Grout-Enriched Roller-Compacted Concrete—Phase I Investigation

by James E. McDonald

BACKGROUND

Because of the relatively low workability of roller-compacted concrete (RCC), formed surfaces are typically characterized by significant voids, reduced strength, and poor durability. Consequently, some type of facing system is used for most RCC dams. A wide variety of methods, including cast-in-place concrete, precast concrete, and membrane systems, have been used, individually and in combination, to construct facings for RCC dams that provide a durable surface and minimize permeability of the structure.

Conventional concrete placed simultaneously with the RCC and internally vibrated is the most popular facing system. This method provides an attractive face that is durable and reasonably watertight at a moderate cost. The system, however, has several drawbacks: two mixing plants are required, and achieving full compaction at the RCC-conventional concrete interface can be difficult.[1]

Grout-enriched RCC (GE-RCC) has been used on some recent projects to provide durable RCC surfaces with reduced permeability. In this approach, cementitious grout is poured over about a 0.4-m (1.3-ft) strip of the RCC lift surface along the vertical formwork. Once the grout soaks into the RCC, the mixture can be successfully consolidated with internal vibrators (Figure 1) to form a homogenous, impervious RCC facing.[2]

According to Forbes,[2] the primary benefits of GE-RCC include

- High-quality formed finish.
- Enhanced durability.
- Impervious face.
- Facing that is homogenous and monolithic with the adjacent RCC.
- Ease of construction.
- Low cost.

[1] Hansen, K. D., "The Many Faces of RCC," *Civil Engineering*, ASCE, Vol 71, No. 4, Reston, VA, pp 48-53, April 2001.

[2] Forbes, B. A., "Grout Enriched RCC: A History and Future," International Water Power & Dam Construction, Wilmington Business Publishing, Dartford, Kent, UK, pp 34-38, June 1999.

Figure 1. Consolidation of GE-RCC along upstream face of dam
(after Forbes 1999)

The main requirements and limitations of GE-RCC are as follows:

- The parent RCC needs to have a medium to high paste content with reasonable workability (Vebe consistency of about 20 sec).
- Quality control relies on good inspection and an understanding of the requirements by those responsible for grout application and consolidation.
- Lift joint treatment is necessary, similar to conventional concrete lift surfaces.
- More difficult to obtain level, troweled surfaces with GE-RCC compared with conventional concrete.

The grout-enriched RCC technique has been successfully used in nearly all of the RCC dams constructed in China since 1990. The method has also been used with similar success on RCC dams in Australia, New Zealand, Jordan, and Algeria. Visual inspections of the formed surfaces and cores taken from these structures indicate that the GE-RCC facings are aesthetically pleasing and homogenous; however, available technical data on material properties are very limited. Consequently, a study was initiated by the U.S. Army Corps of Engineers to investigate the potential for use of GE-RCC in hydraulic structures and to determine pertinent material properties. Initial results of this study are summarized herein.

SCOPE

The first phase of the GE-RCC study was initiated in April 2001. This effort included proportioning a series of grout mixtures and determining pertinent fresh and hardened properties, and a preliminary evaluation of techniques to obtain optimum consolidation of GE-RCC, placement of a full-scale test section in connection with the North Fork Hughes River Dam (NFHRD), and laboratory testing of cores from the test section to determine pertinent material properties.

LABORATORY STUDY

The objectives of the Phase I laboratory study were to

- Proportion air-entrained grout mixtures for optimum enrichment of the RCC.
- Establish grout volume necessary for air-entrained grout enrichment of the RCC.
- Evaluate placement and consolidation procedures to maximize grout penetration.
- Determine pertinent plastic and hardened GERCC properties.

Materials from the NFHRD were shipped to the Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS, for laboratory tests. The project RCC Mixture No. 2 (designated throughout this report as RCC Mixture 2A) was selected as the representative RCC mixture and used for the laboratory studies. The mixture was batched with an equivalent cement content of 195 lb/yd^3, 59 percent Class F fly ash replacement by equivalent volume of cement with a *w/c* of 1.05. The average Vebe consistency of the mixture was 28 sec with an entrapped air content of 0.5 percent. The mixture was re-proportioned throughout the course of this work to achieve greater workability in an effort to facilitate mixing of the grout and RCC.

Grout mixtures were proportioned with the NFHRD project Type I/II cement and Class F fly ash. Water-cement ratios ranged from 0.36 to 1.00. A variety of air-entrainment and antiwashout admixtures were used in the grout mixtures. A series of GE-RCC specimens were fabricated to determine if the grout and RCC could be satisfactorily combined with internal or external vibration and to evaluate the resulting air-void system.

Grout Mixtures

Fifteen air-entrained grout mixtures were proportioned with four water-cement ratios and three air-entraining admixtures and one antiwashout admixture. Flows for the various mixtures generally ranged from 10 to 20 sec. Air contents ranged from approximately 10 to 25 percent. Compressive strengths ranged from 670 to more than 4,000 psi at 28 days.

Mixtures proportioned with a 0.5 *w/c* or less exhibited little or no bleeding and appeared suitable for grout enrichment of RCC. The addition of fly ash to the grouts appeared to improve workability.

Air contents and flows ranged from 13.0 to 20.1 percent and 14 to 20 sec, respectively, for a given dosage of air-entraining admixture. Based on the limited tests conducted, the MB VR admixture provided the highest air content for a given dosage. The air-void system entrained with the MB VR admixture exhibited good long-term stability under static conditions. However, insertion of a nominal 1-in. vibrator into the freshly mixed grout for 15 sec resulted in air content losses of more than 50 percent. Adding an antiwashout admixture to selected grout mixtures resulted in significant reductions in air content with minimal improvement in stability of the air-void system during vibration.

Combined Grout and RCC Mixtures

Various combinations of grout mixtures J and P and RCC mixtures 2A and 2D were mixed in a concrete mixer to determine the volume of grout required to obtain the desired entrained air content in the composite sample. The entrained air contents in the grout ranged from 18.9 to 29.0 percent, and the entrapped air contents in the RCC ranged from 0.3 to 0.6 percent. Results of these tests (Figures 2 and 3) indicated that the volume of grout in the composite must be 20 to 25 percent or higher to produce an entrained-air content of 4 to 5 percent in the GE-RCC. The composite samples exhibited a minimum slump of 2 in.

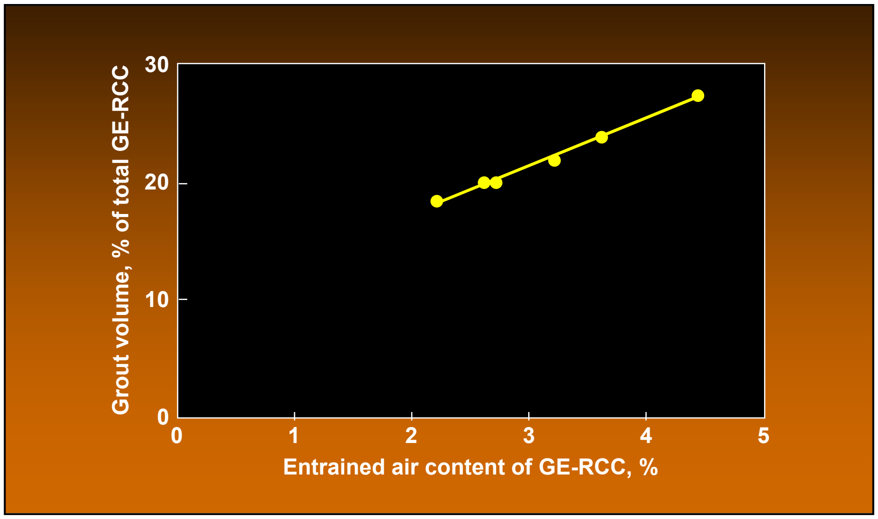

Figure 2. Grout volume versus entrained air content of GE-RCC

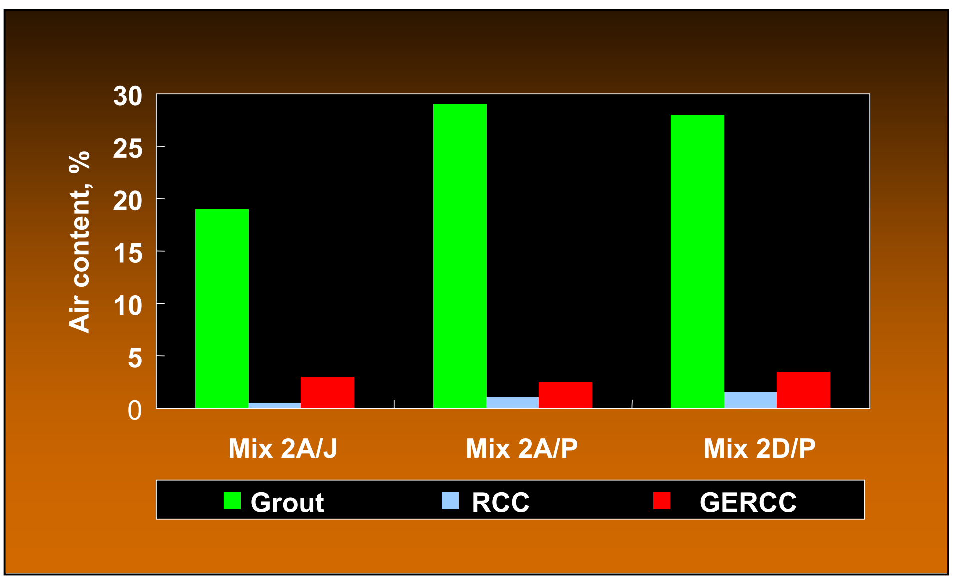

Figure 3. Typical air contents of the individual constituents and the GE-RCC combined in a high-shear concrete mixer

GE-RCC Placing and Mixing

A series of tests were made in an attempt to determine the optimum location for grout placement within an RCC lift and the effectiveness of internal and external vibration in distributing the grout throughout the RCC matrix. The initial tests were conducted in nominal 5-gal plastic buckets with red dye added to the grout in all tests to aid in visual observations.

Test B-1. Two tests were conducted using approximately 5 to 6 percent grout by volume of the GE-RCC. In the first test, RCC Mixture 2A was placed on top of a non-air-entrained grout mixture proportioned with a 1.0 *w/c*. The same materials were used in the second test with the grout placed on top of the RCC. The materials were consolidated with 4 to 5 penetrations of a nominal 1-in.-diame internal vibrator. The relatively thin grout placed on top of the RCC did not readily penetrate although the RCC was placed loosely. Mixing of the grout and RCC was confined to small zones immediately adjacent to the vibrator. When placed on the bottom, the grout tended to migrate up the sidewalls of the bucket and up pathways left by the vibrator shaft. Internal vibration did not produce the desired mixing in either case.

Test B-2. This test was similar to B-1 except that RCC was placed on top of a non-air-entrained grout mixture proportioned at a 0.75 *w/c*. Again, internal vibration did not produce the desired mixing of the grout and RCC except in the small zones immediately adjacent to the vibrator insertion points. The more viscous grout also tended to migrate up the sidewalls of the bucket and up pathways left by the vibrator shaft.

Test B-3. The final test of the initial series was conducted using approximately 10 to 12 percent grout by volume of the GE-RCC. In this case, the non-air-entrained grout mixture, proportioned with a 0.75 *w/c*, was equally divided between the bottom and top of the RCC lift. Internal vibration was the same as in previous tests with similar results. Mixing of the grout and RCC was confined to small zones immediately adjacent to the vibrator insertion points. The grout placed on the bottom tended to migrate up the sidewalls of the bucket and up pathways left by the vibrator shaft, and the grout placed on the top did not penetrate into the RCC.

Test S-1. Nominal 12-in. cube specimens fabricated in the ends of steel beam molds were used for the second series of tests. In the first test, approximately 2 in. of grout mixture M (15 to 20 percent by total volume) was placed in the bottom of the mold and covered with RCC Mixture 2A. The RCC was lightly hand-tamped to simulate dozer spreading and vibrated with five insertions of a nominal 2-in. internal vibrator, one insertion at each corner and one in the center. As previously observed with the smaller bucket samples, the grout easily migrated up the sidewalls of the form and up pathways left by the vibrator shaft. Fairly good distribution of grout and RCC was observed in the bottom 6 in. of the specimen, but this was attributed to placing loose RCC directly into the grout that was pooled in the bottom of the form. Large areas located in the top half of the specimen between vibrator penetrations exhibited no mixing, as evidenced by the lack of red grout.

Test S-2. The second test was conducted with the same materials and quantities as Test S-1 except the grout was placed on top of the lightly hand-tamped RCC. The specimen was vibrated using five insertions of the 2-in. internal vibrator, one insertion at each corner and one in the center. At each insertion point, the vibrator was held in place longer (approximately 10 to 15 sec) compared to the previous test. The grout did not migrate down the formed faces of the specimen except at the very top of the specimen. Grout was observed in the zones where the vibrator penetrated; however, there was minimal mixing of the RCC and grout overall.

Test S-3. This test was conducted with RCC Mixture 2A and grout Mixture P. Approximately 2 in. of grout (15 to 20 percent by total volume) was placed at the bottom of the mold and covered with RCC. The RCC was tamped in place with a shovel, and the specimen was vibrated using five insertions of a 2-in. internal vibrator, one insertion at each corner and one in the center. Each penetration of the vibrator was limited to approximately 7-in. depth so that the tip of the vibrator did not enter the grout zone at the bottom of the specimen. Grout covered all of the formed faces of the specimen. Fairly good distribution of grout and RCC was observed in the bottom 6 in. of the specimen (similar to Test S-1), but this was again attributed to placing loose RCC directly into the grout that was pooled in the bottom of the form. Large areas in the top one-half of the specimen showed no evidence of mixing. There was no evidence that the increased fluidity of grout Mixture P, compared with Mixture M, produced better grout distribution.

Test S-4. This test specimen was fabricated using the same materials as S-3 except that the grout was placed on the top of the shovel-tamped RCC. Approximately 1 in. of grout remained on the top surface after vibration. The maximum depth of grout penetration was approximately 1.5 to 2 in. into the RCC. Only the top portions of the formed faces of the specimen were covered with grout. Overall, the grout and RCC was poorly mixed.

Test S-5. The RCC mixture was revised to increase workability in this test. The test was conducted with RCC Mixture 2B (17 sec Vebe consistency) and grout Mixture P. Approximately 2 in. of grout (15 to 20 percent by total volume) was placed in the bottom of the mold and covered with RCC. The specimen was covered with a 3/4-in.-thick plywood plate and compacted with a pneumatic pole tamper to simulate a plate compactor. Formed faces of the specimen were covered with grout, but there was no grout under the plywood plate. There appeared to be little or no migration of grout to the top half of the specimen. The bottom one-half of the specimen had a slump consistency; however, there were also distinct zones at the bottom of the specimen that were clearly not mixed. An air content test conducted on the bottom portions of the specimen indicated an air content of 0.2 percent (corrected with an assumed aggregate correction factor of 0.8 percent).

Test S-6. The final test of this series was the same as Test S-5 except that the grout was placed at the center of the RCC. Grout was noted on the formed faces but was not observed under the plywood plate. The grout extended from the center of the RCC lift up approximately 3 in. The grout and RCC did not appear to be well mixed. In both tests conducted with the pole tamper, there was less evidence of grout and RCC mixing compared with tests conducted with internal vibration.

Test R-1. Additional tests were conducted with a RCC mixture that was again revised to increase workability (10 to 12 sec Vebe consistency). This test was conducted with RCC Mixture 2D and Grout Mixture P. Approximately 5 to 6 percent grout by volume of the total GE-RCC was placed in the bottom of a 5-gal bucket and covered with RCC. The specimen was vibrated with a single insertion of the 2-in. vibrator and held until the entire mass appeared to mobilize. Grout migrated up the sidewalls of the bucket and up pathways left by the vibrator shaft; however, very little mixing of the grout and RCC was observed.

Test R-2. This test was identical to R-1 except that the specimen was vibrated with four insertions of the 2-in. vibrator. Results of this test were essentially the same as Test R-1: grout migrated up the sidewalls of the bucket and pathways left by the vibrator shaft, with very little mixing of the grout and RCC between the locations where the vibrator was inserted.

Test R-3. This test was identical to R-1 except that after the 2-in. vibrator was moved in a circular stirring motion after insertion. Very little mixing of the grout and RCC was observed. It appeared that the entire sample rotated with the movement of vibrator shaft; therefore, very little mixing was accomplished.

Test R-3a. RCC Mixture 2C and Grout Mixture P were used for this test in a Vebe pot to determine if external vibration applied to the bottom of the specimen would improve mixing of the grout and RCC. Approximately 15 percent grout by volume of the GE-RCC was placed in the bottom of a Vebe pot and covered with RCC. The sample was then vibrated for approximately 30 sec. Grout migrated up the sidewalls of the pot with some accumulation of grout at the surface. Although the grout was dispersed throughout the specimen, the grout and RCC were not well mixed. The bottom one-half of the specimen appeared to be better mixed compared to the top, but this was probably the result of placing loose RCC directly into the grout that was pooled in the bottom of the pot.

Test R-4. This test was conducted with RCC Mixture 2D and Grout Mixture P. Approximately 15 percent grout by volume of the GE-RCC was placed at the bottom of a 5-gal bucket and covered with RCC. A 2-in. vibrator was inserted into the specimen and the vibrator was twice moved diametrically across the specimen, forcing the vibrator shaft to move through the RCC and grout. Stirring the sample with the vibrator appeared to be a significantly more effective mixing technique compared with multiple vibrator insertions. Grout distribution within the RCC was better than in any of the previous tests. A portion of the GE-RCC was used to cast a 3.5- by 4.5- by 16-in. beam for testing to determine resistance to cycles of freezing and thawing.

Test R-5. This test was identical to R-4 except that approximately 20 percent grout by volume of GE-RCC was placed at the bottom of the bucket before covered with RCC. Also, four diametric stirring passes were made with the vibrator compared with two passes in Test R-4. Once again, the vibrator stirring technique appeared to be a significantly more effective mixing technique compared to simply inserting the vibrator at selected locations. After visual examination of the sample, remnants of the GE-RCC were tested to determine air content. The GE-RCC exhibited an air content of only 0.2 percent. Apparently, the high air content of the grout is lost during vibratory mixing of the GE-RCC.

Block test. In the final test, a larger sample was cast for subsequent coring to provide specimens for testing to determine properties of hardened GE-RCC that was mixed in place. Three sides of the 18- by 36- by 14-in. form were fabricated with Plexiglas to allow increased visual observation of the materials during placing and mixing. The test was conducted with RCC Mixture 2D and Grout Mixture P. Approximately 25 percent grout by volume of the GE-RCC was placed in the bottom of the form and covered by RCC placed with shovels. A vibrator was inserted full depth into the specimen at one end and pulled full length of the formed specimen and then extracted. This process was repeated until four passes were made through the full length of the specimen, spaced equally across the width. This mixing technique appeared to disperse the grout throughout the RCC. Subsequent coring and sawing confirmed these observations: with the exception of a relatively small zone at the top of the specimen near the left rear corner, the red grout was uniformly distributed throughout the block.

Properties of Hardened RCC and GE-RCC

The addition of 20 percent grout by volume of the GE-RCC increased the 27-day strengths of RCC Mixtures 2A and 2D by 94 and 163 percent, respectively, for specimens cast from materials mixed in a laboratory mixer (Figure 4). Similarly, the addition of 27.3 percent grout by volume of the GE-RCC increased the 27-day strength of RCC Mixture 2D by 209 percent. The compressive strengths of cores obtained from the GE-RCC block, 25 percent grout by volume mixed with RCC Mixture 2D by internal vibration, averaged 910 and 1,150 psi at 29 and 78 days, respectively. The strength at the earlier age is essentially the same as the strength of specimens of similar age and material (20 percent grout by volume) blended in a laboratory mixer.

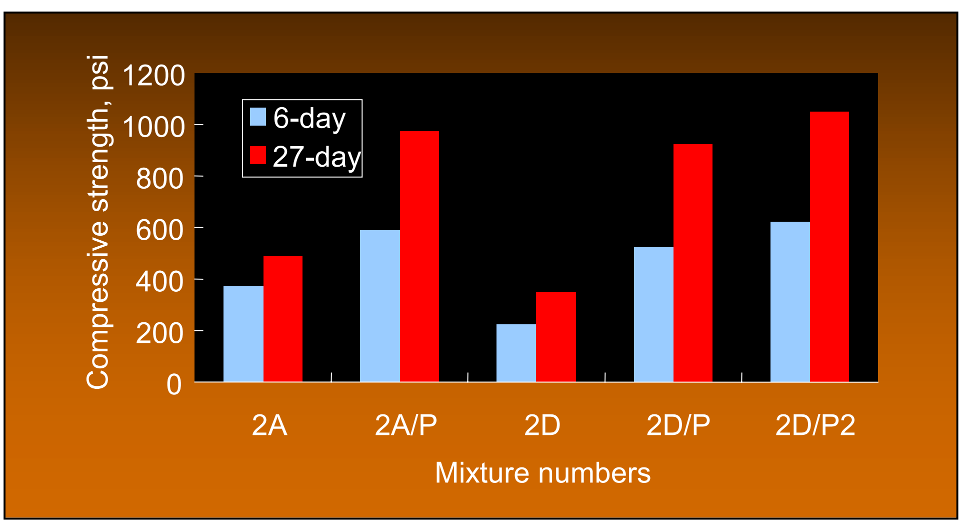

Figure 4. Effect of grout enrichment on compressive strength

Beams (3.5 by 4.5 by 16 in.) were cast from RCC and GE-RCC mixtures where the materials were mixed in laboratory mixers. Similar specimens were sawed from the GE-RCC block. These specimens were tested in accordance with ASTM C 666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure A, Rapid Freezing and Thawing in Water. Results of these tests are summarized in Figure 5.

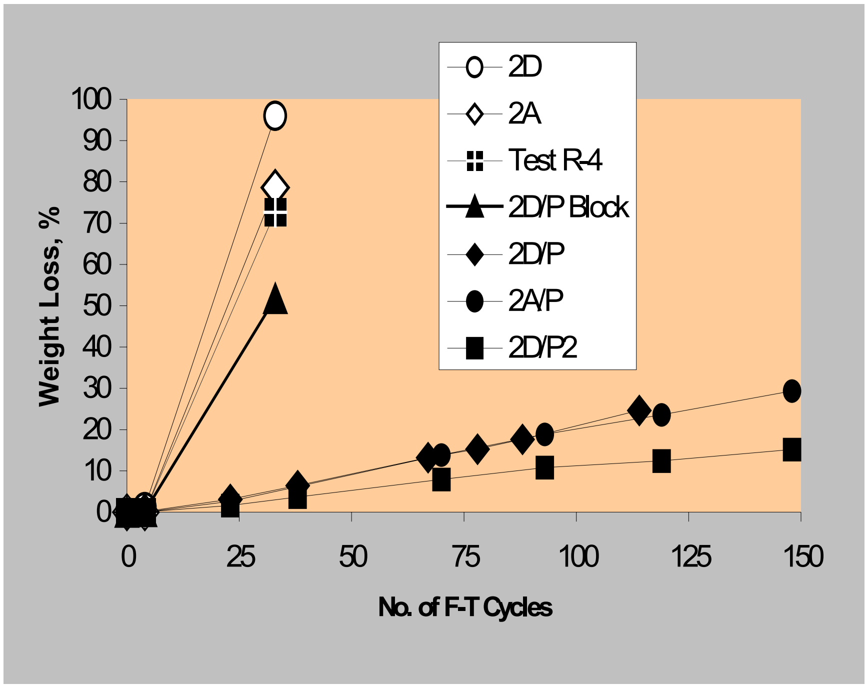

Figure 5. Results of freeze-thaw tests

As expected, the non-air-entrained RCC mixtures (2A and 2D) exhibited essentially no resistance to cycles of freezing and thawing with minimum weight losses of 70 percent after only 33 cycles. However, enrichment of these RCC mixtures with air-entrained grout (20 percent grout by volume with an air content of 29 percent) resulted in significant improvements in freeze-thaw resistance. GE-RCC Mixtures 2A/P and 2D/P exhibited essentially the same resistance to freezing and thawing with average weight losses of 24 and 25 percent after 119 and 114 cycles, respectively. Increasing the volume of grout in the GE-RCC resulted in further increases in resistance to freezing and thawing. GE-RCC Mixture 2D/P2 (27.3 percent grout by volume with an air content of 28 percent) exhibited an average weight loss of 15 percent after 148 cycles. In contrast to the performance of GE-RCC specimens cast from materials mixed in laboratory mixers, specimens of similar materials mixed with internal vibration exhibited essentially no resistance to cycles of freezing and thawing. The specimen cast from GE-RCC mixed in a bucket by stirring with a vibrator (Test R-4) exhibited a weight loss of 73 percent after only 33 cycles, essentially the same result obtained with non-air-entrained RCC. Specimens obtained from the larger GE-RCC block (2D/P) performed only slightly better with an average weight loss of 52 percent after 33 cycles.

Following completion of the freeze-thaw testing, samples of each material were examined to determine air contents of the hardened specimens. Results of the air-void system evaluation correlated well with results of the freeze-thaw testing. RCC Mixtures 2A and 2D did not contain entrained air and performed very poorly when subjected to cycles of freezing and thawing. In contrast, GE-RCC Mixture 2D/P2, with the highest intentionally entrained air content (3.29 percent) and the highest volume of entrapped air voids less than 1-mm diameter (1.24 percent), exhibited the best resistance to cycles of freezing and thawing. Also, Mixture 2D/P2 was the only mixture with an air-void spacing factor less than 0.008 in., the spacing factor generally considered to be the maximum allowable for resistance to freezing and thawing. The two remaining GE-RCC Mixtures (2A/P and 2D/P) that were mixed in laboratory mixers exhibited significantly lower entrained and entrapped (<1 mm) air contents, 1.28 and 1.62 percent total, respectively. However, the spacing factors for these mixtures were only slightly higher than 0.008 in. (0.0085 and 0.0100 in.), and the freeze-thaw resistance of these mixtures was similar to that of Mixture 2D/P2.

Results of the air-void system examination illustrate the significant adverse impact of mixing GE-RCC with internal vibration. Combining RCC Mixture 2D with 20 percent by total volume of Grout Mixture P (29 percent air content) in a laboratory mixer resulted in a GE-RCC mixture with an air-void (<1 mm) content and spacing factor of 1.6 percent and 0.010 in., respectively, that exhibited relatively good resistance to cycles of freezing and thawing. In comparison, combining similar materials with a slightly higher grout volume (25 percent) in the GE-RCC block with internal vibration resulted in the same air-void (<1 mm) content; however, vibration resulted in a spacing factor (0.021) that was more than twice that obtained with conventional mixing. Consequently, the GE-RCC block exhibited poor resistance to cycles of freezing and thawing. Combining similar materials with a lower grout volume (15 percent) with internal vibration in a Test R-4 resulted in a significantly lower air-void (<1 mm) content (0.45 percent) and an even higher spacing factor (0.024). As a result, the freeze-thaw resistance of the GE-RCC in Test R-4 was very poor, essentially the same as exhibited by non-air-entrained RCC.

FIELD TEST SECTION

A field test was conducted on May 17, 2001, to evaluate various methods for construction of GE-RCC. The test section was located at the site of an RCC dam under construction on the North Fork of the Hughes River near Harrisville, WV. The contractor for construction of the dam, Barnard Construction Company, Inc., constructed the test section. The field test was conducted under the direction of the RCC Steering Committee. David Kiefer (U.S. Army Corps of Engineers, Louisville District) chairs the committee that was formed in November 2000 to advance RCC technology. Committee members represent both the public and private sectors.

The test section was approximately 16 ft wide and 32 ft long and was formed on three sides. The RCC was placed in 1-ft lifts, and each lift was divided into five zones (A through E) for evaluation of different construction techniques. Results of the field test are summarized in the following sections.

Lift 1

The RCC for this lift was a mixture containing crushed coarse aggregate and manufactured sand that was used in the North Fork Dam. Unfortunately, the author has been unable to obtain proportions for any of the RCC or grout mixtures used in the test section. The Vebe time of this mixture was reportedly about 20 sec. The grout used in this lift contained natural sand, an air-entraining admixture, and exhibited a flow of approximately 15 sec.

The grout in Zone A was placed at the bottom and middle of the RCC lift. The GE-RCC was vibrated with a plate vibrator. The grout appeared to travel up the form face, and the top of the lift was smooth after compaction. Unfortunately, the dye provided was not used in the grout. This omission made it difficult to accurately determine how the grout was dispersed within the RCC; however, it did not appear that the grout was mixed into the RCC.

The grout in Zone B was placed on top of the RCC lift, and internal vibration was provided with two 3-in. vibrators mounted on a small hydraulic backhoe (Figure 6). The grout appeared to be too thick to

Figure 6. Vibration of Lift 1, Zone B

permeate down through the RCC, and an insufficient quantity of grout was placed on top of the RCC. The vibrators made post-holes in the RCC, which then filled with grout. The grout did not appear to be mixed into the RCC.

The grout in Zone C was placed at the bottom of the RCC lift, and internal vibration was provided with two 3-in. vibrators mounted on a small hydraulic backhoe. Results were essentially the same as previously described for Zone B.

The grout in Zone D was placed in the middle of the RCC lift, and internal vibration was provided with two 3-in. vibrators mounted on a small hydraulic backhoe. An insufficient amount of grout was placed. Initial vibration created post-holes in the RCC. The backhoe was then used to drag the vibrators through the RCC, creating ditches into which more grout was placed. An electric 2-in. vibrator was then used to provide additional vibration. It was not clear if this method provided adequate mixing of the RCC and the grout.

The grout in Zone E was placed in the middle and bottom of the RCC lift, and internal vibration was provided with vibrators mounted on a small hydraulic backhoe. An insufficient amount of grout was placed. The vibrators made post-holes in the RCC, but the grout was not drawn into the holes. The grout did not appear to mix with the RCC.

Lift 2

The RCC for this lift was also a mixture used in the North Fork Dam. The RCC reportedly contained the same materials as in Lift 1 but was a little wetter with a Vebe time of 15 sec. The neat-cement grouts (1.5 and 1.0 *w/c*) contained intentionally entrained air. These grouts were reportedly very wet.

Zone A was divided into two sections. The RCC in Zone A1 was left about 2 to 3 in. below the lift line, and grout with a 1.5 *w/c* was placed on top of the RCC and allowed to stand for a few minutes. The GE-RCC was vibrated with a 2-in. electric vibrator attached to a metal rod to aid in insertion of the vibrator. This method appeared to work very well, and the GE-RCC appeared to be fairly well mixed. The vibrator would leave a post-hole when removed, but it would then close when the adjacent concrete was vibrated. This phenomenon is typical of low-slump mass concrete placements.

The RCC in Zone A2 was also left below the lift line and the 1:1 grout placed on top. The grout appeared to soak into the RCC but when the top 1 in. was removed with a shovel, it was apparent that the grout had penetrated only a short distance into the RCC. The GE-RCC in Zone A2 did not respond to internal vibration as well as it did in Zone A1. However, it should be noted that, because of delays in the operation, the RCC in Zone A2 was more than 1 hr old at the time of vibration.

In Zone B, the grout was injected into the RCC with a stinger pipe with a closed, pointed end and holes drilled into the sides (Figure 7). The stinger was approximately 1-in. in diameter with 3/8-in.-diam holes. The RCC was placed to the full lift thickness, spread, and tracked into place with a dozer. The stinger was then inserted into the RCC at approximately 12 in. on center, and grout with a 1.5 *w/c* was injected. The stinger could only be inserted a few inches by hand, and further insertion required driving with a rubber mallet. The need for driving slowed the process; however, grout injection progressed smoothly and grout was observed penetrating into the RCC and into previous injection holes. The GE-RCC was vibrated with a 2-in. vibrator, and the grout appeared to be fairly well dispersed within the RCC. Vibrator holes would close with adjacent vibration.

Figure 7. Grout injection with a stinger pipe and consolidation with internal vibration

Construction of Zone C was essentially the same as Zone B except that grout with a 1.0 *w/c* was injected. Construction of this zone was more difficult compared to Zone B. That is, the grout did not move to adjacent stinger holes as well as in Zone B, and vibrator holes did not close with adjacent vibration. The age of the RCC, more than 1 hr old when grout was injected, is believed to have been a significant factor in the difficulties experienced.

In Zone D, grout was sprayed onto the RCC as it was placed and spread against the formed face. The air-entrained grout had a 1.0 *w/c*. The objective was to control the grout spraying to obtain GE-RCC with a grout volume that was 20 to 25 percent of the total. The grout and RCC appeared to mix well with the spraying technique. The GE-RCC at the form appeared to be a uniform mixture and was easily penetrated with a 2-in. vibrator. Attempts to use a vibratory plate resulted in the plate partially sinking into the GE-RCC.

Air-entrained grout (1.0 *w/c*) was also applied with the spray technique as RCC was spread next to the form (Figure 8) in Zone E. The grout and RCC appeared to mix very well. The GE-RCC to within about 4 in. of the form was consolidated with a dozer used for RCC placement. A vibratory roller was then used for further compaction of the GE-RCC. No internal vibration was used in this zone. The GE-RCC appeared to be a uniform concrete mixture. A test on a sample of the GE-RCC indicated that the slump was 1-3/4 in.

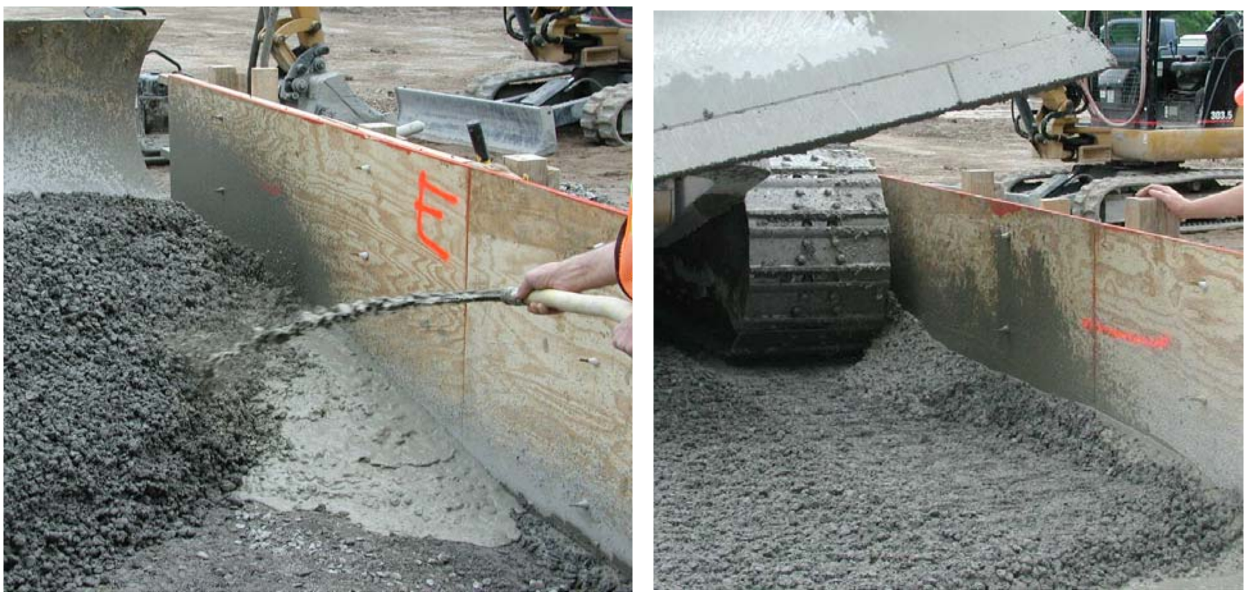

Figure 8. Spraying grout onto the RCC as it is spread, followed by consolidation with a dozer

Lift 3

The RCC for this lift was also a mixture used in the North Fork Dam construction but with a significantly higher cementitious content compared to the RCC used in the previous two lifts. The RCC contained 110 and 180 lb/yd^3 of fly ash and cement, respectively. The RCC reportedly had an approximate Vebe time of 15 sec. Also, an air-entrained RCC mixture containing natural sand was used in Zones D and E. The grout in Lift 3 was a neat-cement grout that contained entrained air in all zones except Zone A. A plasticizer was added to the grout (1.0 *w/c*) to reduce its time of efflux. The grout was reportedly very wet.

The grout in Zone A was placed on top of the RCC lift and allowed to stand for several minutes. The grout appeared to permeate into the RCC during this period. The GE-RCC was consolidated with a 2-in. internal vibrator. The grout and RCC appeared to be well mixed with this method. Some grout remained on the surface after consolidation, indicating that an excessive amount of grout was placed.
Zone B of this lift was constructed with the stinger pipe previously described in Lift 2, Zone B. The RCC was placed to the full lift thickness and spread into place. However, the RCC was not tracked with the dozer, so that it would be in a relatively loose state when the grout was injected. The stinger penetrated the RCC much easier compared to similar operations in Lift 2. The grout appeared to flow into the surrounding RCC and, following internal consolidation with a 2-in. vibrator, the GE-RCC appeared to be adequately mixed.

Zone C was constructed with essentially the same materials and methods as previously described for Zone B of this lift with the same results.

Construction of Zone D was very similar to that previously described for Zone D of Lift 2, except that an air-entrained RCC mixture containing natural sand fine aggregate was used in this zone. The air-entrained grout containing a plasticizer was sprayed onto the RCC as it was spread or placed up to the form and the GE-RCC was consolidated with internal vibration. A test on a sample retrieved immediately following consolidation indicated that the GE-RCC had an air content of 7.0 percent.

Construction of Zone E was very similar to that previously described for Zone E of Lift 2, except that an air-entrained RCC mixture containing natural sand fine aggregate was used in this zone. The air-entrained grout containing a plasticizer was sprayed onto the RCC during its placement against the formed face. The GE-RCC was consolidated externally by tracking with a dozer followed by a vibratory roller. The grout and RCC appeared to be well mixed with this procedure; unfortunately, rain prevented obtaining a sample from this zone for a determination of air content.

Test Section Examination

After removal of formwork, the formed faces of the test section were visually examined to determine the relative appearance of the GE-RCC constructed with the various materials and procedures. The surface in Zone A exhibited localized areas of honeycomb, primarily in Lift 2, that could be the result of reported delays in vibration. The Zone B surface was smooth and appeared to be well consolidated with no significant surface defects. The Zone C surface appeared to be the roughest of all surfaces with significant areas of honeycomb. Reported difficulties in grout injection and consolidation because of the advanced age of the RCC in Lift 2 probably contributed to these surface defects. A horizontal core drilled through the most severe defect indicated that the honeycomb was confined to the outer 2 in. of the section with well-consolidated GE-RCC in the interior. Spraying the grout onto the RCC as it was being placed or spread against the form and internal (Zone D) or external consolidation (Zone E) resulted in exposed faces that were generally uniform and smooth with the appearance of cast-in-place concrete.

Test Section Coring

A plan for coring the test section was developed by the RCC Steering Committee. Because of the difficulties encountered during construction of Lift 1 and time and funding constraints, the Committee decided not to obtain cores from Lift 1. In general, two horizontal cores were obtained from each zone of Lifts 2 and 3. Also, one vertical core was obtained form Zones A and B, and two vertical cores were obtained from Zone D. A total of 24 cores were obtained during July 2001. All cores were 4-in. in diameter and ranged in length from 28 to 44 in. The cores were shipped to the Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS, in PVC pipe with taped ends.

LABORATORY CORE TESTING

A visual examination indicated that the GE-RCC cores were in generally good condition, as shown in Figure 9. Based on the visual examination, portions of the cores were designated for specific tests and the specimens were sawed to appropriate lengths. For example, the transverse marks on the cores shown in Figure 9 are locations for saw cuts. The symbols x, F-T, and C (marked in white) identify specimens for hardened air content, freeze-thaw resistance, and compressive strength tests, respectively. In addition, the density of each freeze-thaw and compressive strength specimen was determined prior to testing. It was attempted to select the specimens in a manner that would provide a profile of material properties from the

Figure 9. Typical condition of GE-RCC cores

formed face or top of the test section to the interior of the section. Overall, 23 and 28 specimens were tested for compressive strength (ASTM C 39) and freeze-thaw resistance (ASTM C 666) tests, respectively. Also, 51 specimens each were tested for hardened air-void parameters (ASTM C 457) and density.

Results of the compressive strength tests on the 4- by 8-in. cores are summarized in Figure 10. The average compressive strengths for each zone of both lifts were in excess of 1,500 psi when tested at approximately 150 days age. The GE-RCC from Zones B and C of Lift 3 exhibited the highest average strengths. In each zone, the RCC was placed to the full lift thickness and spread into place. However, the RCC was not tracked with the dozer, so that it would be in a relatively loose state when grout (1.0 *w/c*) was injected with a stinger pipe. The GE-RCC was consolidated with a 2-in. vibrator. Unfortunately, no cores were obtained from any of the RCC mixtures without grout enrichment for comparison purposes. There was no obvious relationship between compressive strength and core location relative to the formed face or top of the test section.

Results of tests to determine saturated-surface-dry (SSD) densities of the compressive strength and freeze-thaw specimens are summarized in Figure 11. Overall, values for SSD densities ranged from 140.7 to 154.7 lb/ft^3. Average densities for the various zones in the two lifts ranged from 143.5 to 150.4 lb/ft^3. With the possible exception of Zone D in Lift 3, results of the density tests were fairly consistent. Air-entrained RCC was placed in Zones D and E of Lift 3. A test on a sample retrieved from the Zone D placement indicated that the GE-RCC had a plastic air content of 7.0 percent. In general, densities were slightly higher with increased depth from the formed face and slightly lower with increased depth from the top of the test section.

Results of tests to determine air-void parameters of the hardened GE-RCC are summarized in Table 1. Overall, values for entrained air content (spherical air voids <1 mm in diameter) ranged from 0 to 5.44 percent. These intentionally entrained air voids will contribute to freeze-thaw resistance if they are properly distributed within the paste. The specimen that exhibited the highest value was a portion of core

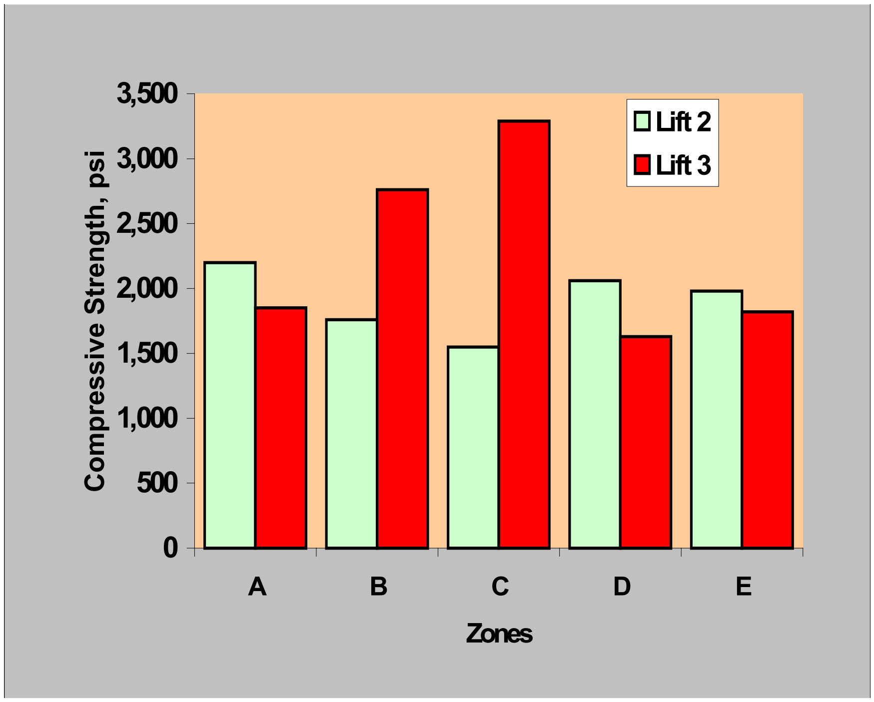

Figure 10. Summary of compressive strength test results

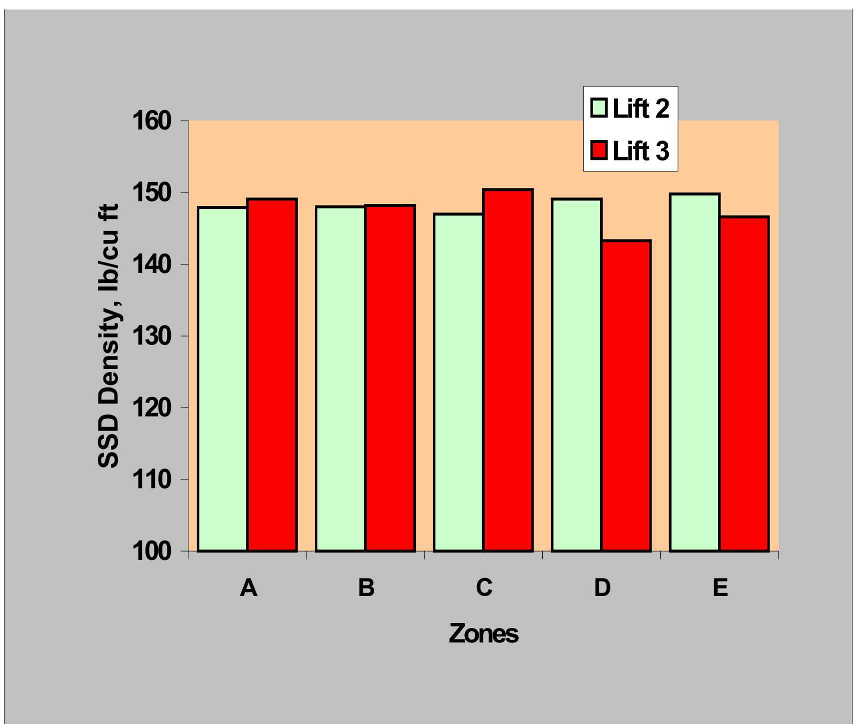

Figure 11. Summary of SSD density test results

from Zone D in Lift 3 at a depth of 1 in. from the formed face. A test during construction indicated that the plastic GE-RCC in Zone D of Lift 3 had a total air content of 7.0 percent. In general, entrained-air contents were highest for portions of core near the formed surface and decreased with depth, particularly in Zone D, where the air-entrained grout was sprayed onto the RCC as it was placed or spread against the formed face (Figure 12).

Three of the four zones that exhibited average entrained-air contents of about 1 percent or more were constructed with the grout spraying method and two of these zones used air-entrained RCC. The fourth zone (Zone A in Lift 2) was constructed by placing air-entrained grout on top of the RCC lift, allowing it to stand for a few minutes, then consolidating the GE-RCC with internal vibration.

Both entrained (spherical) and entrapped (angular) air voids less than 1-mm diameter should contribute to freeze-thaw resistance if they are properly distributed. The average values for air voids less than 1-mm diameter for the various zones in the two lifts ranged from 0.78 to 4.66 percent (Figure 13). The higher values were associated with Zones D and E where the grout was applied by spraying onto the RCC as it was being spread in both lifts. The GE-RCC in Zones D and E of Lift 3, where air-entrained RCC was used, exhibited significantly higher air-void (<1 mm) contents compared to Lift 2 where non-air-entrained RCC was used.

Overall, values for large (>1 mm) entrapped air voids ranged from 0.14 to 15.98 percent. Average values for these entrapped air voids for the various zones in the two lifts ranged from 0.71 to 6.52 percent. The higher values were associated with Zone C in Lift 2 and Zones D and E in Lift 3. Difficulties in consolidating Zone C, attributed to the age of the RCC when grout was injected, could have contributed to the high volume of large air voids. A petrographic examination was conducted on four cores from the air-entrained RCC used in Zones D and E in Lift 3. This examination indicated that the concrete was an over-sanded mixture with some relatively large voids in the paste; however, most of the entrapped voids were created by sand particles touching each other.

Values for total air content ranged from 0.41 to 17.98 percent. In general, specimens from near the formed face exhibited the higher values for total air content. Average values for total air content for the various zones in the two lifts ranged from 1.48 to 11.18 percent (Figure 14). The data for total air content and large (>1 mm) entrapped air voids exhibited similar trends, and it is obvious that the large entrapped air voids represent a significant portion of the total air content. Average values for these large entrapped air voids for the various zones in the two lifts ranged from 34 to 84 percent of the total air content, with an overall average of approximately 60 percent.

In addition to the quantity and size of air voids, the distribution of voids also has a significant effect on resistance to cycles of freezing and thawing. An air-void spacing factor of 0.008 in. is generally considered to be the maximum allowable for resistance to freezing and thawing. Only 10 of the 51 specimens exhibited a spacing factor of less than 0.008 in. Nine of the ten specimens were from Zones D and E in Lift 3 where air-entrained RCC was placed. The tenth specimen was from Zone C in Lift 2. One specimen from Zone C in Lift 3 exhibited a spacing factor of 0.0085. All of the remaining specimens from the test section exhibited spacing factors of more than 0.001 in. There was no apparent correlation between air-void spacing factors and depth from the formed surface.

Six of the seven specimens from Zone D in Lift 3 exhibited spacing factors that ranged from 0.0033 to 0.0049 in. The remaining specimen from this group exhibited a spacing factor of 0.0125 in. The average air-void spacing factor was 0.0063 in. for Zone D in Lift 3, which was significantly lower than any of the other sections (Figure 15). Three of the five specimens from Zone E in Lift 3 exhibited spacing factors that ranged from 0.0053 to 0.0064 in. The two remaining specimens from this group exhibited spacing

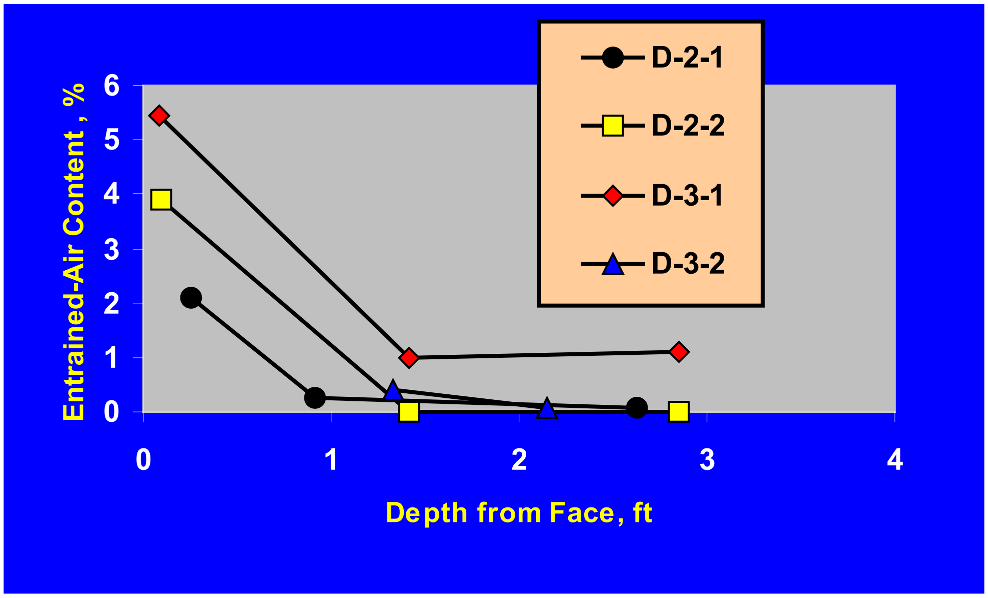

Figure 12. Relation between entrained-air content and depth from formed face, Zone D

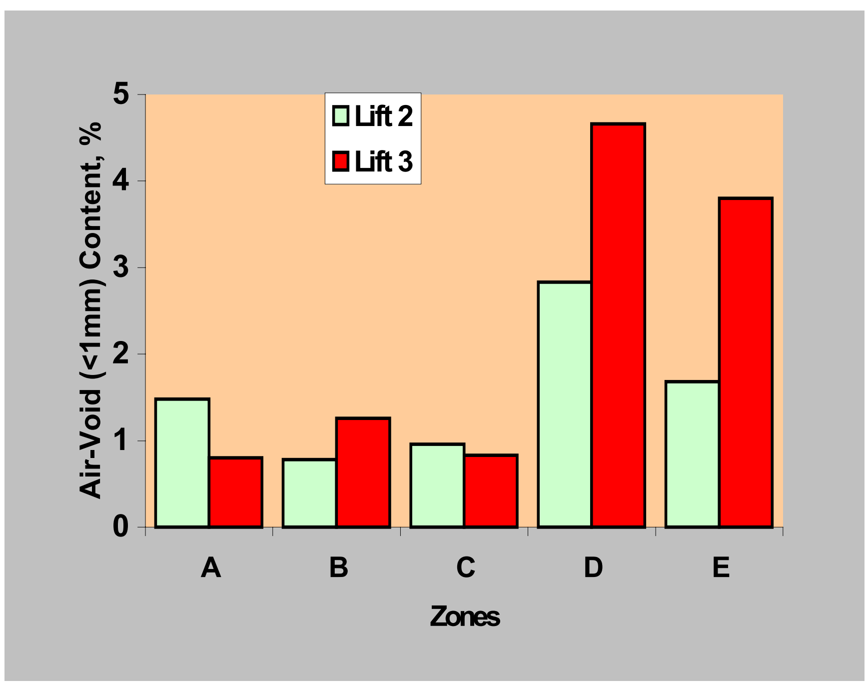

Figure 13. Summary of air-void (<1 mm) content data

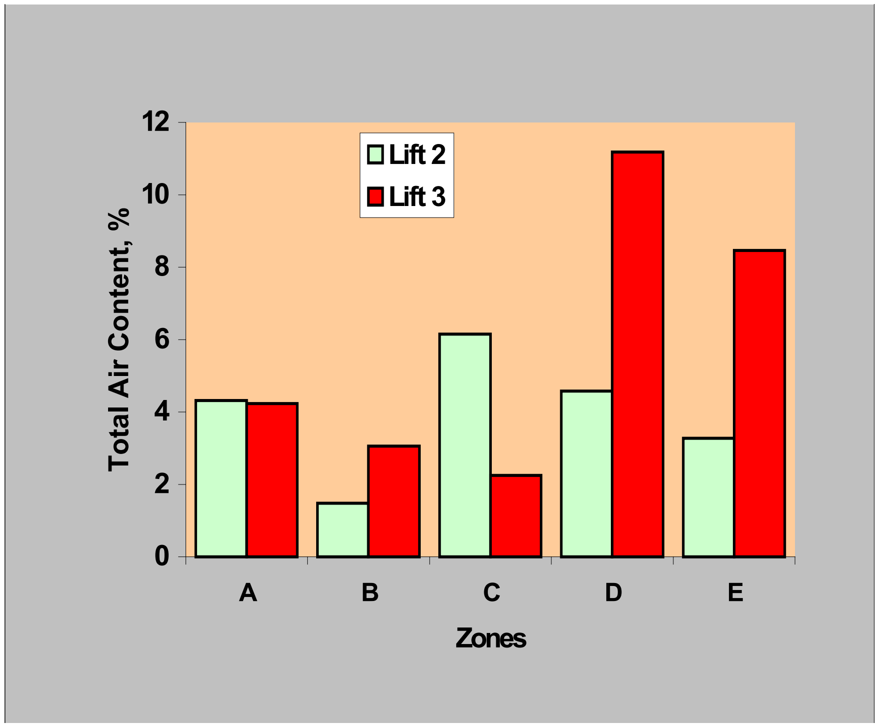

Figure 14. Summary of total air content data

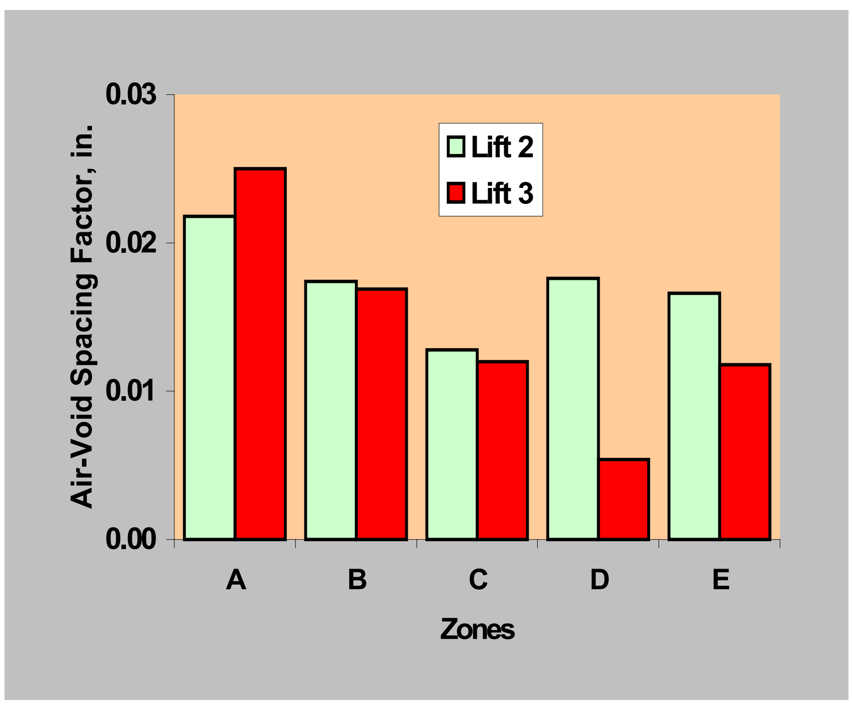

Figure 15. Summary of air-void spacing factor data

factors of 0.0153 and 0.0260 in. A comparison of the results of limited tests on specimens from Zones D and E in Lift 3 indicates that internal vibration of GE-RCC provides a more desirable air-void system compared to tracking with a dozer followed by a vibratory roller.

In general, freeze-thaw test specimens were 16 in. long; however, breaks in some cores during drilling necessitated the use of slightly shorter specimens in a few cases. Specimens were subjected to accelerated cycles of freezing and thawing in accordance with ASTM C 666. Performance of the GE-RCC was monitored by periodically measuring the loss in mass of individual specimens. Testing continued for 350 cycles, or until a specimen exhibited a loss in mass of a least 25 percent. Specimens from the various zones exhibited a wide range in performance (Figure 16). For comparison purposes, test results were used to calculate the number of freeze-thaw cycles required to achieve 25 percent mass loss in each specimen.

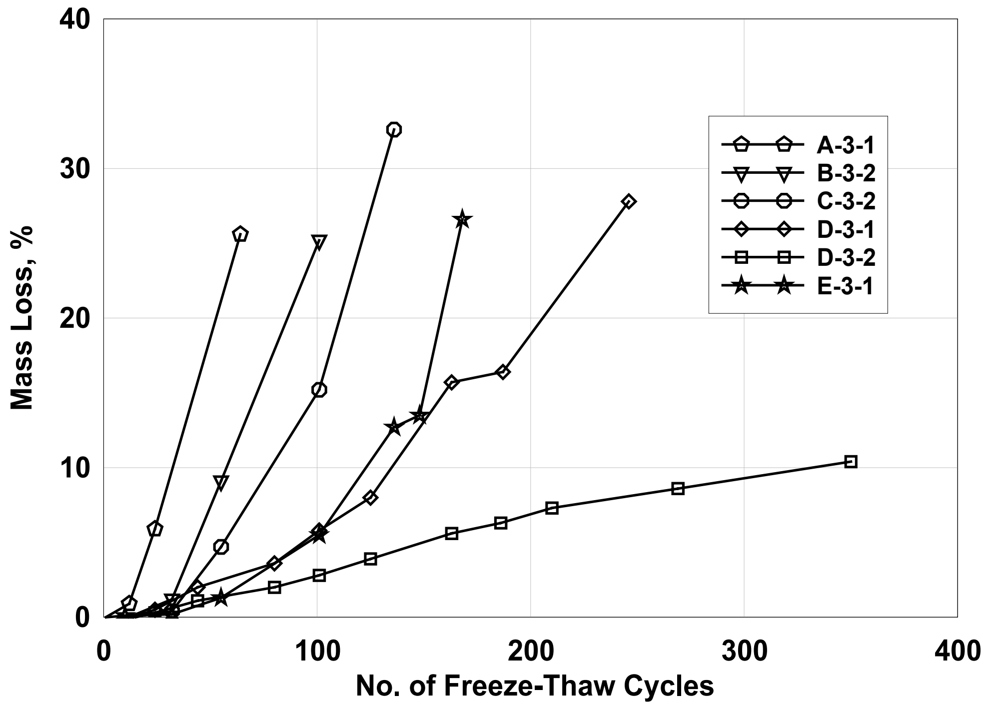

Figure 16. Results of freeze-thaw tests on selected specimens from each zone of Lift 3

Only 1 of the 28 specimens was able to withstand 350 cycles of freezing and thawing (Figure 16) with a mass loss of less than 25 percent. This specimen (D-3-2) was obtained from Zone D in Lift 3 and extended from the formed face to a depth of 16 in. An examination of a specimen immediately adjacent to the interior end of the freeze-thaw specimen indicated that the GE-RCC at this point had an air-void (<1 mm) content of 5.0 percent with a spacing factor of 0.0049 in. Another freeze-thaw specimen (D-3-1), obtained from a second core from Zone D in Lift 3, exhibited relatively poor performance. This specimen extended from 1 in. inside the form to a depth of 17 in. Examination of specimens immediately adjacent to each end of the freeze-thaw specimen indicated that the air-void (<1 mm) contents were 6.7 and 7.6 percent at depths of 1 and 17 in., respectively. The spacing factor was 0.0048 in. at the interior end of the specimen, essentially the same as specimen D-3-2 at the same depth. However, the spacing factor at the end of the freeze-thaw specimen near the formed face was 0.0125 in., significantly higher than the maximum of 0.008 in. for resistance to freezing and thawing.

Averaging the results of the two tests on specimens from Zone D in Lift 3 indicates that more than 300 cycles of freezing and thawing would be required for the GE-RCC to reach 25 percent mass loss

(Figure 17). In comparison, the second-best performer in freeze-thaw tests, GE-RCC from Zone E in Lift 3, exhibited 25 percent mass loss after an average of only 136 cycles. Specimens from Zone E exhibited erratic air-void parameters: the average air-void (<1 mm) content ranged from 0.8 to 6.1 percent with an average of 3.7 percent and spacing factors ranged from 0.0053 to 0.0260 in. with an average of 0.0118 in. This lower air-void content and higher spacing factor compared with Zone D is reflected in the reduced resistance to cycles of freezing and thawing. The average air-void (<1 mm) content in the remaining eight placement areas ranged from 0.8 to 2.8 percent with an average of 1.3 percent. Average spacing factors in the same placement areas ranged from 0.0120 to 0.0250 in. with an average of 0.0175 in. As a consequence of these inadequate air-void systems, the number of freeze-thaw cycles required to cause a mass loss of 25 percent ranged from 38 to 105 with an average of only 75 cycles.

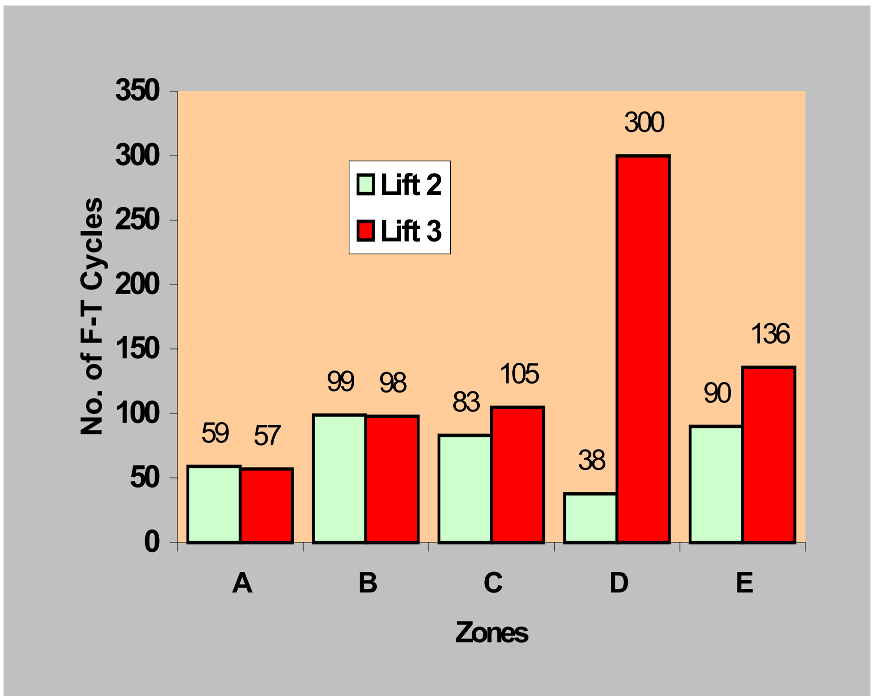

Figure 17. Number of freeze-thaw cycles required for a loss in mass of 25%

CONCLUSIONS AND RECOMMENDATIONS

Roller-compacted concrete, even when loosely placed, is fairly tight with few interconnected voids. Consequently, the fluid (*w/c* > 0.75), neat-cement grout mixtures proportioned in the laboratory did not seep into the RCC when placed on top of the lift. Neither internal nor external vibration produced good mixing in laboratory trials, regardless of where the grout was placed or the consistency of the grout and RCC. During vibration, grout migration was generally limited to movement along formed surfaces and into pathways left by the internal vibrator. The best distribution of grout within the RCC was achieved by dragging an immersed vibrator through the materials; however, none of the GE-RCC specimens appeared to be uniformly mixed.

Despite the difficulties in mixing the GE-RCC, laboratory test results demonstrate that grout enrichment of RCC can have a significant impact on compressive strength. In general, compressive strengths of GE-RCC mixed in a laboratory mixer or combined by vibration were 2 to 3 times higher than the RCC alone.

Combining air-entrained grout and RCC in a laboratory mixer resulted in GE-RCC with significantly increased resistance to cycles of freezing and thawing compared with non-air-entrained RCC. In contrast, specimens of similar materials mixed with internal vibration exhibited essentially no resistance to cycles of freezing and thawing. The air-void systems entrained in the grout mixtures were extremely unstable when subjected to vibration. This instability was obvious in vibration tests on both the grout alone and in combination with the RCC. Additional laboratory testing is necessary to determine the optimum combination of materials and proportions to produce an adequate entrained air-void system that is stable when subjected to vibration.

It was the consensus of observers during construction of the test section that the sanded grout used in Lift 1 did not provide satisfactory results. The difficulties encountered during vibration of the GE-RCC were similar to problems experienced in the laboratory with neat-cement grout even though much larger consolidation equipment was used in the field test. Since no cores were obtained from this lift, quantitative conclusions about the relative performance of the various application and consolidation procedures used are impossible. The air-void stability of sanded grouts should be examined, and the potential for application of air-entrained sanded grouts by spraying or other means should be investigated.

Spraying the grout onto the RCC as it was being placed or spread against the form and internal or external consolidation resulted in exposed faces that were uniform and smooth with the appearance of cast-in-place concrete. Injection of the grout with a stinger pipe and placing the grout on lift surfaces followed by internal consolidation both resulted in a satisfactory surface, provided the procedures were accomplished in a timely manner. Delays in construction with these methods resulted in localized areas of surface honeycomb. Cores from all zones indicated that, overall, the GE-RCC was homogeneous with only a few isolated voids.

The average compressive strengths for each zone of both lifts were in excess of 1,500 psi when tested at approximately 150 days age. In the two zones exhibiting the highest average strengths (2,760 and 3,290 psi), the RCC was placed to the full lift thickness and spread into place; however, the RCC was not tracked with the dozer so that it would be in a relatively loose state when grout (1.0 *w/c*) was injected with a stinger pipe followed by internal consolidation.

Grout enrichment of non-air-entrained RCC in this investigation did not result in air-void systems necessary for freeze-thaw durability. The eight placements that used non-air-entrained RCC exhibited useful air contents (air voids <1-mm diameter) ranging from 0.8 to 2.8 percent with an average of 1.3 percent. Average spacing factors in the same placement areas ranged from 0.0120 to 0.0250 in. with an average of 0.0175 in., more than twice the maximum for freeze-thaw durability. As a consequence of these inadequate air-void systems, the number of freeze-thaw cycles required to cause a mass loss of 25 percent ranged from 38 to 105 with an average of only 75 cycles.

The only two placements that exhibited air-void contents (<1 mm) higher than 3.5 percent were constructed by spraying air-entrained grout onto air-entrained RCC as it was being placed or spread against the form. Subsequent consolidation of one placement by internal vibration resulted in GE-RCC with an average air-void content of 4.7 percent with an average spacing factor of 0.0054. A specimen from this placement exhibited a mass loss of only 10 percent after 350 cycles of freezing and thawing. Consolidation of the second placement by tracking with a dozer followed by a vibratory roller resulted in GE-RCC with an average air-void content of 3.8 percent with an average spacing factor of 0.0118. This lower air-void content and higher spacing factor resulted in a mass loss of 25 percent after an average of 136 cycles of freezing and thawing.

Results of these limited tests indicate that internal vibration of GE-RCC provides a more desirable air-void system compared to tracking with a dozer followed by a vibratory roller. Also, the GE-RCC should have a minimum air-void (<1 mm) content of 4.5 percent and a spacing factor less than 0.008 in. Additional study is needed to optimize materials, proportions, and construction procedures that will provide the air-void systems necessary for GE-RCC that is resistant to cycles of freezing and thawing.

POINT OF CONTACT

For additional information, contact the Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center (CEERD-GM-R), Vicksburg, MS 39180-6199; e-mail *GSL-Info@erdc.usace.army.mil*.

Table 1
Results of Hardened Air Content Tests on Field Test Cores, GE-RCC Phase I Studies

Placement	No. of Tests	Entrained Air Voids <1 mm, %			Entrapped Voids <1 mm, %			Entrapped Voids >1 mm, %			Total Air Content, %			Spacing Factor, in.		
		Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Zone A																
Lift 2	2	0.45	1.48	0.96	0.30	0.75	0.52	2.37	3.29	2.83	4.14	4.48	4.31	0.0206	0.0229	0.0218
Lift 3	7	0.30	1.11	0.50	0	0.82	0.30	0.30	8.90	3.43	1.05	10.83	4.23	0.0147	0.0332	0.0250
Zone B																
Lift 2	2	0.07	0.52	0.30	0.30	0.66	0.48	0.37	1.05	0.71	1.10	1.87	1.48	0.0161	0.0187	0.0174
Lift 3	8	0.15	2.15	0.70	0.30	1.04	0.56	0.30	5.65	1.80	1.11	8.84	3.06	0.0116	0.0287	0.0169
Zone C																
Lift 2	3	0.16	0.81	0.54	0.15	0.81	0.42	0.81	12.94	5.19	1.76	13.91	6.15	0.0077	0.0174	0.0128
Lift 3	4	0.27	0.85	0.49	0	0.71	0.34	0.14	2.43	1.41	0.41	3.61	2.25	0.0085	0.0170	0.0120
Zone D																
Lift 2	8	0	3.89	1.00	0.32	6.99	1.83	0.67	2.82	1.57	1.38	9.11	4.58	0.0098	0.0216	0.0176
Lift 3	7	0.08	5.44	1.48	0.58	6.57	3.18	0.99	15.98	6.52	7.94	17.84	11.18	0.0033	0.0125	0.0054
Zone E																
Lift 2	5	0	0.94	0.30	0.43	2.03	1.38	0.86	2.66	1.59	2.23	4.47	3.28	0.0114	0.0217	0.0166
Lift 3	5	0	3.55	1.16	0.77	5.14	2.64	0.98	7.28	4.66	2.61	13.18	8.46	0.0053	0.0260	0.0118