

Effect of Density on Strength and Freeze-Thaw Durability of Roller Compacted Concrete

Norbert Delatte¹, Member ISCP, Nader Amer¹, and Chris Storey²

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. Laboratory specimens achieved density and strength comparable with cores extracted from field test strips. The effects of water-cement ratio and degree of compaction on the freeze-thaw resistance of gyratory compacted RCC were also investigated.

Introduction

This research project was initiated to investigate the effects of density on the strength and freeze-thaw durability of roller compacted concrete. Roller-compacted concrete (RCC) pavements are durable and can be built rapidly and economically. RCC is gaining the interest of state transportation agencies for paving applications, and at least two states (South Carolina and Tennessee) have constructed test sections. RCC has become more attractive for these agencies because of its low cost, minimal maintenance requirements, and long-term reliability (Amer 2002, Amer et al., 2003, Delatte et al., 2003). Although RCC offers many benefits, transportation agencies find it difficult to control construction and ensure quality RCC pavements due to the lack of available quality control methods.

In the past few years, extensive research has been carried out for RCC pavements. Topics of interest include the evaluation of curling and warping, freeze-thaw durability, use of admixtures, and methods to improve RCC surfaces. Many of these research needs may be addressed through laboratory studies.

¹ Graduate Research Assistant and Associate Professor, Civil & Environmental Engineering Department, Stilwell Hall, Euclid Avenue at East 24th Street, Cleveland State University, Cleveland, Ohio – 44115, email: n.delatte@csuohio.edu

² Structural Design Engineer, LBYD Inc. (Lane Bishop York Delahay), 716 South 30th Street, Birmingham, Alabama, 35233

In the past, there have been some difficulties in fabricating RCC specimens for evaluating field performance. Since RCC pavements use hot mix asphalt placement and compaction equipment and techniques, the use of a gyratory compactor to develop hot mix asphalt laboratory and field specimens was investigated (Amer 2002). Figure 1 shows the gyratory compactor used in this research.



Figure 1: Laboratory Gyratory Compactor

The compactor principle and operation is discussed thoroughly by Amer (2002). As the number of gyrations increases, the specimen is compacted and its density is increased. Figure 2 illustrates the increase in unit weight during 100 gyrations. The unit weight asymptotically approaches a theoretical maximum.

Once a predetermined number of gyrations has been achieved, the specimen is removed from the compactor for curing, determination of density, and strength testing. Figure 3 illustrates specimens removed after 50, 75, and 100 gyrations. Clear differences in the specimen surface textures may be observed.

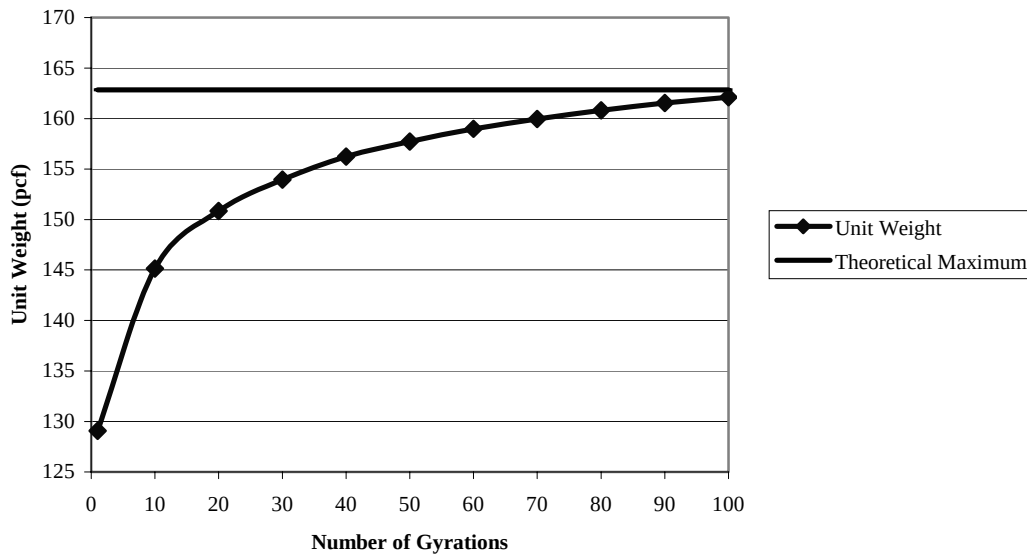


Figure 2. Unit weight versus number of gyrations, test series A

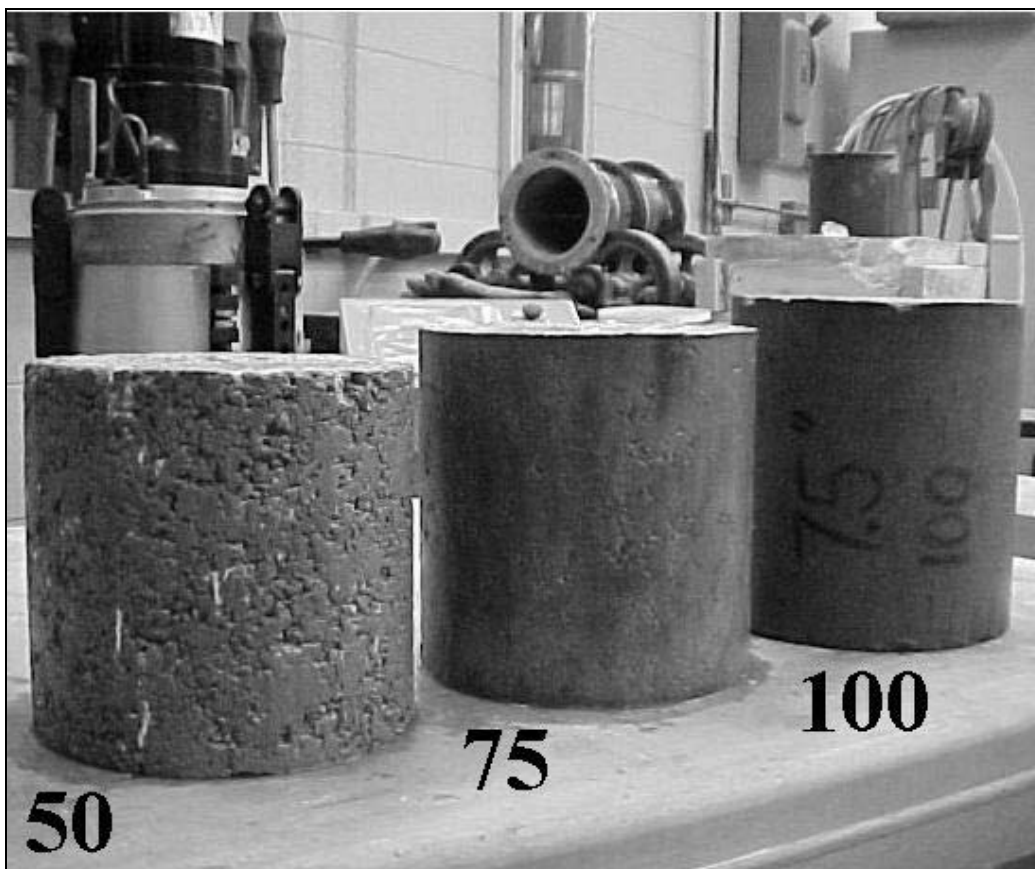


Figure 3. Different surface textures for different number of gyrations

Research and Practical Significance

This research makes it possible to investigate the mechanical properties and durability of roller compacted concrete while replicating field density conditions. The results may be applied by field engineers planning and building roller compacted concrete pavements, as well as by researchers investigating roller compacted concrete properties. By providing improved predictions of field density and properties, the gyratory compactor makes it possible to enhance the strength, durability, and economy of RCC pavements.

Research Methods and Experimental Program

During the course of this research project two large industrial RCC pavements were under construction within a short distance of the laboratory. It was possible to obtain materials and test results from the two projects in order to compare laboratory and field results. The research used the aggregate blends and mixture proportions from these two projects.

The first step in the research was to carry out a proof of concept test to verify that satisfactory RCC test specimens could be made with a laboratory gyratory compactor. The test produced the specimens shown in figure 3, as well as the relationships between the number of gyrations and compressive and splitting tensile strength shown in figures 4 and 5 (Amer 2002, Amer et al., 2003). Full proof of concept test results are reported in Amer (2002) and Delatte et al. (2003).

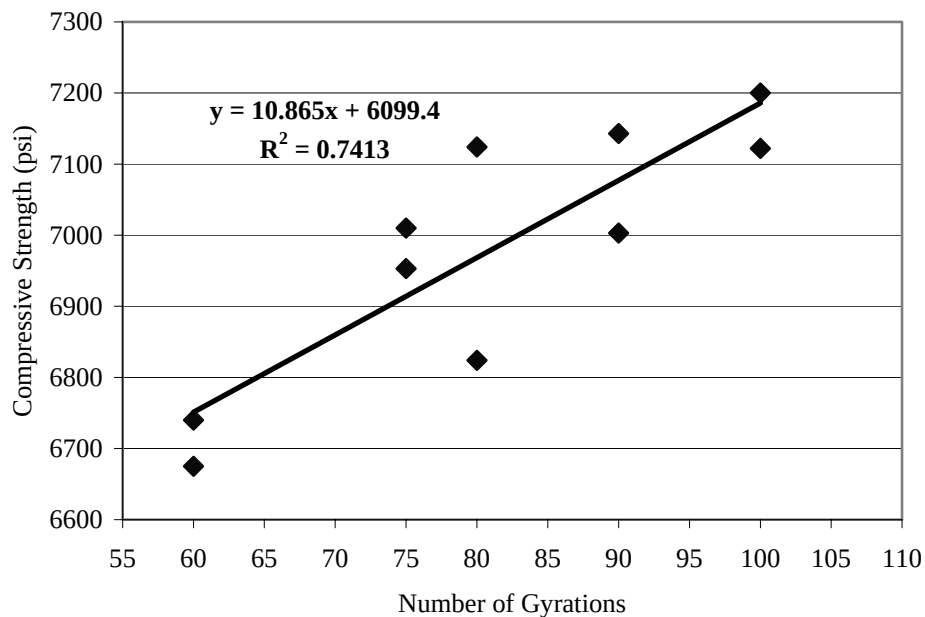


Figure 4. Compressive strength development with increasing number of gyrations

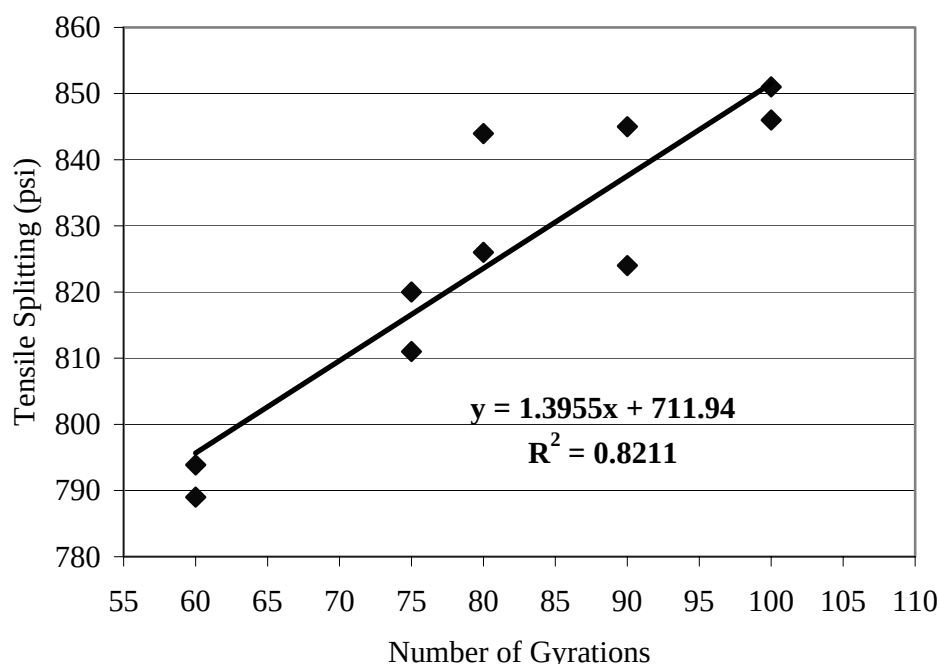


Figure 5. Splitting tensile strength development with increasing number of gyrations

Following the proof of concept testing, several test series were carried out to investigate the effects of several parameters on RCC strength. The tests were used to:

- Determine how compressive strength changes with specimen density (degree of compaction)
- Determine how splitting tensile strength changes with specimen density (degree of compaction)
- Determine how specimen aspect ratio affects 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 a laboratory study, and the last two were achieved by comparing the strength results of field cores with specimens made in the lab with the same materials. Table 1 summarizes the test specimens produced during this phase of the research, and table 2 shows the two mix designs used.

Once the effect of density on strength was investigated, further testing was carried out to determine the best way to design RCC to achieve a specific strength, and to evaluate the resistance of various RCC mixtures to freezing and thawing. These two test programs are discussed further below.

Table 1. Summary of Test Specimens Produced

Test Series	Application	Specimens Produced	Number of Gyration	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
		10	75	Splitting tensile strength for 1, 3, 7, 14, and 28 days

Table 2. Mix Designs – Parametric Study

Mix Design	Cement lb/yd^3	Fly Ash lb/yd^3	Water lb/yd^3	w/cm ratio	Blended Aggregate lb/yd^3
Test Series A	425	150	210	0.37	3,600-3,700
Test Series B	550	0	220	0.40	3,400-3,500

Note: $1 \text{ lb/yd}^3 = 0.59 \text{ kg/m}^3$

Effect of Density on Strength

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 the two previously referenced industrial paving projects.

The research program investigated ways to:

- Create design curves to help engineers design an RCC mixture.
- Determine the optimum water/cement ratio by determining the number of gyrations most appropriate to achieve the desired strength.
- Investigate how unit weight increases with a higher number of gyrations.

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. Mixture proportions investigated during this stage of the research are shown in table 3.

Table 3: RCC mixture proportions investigated

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

Results obtained were consistent and within the ranges indicated for RCC pavements by ACI and the USACE documents (ACI 1995, USACE 2000). Densities were about 96 to 100% of the theoretical maximum constituent density (TMCD). A theoretical maximum constituent density (TMCD) may be defined as the density of the RCC constituent materials if it were possible to remove all air voids from the mixture. Using the percentages of all the components in the mix design and their specific gravities, the TMCD may be calculated using the following equation:

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

Where P stands for percentage of the total weight of materials used in the mix, and RD is relative density of each constituent material. The 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 (Atkins, 1997). It is possible for TMCD to exceed 100% due to concrete shrinkage during the curing process. The TMCD corresponds to about 106 % of Proctor, based on the six tests performed as part of this research. The maximum unit weight may be calculated using the previous TMCD value in the following equation:

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

where γ is the maximum unit weight, and γ_w is the unit weight of water which is equal to 62.4 lb/ft³ (1,000 kg/m³). The difference between the field density and the TMCD also corresponds to the amount of entrapped air in the RCC.

The relationships between strength (compressive and splitting tensile) and density for the three mix designs are shown in figures 6 and 7. 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 predict the actual in place strength of the pavement.

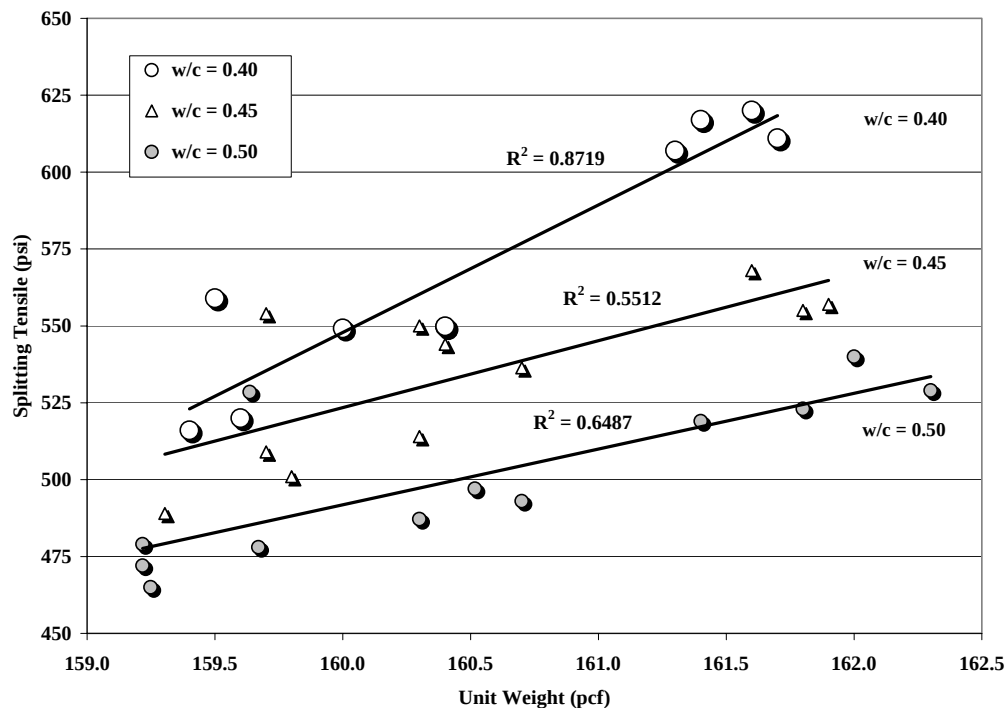


Figure 6. Splitting tensile strength versus unit weight (1 psi = 6.89 kPa, 1 pcf = 16.0 kg/m³)

For example, if the desired splitting tensile strength is 550 psi (3,790 kPa) 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 160 pcf (2,560 kg/m³). If 0.45 is the water/cement ratio then the unit weight must be 161.3 (2,590 kg/m³). 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. Therefore, this method allows the project engineer to balance material costs and construction methods to ensure quality. Figure

6 also shows that the RCC with the lowest water/cement ratio (0.40) benefits the most from increased compaction.

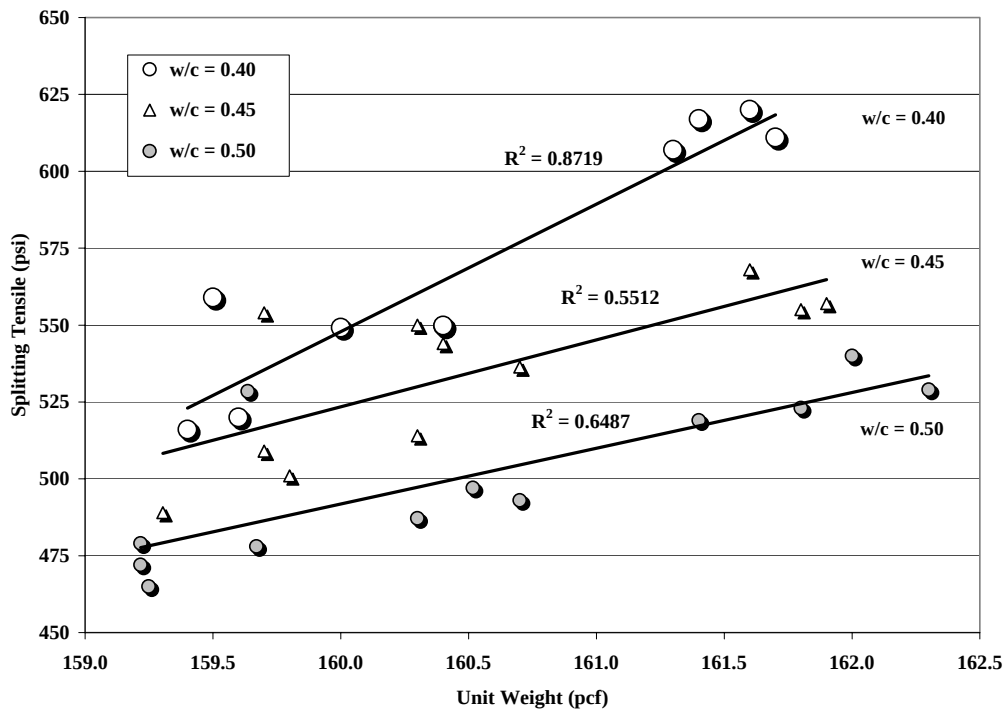


Figure 7. Splitting tensile strength versus unit weight (1 psi = 6.89 kPa, 1 pcf = 16.0 kg/m³)

The reported strength and dry density results from the two industrial paving projects were obtained. Strength results in both test series were very close. In test series A, 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 compressive strength difference was 4.7 % between the lab and the field, but splitting tensile difference was less than 2 %. The average Proctor dry density achieved in the field was 145.6 pcf (2,330 kg/m³). For laboratory specimens, the wet density average, for the same test series, was 157.4 pcf (2,520 kg/m³). Dry density may be obtained using the following relation (Atkins, 1997):

$$\gamma_d = \gamma_w / (1 + w) \quad (3)$$

where γ_d is the dry density and γ_w is the wet density, and w is the water content. Therefore, the dry density of the laboratory specimens is 147.5 lb/ft³, (2,360 kg/m³) 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 some had been fabricated using an impact hammer. These were drilled with a 3.75-inch (95 mm) core bit, and more than 50 cores were obtained.

The cores were tested for density and either compressive or splitting tensile strength. Results are shown in figures 8 and 9, along with best-fit lines and 28-day 75 gyration specimens from test series B. The laboratory specimens are consistent with the densest and strongest specimens. However, it seems clear that specimens in the 50 to 60 gyration range, rather than 75 gyrations, would provide a better approximation of the field properties from this test strip.

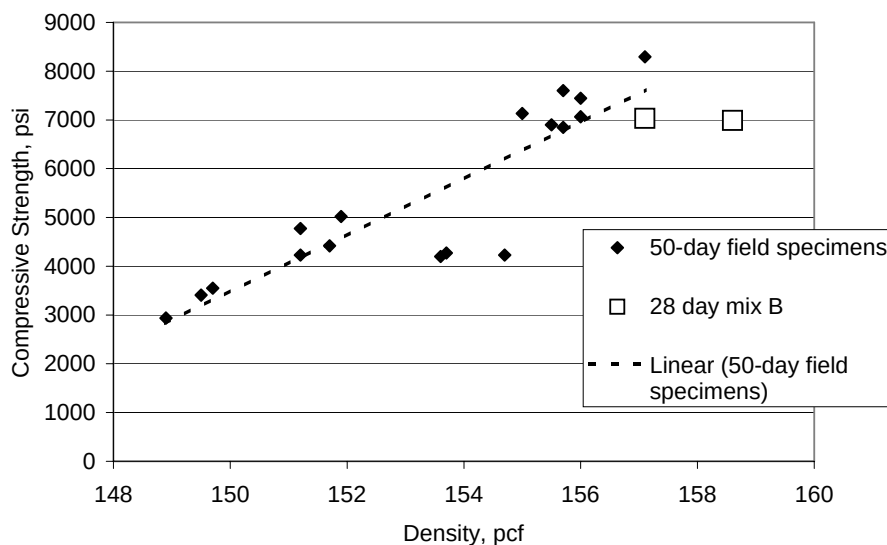


Figure 8. Density versus compressive strength of cores

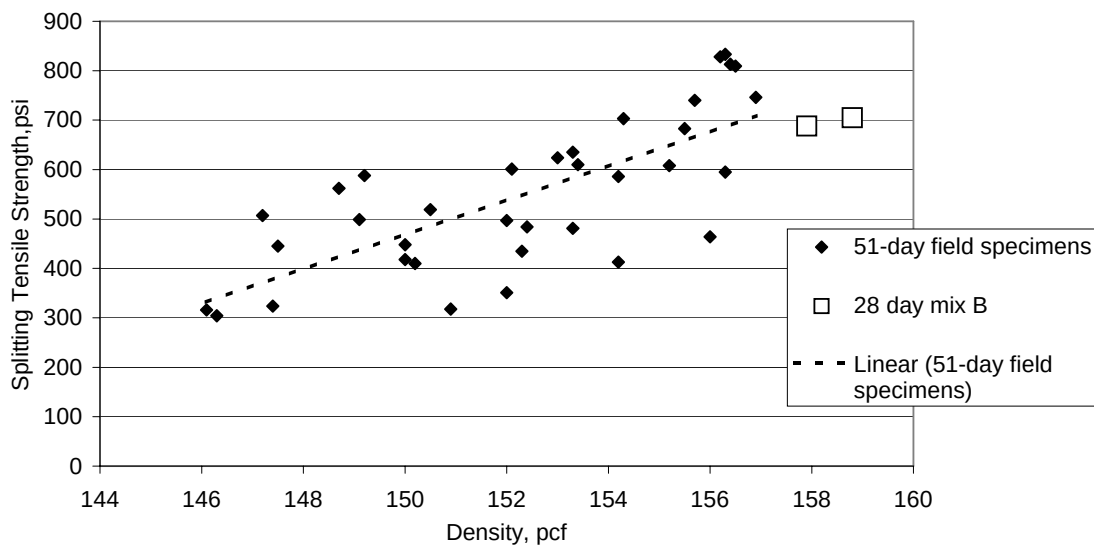


Figure 9. Density versus splitting tensile strength of cores

Effect of Density on Freeze-Thaw Durability

Although the strength of RCC has been thoroughly investigated, the freeze-thaw durability of RCC remains a topic of contention. Piggott (1999) found excellent field performance of RCC in harsh environments, including northern states and Canada. In contrast, ACI Committee 211 (2003) states that “RCC should not be considered resistant to freezing and thawing unless it is air-entrained or some other protection against critical saturation is provided.” This statement appears to be based on theory and not on field observations.

Therefore, following the investigation of strength properties, the next phase was to evaluate the freeze-thaw durability of RCC. The main objectives of this phase of research program were to determine the effects of the following variables on the freeze-thaw resistance of concrete.

- Density
- Cement content
- Water/cement (w/c) ratio

Test variables for the study were degree of compaction (50 or 90 gyrations), low and high water content (220 and 255 pounds per cubic yard (131 and 151 kg/m³)), and w/c ratio (0.40, 0.45, and 0.50 for low water content and 0.50, 0.60, and 0.70 for high water content). The gyratory compactor was used to produce two replicate specimens for each combination of test variables, for a total of 24 specimens.

Only the low water content test results, which are representative of RCC pavement construction, are reported in this paper. Other details, including the results from the high water content specimens representing dam RCC, are reported in Delatte and Storey (2005).

Specimens were 6 inches (150 mm) in diameter and ranged in height from 6.25 to 6.5 inches (159 to 165 mm), with an average of 6.32 inches (161 mm). After mixing and compaction, the specimens were cured in a water bath for 14 days. After curing, the specimens were sawn into prisms.

Typically, prisms for ASTM C 666 are cast in beam molds to produce specimens 3 x 4 x 16 inches long (75 by 100 by 400 mm). However, beam specimens of this type are not representative of field compacted RCC, because it is very difficult to compact the RCC within the molds. As a result, sawn prisms were used for this study. The drawback of the use of the gyratory compactor was the relatively shorter length of the specimens.

Prisms were placed in a freeze-thaw machine for testing in accordance with ASTM C 666 Procedure A, freezing and thawing in water (ASTM, 1992). The machine was programmed for 36 cycles of freezing and thawing over 6 days, with a total of 300 cycles applied in just over 8 weeks. The machine is designed to hold 18 prisms 3 x 4 x 16 inches long (75 by 100 by 400 mm). Since the RCC prisms were considerably shorter, several prisms could be tested in each specimen container. Figure 10 illustrates a specimen with severe freeze-thaw damage.



Figure 10. Specimen with freeze-thaw damage

Typically the freeze-thaw durability of concrete is assessed by measuring the fundamental flexural frequency of the specimen, using a sonometer (ASTM, 1992). In this instance, due to the short length of the RCC specimens, the frequency results were not considered to be reliable. Therefore, the mass loss of each specimen was determined instead, up to a total of 300 cycles.

Figures 11 and 12 compare mass loss of different specimens at 103 and 133 cycles, respectively. There is obviously considerable variation in mass loss. However, the denser specimens suffered less mass loss than the less dense specimens. The specimens with the lowest w/c ratio also achieved the greatest density. Mass loss decreased significantly with decreasing w/c ratio.

Further research is needed to develop relationships between field performance and mass loss. It will be necessary to develop a limit or range of limits on mass loss to use in mixture design and evaluation. Additional details on the testing and results are provided in Delatte and Storey (2005). They suggested a mass loss failure criterion for RCC of approximately 7 to 8 %.

Recommendations for RCC Mixture Design and Proportioning

With conventional concrete, strength and durability are functions of the materials selected and the mixture proportions, provided that the fluid mixture may be reasonably well consolidated. In contrast, with RCC, a range of field densities are possible based on the placing and compaction equipment used.

Therefore, it is recommended that design procedures for RCC mixtures consider the level of compaction attained in the field. Ideally, design methods should

employ equipment that can closely replicate field compaction. The gyratory compactor is a suitable apparatus for replicating field density. Previous research (Amer, 2002) found a coefficient of variation of density of 0.66 %.

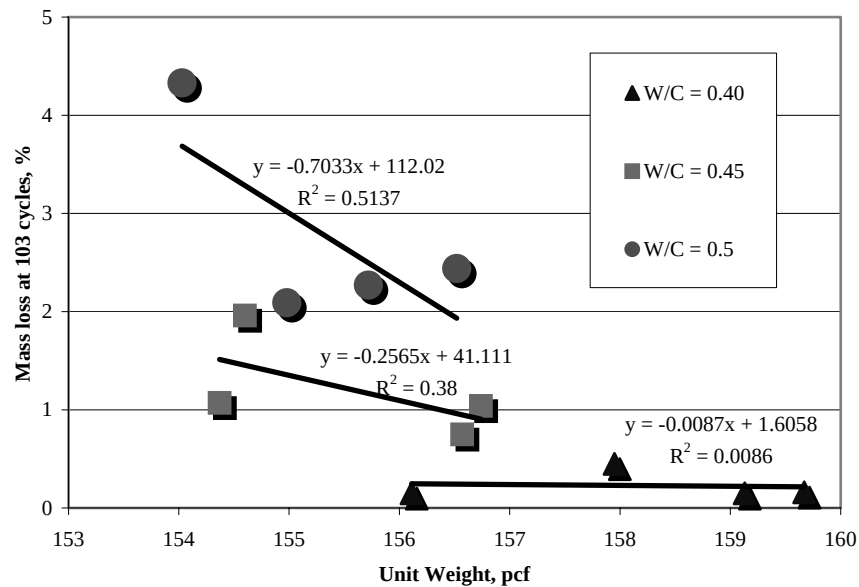


Figure 11. Mass loss (103 cycles) versus unit weight

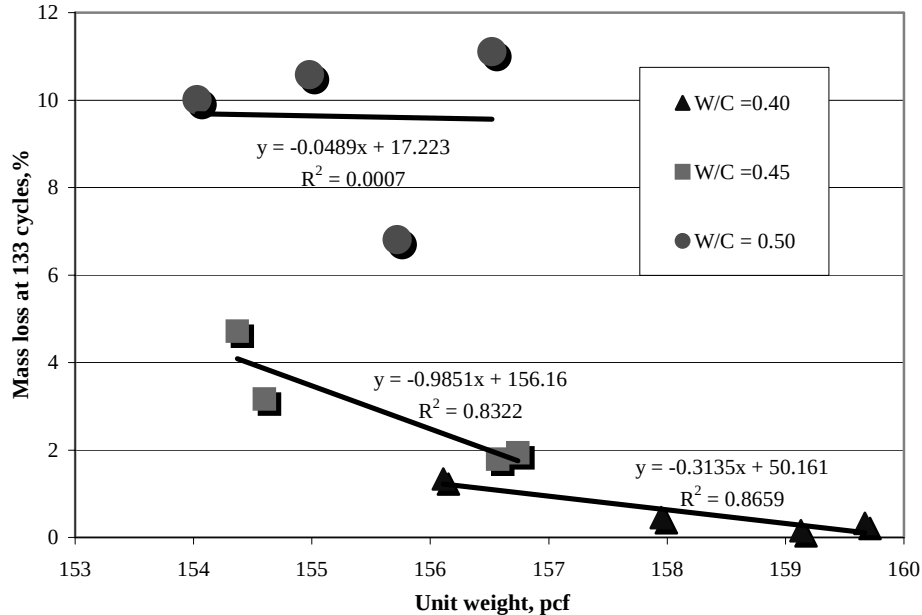


Figure 12. Mass loss (133 cycles) versus unit weight

Summary and Conclusions

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. This is important, because an increase of 1 or 2 percentage points in density can result in strength increases of approximately 10 to 17 %.

This research program has demonstrated that a gyratory compactor may be used to produce laboratory specimens that accurately and repeatably replicate field conditions. Strength and density results for RCC specimens fabricated using the gyratory compactor were consistent. Satisfactory agreement with field results was obtained. 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.

The effects of density and mixture parameters on the strength and density of RCC have been shown. The mixture parameters of interest include the water/cementitious material ratio, the maximum size of aggregate, and the water content. For the relatively narrow ranges tested, freeze-thaw durability of RCC was affected more strongly by w/c ratio than density. Freeze-thaw resistance increases as w/c ratio decreases and cement/paste content increases.

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.

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