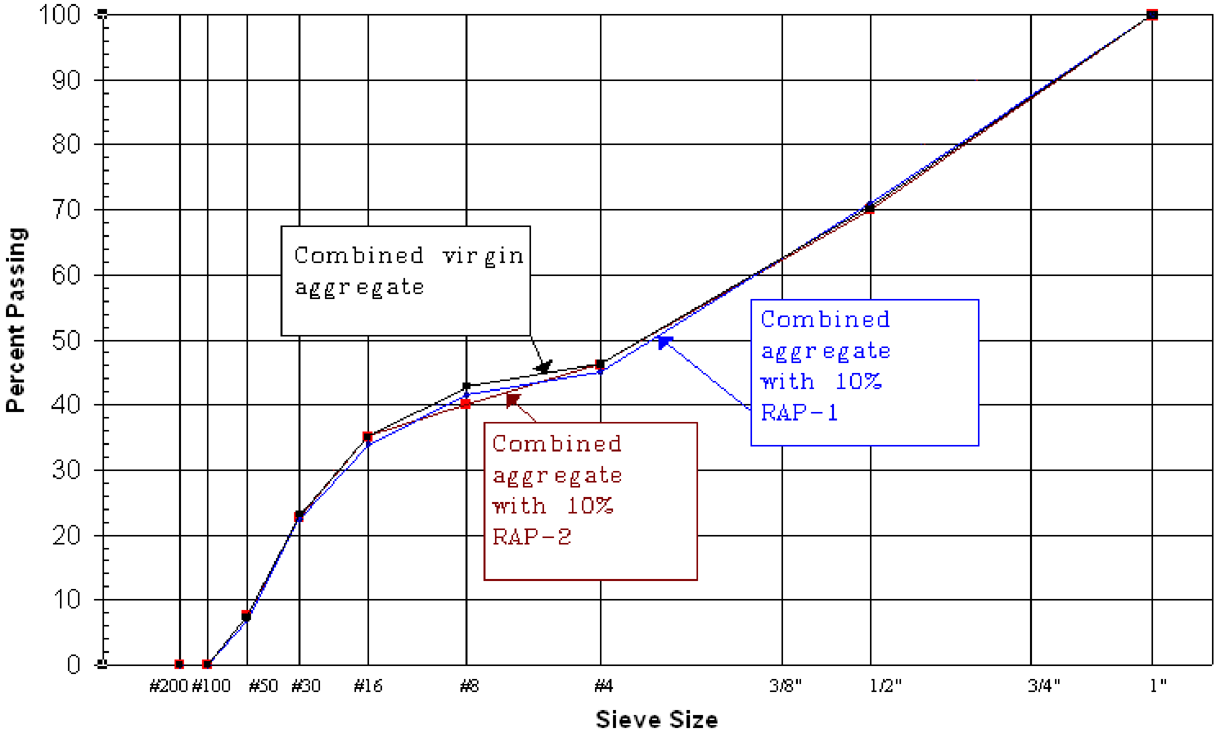

Figure 3-4. Combined gradation plots for concrete mixtures containing 10% RAP.

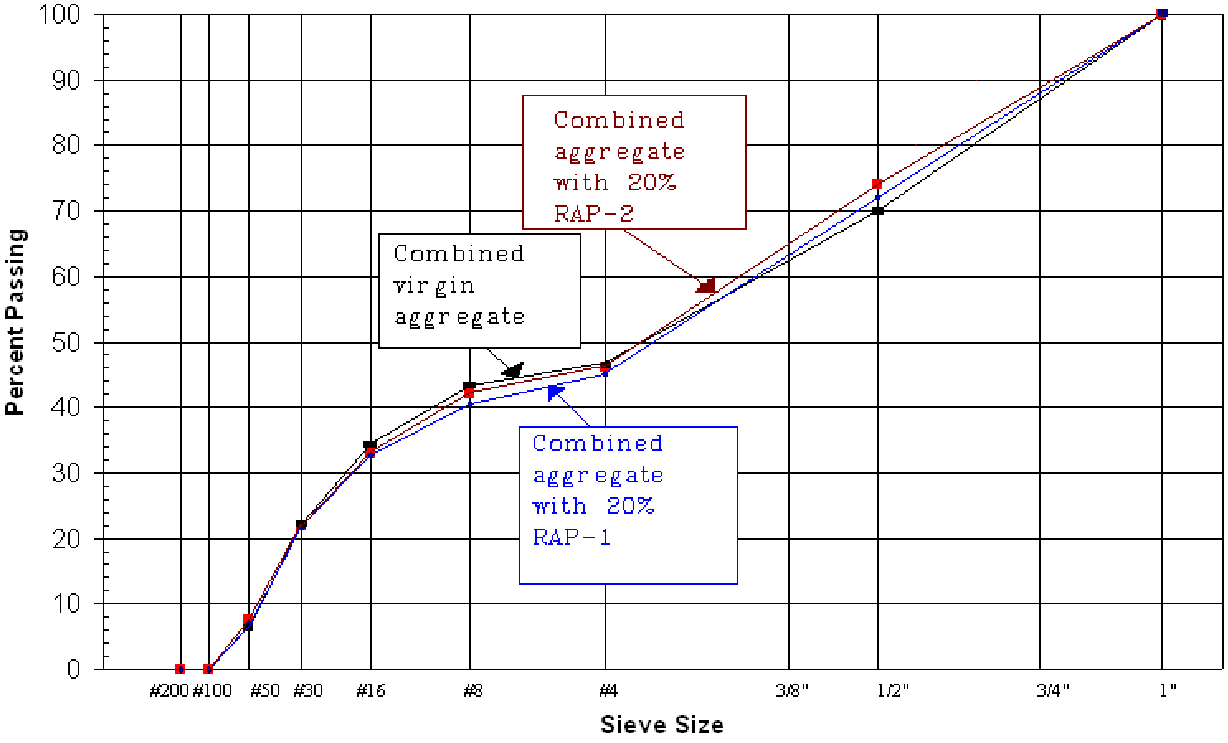

Figure 3-5. Combined gradation plots for concrete mixtures containing 20% RAP.

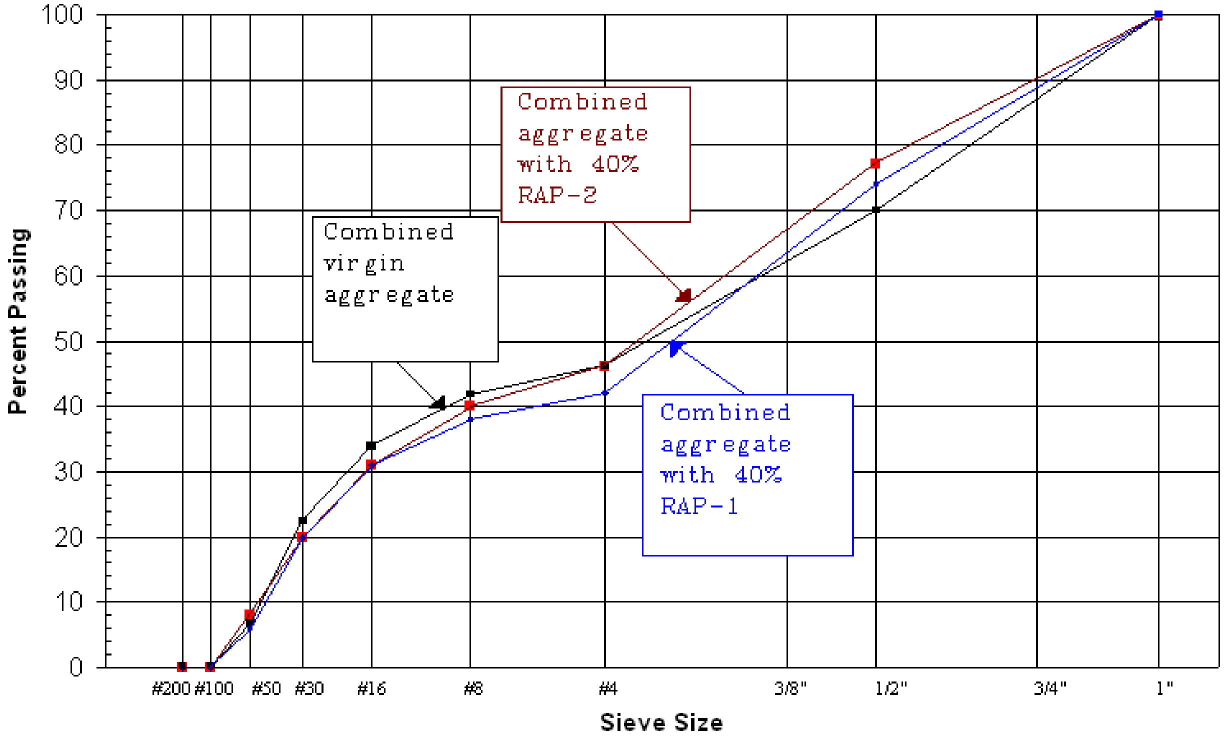

Figure 3-6. Combined gradation plots for concrete mixtures containing 40% RAP.

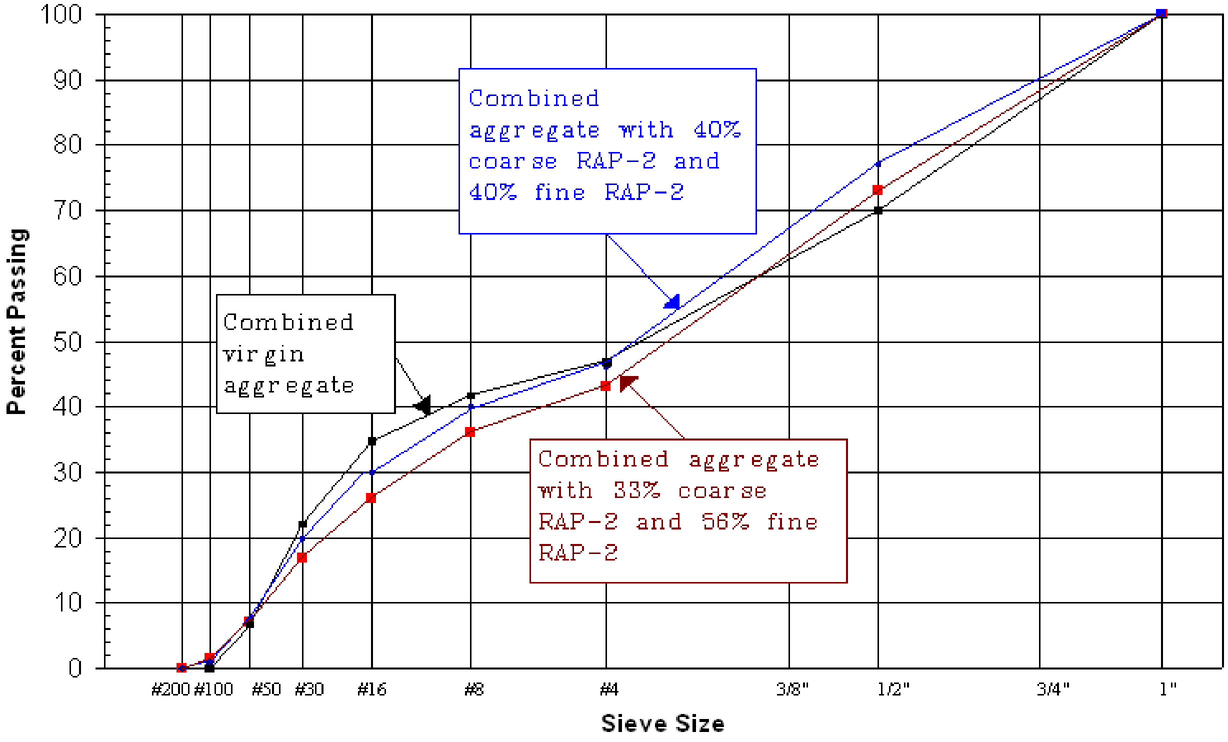

Figure 3-7. Combined gradation plots for concrete mixtures containing different RAP-2 contents.

3.4 Fabrication and Curing of Concrete Specimens

Concrete mixtures were produced in the laboratory using a drum mixer with a capacity of 9 cubic feet (ft^3), as shown in Figure 3-8. For each concrete mix, about 5 ft^3 of fresh concrete was produced to fabricate twelve 4″ × 8″ cylinders, six 6″ × 12″ cylinders, four beams (6″ × 6″ × 12″) and three prisms (3″ × 3″ × 11.25″). Table 3-12 shows the details of tests performed on the concrete samples with various specimen sizes and curing periods.

Figure 3-8. Concrete mixer used.

Table 3-12. Tests Performed on Concrete Samples

Test	Specimen Size	Curing Period
Compressive and elastic modulus	4″ × 8″ cylinder	14 days, 28 days and 90 days
Flexural strength	6″ × 6″ × 12″ beam	14 days, 28 days and 90 days
Splitting tensile strength	6″ × 12″ cylinder	14 days, 28 days and 90 days
Coefficient of thermal expansion	4″ × 8″ cylinder	14 days, 28 days and 90 days
Drying shrinkage	3″ × 3″ × 11.25″ prism	14 days, 28 days and 90 days

3.4.1 Concrete Preparation

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

1) Filled cloth bags with the aggregates and RAP required for the concrete mix;
2) Dried the fine aggregates for at least 24 hours in an oven at 230° F, and then let it cool for another 24 hours;
3) Soaked the coarse aggregate and RAP material for at least 48 hours and let it sit outside the tank for at least 30 minutes before weighing;
4) Based on the mix design, weighed the coarse aggregate, fine aggregate, coarse RAP, fine RAP, cement, and water using a weighing scale as shown in Figure 3-9;

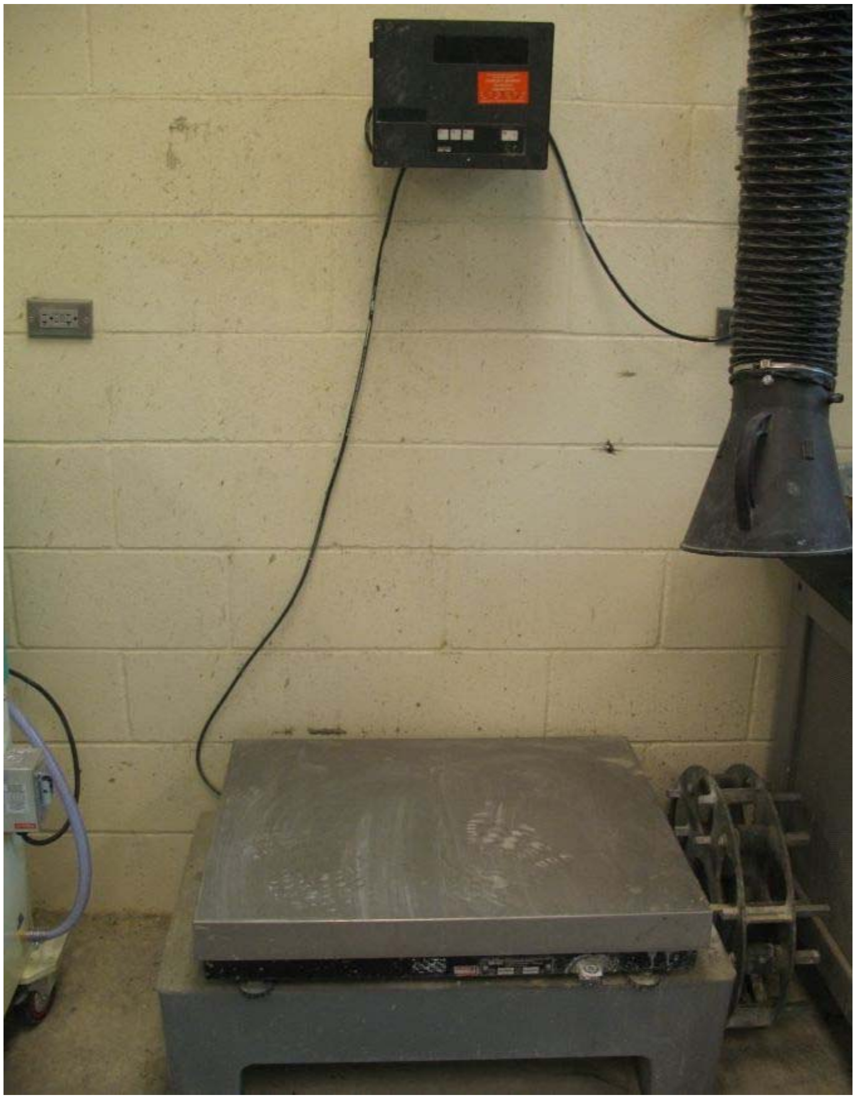

Figure 3-9. Weighing scale used.

5) Placed the coarse aggregate, fine aggregate, coarse RAP, and fine RAP in a drum mixer (Figure 3-8);
6) Ran the mixer for 30 seconds;
7) Added more than half of the mixing water and mixed it for 1 minute;
8) Placed cement into the mixer and mixed it for 3 minutes, followed by a 2-minute rest, followed by 3 minutes of mixing; and
9) Performed fresh concrete property tests as presented in Section 3.5.

3.4.2 Sample Preparation

After the concrete was produced, some portion of the concrete was immediately used for conducting tests to determine fresh concrete properties as discussed in Section 3.5. The remaining concrete was used to fabricate different samples as follows:

1) Placed concrete in molds such that they were half filled;
2) Placed the molds on a vibrating table and vibrated for 45 seconds. Then, filled the molds completely and vibrated it for another 45 seconds;
3) Beams were vibrated using a hand-held internal vibrator as shown in Figure 3-10, and cylinders were vibrated using a table vibrator as shown in Figure 3-11;

Figure 3-10. Internal vibrator used to consolidate beam samples.

Figure 3-11. Table vibrator used to consolidate cylinder samples.

4) Finished the concrete surface with a hand trowel;
5) Covered the concrete with polythene sheets as shown in Figure 3-12; and

Figure 3-12. Polythene sheets used to cover samples.

6) Removed the samples from the molds after 24 hours and placed them in a moist curing room as shown in Figure 3-13.

Figure 3-13. Samples in standard moist room.

3.5 Tests on Fresh Concrete

Table 3-13 provides the list of ASTM standard tests performed on the fresh concrete used in this study. The properties of the fresh concrete mixtures are presented in Tables 3-14, 3-15 and 3-16.

Table 3-13. Standards for Fresh Concrete Tests Used

Test	Standard
Slump	ASTM C143
Unit weight	ASTM C138
Air content	ASTM C173
Temperature	ASTM C1064

Table 3-14. Properties of Fresh Concrete using RAP-1

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Slump (inches)	Unit Weight (lb/ft^3)	Air Content (%)	Temperature (° F)
Set-1 RAP-1	1	0.53	508	270	4.25	142	1.20	73
	2	0.53	508	270	5.25	143	2.20	73
	3	0.53	508	270	6.20	143	1.00	73
	4	0.53	508	270	7.00	139	1.50	73
Set-2 RAP-1	1	0.53	508	270	4.75	143	2.00	75
	2	0.53	508	270	5.00	142	1.75	77
	3	0.53	508	270	7.50	141	1.50	76
	4	0.53	508	270	6.25	139	1.50	75
Set-3 RAP-1	1	0.53	508	270	5.75	143	2.25	73
	2	0.51	508	260	5.50	142	1.75	75
	3	0.48	508	245	4.00	141	2.50	73
	4	0.43	508	215	1.25	133	3.25	73

Table 3-15. Properties of Fresh Concrete using RAP-2 (Set-1 and Set-2)

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Slump (inches)	Unit Weight (lb/ft^3)	Air Content (%)	Temperature (° F)
Set-1 RAP-2	1	0.53	508	270	6.00	142	1.50	72
	2	0.53	508	270	7.00	140	2.00	73
	3	0.53	508	270	8.50	141	2.00	75
	4	0.53	508	270	8.50	140	4.50	79
Set-2 RAP-2	1	0.48	562	270	3.75	138	2.25	77
	2	0.48	562	270	8.75	134	3.25	77
	3	0.43	628	270	5.75	137	2.00	76
	4	0.43	628	270	7.75	133	2.75	75

Table 3-16. Properties of Fresh Concrete using RAP-2 (Set-3)

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Slump (inches)	Unit Weight (lb/ft^3)	Air Content (%)	Temperature (° F)
Set-3 RAP-2	1	0.43	628	270	2.00	141	2.40	74
	2	0.43	628	270	6.00	136	5.00	69
	3	0.43	628	270	9.00	133	6.00	66
	4	0.43	628	270	5.00	136	3.00	74
	1	0.48	562	270	2.25	140	3.00	78
	2	0.48	562	270	3.00	138	2.90	74
	3	0.48	562	270	7.25	136	3.40	76
	1	0.53	508	270	3.50	140	2.50	68
	2	0.53	508	270	3.25	137	3.00	72
	3	0.53	508	270	2.50	135	3.20	73

3.5.1 Slump Test

The slump test was run in accordance with ASTM C143. This test is very useful in detecting variations in the uniformity of a mix of given nominal proportions, and is a measure of consistency of the fresh concrete. This test is conducted immediately after the concrete has been made.

3.5.2 Unit Weight Test

This test was used to verify the density of the concrete mixtures as per the procedures of ASTM C138 standard.

3.5.3 Air Content Test

The air content test by volumetric method was run in accordance with ASTM C173 to determine the air content of the freshly mixed concrete.

3.5.4 Temperature Test

This test was run in accordance with ASTM C1064. It measured the temperature of the freshly mixed concrete.

3.6 Tests on Hardened Concrete

3.6.1 Compressive Strength and Elastic Modulus Test

The standard test procedures of ASTM C39 and ASTM C469 were followed in running the compressive strength and elastic modulus test on 4″ × 8″ cylindrical specimens. The two ends of the specimen were ground evenly before testing to ensure even loading during test. Two 4″ displacement gages, held by four springs were mounted on the sides of the specimen. The specimen was then placed in a MTS 810 material testing system as shown in Figures 3-14 and 3-15. The testing machine was hydraulic controlled with a maximum capacity of 220 kips. Load was applied to the specimen at a constant loading rate of 26 kip/minute until complete failure

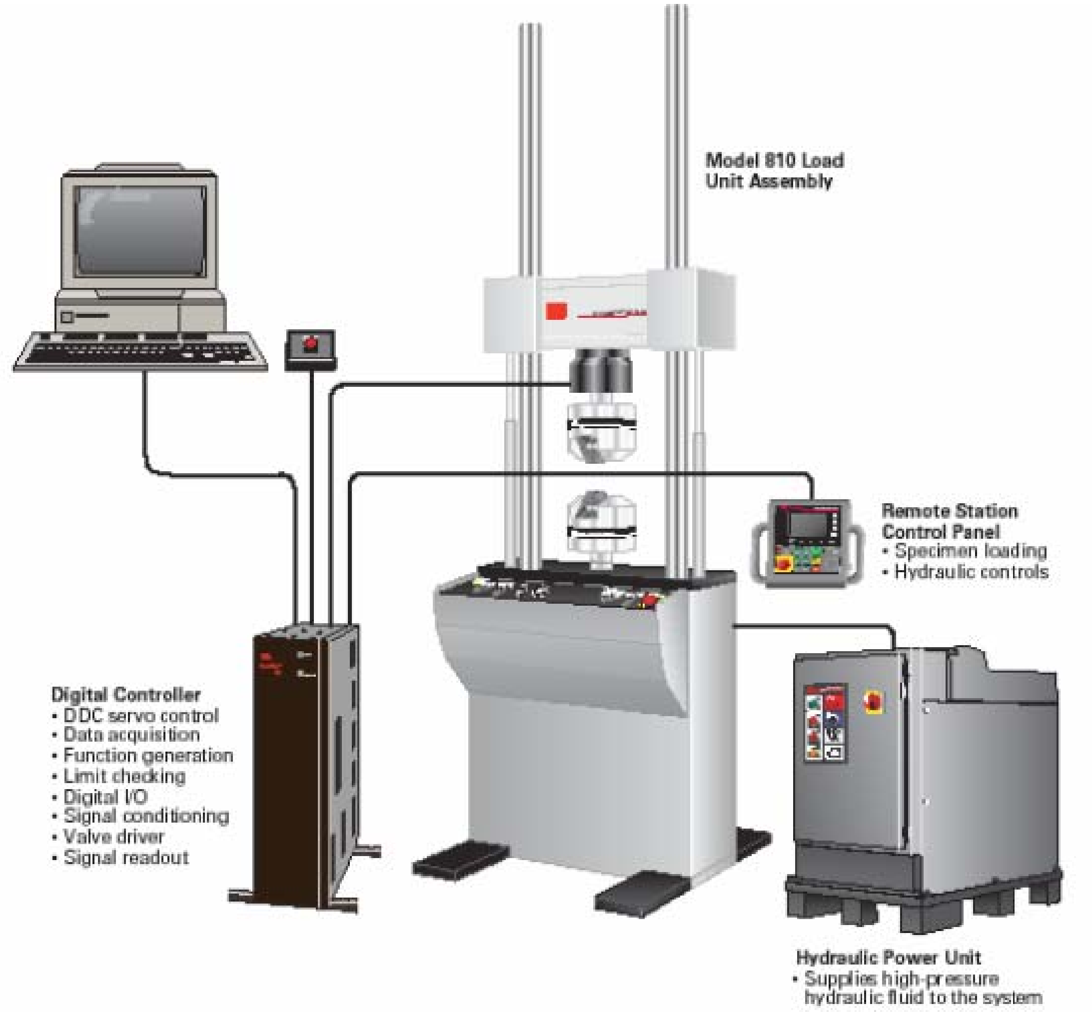

Figure 3-14. Material testing system (MTS) 810 [Li, G., 2004].

Figure 3-15. Failure of concrete cylinder in compressive strength test.

occurred. The output from the displacement gages and the load cell from the testing machine were connected to a data acquisition system, which recorded the data during the test. The average displacement reading was used to calculate the strain, and the reading from the load cell was used to calculate the stress. The maximum stress reading was used as the compressive strength for the concrete.

The modulus of elasticity was calculated as follows:

$$E = (S_2 - S_1)\frac{1}{(\varepsilon_2 - 0.000050)}$$

where E = chord modulus of elasticity, psi;

S_2 = stress corresponding to 40% of ultimate load;

S_1 = stress corresponding to a longitudinal strain, ε_1, of 50 millionths, psi; and

ε_2 = longitudinal strain produced by stress S_2.

3.6.2 Flexural Strength Test

The flexural strength test was run in accordance with ASTM C78. The 6″ × 12″ beam specimens were tested at each age and the average strength was computed. Before testing, the two loading surfaces were ground evenly by using a grinding stone to support the applied load uniformly. The flexural strength was calculated according to the type of fracture in the beam as follows:

1) If the fracture initiated in the tension surface within the middle third of the span length, the modulus of rupture was calculated as follows:

$$R = \frac{PL}{bd^2}$$

where R = modulus of rupture, psi;

P = maximum applied load indicated by the testing machine, lbf;

L = span length, inches;

b = average depth of specimen, in, at the fracture; and

d = average depth of specimen, in, at the fracture.

2) If the fracture occurred in the tension surface outside of the middle third of the span length by not more than 5% of the span length, the modulus of rupture was calculated as follows:

$$R = \frac{3Pa}{bd^2}$$

where R = modulus of rupture in psi;

P = maximum applied load indicated by the testing machine in lbf;

a = average distance between line of fracture and the nearest support measured on the tension surface of the beam, in, or mm;

b = average depth of specimen, in, or mm, at the fracture; and

d = average depth of specimen, in, or mm, at the fracture.

3) If the fracture occurred in the tension surface outside of the middle third span length by more than 5% of the span length, the results of the test were discarded.

3.6.2.1 Test procedure

The following steps were followed to run the beam test on an Instron 3384 loading frame as shown in Figure 3-16:

1) Beam surfaces (top and bottom) were smoothened with sand paper and cleaned with acetone;
2) One strain gage was glued on each of the smoothened top and bottom surfaces with special Loctite 454 glue;
3) The glue was allowed to dry to obtain a perfect bond between the strain gage and the beam;
4) The wires were secured in the area where they connect to the strain gages using normal tape;
5) The beams were placed properly centered on the loading frame, such that the one-third marks accurately aligned with the loading platens as shown in the Figure 3-16;
6) The strain gages were attached to the SCXI-1000 unit using a quarter bridge configuration; and

7) The testing machine was run at a rate of 30 lbs/sec while acquiring both voltage data (from the strain gages) and the load cell data.

Figure 3-16. Test set-up used for flexural strength test.

3.6.2.2 Data analysis

The following steps were followed in calculating stresses and strains in the flexural strength tests:

1) Value Vo was determined from the voltage output data using the following equation:

$$Vo = \frac{Vr - Vi}{Ve}$$

where Vr = variable voltage in volt;

Vi = initial voltage in volt; and

Ve = excitation voltage in volt.

2) Strain, ε, was calculated using the following equation:

$$\varepsilon = \frac{-4Vo}{GF\,(1+2Vo)}$$

where GF = gage factor.

3) Stress, σ, was calculated from the load output data using following equations:

$$\sigma = M * \frac{c}{I}$$

where c = half of the depth in inches;

M = maximum bending moment in the beam; and

I = moment of inertia.

$$M = P * \frac{L}{6}$$

where P = applied load in psi; and

L = span length in inches.

4) The maximum stress was determined at failure and noted as the flexural strength of the beam.

Figures 3-17 and 3-18 show the failure of a beam without RAP material and that with RAP material, respectively.

Figure 3-17. Failure of the beam without RAP material.

Figure 3-18. Failure of the beam containing RAP material.

3.6.3 Splitting Tensile Strength Test

The splitting tensile strength of concrete was run in accordance with ASTM C496. Cylindrical specimens (6″ × 12″) were used to determine splitting tensile strength. Four lines were drawn along the center of the cylinder to mark the edges of the loaded plane and to help align the test specimen before the application of load. Figure 3-19 shows a typical set-up of the cylinder during testing. A strip of wood, 3-mm thick and 25-mm wide, was inserted between the cylinder and the platens; this helped the applied force to be uniformly distributed. Load was applied and increased until failure by indirect tension in the form of splitting along the vertical diameter took place. Figure 20 shows the failed specimens from splitting tensile strength test. The splitting tensile strength of a cylinder specimen was calculated using the following equation:

$$T = \frac{2 \times P}{\pi \times L \times D}$$

where T = splitting tensile strength of cylinder in psi;

P = maximum applied load in lbf;

L = length of cylinder in inch; and

D = diameter of cylinder in inch.

Figure 3-19. Test set-up for splitting tensile strength test.

Figure 3-20. Failure of concrete cylinders in indirect tension.

3.6.4 Free Shrinkage Test

The free shrinkage measurement was made in accordance with ASTM C157 using 3″ × 3″ × 11.25″ square prism specimens. Figure 3-21 shows a mold used to cast the sample. Steel end plates with a hole at their centers were used to install gage studs at both ends of the specimen.

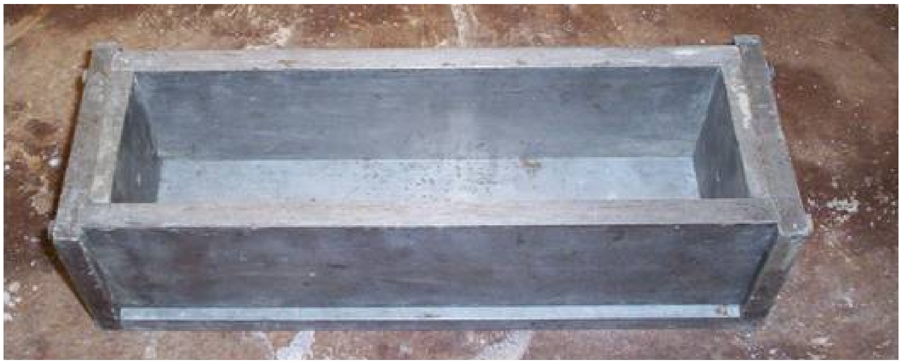

Figure 3-21. Mold for free shrinkage test.

The specimens were removed from the molds at an age of 23.5 ± 0.5 hours (after the addition of water to cement during the mixing operation) and then placed in lime-saturated water, which was maintained at 73.4 ± 1° F (23.0 ± 0.5° C) for a minimum of 30 min. At an age of 24 ± 0.5 hours, the specimens were removed from water storage one at a time, and wiped with a damp cloth. An initial reading was immediately taken with a length comparator. The specimens were then stored in the drying room and comparator readings were taken for each specimen after a curing age of 14 days, 28 days and 90 days. Figure 3-22 shows the test set-up of the free shrinkage test. The length change of a specimen at any age after the initial comparator reading was calculated as follows:

$$\Delta L_x = \frac{CRD - initial\ CRD}{G} \times 100$$

where ΔL_x = length change of specimen at any age, %;

CRD = difference between the comparator reading of the specimen and the reference bar; and

G = gage length.

Figure 3-22. Set-up for shrinkage test.

3.6.5 Coefficient of Thermal Expansion (CTE) Test

The CTE test was run in accordance with AASHTO TP60. The test set-up is shown in Figure 3-23. The samples were sawed using a sawing machine as shown in Figure 3-24, and then ground using a grinding machine as shown in Figure 3-25. This helped make the samples the desired length (7± 0.1 inch) required for the test.

The procedure used for the CTE test was as follows:

1) The support frame was placed with the LVDT attached in the water bath and the bath filled with cold tap water. The four temperature sensors were placed in the bath at locations that

provided an average temperature for the bath as a whole. To avoid any sticking at the points of contact with the specimen, a very thin film of silicon grease was put on the end of the support buttons and LVDT tip.

Figure 3-23. Set-up for coefficient of thermal expansion test.

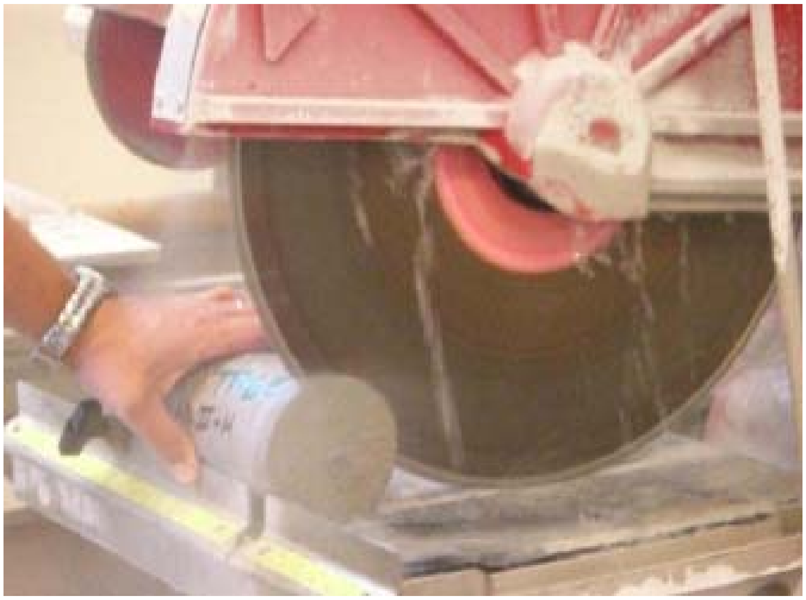

Figure 3-24. Saw used for cutting concrete cylinder samples.

Figure 3-25. Grinder used for grinding concrete cylinder samples.

2) The specimen was removed from the moist room, and at room temperature, its length was measured to the nearest 0.1 mm (0.004 in.). After measuring the length, the specimen was placed in the support frame located in the controlled temperature bath, making sure that the lower end of the specimen was firmly seated against the support buttons, and the LVDT tip was seated against the upper end of the specimen.
3) The LVDT and temperature sensors were connected to a data acquisition system, which was connected to a laptop computer.
4) The temperature of the water bath was set to 10 ± 1° C (50 ± 2° F). When the bath reached this temperature, the bath was allowed to remain at this temperature until thermal equilibrium of the specimen had been reached, as was indicated by consistent readings of the LVDT to the nearest 0.00025 mm (0.00001 in.) taken every 10 minutes over a one-half hour period.

5) The temperature readings were recorded from the four sensors to the nearest 0.1° C (0.2° F). The LVDT reading was recorded to the nearest 0.00025 mm (0.00001 in.). These were the initial readings.
6) The temperature of the water bath was set to 50 ± 1° C (122 ± 2° F). When the bath reached this temperature, the bath was allowed to remain at this temperature until thermal equilibrium of the specimen had been reached, as was indicated by consistent readings of the LVDT to the nearest 0.00025 mm (0.00001 in.).
7) The temperature readings were recorded from the four sensors to the nearest 0.1° C (0.2° F). The LVDT reading was recorded to the nearest 0.00025 mm (0.00001 in.). These were the second readings.
8) The temperature of the water bath was set to 10 ± 1° C (50 ± 2° F). When the bath reached this temperature, the bath was allowed to remain at this temperature until thermal equilibrium of the specimen had been reached.
9) The temperature readings were recorded from the four sensors to the nearest 0.1° C (0.2° F). The LVDT reading was recorded to the nearest 0.00025 mm (0.00001 in.). These were the final readings.

The CTE of one expansion or contraction test segment of a concrete specimen was calculated as follows:

$$CTE = \frac{\left(\Delta L_a / L_0\right)}{\Delta T}$$

where ΔL_a = actual length change of specimen during temperature change, mm or in.;

L_0 = measured length of specimen at room temperature, mm or in.; and

ΔT = measured temperature change (average of the four sensors), ºC.

The test result was the average of the two CTE values obtained from the expansion test segment and contraction test segment, and was calculated as follows:

$$CTE = \frac{CTEexpansion + CTEcontraction}{2}$$

CHAPTER 4
RESULTS OF TESTS ON CONCRETE CONTAINING RAP

4.1 Introduction

This chapter presents the results of the laboratory testing program on concretes containing RAP. It includes the results of compressive strength, elastic modulus, flexural strength, splitting tensile strength, free shrinkage, and coefficient of thermal expansion tests on the different concrete mixtures incorporating different amounts of RAP evaluated in this study. The effects of RAP on the properties of concrete are discussed.

4.2 Analysis of Compressive Strength Test Results

4.2.1 Compressive Strength Test Results

The average compressive strengths at various curing periods of different concrete mixtures are presented in Tables 4-1 and 4-2. The individual compressive strength values are shown in Table B-1 of Appendix B.

Table 4-1. Compressive Strength of the Concrete using RAP-1

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Compressive Strength (psi)		
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days	90 days
Set-1 RAP-1	1	0.53	100	0	100	0	0	5445	5596	6033
	2	0.53	90	10	90	10	10	4484	4936	4976
	3	0.53	80	20	80	20	20	3188	3778	3957
	4	0.53	60	40	60	40	40	2444	2521	2657
Set-2 RAP-1	1	0.53	100	0	100	0	0	5683	5779	6353
	2	0.53	90	10	90	10	10	4643	4746	5230
	3	0.53	80	20	80	20	20	3338	3365	3783
	4	0.53	60	40	60	40	40	2336	2240	2766

Table 4-2. Compressive Strength of the Concrete using RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Compressive Strength (psi)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	4471	2970
	2	0.48	66	34	47	53	40	3114	3152
	3	0.43	82	18	76	24	20	3274	4687
	4	0.43	67	33	44	56	40	2516	3342
Set-2 RAP-2	1	0.43	100	0	100	0	0	6293	6608
	2	0.43	82	18	77	23	20	3524	3808
	3	0.43	67	33	44	56	40	2460	2390
	4	0.43	67	33	44	56	40	2400	2950
	1	0.48	100	0	100	0	0	5415	6059
	2	0.48	82	18	77	23	20	3662	4002
	3	0.48	66	34	47	53	40	2640	2750
	1	0.53	100	0	100	0	0	4014	4690
	2	0.53	82	18	76	24	20	3215	3609
	3	0.53	67	33	44	56	40	2182	2400

4.2.2 Effect of RAP on Compressive Strength of Concrete

Results shown in Figures 4-1 through 4-3 show a reduction in compressive strength of concrete mixes made with RAP-1 as compared with the reference mix. The strength of concrete made with a maximum percentage of equal proportion of coarse RAP and fine RAP decreased the most among all the concrete mixtures. For a 0.53 w/c ratio at 14 days, the strengths of Mixes 2, 3, and 4 were 70%, 60%, and 40%, respectively, of that of the reference mix. At 28 days, the strengths of Mixes 2, 3, and 4 were 76%, 62%, and 42%, respectively, of that of the reference mix. At 90 days, the strengths of Mixes 2, 3, and 4 were 80%, 60%, and 45%, respectively, of that of the reference mix. There was a consistent reduction in the strength of the mix containing RAP at different curing periods. Figures 4-4 and 4-5 show similar trends for the concrete containing RAP-2 with different w/c ratios. For a 0.43 w/c ratio, the reduction in compression strength was 42% and 64% compared with the control mix for mixtures containing

20% and 40% RAP, respectively. For a 0.48 w/c ratio, the reduction in compression strength was 34% and 55% compared with the control mix for mixtures containing 20% and 40% RAP, respectively. For a 0.53 w/c ratio, the reduction in compression strength was 23% and 49% compared with the control mix for mixtures containing 20% and 40% RAP, respectively. Thus, the reduction in compressive strength of concrete containing RAP reduced as the w/c ratio of the mix increased. The reduction of the strength in the mix containing RAP could be due to the lower strength of the RAP as compared with the aggregate. Another possible cause could be the weaker bonding between the aged asphalt film and the concrete matrix.

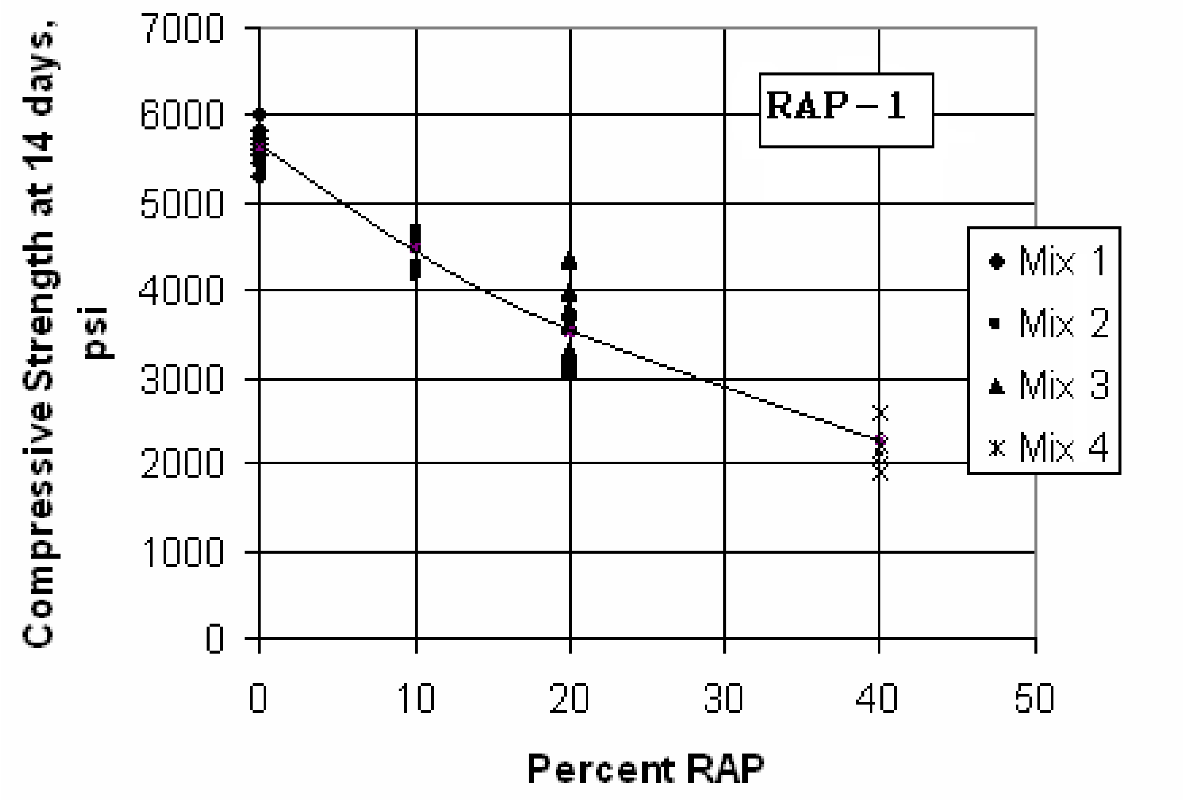

Figure 4-1. Effect of RAP-1 on compressive strength of concrete with a 0.53 w/c ratio at 14 days.

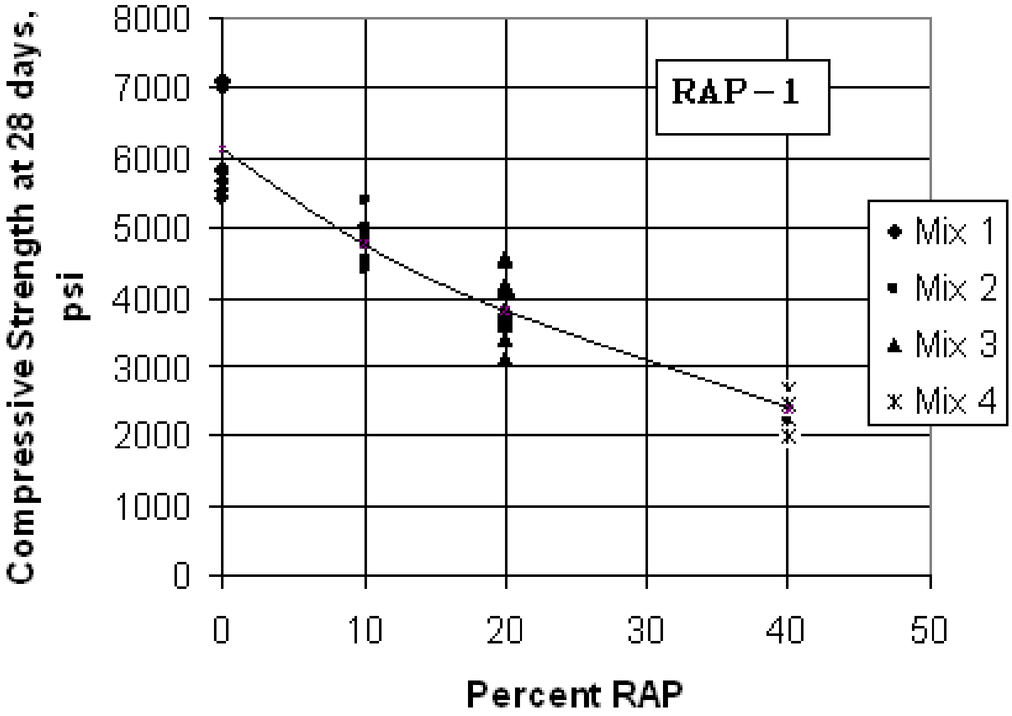

Figure 4-2. Effect of RAP-1 on compressive strength of concrete with a 0.53 w/c ratio at 28 days.

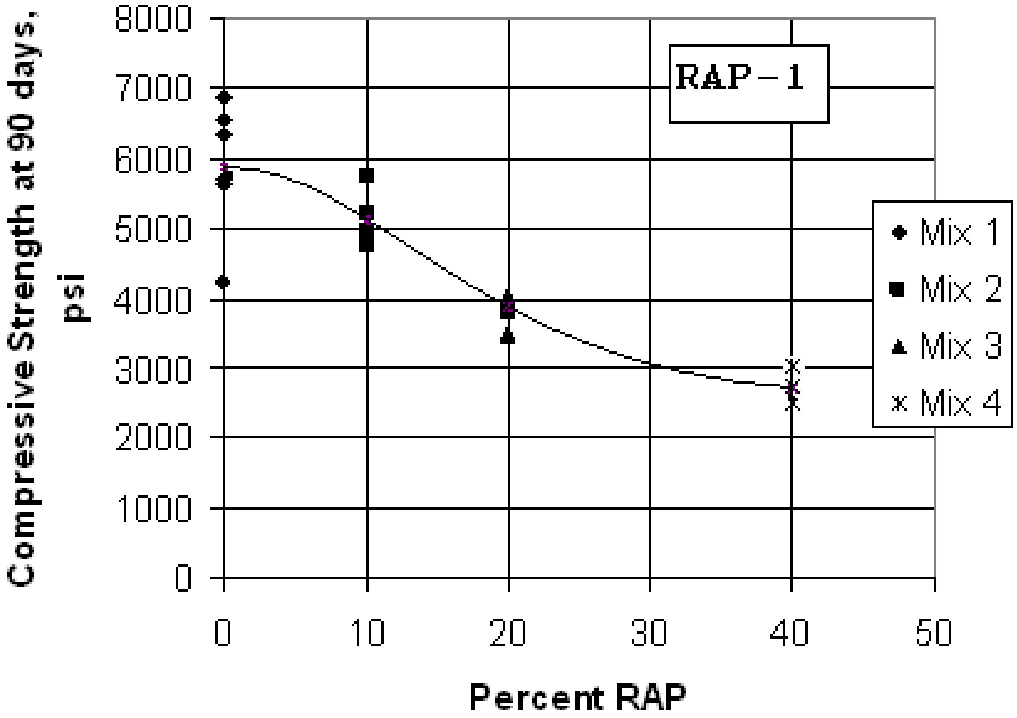

Figure 4-3. Effect of RAP-1 on compressive strength of concrete with a 0.53 w/c ratio at 90 days.

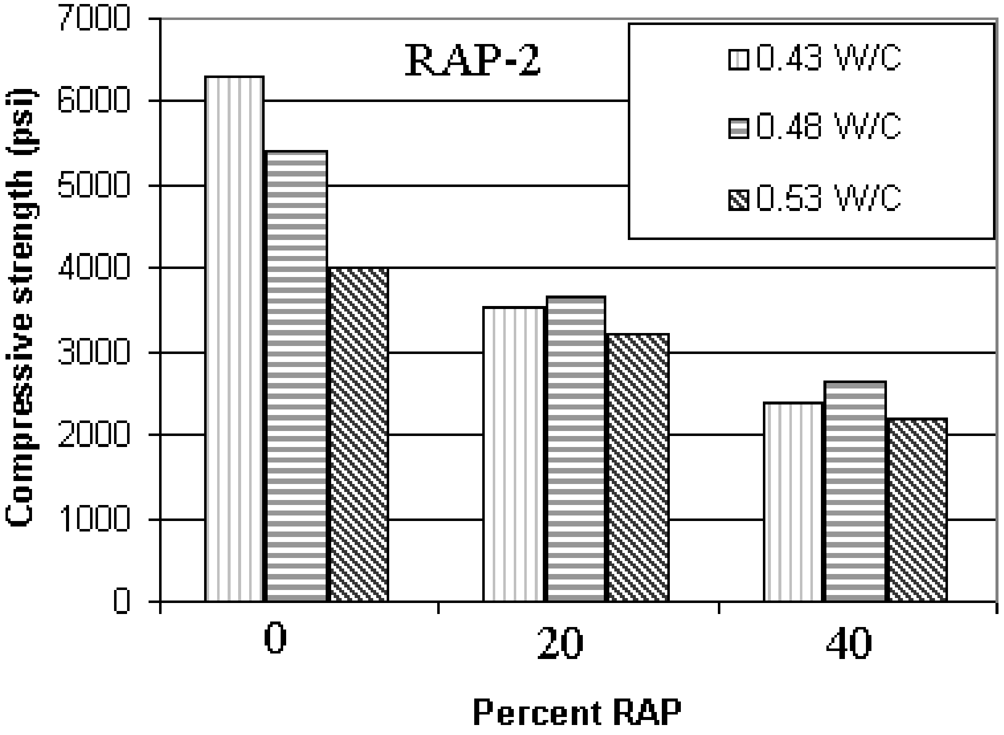

Figure 4-4. Effect of RAP-2 on compressive strength at 14 days.

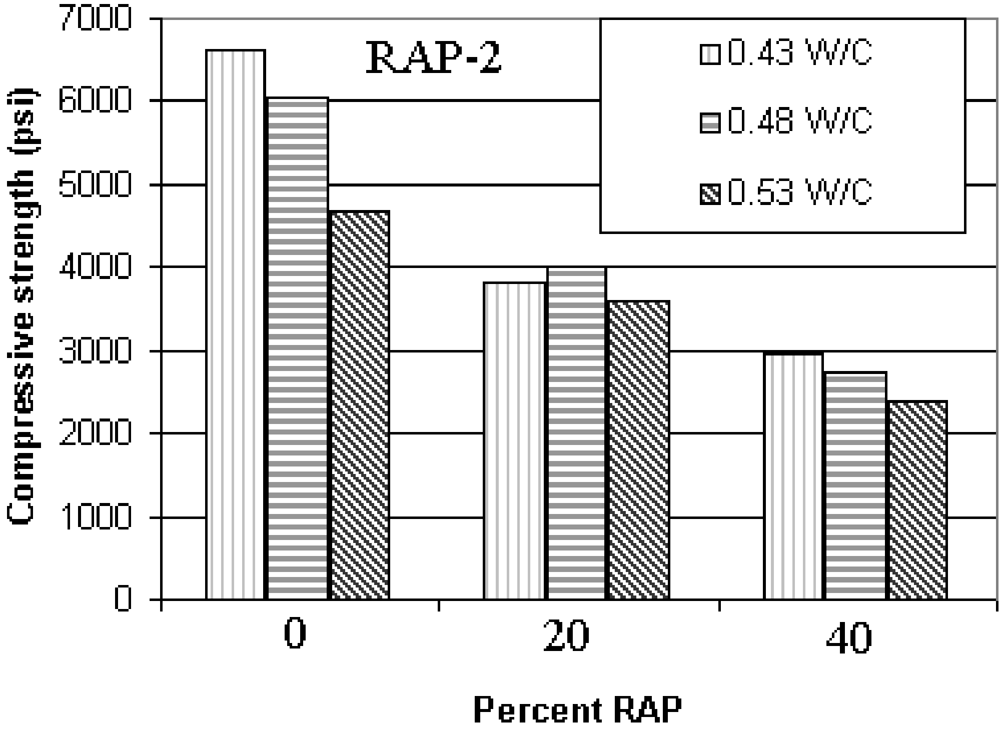

Figure 4-5. Effect of RAP-2 on compressive strength at 28 days.

4.3 Analysis of Elastic Modulus Test Results

4.3.1 Elastic Modulus Test Results

The average elastic moduli at various curing periods of different concrete mixtures are presented in Tables 4-3 and 4-4. The individual elastic modulus values are shown in Table B-2 of Appendix B.

Table 4-3. Elastic Modulus of the Concrete using RAP-1

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Elastic Modulus ($\times 10^6$ psi)		
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days	90 days
Set-1 RAP-1	1	0.53	100	0	100	0	0	4.44	4.78	4.72
	2	0.53	90	10	90	10	10	3.82	4.00	4.13
	3	0.53	80	20	80	20	20	3.35	3.40	3.57
	4	0.53	60	40	60	40	40	2.31	2.35	2.50
Set-2 RAP-1	1	0.53	100	0	100	0	0	4.60	4.90	4.76
	2	0.53	90	10	90	10	10	4.17	4.51	4.55
	3	0.53	80	20	80	20	20	3.41	3.75	3.53
	4	0.53	60	40	60	40	40	2.27	2.30	2.62

Table 4-4. Elastic Modulus of the Concrete using RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Elastic Modulus ($\times 10^6$ psi)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	3.17	2.81
	2	0.48	66	34	47	53	40	2.30	2.27
	3	0.43	82	18	76	24	20	3.23	3.90
	4	0.43	67	33	44	56	40	2.25	3.29
Set-2 RAP-2	1	0.43	100	0	100	0	0	4.15	4.09
	2	0.43	82	18	77	23	20	2.80	2.90
	3	0.43	67	33	44	56	40	1.77	1.85
	4	0.43	67	33	44	56	40	2.34	2.08
	1	0.48	100	0	100	0	0	3.93	4.07
	2	0.48	82	18	77	23	20	2.96	2.99
	3	0.48	66	34	47	53	40	2.15	2.07
	1	0.53	100	0	100	0	0	3.46	3.73
	2	0.53	82	18	77	23	20	2.85	2.97
	3	0.53	67	33	44	56	40	1.86	1.96

4.3.2 Effect of RAP on Elastic Modulus of Concrete

Figure 4-6 presents the results of the elastic modulus test. It shows there was a systematic reduction of the elastic modulus of concrete containing RAP. For the concrete containing RAP-1 with a 0.53 w/c ratio, the elastic modulus at 14 days for Mixes 2, 3, and 4 was 88%, 75%, and 54%, respectively, of that of the reference mix. For RAP-1 with a 0.53 w/c ratio at 28-day, the elastic modulus of Mixes 2, 3, and 4 was 86%, 73%, and 49%, respectively, of that of the reference mix. For RAP-1 with a 0.53 w/c ratio at 90 days, the elastic modulus of Mixes 2, 3, and 4 was 79%, 70%, and 55%, respectively, of that of the reference mix. Therefore, consistent reduction in the elastic modulus for mixtures containing RAP-1 at different curing periods was observed.

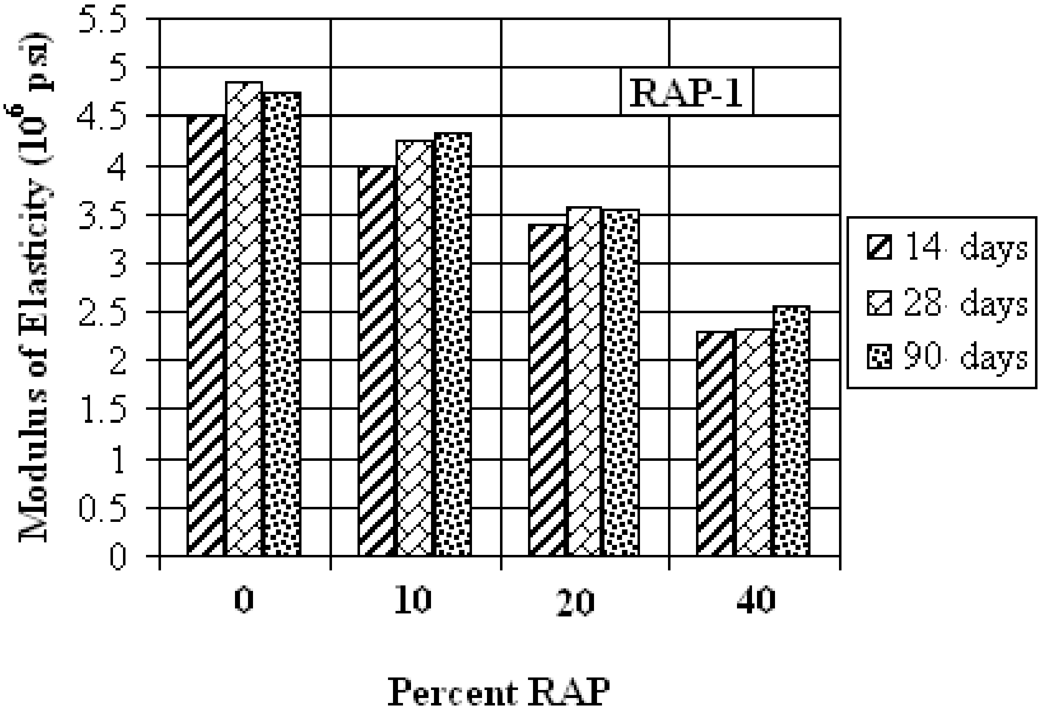

Figure 4-6. Effect of RAP-1 on elastic modulus of concrete with a 0.53 w/c ratio.

Figures 4-7 and 4-8 show the results of the elastic modulus test for the concrete mixtures containing RAP-2. It can be observed that, for all the different w/c ratios, the reduction in modulus of elasticity increased with the percentage of RAP content in the concrete mixtures. It is well known that the elastic modulus of concrete is highly affected by the modulus of elasticity of the aggregate and the content of aggregate in a mix. RAP, being softer than the natural aggregate, demonstrated a lower modulus of elasticity and decreased the elastic modulus of the concrete. Thus, an increase in the content of RAP in the mix further reduced the elastic modulus of the concrete.

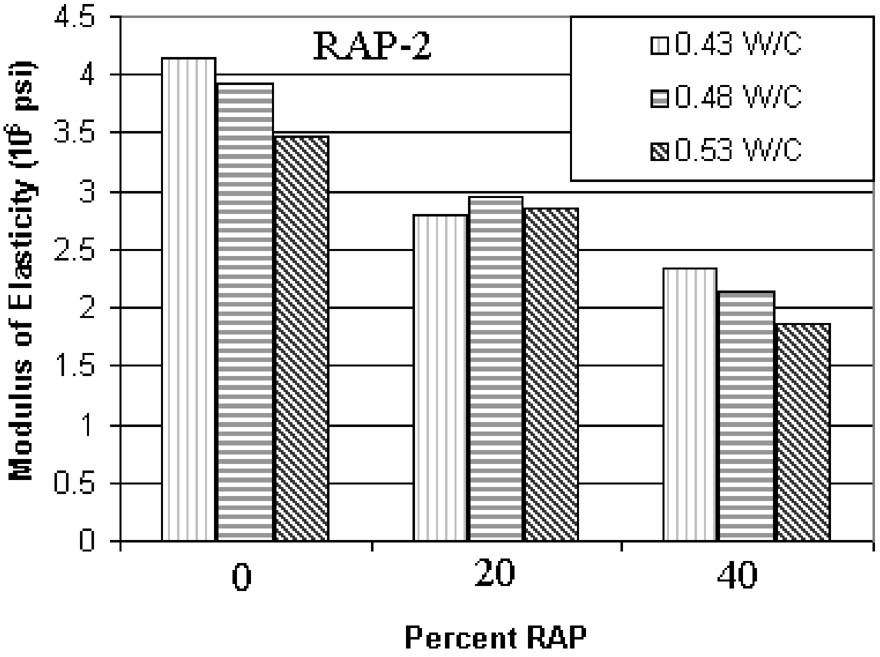

Figure 4-7. Effect of RAP-2 on elastic modulus of concrete at 14 days.

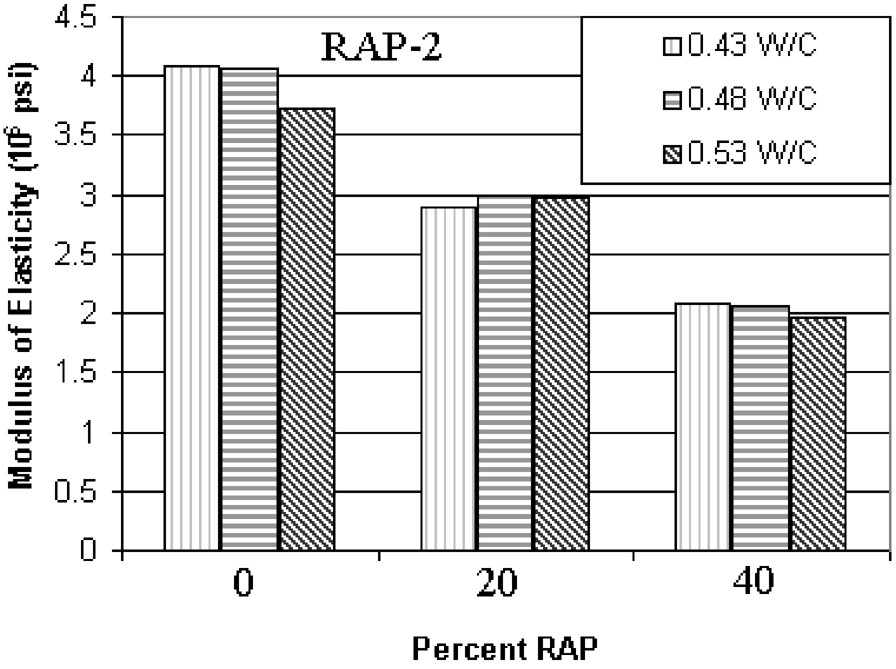

Figure 4-8. Effect of RAP-2 on elastic modulus of concrete at 28 days.

4.4 Analysis of Flexural Strength Test Results

4.4.1 Flexural Strength Test Results

The average flexural strengths at various curing periods of different concrete mixtures are presented in Tables 4-5 and 4-6. The individual flexural strength values are shown in Table B-3 of Appendix B.

Table 4-5. Flexural Strength of the Concrete using RAP-1

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Flexural Strength (psi)		
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days	90 days
Set-1 RAP-1	1	0.53	100	0	100	0	0	883	940	976
	2	0.53	90	10	90	10	10	807	940	845
	3	0.53	80	20	80	20	20	829	750	756
	4	0.53	60	40	60	40	40	715	570	677
Set-2 RAP-1	1	0.53	100	0	100	0	0	802	969	763
	2	0.53	90	10	90	10	10	781	868	572
	3	0.53	80	20	80	20	20	705	709	553
	4	0.53	60	40	60	40	40	578	640	510

Table 4-6. Flexural Strength of the Concrete using RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Flexural Strength (psi)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	477	482
	2	0.48	66	34	47	53	40	393	410
	3	0.43	82	18	76	24	20	484	539
	4	0.43	67	33	44	56	40	394	404
Set-2 RAP-2	1	0.43	100	0	100	0	0	763	912
	2	0.43	82	18	76	24	20	612	705
	3	0.43	67	33	44	56	40	460	523
	4	0.43	67	33	44	56	40	560	580
	1	0.48	100	0	100	0	0	723	804
	2	0.48	82	18	77	23	20	593	634
	3	0.48	66	34	47	53	40	506	580
	1	0.53	100	0	100	0	0	675	739
	2	0.53	66	34	47	53	40	576	592
	3	0.53	82	18	76	24	20	465	483

4.4.2 Effect of RAP on Flexural Strength of Concrete

Figure 4-9 shows the effect of RAP-1 on the flexural strengths of the concrete with a w/c ratio of 0.53 evaluated at different curing times. At 14 days, the flexural strength of Mixes 2, 3, and 4 was 93%, 90%, and 75%, respectively, of that of the reference mix. At 28 days, the flexural strength of Mixes 2, 3, and 4 was 95%, 75%, and 65%, respectively, of that of the reference mix. At 90 days, the flexural strength of Mixes 2, 3, and 4 was 80%, 75%, and 70%, respectively, of that of the reference mix.

Figures 4-10 and 4-11 show the effect of RAP-2 on the flexural strength of the concrete with different w/c ratios evaluated at 14 days and 28 days, respectively. Similar trends can be observed in these two figures. The average flexural strength decreased by 20% for the concrete containing 20% RAP-2 and decreased by 30% for the concrete containing 40% RAP.

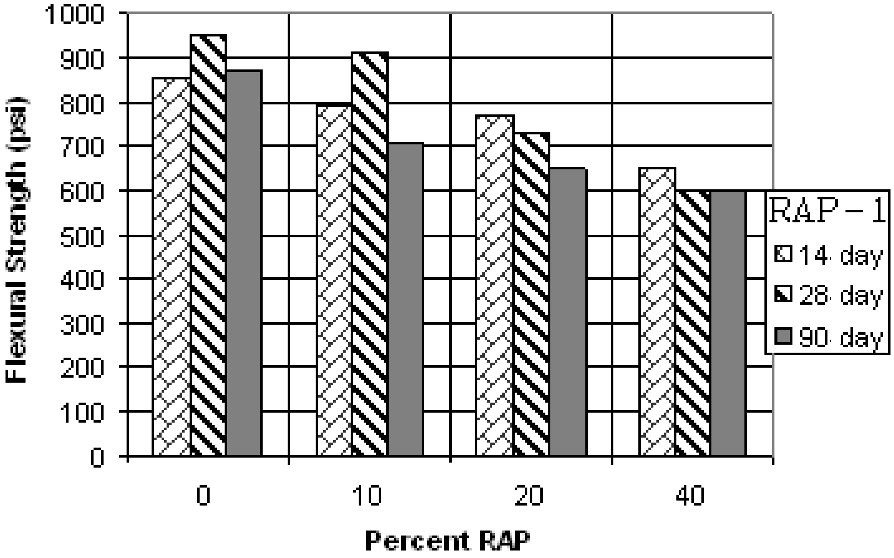

Figure 4-9. Effect of RAP-1 on flexural strength of concrete with a 0.53 w/c ratio.

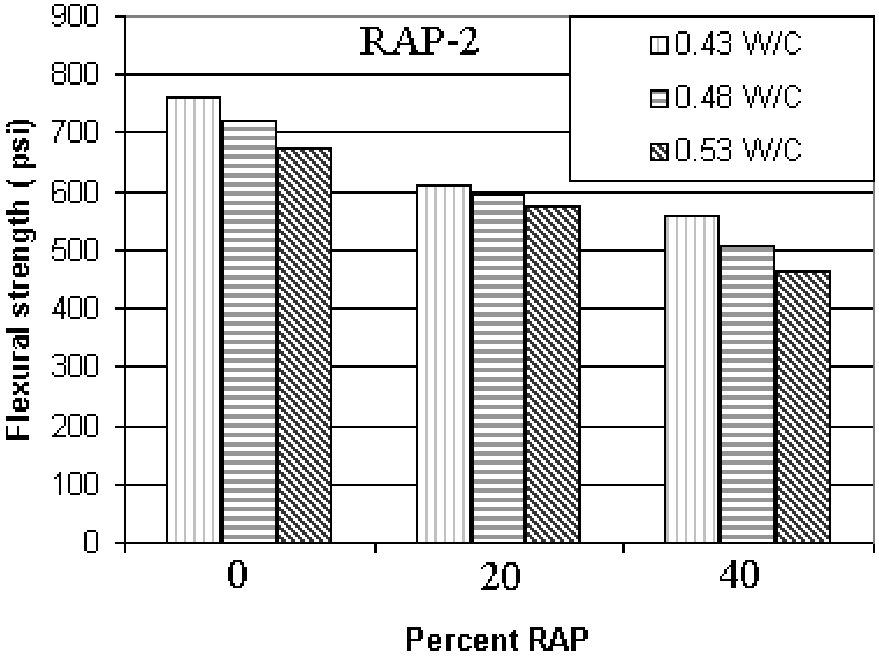

Figure 4-10. Effect of RAP-2 on flexural strength of concrete at 14 days.

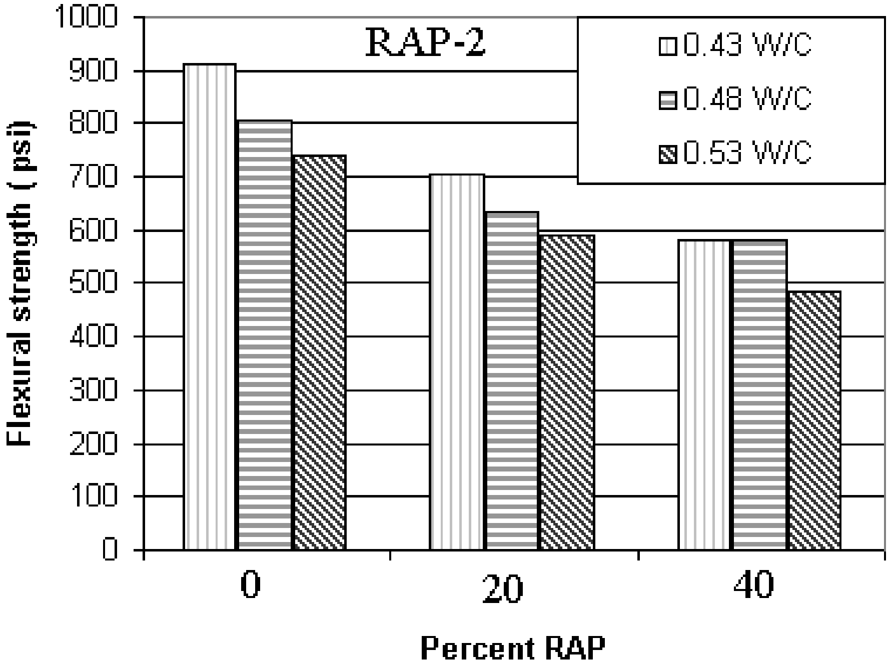

Figure 4-11. Effect of RAP-2 on flexural strength of concrete at 28 days.

Figure 4-12 shows the comparison in the reduction of compressive strength with the corresponding reduction in flexural strength as a result of using RAP-1 in the concrete mixtures.

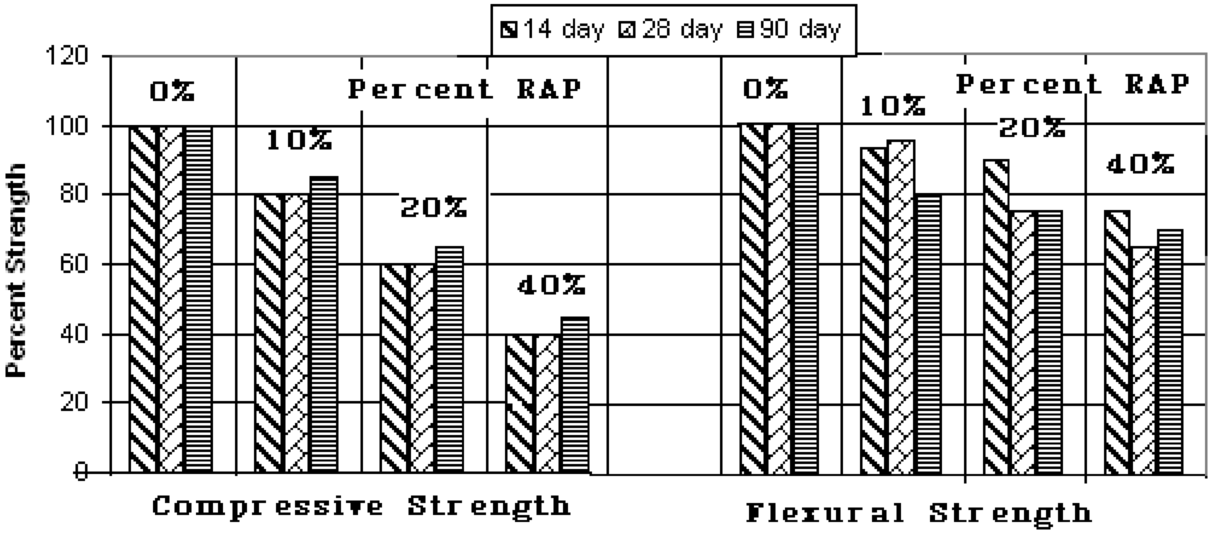

Figure 4-12. Reduction in compressive and flexural strength for the concrete containing RAP-1.

The average reduction in compressive strength was 18%, 38%, and 58% for Mixes 2, 3, and 4, respectively. The corresponding average reduction in flexural strength was 10%, 20%, and 30% for Mixes 2, 3, and 4, respectively. Thus, it can be seen that the reductions in compressive strength were higher than the reductions in flexural strength for all the mixtures containing RAP-1.

4.4.3 Effect of RAP on Modulus of Toughness of Concrete

Figure 4-13 shows the stress-strain plots from beam tests on concrete mixtures containing RAP-1 with a w/c ratio of 0.53. Table 4-7 shows the values of modulus of toughness of these concrete mixtures computed from these plots. It can be observed that the modulus of toughness generally increased as the percent RAP used in the concrete mix increased. The modulus of toughness of Mixes 2, 3, and 4 in tension zone was 108%, 250%, and 255%, respectively, of that of Mix 1.

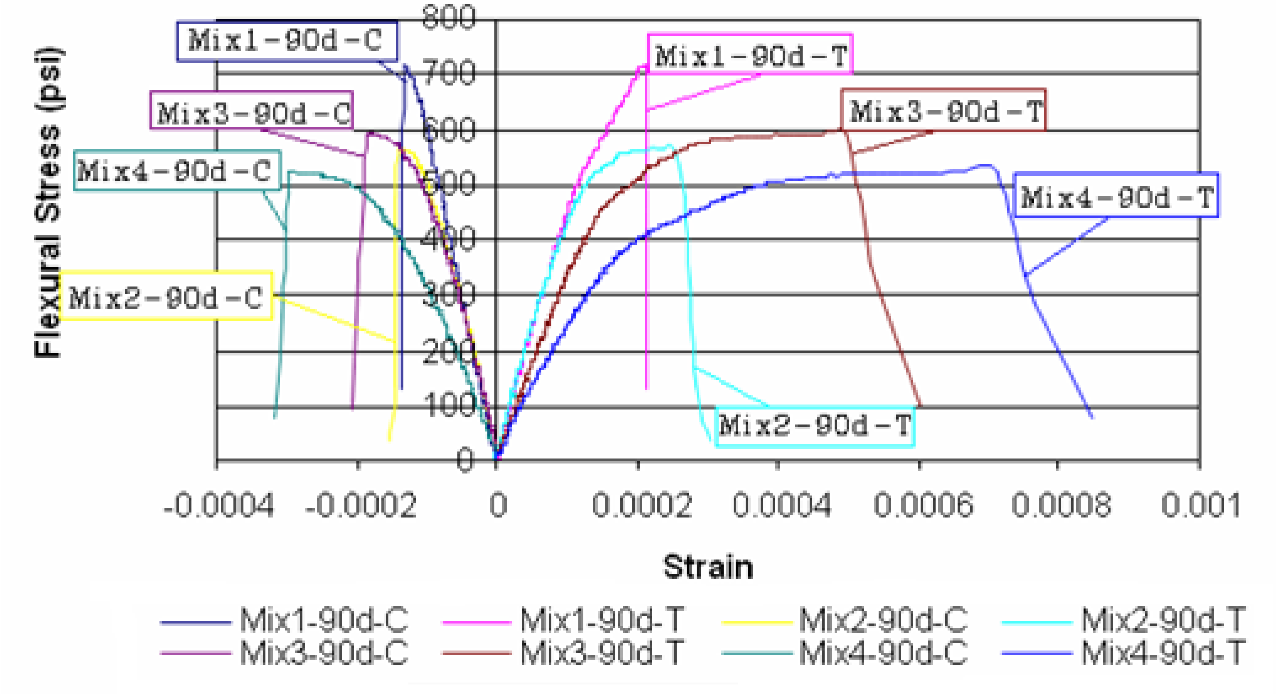

Figure 4-13. Stress-strain plots from beam test on concrete mixtures with 0.53 w/c ratio and different RAP-1 contents.

Table 4-7. Modulus of Toughness of Concrete Containing RAP-1 at 90 Days

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Modulus of Toughness (lb-in/in^3)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Tension	Compression
Set-2 RAP-1	1	0.53	100	0	100	0	0	0.13	0.05
	2	0.53	90	10	90	10	10	0.14	0.04
	3	0.53	80	20	80	20	20	0.32	0.08
	4	0.53	60	40	60	40	40	0.33	0.11

Figures 4-14 and 4-15 show the stress-strain plots from beam tests on concrete mixtures containing RAP-2 at 14 days and 28 days, respectively. Tables 4-8 and 4-9 show the values of modulus of toughness of these concrete mixtures computed from these plots. Similarly, it can be observed that the modulus of toughness generally increased as the percent RAP used in the concrete mix increased.

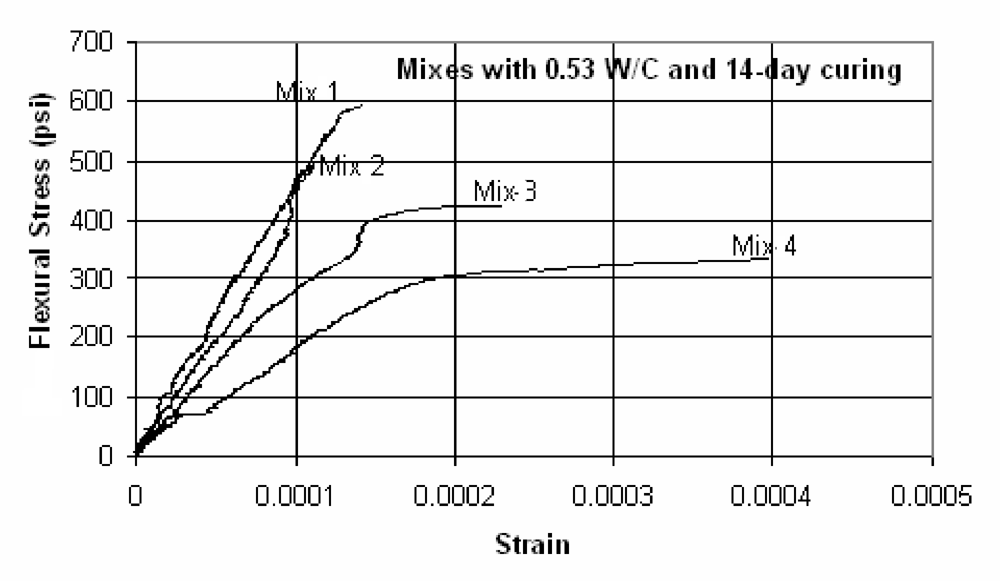

Figure 4-14. Stress-strain plots from beam test for mixtures with different RAP-2 contents at 14 days.

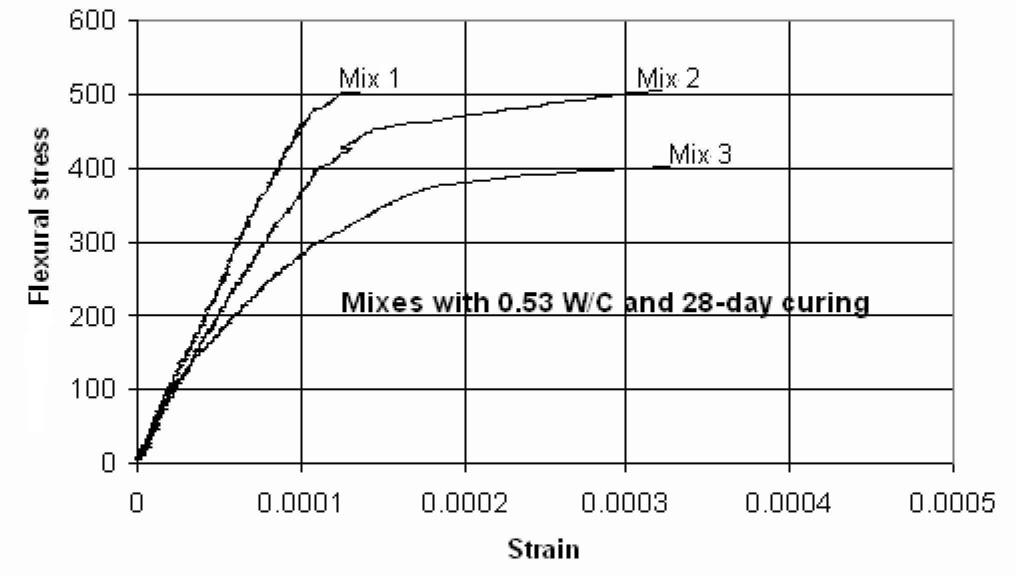

Figure 4-15. Stress-strain plots from beam test for mixtures with different RAP-2 contents at 28 days.

Table 4-8. Modulus of Toughness of Concrete Containing RAP-2 at 14 Days

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Modulus of Toughness (lb-in/in^3)
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		
Set-1 RAP-2	1	0.53	100	0	100	0	0	0.04
	2	0.53	90	10	90	10	10	0.03
	3	0.53	80	20	80	20	20	0.06
	4	0.53	60	40	60	40	40	0.09

Table 4-9. Modulus of Toughness of Concrete Containing RAP-2 at 28 Days

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Modulus of Toughness (lb-in/in^3)
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		
Set-1 RAP-2	1	0.53	100	0	100	0	0	0.04
	2	0.53	90	10	90	10	10	0.14
	3	0.53	80	20	80	20	20	0.10
	4	0.53	60	40	60	40	40	/

4.5 Analysis of Splitting Tensile Strength Test Results

4.5.1 Splitting Tensile Strength Test Results

The average split tensile strengths at various curing periods of different concrete mixtures containing RAP-1 and RAP-2 are shown in Tables 4-10 and 4-11, respectively. Individual splitting tensile strength values are shown in Table B-4.

Table 4-10. Splitting Tensile Strength of the Concrete Containing RAP-1 (Set-2)

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Splitting Tensile Strength (psi)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-2 RAP-1	1	0.53	100	0	100	0	0	533	607
	2	0.53	90	10	90	10	10	387	417
	3	0.53	80	20	80	20	20	364	360
	4	0.53	60	40	60	40	40	211	/

Table 4-11. Splitting Tensile Strength of the Concrete Containing RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Splitting Tensile Strength (psi)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	335	378
	2	0.48	66	34	47	53	40	281	300
	3	0.43	82	18	76	24	20	365	444
	4	0.43	67	33	44	56	40	289	312
Set-2 RAP-2	1	0.43	100	0	100	0	0	523	545
	2	0.43	82	18	76	24	20	329	403
	3	0.43	67	33	44	56	40	259	280
	4	0.43	67	33	44	56	40	/	/
	1	0.48	100	0	100	0	0	487	530
	2	0.48	82	18	77	23	20	390	405
	3	0.48	66	34	47	53	40	276	279
	1	0.53	100	0	100	0	0	382	412
	2	0.53	82	18	76	24	20	328	338
	3	0.53	67	33	44	56	40	280	267

4.5.2 Effect of RAP on Splitting Tensile Strength of Concrete

Figure 4-16 shows the comparison of the splitting tensile strengths of concrete containing different amounts of RAP-1 with a w/c ratio of 0.53. The splitting tensile strengths of Mixes 2, 3, and 4 at 14 days were 74%, 70%, and 40%, respectively, of that of the reference mix. At 28 days, the splitting tensile strengths of Mixes 2 and 3 were 77% and 67%, respectively, of that of the reference mix.

Figures 4-17 and 4-18 show the comparison of the splitting tensile strengths of concrete containing different amounts of RAP-2 at 14 days and 28 days, respectively. The average reduction in splitting tensile strength for all the different w/c ratios and different curing periods were 25% for concrete containing 20% RAP-2 and 45% for concrete containing 40% RAP-2. Figure 4-19 shows the comparison in the reduction in splitting tensile strength with the corresponding reduction in compressive strength and flexural strength for the concretes using RAP-1. The average reduction in compressive strength was 18%, 38%, and 58% for Mixes 2, 3, and 4, respectively. The average reduction in flexural strength was 10%, 20%, and 30% for Mixes 2, 3, and 4, respectively. The average reduction in splitting tensile strength was 25%, 30%, and 60%

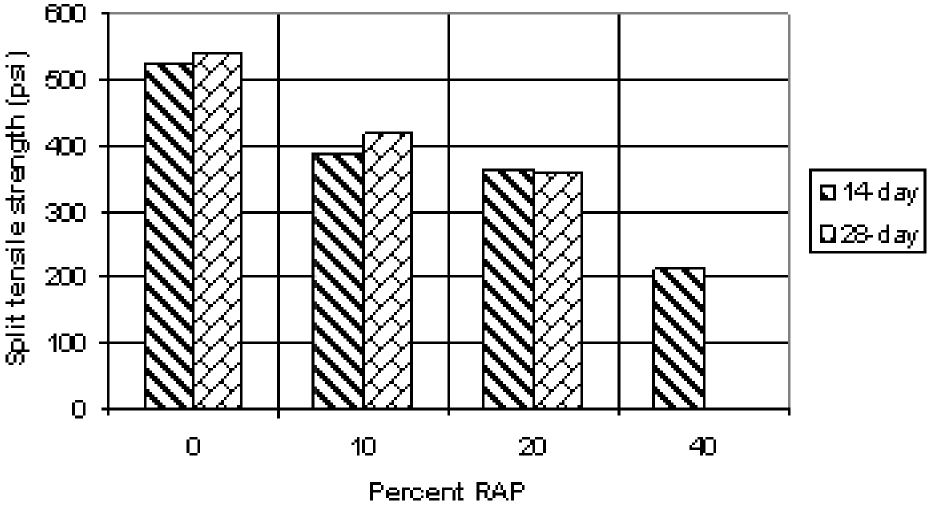

Figure 4-16. Effect of RAP-1 on splitting tensile strength of concrete at a 0.53 W/C ratio.

for Mixes 2, 3, and 4, respectively. Reduction in splitting tensile strength was higher than that in flexural strength for this set of mixtures containing RAP-1.

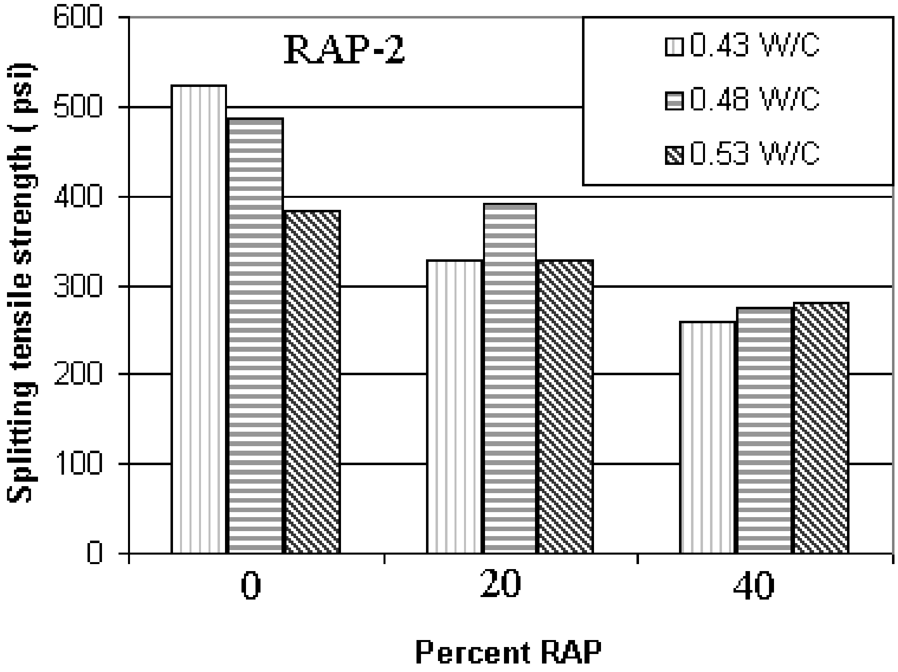

Figure 4-17. Effect of RAP-2 on splitting tensile strength of concrete at 14-days.

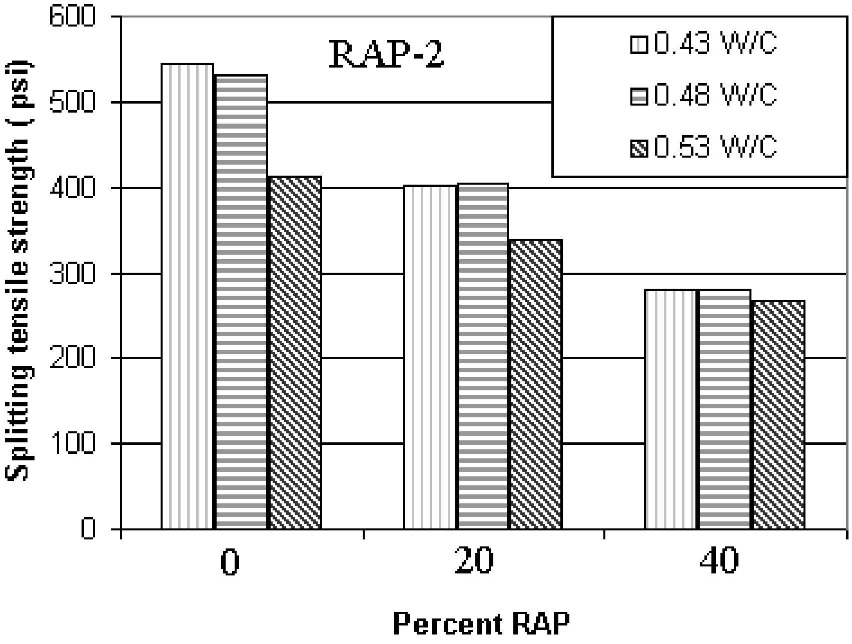

Figure 4-18. Effect of RAP-2 on splitting tensile strength of concrete at 28-days.

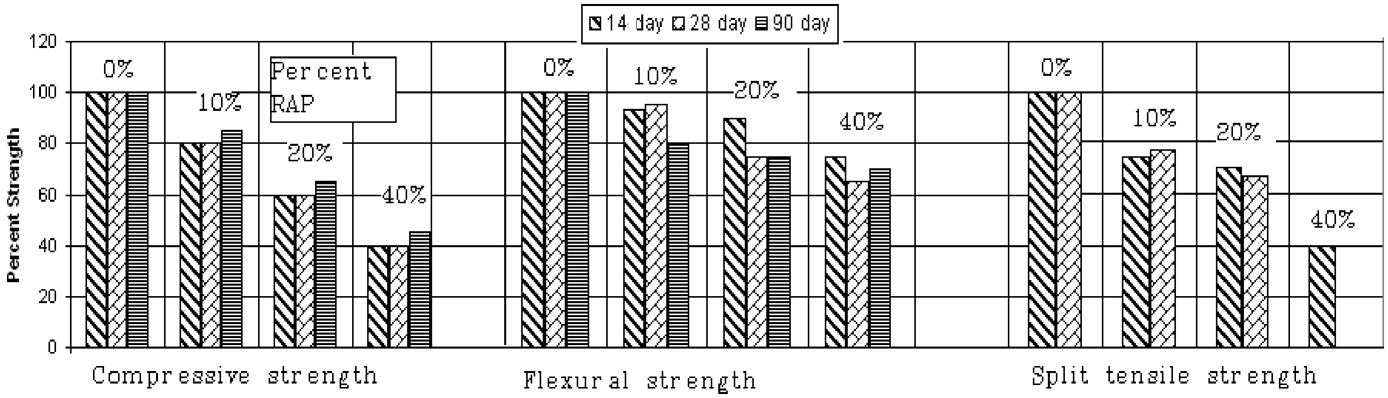

Figure 4-19. Reduction in compressive, flexural and splitting tensile strength for the concrete containing RAP-1.

4.6 Analysis of Free Shrinkage Test Results

4.6.1 Free Shrinkage Test Results

The average free shrinkage values at various curing periods of different concrete mixtures containing RAP-1 and RAP-2 are presented in Table 4-12 and Table 4-13, respectively. The individual free shrinkage strain values are shown in Table B-5 of Appendix B.

Table 4-12. Free Shrinkage of the Concrete using RAP-1

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Shrinkage (10^{-6} in/in)		
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days	90 days
Set-1 RAP-1	1	0.53	100	0	100	0	0	73	250	/
	2	0.53	90	10	90	10	10	85	215	/
	3	0.53	80	20	80	20	20	73	120	277
	4	0.53	60	40	60	40	40	67	187	337
Set-2 RAP-1	1	0.53	100	0	100	0	0	150	287	353
	2	0.53	90	10	90	10	10	103	240	353
	3	0.53	80	20	80	20	20	220	283	390
	4	0.53	60	40	60	40	40	210	327	507

Table 4-13. Free Shrinkage of the Concrete using RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Shrinkage (10^{-6} in/in)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	127	276
	2	0.48	66	34	47	53	40	140	300
	3	0.43	82	18	76	24	20	153	260
	4	0.43	67	33	44	56	40	140	273
Set-2 RAP-2	1	0.43	100	0	100	0	0	190	300
	2	0.43	82	18	77	23	20	167	275
	3	0.43	67	33	44	56	40	150	273
	4	0.43	67	33	44	56	40	/	/
	1	0.48	100	0	100	0	0	130	280
	2	0.48	82	18	77	23	20	250	340
	3	0.48	66	34	47	53	40	230	350
	1	0.53	100	0	100	0	0	130	250
	2	0.53	82	18	76	24	20	120	233
	3	0.53	67	33	44	56	40	106	227

4.6.2 Effect of RAP on Free Shrinkage of Concrete

Figure 4-20 shows plots of average shrinkage versus time for the concrete mixes containing RAP-1. The concretes containing RAP-1 appeared to have similar shrinkage to that of the control mix, except for Mix 4 (with 40% RAP-1) at 90 days, which had a relatively higher value compared to the others.

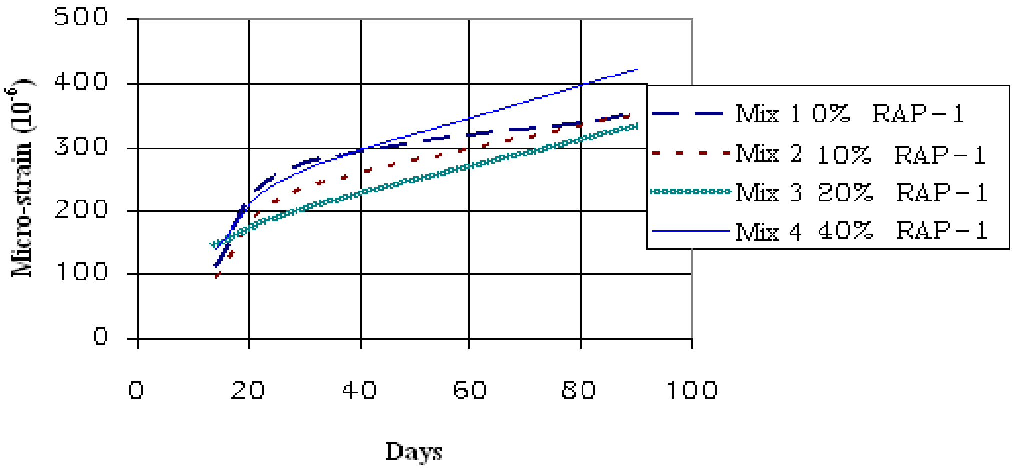

Figure 4-20. Free shrinkage strain for concrete mixtures with different RAP-1 contents.

Figure 4-21 shows plots of the average shrinkage versus time for the concrete mixes containing RAP-2 and with different w/c ratios. It can be seen that for the concrete mixes with w/c ratio of 0.43 and 0.53, the shrinkage strains of concrete containing RAP appear to be lower than those of the control mix. However, for the mixes with a w/c ratio of 0.48, the concrete mixes with containing RAP appear to have higher shrinkage strains than that of the control mix.

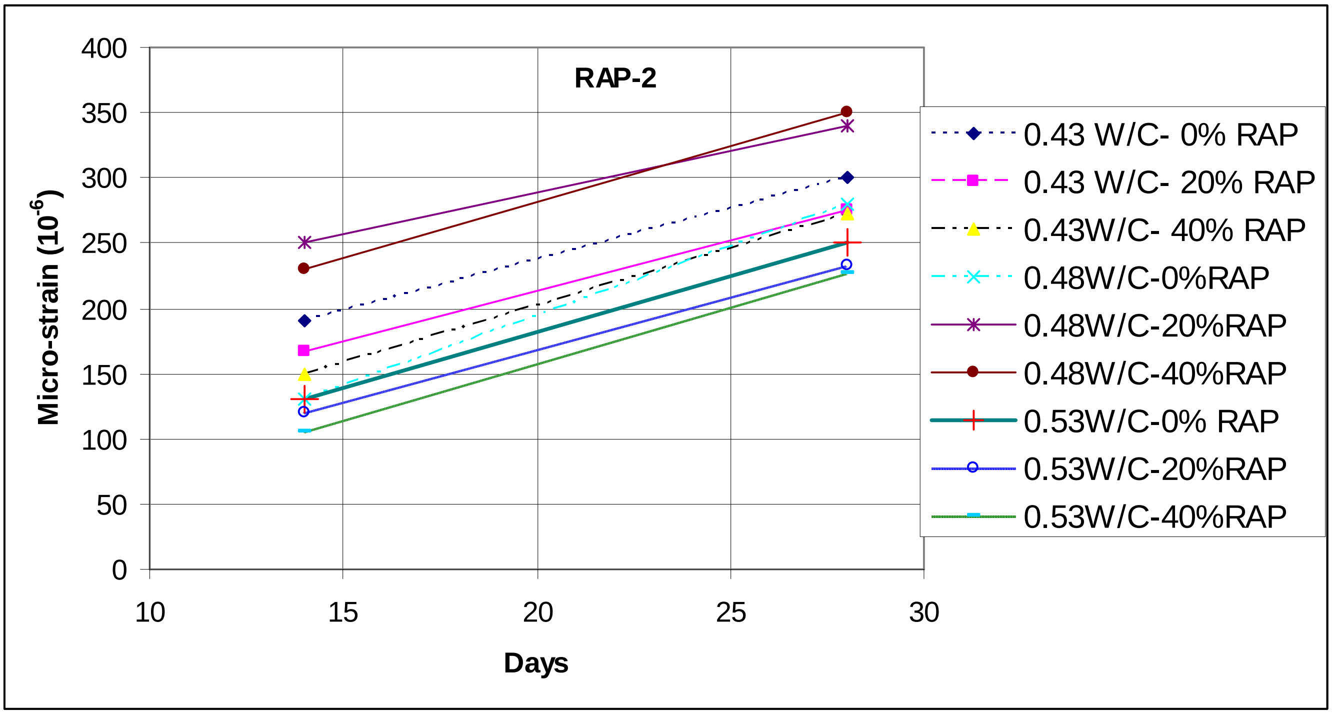

Figure 4-21. Free shrinkage strain for concrete mixtures with different RAP-2 contents.

4.7 Analysis of Coefficient of Thermal Expansion Test Results

4.7.1 Coefficient of Thermal Expansion Test Results

The average coefficients of thermal expansion at various curing periods of the concrete mixes containing RAP-1 and RAP-2 are shown in Tables 4-14 and 4-15, respectively. Individual coefficient of thermal expansion values are shown in Table B-6.

Table 4-14. Coefficient of Thermal Expansion of the Concrete using RAP-1

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Coefficient of Thermal Expansion (10^{-6}/°F)		
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days	90 days
Set-1 RAP-1	1	0.53	100	0	100	0	0	5.97	6.05	6.19
	2	0.53	90	10	90	10	10	6.00	6.07	6.27
	3	0.53	80	20	80	20	20	5.85	6.43	6.12
	4	0.53	60	40	60	40	40	6.36	6.20	6.29
Set-2 RAP-1	1	0.53	100	0	100	0	0	5.79	5.55	5.79
	2	0.53	90	10	90	10	10	5.85	5.96	5.63
	3	0.53	80	20	80	20	20	5.81	5.72	5.86
	4	0.53	60	40	60	40	40	5.97	6.13	5.99

Table 4-15. Coefficient of Thermal Expansion of the Concrete using RAP-2

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	Coefficient of Thermal Expansion (10^{-6}/°F)	
			Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		14 days	28 days
Set-1 RAP-2	1	0.48	82	18	77	23	20	6.49	5.75
	2	0.48	66	34	47	53	40	5.74	5.90
	3	0.43	82	18	76	24	20	6.03	6.34
	4	0.43	67	33	44	56	40	5.94	6.17
Set-2 RAP-2	1	0.43	100	0	100	0	0	5.28	5.43
	2	0.43	82	18	76	24	20	/	/
	3	0.43	67	33	44	56	40	/	/
	4	0.43	67	33	44	56	40	/	/
	1	0.48	100	0	100	0	0	4.90	5.25
	2	0.48	82	18	76	24	20	5.00	5.11
	3	0.48	66	34	47	53	40	5.25	5.08
	1	0.53	100	0	100	0	0	/	/
	2	0.53	82	18	76	24	20	/	5.18
	3	0.53	66	34	47	53	40	/	4.97

4.7.2 Effect of RAP on Coefficient of Thermal Expansion of Concrete

Coefficient of thermal expansion of a concrete mix depends mainly on the aggregate type and the amount of aggregate in a mix. Limestone is known to have the lowest coefficients of thermal expansion compared to rocks such as sandstone and granite. Since RAP contains asphalt, it would tend to have a higher coefficient of thermal expansion as compared with the aggregate in the mix. However, it is very difficult to predict the exact difference in coefficient of thermal between the RAP mix and the reference mix. This could be due to the variation in the properties of the RAP. For the mixtures containing RAP-1, the increase in coefficient of thermal expansion was within 5% of that of the reference mix at different curing periods. For the mixtures containing RAP-2 in Set-1, there was a decrease in coefficient of thermal as compared with the reference mix. At 14 days of curing, the reductions were 5%, 8%, and 6% for Mixes 2, 3, and 4, respectively. For the mixtures containing RAP-2 in set-2, the mixes containing RAP showed a slight increase in the coefficient of thermal expansion.

4.8 Summary of Test Results

The main findings from results of tests on concrete containing RAP are summarized as follows:

1. Compressive strength, flexural strength, splitting tensile strength, and elastic modulus of concrete decreased as the percentage of RAP increased in a concrete mix.
2. Reduction in flexural strength of the concrete containing RAP was lower than compressive strength and splitting tensile strength of the concrete mix containing RAP.
3. Failure strain and modulus of toughness of concrete increased as the percentage of RAP increased in a concrete mix.
4. The shrinkage strain of the concrete increased slightly with increasing RAP content.
5. The coefficient of thermal expansion appeared to increase slightly with the use of one RAP and decrease slightly with the use of a second RAP.

CHAPTER 5
EVALUATION OF POTENTIAL PERFORMANCE OF CONCRETE CONTAINING RAP IN PAVEMENT

5.1 Critical Stress Analysis to Assess Potential Performance of Concrete Containing RAP

Analysis was done to determine how each of the concrete mixes with different RAP content would perform if it were used in a typical concrete pavement in Florida. Using the measured elastic modulus and the coefficient of thermal expansion to model the concrete, analysis was performed to determine the maximum stresses in the concrete slab if it were loaded by a 22-kip axle load applied at two critical loading positions, namely: 1) at the slab corner; and 2) at the middle of the slab edge. Temperature differentials of +20° F and −20° F in the concrete slab were used in the analyses.

The FEACONS IV (Finite Element Analysis of CONcrete Slabs, version IV) program was used to perform the stress analysis. The FEACONS program was previously developed at the University of Florida for FDOT for the analysis of PCC pavements subjected to load and thermal effects, and has demonstrated to be a fairly effective and reliable tool for this type of analysis.

Figure 5-1 shows the finite element model used to perform the stress analysis. The detailed input guide for the FEACONS IV program is provided in Appendix A of this report.

The following parameters were used to model the concrete pavement:

1) Slab thickness = 10″; slab length = 15′; slab width = 12′ ;
2) Subgrade modulus, k_s = 0.3 kci; edge stiffness, k_e = 30 ksi; and
3) Joint linear stiffness, k_l = 500 ksi; joint torsion stiffness k_t = 1000 k-in/in.

The two loading positions of the 22-kip single-axle load used in the analysis are shown in Figure 5-2. The middle of the slab edge is the most critical loading position in the day time when the temperature differential in the slab is positive, while the slab corner is the most critical loading position at night when the temperature differential is negative.

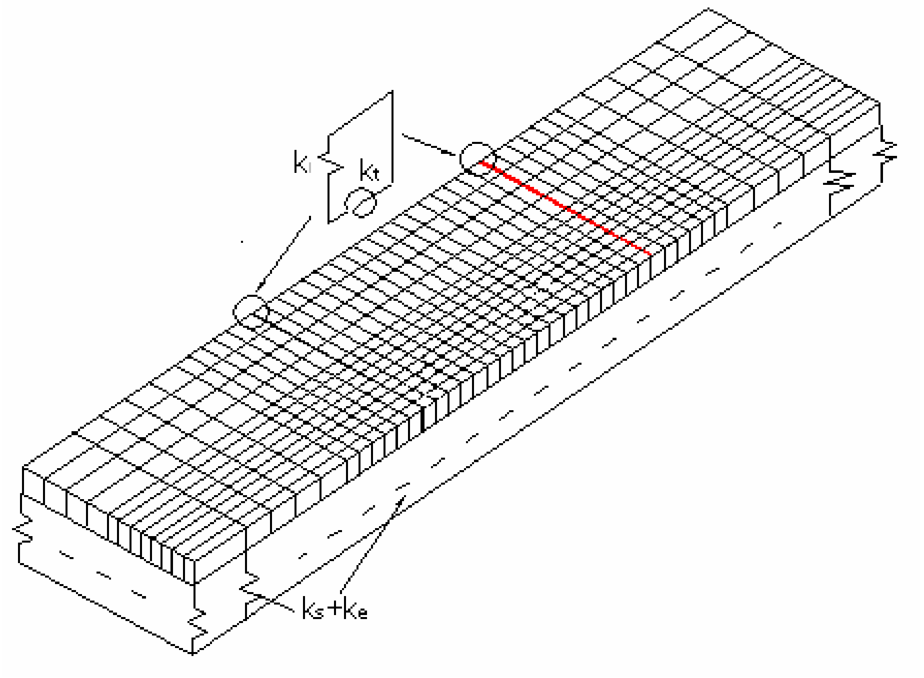

Figure 5-1. Finite element model used in FEACONS IV analysis.

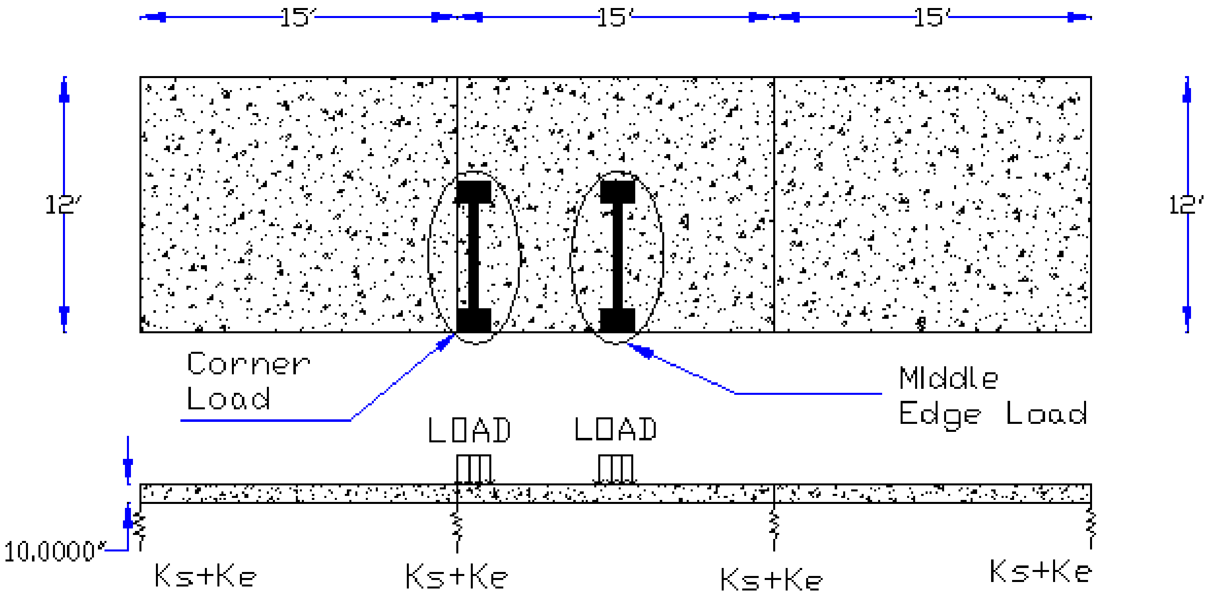

Figure 5-2. The 22-kip axle wheel load at slab corner and middle edge.

5.2 Results of Critical Stress Analysis

The computed maximum stresses in the concrete slab from the critical stress analysis are presented in Tables 5-1 through 5-10 for the concrete mixes containing different amounts of RAP-1 and RAP-2. The ratios of maximum stress to the flexural strength of the concrete were also computed and presented in these tables. This stress-strength ratio is related to the number of stress cycles to fatigue failure. A lower stress strength ratio means a higher number of stress cycles to failure and means a better performing concrete.

From the results presented in Table 5-1 through Table 5-10, it can be seen that the most critical loading condition, which results in the maximum computed stresses, was the condition when the 22-kip axle load was applied at the middle edge of the slab when the temperature differential was +20° F. Thus, the comparison of potential performance of the different concrete mixes was made based on the computed stress-strength ratios at this condition.

Figures 5-3 shows the plots of average computed stress-strength ratios in the concrete slab using the concretes containing RAP-1, for the conditions of a 22-kip single-axle load applied at the slab mid edge and a slab temperature differential of +20° F. It can be seen that the concrete containing 40% RAP had a lower stress-strength ratio than the concretes containing 10% and 20% RAP at all curing times. The concrete containing 40% RAP showed a lower stress-strength ratio than the control concrete at 14 and 28 days, and a slightly higher stress-strength ratio than the control concrete at 90 days.

Figures 5-4 and 5-5 show the plots of average maximum computed stress-strength ratios in the concrete slab using the concretes containing RAP-2 for the most critical condition of a 22-kip single-axle load applied at the slab mid edge and a slab temperature differential of +20° F for curing times of 14 days and 28 days, respectively. At the curing time of 14 days (as shown

Table 5-1. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-1) at 14 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	14-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4440	883	387	450	0.44	0.51
2	0.53	90	10	90	10	10	6.00	3820	807	371	408	0.46	0.50
3	0.53	80	20	80	20	20	6.00	3350	829	354	376	0.43	0.45
4	0.53	60	40	60	40	40	6.00	2310	715	297	296	0.42	0.41
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4440	883	310	292	0.35	0.33
2	0.53	90	10	90	10	10	6.00	3820	807	276	260	0.33	0.32
3	0.53	80	20	80	20	20	6.00	3350	829	249	234	0.30	0.28
4	0.53	60	40	60	40	40	6.00	2310	715	182	174	0.25	0.24
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4440	883	161	177	0.18	0.20
2	0.53	90	10	90	10	10	6.00	3820	807	154	171	0.19	0.21
3	0.53	80	20	80	20	20	6.00	3350	829	149	165	0.18	0.20
4	0.53	60	40	60	40	40	6.00	2310	715	135	149	0.19	0.21

Table 5-2. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-1) at 28 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4780	940	398	470	0.42	0.50
2	0.53	90	10	90	10	10	6.00	4000	940	373	421	0.39	0.45
3	0.53	80	20	80	20	20	6.00	3400	750	356	380	0.47	0.51
4	0.53	60	40	60	40	40	6.00	2350	639	298	299	0.47	0.47
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4780	940	328	308	0.35	0.33
2	0.53	90	10	90	10	10	6.00	4000	940	286	269	0.30	0.27
3	0.53	80	20	80	20	20	6.00	3400	750	252	237	0.34	0.32
4	0.53	60	40	60	40	40	6.00	2350	639	185	176	0.32	0.28
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4780	940	164	181	0.17	0.19
2	0.53	90	10	90	10	10	6.00	4000	940	157	173	0.17	0.18
3	0.53	80	20	80	20	20	6.00	3400	750	150	166	0.20	0.22
4	0.53	60	40	60	40	40	6.00	2350	639	135	150	0.24	0.23

Table 5-3. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-1) at 90 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	90-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE $(10^{-6}/^\circ F)$	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4720	976	396	467	0.41	0.48
2	0.53	90	10	90	10	10	6.00	4130	845	376	429	0.44	0.51
3	0.53	80	20	80	20	20	6.00	3570	756	362	392	0.48	0.52
4	0.53	60	40	60	40	40	6.00	2500	677	307	311	0.45	0.46
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4720	976	324	305	0.33	0.31
2	0.53	90	10	90	10	10	6.00	4130	845	293	276	0.35	0.33
3	0.53	80	20	80	20	20	6.00	3570	756	262	246	0.35	0.33
4	0.53	60	40	60	40	40	6.00	2500	677	195	184	0.29	0.27
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4720	976	164	180	0.17	0.18
2	0.53	90	10	90	10	10	6.00	4130	845	158	174	0.19	0.21
3	0.53	80	20	80	20	20	6.00	3570	756	152	168	0.20	0.22
4	0.53	60	40	60	40	40	6.00	2500	677	137	153	0.20	0.23

Table 5-4. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-2) at 14 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	14-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4600	801	392	459	0.49	0.57
2	0.53	90	10	90	10	10	6.00	4170	780	378	432	0.48	0.55
3	0.53	80	20	80	20	20	6.00	3410	704	356	381	0.51	0.54
4	0.53	60	40	60	40	40	6.00	2270	558	296	292	0.53	0.52
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4600	801	319	300	0.40	0.37
2	0.53	90	10	90	10	10	6.00	4170	780	296	278	0.38	0.36
3	0.53	80	20	80	20	20	6.00	3410	704	252	237	0.36	0.34
4	0.53	60	40	60	40	40	6.00	2270	558	180	171	0.32	0.31
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4600	801	163	179	0.20	0.23
2	0.53	90	10	90	10	10	6.00	4170	780	159	175	0.20	0.22
3	0.53	80	20	80	20	20	6.00	3410	704	150	166	0.21	0.24
4	0.53	60	40	60	40	40	6.00	2270	558	134	149	0.24	0.27

Table 5-5. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-2) at 28 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4900	969	402	478	0.42	0.49
2	0.53	90	10	90	10	10	6.00	4510	867	389	453	0.45	0.52
3	0.53	80	20	80	20	20	6.00	3750	709	369	403	0.52	0.57
4	0.53	60	40	60	40	40	6.00	2300	640	297	295	0.46	0.46
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4900	969	334	314	0.35	0.32
2	0.53	90	10	90	10	10	6.00	4510	867	314	295	0.36	0.34
3	0.53	80	20	80	20	20	6.00	3750	709	272	256	0.38	0.36
4	0.53	60	40	60	40	40	6.00	2300	640	182	173	0.28	0.27
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4900	969	166	182	0.17	0.19
2	0.53	90	10	90	10	10	6.00	4510	867	162	178	0.19	0.21
3	0.53	80	20	80	20	20	6.00	3750	709	154	170	0.22	0.24
4	0.53	60	40	60	40	40	6.00	2300	640	135	149	0.21	0.23

Table 5-6. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-1 (Set-2) at 90 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	90-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4760	763	397	469	0.52	0.61
2	0.53	90	10	90	10	10	6.00	4550	572	390	457	0.68	0.80
3	0.53	80	20	80	20	20	6.00	3530	553	361	389	0.65	0.70
4	0.53	60	40	60	40	40	6.00	2620	510	316	321	0.62	0.63
Temperature difference of −20° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4760	763	327	307	0.43	0.40
2	0.53	90	10	90	10	10	6.00	4550	572	316	297	0.55	0.52
3	0.53	80	20	80	20	20	6.00	3530	553	259	244	0.47	0.47
4	0.53	60	40	60	40	40	6.00	2620	510	203	191	0.40	0.40
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	6.00	4760	763	165	181	0.22	0.24
2	0.53	90	10	90	10	10	6.00	4550	572	162	170	0.28	0.30
3	0.53	80	20	80	20	20	6.00	3530	553	151	167	0.27	0.30
4	0.53	60	40	60	40	40	6.00	2620	510	139	154	0.27	0.23

Table 5-7. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-2 (Set-1) at 14 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	14-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE $(10^{-6}/^\circ F)$	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.48	82	18	77	23	20	5.12	3170	477	320	334	0.67	0.70
2	0.48	66	34	47	53	40	5.12	2300	393	275	274	0.70	0.70
3	0.43	82	18	76	24	20	5.12	3230	484	324	338	0.67	0.70
4	0.43	67	33	44	56	40	5.12	2250	394	272	270	0.69	0.69
Temperature difference of –20° F between top and bottom:													
1	0.48	82	18	77	23	20	5.12	3170	477	205	192	0.43	0.40
2	0.48	66	34	47	53	40	5.12	2300	393	157	152	0.39	0.38
3	0.43	82	18	76	24	20	5.12	3230	484	208	194	0.42	0.40
4	0.43	67	33	44	56	40	5.12	2250	394	154	150	0.39	0.38

Table 5-8. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-2 (Set-1) at 28 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.48	82	18	77	23	20	5.12	2810	482	302	310	0.62	0.64
2	0.48	66	34	47	53	40	5.12	2270	410	273	271	0.66	0.66
3	0.43	82	18	76	24	20	5.12	3900	539	350	380	0.64	0.70
4	0.43	67	33	44	56	40	5.12	3290	404	322	343	0.79	0.84
Temperature difference of −20° F between top and bottom:													
1	0.48	82	18	77	23	20	5.12	2810	482	186	176	0.38	0.36
2	0.48	66	34	47	53	40	5.12	2270	410	155	151	0.37	0.36
3	0.43	82	18	76	24	20	5.12	3900	539	242	225	0.44	0.41
4	0.43	67	33	44	56	40	5.12	3290	404	211	197	0.52	0.48

Table 5-9. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-2 (Set-2) at 14 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	14-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.28 (5.12)*	4154	762	358	395	0.47	0.52
2	0.43	82	18	77	23	20	5.12*	2790	612	302	309	0.49	0.50
3	0.43	67	33	44	56	40	5.12*	1770	460	239	233	0.52	0.50
4	0.43	67	33	44	56	40	5.12*	2340	560	276	277	0.49	0.49
1	0.48	100	0	100	0	0	5.08 (5.12)*	3930	723	351	382	0.48	0.53
2	0.48	82	18	77	23	20	5.18 (5.12)*	2958	593	310	320	0.52	0.54
3	0.48	67	33	44	56	40	4.97 (5.12)*	2122	506	262	260	0.52	0.51
1	0.53	100	0	100	0	0	5.12*	3460	674	332	353	0.49	0.52
2	0.53	82	18	77	23	20	4.94 (5.12)*	2850	576	304	313	0.53	0.54
3	0.53	67	33	44	56	40	5.11 (5.12)*	1860	465	245	241	0.53	0.52
Temperature difference of −20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.28 (5.12)*	4154	762	254	237	0.33	0.31
2	0.43	82	18	77	23	20	5.12*	2790	612	184	175	0.30	0.29
3	0.43	67	33	44	56	40	5.12*	1770	460	125	127	0.27	0.28
4	0.43	67	33	44	56	40	5.12*	2340	560	160	154	0.28	0.27
1	0.48	100	0	100	0	0	5.08 (5.12)*	3930	723	243	227	0.34	0.31
2	0.48	82	18	77	23	20	5.18 (5.12)*	2958	593	194	183	0.33	0.31
3	0.48	67	33	44	56	40	4.97 (5.12)*	2122	506	145	142	0.29	0.28
1	0.53	100	0	100	0	0	5.12*	3460	674	220	205	0.33	0.30
2	0.53	82	18	77	23	20	4.94 (5.12)*	2850	576	188	178	0.33	0.31
3	0.53	67	33	44	56	40	5.11 (5.12)*	1860	465	131	129	0.28	0.28

*Coefficient of thermal expansion used for analysis.

Table 5-10. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete with RAP-2 (Set-2) at 28 Days

Mix #	W/C Ratio	Coarse		Fine		Total RAP (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RAP (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE $(10^{-6}/^\circ F)$	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.43 (5.12)*	4090	912	357	391	0.39	0.43
2	0.43	82	18	77	23	20	5.12*	2870	705	304	314	0.43	0.45
3	0.43	67	33	44	56	40	5.12*	1850	523	245	240	0.47	0.46
4	0.43	67	33	44	56	40	5.12*	2082	580	260	257	0.45	0.44
1	0.53	100	0	100	0	0	5.12*	3730	739	343	370	0.46	0.50
2	0.53	82	18	77	23	20	4.90 (5.12)*	2970	591	310	321	0.52	0.54
3	0.53	67	33	44	56	40	5.00 (5.12)*	1958	483	252	248	0.52	0.51
1	0.48	100	0	100	0	0	5.25 (5.12)*	4070	803	356	390	0.44	0.49
2	0.48	82	18	77	23	20	/ (5.12)*	2988	633	311	321	0.49	0.51
3	0.48	67	33	44	56	40	/ (5.12)*	2054	580	258	254	0.44	0.44
Temperature difference of −20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.43 (5.12)*	4090	912	251	234	0.28	0.26
2	0.43	82	18	77	23	20	5.12*	2870	705	188	178	0.27	0.25
3	0.43	67	33	44	56	40	5.12*	1850	523	130	131	0.25	0.25
4	0.43	67	33	44	56	40	5.12*	2082	580	144	142	0.25	0.25
1	0.53	100	0	100	0	0	5.12*	3730	739	234	218	0.32	0.29
2	0.53	82	18	77	23	20	4.90 (5.12)*	2970	591	194	183	0.33	0.31
3	0.53	67	33	44	56	40	5.00 (5.12)*	1958	483	137	136	0.28	0.28
1	0.48	100	0	100	0	0	5.25 (5.12)*	4070	803	250	233	0.31	0.29
2	0.48	82	18	77	23	20	/ (5.12)*	2988	633	195	184	0.31	0.29
3	0.48	67	33	44	56	40	/ (5.12)*	2054	580	141	139	0.24	0.24

*Coefficient of thermal expansion used for analysis.

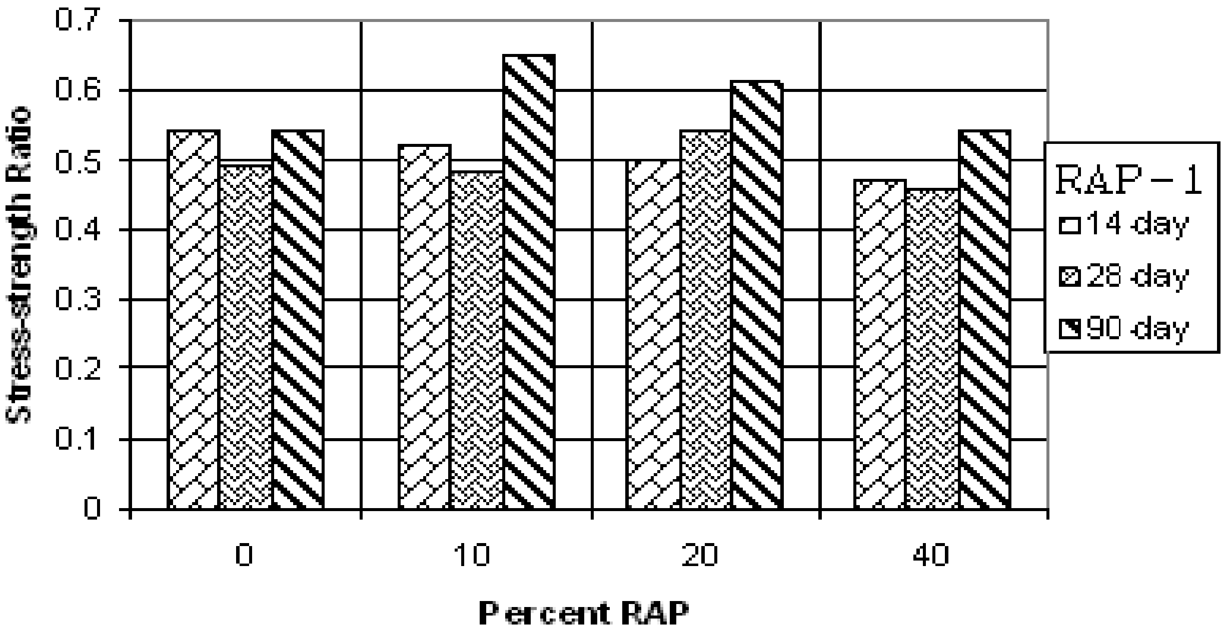

Figure 5-3. Average stress-strength ratios for concretes containing RAP-1 (for 22-kip axle load applied at the slab mid edge and a temperature differential of +20° F).

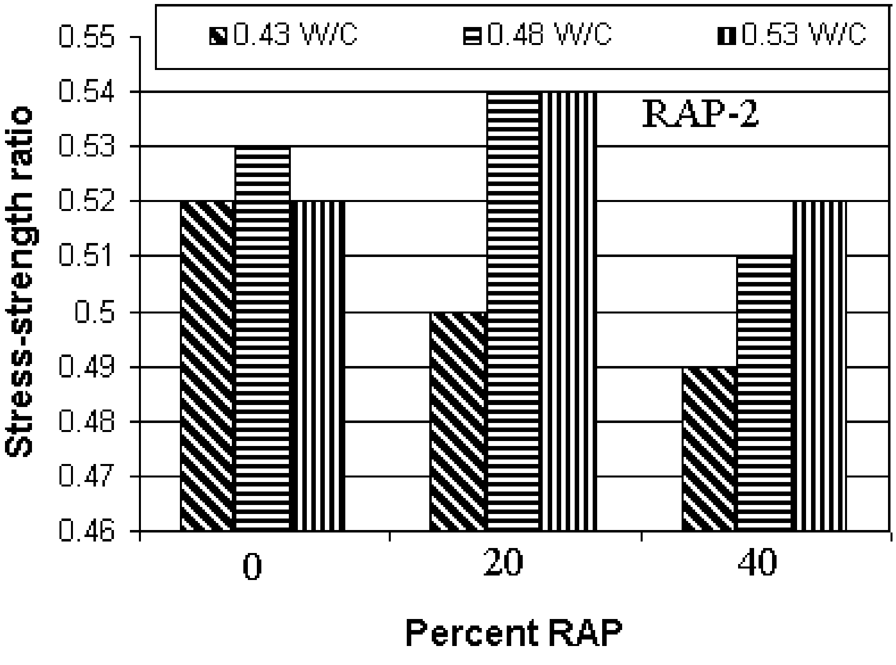

Figure 5-4. Average stress-strength ratios for concretes containing RAP-2 at 14 days (for 22-kip axle load applied at the slab mid edge and a temperature differential of +20° F).

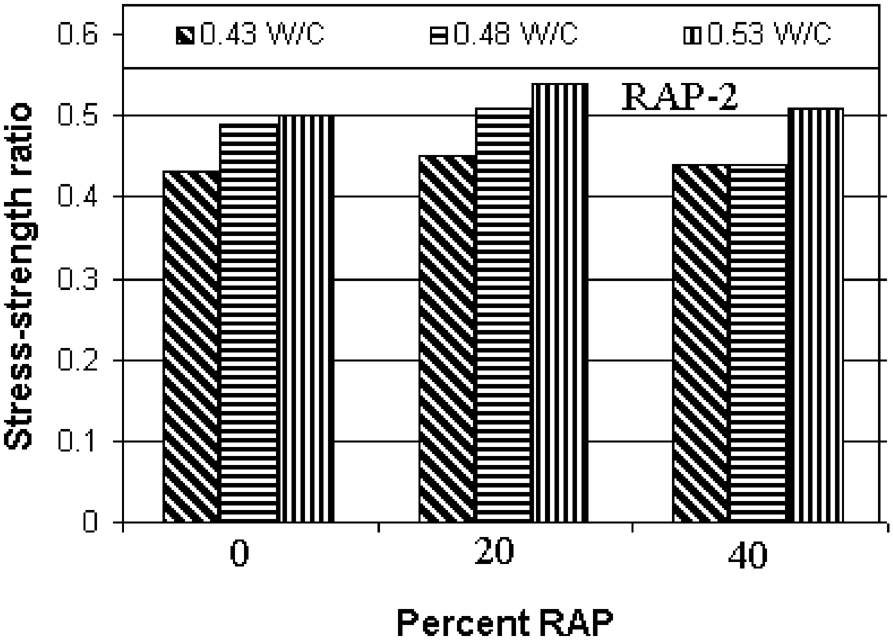

Figure 5-5. Average stress-strength ratios for concretes containing RAP-2 at 28 days (for 22-kip axle load applied at the slab mid edge and a temperature differential of +20° F).

in Figure 5-4), the concrete mixes containing 40% RAP-2 showed lower stress-strength ratios than the concretes containing 20% RAP and the reference mix for all w/c ratios. At the curing time of 28 days (as shown in Figure 5-5), the concrete mixes containing 40% RAP-2 showed lower stress-strength ratios than the concretes containing 20% RAP for all w/c ratios. However, the concrete mixes containing 40% RAP-2 showed lower stress-strength ratios than the reference mix at only the w/c ratio of 0.48, but slightly higher values at the w/c ratios of 0.43 and 0.53.

5.3 Summary of Findings

When finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses in the pavement were found to decrease as the RAP content of the content increased, due to a decrease in the elastic modulus of the concrete. Though the flexural strength of the concrete decreased as the RAP content increased, an increase in RAP content resulted generally in a decrease in the maximum stress to flexural strength ratio for the concrete. This indicates that using a concrete containing RAP could possibly result in improvement in the performance of concrete pavements.

CHAPTER 6
TESTING PROGRAM TO EVALUATE CONCRETE CONTAINING RCA

6.1 Introduction

This chapter describes the laboratory testing program utilized to evaluate the use of Recycled Concrete Aggregate (RCA) in concrete. It provides the mix proportion and mix ingredients used for the concrete mixtures in this testing program. It also explains the method of preparation of the concrete test specimens and the testing methods used in this testing program.

6.2 Concrete Mix Proportions

The percentages of RCA incorporated in the different concrete mixtures evaluated are shown in Table 6-1. The mix proportions for these different mixtures are shown in Table 6-2.

6.3 Mix Ingredients

The properties of the ingredients used for the mix are described as follows:

6.3.1 Water

Tap water supplied by the City of Gainesville was used for the mix.

Table 6-1. Concrete Mixes Containing RCA Evaluated

Set #	Mix #	W/C Ratio	Cement Content (lb/cy)	Coarse		Fine		Total RCA (%)
				Virgin Aggregates (%)	RCA (%)	Virgin Aggregates (%)	RCA (%)	
Set-1	1	0.43	628	100	0	100	0	0
	2	0.43	628	75	25	75	25	25
	3	0.43	628	50	50	50	50	50
Set-2	1	0.48	563	100	0	100	0	0
	2	0.48	563	75	25	75	25	25
	3	0.48	563	50	50	50	50	50
Set-3	1	0.53	508	100	0	100	0	0
	2	0.53	508	75	25	75	25	25
	3	0.53	508	50	50	50	50	50

Note: Percentage of aggregate is computed by volume.

Table 6-2. Mix Proportions for Concrete Containing RCA

Set #	Mix #	W/C Ratio	Cement Content (lb/cy)	Water Content (lb/cy)	Virgin Aggregate (lb/cy)		RCA (lb/cy)	
					Coarse	Fine	Coarse	Fine
Set 1	1	0.43	628	270	1726	1198	0	0
	2	0.43	628	270	1294	898	426	266
	3	0.43	628	270	863	599	853	531
Set-2	1	0.48	563	270	1755	1219	0	0
	2	0.48	563	270	1316	914	434	270
	3	0.48	563	270	878	610	876	540
Set-3	1	0.53	508	270	1781	1237	0	0
	2	0.53	508	270	1335	927	440	275
	3	0.53	508	270	891	619	879	549

6.3.2 Cement

Portland cement Type I/II supplied by Florida Rock Industry was used. Tables 6-3 and 6-4 show the physical and chemical properties of the cement as determined by FDOT personnel.

Table 6-3. Physical Properties of Type I/II Portland Cement Used

Test	Standard Specification	Cement
Loss on Ignition	ASTM C114	2.6%
Loss on Ignition (Acid Insoluble)	ASTM C114	0.08%
7-Day Compressive Strength	ASTM C109	4880 psi
Time of Setting (Initial)	ASTM 266	101 min
Time of Setting (Final)	ASTM 266	200 min

Table 6-4. Chemical Properties of Type I/II Portland Cement Used

Constituents	Percentage
Aluminum oxide	5.0%
Ferric oxide	4.2%
Magnesium oxide	0.7%
Sulfur trioxide	3.1%
Tricalcium aluminate	6.0%
Tricalcium silicate	69.0%
Total alkali as Na_2O	0.41%

6.3.3 Virgin Aggregates

Silica sand from Goldhead of Florida was used as the virgin fine aggregate, and Number 57 Miami Oolite limestone was used as the virgin coarse aggregate. The physical properties of this aggregate were determined by FDOT personnel. The results of these properties for fine and coarse aggregate are shown in Tables 6-5 and 6-6. Figure 6-1 shows the gradation plots for the fine and coarse aggregates.

Table 6-5. Specific Gravity and Water Absorption of Virgin Aggregates Used

Property	Coarse Aggregates	Fine Aggregates
SSD specific gravity	2.37	2.64
Dry bulk specific gravity	2.30	2.63
Dry apparent specific gravity	2.53	2.65
Absorption	4.0	0.4
LA abrasion loss	37	/

Table 6-6. Results of Sieve Analysis on the Virgin Aggregates Used

Sieve Size	Sieve Size (mm)	Percentage Passing	
		Coarse Aggregates	Fine Aggregates
1.5″	37.0	100	/
1″	25.0	100	/
0.5″	12.5	50	/
#4	4.75	7	100
#8	2.36	4	98
#16	1.18	/	87
#30	0.60	/	64
#50	0.30	/	35
#100	0.15	/	7
Fineness Modulus			2.09

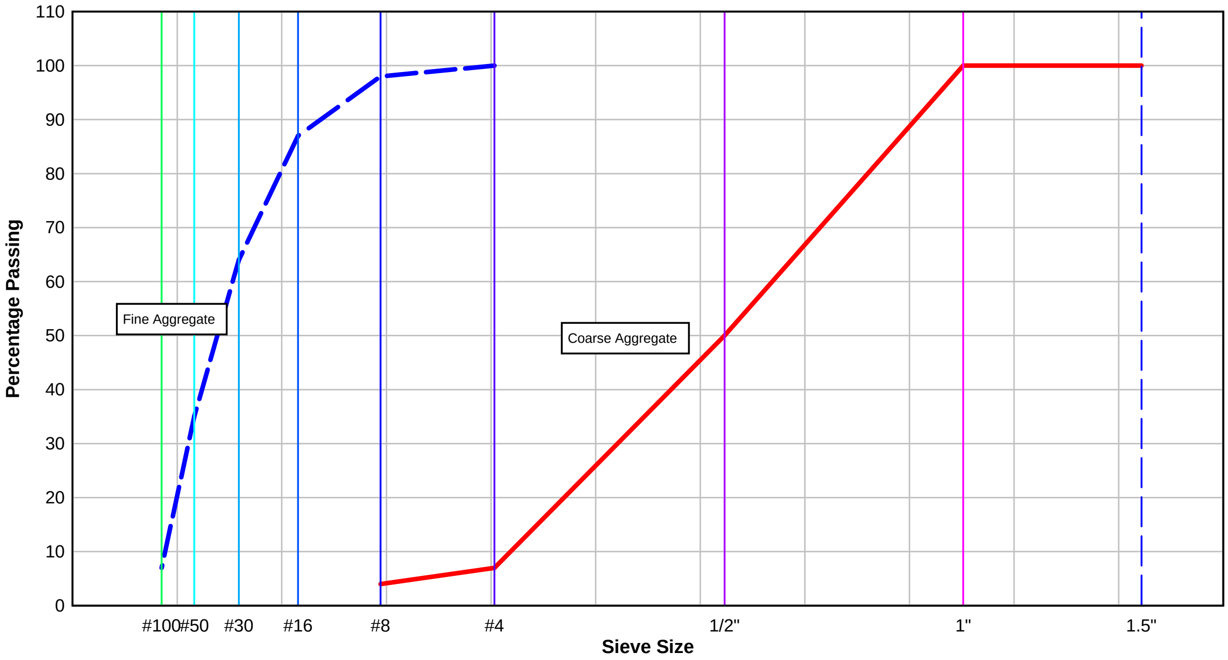

Figure 6-1. Gradation plots for the virgin aggregates used.

6.3.4 Recycled Concrete Aggregates (RCA)

The RCA was obtained from a stockpile of Kimmins Construction Corporation in Tampa. The RCA contained some deleterious materials such as wood, plastics, metals, and glass. These materials were handpicked from the stockpile and also after sieving. Figure 6-2 shows some of the deleterious materials which were removed from the RCA. The RCA material was separated into coarse and fine portions using a #4 sieve. Figures 6-3 and 6-4 show, respectively, the coarse and the fine material which had been separated by a mechanical shaker. Tests were run on the RCA material to determine the specific gravity, water absorption, gradation and LA abrasion loss. The results of sieve analysis on the RCA material are shown in Table 6-7. Figure 6-5 shows the gradation of the RCA coarse and fine portions. The specific gravity and water absorption of the RCA materials are shown in Table 6-8.

Figure 6-2. Deleterious materials from a stockpile of RCA.

Figure 6-3. Separated coarse RCA.

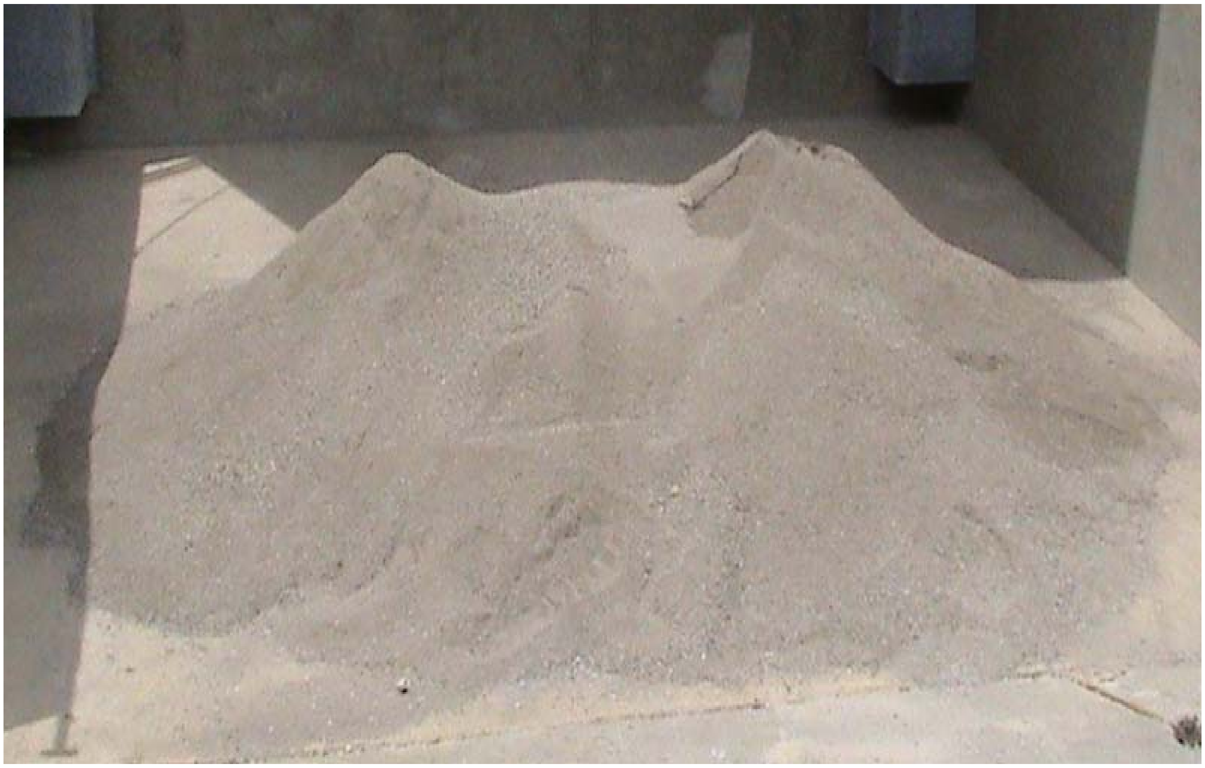

Figure 6-4. Separated fine RCA.

Table 6-7. Results of Sieve Analysis on the RCA Used

Sieve Size	Sieve Size (mm)	Percentage Passing	
		Coarse Aggregates	Fine Aggregates
1.5”	37.0	100	
1”	25.0	96	
0.5”	12.5	60	
#4	4.75	10	98.7
#8	2.36	4.0	88.5
#16	1.18	/	69.8
#30	0.60	/	51.6
#50	0.30	/	33.9
#100	0.15	/	20.6
Fineness Modulus			2.40

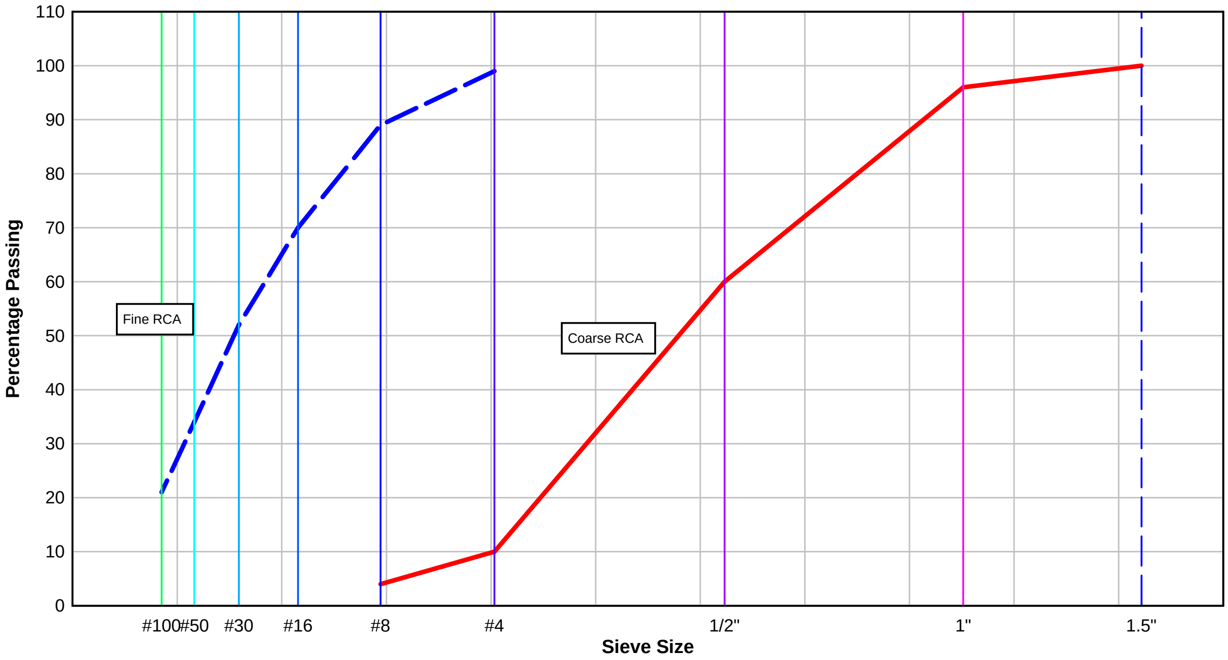

Figure 6-5. Gradation plots for the RCA used.

Table 6-8. Specific Gravity and Water Absorption of the RCA Used

Property	Coarse RCA	Fine RCA
SSD specific gravity	2.34	2.34
Dry bulk specific gravity	2.19	2.19
Dry apparent specific gravity	2.58	2.56
Absorption	6.93	6.46
LA abrasion loss	49	/

6.3.5 Combined Gradation Curve

Figures 6-6 and 6-7 show the gradations of the combined aggregates with 25% and 50% RCA, respectively. Comparisons of the gradations for the coarse and fine aggregates containing 25% and 50% RCA are also shown in Figures 6-8 and 6-9, respectively.

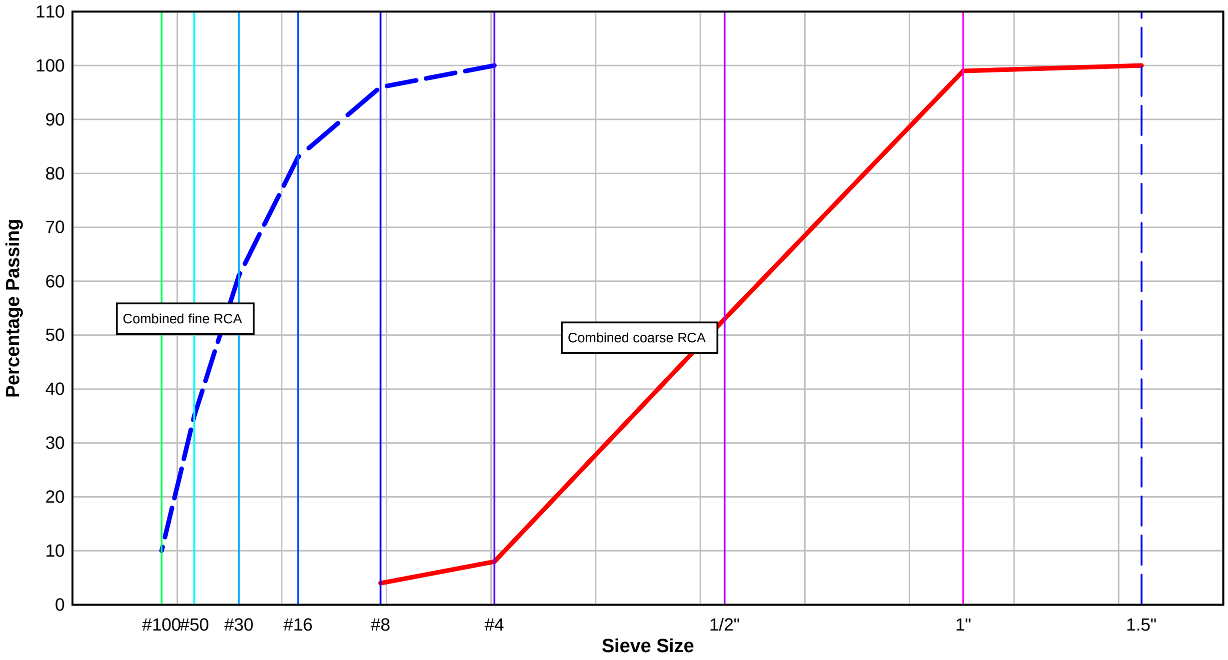

Figure 6-6. Gradation plots for the combined aggregates with 25% RCA.

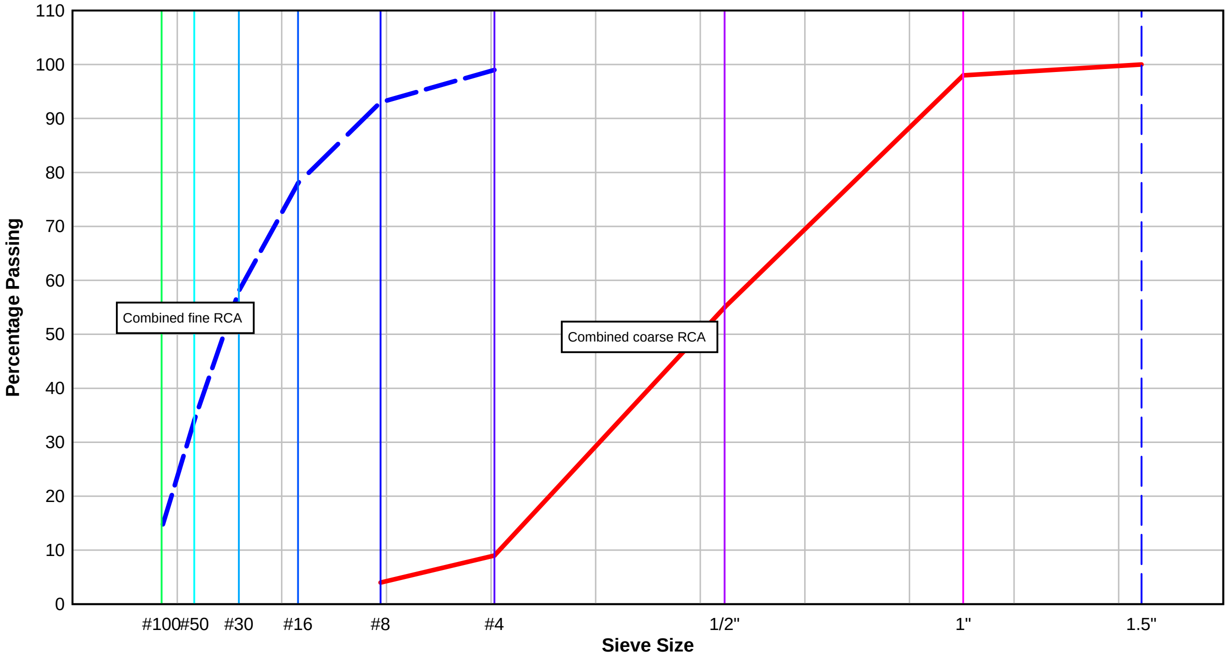

Figure 6-7. Gradation plots for the combined aggregates with 50% RCA.

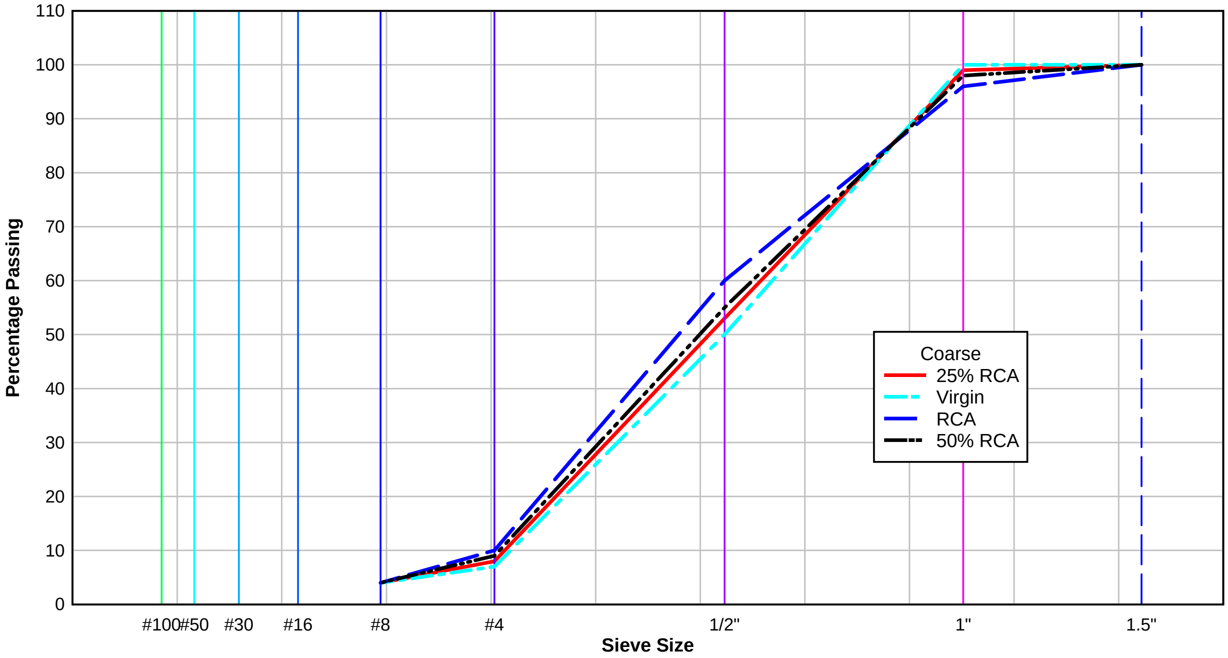

Figure 6-8. Comparison of gradation for coarse aggregates.

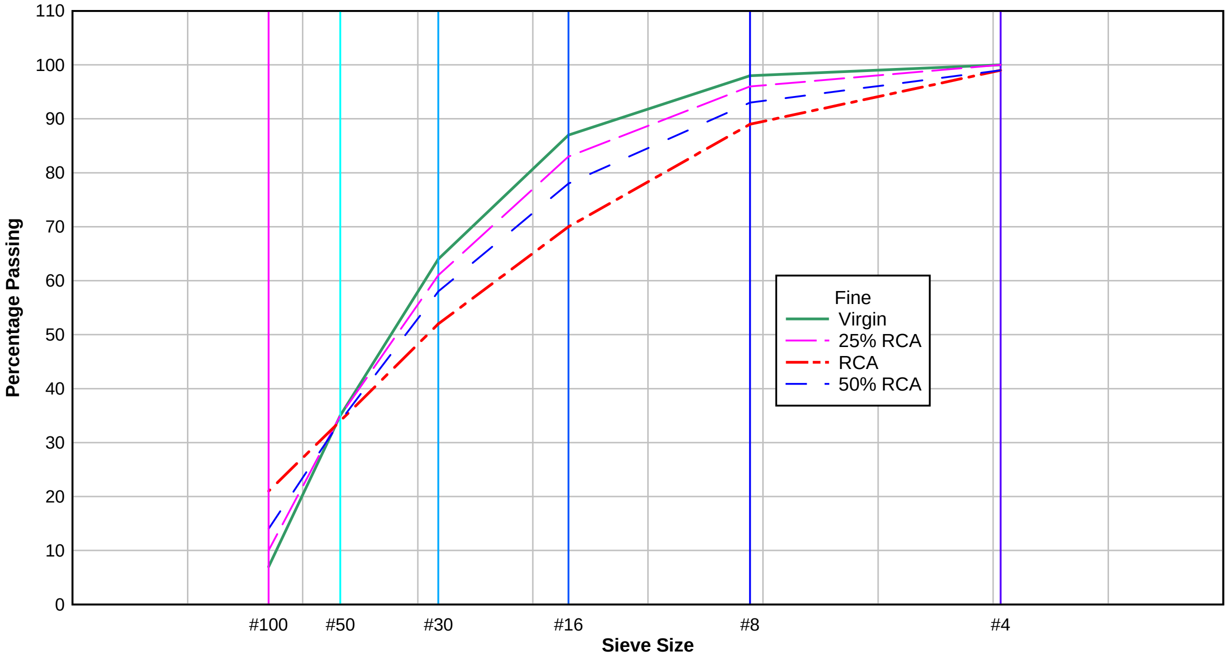

Figure 6-9. Comparison of gradation for fine aggregates.

6.4 Fabrication and Curing of Concrete Specimen

For each concrete mix, about 7 ft^3 of fresh concrete was produced to fabricate twelve 6″ × 12″ cylinders, six 4″ × 8″ cylinders, six beams (6″ × 6″ × 22″), and three prisms (3″ × 3″ × 11.25″). Table 6-9 shows the details of tests performed on concrete samples with various specimen sizes and curing periods.

Table 6-9. Tests Performed on the Concrete Samples

Test	Specimen Size	Curing Period
Compressive Strength	6″ × 12″ Cylinder	14 and 28 days
Elastic Modulus	6″ × 12″ Cylinder	14 and 28 days
Flexural Strength	6″ × 6″ × 22″ Beam	14 and 28 days
Splitting Tensile Strength	6″ × 12″ Cylinder	14 and 28 days
Coefficient of Thermal Expansion	4″ × 8″ Cylinder	28 days
Drying Shrinkage	3″ × 3″ × 11.25″ Prism	28 days

The procedures for preparation and curing of concrete specimens for this testing program were similar to those used in the testing program to evaluate concrete containing RAP as described in Section 3.4 in Chapter 3 of this report. The main difference was that RCA, instead of RAP, was added to the mixtures in this testing program.

6.5 Tests on Fresh Concrete

Table 6-10 provides the list of ASTM standard tests performed on the fresh concrete used in this testing program study. These tests were previously described in Section 3.5 of Chapter 3. The properties of the fresh concrete mixtures are presented in Table 6-11.

Table 6-10. Tests Performed on the Fresh Concrete

Test	Standard
Slump	ASTM C143
Unit Weight	ASTM C138
Air Content	ASTM C173
Temperature	ASTM C1064

Table 6-11. Properties of the Fresh Concrete Containing RCA

Set #	Mix #	W/C Ratio	Cement (lb/cy)	Water (lb/cy)	Slump (in)	Unit Weight (lbs/ft^3)	Air Content (%)	Temperature (^{o}F)
Set-1	1	0.43	628	270	1.00	142	2.0	78
	2	0.43	628	270	1.00	141	2.0	78
	3	0.43	628	270	1.00	140	1.2	79
Set-2	1	0.48	563	270	1.50	142	2.0	78
	2	0.48	563	270	1.00	141	2.0	78
	3	0.48	563	270	1.00	139	1.3	80
Set-3	1	0.53	508	270	1.50	141	2.0	77
	2	0.53	508	270	3.25	140	1.6	78
	3	0.53	508	270	1.75	139	1.4	81

6.6 Tests on Hardened Concrete

The tests on the hardened concrete specimens in this testing program (as listed in Table 6-9) were similar to those used in the testing program to evaluate concrete containing RAP. The procedures for these tests on the hardened concrete were previously described in Section 3.6 in Chapter 3 of this report.

CHAPTER 7
RESULTS OF TESTS ON CONCRETE CONTAINING RCA

7.1 Introduction

This chapter presents the results of compressive strength, elastic modulus, flexural strength, splitting tensile strength, free shrinkage, and coefficient of thermal expansion tests on the different concrete mixtures containing RCA. The effects of RCA on the properties of concrete are discussed.

7.2 Analysis of Test Results and Discussion

7.2.1 Compressive Strength Test Results

The average compressive strengths at various curing periods of different concrete mixtures are presented in Table 7-1. The individual compressive strength values are shown in Table C-1 of Appendix C.

Table 7-1. Compressive Strength Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Compressive Strength (psi)	
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		14 days	28 days
Set-1	1	0.43	100	0	100	0	0	5241	5425
	2	0.43	75	25	75	25	25	5442	6031
	3	0.43	50	50	50	50	50	4934	5404
Set-2	1	0.48	100	0	100	0	0	4921	5317
	2	0.48	75	25	75	25	25	5287	5578
	3	0.48	50	50	50	50	50	4892	5083
Set-3	1	0.53	100	0	100	0	0	4350	4508
	2	0.53	75	25	75	25	25	4403	4874
	3	0.53	50	50	50	50	50	4392	4617

7.2.1.1 Effect of RCA on compressive strength

Figures 7-1 through 7-3 show a comparison of compressive strength of concrete mixes made with different percentage RCA with w/c ratios of 0.43, 0.48 and 0.53, respectively.

For the mixes with a 0.53 w/c ratio, the compressive strength at 14 days increased by about 1% for both 25% RCA and 50% RCA as compared with the control mix. At 28 days, the compressive strength increased by 8% and 2% for 25% RCA and 50% RCA, respectively.

For the mixes with a 0.43 w/c ratio, the 14-day compressive strength of the mix incorporating 25% RCA was higher by 4%, while the mix with 50% RCA was lower by 6%, as compared with the control mix. The 28-day compressive strength was higher by 11% and lower by 0.4% for the mixes containing 25% and 50% RCA, respectively, as compared with the control mix.

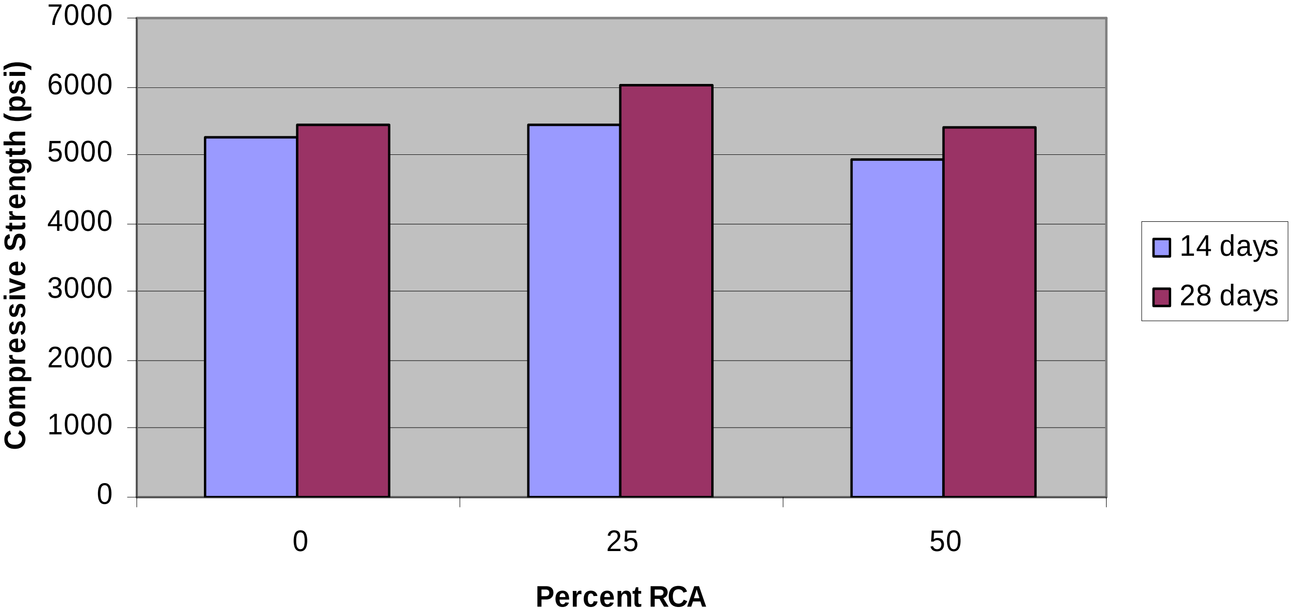

Figure 7-1. Effect of RCA on compressive strength of concrete with a 0.43 w/c ratio.

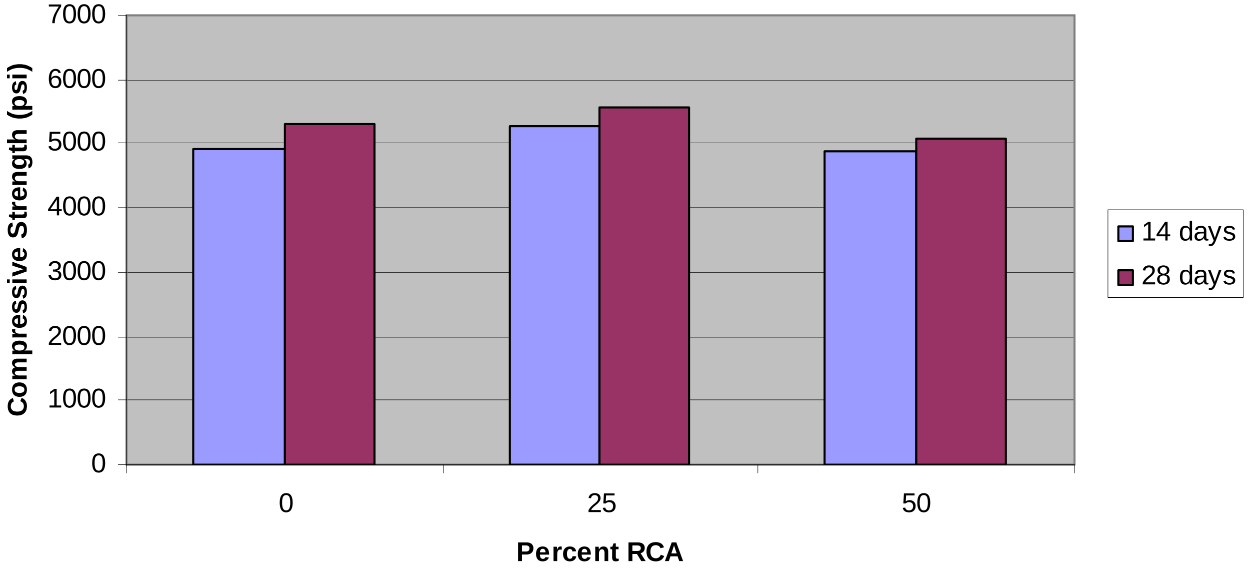

Figure 7-2. Effect of RCA on compressive strength of concrete with a 0.48 w/c ratio.

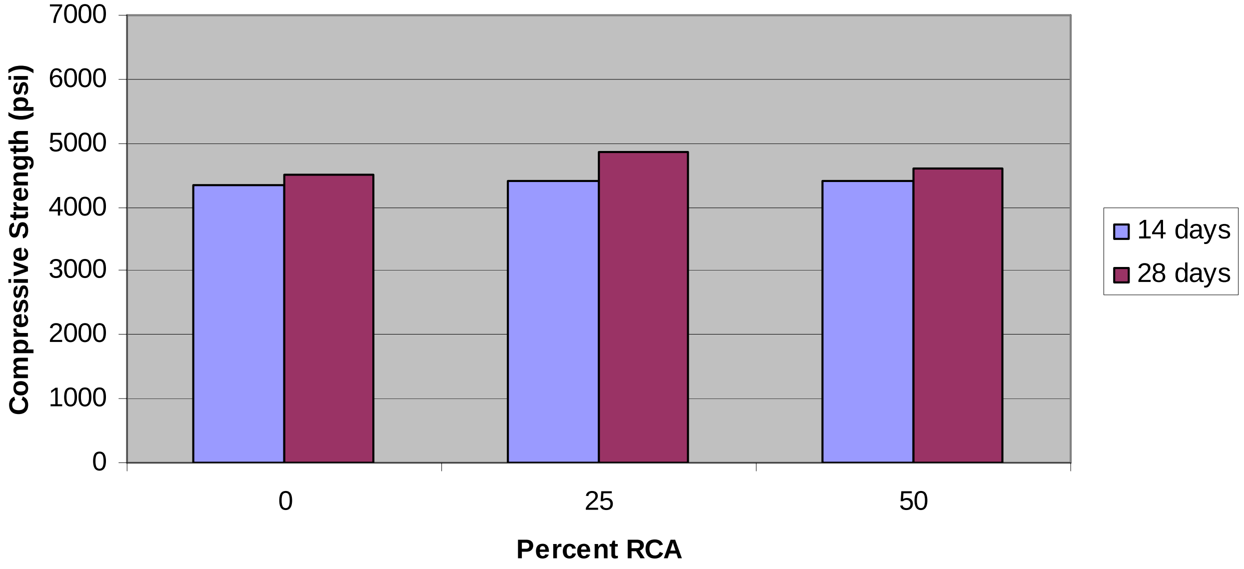

Figure 7-3. Effect of RCA on compressive strength of concrete with a 0.53 w/c ratio.

For the mixes with a 0.48 w/c ratio, the compressive strength at 14 days increased by 7% and decreased by 0.6% for 25% RCA and 50% RCA, respectively, as compared with the control mix. The compressive strength at 28 days increased by 5% and decreased by 4% for 25% RCA and 50% RCA, respectively.

From the above, the compressive strength was generally reduced to about 6% for concrete containing 50% RCA at 28 days. There was, however, an apparent increase in the compressive strength of the 25% RCA concrete. This could be due to the variability in the test results. It can also be seen that the compressive strength increased from 14 days to 28 days in all instances.

7.2.1.2 Effect of w/c ratio on compressive strength

The compressive strength of concrete depends mainly on its w/c ratio. In Figures 7-4 and 7-5, there was a consistent decrease in compressive strength as the w/c ratio increased for both the control and the RCA concrete.

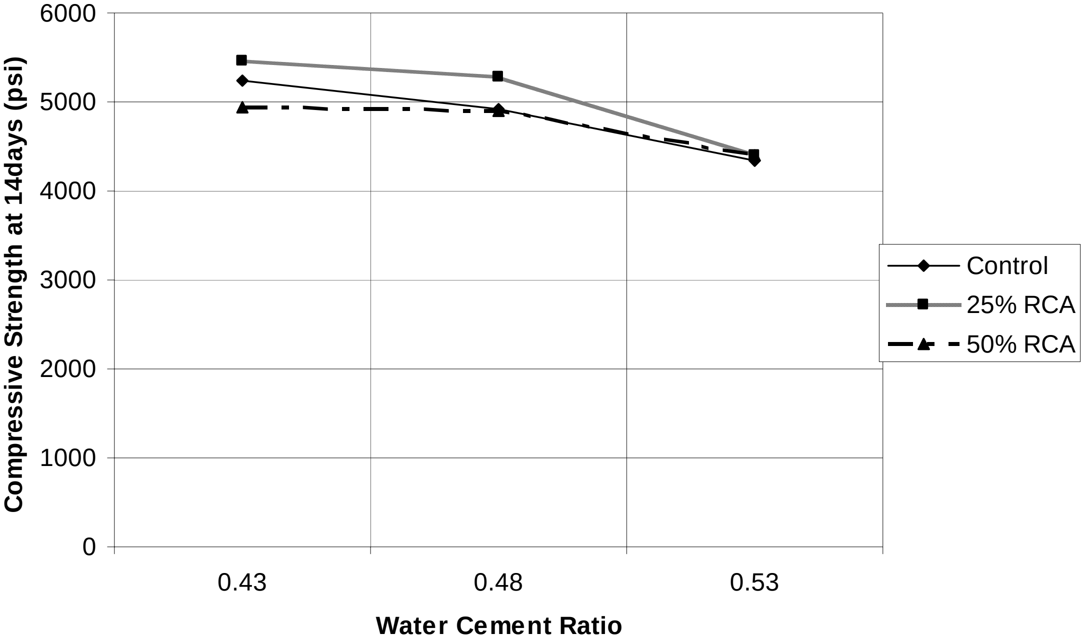

Figure 7-4. Effect of w/c ratio on compressive strength at 14 days.

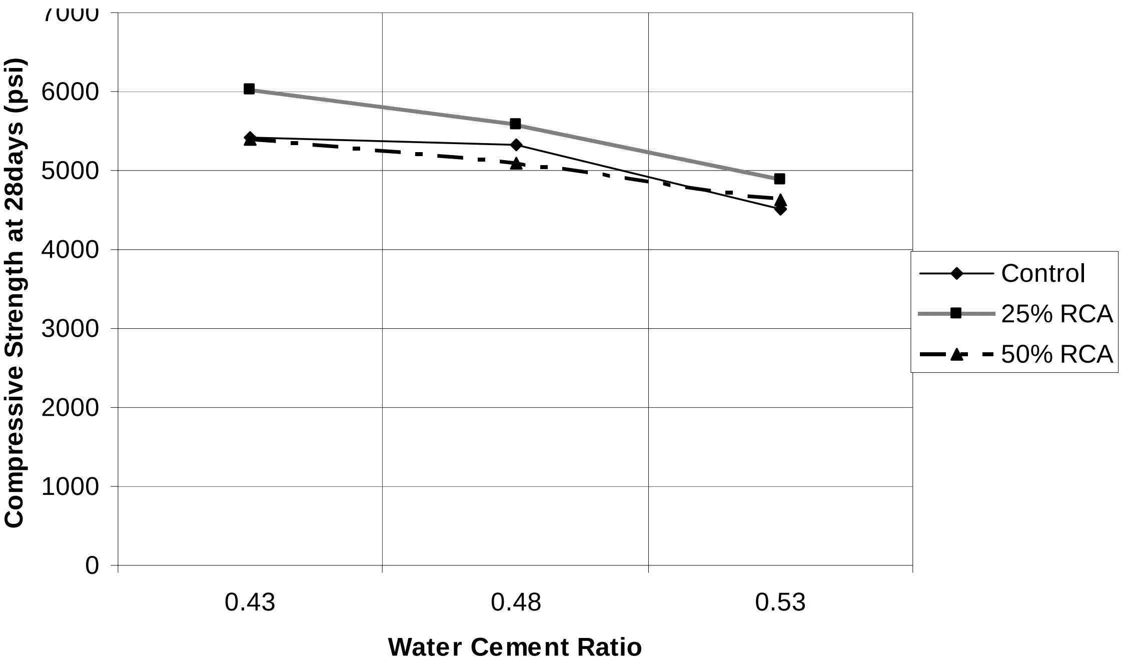

Figure 7-5. Effect of w/c ratio on compressive strength at 28 days.

7.2.2 Elastic Modulus Test Results

The average elastic moduli at various curing periods of different concrete mixtures are presented in Table 7-2. The individual elastic modulus values are shown in Table C-2 of Appendix C.

Table 7-2. Elastic Modulus Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Elastic Modulus ($\times 10^6$ psi)	
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		14 days	28 days
Set-1	1	0.43	100	0	100	0	0	3.90	4.08
	2	0.43	75	25	75	25	25	3.83	3.96
	3	0.43	50	50	50	50	50	3.71	3.69
Set-2	1	0.48	100	0	100	0	0	3.85	3.88
	2	0.48	75	25	75	25	25	3.90	4.01
	3	0.48	50	50	50	50	50	3.48	3.67
Set-3	1	0.53	100	0	100	0	0	3.55	3.70
	2	0.53	75	25	75	25	25	3.44	3.72
	3	0.53	50	50	50	50	50	3.15	3.33

7.2.2.1 Effect of RCA on the elastic modulus of concrete

Figures 7-6 through 7-8 present the comparisons of the elastic moduli of concrete containing different amounts of RCA for w/c ratios of 0.43, 0.48 and 0.53. It shows that there was a general reduction of elastic modulus of concrete as the percentage of RCA increased. At a 0.43 w/c ratio, the elastic modulus at 14 days decreased by 2% and 5% for 25% RCA and 50% RCA, respectively, as compared with the control mix. The elastic modulus at 28 days decreased by 3% and 10% for 25% RCA and 50% RCA, respectively.

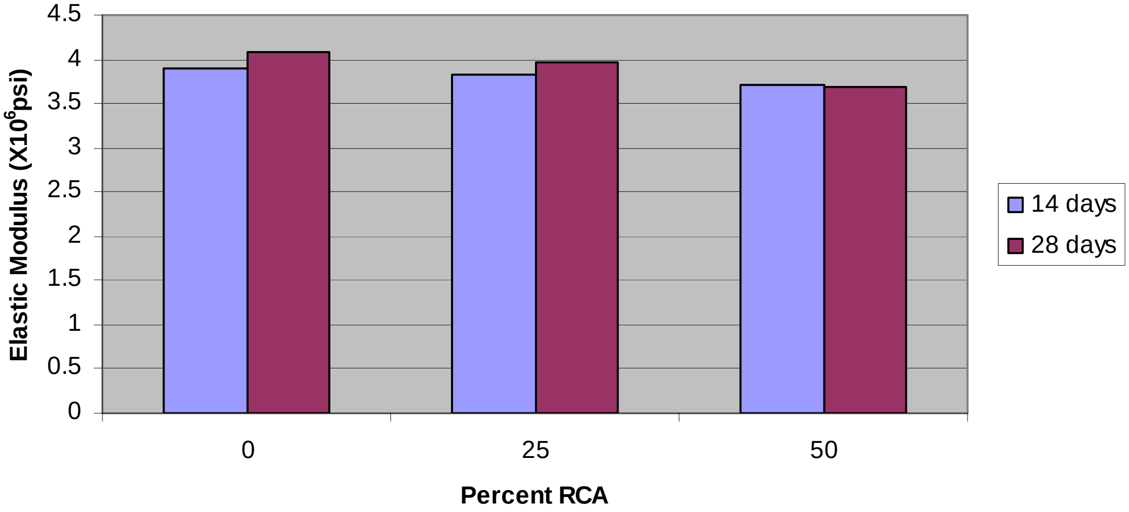

Figure 7-6. Effect of RCA on elastic modulus of concrete with a 0.43 w/c ratio.

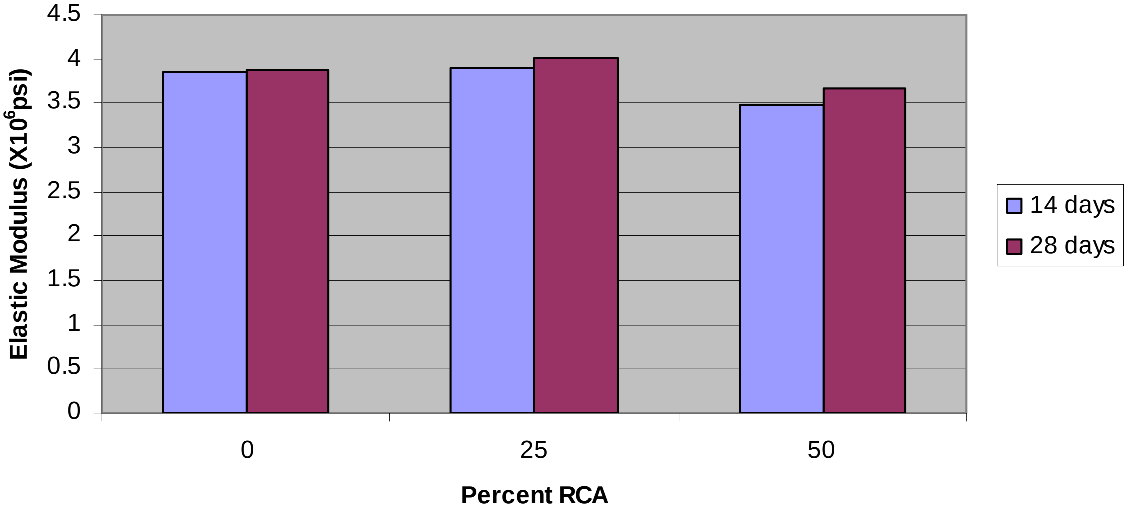

Figure 7-7. Effect of RCA on elastic modulus of concrete with a 0.48 w/c ratio.

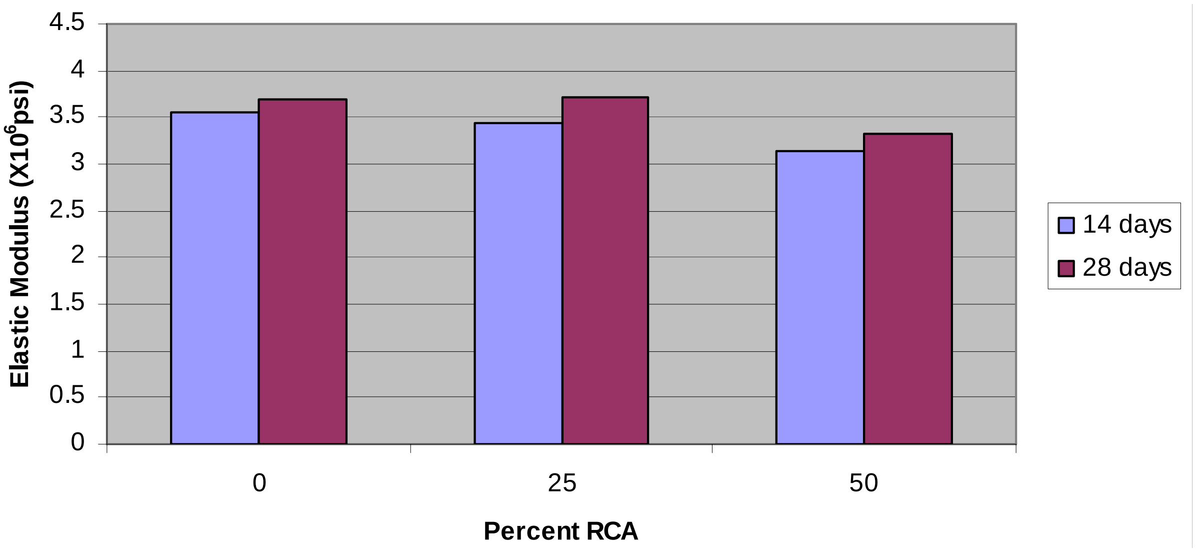

Figure 7-8. Effect of RCA on elastic modulus of concrete with a 0.53 w/c ratio.

For a 0.48 w/c ratio, the elastic modulus at 14 days increased by 1% and decreased by 10% for 25% RCA and 50% RCA, respectively, as compared with the control mix. At 28 days, the compressive strength increased by 4% and decreased by 3% for 25% RCA and 50% RCA, respectively.

For a 0.53 w/c ratio, the elastic modulus at 14 days decreased by 3% and 11% for 25% RCA and 50% RCA, respectively, as compared with the control mix. At 28 days, the elastic modulus increased by 0.5% and decreased by 10% for 25% RCA and 50% RCA, respectively.

From the above results, there was a decrease of about 10% in elastic modulus for concrete containing 50% RCA at 28 days.

7.2.2.2 Effect of w/c ratio on the elastic modulus of concrete

Figures 7-9 and 7-10 present the effect of w/c ratio on the elastic modulus of concrete at 14 and 28 days, respectively. There was a consistent decrease in elastic modulus as the w/c ratio increased for both the control and the RCA concrete.

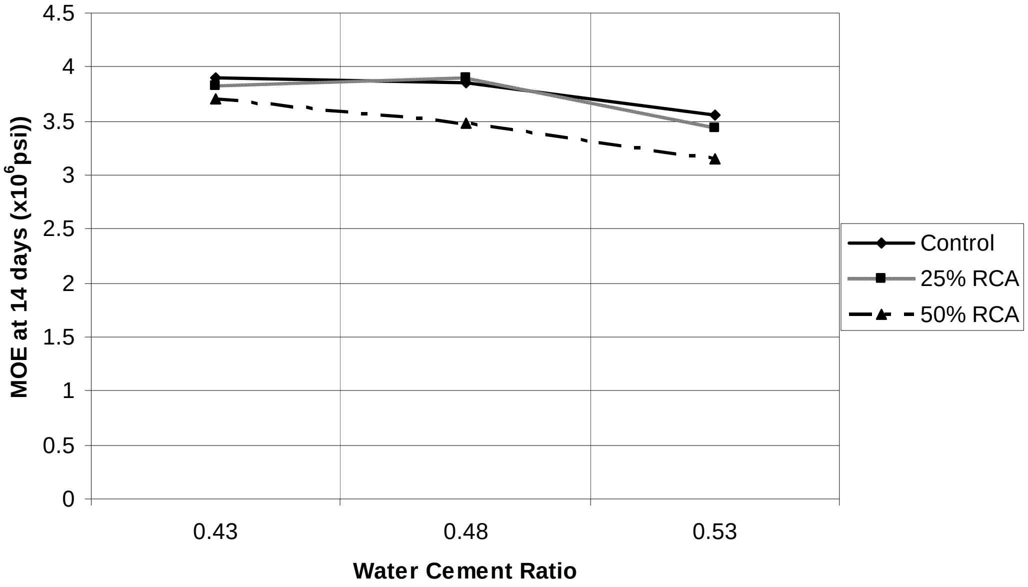

Figure 7-9. Effect of w/c ratio on elastic modulus at 14 days.

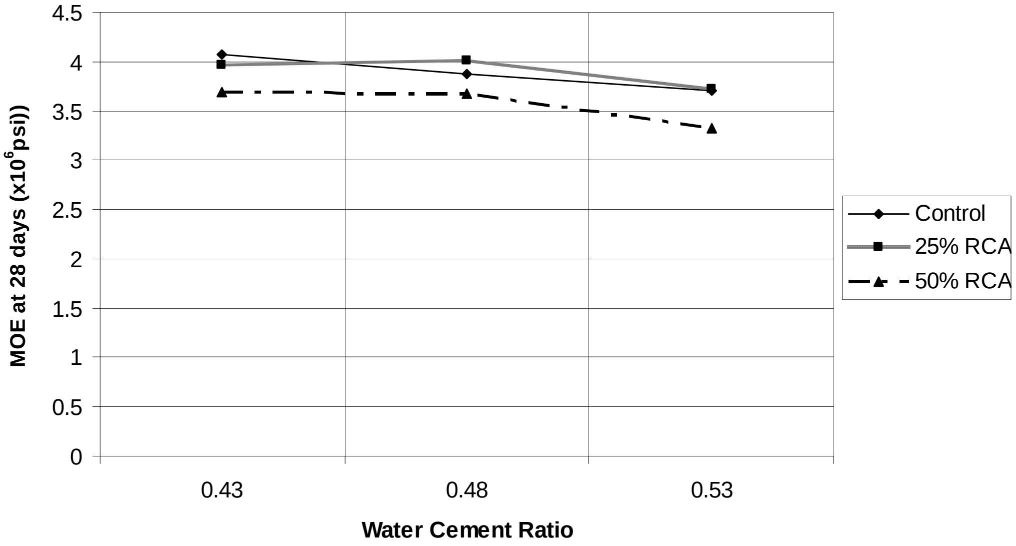

Figure 7-10. Effect of w/c ratio on elastic modulus at 28 days.

7.2.3 Flexural Strength of Concrete

The average flexural strength at various curing periods of different concrete mixtures is presented in Table 7-3. The individual flexural strength values are shown in Table C-3 of Appendix C.

Table 7-3. Flexural Strength Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Flexural Strength (psi)	
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		14 days	28 days
Set-1	1	0.43	100	0	100	0	0	767	778
	2	0.43	75	25	75	25	25	717	768
	3	0.43	50	50	50	50	50	706	771
Set-2	1	0.48	100	0	100	0	0	718	761
	2	0.48	75	25	75	25	25	672	754
	3	0.48	50	50	50	50	50	636	688
Set-3	1	0.53	100	0	100	0	0	654	659
	2	0.53	75	25	75	25	25	628	664
	3	0.53	50	50	50	50	50	576	675

7.2.3.1 Effect of RCA on flexural strength

Results shown in Figures 7-11 through 7-13 show a comparison of flexural strength of concrete mixes made with different percentage RCA. For the concrete mixes with a 0.43 w/c ratio, the flexural strength at 14 days decreased by 7% and 8% for 25% RCA and 50% RCA, respectively, as compared with the control mix. The flexural strength at 28 days decreased by about 1% for both 25% RCA and 50% RCA.

For the concrete mixes with a 0.48 w/c ratio, the flexural strength at 14 days decreased by 6% and 11% for 25% RCA and 50% RCA, respectively, as compared with the control mix. At 28 days, it decreased by 1% and 10% for 25% RCA and 50% RCA, respectively.

For the concretes with a 0.53 w/c ratio, the flexural strength at 14 days decreased by 4% and 12% for 25% RCA and 50% RCA, respectively, as compared with the control mix. At 28 days, it increased by 1% and 2% for 25% RCA and 50% RCA, respectively.

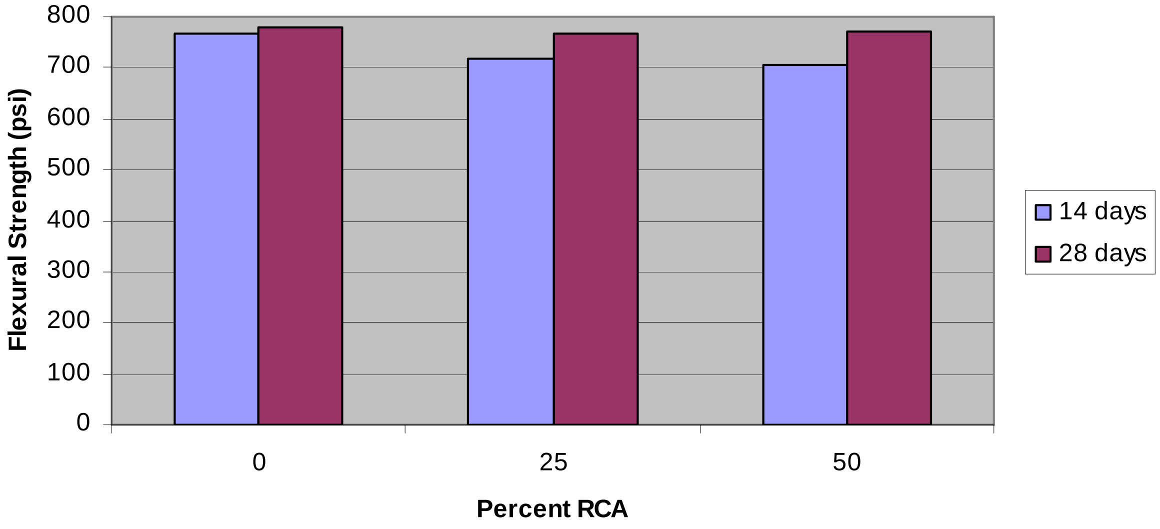

Figure 7-11. Effect of RCA on flexural strength of concrete with a 0.43 w/c ratio.

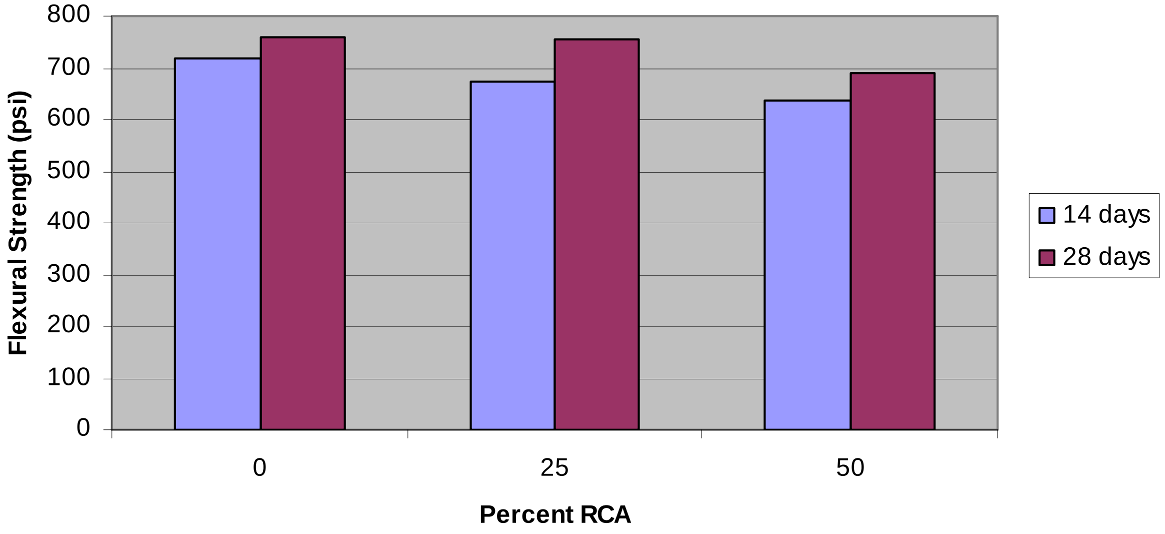

Figure 7-12. Effect of RCA on flexural strength of concrete with a 0.48 w/c ratio.

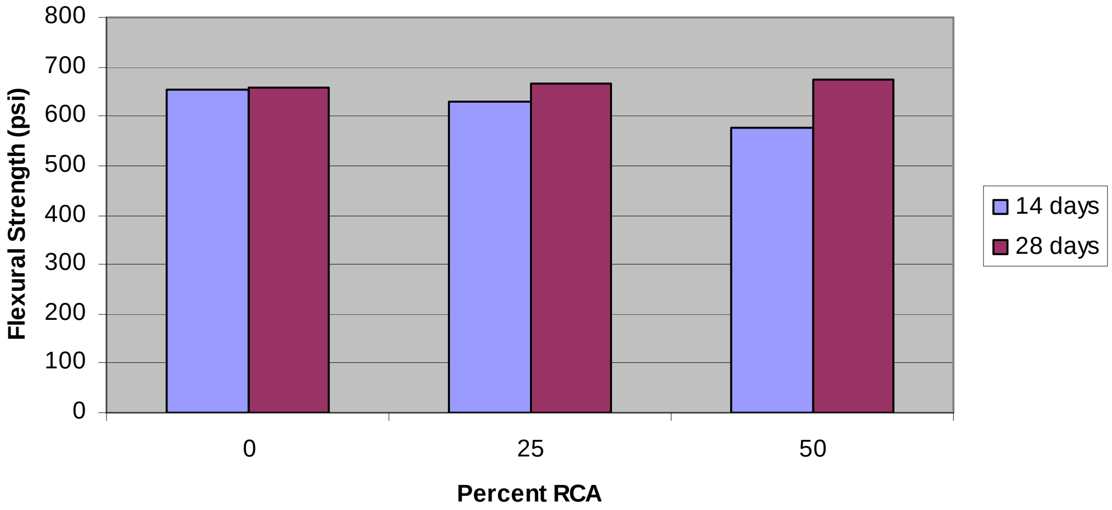

Figure 7-13. Effect of RCA on flexural strength of concrete with a 0.53 w/c ratio.

The above results show a general reduction in flexural strength with increasing percentage of RCA at 14 days for the different w/c ratios. At 28 days, there was also a general reduction in flexural strength with the use of RCA for w/c ratios of 0.43 and 0.48. However, for the concrete mixes with a 0.53 w/c ratio, there was an increase in flexural strength as the RCA percentage increased. It can also be seen that the flexural strength increased from 14 days to 28 days in all cases.

7.2.3.2 Effect of w/c ratio on the flexural strength

Figures 7-14 and 7-15 present the effect of w/c ratio on the flexural strength of concrete at 14 and 28 days, respectively. There was a consistent decrease in flexural strength as the w/c ratio increased for both the control and the RCA concrete.

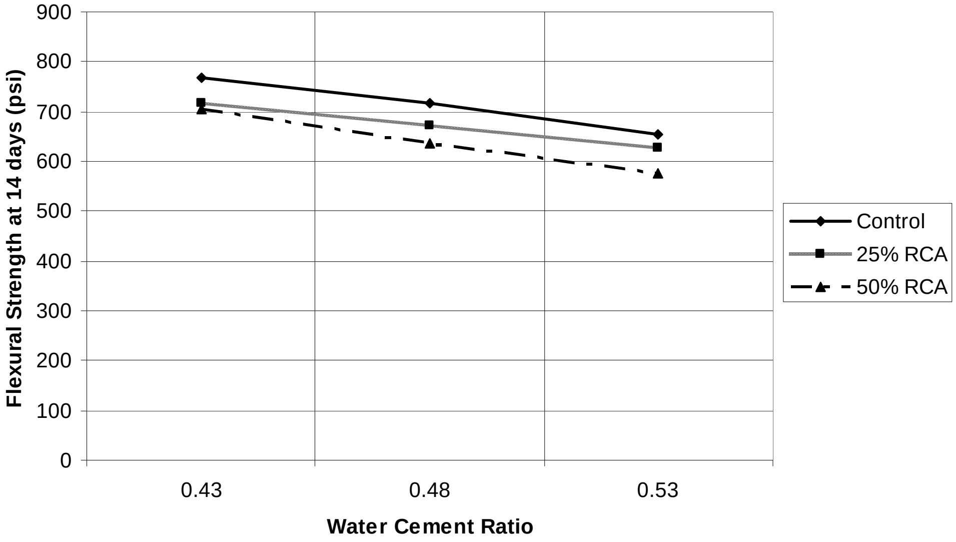

Figure 7-14. Effect of w/c ratio on flexural strength at 14 days.

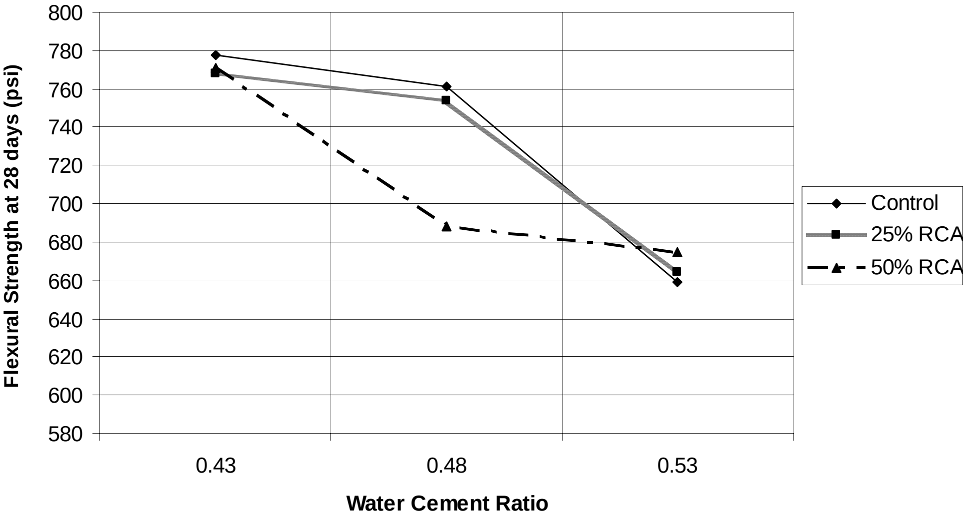

Figure 7-15. Effect of w/c ratio on flexural strength at 28 days.

7.2.4 Splitting Tensile Strength

The average splitting tensile strength at various curing periods of different concrete mixtures are presented in Table 7-4. The individual splitting tensile strength values are shown in Table C-4 of Appendix C.

Table 7-4. Splitting Tensile Strength Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Splitting Tensile Strength (psi)	
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		14 days	28 days
Set-1	1	0.43	100	0	100	0	0	590	537
	2	0.43	75	25	75	25	25	559	601
	3	0.43	50	50	50	50	50	455	522
Set-2	1	0.48	100	0	100	0	0	538	557
	2	0.48	75	25	75	25	25	536	513
	3	0.48	50	50	50	50	50	508	540
Set-3	1	0.53	100	0	100	0	0	485	474
	2	0.53	75	25	75	25	25	439	483
	3	0.53	50	50	50	50	50	390	476

7.2.4.1 Effect of RCA on splitting tensile strength

Figures 7-16 through 7-18 show a comparison of splitting tensile strength of concrete mixes made with different percentage RCA for w/c ratios of 0.43, 0.48 and 0.53, respectively.

For the concretes with a 0.43 w/c ratio, the 14-day splitting tensile strength decreased by 5% and 23% with the incorporation of 25% and 50% RCA, respectively. The 28-day strength increased by 12%, and decreased by 3% with the incorporation of 25% and 50% RCA, respectively.

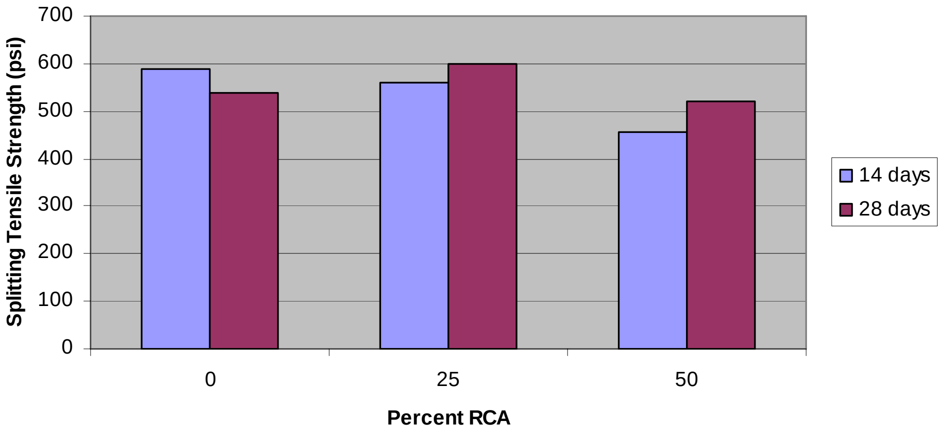

Figure 7-16. Effect of RCA on splitting tensile strength of concrete at a 0.43 w/c ratio.

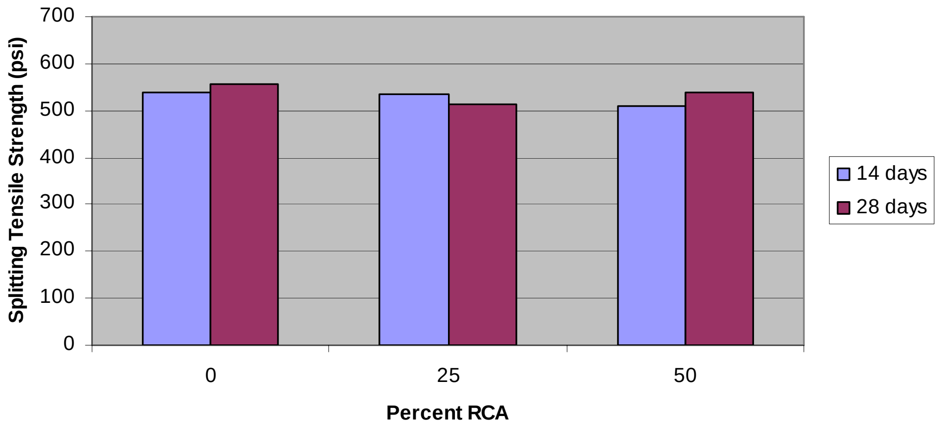

Figure 7-17. Effect of RCA on splitting tensile strength of concrete with a 0.48 w/c ratio.

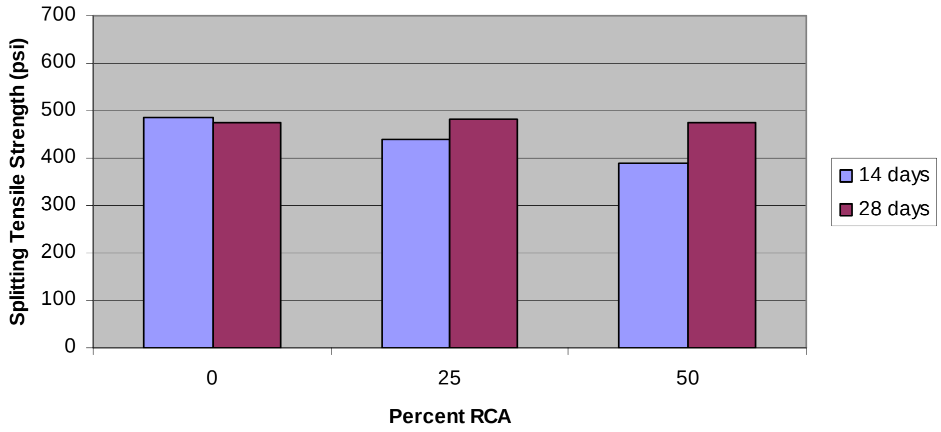

Figure 7-18. Effect of RCA on splitting tensile strength of concrete with a 0.53 w/c ratio.

For the concretes with a 0.48 w/c ratio, the 14-day splitting tensile strength decreased by 0.4% and 6%, and the 28-day strength decreased by 8% and 3% with the incorporation of 25% and 50% RCA, respectively.

For the concretes with a 0.53 w/c ratio, the 14-day splitting tensile strength decreased by 9% and 20%, while the 28-day strength increased by 2% and 0.4% with the incorporation of 25% and 50% RCA, respectively.

The above results show that there was a general reduction in splitting tensile strength with increasing percentage of RCA at 14 days for all the mixes evaluated. However, at 28 days, the trend was not so consistent. Generally, the splitting tensile strength of the RCA mixes was about the same as that of the control mix at 28 days.

7.2.4.2 Effect of w/c ratio on the splitting tensile strength

Figures 7-19 and 7-20 show the plots of splitting tensile strength versus w/c ratio for the RCA mixes at 14 days and 28 days, respectively. There was generally a decrease in splitting tensile strength as the w/c ratio increased for both the control and the RCA concrete.

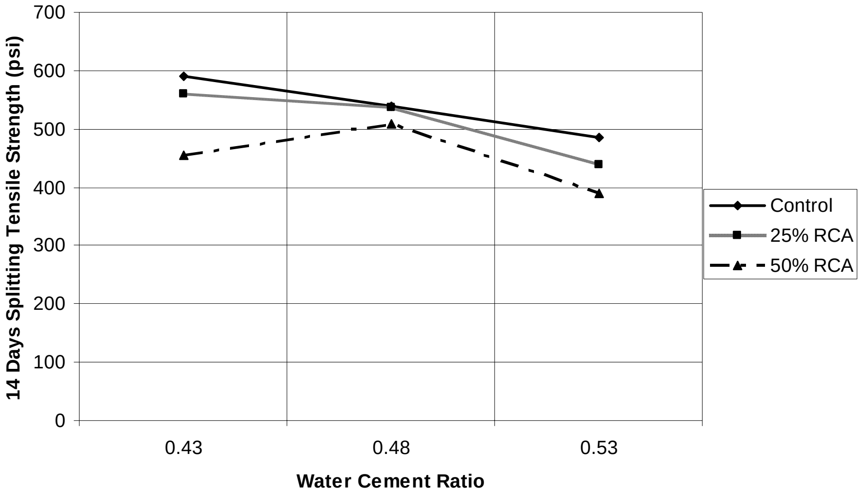

Figure 7-19. Effect of w/c ratio on splitting tensile strength at 14 days.

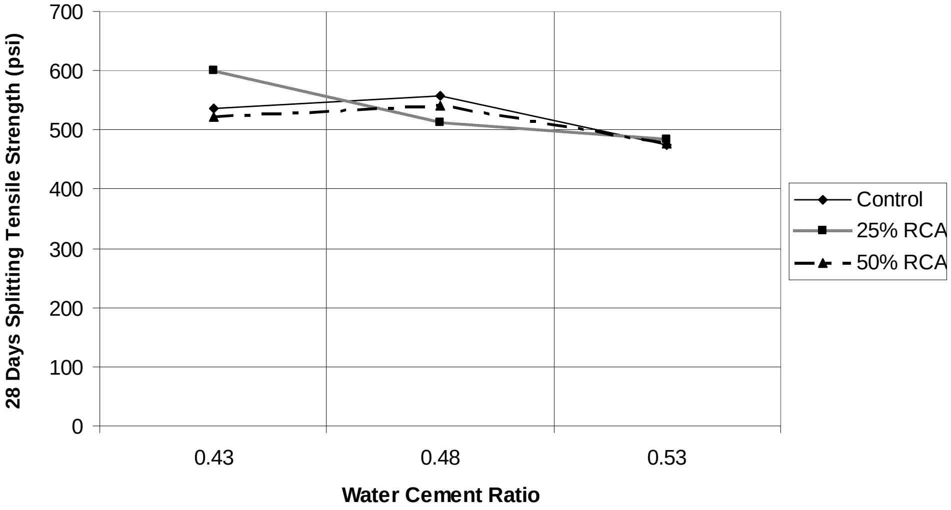

Figure 7-20. Effect of w/c ratio on splitting tensile strength at 28 days.

7.2.5 Free Shrinkage Test Results

The average free shrinkage values at various curing periods of different concrete mixtures are presented in Table 7-5. The individual free shrinkage strain values are shown in Table C-5 of Appendix C.

Table 7-5. Free Shrinkage Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Free Shrinkage (10^{-6} in/in)
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		28 days
Set-1	1	0.43	100	0	100	0	0	57
	2	0.43	75	25	75	25	25	167
	3	0.43	50	50	50	50	50	57
Set-2	1	0.48	100	0	100	0	0	87
	2	0.48	75	25	75	25	25	57
	3	0.48	50	50	50	50	50	107
Set-3	1	0.53	100	0	100	0	0	20
	2	0.53	75	25	75	25	25	77
	3	0.53	50	50	50	50	50	270

7.2.5.1 Effect of RCA on free shrinkage

Figures 7-21 through 7-23 show a comparison of free shrinkage at 28 days of concrete mixes made with different percentage RCA. For the concretes with a 0.43 w/c ratio, the free shrinkage of concrete containing 25% RCA was higher than that of the control by 193%, while the free shrinkage of the concrete containing 50% RCA was about the same as that of the control concrete.

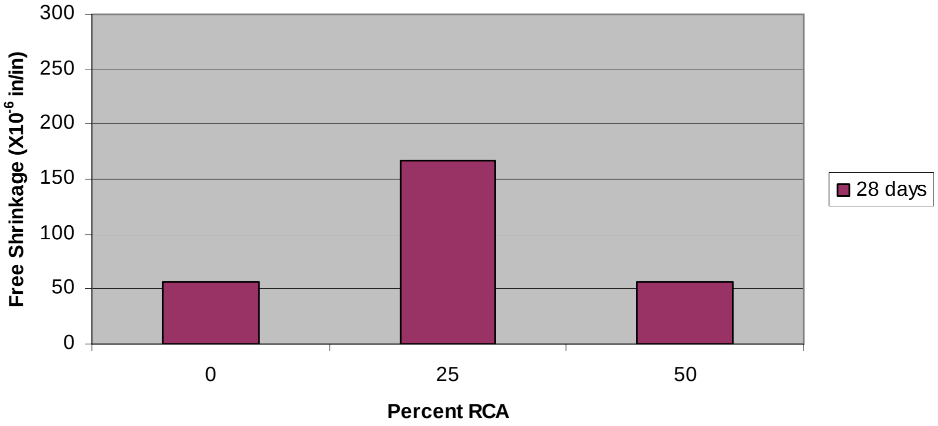

Figure 7-21. Effect of RCA on free shrinkage of concrete with a 0.43 w/c ratio.

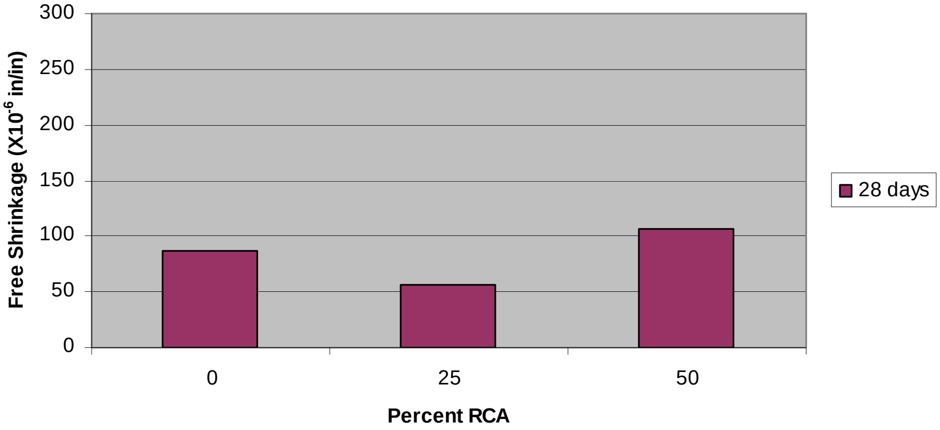

Figure 7-22. Effect of RCA on free shrinkage of concrete with a 0.48 w/c ratio.

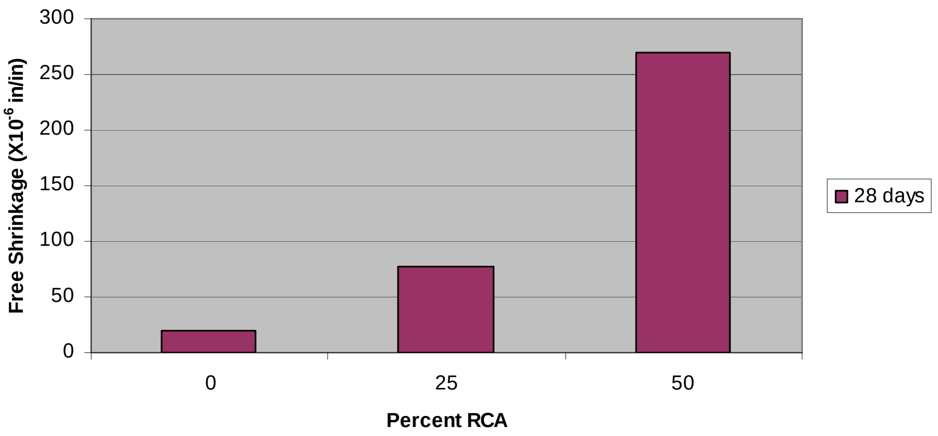

Figure 7-23. Effect of RCA on free shrinkage of concrete with a 0.53 w/c ratio.

For the concretes with a 0.48 w/c ratio, the free shrinkage of the concrete containing 25% RCA was lower by 34% while the concrete containing 50% RCA was higher by 23% as compared with that of the control concrete.

For the concretes with a 0.53 w/c ratio, the free shrinkage of the concrete containing 25% RCA was higher by 285% and the concrete containing 50% RCA was higher by 1250% as compared with the control mix.

Figure 7-24 shows plots of free shrinkage versus percent RCA for concrete mixes with three different w/c ratios. It can be seen that, in general, there was an increase in free shrinkage as the percentage of RCA increased.

7.2.5.2 Effect of w/c ratio on free shrinkage

From the shrinkage data presented in Table 7-5 and Figure 7-24, it can be observed that, for the concrete mixes containing 50% RCA, free shrinkage increased as the w/c ratio increased. However, for the mixes containing 25% RCA, there was no clear trend. This may be due to the high variability of the free shrinkage measurements.

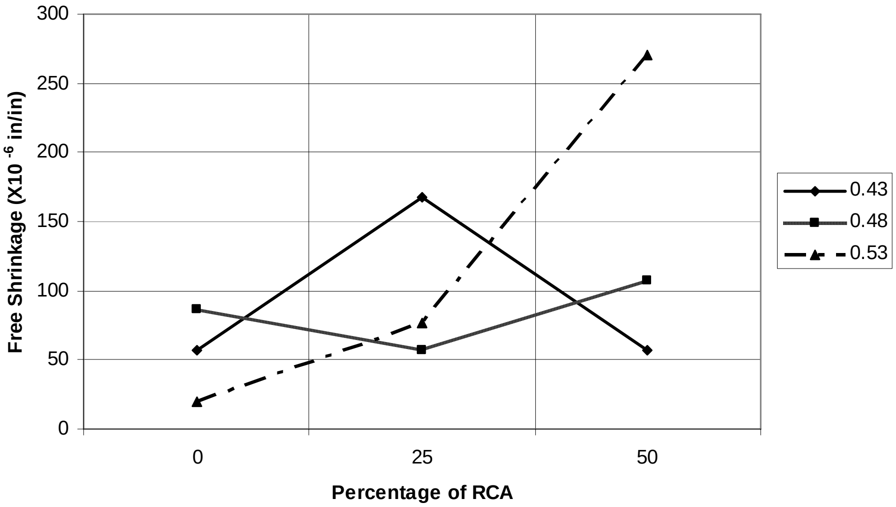

Figure 7-24. Plots of free shrinkage versus percent RCA for concrete with different w/c ratios.

7.2.6 Coefficient of Thermal Expansion

The mean coefficients of thermal expansion at 28 days of curing for the different concrete mixtures are shown in Table 7-6. Individual coefficient of thermal expansion values are shown in Table C-6 of Appendix C.

Table 7-6. Coefficient of Thermal Expansion Test Results

Set #	Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	Coefficient of Thermal Expansion (10^{-6}/° F)
			Aggregate (%)	RCA (%)	Aggregate (%)	RCA (%)		28 days
Set-1	1	0.43	100	0	100	0	0	5.51
	2	0.43	75	25	75	25	25	5.41
	3	0.43	50	50	50	50	50	5.16
Set-2	1	0.48	100	0	100	0	0	5.39
	2	0.48	75	25	75	25	25	5.46
	3	0.48	50	50	50	50	50	5.29
Set-3	1	0.53	100	0	100	0	0	5.26
	2	0.53	75	25	75	25	25	5.20
	3	0.53	50	50	50	50	50	5.47

7.2.6.1 Effect of RAP on coefficient of thermal expansion of concrete

Figures 7-25 through 7-27 show the coefficient of thermal expansion for concrete with different RCA contents at different w/c ratios at a curing time of 28 days. At a 0.43 w/c ratio, the coefficient of thermal expansion was higher by 2% and 6% with 25% and 50% RCA, respectively, as compared with the control mix. At a 0.48 w/c ratio, the coefficient of thermal expansion was higher by 1% with 25% RCA and was lower by 2% with 50% RCA, as compared with the control mix. At a 0.53 w/c ratio, the coefficient of thermal expansion was lower at 25% RCA and was higher at 50% RCA, as compared with the control mix. There appears to be no clear difference in coefficient of thermal expansion between the mixes containing RCA and the control mix. The slight difference may be due to the variability in the test results.

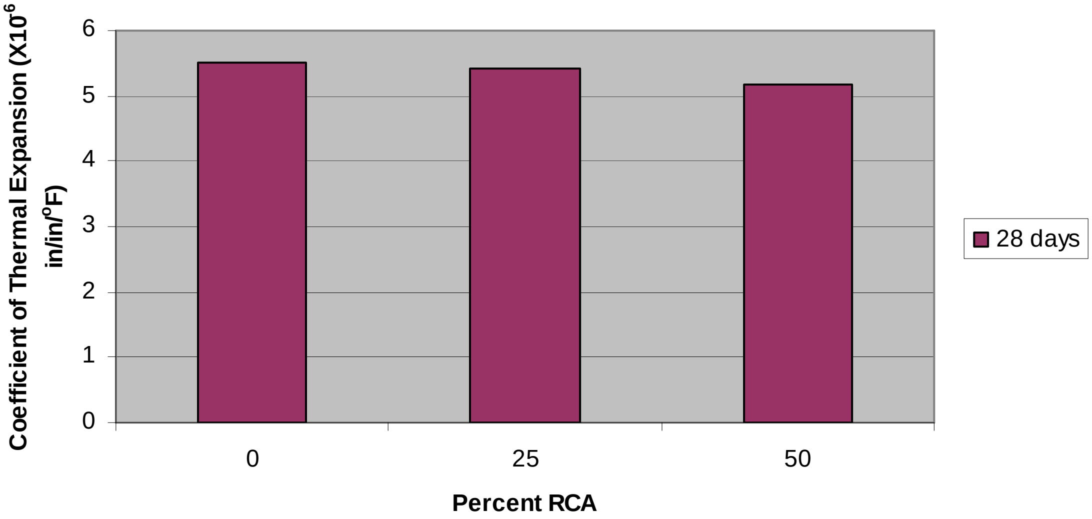

Figure 7-25. Effect of RCA on coefficient of thermal expansion of concrete with a 0.43 w/c ratio.

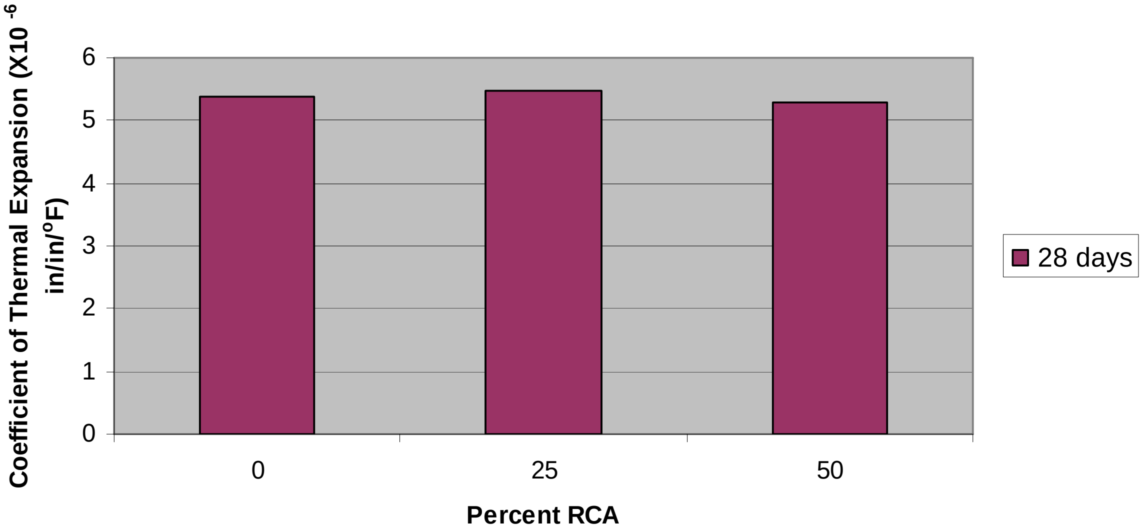

Figure 7-26. Effect of RCA on coefficient of thermal expansion of concrete with a 0.48 w/c ratio.

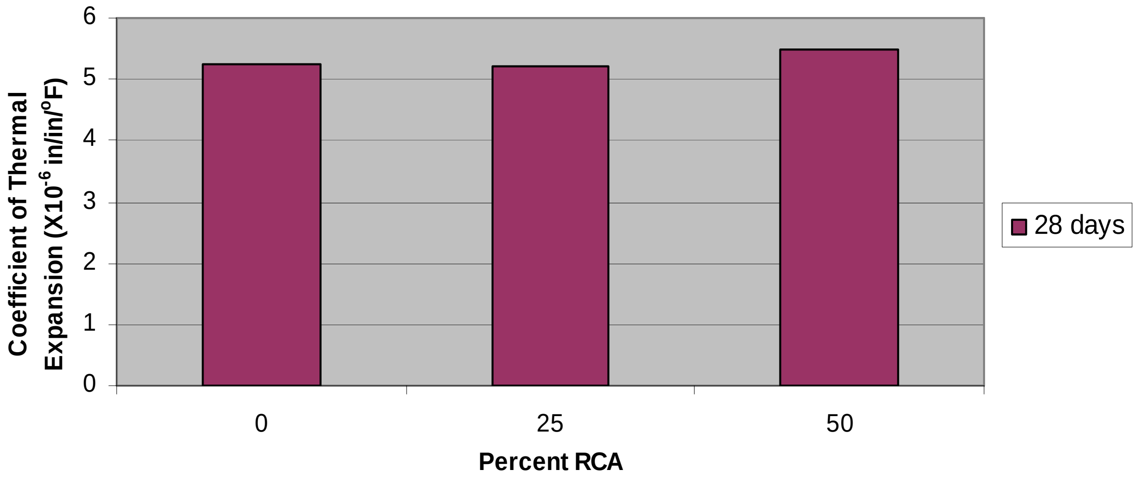

Figure 7-27. Effect of RCA on coefficient of thermal expansion of concrete with a 0.53 w/c ratio.

7.2.6.2 Effect of w/c ratio on the coefficient of thermal expansion

In Figure 7-28, there was no difference in the coefficient of thermal expansion as the w/c ratio changed for both the concrete containing the RCA and the control mix.

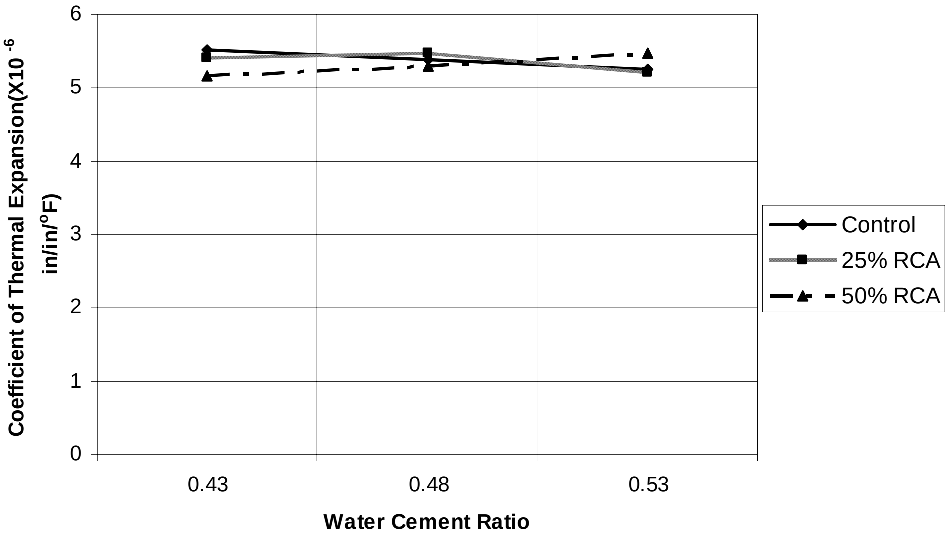

Figure 7-28. Effect of w/c ratio on coefficient of thermal expansion at 28 days.

7.3 Summary of Test Results

The main findings from the results of the tests on concrete containing RCA are summarized as follows:

1. Compressive strength was reduced slightly as the percentage of RCA increased up to 50%;
2. Elastic modulus was reduced slightly as the percentage of RCA increased up to 50%;
3. Flexural strength was about the same as that of the control mix for concrete containing RCA up to 50%;
4. Splitting tensile strength was about the same as the control mix for concrete containing RCA up to 50%;
5. Free shrinkage of the concrete increased slightly with increasing RCA content; and
6. The coefficient of thermal expansion was about the same as the control mix for concrete containing RCA up to 50%.

CHAPTER 8
EVALUATION OF POTENTIAL PERFORMANCE OF CONCRETE CONTAINING RCA IN PAVEMENT

8.1 Critical Stress Analysis to Assess Potential Performance of Concrete Containing RCA

Nine different concrete mixes were analyzed to determine their performance on a typical concrete pavement in Florida. Their elastic modulus, compressive strength, density, and coefficient of thermal expansion were used to model the concrete. Analysis was performed to determine the maximum stresses in the concrete slab if it were loaded by a 22-kip wheel applied at the critical loading positions, i.e., at the slab corner and at the middle edge as shown in Figure 5-2 in Chapter 5. Temperature differentials of +20° F, 0° F, and −20° F in the concrete slab were used in the analysis.

The FEACONS IV program, which has been described in Section 5.1 of Chapter 5, was used to perform the stress analysis. Analysis using the FEACONS model was performed to determine stresses in a 10″ concrete pavement slab if it were loaded by a 22-kip axle load at two critical loading positions, namely at the slab corner and at the middle of the slab edge. The middle of the slab edge was the most critical loading position in the day time when the temperature differential in the slab was positive, while the slab corner was the most critical loading position at night when the temperature differential was negative. The following parameters were used to model the concrete pavement.

1. Slab thickness = 10″; slab length = 15′; slab width = 12′
2. Subgrade modulus, k_s = 0.3 kci; edge stiffness, k_e = 30 ksi
3. Joint linear stiffness, k_l = 500 ksi; joint torsion stiffness k_t = 1000 k-in/in.

8.2 Results of Critical Stress Analysis

The computed maximum stresses in the concrete slab from the critical stress analysis are presented in Tables 8-1 through 8-3 for the concrete mixes containing different amounts of RCA and with different w/c ratios. The ratios of maximum stress to the flexural strength of the concrete were also computed and presented in these tables.

From the results in Table 8-1 through Table 8-3, it can be seen that the most critical loading condition, which resulted in the maximum computed stress, was the condition when the 22-kip axle load was applied at the middle edge of the slab when the temperature differential was +20° F. Thus, the comparison of potential performance of the various concrete mixes was made based on the computed stress-strength ratio at this condition.

Figures 8-1 through 8-3 show the comparison of the computed stress-strength ratios for this critical loading condition for the concretes with different RCA contents. For the concrete mixtures with a 0.43 w/c ratio, the concrete using 50% RCA had a slightly lower stress-strength ratio (0.61) than that of the control mix (0.62). However, for the concrete mixtures with w/c ratios of 0.48 and 0.53, the control mix had a slightly lower computed stress-strength ratio (0.62 and 0.64, respectively) than that of the concrete containing 50% RCA (0.65).

Based on the comparison of computed stress-strength ratios, it can be seen that the potential performance of the RCA concrete as a pavement concrete is somewhat comparable to that of a conventional concrete using virgin aggregates.

Table 8-1. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete Containing RCA and a 0.43 W/C Ratio

Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RCA (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.83	4080	778	400	483	0.51	0.62
2	0.43	75	25	75	25	25	5.41	3960	768	410	510	0.53	0.66
3	0.43	50	50	50	50	50	5.16	3690	771	388	474	0.50	0.61
Temperature difference of –20° F between top and bottom:													
1	0.43	100	0	100	0	0	5.83	4080	778	333	312	0.43	0.40
2	0.43	75	25	75	25	25	5.41	3960	768	354	332	0.46	0.43
3	0.43	50	50	50	50	50	5.16	3690	771	312	291	0.40	0.38
Temperature difference of 0° F between top and bottom:													
1	0.43	100	0	100	0	0	5.83	4080	778	170	187	0.22	0.24
2	0.43	75	25	75	25	25	5.41	3960	768	175	192	0.23	0.25
3	0.43	50	50	50	50	50	5.16	3690	771	170	186	0.22	0.24

Table 8-2. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete Containing RCA and a 0.48 W/C Ratio

Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RCA (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE ($10^{-6}/°F$)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.48	100	0	100	0	0	5.84	3880	761	392	471	0.52	0.62
2	0.48	75	25	75	25	25	5.46	4010	754	402	489	0.53	0.65
3	0.48	50	50	50	50	50	5.29	3670	688	384	447	0.56	0.65
Temperature difference of –20° F between top and bottom:													
1	0.48	100	0	100	0	0	5.84	3880	761	322	300	0.42	0.39
2	0.48	75	25	75	25	25	5.46	4010	754	337	315	0.45	0.42
3	0.48	50	50	50	50	50	5.29	3670	688	306	278	0.44	0.40
Temperature difference of 0° F between top and bottom:													
1	0.48	100	0	100	0	0	5.84	3880	761	170	186	0.22	0.24
2	0.48	75	25	75	25	25	5.46	4010	754	172	188	0.23	0.25
3	0.48	50	50	50	50	50	5.29	3670	688	167	184	0.24	0.27

Table 8-3. Computed Maximum Stresses and Stress-Strength Ratios in a Typical Concrete Pavement Subjected to a 22-kip Single-Axle Load using Properties of Concrete Containing RCA and a 0.53 W/C Ratio

Mix #	W/C Ratio	Coarse		Fine		Total RCA (%)	28-Day Mean			Computed Stress (psi)		Stress Ratio	
		Aggregate (%)	RCA (%)	Aggregate (%)	RAP (%)		Water-Saturated CTE (10^{-6}/° F)	Modulus of Elasticity (ksi)	Modulus of Rupture (psi)	Slab Corner	Middle Edge	Slab Corner	Middle Edge
Temperature difference of +20° F between top and bottom:													
1	0.53	100	0	100	0	0	4.98	3700	659	372	420	0.56	0.64
2	0.53	75	25	75	25	25	5.20	3720	664	376	439	0.57	0.66
3	0.53	50	50	50	50	50	5.47	3300	675	376	437	0.56	0.65
Temperature difference of –20° F between top and bottom:													
1	0.53	100	0	100	0	0	4.98	3700	659	278	259	0.42	0.39
2	0.53	75	25	75	25	25	5.20	3720	664	292	272	0.44	0.41
3	0.53	50	50	50	50	50	5.47	3300	675	293	274	0.43	0.41
Temperature difference of 0° F between top and bottom:													
1	0.53	100	0	100	0	0	4.98	3700	659	162	178	0.25	0.27
2	0.53	75	25	75	25	25	5.20	3720	664	165	182	0.25	0.27
3	0.53	50	50	50	50	50	5.47	3300	675	163	179	0.24	0.27

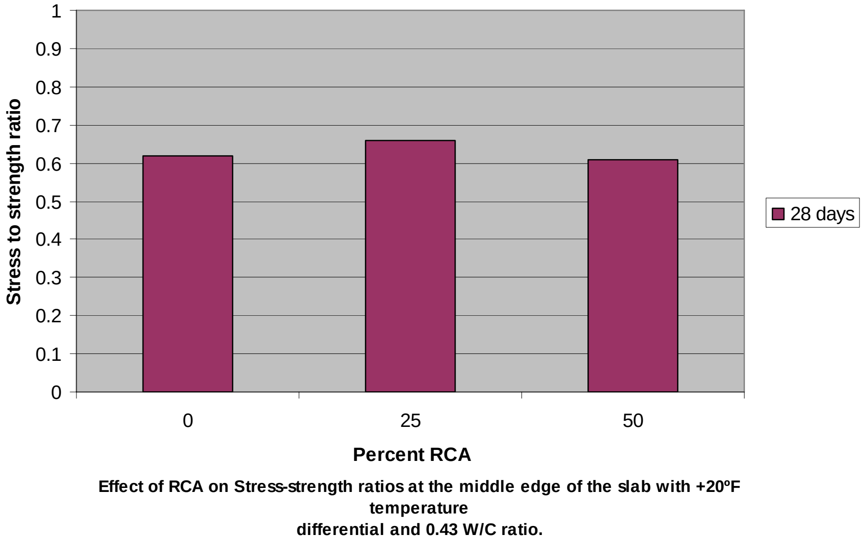

Figure 8-1. Comparison of stress-strength ratios for concretes using different amounts of RCA and a 0.43 w/c ratio.

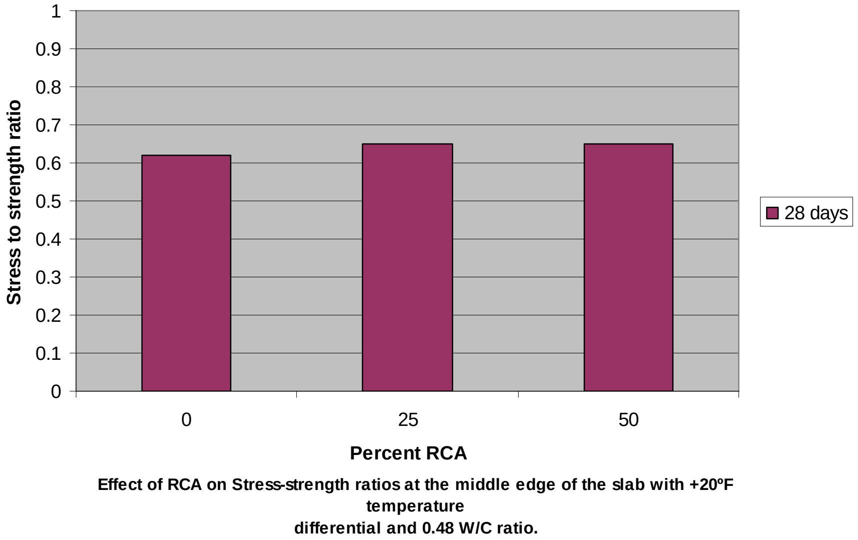

Figure 8-2. Comparison of stress-strength ratios for concretes using different amounts of RCA and a 0.48 w/c ratio.

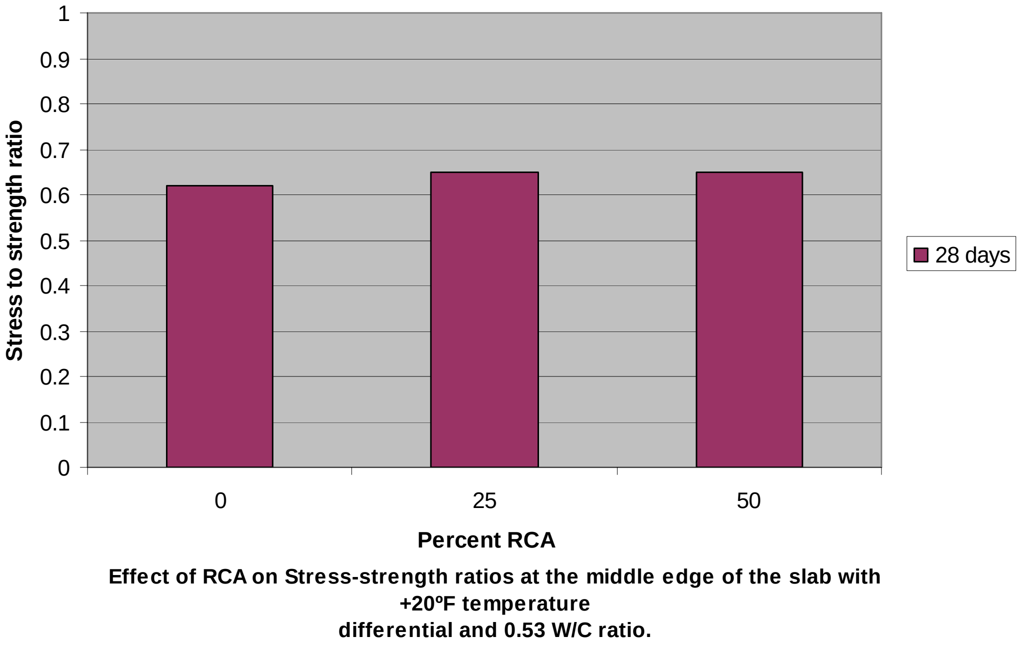

Figure 8-3. Comparison of stress-strength ratios for concretes using different amounts of RCA and a 0.53 w/c ratio.

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions from the Evaluation of Concrete Containing RAP

The feasibility of using concrete containing recycled asphalt pavement (RAP) in concrete pavement applications was evaluated. Concrete containing 0%, 10%, 20%, and 40% of RAP were produced in the laboratory, and evaluated for their properties that are relevant to performance of concrete pavements. Results of the laboratory testing program indicate that compressive strength, splitting tensile strength, flexural strength, and elastic modulus of the concrete decreased as the percentage of RAP increased. The coefficient of thermal expansion appeared to increase slightly when the first RAP was incorporated, and to decrease slightly when a second RAP was used. The drying shrinkage appeared to increase slightly with the use of RAP in concrete. When a finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses in the pavement were found to decrease as the RAP content of the content increased, due to a decrease in the elastic modulus of the concrete. Though the flexural strength of the concrete decreased as RAP was incorporated in the concrete, the resulting maximum stress to flexural strength ratio for the concrete was reduced as compared with that of a reference concrete with no RAP. This indicates that using a concrete containing RAP could possibly result in improvement in the performance of concrete pavements.

9.2 Conclusions from the Evaluation of Concrete Containing RCA

The feasibility of using concrete containing recycled concrete aggregate (RCA) in concrete pavement applications was evaluated. Concrete containing 0%, 25%, and 50% of RCA were produced in the laboratory and evaluated for their properties that are relevant to performance of concrete pavements. Results of the laboratory testing program indicate that compressive strength and elastic modulus decreased slightly as the percentage of RCA increased. The splitting tensile strength, flexural strength, and coefficient of thermal expansion were about the same for the control mix and the concrete containing RCA. The drying shrinkage decreased slightly as the percentage of RCA increased. When a finite element analysis was performed to determine the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions, the maximum stresses to strength ratios in the pavement were found to be about the same for the control mix and concrete containing RCA. Thus, a concrete using RCA will likely have the same performance as a conventional concrete using virgin aggregates. With the use of RCA up to about 50%, there will likely not be much difference in its performance compared with concrete containing virgin aggregate. Thus, the main advantages for the use of the RCA would be the economical and environmental benefits.

9.3 Recommendations on Concrete Containing RAP

The results of a laboratory testing program and finite element analysis indicate that the use of RAP as aggregate replacement in pavement concrete appears to be not only feasible but also offer the possibility of improving the performance of concrete pavement. It is thus recommended that further research be conducted in this area to further substantiate this finding. It is recommended that further research work be done in the following areas:

1) To conduct a full factorial experiment to investigate the properties of concrete containing RAP as affected by: a) the mechanical properties of the RAP; b) the gradation of the RAP; c) properties of the virgin aggregate; d) w/c of the concrete; and e) mineral admixtures such as fly ash and ground blast-furnace slag;
2) To evaluate the potential performance of the various concrete mixes tested in the factorial experiment using finite element analysis where the maximum stresses in typical concrete

pavements in Florida under critical temperature and load conditions would be determined using the measured properties–the results of these analyses can then be used to develop a method for optimizing a concrete mix design incorporating RAP; and

3) To conduct accelerated pavement testing on concrete pavement slabs made with concrete containing RAP to evaluate the actual field performance of these concrete mixes.

9.4 Recommendations on Concrete Containing RCA

The results of a laboratory testing program and finite element analysis indicate that the use of RCA as aggregate replacement in pavement concrete appears to be feasible and offer comparable performance as that of a concrete containing virgin aggregates. It is thus recommended that further research be conducted in this area to further validate this finding. It is recommended that further research work be done in the following areas:

1) To conduct a full factorial experiment to investigate the properties of concrete containing RCA as affected by: a) the mechanical properties of the RCA; b) the gradation of the RCA; c) properties of the virgin aggregate; d) w/c of the concrete; and e) mineral admixtures such as fly ash and ground blast-furnace slag;
2) To evaluate the potential performance of the various concrete mixes tested in the factorial experiment using finite element analysis where the maximum stresses in typical concrete pavements in Florida under critical temperature and load conditions would be determined using the measured properties–the results of these analyses can then be used to develop a method for optimizing a concrete mix design incorporating RCA;
3) To conduct accelerated pavement testing on concrete pavement slabs made with concrete containing RCA to evaluate the actual field performance of these concrete mixes;
4) To perform a life-cycle cost analysis to determine the actual cost savings from using RCA;
5) To perform a computer x-ray tomography on the RCA to assess the degree of distress existing in it; and
6) To perform a scanning electron microscopy to exam the microstructure of the concrete containing RCA and determine how the various constituents can be improved.

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APPENDIX A
INPUT GUIDE FOR FEACONS IV PROGRAM

There are two types of input for the FEACONS IV program they are:

1) The input data which describe the problem.
2) The command statements which give specific instructions for execution of the program.

Both the input data and the command statements must appear in the input file in the same order as specified. All of the input data are free-formatted so that the data are not limited to any specific columns. Adjoining data must be separated by a blank or a comma. However, a command statement must start at the first column of each line. Input for the program is listed in Table A-1.

Table A-1. Input Guide for FEACONS IV Program

Item	Input	Mandatory (M) or Optional (O)
1	Number of runs	M
2	Number of x-divisions on slab #1 Number of x-divisions on slab #2 Number of x-divisions on slab #3 Number of y-divisions	M
3	Number of bonded layers (1 or 2)	M
4	Thickness of top layer (in inches), Elastic modulus of top layer (in ksi), Poisson’s ratio of both layers	M
5	Skip if number of bonded layers = 1, otherwise Thickness of second layer (in inches) Elastic modulus of second layer (in ksi)	
6	Thickness of subbase (in inches) Elastic modulus of subbase layer (ksi) (enter 0, 0 if not used)	M
7	x-coordinates of nodes along the x axis (in inches)	M
8	y-coordinates of nodes along the y axis (in inches)	M
9	Command LINEAR (for linear sub-grade), or NONLINEAR (for nonlinear sub-grade)	M
10	Subgrade modulus in kci (if LINEAR), or Coefficient A, Coefficient B (if NONLINERAR) (The force-deflection relationship is: F = Ad + Bd2, where F = force/area in ksi, and d = deflection in inches)	M

Table A-1. Continued

Item	Input	Mandatory (M) or Optional (O)
11	Command GAP (if initial gaps are to be read), or NO GAP	M
12	Skip if NO GAP. Otherwise, input: Number of gaps Node number, Depth of gap in inches (Use one line for each node with gap)	M
13	Command CONC FORCE (if concentrated loads are to be read in), or NO CONC FORCE	M
14	Skip if NO CONC FORCE, Otherwise: Number of Concentrated Forces (on one line) Node number, Magnitude of load in kips (use one line for each node)	M
15	Command UNIF LOAD (if uniform load is to be read in), or NO UNIF LOADS	M
16	Skip if NO UNIF LOAD. Otherwise: Number of elements with uniform loads (on one line) Element number, Uniform load in ksi (use one line for each element)	M
17	Density of 1st layer (in pcf)	M
18	Skip if number of layers = 1, otherwise Density of 2nd layer (in pcf)	M
19	Command TEMPERATURE EFFECT (if effects of temperature differentials are to be considered) or No TEMPERATURE EFFECT (Temperature effect cannot be considered if a subbase layer is used.)	M
20	Skip if NO TEMPERATURE EFFECT. Otherwise: Coefficient of thermal expansion (in 1/.F), Temperature at the top of the slab (in .F) Temperature at the bottom of the slab (in .F)	M
21	Spring coefficient for the edges (in ksi)	M
22	Linear spring coefficient for the joints (in ksi), Torsional spring coefficient for the joints (in k-in)	M
23	Linear spring coefficient for the dowel joints (in ksi), Torsional spring coefficient for the dowel joints (in k/in) SLIP (in inches)	M
24	Number of load increments to compute the effects of slab weight, Number of load increments to compute the effects of temperature Differentials, Number of load increments to compute the effects of applied loads	M
25	Command PRINT INITIAL DEFLECTION (if deflection caused by the combined effects of slab weight and temperature differentials are to be printed)	O
26	If the command PRINT INTIAL DEFLECTION is read in, read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between the nodes (the last three numbers represent a node set. The next node set follows here if there is more than one node set)	O

Table A-1. Continued

Item	Input	Mandatory (M) or Optional (O)
27	Command PRINT DEFLECTION (if deflections caused by applied loads are to be printed)	O
28	If PRINT DEFLECTION is read in, read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between the nodes (Similar to No.26)	O
29	Command PRINT MAXIMUM DEFLECTION, read in: (If maximum deflections between specific nodes are to be printed)	O
30	If PRINT MAXIMUM DEFLECTION, read in: Number of sets of nodes, Starting node number, Ending node number, Increment (Similar to No.26)	O
31	Command PRINT MOMENTS (If moments at the nodes are to be printed)	O
32	If PRINT MOMENTS, read in: Number of sets of nodes, Starting node number, Ending node number, Increment (Similar to no.26)	O
33	Command PRINT MAXIMUM MOMENTS if maximum moments between specific nodes are to be printed)	O
34	If PRINT MAXIMUM MOMENTS, read in: Number of sets of nodes, Starting node number, Ending node number, Increment (Similar to No.26)	O
35	Command PRINT TOP STRESSES (If stresses at the top of the slabs are to be printed)	O
36	If PRINT TOP STRESSES, read in: Number of sets of nodes, Starting node number, Ending node number, Increment (Similar to No.26)	O
37	Command PRINT MAXIMUM STRESSES (If maximum stresses between specific nodes are to be printed)	
38	If PRINT BOTTOM STRESSES, read in: (Similar to No.26)	
39	Command PRINT 1STLAYER BOTTOM STRESSES (if stresses at the bottom of the top layer are to be printed)	

Table A-1. Continued

Item	Input	Mandatory (M) or Optional (O)
40	If PRINT MAXIMUM STRESSES, then read in: Number of sets of nodes, Starting node number, Ending node number, Increment (Similar to No.26)	
41	Command PRINT BOTTOM STRESSES (If stresses at the bottom of the slabs are to be printed)	
42	If PRINT PRINCIPAL STRESSES, then read in: Number of sets of nodes, DEG, Starting node number, Ending node number,Increment (If DEG = 1, angles will be in degrees. If DEG = 2, angles will be in radians.) (The last four numbers represent a node set. The next node set follows here if there is more than one node set)	
36A	Command PRINT 1STLAYER BOTTOM STRESSES (If stresses at the bottom of the top layer are to be printed)	O
36B	If PRINT 1STLAYER BOTTOM STRESSES is read in, read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between the nodes. (This is similar to item 26)	O
38A	Command PRINT 2NDLAYER TOP STRESSES (if stresses at the top of the bottom layer are to be printed)	O
38B	If PRINT 2NDLAYER TOP STRESSES is read in, read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between nodes. (This is similar to item 26)	O
38C	Command PRINT SUBBASE TOP STRESSES (if stresses at the top of the unbonded subbase layer are to be printed)	O
38D	If PRINT SUBBASE TOP STRESSES read in, read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between the nodes. (This is similar to item 26)	O
39	Command PRINT MAXIMUM STRESSES 1STLAYER TOP (if maximum stresses at the top of the top layer, between specific nodes, are to be printed) [revised]	O
40	If PRINT MAXIMUM STRESSES 1STLAYER TOP, then read in: Total number of sets of nodes to be printed, Starting node number, Ending node number, Increment between the nodes. (Similar to No.26) [revised]	O

Table A-1. Continued

Item	Input	Mandatory (M) or Optional (O)
40A	Command PRINT MAXIMUM STRESSES 1STLAYER BOTTOM (if maximum stresses at the bottom of the top layer, between specific nodes, are to be printed)	O
40B	If PRINT MAXIMUM STRESSES 1STLAYER BOTTOM, then (inputs similar to item 26)	O
40C	Command PRINT MAXIMUM STRESSES 2NDLAYER BOTTOM (if maximum stresses at the bottom of the bottom layer, between specific nodes, are to be printed)	O
40D	If PRINT MAXIMUM STRESSES 2NDLAYER BOTTOM, then (inputs similar to item 26)	O
40E	Command PRINT MAXIMUM STRESSES 2NDLAYER TOP (if maximum stresses at the top of the bottom layer, between specific nodes, are to be printed)	O
40F	Command PRINT MAXIMUM STRESSES SUBASE TOP (if maximum stresses at the top of the unbonded subbase layer, between specific nodes, are to be printed)	O
43	Command PRINT MAXIMUM PRINCIPAL STRESSES (If maximum principal stresses between specific nodes are to be printed) (For top stresses only)	O
44	If PRINT MAXIMUM PRINCIPAL STRESSES, then: Number of sets of nodes, Starting node number, Ending node number, Increment. (Similar to item 26)	O
45	Command FINISH (This is to mark the end of a set of data. The next set of data in the same formats as items (2) through (39) follows here, if there is more than one run to be made.)	M

Numbering of Nodes and Element

In using the FEACONS IV program, it is essential that the nodes and the elements of the chosen finite-element mesh are numbered properly. The nodes and elements are numbered from left to right and from bottom to top such that they start at the lower left corner of the first slab, and proceed up in the vertical direction for the full width of the slab. The number of nodes and the y coordinates of the chosen nodes in the y direction (along the width) in each slab should be the same as those of the other slabs. However, the number of nodes and distances between two nodes in the x direction (along the length) may vary from one slab to another.

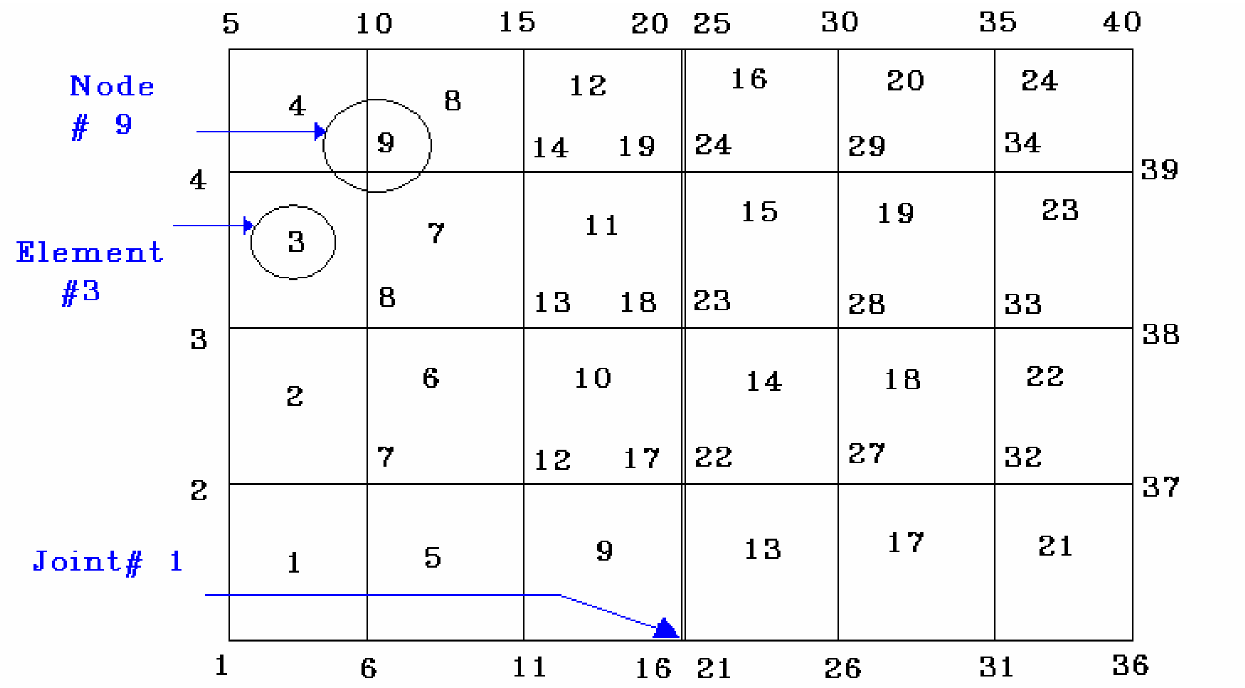

Figure A-1. Example of number of nodes and elements.

APPENDIX B
LABORATORY TEST RESULTS FOR RAP STUDY

Table B-1. Results of Compressive Strength Tests (psi)

Set #	Mix #	Compressive Strength (psi)								
		14 Days			28 Days			90 Days		
		1	2	3	1	2	3	1	2	3
Set-1 RAP-1	1	5315	5548	5472	5818	5434	5536	6349	5717	4213
	2	4527	4239	4685	4999	4867	4942	5228	4909	4773
	3	3084	3269	3210	3711	3807	3818	3981	3910	3981
	4	2436	2381	2516	2693	2371	2497	2527	2768	2677
Set-2 RAP-1	1	5621	5745	/	5810	5670	5857	6538	6881	5641
	2	4663	/	4623	4431	4411	5396	4969	5741	4981
	3	3300	3594	3120	3385	3623	3088	3495	4016	3839
	4	2212	2221	2575	2251	2013	2457	2498	3038	2763
Set-3 RAP-1	1	4540	5690	5359	5879	6100	5806			
	2	4370	4075	3160	5170	4980	5230			
	3	3230	3470	3710	5371	4365	4647			
	4	2946	3700	3520	3883	4207	3644			
Set-1 RAP-2	1	5836	5673	6025	7000	7119	7101			
	2	4300	4150	4462	4523	4543	4746			
	3	3758	4360	3970	4136	4141	4543			
	4	2000	1904	/	/	/	/			
Set-2 RAP-2	1	4640	4391	4383	2548	2271	4090			
	2	2769	3257	3316	2961	3451	3045			
	3	2554	4632	2637	4555	4792	4716			
	4	2203	2699	2647	3358	3206	3464			
Set-3 RAP-2	1	6225	6435	6219	6703	6501	6620			
	2	3471	3600	3500	3925	3640	3861			
	3	2400	2520	2460	2405	2322	2442			
	4	2390	2400	2350	2760	2939	3140			
	1	4804	5470	5971	6352	5742	6084			
	2	3585	3824	3575	4120	3961	3925			
	3	2542	2718	2660	2900	2700	2650			
	1	3713	4222	4108	4686	4511	4884			
	2	3303	3082	3261	3706	3600	3521			
	3	2098	2250	2198	2435	2433	2330			

Table B-2. Results of Elastic Modulus Tests (× 10^6 psi)

Set #	Mix #	Elastic Modulus (× 10^6 psi)								
		14 Days			28 Days			90 Days		
		1	2	3	1	2	3	1	2	3
Set-1 RAP-1	1	4.12	4.81	4.40	/	4.71	4.85	4.62	4.57	4.97
	2	3.71	3.90	3.86	3.98	/	4.02	3.95	4.20	4.23
	3	3.29	3.45	3.31	/	3.34	3.45	3.56	3.71	3.43
	4	2.46	2.17	2.32	2.35	2.35	/	2.59	2.30	2.60
Set-2 RAP-1	1	4.47	4.73	/	4.99	5.25	4.47	4.89	4.89	4.50
	2	4.10	/	4.24	4.23	4.13	5.18	/	4.45	4.64
	3	3.19	3.42	3.61	3.21	3.38	4.65	3.37	3.77	3.44
	4	2.31	2.15	2.34	2.33	2.32	2.24	2.95	2.52	2.39
Set-3 RAP-1	1	4.74	3.95	4.13	5.41	4.83	4.44			
	2	4.03	3.80	4.52	4.07	3.98	4.03			
	3	3.40	3.45	3.09	3.81	3.26	3.45			
	4	2.77	2.75	2.79	3.02	2.69	2.66			
Set-1 RAP-2	1	4.05	4.25	4.50	4.39	4.73	4.68			
	2	3.86	3.51	3.93	3.99	3.51	3.77			
	3	2.93	3.34	3.09	3.25	2.91	3.51			
	4	2.98	2.21	/	/	/	/			
Set-2 RAP-2	1	3.16	3.35	3.00	2.80	2.82	2.81			
	2	2.06	2.44	2.40	2.32	2.39	2.10			
	3	3.16	3.30	/	3.85	3.95	3.91			
	4	2.32	2.23	2.21	3.30	3.23	3.35			
Set-3 RAP-2	1	4.15	4.17	4.14	4.10	4.08	4.09			
	2	2.81	2.86	2.70	2.90	2.85	2.85			
	3	1.75	1.80	1.77	1.85	1.81	1.90			
	4	3.95	3.95	3.89	4.10	4.00	4.10			
	1	3.95	3.95	3.89	4.10	4.00	4.10			
	2	2.95	2.97	2.96	2.98	3.01	2.99			
	3	2.17	2.23	2.02	2.10	2.08	2.02			
	1	3.58	3.35	3.45	3.70	3.80	3.70			
	2	2.88	2.88	2.78	2.94	2.98	2.99			
	3	1.86	1.84	1.88	1.95	1.95	1.96			

Table B-3. Results of Flexural Strength Tests (psi)

Set #	Mix #	Flexural Strength (psi)					
		14 Days		28 Days		90 Days	
		1	2	1	2	1	2
Set-1 RAP-1	1	843	923	879	1001	1003	949
	2	839	775	808	1074	848	841
	3	903	755	707	793	723	790
	4	682	748	558	582	533	821
Set-2 RAP-1	1	802	/	969	970	807	719
	2	840	721	900	836	568	576
	3	760	649	766	653	513	592
	4	599	557	564	716	523	496
Set-3 RAP-1	1	547	524	572	568		
	2	569	548	534	/		
	3	520	/	/	/		
	4	423	509	538	496		
Set-1 RAP-2	1	550	608	550	537		
	2	513	552	484	543		
	3	463	430	457	424		
	4	378	400	/	/		
Set-2 RAP-2	1	488	466	455	510		
	2	381	406	419	402		
	3	466	502	546	532		
	4	440	347	412	396		
Set-3 RAP-2	1	735	790	918	906		
	2	638	586	693	716		
	3	443	476	517	528		
	4	488	466	455	510		
	1	743	703	805	802		
	2	600	586	665	602		
	3	526	486	570	590		
	1	652	696	715	763		
	2	595	557	605	578		
	3	458	472	488	478		

Table B-4. Results of Splitting Tensile Strength Tests (psi)

Set #	Mix #	Splitting Tensile Strength (psi)					
		14 Days			28 Days		
		1	2	3	1	2	3
Set-1 RAP-1	1	572	497	454	492	503	416
	2	332	389	390	484	489	490
	3	206	267	310	401	327	395
	4	307	330	316	326	336	391
Set-1 RAP-2	1	509	524	568	577	609	636
	2	410	367	/	351	432	468
	3	342	346	405	354	359	370
	4	197	243	196	/	/	/
Set-2 RAP-2	1	361	377	413	375	346	294
	2	292	247	316	292	293	322
	3	314	434	365	459	424	467
	4	262	330	289	325	318	306
Set-3 RAP-2	1	560	507	500	500	537	599
	2	290	360	336	386	406	416
	3	265	244	268	270	308	260
	4	/	/	/	/	/	/
	1	528	606	445	463	522	605
	2	423	330	416	398	393	425
	3	281	268	279	280	262	294
	1	418	406	320	486	372	380
	2	330	360	325	285	326	372
	3	250	275	276	262	272	307

Table B-5. Results of Free Shrinkage Tests (10^{-6} in/in)

Set #	Mix #	Free Shrinkage (10^{-6} in/in)								
		14 Days			28 Days			90 Days		
		1	2	3	1	2	3	1	2	3
Set-1 RAP-1	1	60	130	30	180	410	160	/	/	/
	2	80	90	/	220	210	/	/	/	/
	3	60	50	110	140	80	140	300	190	340
	4	130	60	10	280	170	110	360	330	320
Set-2 RAP-1	1	140	140	170	270	270	320	360	330	370
	2	60	90	160	200	230	290	350	320	390
	3	210	200	250	290	260	300	440	350	380
	4	240	180	210	380	280	320	540	430	550
Set-3 RAP-1	1	200	110	130	260	310	300			
	2	140	110	150	180	150	190			
	3	135	110	/	230	220	250			
	4	150	140	120	120	130	130			
Set-1 RAP-2	1	100	110	190	190	220	280			
	2	140	110	/	180	150	/			
	3	200	150	230	310	260	250			
	4	190	210	150	/	/	/			
Set-2 RAP-2	1	150	130	110	250	290	270			
	2	160	140	130	250	230	250			
	3	140	130	150	240	210	290			
	4	180	160	150	280	310	320			
Set-3 RAP-2	1	160	190	220	300	330	280			
	2	160	150	190	290	270	270			
	3	140	160	150	280	260	280			
	4	/	/	/	/	/	/			
	1	110	120	160	280	280	280			
	2	260	210	280	350	310	360			
	3	220	200	270	370	330	/			
	1	130	120	140	230	240	270			
	2	70	120	170	230	230	240			
	3	160	70	90	260	210	210			

Table B-6. Results of Coefficient of Thermal Expansion Tests (10^{-6}/° F)

Set #	Mix #	Coefficient of Thermal Expansion (10^{-6}/° F)								
		14 Days			28 Days			90 Days		
		1	2	3	1	2	3	1	2	3
Set-1 RAP-1	1	5.70	6.17	6.04	6.34	6.07	5.76	6.43	6.08	6.06
	2	6.58	5.47	5.98	5.80	6.15	6.23	6.14	6.35	6.32
	3	5.35	5.84	6.36	5.92	6.85	6.50	5.92	6.03	6.40
	4	6.13	6.43	6.53	5.60	6.51	6.48	5.97	6.04	6.85
Set-2 RAP-1	1	5.53	5.67	6.19	5.41	5.45	5.79	5.64	5.61	6.14
	2	5.78	5.80	5.98	5.88	6.01	5.99	5.29	5.73	5.87
	3	5.79	5.60	6.04	5.69	5.65	5.82	5.88	5.75	5.95
	4	5.73	6.03	6.16	5.86	5.89	6.64	5.97	5.83	6.16
Set-3 RAP-1	1	5.17	4.82	4.79	5.33	5.00	5.76			
	2	/	/	/	5.08	5.33	4.64			
	3	5.06	4.94	4.75	5.39	4.78	4.88			
	4	5.23	4.98	4.79	5.45	5.35	5.25			
Set-1 RAP-2	1	5.56	5.52	5.11	/	/	/			
	2	5.44	5.20	4.64	/	/	/			
	3	5.02	4.97	4.79	/	/	/			
	4	5.12	5.30	4.75	/	/	/			
Set-2 RAP-2	1	6.52	6.64	6.32	5.97	5.81	5.46			
	2	5.68	5.48	6.05	6.15	5.75	5.79			
	3	6.07	6.33	5.70	6.24	6.30	6.49			
	4	6.32	5.79	5.71	6.57	5.95	5.98			
Set-3 RAP-2	1	5.24	5.28	5.34	5.61	5.18	5.52			
	2	/	/	/	/	/	/			
	3	/	/	/	/	/	/			
	4	/	/	/	/	/	/			
	1	5.02	4.73	5.00	5.40	4.99	5.36			
	2	5.08	5.20	4.76	5.06	5.14	5.12			
	3	5.07	5.30	5.34	4.98	5.09	5.18			
	1	/	/	/	/	/	/			
	2	/	/	/	5.04	5.36	5.15			
	3	/	/	/	4.86	5.10	4.94			

APPENDIX C
LABORATORY TEST RESULTS FOR RCA STUDY

Table C-1. Results of Compressive Strength Tests (psi)

w/c	Compressive Strength (psi)					
	Test at 14 Days			Test at 28 Days		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Control Mix :						
0.43	5156	5122	5443	5495	5413	5367
0.48	4956	4875	4932	5355	5391	5205
0.53	4255	4203	4591	4527	4534	4463
25% RCA :						
0.43	5371	5462	5524	6008	5914	6171
0.48	5227	5421	5213	5608	5555	5570
0.53	4518	4433	4257	4982	4798	4841
50% RCA :						
0.43	4857	4872	5072	5571	5572	5070
0.48	4693	4931	5051	5048	5185	5015
0.53	4318	4484	4375	4625	4586	4640

Table C-2. Results of Elastic Modulus Tests (× 10^6 psi)

w/c	Elastic Modulus (× 10^6 psi)			
	Test at 14 Days		Test at 28 Days	
	Sample 1	Sample 2	Sample 1	Sample 2
Control Mix :				
0.43	3.9	3.9	4.00	4.15
0.48	3.85	3.85	3.90	3.85
0.53	3.55	3.55	3.65	3.75
25% RCA :				
0.43	3.85	3.80	3.93	3.98
0.48	3.87	3.92	4.02	4.00
0.53	3.45	3.42	3.68	3.75
50% RCA :				
0.43	3.47	3.95	3.73	3.65
0.48	3.50	3.45	3.68	3.65
0.53	3.10	3.20	3.35	3.30

Table C-3. Results of Flexural Strength Tests (psi)

w/c	Flexural Strength (psi)					
	Test at 14 Days			Test at 28 Days		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Control Mix :						
0.43	754	791	755	728	778	827
0.48	710	730	713	780	742	759
0.53	637	658	666	664	648	664
25% RCA :						
0.43	685	710	756	809	747	748
0.48	631	689	696	794	726	741
0.53	633	629	621	668	647	678
50% RCA :						
0.43	700	731	686	757	790	767
0.48	555	641	712	719	706	638
0.53	583	553	591	647	715	665

Table C-4. Results of Splitting Tensile Strength Tests (psi)

w/c	Splitting Tensile Strength (psi)					
	Test at 14 Days			Test at 28 Days		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Control Mix :						
0.43	633	528	610	562	509	539
0.48	539	515	559	545	560	567
0.53	466	501	489	561	439	422
25% RCA :						
0.43	589	581	506	567	594	643
0.48	478	619	510	498	506	535
0.53	438	428	450	434	549	467
50% RCA :						
0.43	375	479	510	402	631	534
0.48	491	477	555	556	525	539
0.53	371	321	478	475	468	485

Table C-5. Results of Free Shrinkage Tests (10^{-6} in/in)

w/c	Free Shrinkage (10^{-6} in/in)		
	Test at 28 Days		
	Sample 1	Sample 2	Sample 3
Control Mix :			
0.43	50	70	50
0.48	20	70	170
0.53	30	0	30
25% RCA :			
0.43	140	190	170
0.48	80	50	40
0.53	80	40	110
50% RCA :			
0.43	50	60	60
0.48	80	170	70
0.53	270	270	270

Table C-6. Results of Coefficient of Thermal Expansion Tests (10^{-6}/° F)

w/c	Coefficient of Thermal Expansion (10^{-6} /° F)		
	Test at 28 Days		
	Sample 1	Sample 2	Sample 3
Control Mix :			
0.43	5.83	5.37	5.32
0.48	5.85	5.31	5.01
0.53	4.98	5.45	5.36
25% RCA :			
0.43	5.76	5.00	5.48
0.48	5.54	5.35	5.49
0.53	5.19	5.31	5.09
50% RCA :			
0.43	5.23	5.28	4.97
0.48	5.38	5.43	5.05
0.53	5.73	5.19	5.47