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# **Effect of Density on Mechanical Properties and Durability of Roller Compacted Concrete**

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## **KEYWORDS**

freeze-thaw durability, gyratory compactor, roller compacted concrete.

## **ABSTRACT**

Roller compacted concrete (RCC) is a durable, economical, low maintenance material for low speed, heavy duty paving applications. However, it is difficult to prepare laboratory specimens to represent field performance, because RCC is very dry and requires considerable compactive effort to achieve field densities. The gyratory compactor, commonly used to prepare hot mix asphalt specimens, may be used in preparing specimens for laboratory testing. Materials and mix designs from two industrial paving projects were used to prepare specimens for comparison. Results indicated that the gyratory compactor produced specimens with mechanical properties consistent with those achieved in the field. Specimens had high strength and consistent density, with low variability. The effects of density and specimen size on compressive and splitting tensile strength were investigated. The number of gyrations applied to the specimen may be used to duplicate the desired field density. Moreover, the effects of water-cement ratio and degree of compaction on the freeze-thaw resistance of gyratory compacted RCC have been investigated. Due to the consistency and compatibility of results obtained, the gyratory compactor may be used to replace the modified Vebe apparatus, the vibrating table, and the vibrating hammer because of some limitations in preparing RCC specimens using these methods.

## **REFERENCE**

Amer, Nader; Storey, C., and Delatte, N., *Effect of Density on Mechanical Properties and Durability of Roller Compacted Concrete*, SN2940, Portland Cement Association, Skokie, Illinois, USA, 2007, 61 pages.

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## INTRODUCTION

Over the past 26 years, many roller compacted concrete (RCC) pavement projects have been constructed in North America. RCC has proven to be a reliable, economical, durable material for low speed, heavy duty pavements. One of the pioneers in using RCC in the United States was the Army Corps of Engineers (USACE) which used RCC extensively for tank test roads and equipment hardstands. Other successful projects documented by the Portland Cement Association (PCA) include ports and intermodal terminals, storage areas, and roads (Piggott 1999). RCC pavements have been used for:

- Highway weigh stations
- Airport aprons
- Docks and container ports
- Multimodal facilities
- Heavy industrial facilities such as logging and automobile manufacturing

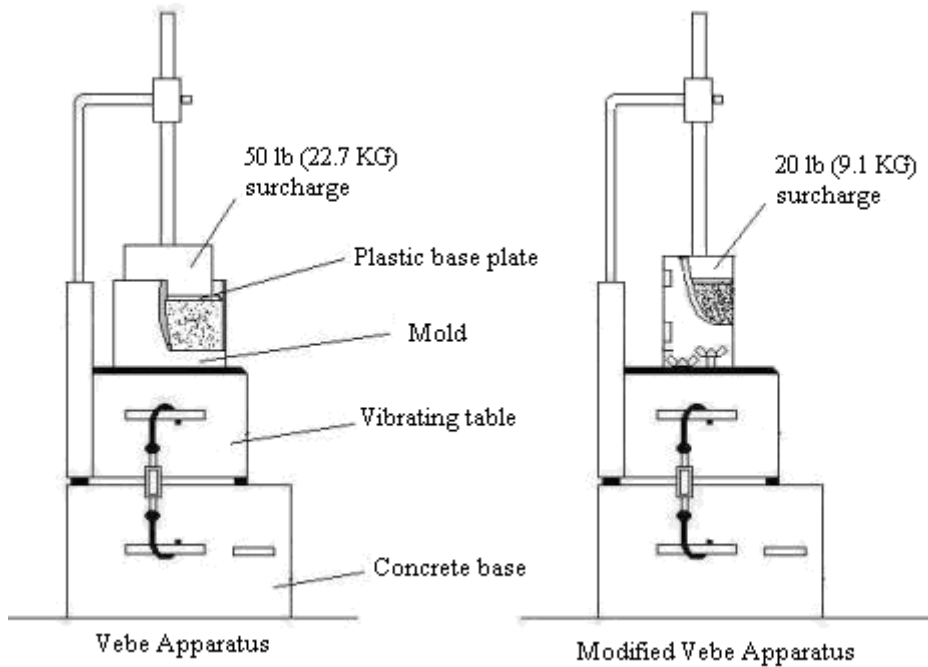
Extensive research has been carried out for both RCC pavements and dams. Many of those involved with the industry started to show interest in more research to better understand the mechanical behavior of RCC. Points of interest include the evaluation of curling and warping, freeze-thaw durability, use of admixtures, methods to improve RCC surfaces, and the use of overlays on RCC. Laboratory work is essential to investigate these topics. Even though the performance of RCC has been unquestionably impressive, it is necessary to find better ways of predicting field performance. In the past, it has been difficult to fabricate consistent laboratory specimens. The research team proposed using the gyratory compactor developed by the Strategic Highway Research Program (SHRP) to fabricate RCC specimens for testing. RCC construction is not that different from asphalt pavement construction. Therefore, the research team hypothesized that the gyratory compactor could be used to fabricate RCC specimens to match field test results. (Amer, Delatte, and Storey 2003)

Before this hypothesis could be verified, one question that had to be answered was whether it was possible to fabricate an RCC specimen in a gyratory compactor and remove it intact for subsequent testing. A pilot test showed that it was possible. The biggest task was then to show the consistency and reliability of test results obtained for RCC gyrated specimens, the main reason this machine was being used. Other methods

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for producing RCC specimens have some drawbacks such as variability in quality, difficulty in preparing samples, and extensive correlation requirements. The most common equipment used to fabricate and investigate RCC properties includes the Proctor moisture-density equipment, the modified Vebe apparatus shown in Figure 1, and the Hilti impact hammer shown in Figure 2.



**Figure 1. Vebe consistency apparatus and modified Vebe apparatus.**



**Figure 2. The vibrating hammer in the field (provided by PCA).**

Proctor and Vebe tests are used to evaluate density and consistency, whereas the impact hammer is used to compact specimens for later strength testing. In this research, the gyratory compactor was investigated as an alternative to the impact hammer for preparing

laboratory and field specimens. Unlike the gyratory compactor, an impact hammer can only prepare specimens to a single compactive effort with a single density. The impact hammer can be user dependent, which makes results differ from one site to another even when using the same mix. On the other hand, consistency is assured with the gyratory compactor even though different models are available for it. The one used throughout most of this research was a lightweight, easily moved gyratory compactor. It also prepares a specimen in less than 10 minutes. Therefore, it takes almost the same time as the Hilti hammer to prepare specimens in the field or the lab, but the gyratory compactor has an advantage due to its ability to prepare specimens to any desired density (Amer 2002). As will be seen later in this research, results are consistent and applicable to RCC pavements for a wide variety of heavy duty, low speed, applications, and to dams. Existing mixture design and test methods for RCC were investigated for comparison with the results obtained from the gyratory compactor. The USACE ETL1110-2-2006 and the American Society for Testing and Materials (ASTM) D 1557 were the main procedures considered.

## Common Design Procedures

Two methods of mixing and producing RCC mixtures were evaluated for the purpose of this research. The USACE procedure uses a step-by-step process for selecting proportions (USACE, 2000). The modified Proctor-density testing procedure, on the other hand, is used to determine the maximum dry density and optimum moisture content for a RCC mixture then the constituents are adjusted (ASTM D 1557 2004).

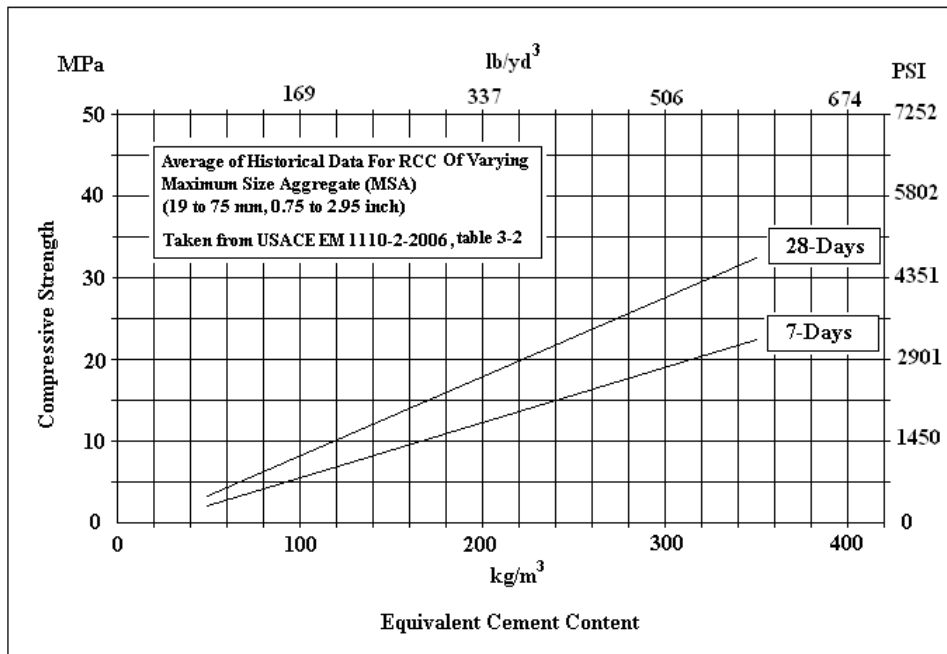
**USACE procedure.** The USACE procedure starts by determining the performance requirements for the RCC pavement, such as strength and durability. Then, material testing is performed to evaluate aggregate gradation, aggregate specific gravity, etc. From the water content table (USACE Table 3-3, 2000), the amount of water is estimated. In that table, the water content depends on time determined by the modified Vebe apparatus. Applicable information from Table 3-3 has been converted and extracted as Table 1 for the 19-mm ( $\frac{3}{4}$ -in.) maximum size coarse aggregate typically used for pavements. The table provides the amounts for water content, sand content, mortar content, paste-mortar ratio, and entrapped air content. Figure 3 gives the amount of cement required by taking the compressive strength across the chart. Figure 3 is part of a more comprehensive graph produced by USACE to represent the relationship between compressive strength and cement content.

Next, the amounts of coarse and fine aggregate required are computed from Tables 1 and 2 (USACE Tables 3-1, 3-3 2000).



**Table 1. Water and Aggregate Estimates from USACE Table 3-3 (USACE 2000)**

Water Content, Sand Content, Mortar Content, Paste-Mortar Ratio, and Entrapped Air Content		
Typical Values for Use in Estimating RCC Trial Mixture Proportions		
Contents	Nominal Maximum Size of Aggregate 19 mm (¾ inch)	
	Average	Range
Water content, lb/yd <sup>3</sup> (kg/m <sup>3</sup> )		
a) Vebe <30 sec	253 (150)	224-305 (133-181)
b) Vebe >30 sec	226 (134)	185-259 (110-154)
Sand content, % of total aggregate volume		
a) Crushed aggregate	55	49-59
b) Rounded aggregate	43	38-45
Mortar content, % by volume		
a) Crushed aggregate	70	63-73
b) Rounded aggregate	55	53-57
Paste: mortar ratio, $V_p/V_m$ , by volume	0.41	0.27-0.55
Entrapped air content, %	1.5	0.1-4.2



**Figure 3. USACE guidance for selecting cement content (USACE 2000).**

**Table 2. Ideal Aggregate Grading From USACE Table 3-1 (USACE 2000)**

Ideal Coarse Aggregate Grading	
Sieve Size	Cumulative Percent Passing
	4.75 to 19.0 mm (No. 4 to 3/4 in.)
1 in. (25.0 mm)	100
3/4 in. (19 mm)	100
1/2 in. (12.5 mm)	63
3/8 in. (9.5 mm)	41
No. 4 (4.75 mm)	-

After the calculation of volumes and masses for the constituents of the mixture, the results are compared again with given information in Table 1, USACE Table 3-3. The next step is to determine the volume of paste and the ratio of paste volume to mortar volume. Finally, the mixture is assessed by trial batching (Amer 2003).

**Modified Proctor density procedure.** The modified Proctor density procedure begins by fixing the approximate amount of cementitious material and aggregate for the RCC pavement. Then the modified Proctor density test specified in ASTM D-1557 is used to develop the moisture-density curve for the RCC mixture. To achieve optimum density, modifications can be applied to the aggregate content. The optimum density is an indication of specific moisture content, which is used to determine the amount of water required for the mix. Test cylinders are fabricated to investigate if the strength requirements are achieved. If not, then the mix design would not change except for modifications in the cement content keeping the aggregate and water content the same. The number of trial batches depends heavily on the experience of the laboratory engineer using the modified Proctor density procedure. RCC pavement consultants use this method as the common practice, while the USACE method is a more thoroughly researched method. The USACE procedure might be more helpful in reducing the amount of time and trial batches (Amer 2003).

**The Brovold gyratory compactor.** The gyratory compactor commonly used to prepare hot mix asphalt specimens may offer another approach to fabricating specimens and designing mixtures. The first stage of testing resulted in some promising preliminary results. The gyratory compactor gave consistent and reliable results, proving it can compact different RCC mixes. This encouraged the idea of improving the procedure of RCC mixture proportioning. The mix design procedure improvement is based upon two major principles. The first is that the gyratory compactor produces specimens with consistent densities, with a coefficient of variation between 0.66 and 0.99 and a low standard deviation of  $17.3 \text{ kg/m}^3$  (1.08 pcf) to  $24.7 \text{ kg/m}^3$  (1.54 pcf). The second is the increase in strength with the increase of compaction. The compaction effort is applied by the gyratory compactor and can be indicated by a set number of gyrations (Amer 2002).

Organizations such as ASTM, American Concrete Institute (ACI), PCA, and USACE have investigated standards and test methods for RCC. The present research is investigating the mechanical properties of RCC to support the work of some of these organizations. For example, it was found in this research that the splitting tensile strength of RCC specimens prepared using the gyratory compactor was between 8% and 14% of the compressive strength. These results agree with known engineering property relationships for conventional concrete (Amer 2002).

Another area of interest would be to investigate freeze-thaw performance of gyrated RCC specimens and relate that to RCC pavement and dam performance. RCC pavements are widely used in Canada and North America where weather conditions are a major issue, especially during winter. Therefore, the study of freeze-thaw resistance was addressed since it is an important design factor. RCC reacts very well in general under severe cold weather, but this fact has been concluded from long-life performance rather than design or lab evaluations. It would give a much better understanding of the material behavior if a study is made to evaluate the freeze-thaw resistance of RCC pavements through laboratory tests rather than trial and error. To evaluate freeze-thaw, ASTM C-666 is used to measure the deterioration of concrete. There are 300 cycles in the rapid freeze-thaw test where one cycle takes about four hours to be completed. ASTM C-666 allows 36 cycles to be performed at the same time. Therefore, 36 cycles will take up to six days to be completed, which means testing will take a total of eight and a half weeks to be accomplished. Some investigations have been conducted on freeze-thaw resistance, and they gave a wide range of results with different performance ranges (Cortez 1990, Marchand 1990).

## **RESEARCH OBJECTIVES**

Research was divided into three major stages. Stage one was the proof-of-concept stage where the gyratory compactor was successfully used to produce RCC specimens. It was also possible to test these specimens and compare them to field results for actual projects that provided the material used in the research. The second stage dealt with developing a modified RCC mix design procedure using the gyratory compactor with existing procedures. Finally, a study was made in stage three of the freeze-thaw effects on RCC samples produced by the gyratory compactor.

### **Stage 1: Validating the Use of the Gyratory Compactor**

A gyratory compactor was used to duplicate field compaction, using the material and mix designs from industrial paving projects. In order to provide an outline for a valid testing procedure, it was necessary to achieve the following objectives:

- Determine how unconfined compressive strength changes with specimen density (degree of compaction).
- Determine how splitting tensile strength changes with specimen density.
- Determine how specimen's length to height ratio affects unconfined compressive strength.
- Determine how RCC strength develops with specimen age.

- Validate that laboratory specimens have density and strength consistent with field specimens.
- Determine the number of gyrations to select in order to match field density.

The first four objectives were achieved through laboratory testing. To validate the results, it was necessary to compare laboratory results with field properties. This was possible due to having data available for two RCC paving projects in Alabama. Actual materials and mix designs from these two projects were used for the laboratory tests. These are referred to as test sets A and B. A third, smaller, test set C investigated the properties of a dam RCC mix in order to demonstrate wider applicability of the methods. The last two objectives specified earlier for stage one were achieved by comparing strength results of field cores with specimens fabricated in the lab using the same materials. A detailed description of the gyratory compactor used and its operation are available in the references (Amer 2002).

**Test program.** Over 100 specimens were fabricated to evaluate and achieve the previous objectives. The wet density was determined by weighing each specimen in air and water. The gyratory compactor specimens showed very consistent results for strength and density. Test series (A) consisted of 40 specimens tested for strength using a mix design similar to that used for an industrial paving project. Twenty specimens were prepared to study the effect of compaction on strength by comparing specimens compacted with 60, 75, 80, 90, and 100 gyrations to the same height of 150 mm (6 in.). A different mix design from a different industrial paving project was used for test series B. All specimens were compacted to 75 gyrations. The difference between test series A and B was in materials and mix designs, as shown in Table 3.

**Table 3. RCC Mix Designs Used in Stage One**

Mix Design	Cement	Fly Ash	Water	W/CM ratio	Blended Aggregate
Test Series A	252 (425)	89 (150)	125 (210)	0.37	2169 (3656)
Test Series B	326(550)	0	131 (220)	0.40	2067 (3484)
Test Series C	207 (350)	0	128 (215)	0.61	2166 (3650)

Units are in Kg/m<sup>3</sup> (<sup>lb</sup>/yd<sup>3</sup>)

Using field and laboratory results from these two series helped determine the proper number of gyrations to replicate field conditions of compaction and strength. Also, results can be used to investigate repeatability, to determine the effect of compaction on strength, and to observe strength development. Test series B had 20 specimens rather than 40 because test series A had already determined an appropriate number of gyrations to replicate field conditions. It was discovered that a lower number of gyrations replicates, to some extent, compaction in the field. In test series B, the specimens were compacted with 75 gyrations rather than both 75 and 100.

Test series C investigated the mix design and materials used for a dam construction project. The purpose was to have an additional comparison between field and laboratory results using a dam mix. This mix had a much higher aggregate proportion

compared to cementitious materials. The water-cement ratio was also different – 0.60 compared to 0.40 for test series A and B. Table 4 summarizes the number of cylinders produced with the gyratory compactor, the different test series, and the purpose of testing.

Results obtained from all three series show that the gyratory compactor produced specimens with consistent density and strength. These results are shown in the research results section. Because this was the first time the gyratory compactor was used to fabricate concrete specimens, gyrations ranging between 50 and 100 were applied during the fabricating period to determine which number would best represent field conditions. Applying 75 gyrations was found to better represent field conditions, which meant that 100 gyrations were more than were needed.

**Table 4. Summary of Test Specimens Fabricated by the Gyratory Compactor – Stage One**

Test Series	Application	Specimens Produced	Number of Gyrations	Purpose of Test
POC	Trial	2	50	Proof of Concept (POC) – Compressive and splitting tensile strength tests
		2	75	
		8	100	
A	Pavement	10	75	Compressive strength for 1, 3, 7, 14, and 28 days
		10	100	
		10	75	Splitting tensile strength for 1, 3, 7, 14, and 28 days
		10	100	
Modified B	Pavement	4	60	To study the effect of different compaction efforts on compressive and tensile strength after 28 days. (Strength versus number of gyrations)
		4	75	
		4	80	
		4	90	
		4	100	
A	Pavement	8	75	Test specimens with different heights for strength after 28 days
B	Pavement	10	75	Compressive strength for 1, 3, 7, 14, and 28 days Splitting tensile strength for 1, 3, 7, 14, and 28 days
		10	75	
C	Dam	3	100	Compressive strength at 28 days Splitting tensile at 28 days
		3	100	

## Stage 2: RCC Modified Mix Design Procedure

The next stage was to develop the theoretical framework for a modified mix design procedure using the gyratory compactor. The traditional methods discussed previously provide properties at a single level of compactive effort. In contrast, it is possible to vary the degree of compaction using the gyratory compactor. A second objective of the research was to investigate the variation of RCC properties with water-cement ratio and compaction level. For this investigation, the amount of water and the aggregate gradation were kept constant, and the amount of cement was varied. Aggregates used came from an actual project that had been successfully constructed and is performing according to design. The main feature that distinguishes the gyratory compactor is the compacting effort produced by the number of gyrations. The number of gyrations and the unit weight of specimens were important variables in this investigation. The research program investigated ways to:

- Create example design curves to help engineers design an RCC mixture.
- Determine the water-cement ratio for the mix by determining the number of gyrations most appropriate to achieve the desired strength.
- Document how unit weight increases with a higher number of gyrations.
- Compare results to previous work with the gyratory compactor to verify the theory.

These were accomplished by testing specimens from three different mix designs compacted to three different levels of compaction (number of gyrations). The mix designs had different water-cement ratios. Comparison between the achieved results and previous work from stage one show low variability, as will be seen in the results section.

**Test program.** The gyratory compactor was used to fabricate 18 specimens that were tested in splitting tension (ASTM C 496 2000) after 14 days of curing. The matrix proposed for the mix design consists of nine points representing the 18 cylinders, with two cylinders for each point. The design curves have three curves where each curve is represented by six points. Water-cement ratios used were 0.40, 0.45, and 0.50, and represent the range of common practice in RCC mix designs. Numbers of gyrations applied were 50, 65, and 90. Previous work concluded that 60 gyrations gave a compactive effort that simulates field compaction (Amer 2003). Mixture proportions are shown in Table 5.

**Table 5. RCC Mixture Proportions Investigated for Design Curves – Stage Two**

Mix Design	Cement (kg/m <sup>3</sup> ) lb/yd <sup>3</sup>	Water (kg/m <sup>3</sup> ) lb/yd <sup>3</sup>	w/c ratio	Blended Aggregate (kg/m <sup>3</sup> ) lb/yd <sup>3</sup>
Curve 1	(326) 550	(131) 220	0.40	(2,067) 3,484
Curve 2	(290) 489	(131) 220	0.45	(2,097) 3,535
Curve 3	(261) 440	(131) 220	0.50	(2,123) 3,578

Also, compaction above 65 gyrations gave similar results, since a higher number of gyrations provided little additional compaction. More specimens with a lower number of gyrations will be fabricated in the future to further validate the outcome of this research. It is expected that efficient compaction levels can be reached with a lower number of gyrations, around 60. Unit weights for lab specimens were compared to field density. Unit weight has been found to be an excellent indicator of strength for RCC (Delatte 2003). Finally, six modified Proctor tests were performed to compare Proctor density results with the specimens produced by the gyratory compactor.

### Stage 3: Freeze-Thaw Durability of Gyratory Compacted RCC

The main objective for this section was to evaluate how freeze-thaw resistance is affected by the water-cement ratio and the degree of compaction. The laboratory investigation included the following objectives:

- Determine the effect of various densities on freeze-thaw resistance.
- Evaluate the resistance of RCC samples produced with the gyratory compactor through cycles of freeze and thaw.
- Determine the effect of various water-cement ratios on freeze-thaw resistance.
- Compare durability of RCC pavements and dams.
- Evaluate the mass loss resulting from freeze-thaw cycles.

**Test program.** Two modified mix designs were used for the purpose of this research. Both of them are actual projects mix designs from Vance, Alabama, and Prairie Creek, Texas. The first involved a pavement at the Mercedes Plant, whereas the other is for a dam. Twelve specimens were fabricated for each mix design series. Three water-cement ratios of 0.40, 0.45, and 0.50 were used. Therefore, there were three sets of different water-cement ratios with four specimens in each set. In each set of four specimens, two were compacted to 50 gyrations while the other two were compacted to 90. For the dam specimens, the same number of sets and specimens was produced, but with water-cement ratios of 0.50, 0.60, and 0.70. Table 6 shows the mix designs used with different water-cement ratios for the pavement series, while Table 7 gives the mix design proportions for the dam series.

**Table 6. Pavement Series Mix Proportions – Stage Three**

Mix Design	Mix 1	Mix 2	Mix 3
W/C Ratio	0.40	0.45	0.50
Water $\text{kg/m}^3$ ( $\text{lb/yd}^3$ )	131 (220)	131 (220)	131 (220)
Cement $\text{kg/m}^3$ ( $\text{lb/yd}^3$ )	326 (550)	290 (489)	261 (440)
Pre-blended Aggregate $\text{kg/m}^3$ ( $\text{lb/yd}^3$ )	2067 (3484)	2097 (3535)	2123 (3578)

**Table 7. Dam Series Mix Proportions – Stage Three**

Mix Design	Mix 1	Mix 2	Mix 3
W/C Ratio	0.50	0.60	0.70
Water kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	151 (255)	151 (255)	151 (255)
Cement kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	303 (510)	252 (425)	216 (364)
Manufactured Sand kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	266 (448)	573 (966)	583 (983)
# 67 Stone kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	1367 (2304)	1398 (2357)	1419 (2391)

Freeze-thaw testing was conducted following ASTM C 666 (ASTM 1992). Specimens were evaluated and inspected every 30 to 36 freeze-thaw cycles, up to 300 cycles, unless the specimen failed earlier. Specimens with higher densities and lower water-cement ratios had better resistance against freeze-thaw deterioration (Storey 2004). Materials used for the pavement series were as follows. Aggregates are a blend of #78 coarse particles and #821 manufactured fine particles of crushed limestone provided by Vulcan Materials in Alabama blended specially for RCC projects. Table 8 shows the gradation of the aggregates used.

**Table 8. Mercedes Project Aggregate Gradation – Pavement Series**

Sieve Size	% Passing	Typical Maximum and Minimum % Passing Limits	
25.00 mm (1 in.)	100	100	100
19.00 mm (¾ in.)	100	83	100
12.50 mm (½ in.)	98	72	93
9.50 mm (⅜ in.)	89	62	82
4.75 mm (#4)	66	51	69
2.36 mm (#8)	50	38	56
1.18 mm (#16)	33	28	46
600 µm (#30)	21	18	36
300 µm (#50)	14	11	27
150 µm (#100)	6	6	18
75 µm (#200)	2	2	8

Fineness modulus was 4.21 with a nominal maximum size aggregate of 12.50 mm (½ in.). Cement type was Type I/II portland cement. The mix design is shown in Table 6. The dam series followed the mix design and material type used in the Prairie Creek Detention dam in Texas. The dam is used to retain water during heavy rainfalls. Design information and the mix were taken from the PCA Design Manual for Small RCC Dams (Schnabel 2003). Aggregates used were different than the one specified where a #67 stone and natural sand were used instead. Aggregate sieve analyses indicated a mix of 70% #67 stone and 30% natural sand with a fineness modulus of 3.70 for the stone and



1.94 for the sand. The Nominal Maximum Size Aggregate (NMSA) was 19 mm ( $\frac{3}{4}$  in.); typical NMSA for dams is three in. (Storey 2004, USACE 2000). Figure 4 shows the aggregate gradation used for this research along with the maximum and minimum specifications for the dam project.

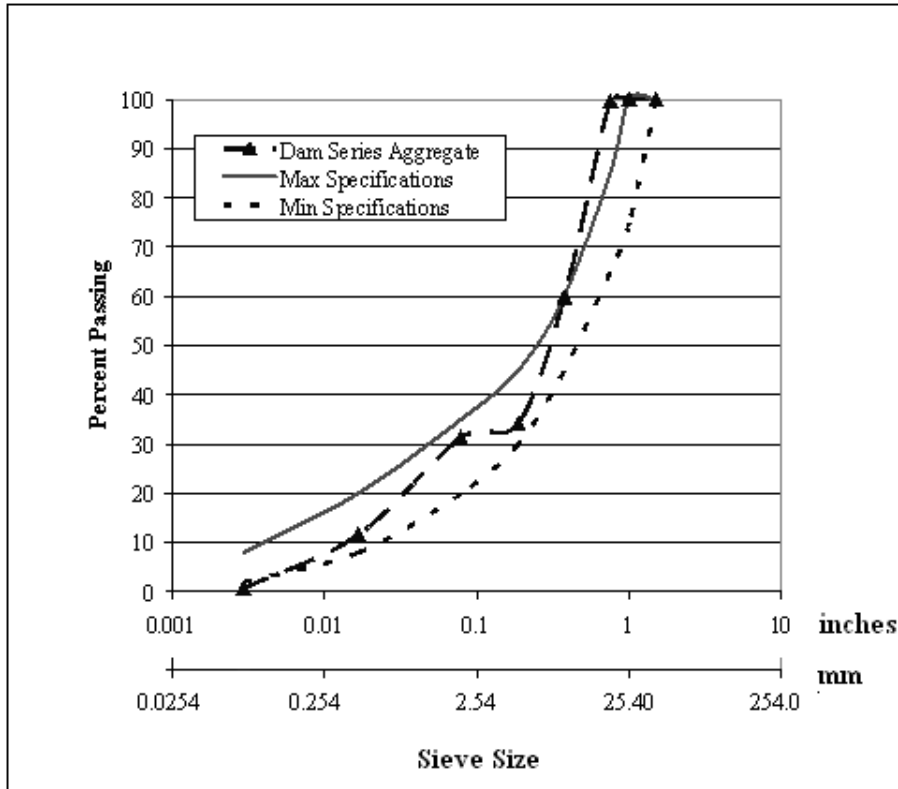


Figure 4. Dam series aggregate gradation.

Other parameters available for the Prairie Creek dam project were a water-cement ratio of 0.88 and a specified unconfined compressive strength of 25 MPa (3600 psi) at 28 days. Original mixture proportions are shown in Table 9.

Table 9. Mix Design Proportions for Prairie Creek Dam Project

Material	Weight kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	Percent of Weight
Cement	173 (291)	6.96
Fine Aggregate	972 (1638)	39.14
Coarse Aggregate	1187 (2001)	47.81
Water	151 (255)	6.09

## RESEARCH RESULTS

### Stage One: Gyratory Compactor Validation Results

A proof of concept was necessary to validate the use of the gyratory compactor to fabricate RCC specimens. Different test series were used to determine the proper number of gyrations, which reflects the compaction effort. The first series consisted of specimens compacted to 40 gyrations. These specimens suffered edge chipping when extracted from the gyratory compactor because they were not dense enough. Also, some 40 gyration samples broke down in the water tank during curing. The conclusion was to increase the compaction effort, or in other words, the number of gyrations. The next series was compacted to 50 gyrations. The surface had the same rough texture, but samples were denser. Therefore, the minimum acceptable number of gyrations should be between 45 and 50 in order to avoid breakage or chipping during specimen removal and handling.

Obviously, an important parameter is the density of RCC. A theoretical maximum constituent density (TMCD) can be considered as the maximum possible density of the RCC constituent materials. This is possible when all air voids are removed from the mixture. The TMCD may be calculated using the percentages of all components in the mix design and their specific gravities in the following equation:

$$\text{TMCD} = \frac{P_c + P_f + P_{ca} + P_{fa} + P_w}{\frac{P_c}{RD_c} + \frac{P_f}{RD_f} + \frac{P_{ca}}{RD_{ca}} + \frac{P_{fa}}{RD_{fa}} + \frac{P_w}{RD_w}} \quad \text{Equation (1)}$$

where P stands for percentage of the total weight of materials used in the mix, and RD is the relative density of each constituent material. Subscripts c, f, ca, fa, and w represent cement, fly ash, coarse aggregate, fine aggregate, and water, respectively. This equation is adapted from hot mix asphalt volumetric mix design (Delatte and Amer 2003). TMCD could exceed 100% due to concrete shrinkage during the curing process. The maximum unit weight may be calculated using the previous TMCD value in the following equation:

$$\gamma = \text{TMCD} \times \gamma_w \quad \text{Equation (2)}$$

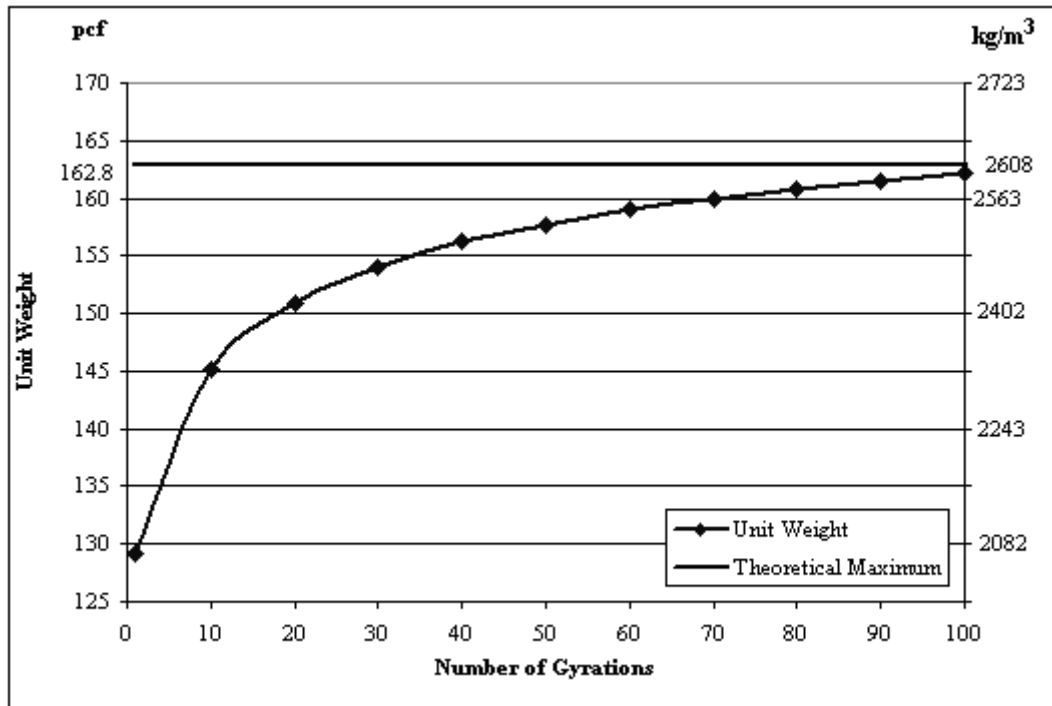
where  $\gamma$  is the maximum unit weight, TMCD is the theoretical maximum constituent density, and  $\gamma_w$  is the unit weight of water, which is equal to 1000 kg/m<sup>3</sup> (62.4 pcf). Density results were very consistent with a coefficient of variation between 0.66 and 0.99, and standard deviation values between 17.3 and 24.7 kg/m<sup>3</sup> (1.08 and 1.54 pcf). Table 10 summarizes the density results for RCC specimens produced by the gyratory compactor.

**Table 10. Strength Results for Specimens with Different Number of Gyration (Amer 2002)**

Number of Gyration	Unit Weight pcf (kg/m <sup>3</sup> )		Splitting Tensile psi (kPa)		Unit Weight pcf (kg/m <sup>3</sup> )		Compressive Strength psi (MPa)	
	60	158.9	2545.42	794	5475	158.3	2535.33	6740
60	159.5	2555.03	789	5440	158.5	2538.54	6680	46
75	160.8	2575.86	809	5578	158.5	2538.54	6950	48
75	159.6	2556.63	811	5592	159.9	2560.96	7010	48
80	158.0	2531.00	844	5819	159.6	2556.15	6820	47
80	159.2	2550.22	826	5695	160.3	2567.36	7120	49
90	160.1	2564.64	851	5868	159.8	2559.36	7000	48
90	160.3	2567.85	845	5826	160.4	2568.97	6700	46
100	159.9	2561.44	846	5833	160.7	2573.77	7120	49
100	159.7	2558.23	838	5778	160.0	2562.56	7200	50

All results were tested at 28 days.

Figure 5 shows the trend of the increase in the unit weight with the increase in the number of gyrations.

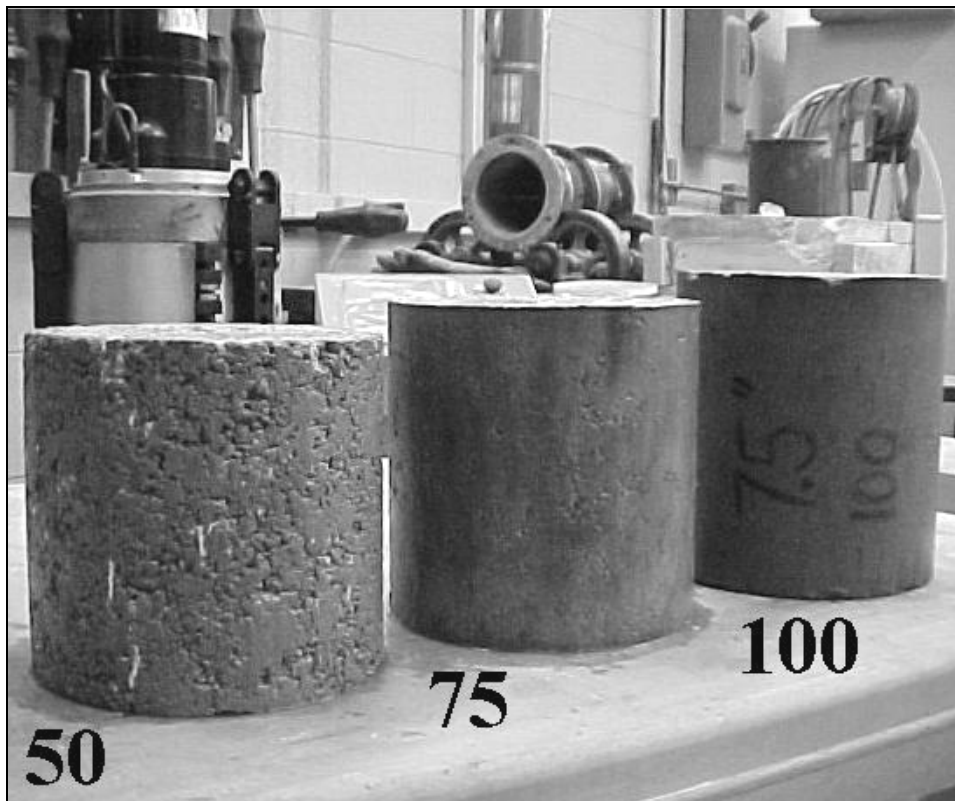


**Figure 5. Unit weight versus number of gyrations, test series A.**

However, some samples had less density with more gyrations. There were two possible reasons. First, the Brovold gyratory compactor has to be greased each time a specimen is made due to the water seeping from samples as they are compacted. Each sample took approximately ten minutes to prepare, which meant different hydration levels between early and late samples. Second, there was no order in which samples were

compacted. To achieve the desired trend of having higher strength with a higher number of gyrations, a more controlled system of fabrication may be followed in the future with more samples and a lower number of gyrations. Also, each group of gyration number will be fabricated from a smaller laboratory mix to ensure having the same hydration and workability conditions. Last, a more efficient gyratory compactor is recommended to reduce time of fabrication where greasing is not a hindrance. Such a gyratory compactor does exist and is available from Pine Inc. The more efficient compactor has been obtained by Cleveland State University for RCC research work.

As expected, the unit weight increases rapidly at the beginning when the material is still relatively loose. As the sample becomes denser, the rate of increase in unit weight becomes smaller until it nearly flattens out. Density levels differ according to the number of gyrations applied. Figure 6 shows the difference in surface texture between specimens compacted to different levels of compaction. By inspection, the appearance of RCC in the field generally follows the texture of specimens compacted between 50 and 75 gyrations. Trials have been carried out to test specimens with a lower number of gyrations, down to 30 gyrations. It was very hard to remove specimens with a low number of gyrations from the gyratory compactor due to the specimens not being dense enough. However, when using lower water-cement ratios, samples with 20 and 30 gyrations were fabricated successfully and tested for strength.



**Figure 6. Different surface textures for different numbers of gyrations.**

## Stage Two: Modified Mix Design and Design Curve Results

Results of the specimens fabricated using the gyratory compactor are shown in Tables 11 through 13 and in Figure 7. It can be concluded from the results, as indicated previously, that strength increases with increasing density and with decreasing water-cement ratio.

**Table 11. Splitting Tensile Results for W/C Ratio of 0.40**

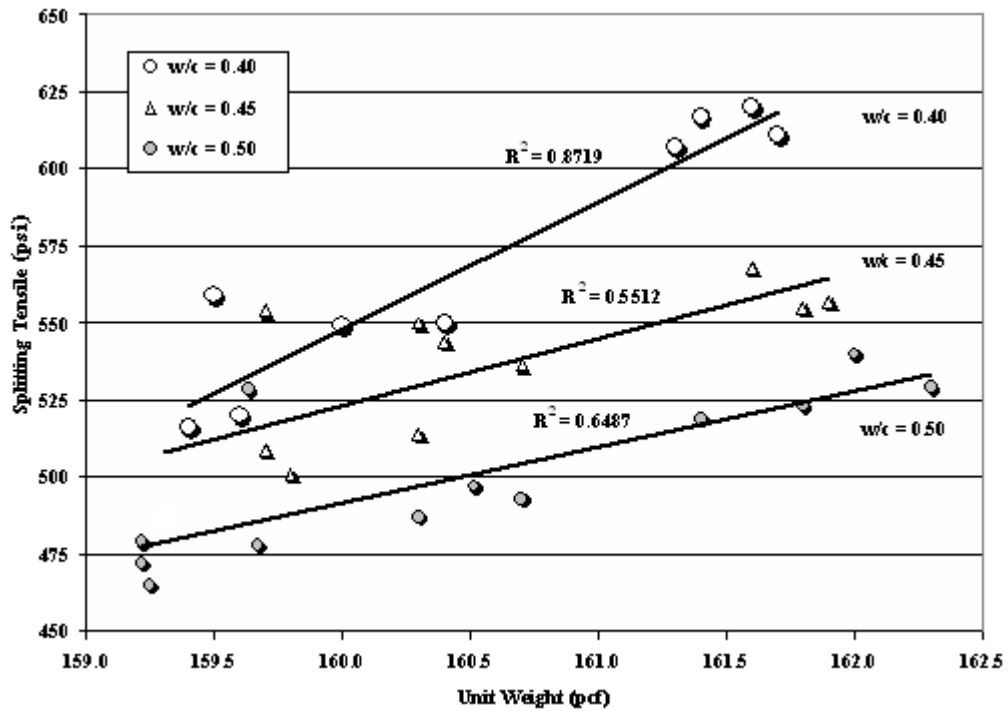
Water-Cement Ratio 0.40						
Sample	No. of Gyration	Unit Weight		TMCD %	Splitting Tensile	
		pcf	(kg/m <sup>3</sup> )		psi	(kPa)
1	50	159.6	2556.55	97%	520	3,590
2	50	159.4	2553.34	97%	516	3,560
3	65	160.0	2562.95	98%	549	3,790
4	65	159.5	2554.94	97%	559	3,850
5	65	160.4	2569.36	98%	550	3,790
6	65	160.4	2569.36	98%	550	3,790
7	90	161.6	2588.58	99%	620	4,270
8	90	161.7	2590.19	99%	611	4,210
9	90	161.4	2585.38	98%	617	4,250
10	90	161.3	2583.78	98%	607	4,190

**Table 12. Splitting Tensile Results for W/C Ratio of 0.45**

Water-Cement Ratio 0.45						
Sample	No. of Gyration	Unit Weight		TMCD %	Splitting Tensile	
		pcf	(kg/m <sup>3</sup> )		psi	(kPa)
1	50	159.8	2559.75	98%	501	3,450
2	50	159.7	2558.15	98%	509	3,510
3	50	160.3	2567.76	98%	514	3,540
4	65	160.4	2569.36	98%	544	3,750
5	65	160.7	2574.17	98%	536	3,700
6	65	160.3	2567.76	98%	550	3,790
7	65	159.7	2558.15	98%	554	3,820
8	90	161.6	2588.58	99%	568	3,920
9	90	161.9	2593.39	99%	557	3,840
10	90	161.8	2591.79	99%	555	3,830

**Table 13. Splitting Tensile Results for W/C Ratio of 0.50**

Water-Cement Ratio 0.50						
Sample	No. of Gyration	Unit Weight		TMCD %	Splitting Tensile	
		pcf	(kg/m <sup>3</sup> )		psi	(kPa)
1	50	159.7	2558.15	98%	478	3,300
2	50	159.3	2551.74	97%	472	3,250
3	50	159.3	2551.74	97%	479	3,300
4	65	159.6	2556.55	98%	528	3,640
5	65	160.3	2567.76	98%	487	3,360
6	65	160.5	2570.96	98%	497	3,430
7	65	160.7	2574.17	98%	493	3,400
8	90	161.8	2591.79	99%	523	3,600
9	90	160.4	2569.36	99%	519	3,580
10	90	162.0	2594.99	99%	540	3,720
11	90	162.4	2601.40	99%	529	3,650



**Figure 7. Splitting tensile strength versus unit weight (1 psi = 6.89 kPa, 1 pcf = 16.0 kg/m<sup>3</sup>).**

Due to using a finer aggregate than that used in earlier mixes, values of the splitting tensile strength are lower than those achieved on previous testing sessions. The maximum aggregate size was 12.7 mm (½ in.), compared to 19.0 mm (¾ in.) and 25.4 mm (1 in.) MSA often used in RCC pavement construction. The difference, however, is less than 689 kPa (100 psi), which keeps the results within the acceptable ranges of strength. Results from the three sets tested can be summarized as follows:

Set One:

- Set one had a 0.40 water-cement ratio and was compacted to 50, 65, and 90 gyrations.
- Strength ranged between 3,790 kPa and 4,550 kPa (550 and 660 psi). This range takes into account other strength results obtained from earlier test sessions in stage one in addition to stage two.
- Unit weight results increase with an increasing number of gyrations. Unit weight range is between 2,550 kg/m<sup>3</sup> and 2,590 kg/m<sup>3</sup> (159 and 162 pcf).

Set Two:

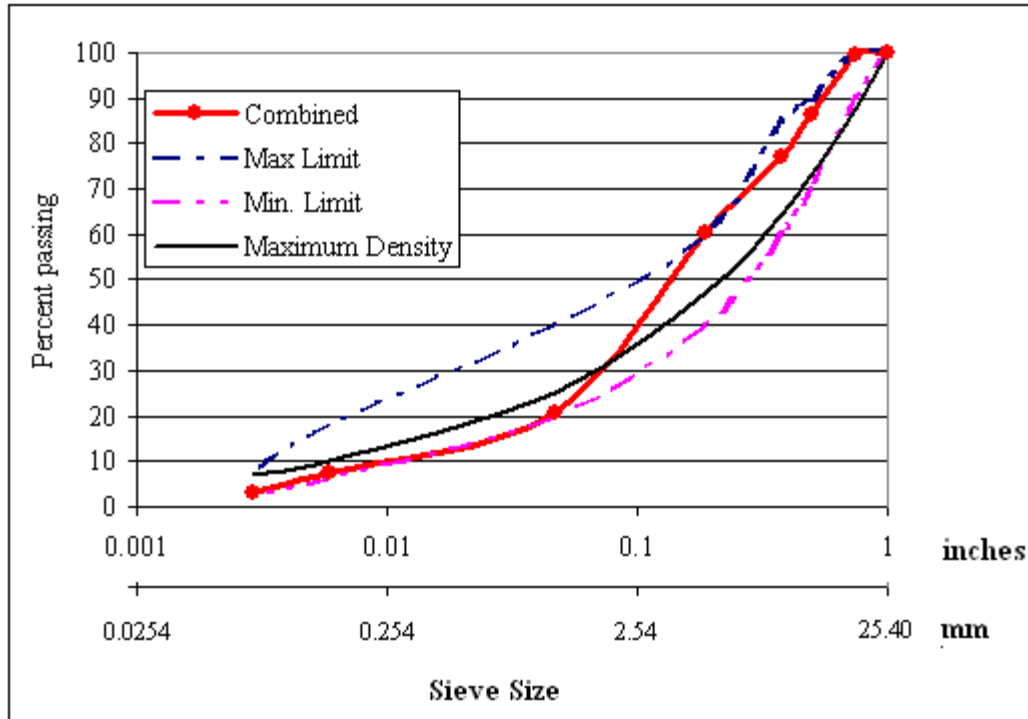
- The second set had a 0.45 water-cement ratio.
- Strength ranged between 3,510 kPa and 3,930 kPa (510 and 570 psi).
- The unit weight range was between 2,560 kg/m<sup>3</sup> and 2,580 kg/m<sup>3</sup> (160 and 161 pcf).

Set Three:

- The last set had a 0.50 water-cement ratio.
- Strength ranged between 3,380 kPa and 3,510 kPa (490 and 510 psi), which is lower than the two previous sets. This is expected when increasing the water-cement ratio.
- The unit weight ranges are between 2,550 kg/m<sup>3</sup> and 2,580 kg/m<sup>3</sup> (159 and 161 pcf).

In summary, with a higher number of gyrations and a lower water-cement ratio, the density and strength of the specimen will increase. The increase is between 280 and 689 kPa (40 and 100 psi) depending on the water-cement ratio.

For the mixes evaluated in this research, about 75% to 85% of RCC is aggregate. Therefore, it is important to select a well-graded aggregate that will perform adequately. To achieve this, aggregates used in this research were brought from an RCC industrial pavement project at the Mercedes-Benz Plant located near Vance, Alabama. Figure 8 shows the gradation for the aggregates used compared to typical specifications for RCC.



**Figure 8. Combined aggregate gradation for RCC.**

The aggregate consisted of a preblended combination of manufactured fine and #78 coarse particles. The particles were made up of crushed limestone with a fineness modulus of 4.21. The aggregate has an NMSA of 12.7 mm (½ in.). The research aggregate is finer than the typical specification for RCC. Finer aggregate produces a smoother surface and is easier to compact. Strength, however, may be lower.

**Modified Proctor results.** Six specimens were tested for modified Proctor and gave an average dry density of 2,347 kg/m<sup>3</sup> (146.5 pcf) with a standard deviation of 37.6 kg/m<sup>3</sup> (2.35 pcf) and a coefficient of variation of 1.6 %. The corresponding wet density was 2,470 kg/m<sup>3</sup> (154.1 pcf) at 5.2% moisture by weight. This means that these specimens' densities are 103% and 105% of the modified Proctor density. These values do not necessarily represent the optimum moisture content, as the tests were done with one moisture content. This is acceptable as previous research shows that with excellent field compaction, densities can reach approximately 2,550 kg/m<sup>3</sup> (159 pcf) that is 103% of modified Proctor (Amer 2002).

### **Stage Three: Freeze-Thaw Durability of Gyated RCC Specimens**

Prisms are used when testing for freeze-thaw durability. The gyratory compactor can only produce 6-in. cylinders, which means prisms have to be cut from those cylinders. The typical sizes for prisms as specified in ASTM C 666 are three and five in. for the width and depth, and between 11 and 16 in. in length. Due to having a maximum length of 7.5 in. for the gyated cylinder, the length range cannot be achieved. However, the depth and width were according to standards with 3 x 4 in. A Norton stationary wet concrete saw



was used along with fabricated jigs to saw the prisms. Figure 9 shows the jigs with one side of the specimen sawn.



**Figure 9. Photo of jigs with one side sawn of an RCC specimen.**

All specimens were cut after 14 days of fabrication in the gyratory compactor. Specimens were cured for 7 days in a water tank. After cutting the specimen from all four sides, the final product is a 3 x 4-in. prism. Figure 10 shows the finished prisms in the freezer to go through the freezing cycle. The length varied from one specimen to the other, depending on the cylinder's height achieved from compaction. In other words, the length of the prism is the final height of the cylinder prepared in the gyratory compactor. Table 14 gives the final dimensions for all prisms.

The measurement of the unit weight is essential because of its relation to strength. As seen in Table 15, the specimens with 90 gyrations had higher unit weight than those with 50 gyrations. It was also noted that as the water-cement ratio decreased, the unit weight decreased. This is the reason why the unit weights of the pavement series had larger values than the dam series, due to having more cement with the lower water-cement ratio.

**Table 14. Measurements of RCC Test Specimens (Storey 2004)**

Specimen ID	Weight		Length		Width		Depth	
	lb	kg	in.	(mm)	in.	(mm)	in.	(mm)
1	6.73	3.06	6.39	162.31	4.00	101.60	2.99	75.95
2	6.69	3.04	6.19	157.23	4.05	102.87	3.01	76.45
3	6.71	3.05	6.28	159.51	4.02	102.11	3.01	76.45
4	6.34	2.88	5.82	147.83	4.01	101.85	2.99	75.95
5	6.57	2.98	6.31	160.27	4.04	102.62	2.91	73.91
6	6.63	3.01	6.45	163.83	4.01	101.85	3.03	76.96
7	6.69	3.04	6.36	161.54	4.02	102.11	3.01	76.45
8	6.71	3.05	6.37	161.80	4.01	101.85	2.99	75.95
9	6.69	3.04	6.31	160.27	4.05	102.87	3.03	76.96
10	6.71	3.05	6.32	160.53	4.08	103.63	3.07	77.98
11	6.61	3.00	6.29	159.77	4.03	102.36	2.95	74.93
12	6.57	2.98	6.15	156.21	4.02	102.11	3.02	76.71
13	6.94	3.15	6.59	167.39	4.02	102.11	3.01	76.45
14	6.53	2.96	6.19	157.23	4.03	102.36	2.95	74.93
15	6.53	2.96	6.21	157.73	4.05	102.87	2.96	75.18
16	6.62	3.01	6.26	159.00	4.02	102.11	3.01	76.45
17	6.91	3.14	6.76	171.70	3.98	101.09	2.98	75.69
18	6.24	2.83	6.07	154.18	4.05	102.87	2.99	75.95
19	6.82	3.10	6.45	163.83	4.01	101.85	3.01	76.45
20	6.74	3.06	6.33	160.78	4.01	101.85	3.02	76.71
21	6.53	2.96	6.19	157.23	4.12	104.65	3.01	76.45
22	6.68	3.03	6.41	162.81	4.02	102.11	3.02	76.71
23	6.91	3.14	6.54	166.12	4.04	102.62	3.04	77.22
24	6.94	3.15	6.55	166.37	4.04	102.62	3.02	76.71



Figure 10. Prisms in freezer before testing.

Table 15. RCC Specimen Unit Weights for Freeze-Thaw Durability Test

W/C Ratio	SSD		H2O		Unit Weight		Average Unit Weight	
	lbs	kg	lbs	kg	pcf	(kg/m <sup>3</sup> )	pcf	(kg/m <sup>3</sup> )
0.40	6.980	3.169	4.190	1.902	156.1	2500.7	157.0	2515.1
0.40	6.870	3.119	4.156	1.887	158.0	2531.2		
0.40	6.990	3.173	4.249	1.929	159.1	2548.8	159.4	2553.6
0.40	6.520	2.960	3.972	1.803	159.7	2558.4		
0.45	6.885	3.126	4.102	1.862	154.4	2473.5	154.5	2475.1
0.45	6.885	3.126	4.106	1.864	154.6	2476.7		
0.45	6.915	3.139	4.159	1.888	156.6	2508.7	156.7	2510.3
0.45	6.910	3.137	4.159	1.888	156.7	2510.3		
0.50	6.840	3.105	4.069	1.847	154.0	2467.1	154.5	2475.1
0.50	6.855	3.112	4.095	1.859	155.0	2483.1		
0.50	6.905	3.135	4.138	1.879	155.7	2494.3	156.1	2500.7
0.50	6.795	3.085	4.086	1.855	156.5	2507.1		
0.50	7.205	3.271	4.304	1.954	155.0	2483.1	155.3	2487.9
0.50	6.740	3.060	4.037	1.833	155.6	2492.7		
0.50	6.860	3.114	4.120	1.870	156.2	2502.3	156.1	2500.7
0.50	6.915	3.139	4.148	1.883	155.9	2497.5		
0.60	7.290	3.310	4.344	1.972	154.4	2473.5	154.6	2476.7
0.60	6.515	2.958	3.889	1.766	154.8	2479.9		
0.60	7.100	3.223	4.251	1.930	155.5	2491.1	155.7	2494.3
0.60	6.970	3.164	4.180	1.898	155.9	2497.5		
0.70	6.565	2.981	3.892	1.767	153.3	2455.9	153.4	2457.5
0.70	6.840	3.105	4.059	1.843	153.5	2459.1		
0.70	7.095	3.221	4.247	1.928	155.5	2491.1	155.5	2491.1
0.70	7.085	3.217	4.243	1.926	155.6	2492.7		

All specimens were tested at 14 days.

**Fundamental frequency testing.** To determine the fundamental frequency for RCC prisms, a Geotest Sonometer was used to convert the voltage into vibrations using a frequency oscillator. Figure 11 shows the sonometer used.



**Figure 11. Sonometer testing device.**

The resulting vibrations help in determining the fundamental resonant frequency of concrete. As the concrete is damaged by the freeze-thaw cycles, it will give a lower frequency that can be measured by the sonometer. According to ASTM C 215, the fundamental transverse vibrations frequency (FTF) was determined as seen in Table 16 on the next page. Other vibration types and detailed schematic drawings of the FTF are available in ASTM C 215 (ASTM C 215, Storey 2004).

In order to measure durability through freeze-thaw testing, some relations need to be found or evaluated. First the dynamic Young's modulus of elasticity was evaluated. It ranges between 3 and 5.5 million psi (20.7 and 37.9 GPa) for RCC dams (USACE 2000). Values in this research came out to be 0.06 and 0.15 million psi (414 and 1,034 MPa), very low compared to typical ranges. Therefore, back calculation was used along with Equation 3 to come up with a 3 million psi Young's modulus of elasticity. This value is associated with a 6488 Hz transverse frequency (Storey 2004).

$$E = C \cdot W \cdot n^2 \quad \text{Equation (3)}$$

From ASTM C 215, C equals  $0.00245 \cdot (L^3 T / bt^3)$  for a prism (L is the length of the specimen in inches; T is a correction factor based on radius of gyration, length of specimen, and Poisson's ratio, approximately 0.20 for RCC; b and t are the dimensions of the cross section in inches); W is the weight of the specimen in pounds; and n is the FTF of the specimen in Hertz (ASTM C 215 1985)

**Table 16. Fundamental Transverse Frequency (FTF) at Each Set of Cycles**

Specimen ID	FTF At 0 Cycles, kHz	FTF At 36 Cycles, kHz	FTF At 70 Cycles, kHz	FTF At 103 Cycles, kHz	FTF At 133 Cycles, kHz	FTF At 166 Cycles, kHz	FTF At 202 Cycles, kHz	FTF At 236 Cycles, kHz	FTF At 268 Cycles, kHz	FTF At 302 Cycles, kHz
1	1.35	1.11	1.36	1.14	1.01	1.07	1.03	1.25	0.93	1.01
2	1.06	1.13	1.23	1.13	1.12	1.11	0.99	0.93	0.90	0.85
3	1.51	1.13	1.01	1.14	1.16	0.90	1.10	1.04	0.99	1.00
4	1.01	1.08	1.31	1.11	0.99	1.23	1.06	1.11	1.00	1.01
5	1.10	1.04	1.39	1.14	1.02	1.19	-	-	-	-
6	1.05	1.09	1.13	1.17	1.18	1.08	1.25	-	-	-
7	1.11	1.02	1.05	1.16	1.06	1.10	0.92	-	-	-
8	1.06	1.06	1.00	1.12	1.12	1.07	0.91	-	-	-
9	1.31	1.19	0.74	1.00	1.15	-	-	-	-	-
10	1.33	1.14	1.14	1.11	1.02	-	-	-	-	-
11	1.15	1.04	1.06	1.13	0.79	-	-	-	-	-
12	1.14	1.02	0.99	1.24	-	-	-	-	-	-
13	1.27	1.03	0.99	1.12	1.07	1.22	1.01	1.17	1.02	1.25
14	1.12	1.11	1.01	1.10	1.14	1.14	1.02	0.97	0.93	0.95
15	1.35	1.33	0.96	1.13	1.12	1.26	0.99	1.10	0.91	1.03
16	1.02	1.12	0.89	1.19	1.15	1.12	0.94	1.04	0.92	1.00
17	1.15	1.14	1.08	1.12	1.18	1.25	-	-	-	-
18	1.21	1.03	1.14	1.05	0.93	1.31	-	-	-	-
19	1.08	1.19	1.00	0.96	1.03	1.23	-	-	-	-
20	1.20	1.06	0.99	0.91	0.94	1.09	-	-	-	-
21	1.13	1.09	1.16	1.09	-	-	-	-	-	-
22	1.11	1.02	1.07	-	-	-	-	-	-	-
23	1.12	1.01	1.10	0.97	-	-	-	-	-	-
24	1.08	1.01	1.15	-	-	-	-	-	-	-

Notes: ( - ) No transverse frequency reading due to specimen failure

To apply the freeze cycles, a Gilson automatic freeze-thaw apparatus was used. Rapid freeze-thaw testing followed the ASTM C 666 procedure. Pictures of this model and details of placing the samples are discussed in detail elsewhere (Storey 2004). The parameters for evaluating the effect of freeze-thaw cycles are weight, length, width, depth, transverse frequency, and visual appearance of prisms. Every 36 cycles or fewer, the cycling ends to take measurements of these parameters after the prisms thaw completely.

Tables 17 and 18 show the first and last data collected for the freeze-thaw testing between 0 and 302 cycles. The rest of the data in between can be found in appendices C and D in (Storey 2004).

**Table 17. Pavement Series Freeze-Thaw Data at 0 Cycles**

S.N.	Weight		Length		Width		Depth		Sonometer Reading (kHz)	Dynamic Modulus of Elasticity (million psi)	
	lb	kg	in	(mm)	in	(mm)	in	(mm)			
1	6.73	3.06	6.39	162.31	4.00	101.60	2.99	75.95	1.35	0.13	0.8964
2	6.69	3.04	6.19	157.23	4.05	102.87	3.01	76.45	1.06	0.07	0.4827
3	6.71	3.05	6.28	159.51	4.02	102.11	3.01	76.45	1.51	0.15	1.0343
4	6.34	2.88	5.82	147.83	4.01	101.85	2.99	75.95	1.01	0.06	0.4137
5	6.57	2.98	6.31	160.27	4.04	102.62	2.91	73.91	1.10	0.08	0.5516
6	6.63	3.01	6.45	163.83	4.01	101.85	3.03	76.96	1.05	0.08	0.5516
7	6.69	3.04	6.36	161.54	4.02	102.11	3.01	76.45	1.11	0.08	0.5516
8	6.71	3.05	6.37	161.80	4.01	101.85	2.99	75.95	1.06	0.08	0.5516
9	6.69	3.04	6.31	160.27	4.05	102.87	3.03	76.96	1.31	0.12	0.8274
10	6.71	3.05	6.32	160.53	4.08	103.63	3.07	77.98	1.33	0.12	0.8274
11	6.61	3.00	6.29	159.77	4.03	102.36	2.95	74.93	1.15	0.09	0.6206
12	6.57	2.98	6.15	156.21	4.02	102.11	3.02	76.71	1.14	0.08	0.5516

\*Visual appearance for all specimens was "original condition"

**Table 18. Pavement Series Freeze-Thaw Data at 302 Cycles**

S.N.	Weight		Length	Width	Depth	Transverse Frequency (kHz)	Visual Appearance
	lb	kg					
13	6.22	2.82	-	-	-	1.01	Major crumbling on ends
14	6.25	2.83	-	-	-	0.85	Major crumbling on ends
15	6.22	2.82	-	-	-	1.00	Major crumbling on ends
16	5.78	2.62	-	-	-	1.01	Major crumbling on ends
17	-	-	-	-	-	-	Specimen Failed
18	-	-	-	-	-	-	Specimen Failed
19	-	-	-	-	-	-	Specimen Failed
20	-	-	-	-	-	-	Specimen Failed
21	-	-	-	-	-	-	Specimen Failed
22	-	-	-	-	-	-	Specimen Failed
23	-	-	-	-	-	-	Specimen Failed
24	-	-	-	-	-	-	Specimen Failed

Note: ( - ) No data available due to specimen failure

The second important relation to be noted is  $P_c$ , which can be calculated at the end of every 36 cycles using Equation 4 (ASTM 1992 b):

$$P_c = \left( \frac{n1^2}{n^2} \right) \cdot 100 \quad \text{Equation (4)}$$

where,  $P_c$  equals the relative dynamic modulus of elasticity, after (c) cycles of freezing and thawing; n equals the fundamental transverse frequency at 0 cycles of freezing and thawing; and n1 equals the fundamental transverse frequency at (c) cycles of freezing and thawing. After calculating  $P_c$ , the samples are placed back in the freeze-thaw machine for additional cycles. This process continues until one the following conditions is met:

- Specimen completes 300 cycles.
- Mass loss reaches 10% or more.
- Relative dynamic modulus of elasticity is at or below 60% of initial modulus.

The last important relation to finalize the freeze-thaw evaluation was calculating the durability factor (DF) for each test specimen. This is achieved using Equation 5 found in ASTM C 666 (ASTM 1992 b):

$$DF = \frac{(P \cdot N)}{M} \quad \text{Equation (5)}$$

Where, DF equals the durability factor of the test specimen; P equals the relative dynamic modulus of elasticity at N cycles, percent; N equals the number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less; and M equals the specified number of cycles at which the exposure is to be terminated

Finally, the relative dynamic modulus of elasticity (RDME) was calculated using Equation 4. Tables 19 and 20 show the results that compare the RDME values for different mixes. Results were not consistent for some samples, as the RDME percentages seen for sample 1 in Table 19 were 68% then 102% after 36 and 70 cycles respectively, while the visual inspection showed no change.

**Table 19. RDME Values for the Pavement Series**

Specimen ID	RDME After 36 Cycles, %	RDME After 70 Cycles, %	RDME After 103 Cycles, %	RDME After 133 Cycles, %	RDME After 166 Cycles, %	RDME After 202 Cycles, %	RDME After 236 Cycles, %	RDME After 268 Cycles, %	RDME After 302 Cycles, %
1	67.6	101.5	71.3	56.0	62.8	58.2	85.7	47.5	56.0
2	113.6	134.6	113.6	111.6	109.7	87.2	77.0	72.1	64.3
3	56.0	44.7	57.0	59.0	35.5	53.1	47.4	43.0	43.9
4	114.3	168.2	120.8	96.1	148.3	110.1	120.8	98.0	100.0
5	89.4	159.7	107.4	86.0	117.0	-	-	-	-
6	107.8	115.8	124.2	126.3	105.8	141.7	-	-	-
7	84.4	89.5	109.2	91.2	98.2	68.7	-	-	-
8	100.0	89.0	111.6	111.6	101.9	73.7	-	-	-
9	82.5	31.9	58.3	77.1	-	-	-	-	-
10	73.5	73.5	69.7	58.8	-	-	-	-	-
11	81.8	85.0	96.6	47.2	-	-	-	-	-
12	80.1	75.4	118.3	-	-	-	-	-	-

Note: ( - ) No data due to specimen failure



**Table 20. RDME Values for the Dam Series**

Specimen ID	RDME After 36 Cycles, %	RDME After 70 Cycles, %	RDME After 103 Cycles, %	RDME After 133 Cycles, %	RDME After 166 Cycles, %	RDME After 202 Cycles, %	RDME After 236 Cycles, %	RDME After 268 Cycles, %	RDME After 302 Cycles, %
13	65.8	60.8	77.8	71.0	92.3	63.2	84.9	64.5	96.9
14	98.2	81.3	96.5	103.6	103.6	82.9	75.0	68.9	71.9
15	97.1	50.6	70.1	68.8	87.1	53.8	66.4	45.4	58.2
16	120.6	76.1	136.1	127.1	120.6	84.9	104.0	81.4	96.1
17	98.3	88.2	94.9	105.3	118.1	-	-	-	-
18	72.5	88.8	75.3	59.1	117.2	-	-	-	-
19	121.4	85.7	79.0	91.0	129.7	-	-	-	-
20	78.0	68.1	57.5	61.4	82.5	-	-	-	-
21	93.0	105.4	93.0	-	-	-	-	-	-
22	84.4	92.9	-	-	-	-	-	-	-
23	81.3	96.5	75.0	-	-	-	-	-	-
24	87.5	113.4	-	-	-	-	-	-	-

Note: ( - ) No data due to specimen failure

Tables 21 and 22 show the values obtained for the durability factor based on ASTM C 666. The DF value will be zero if the specimen failed before completing 300 cycles.

**Table 21. Durability Factors for the Pavement Series Specimens**

Specimen ID	Number of Cycles at which RDME reaches 50 %, or 300 Cycles	Number of Cycles Expected to be Completed	Durability Factor
1	268	300	42
2	300	300	64
3	70	300	10
4	300	300	98
5	166	300	65
6	202	300	95
7	202	300	46
8	202	300	50
9	70	300	7
10	133	300	26
11	133	300	21
12	103	300	41

**Table 22. Durability Factors for the Dam Series Specimens**

Specimen ID	Number of Cycles at which RDME reaches 50 %, or 300 Cycles	Number of Cycles Expected to be Completed	Durability Factor
13	300	300	97
14	300	300	72
15	268	300	41
16	300	300	96
17	166	300	65
18	166	300	65
19	166	300	72
20	166	300	46
21	103	300	32
22	70	300	22
23	103	300	26
24	70	300	26

The interpretation of the durability factor values is explained as follows (Ragan 1990):

- DF less than 40 is unsatisfactory for freeze-thaw durability.
- DF between 40 and 60 has an unreliable performance in freeze-thaw conditions.
- DF greater than 60 is somewhat satisfactory.

The borderline for mass loss in this research was taken to be 10% where more than this value would mean failure of the specimen. Beyond this percentage, specimens were seen to be brittle and hard to measure. Figure 12 is an example of how severe the mass loss for these specimens can get after 236 cycles. Tables 23 and 24 show the mass loss results for the two types of mixes.



**Figure 12. Dam series specimen number 20 at 236 cycles.**

**Table 23. Mass Loss of Specimens for Pavement Series**

Specimen ID	Mass loss at 36 cycles, %	Mass loss at 70 cycles, %	Mass loss at 103 cycles, %	Mass loss at 133 cycles, %	Mass loss at 166 cycles, %	Mass loss at 202 cycles, %	Mass loss at 236 cycles, %	Mass loss at 268 cycles, %	Mass loss at 302 cycles, %
1	0	0.15	0.15	1.34	1.93	3.12	4.01	6.09	7.58
2	0	0	0.45	0.45	1.2	1.94	3.44	5.08	6.58
3	0	0	0.15	0.15	0.75	1.49	3.73	4.32	7.3
4	0	0	0.16	0.32	0.32	0.79	1.89	4.42	8.83
5	0	0.15	1.07	4.72	7.76	15.68	22.07	-	-
6	0	0.45	1.96	3.17	4.68	14.03	22.62	-	-
7	0	0.45	0.75	1.79	5.53	10.91	20.93	-	-
8	0	0.45	1.04	1.94	4.92	9.24	15.65	-	-
9	0.3	2.24	4.33	10.01	26.76	-	-	-	-
10	0	0.45	2.09	10.58	22.8	-	-	-	-
11	0	0.45	2.27	6.81	12.25	-	-	-	-
12	0	0.46	2.44	11.11	-	-	-	-	-

Note: - Specimen failed, no data to report

**Table 24. Mass Loss of Specimens for Dam Series**

Specimen ID	Mass loss at 36 cycles, %	Mass loss at 70 cycles, %	Mass loss at 103 cycles, %	Mass loss at 133 cycles, %	Mass loss at 166 cycles, %	Mass loss at 202 cycles, %	Mass loss at 236 cycles, %	Mass loss at 268 cycles, %	Mass loss at 302 cycles, %
13	0	0	0.29	0.29	0.58	0.86	1.44	1.73	3.17
14	0.15	0.15	0.46	0.46	0.46	0.61	0.61	0.77	1.38
15	0	0.31	0.46	0.61	0.77	1.07	1.07	1.07	1.23
16	0	0.3	0.3	0.45	0.6	0.6	0.91	0.91	1.21
17	0.14	0.43	0.87	2.17	3.62	6.95	10.85	-	-
18	0	0.32	0.8	0.96	1.92	5.13	16.67	-	-
19	0	0	0.29	1.61	3.37	14.81	-	-	-
20	0	0.59	0.89	1.19	2.08	5.93	17.21	-	-
21	0	0.46	3.22	-	-	-	-	-	-
22	0	0.45	4.49	-	-	-	-	-	-
23	0	0.87	2.17	-	-	-	-	-	-
24	0	1.44	-	-	-	-	-	-	-

Note: - Specimen failed, no data to report

## DISCUSSION

### RCC Properties with Different Number of Gyration

**Strength increase with increasing compaction.** Results obtained throughout the testing stages indicate that strength increases with increasing compaction. Surface texture and strength results also show that a lower number of gyrations may duplicate field conditions better than higher numbers. The increase in density caused a compressive strength increase of 6.3% and a splitting tensile strength increase of 6% when the density increased from approximately 97.5% to 98.3% of the TMCD. This applies to specimens gyrated between 60 and 100 gyrations. Figures 13 and 14 summarize the relation between strength and the number of gyrations (Delatte 2003).

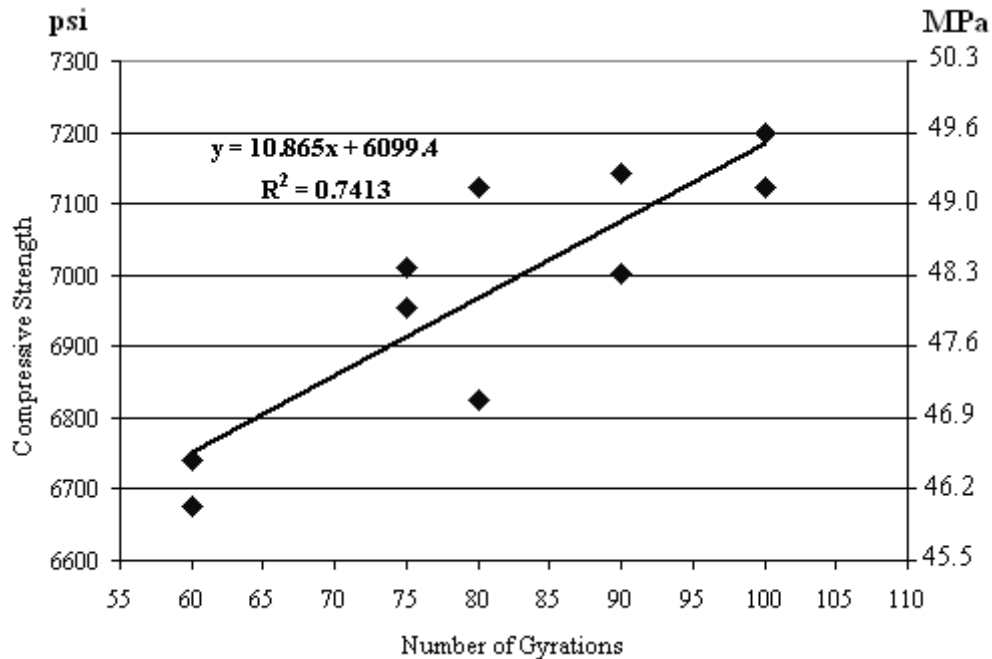
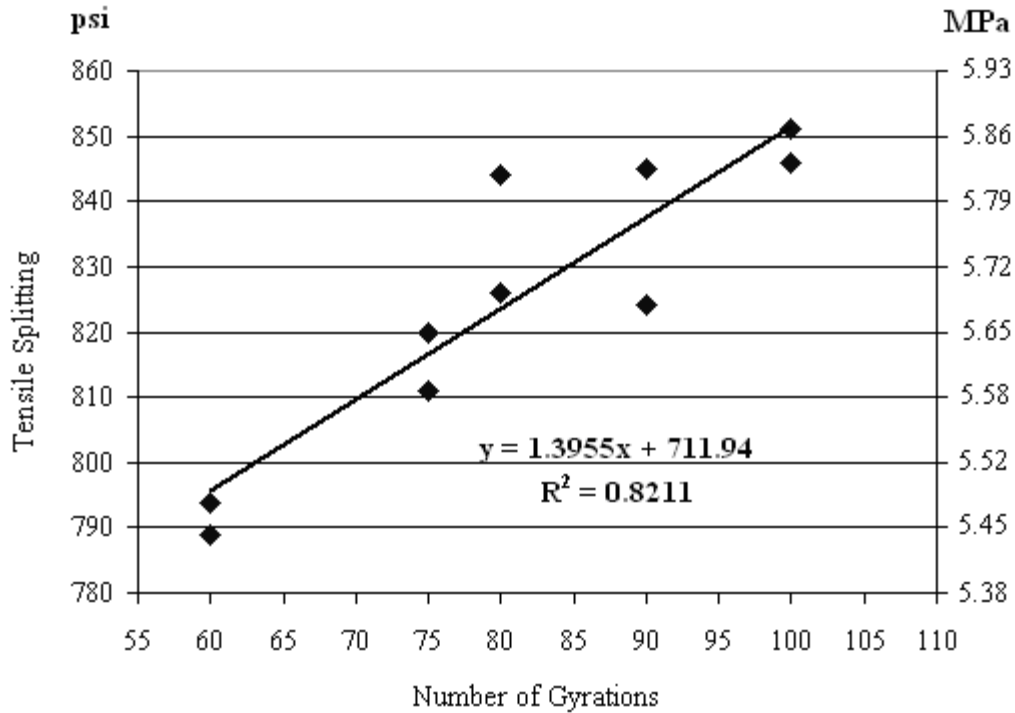


Figure 13. Compressive strength development with an increasing number of gyrations.



**Figure 14. Splitting tensile strength development with an increasing number of gyrations.**

**Strength increase with age.** One of the advantages of using RCC is the ability to carry traffic on the pavement a short time after construction. That is why the compressive and splitting tensile strengths of the RCC were tested at 1, 3, 7, 14, and 28 days. Results are shown in Table 25 and Figures 15 and 16 for specimens compacted to 75 and 100 gyrations. Density and strength are slightly higher for 100 gyrations compared to 75. In each case, the RCC achieved a splitting tensile strength of over 2.07 MPa (300 psi) at one day and over 3.45 MPa (500 psi) at three days (Amer 2002).

**Table 25. Summary of Strength and Density Results**

Age (Days)	Density		Compressive Strength		Density		Splitting Tensile	
	pcf	kg/m <sup>3</sup>	psi	MPa	pcf	kg/m <sup>3</sup>	psi	MPa
Test Series A								
1	161.2	2582.4	2,800	19.3	159.1	2545.9	327	2.3
1	158.8	2544.0	2,680	18.5	161.0	2576.3	365	2.5
3	162.3	2600.0	4,250	29.3	160.1	2561.9	526	3.6
3	162.1	2596.8	4,620	31.9	161.5	2584.3	483	3.3
7	162.1	2596.8	6,050	41.7	162.1	2593.9	625	4.3
7	161.0	2579.2	6,120	42.2	162.9	2606.7	639	4.4
14	161.7	2590.4	6,620	45.6	161.7	2587.5	748	5.2
14	162.4	2601.6	6,600	45.5	161.6	2585.9	754	5.2
28	162.7	2606.5	7,740	53.4	161.9	2590.7	770	5.3
28	162.0	2595.2	7,110	49.0	163.2	2611.5	823	5.7
Test Series B								
1	158.2	2534.4	2020	13.9	157.6	2524.7	340	2.3
1	159.2	2550.4	2070	14.3	158.6	2540.7	354	2.4
3	157.5	2523.2	3750	25.9	159.4	2553.5	440	3.0
3	157.6	2524.8	3960	27.3	157.0	2515.1	476	3.3
7	158.3	2536.0	5290	36.5	158.2	2534.3	544	3.8
7	158.3	2536.0	5440	37.5	157.0	2515.1	560	3.9
14	157.8	2528.0	6030	41.6	157.6	2524.7	610	4.2
14	157.6	2524.8	5800	40.0	157.5	2523.1	648	4.5
28	157.1	2516.7	7030	48.5	157.9	2529.5	688	4.7
28	158.6	2540.8	6990	48.2	158.8	2543.9	705	4.9

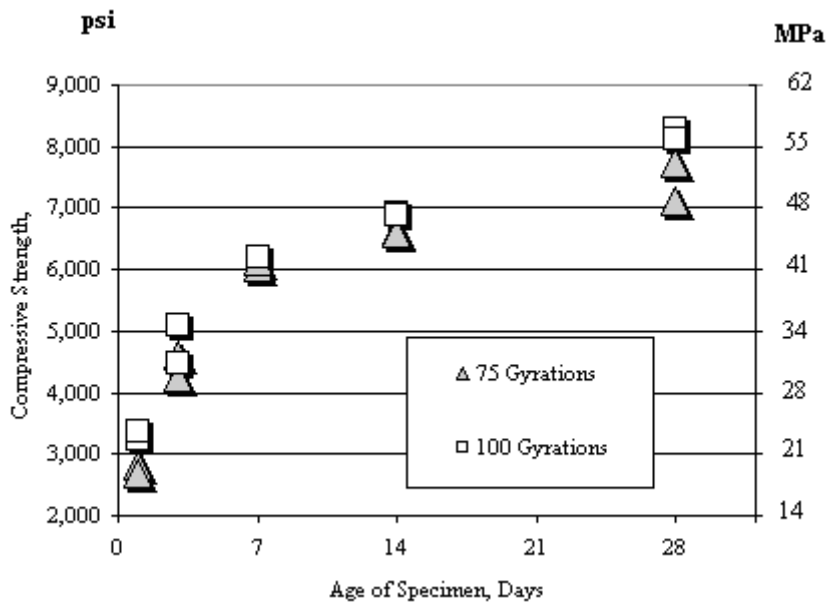


Figure 15. Compressive strength development with age.

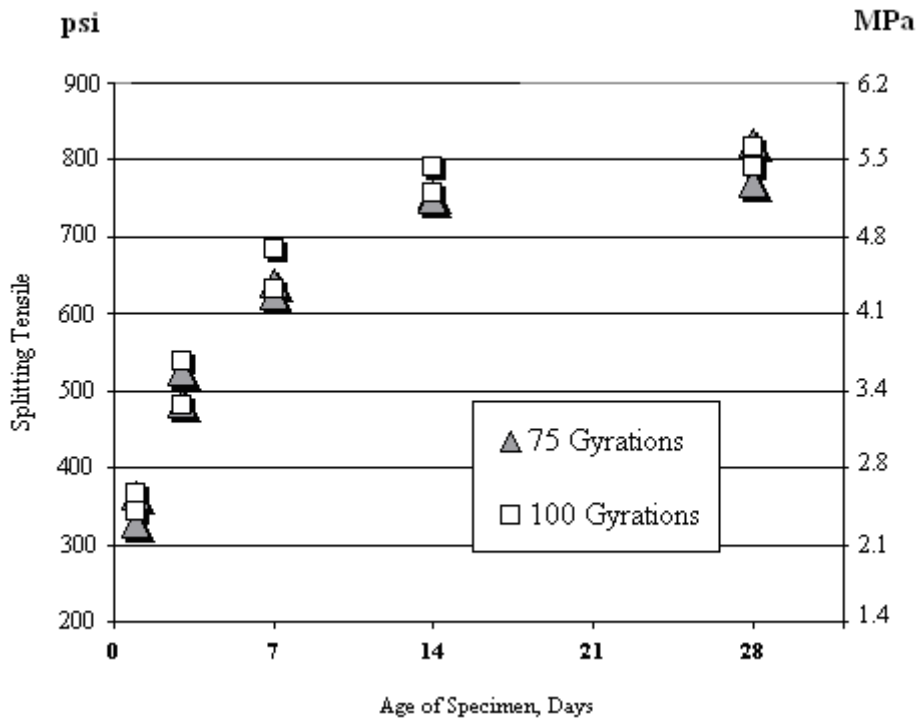
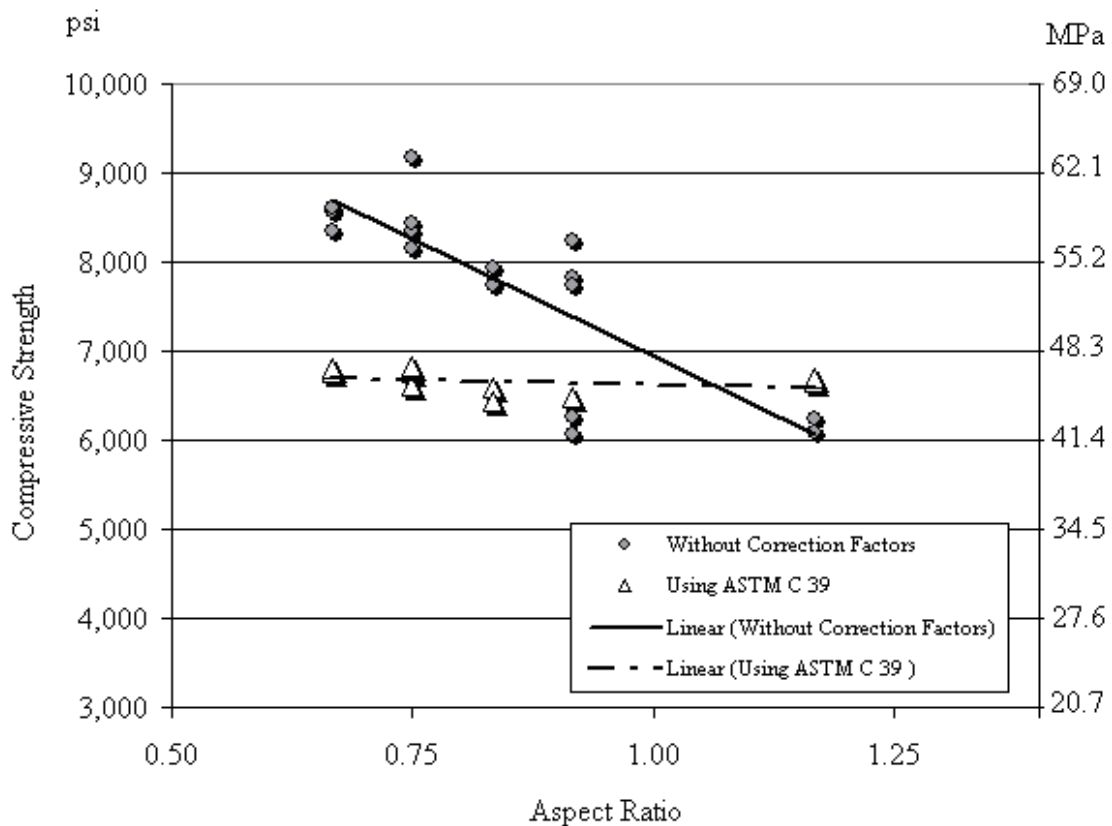


Figure 16. Splitting tensile strength development with age.

**Effect of length to height ratio on strength.** For unconfined compressive strength testing, concrete cylinders typically have a length to height ratio of two. ASTM C 39 provides reduction factors for aspect ratios between 1 and 1.8 (USACE 2000). The gyratory compactor is typically used to produce hot mix asphalt specimens with a length to height ratio of less than one. For hot mix asphalt, the length to height ratio is of no consequence, since the specimens are not tested for strength.

With the compactor used in this research, the maximum practical length to height ratio is approximately 1.17, unless the specimen is made in two layers. Therefore, specimens with varying length to height ratios were fabricated to investigate the appropriateness of the ASTM C 39 reduction factors. Figure 17 shows the strength and density results for RCC specimens with different length to height ratios, with and without applying the correction factors. The ASTM C 39 correction factors are appropriate, and specimens with a minimum length to height ratio of one should be used for RCC compression testing, with the correction factor of 0.87.



**Figure 17. Effect of aspect ratio on compressive strength.**



**Comparison between compressive and splitting tensile strength.** With the consistency of the results for the test specimens, it is possible to develop correlations between splitting tensile and compressive strengths. From the 40 specimens tested in test series A, this comparison is shown in Figure 18. A strong correlation may be developed between splitting tensile strength and the square root of compressive strength. The ratio between splitting tensile and compressive strength for concrete was in the range of 0.08 and 0.14, typical for concrete (ACI 325.10R 1995).

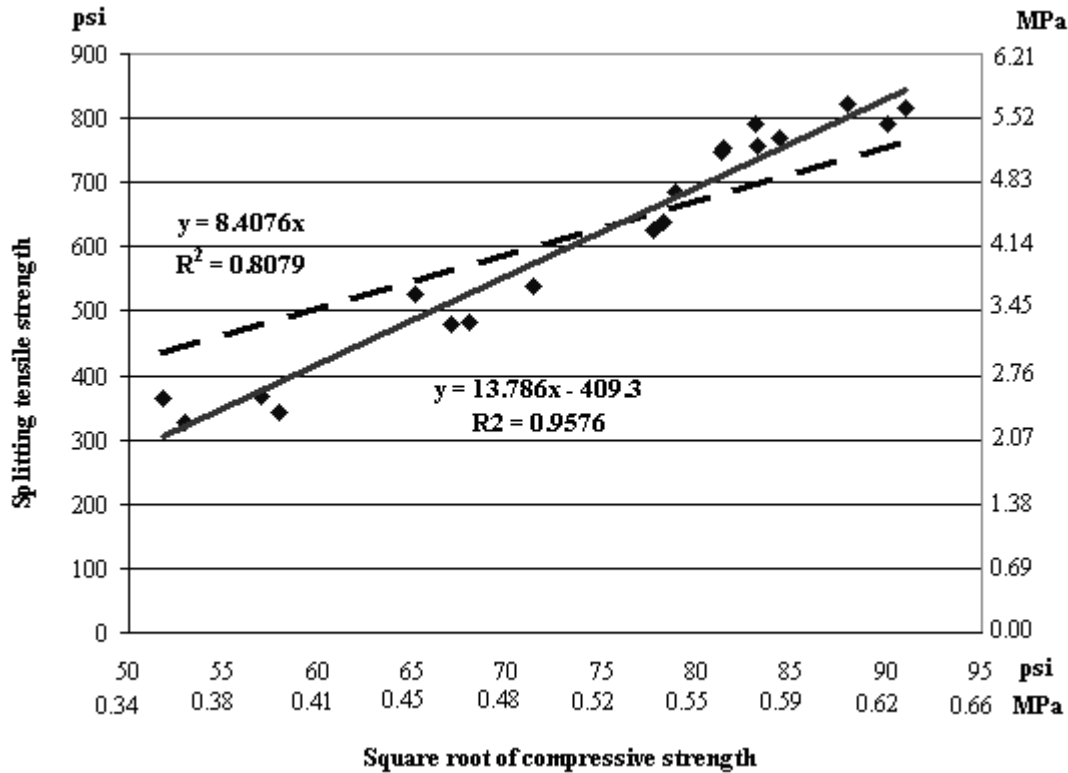


Figure 18. Comparison between compressive and splitting tensile strength.

**Comparison with field results.** The reported strength and dry density results from two industrial paving projects were obtained. These projects had been used to obtain the materials and mix proportions for test series A and B. Strength results in both test series were very close. In test series A the unconfined compressive strength results were about 1.5% higher in the field at 28 days. The splitting tensile strength was only 0.04% higher. In test series B, the unconfined compressive strength difference was 4.7% between the lab and the field, but the splitting tensile difference was less than 2%. The average Proctor dry density achieved in the field was 2,330 kg/m<sup>3</sup> (145.6 pcf). For laboratory specimens, the wet density average, for the same test series, was 2,520 kg/m<sup>3</sup> (157.4 pcf). Dry density may be obtained using the following relation (Delatte and Amer 2003):

$$\gamma_d = \text{TMCD} \times \gamma_w \quad \text{Equation (6)}$$

where  $\gamma_d$  is the dry density and  $\gamma_w$  is the wet density, and  $w$  is the water content. Therefore, the dry density of the laboratory specimens is  $2,360 \text{ kg/m}^3$  (147.5 pcf), which is only 1.3% higher than the field density.

For the project represented by test series B, a large number of broken flexural strength test beams were obtained from the testing laboratory. Some had been sawn from a test strip, and others had been fabricated using an impact hammer. These were drilled with a 95 mm (3.75-in.) core bit, and more than 50 cores were obtained. The cores were tested for density and either unconfined compressive or splitting tensile strength. Results are shown in Figures 19 and 20, along with best-fit lines and 28-day, 75 gyration specimens from test series B.

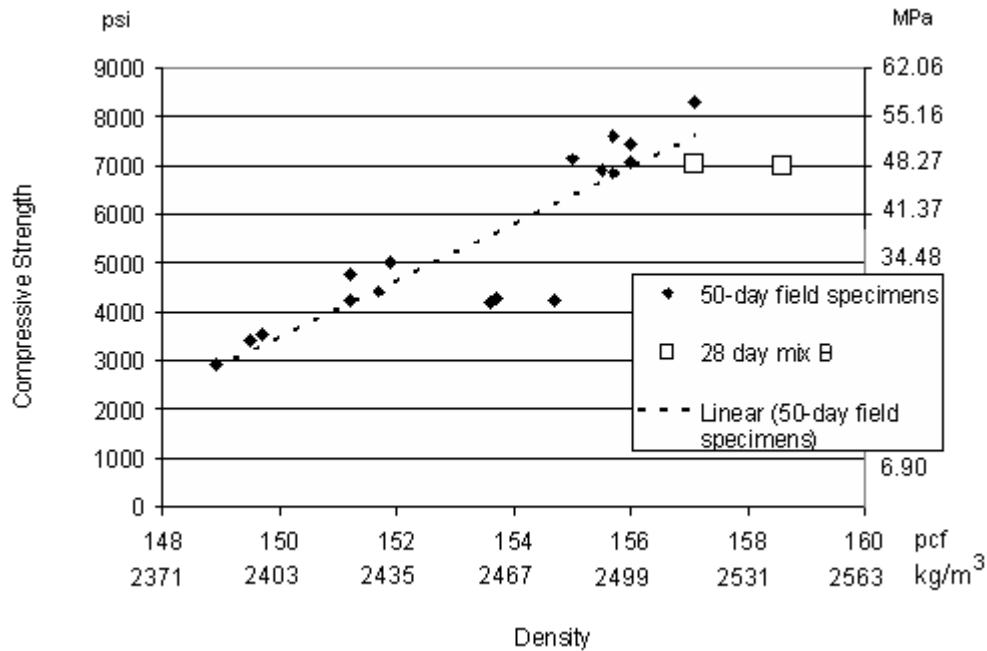
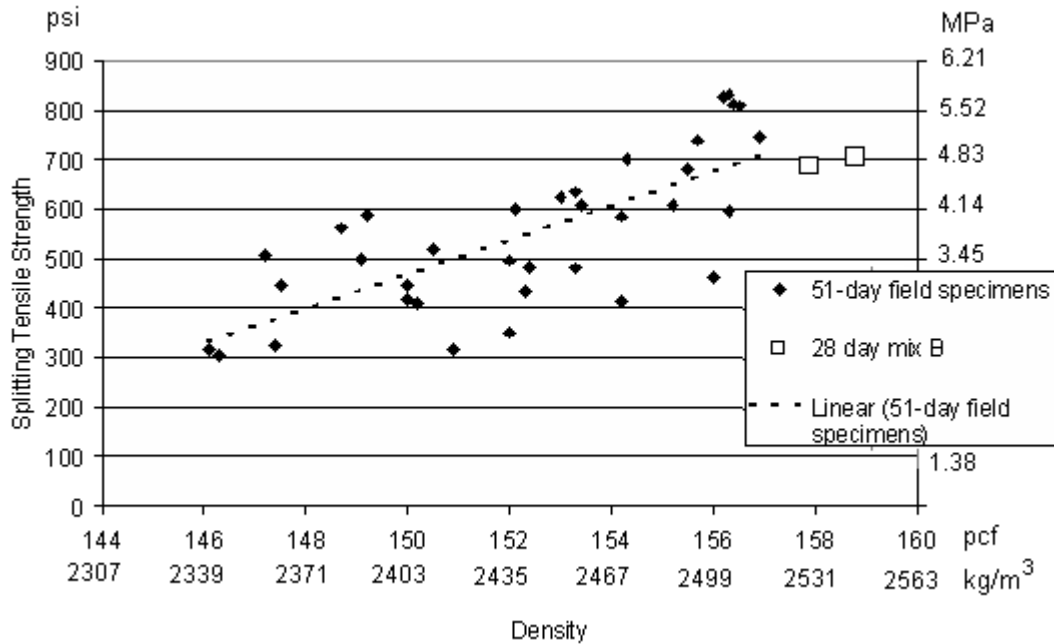


Figure 19. Density versus compressive strength of cores.



**Figure 20. Density versus splitting tensile strength of cores.**

The laboratory specimens are consistent with the densest and strongest specimens. However, it seems clear that specimens in the 50 to 60 gyration range would provide a better approximation of the field properties from this test strip.

**Mass loss versus unit weight in freeze-thaw testing.** Unit weight can be related to mass loss through an approximate relation. Figures 21 through 24 show this relation for the pavement and dam series at 103 and 133 cycles, and at 133 and 166 cycles, respectively. Results indicate that the higher the number of gyrations, and the better the compaction, the lower the mass loss.

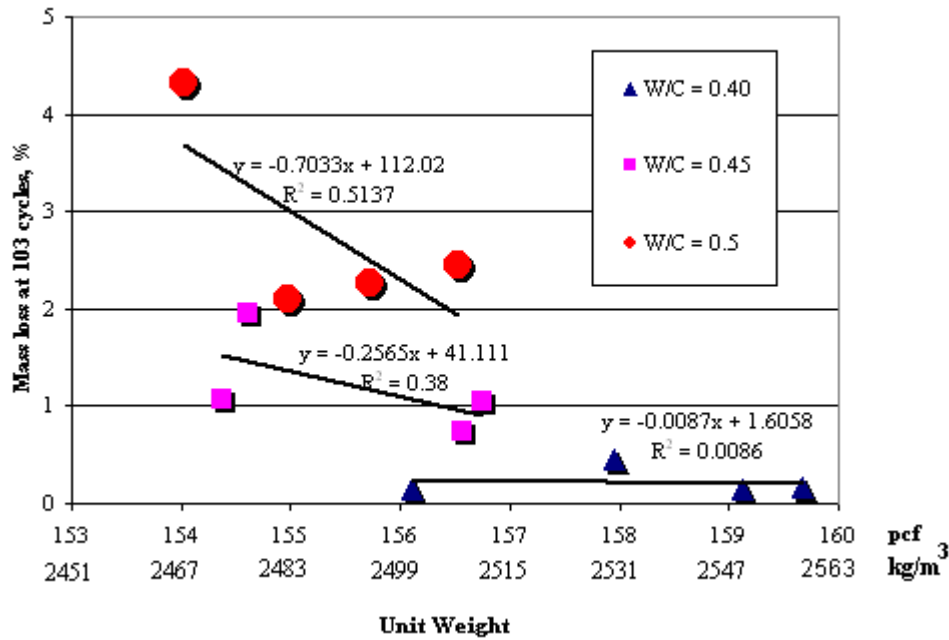


Figure 21. Mass loss (103 cycles) versus unit weight (pavement series).

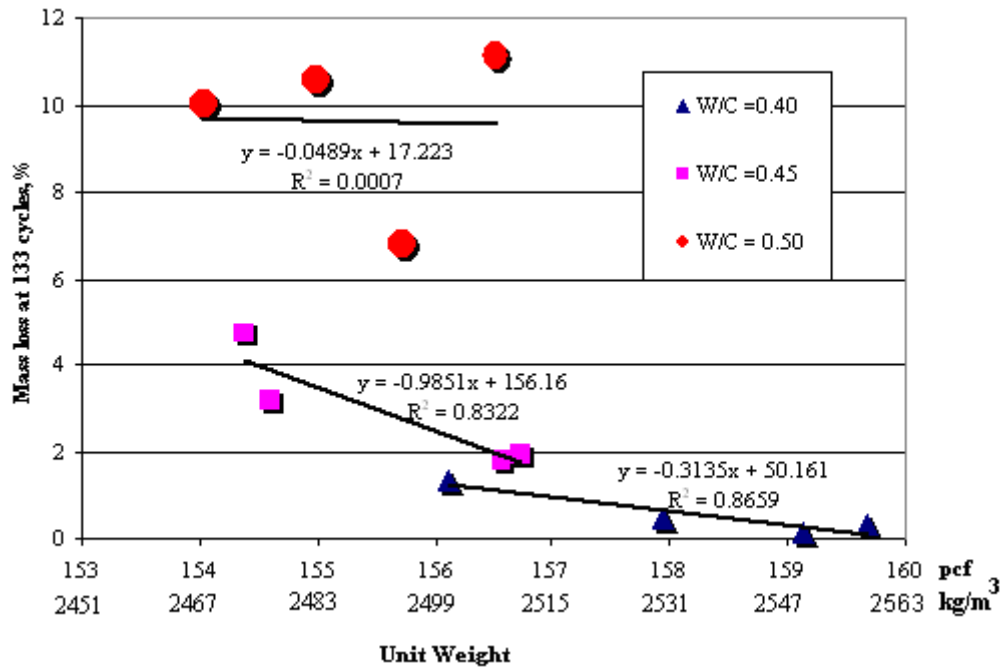


Figure 22. Mass loss (133 cycles) versus unit weight (pavement series).

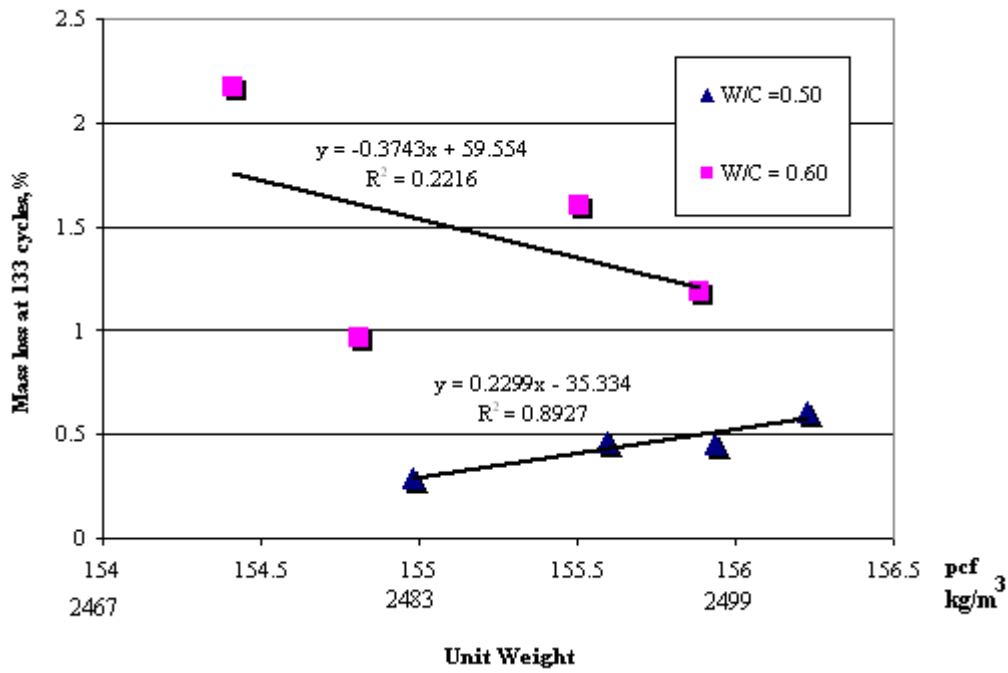


Figure 23. Mass loss (133 cycles) versus unit weight for (dam series).

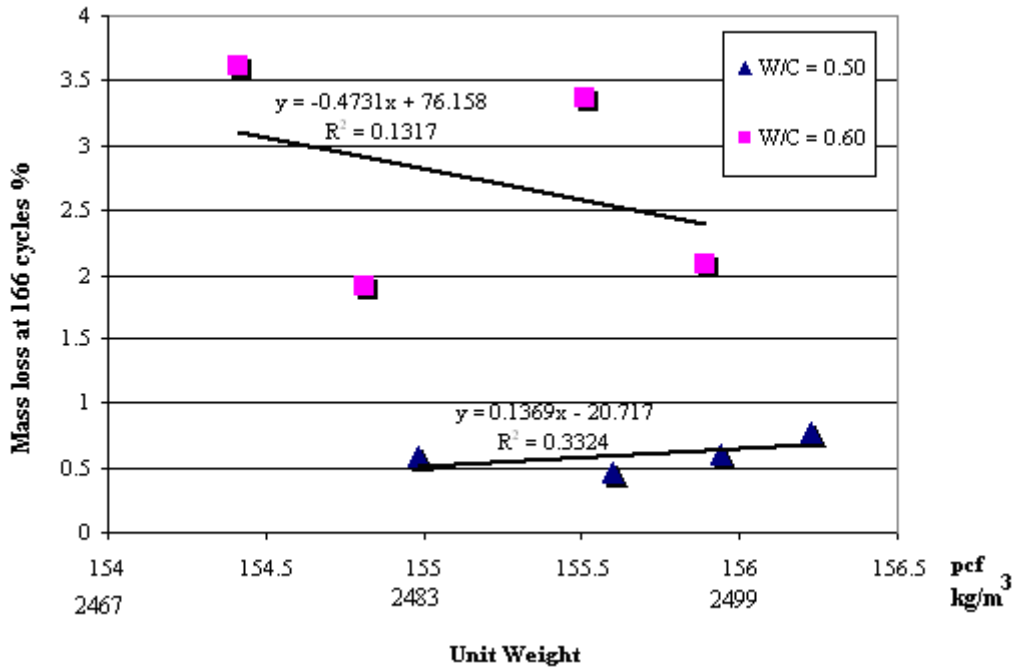
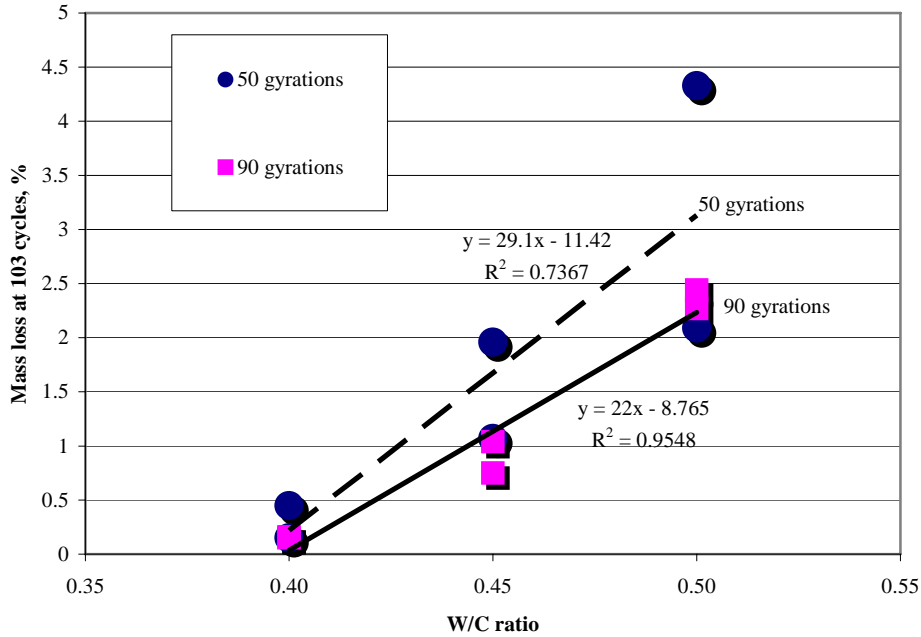
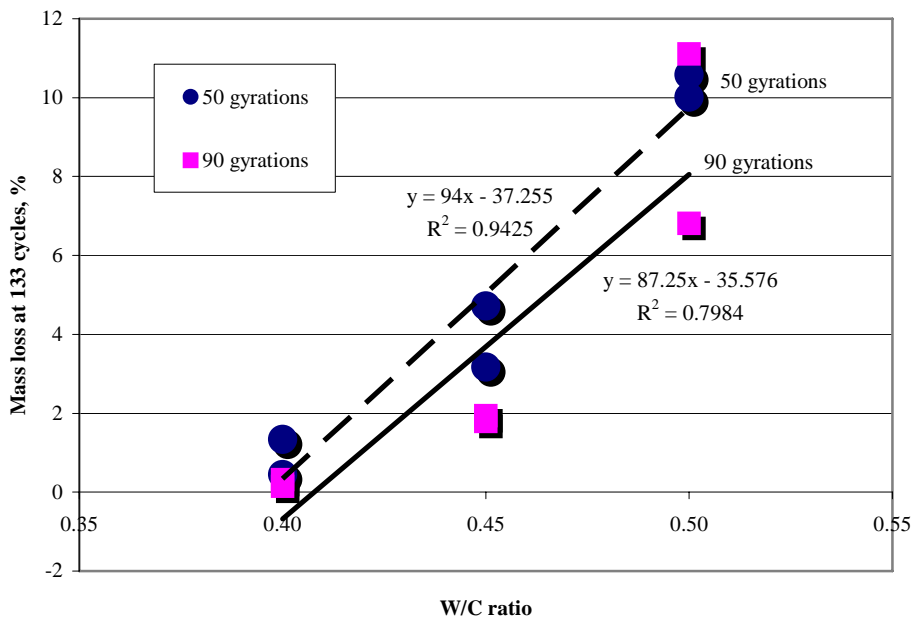


Figure 24. Mass loss (166 cycles) versus unit weight for (dam series).

**Mass loss versus water-cement ratio in freeze-thaw testing.** Figures 25 through 28 show the relation between water-cement ratio and mass loss for the pavement and dam series at 103 and 133 cycles, and at 133 and 166 cycles, respectively. In general, it is noted that as the water-cement ratio increases, the mass loss increases in RCC mixtures.



**Figure 25. Mass loss (103 cycles) versus W/C ratio (pavement series).**



**Figure 26. Mass loss (133 cycles) versus W/C ratio (pavement series).**

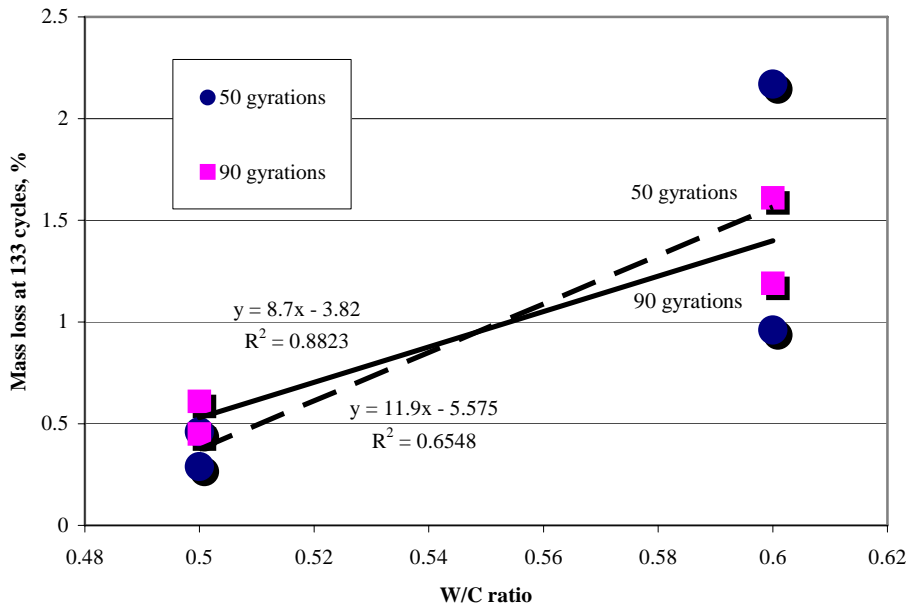


Figure 27. Mass loss (133 cycles) versus W/C ratio (dam series).

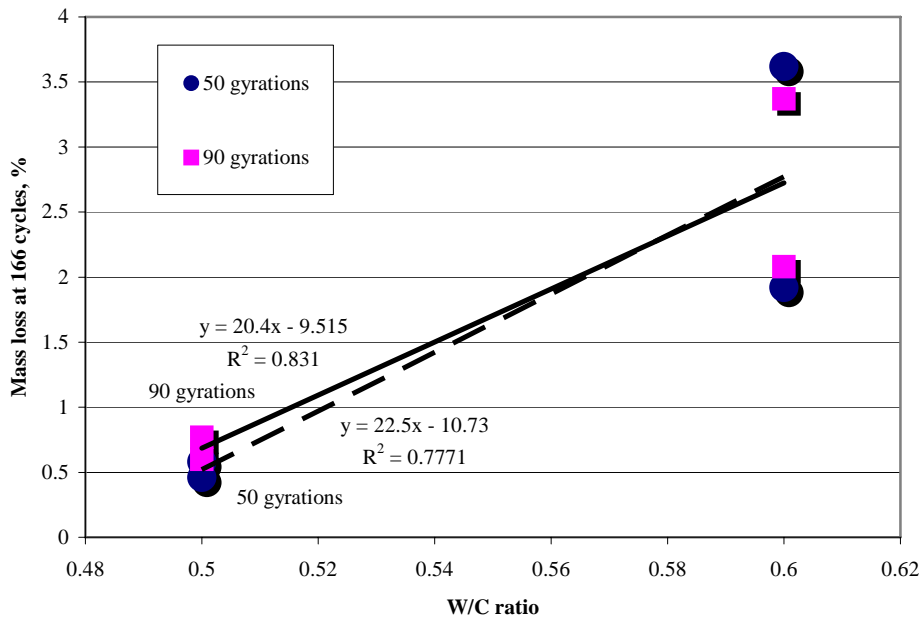
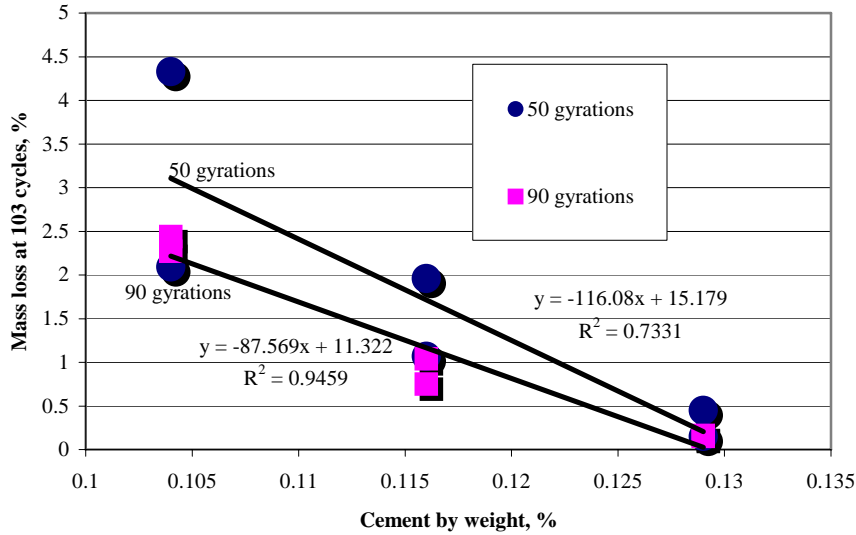
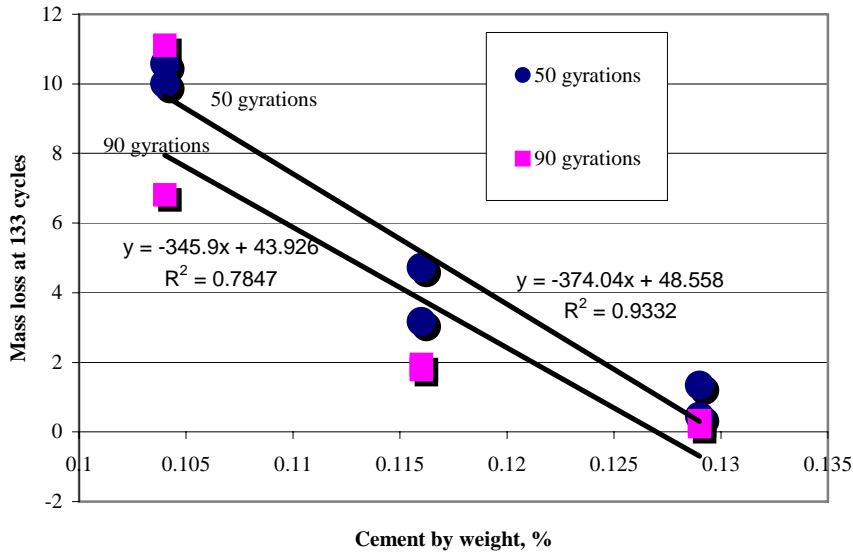


Figure 28. Mass loss (166 cycles) versus W/C ratio (dam series).

**Mass loss versus cement content by weight for freeze-thaw testing.** Figures 29 through 32 illustrate the relationship between the amount of cement in RCC mixes and mass loss due to freeze-thaw testing. As expected from the relation between water-cement ratio and mass loss, having more cement in RCC mixtures will generally reduce mass loss due to freeze-thaw.



**Figure 29. Mass loss (103 cycles) versus cement by weight (pavement series).**



**Figure 30. Mass loss (133 cycles) versus cement by weight (pavement series).**



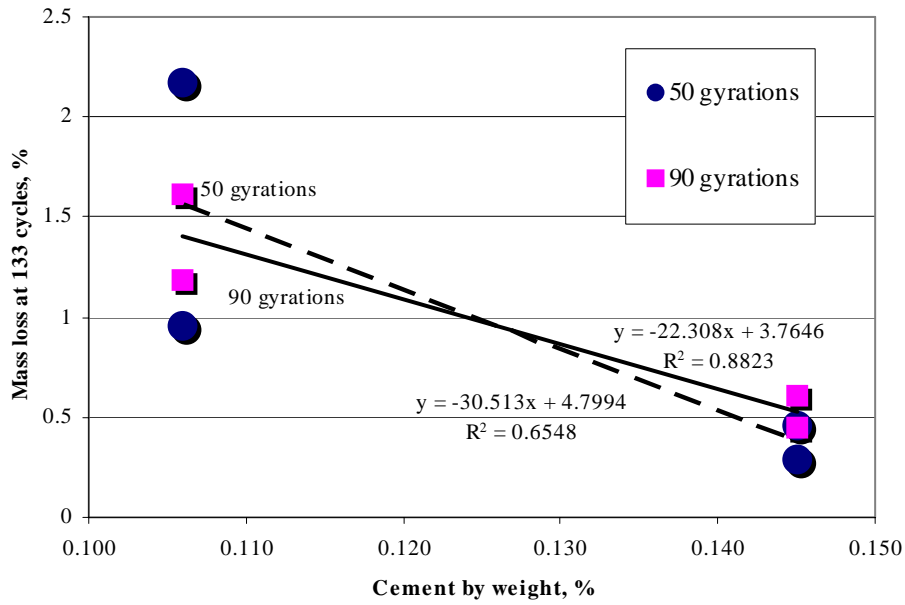


Figure 31. Mass loss (133 cycles) versus cement by weight (dam series).

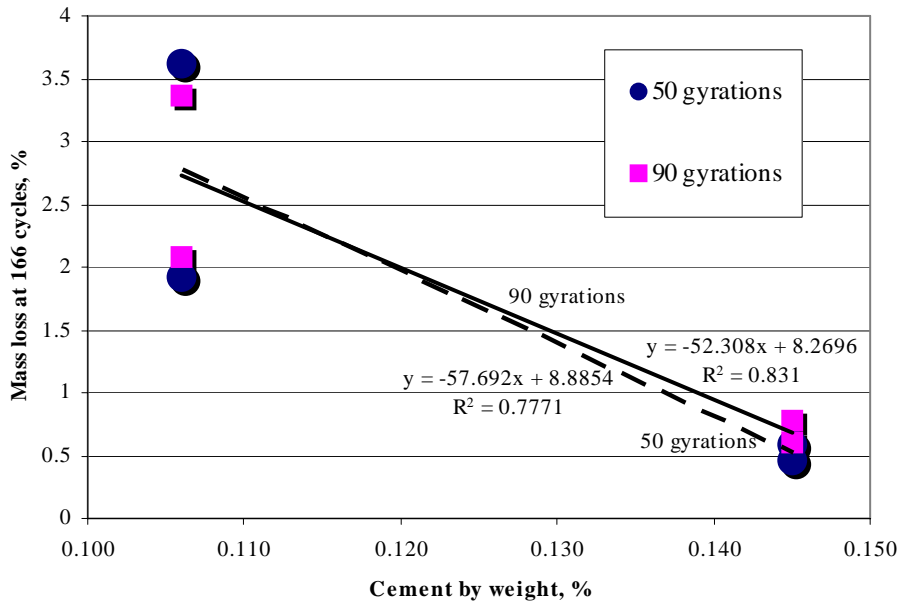


Figure 32. Mass loss (166 cycles) versus cement by weight (dam series).

## CONCLUSIONS

### Proof of Concept and Design Curves

One important obstacle to increased use of RCC has been the difficulty of fabricating laboratory specimens to accurately replicate field mechanical properties. In the past, it has been difficult to predict the mechanical properties and performance of a given RCC mixture. This impediment to the further development of RCC may be overcome by using a gyratory compactor to fabricate specimens to a desired density.

Strength and density results for RCC specimens fabricated using the gyratory compactor were consistent. Satisfactory agreement with field results was obtained. Therefore, the feasibility of using the gyratory compactor for RCC has been demonstrated. The appropriate number of gyrations will depend on the degree of compaction obtained with the equipment used for the project, but will probably be in the range of 50 to 75 to replicate fair and excellent compaction, respectively.

For the immediate future, the gyratory compactor will probably be more useful as a research tool for RCC, and for optimizing mixture proportions for large projects. It will probably take more time for gyratory compaction to be routinely adopted for quality control and quality assurance of RCC construction. Further details about this research are provided in Delatte et al. (2003).

Tests performed on RCC materials from three different projects gave close results to either field results or to properties reported in documents from the ACI and USACE (ACI 207.5R 1999, USACE 2000). Compacting the RCC specimens between 50 and 100 gyrations gave consistent results for density. With the gyratory compactor, it may be possible to produce specimens with densities approximately 96% to 100% of the theoretical maximum constituent density (TMCD). Density achieved by the gyratory compactor was highly consistent when applying either 75 or 100 gyrations. Table 26 shows the coefficient of variation and standard deviation for specimens with 75 or 100 gyrations.

**Table 26. Compaction Percentage at 75 and 100 Gyrations**

Test Series	Samples Tested	Average Density pcf (kg/m <sup>3</sup> )	Standard Deviation pcf (kg/m <sup>3</sup> )	Coefficient of Variation (COV)	TMCD pcf (kg/m <sup>3</sup> )	Average Compaction %
A	40	162.3 (2600)	1.08 (17.3)	0.66	162.9 (2609)	99.6%
B	20	156.7 (2510)	1.54 (24.7)	0.99	157.4 (2521)	99.5%
C	6	152.7 (2446)	1.79 (28.7)	1.19	154.8 (2480)	98.6%

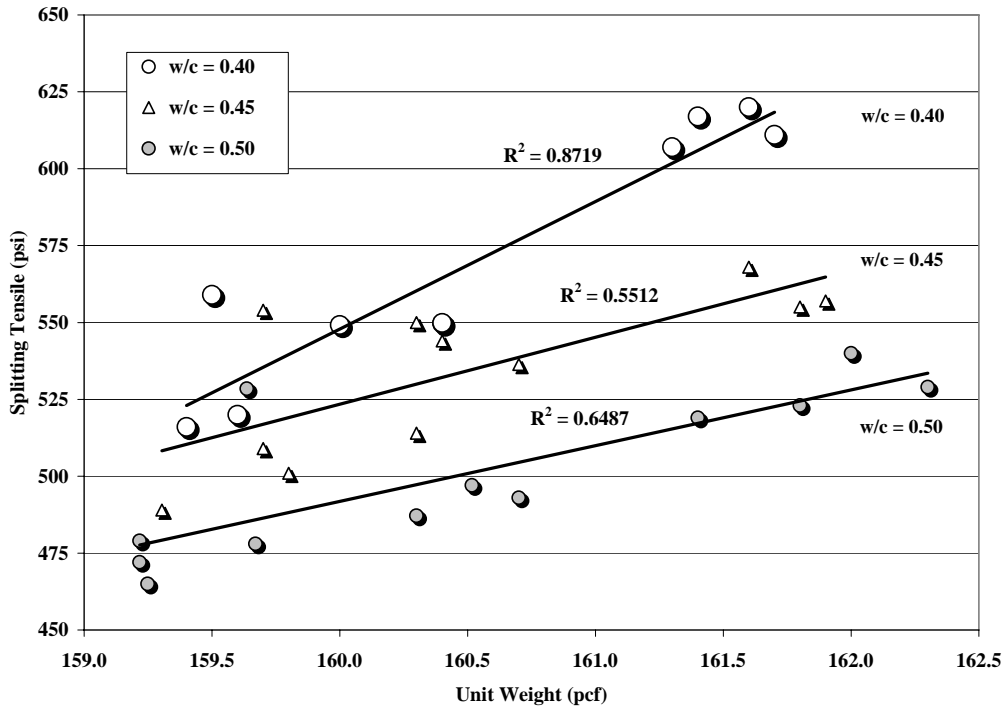
In current practice, it is common to construct a test strip on site with the materials, proportions, and construction equipment that will be used on the project. Test specimens are also fabricated, typically using an impact hammer, and compared to drilled cores and sawn beams from the test strip. Correlation factors between laboratory and field specimens may then be established for project control. This procedure is accurate but has

one serious drawback – it is difficult to investigate a range of materials and mixtures with a single test strip. Therefore, the gyratory compactor makes it possible to investigate a range of mix designs in the laboratory before the test strip is constructed. With proper validation and calibration, test strips may become unnecessary.

In this report, an important modification to existing RCC mixture design and proportioning methods has been proposed. By developing a test matrix of water-cement ratios and compaction, it is possible to select the appropriate cement content to deliver the required strength for a specific RCC pavement project. Since RCC construction in the field is often controlled on the basis of density, this method also makes it possible to determine the actual strength pavement achieved on site.

An example of using this procedure follows. From Figure 33, if the desired strength is 3,790 kPa (550 psi) there are two ways to achieve this strength. The water-cement ratio may be either 0.40 or 0.45. If 0.40 is used then the unit weight must be at least 2,560 kg/m<sup>3</sup> (160 pcf). If 0.45 is the water-cement ratio then the unit weight must be 2,590 kg/m<sup>3</sup> (161.3). Thus, there is a choice of applying less compaction with the lower water-cement ratio, which may mean less time and less effort for construction. However, having a lower water-cement ratio will mean having more cement content, which is the most expensive component in the mix. Therefore, this method allows the project engineer to balance material costs and construction methods to ensure quality. Figure 33 also shows that the RCC with the lowest water-cement ratio (0.40) benefits the most from increased compaction.

Since the method outlined will require considerable laboratory effort, it is probably most appropriate for large projects where it is possible to recover the costs of testing through the amount of cementitious material saved. It also provides an incentive to improve compaction of RCC in the field. This research also builds on a previous investigation of the use of the gyratory compactor for RCC, and illustrates the value of the apparatus for investigating the fundamental mechanical properties and behavior of RCC. It will be important to apply these methods to a wider range of RCC materials, mixtures, and practices.



**Figure 33. Splitting tensile strength versus unit weight (1 psi = 6.89 kPa, 1 pcf = 16.0 kg/m<sup>3</sup>).**

## Limitations of Fundamental Frequency Testing

The maximum height of 190 mm (7.5 in.) achieved by the gyratory compactor imposed a limitation to the length of the prisms used in freeze-thaw testing. The average height actually was found to be 161 mm (6.32 in.), which is much smaller than the minimum length of 280 mm (11 in.) specified by ASTM C 666 for prisms. Section 5 of ASTM C 215 indicates that “very large or very small length to maximum transverse direction are frequently difficult to excite in the fundamental mode of vibration” (120 ASTM 1985). Therefore, the durability factor will not be a proper indication of the durability of RCC specimens. This was concluded after seeing the RDME values dropping to 40% below the initial modulus where it should show that the specimens were not affected at all by the freeze-thaw cycles. A good example of that is sample number 15, which passed 300 cycles successfully whereas the RDME indicated it failed at cycle 70 with a DF value of 41.

## Effect of Mass Loss During Freeze-Thaw Process

Figures 34 and 35 summarize the relation between mass loss and water-cement ratio. Pavement series gyrated with 50 gyrations had a higher rate of mass loss than those compacted to 90 gyrations. Another observation is that the mass loss rate is higher with a lower number of gyrations; however, the amount of mass loss is smaller toward the 300 cycles with a mass loss of 7.08% compared to 8.07% for the 90 gyration specimens.

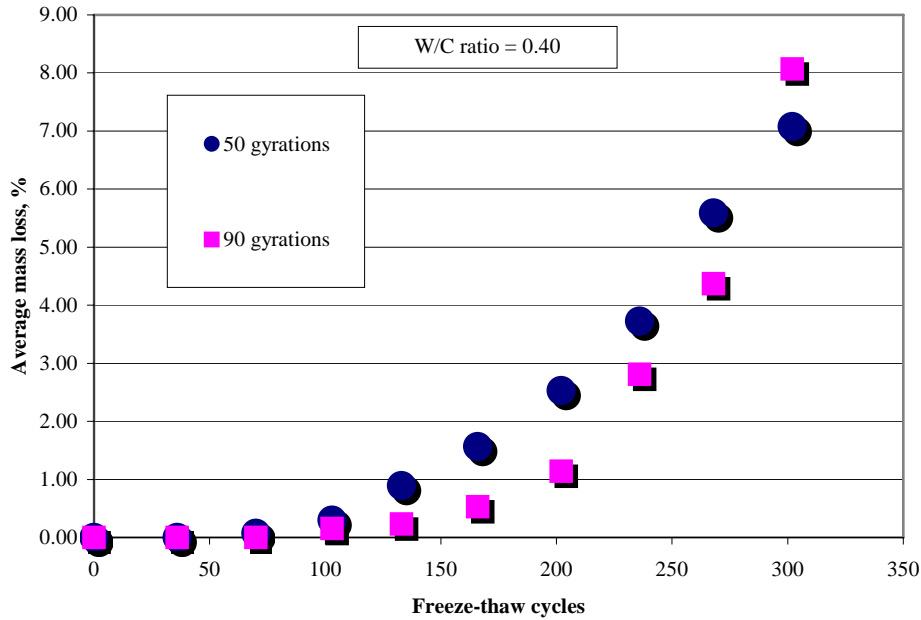


Figure 34. Pavement series average mass loss versus freeze-thaw cycles.

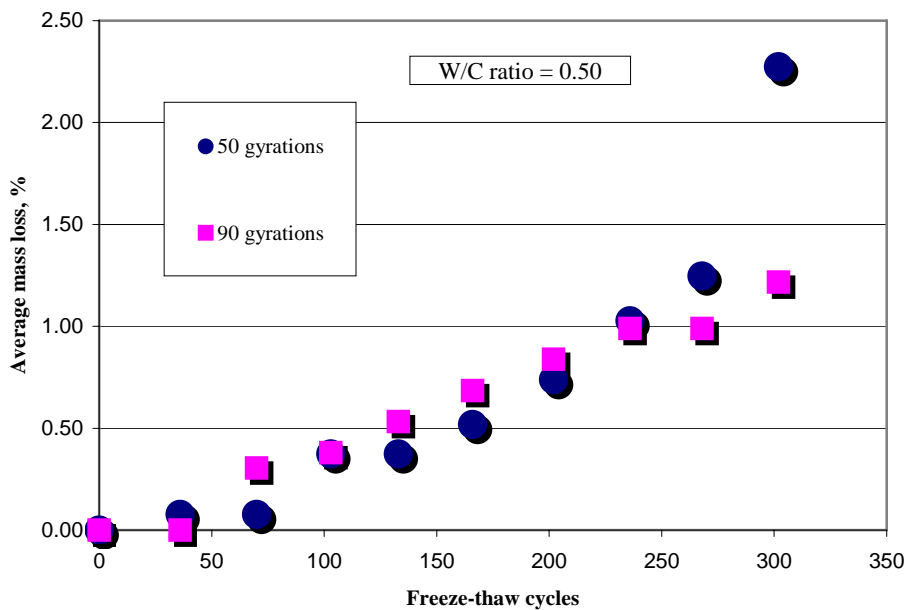


Figure 35. Dam series average mass loss versus freeze-thaw cycles.

The dam series showed some different trends at different cycles. Overall, the mass losses differed, but at the 300 cycles toward the end, the 50 gyration specimens had more mass loss with an average of 2.27% compared to a 1.22% mass loss for the 90 gyration specimens.

## Comparison of Pavement Series to Dam Series RCC

Results showed that the RCC mixes with a low water-cement ratio passed the freeze-thaw testing. They completed 300 cycles successfully without going over 10% of mass loss. Table 27 summarizes the results of mass loss for the low water-cement ratios.

**Table 27. Summary of mass loss for lowest W/C ratios**

Specimen ID	W/C Ratio	Number of Cycles Completed	Mass Loss, %	Average Mass Loss, %
1	0.40	302	7.58	7.08
2	0.40	302	6.58	
3	0.40	302	7.30	8.07
4	0.40	302	8.83	
5	0.50	302	3.17	2.28
6	0.50	302	1.38	
7	0.50	302	1.23	1.22
8	0.50	302	1.21	

The table shows that the dam series with a water-cement ratio performed in a better manner than the pavement series for the same water-cement ratio. One reason for that might be using more cement in the dam series, which fills the voids more efficiently in the RCC mix. This will give better permeability and higher unit weights that help resist freeze-thaw attacks. With the higher water-cement ratios, specimens did not perform well past 70 to 100 cycles. However, the ones with higher cement volume or content performed better overall (Storey 2004).

## Comparison of Mass Loss and Stiffness Using Frequency

An important relation of interest is shown in Equation 7 where mass loss can be compared to stiffness for RCC specimens. This comparison is achieved using transverse frequencies by calculating ( $f$ ).

$$f = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{K}{M}} \quad \text{Equation (7)}$$

where,  $K$  is the stiffness associated with the RCC specimens; and  $M$  is the mass of the RCC specimens. Figures 36 through 39 illustrate the relation between average mass and RDME loss versus number of cycles. Figures only show results for mixes with water-cement ratios of 0.40 and 0.50.

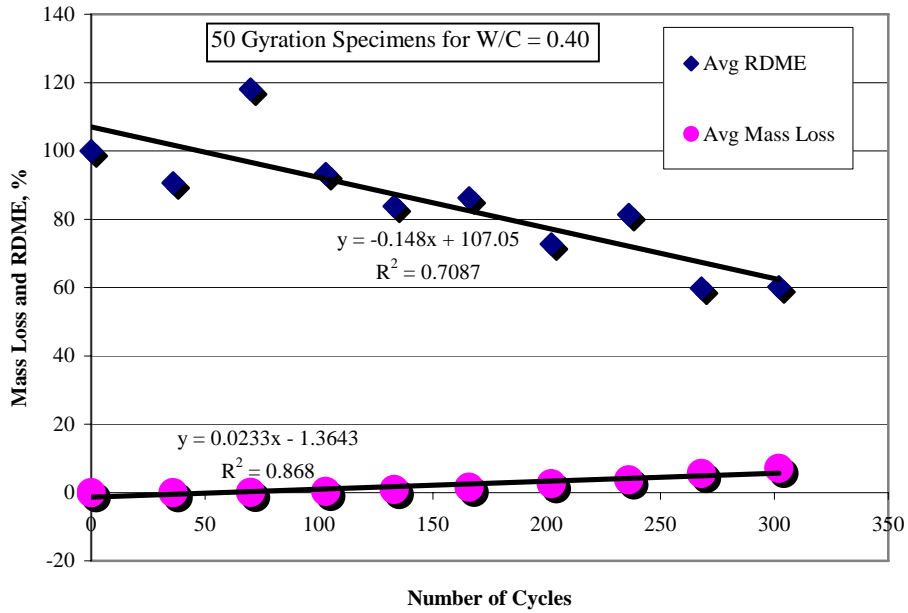


Figure 36. Average mass and RDME loss vs. number of cycles (pavement).

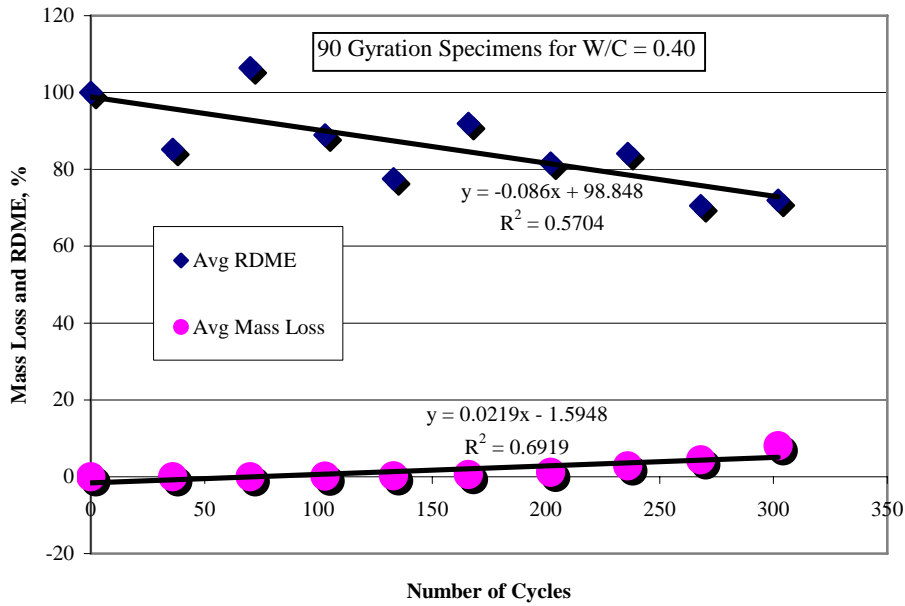


Figure 37. Average mass and RDME loss vs. number of cycles (pavement).

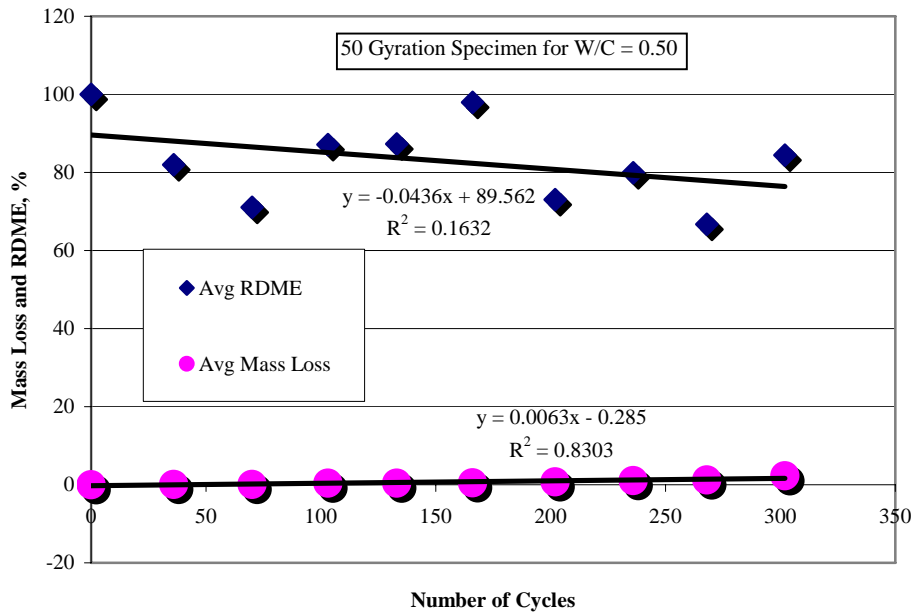


Figure 38. Average mass and RDME loss vs. number of cycles (dam).

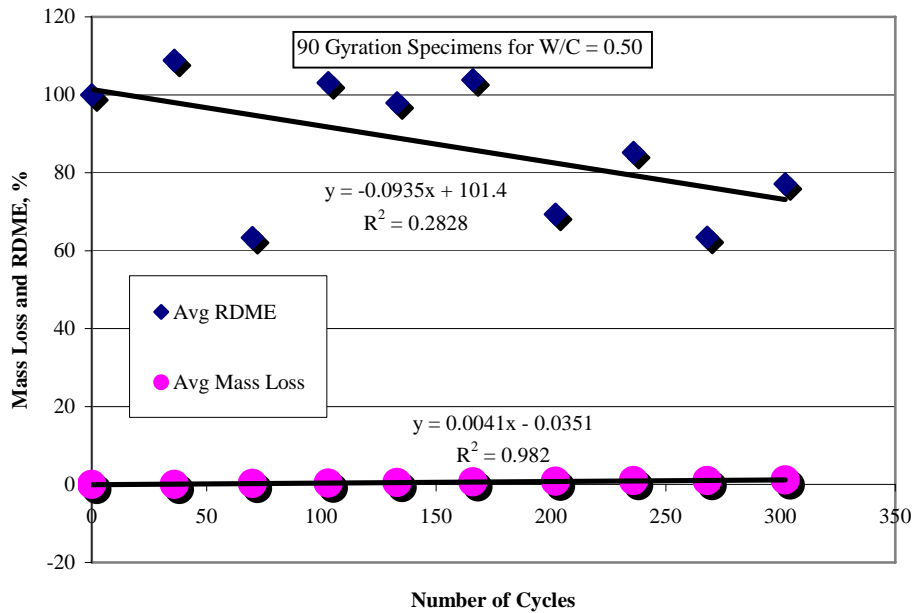


Figure 39. Average mass and RDME loss vs. number of cycles (dam).

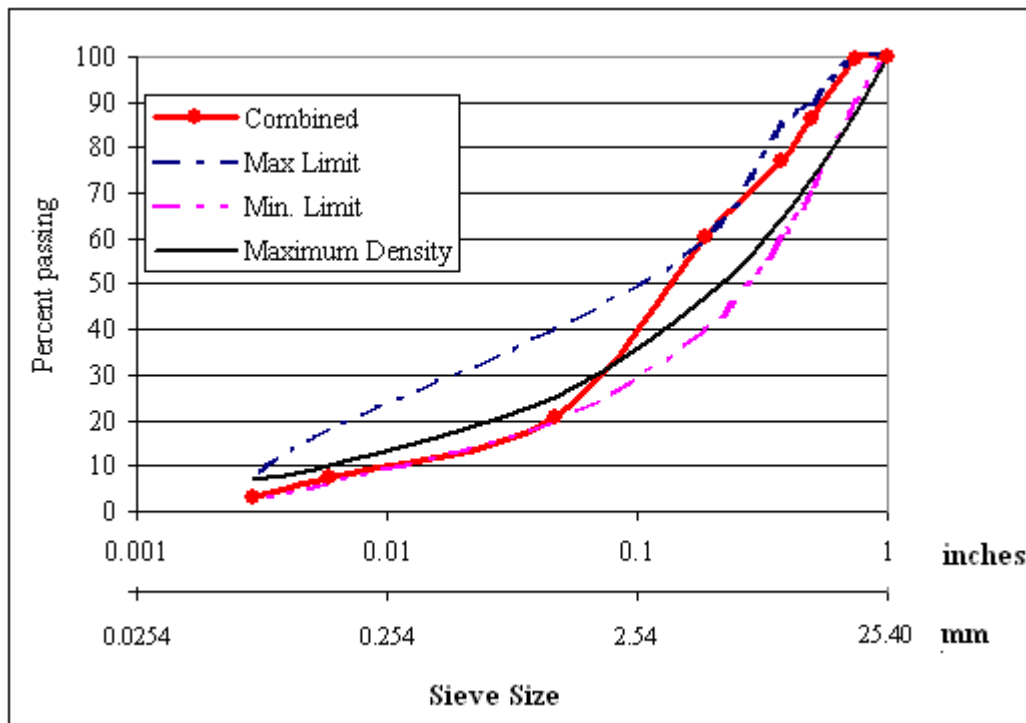
The figures show that RDME or transverse frequency is decreasing while the mass loss is increasing with more cycles of freeze-thaw. Therefore, the stiffness of RCC specimens decreases as a result of decreasing the frequency and mass of specimens. It can be concluded that strength of the RCC specimens decreases with decreasing stiffness, which is lost in a faster rate than mass loss when the frequency decreases after 36 cycles. To summarize the findings of freeze-thaw testing the following can be concluded:



- Freeze-thaw resistance increases as water-cement ratio decreases.
- Freeze-thaw resistance increases as density (compaction) increases.
- Fundamental frequency testing is not valid for the short specimens fabricated using the gyratory compactor.
- Mass loss is a reliable method to determine failure of RCC specimens fabricated using the gyratory compactor.

## SUGGESTED FURTHER RESEARCH

The consistency of testing and agreement with field results suggest a number of promising areas for future research. It is possible to improve the performance and reduce the cost of RCC. One possible improvement would be to use as dense an aggregate gradation as possible. Aggregates play a major role in the performance of RCC. So far, only a few aggregate gradations have been investigated. Figure 40 illustrates the combined aggregate gradation for test series (A) compared to maximum density, as well as some gradation limits developed by the South Carolina Department of Transportation (SCDOT 2001). A maximum density gradation allows the production of stronger RCC with less cement binder.



**Figure 40. Combined aggregate gradation for RCC.**

The modified mix design using the curves should be duplicated across a range of aggregate sizes and gradations, to investigate how the water-cement ratio and density affect strength and other parameters. Strength relationships at 14, 28, and 90 days should

be investigated. For projects that consider early traffic, strength relationships at 8, 24, 48, and 72 hours are essential.

The test strips and laboratory test series investigated during this project have produced specimens with higher density than that required by typical specifications. The SCDOT specification requires a compressive strength of 13.8 MPa (2,000 psi) at 3 days and 34.5 MPa (5,000 psi) at 28 days (SCDOT, 2001). The Canadian Portland Cement Association recommends a 28-day compressive strength of 30 MPa (4,400 psi) and a 90-day flexural strength of 4.0 MPa (580 psi) (CPCA 1995). The test results obtained during this research show that these values may be easily exceeded. Therefore, using gyratory compactor technology it is possible either to reduce the binder requirements and cost of RCC, or to take advantage of higher strength by reducing pavement thickness. It is also possible to iterate through trial batches to optimize properties, rather than relying on the results of a single test strip.

Another area of research is freeze-thaw durability of RCC. Typically freeze-thaw resistance of concrete is obtained through air entrainment, but it has proven to be very difficult to entrain air in RCC. Nevertheless, RCC has been shown to be durable in harsh environments. The gyratory compactor may be used to fabricate specimens to investigate the effect of density on freeze-thaw resistance of RCC.

Recently the SCDOT placed a 200-mm-(8-in.)-thick, 305-m (1,000-ft) RCC test section near Aiken, SC. This pavement has no asphalt overlay, and the performance has been good so far. The agency anticipates using RCC with a 100-mm (4-in.) overlay as an economical, durable pavement and is considering a larger test section. One problem remains rideability, and it is possible that further research will produce RCC mixtures that can be built more smoothly.

Experienced engineers who work with RCC have suggested some important topics of research, including curling and warping for RCC pavements, ways to improve RCC surfaces, the use of admixtures with RCC, evaluation of freeze-thaw performance, and permeability of RCC. The gyratory compactor can help in some of these research areas by allowing preparation of specimens with a range of compaction.

## **ACKNOWLEDGMENTS**

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## REFERENCES

Amer, N. Development and Validation of a New Test Method for Fabricating RCC Specimens. MS Thesis, The University of Alabama at Birmingham, August 2002.

Amer, N.; Delatte, N., and Storey, C., “Using Gyrotory Compaction to Investigate Density and Mechanical Properties of Roller-Compacted Concrete.” *Transportation Research Record*, Vol No. 1834, 2003, pages 77-84.

American Society for Testing and Materials. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. C39–93a, Philadelphia, Pennsylvania 2000. Mindess, S., and Young, J. F. Concrete. Prentice Hall, Inc., Englewood Cliffs, New Jersey, USA, 1981.

American Concrete Institute Committee 207. Roller-Compacted Mass Concrete. ACI 207.5R-99, Farmington Hills, Michigan, USA, 1999.

American Concrete Institute Committee 211. “Guide for Selecting Proportions for No-Slump Concrete.” ACI 211.3R-02, Farmington Hills, Michigan, USA, 2002.

American Concrete Institute Committee 325. State-of-the-Art Report on Roller-Compacted Concrete Pavements. ACI 325.10R-95, Farmington Hills, Michigan, USA, 1995.

ASTM. (1992 a). “Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete.” *C 138-92 a*, Philadelphia, Pennsylvania, USA.

ASTM. (1992 b). “Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.” *C 666-92 b*, Philadelphia, Pennsylvania, USA.

ASTM. (1985). “Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens.” *C 215-85*, Philadelphia, Pennsylvania, USA.

Atkins, Harold N., *Highway Materials, Soils, and Concretes*, Prentice Hall, Inc., Upper Saddle River, New Jersey, USA, 1997.

Barksdale, R. D., *The Aggregate Handbook Supplement*, National Stone Association, Washington, D.C., USA, 1998.

Canadian Portland Cement Association (CPCA), Suggested Specification for Roller Compacted Concrete Paving for Municipal and Industrial Applications, CP014.01P, 1995.05.26.

Cortez, E. R., and Eaton, R. A., “Freeze-Thaw Tests of Full-Scale Roller Compacted Concrete Test Sections,” Special Report 90-25 – United States Army Corps of Engineers, Hyattsville, Maryland, USA, 1990.

Delatte N.; Amer, N., and Storey C., *Improved Management of RCC Pavement Technology*, Report No. 01231, the University Transportation Center for Alabama, Birmingham, Alabama, USA, February, 2003.

Marchand, J.; Pigeon, H.; Isabelle, H. L., and Boisvert, J., “Freeze-Thaw Durability and Deicer Salt Scaling Resistance of Roller Compacted Concrete Pavements.” ACI SP 122-13 – *Paul Klieger Symposium on Performance of Concrete*, 217-236, 1990.

Mindess, S., and Young, J. F., *Concrete*, Prentice Hall, Inc., Englewood Cliffs, New Jersey, USA, 1981.

Piggott, R. W., *Roller Compacted Concrete Pavements – A Study of Long Term Performance*, RP366, Portland Cement Association, Skokie, Illinois, USA, 1999, 65 pages.

Pittman, David Wayne, *Development of a Design Procedure for Roller-Compacted Concrete (RCC) Pavements*. Volume I: Main Text. U.S. Army Corps of Engineers (USACE), Hyattsville, Maryland, USA, Technical Report GL-94-6, March 1994.

Pittman, David Wayne, *Development of a Design Procedure for Roller-compacted Concrete(RCC) Pavements*. Volume II: Appendixes A through E and References. U.S. Army Corps of Engineers (USACE), Hyattsville, Maryland, USA, Technical report GL-94-6, March 1994.

Ragan, S. A.; Pittman, D. W., and Grogan, W. P., “An Investigation of the Frost Resistance of Air-Entrained and Nonair-Entrained Roller-Compacted Concrete (RCC) Mixtures for Pavement Applications.” U.S. Army Corps of Engineers: Technical Report GL-90-18, 1991, Department of the Army, Washington, D.C., USA.

Schnabel Engineering Associates, Inc., *Design Manual for Small RCC Dams*, EB225.01, Portland Cement Association, Skokie, Illinois, USA, 68 pages.

Service d’Expertise en Materiaux Inc., *Frost Durability of Roller-Compacted Concrete Pavements*, RD135, Portland Cement Association, Skokie, Illinois, USA, 2004, 148 pages.

South Carolina Department of Transportation, Roller Compacted Concrete Pavement, Supplemental Specification, May 22, 2001.

U.S. Army Corps of Engineers (USACE), “Roller Compacted Concrete,” Engineer Technical Letter 1110-2-2006, Department of the Army, Washington, D.C., USA, 2000.

U.S. Army Corps of Engineers (USACE), “Roller Compacted Concrete Pavement Design and Construction,” Engineer Technical Letter 1110-3-475, Department of the Army, Washington, D.C., USA, 1995.