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Optimization of Air Entrained Grout Enriched Roller Compacted Concrete for Improving Freeze-Thaw Resistance of Hydraulic Structures

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ABSTRACT

Roller compacted concrete (RCC) is frequently used to construct both gravity dams and stepped spillways and to armor earthen embankments for passing extreme floods. Early experiments on RCC dam applications in the 1980s showed a tendency for seepage to develop along the lift lines. Therefore, RCC dam designers started including an upstream facing system as a watertight barrier. An alternative facing material that has been used extensively overseas and is starting to gain more widespread acceptance in the United States is Grout Enriched RCC (GERCC). The grout enriched method of face construction has been shown to be less expensive than other facing options, particularly on larger dam projects. However, in the United States, the use of GERCC technology has been fairly limited, primarily due to concern over the material's freeze-thaw resistance. The objective of this project is to develop a grout formulation and construction technique that allows the production of air entrained GERCC. The study includes four phases to systemically achieve this objective: optimizing grout formulation including type and dosage of chemical admixtures, evaluation of small scale laboratory samples of RCC and grout combined in a mixer, evaluation of large scale laboratory samples of RCC and grout combined using field construction techniques, and conducting a field trial. The results show that when the grout and RCC are combined in a mixer, good freeze-thaw resistance can be achieved; however, when combined using field techniques, the amount of vibration must be carefully controlled to avoid loss of performance.

Keywords: *Roller Compacted Concrete, Overtopping Protection, Stepped Spillways, Freeze-Thaw Resistance*

1. INTRODUCTION

Roller compacted concrete (RCC) is frequently used to construct gravity dams and stepped spillways and to armor earthen embankments for passing extreme floods. RCC is a no-slump concrete that is typically spread and compacted in lifts with conventional earthmoving equipment. Early experiments on RCC dam applications in the 1980s showed a tendency for seepage to develop along the lift lines. Therefore, RCC dam designers started including an upstream facing system as a watertight barrier, typically constructed of conventional concrete, an exposed geomembrane liner system, or geomembrane-faced precast concrete panels.

An alternative facing material that has been used extensively overseas (in areas having limited freeze-thaw cycles) and is starting to gain more widespread acceptance in the United States is Grout Enriched RCC (GERCC). This innovative process includes the addition of a neat cement grout to the uncompacted RCC at each lift along the upstream and/or downstream face. After the grout has soaked into the RCC, immersion vibrators are used to mix and to consolidate the grout and RCC to produce a seamless zone that is similar to conventional concrete. The grout enriched method of face construction has been shown to be less expensive than other facing options, particularly on larger dam projects (Fitzgerald, 2013). However, in the United States, the use of GERCC technology has been fairly limited, primarily due to concern over the material's freeze-thaw resistance.

1.1. Background

Studies conducted by Cannon (1993) and Hazaree et al (2011) have shown that it is possible to entrain air in standard RCC and achieve reasonable freeze-thaw resistance. However, researchers and contractors attempting to integrate air entraining admixtures into GERCC to improve freeze-thaw resistance have not been successful to date. Forbes (1999) cited an early example at the Horseshoe Bend dam in New Zealand where a freeze-thaw resistant facing was desired. In order to achieve this, the grout was heavily dosed with an air entraining admixture to achieve 3-4% residual air in the GERCC facing. The initial trials using the air entrainer were unsuccessful since the grout became highly foamy and would not soak through the spread RCC layer. McDonald (2002) described the most detailed studies in air entrained GERCC to date. The study consisted of laboratory tests that evaluated the grout formulation, dosage rate, and techniques to combine the grout with the RCC, as well as field trials. The laboratory tests showed that it is very difficult to produce a homogenous mixture by placing the grout on the top and/or bottom of the RCC. In addition, when internal vibrators are used to combine the grout and RCC, the air content of the mixture and, therefore, the freeze thaw resistance decreases substantially. Similar conclusions could also be drawn based upon the field trial, as well as field trials conducted in a separate study conducted by Tatro et al (2008). These two observations highlight the difficulty of using air entrained GERCC: current construction techniques require significant vibration energy to produce a homogenous mixture, but that vibration energy removes much of the entrained air from the grout, reducing the freeze-thaw resistance.

1.2. Research Objective

The objective of this research program is to advance the use of GERCC and promote more cost effective and technically viable construction of gravity dams, stepped spillways, armored earthen embankments, and other hydraulic structures in climates subject to freeze-thaw cycles. Achieving cost-effective GERCC air entrainment and consolidation can significantly advance the competitiveness of RCC versus other alternatives.

2. EXPERIMENTAL PROGRAM

The research program was divided into 4 phases to systemically achieve the research objectives. The first two phases will be described in this paper, as the third and fourth phases are currently in progress. Phase 1 consists of optimizing the grout mixture design, with a focus on evaluating the effect of multiple chemical admixtures. Phase 2 combines the grout mixtures with the RCC in a standard drum mixer and evaluates the properties of the resulting GERCC. Phase 3 combines the grout mixtures with the RCC using both standard and novel techniques that could be applied in the field. Phase 4 consists of a field trial to further evaluate the performance of the grout mixture designs developed in Phases 1 and 2 and the construction techniques developed in Phase 3.

2.1. Phase 1: Grout Optimization

To evaluate the changes in properties of grout with the addition of chemical admixtures, a uniform method of mixing grout was put in place. The water-to-cement ratio for all grout mixes was 0.95, except those containing a water reducing admixture. This value was recommended by the research sponsors (Schnabel Engineering) based on their experience with GERCC. The admixtures were first mixed into the water for a short period of time, after which cement was slowly added. As the cement was added to the batch, a paddle mixer attached to a 1,600 RPM drill was used to agitate the mixture. Once all of the cement was added, the drill was operated at full speed for four minutes.

Once the four minutes of mixing were complete, a standard Marsh Funnel (ASTM D6910) test was performed to measure the fluidity of each mixture. The time for 946 mL of grout to pass through the Marsh funnel was measured and recorded. The Marsh Funnel test was followed by the determination of the air content of the mix, as per ASTM C231/C231M-10. The standard pressure method was used with a Type-B meter. It is important to note that the standard procedure was modified slightly to provide a representative air content by minimizing the amount of foam in the pressure meter during testing. When the grout was added to the pressure meter, it was allowed to overflow the container, removing some foam. Then, a steel rod was used to strike off the excess foam still present on the surface. This procedure was repeated twice for each sample, then tested according to the ASTM standard.

The remainder of the original grout was allowed to sit for 30 minutes. After 30 minutes, the remaining grout was placed on a shake table and subjected to the maximum intensity vibration for 1 minute. This method simulated the internal vibration of concrete enriched with grout after placement. After vibration, the identical air pressure method was used to determine the air content of the mix.

Six different admixtures were evaluated during this phase including organic air entraining admixture (AEA), synthetic AEA, polycarboxylate water reducing admixture (WRA), latex-based water repelling and efflorescence controlling admixture, saline-based efflorescence reducing and water repelling admixture, and powder water resisting and superplasticizing admixture. The water repelling admixtures were added to evaluate their effect on the stability of the air void system and because reducing permeability is another method of increasing the freeze-thaw resistance. Initially, the admixtures were examined individually with multiple dosage rates being evaluated. Then, the admixtures were combined to evaluate the interactions between them and the effects on the stability of the air matrix. A total of 37 grout formulations were evaluated using this procedure.

2.2. Phase 2: Small Scale Laboratory GERCC

Phase 2 determined multiple fresh and hardened properties for the RCC mix, grout and GERCC resulting from a combination of the RCC and grout. Numerous tests were run including flow, air content, bleed, and compressive strength. Samples from each individual mix were also created for freeze-thaw resistance testing. Seven chemical admixture combinations for the grout were individually tested, as well as one series of tests that included grout without any chemical admixtures. The chemical admixture combinations tested in Phase 2 were selected based on their performance during Phase 1.

The first step for this phase consisted of weighing out the materials to produce the RCC mixture, which had been developed based on the mixture design procedures outlined in ACI 211.3R-02, “Guide for Selecting Proportions for No-Slump Concrete,” and refined through a series of trial mixes. The RCC was designed to have a Vebe time of around 30 seconds, and for each mix, the Vebe test was run to evaluate the mixture’s consistency. Following Vebe testing, the unit weight of the RCC was determined. After determining the unit weight of the RCC, the next step was to cast 150 mm by 300 mm cylinders to be tested for 28-day compressive strength. In order to simulate roller-compaction, the cylinders were filled in thirds with a Hilti TE 805 demolition hammer drill used at three intervals to fully compact the concrete inside of the cylinder as per ASTM C1435. Two RCC cylinders were cast for each mix. Aside from cylinders, a 75 mm by 100 mm by 400 mm rectangular prism was also cast in a steel mould to later be used for freeze-thaw resistance testing. To simulate roller-compaction in the rectangular mold, a square block of steel was struck with about ten blows of a rubber mallet at one-quarter intervals down the length of the mold.

The grout was mixed in a heavy duty, high volume colloidal mixing grout plant, ChemGrout CG-600 colloidal series. The amount of cement used for each grout mix was 42.6 kg, and the dosage of both water and chemical admixtures were determined from the results of Phase 1. After an initial four minutes of mixing, the grout was transferred from the mixing tank to the holding tank, where it could be pumped into two 5-gallon buckets to be used for fresh property testing. The first bucket was tested immediately while the second bucket sat for thirty minutes before testing, following the procedure described for Phase 1. The temperature of the grout was immediately determined and recorded. The first bucket of grout was tested for flow, specific gravity, and air content. A Marsh Funnel flow cone test was performed as per ASTM D6910, with the time it took for 946 mL of grout to pour out of the bottom of the cone monitored and recorded as the initial flow.

Following the flow cone test, a mud balance was performed to determine the specific gravity of the grout. The specific gravity was evaluated as a consistency check with the results of air content tests. The test is simple to perform and is commonly used in post-tensioned grouting applications. Following the mud balance test, the air content of the grout was determined as per ASTM C231/C231M-10, using a Type B meter with a vertical air chamber. The same air content method as described in Phase 1 was performed.

Another test was performed to determine the initial bleed of the grout as per ASTM C1741-12, “Standard Test Method for Bleed Stability of Cementitious Post-Tensioning Tendon Grout.” A filtration funnel was filled with fresh grout within 5 minutes of mixing. The funnel was connected to an air supply, and air was pumped into the funnel at a pressure of 172 kPa for five minutes while bleed water travelled through a stem on the bottom of the funnel into a graduated cylinder. After five minutes, the pressure was released and the funnel was tipped in order to remove any excess bleed water to exit the stem. The volume of the collected bleed water in the graduated cylinder was measured to the nearest 0.2 mL.

Thirty minutes after the initial grout mix, the grout previously set aside was placed on a shake table for one minute. It was then tested using the mud balance and air content meter. The specific gravity and air content for the grout after thirty minutes was recorded and evaluated against the grout that was tested immediately after mixing. In order to simulate the conditions that may be found in the field, grout was also circulated through the grout mixing plant itself. For three minutes, grout was pumped through the grout plant at full speed with a valve constricted to generate a pressure of about 345 kPa at the outlet of the pump. The grout was poured into a 5-gallon bucket and once again tested for specific gravity and air content to be evaluated against previous fresh property results.

Following all of the fresh property tests, a pre-calculated amount of grout from the material collected after recirculating through the pump was added to 79.4 kg of the remaining original RCC mix. The grout and RCC were mixed together in a concrete mixer for one minute to form grout-enriched RCC. Once successfully mixed, a Vebe test was performed on the grout-enriched concrete to determine its Vebe time. The unit weight of the grout-enriched concrete was determined using the same method as described for the RCC mix. Two grout-enriched concrete cylinders were created following standard ASTM C31 procedures. Three rectangular freeze-thaw samples were also created using a tamping rod to compact the grout-enriched concrete in two lifts.

Four 75mm by 100 mm by 400 mm freeze-thaw samples resulted from each mix in Phase Three. Three of the samples were enriched with grout and one was standard RCC. As previously stated, these samples were tested for freeze-thaw durability as per ASTM-C666. The specimens were allowed to cure for 14 days while sitting in lime water. At the 14 day curing period, each of the specimens was weighed and tested for fundamental transverse frequency. This process was repeated for every 30 cycles in a freeze-thaw cabinet.

3. RESULTS

3.1. Phase 1: Grout Optimization

The data obtained from Phase 1 included the Marsh Funnel flow times and the air contents of the grout both immediately after mixing and after 30 minutes of rest and one minute of vibration. The flow times for the mixtures without water reducing admixtures were fairly consistent, falling between 26-38 seconds for all the mixtures, which was consistent with the target of 30 seconds. In general, the longer flow times tended to result from mixtures with higher air contents. This makes physical sense as an increase in air content reduces the unit weight of the grout, which reduces pressure within the grout as it exits the funnel, reducing the velocity and increasing the flow time. For the mixtures with water reducer, the flow times varied more significantly until the dosage of admixture and the corresponding reduction in water content were better understood. The final mixture had flow times ranging from 34-38 seconds, depending on the presence of other admixtures.

The average air contents obtained for select tests are shown in Figure 1 and Figure 2. Figure 1 shows the average air content for the samples containing the organic AEA at what was determined to be the optimal dosage. The optimal dosage was the dosage that produced an air content of between 15 and 20%. This target air content was determined based on two criteria. The first criterion was the behaviour of the grout during this study, primarily the amount of foam produced and the stability of the resulting air void matrix. The second criterion was calculations based on the required air content in the GERCC and the typical dosage rates of grout based on existing literature and experience.

Figure 1 also shows the effect of other chemical admixtures on the air content of grouts containing the organic AEA and seems to indicate that the latex based water repelling admixture may increase the effectiveness and the stability of the organic AEA, while the powder water resisting admixture has a significant negative impact. Figure 2 shows the same results for the synthetic AEA at its optimum dosage. By examining these data, it is apparent that the water reducer and the powder water resisting admixture significantly decrease the stability of the air void system, while the latex-based water repelling admixture seems to have little effect. Comparing the performance of the two AEAs, it appears that the synthetic AEA is slightly more stable and can maintain its stability at slightly higher air contents. Therefore, moving forward into Phase 2, more emphasis was placed on the synthetic AEA, and the powder water resisting admixture was excluded from further testing based on its detrimental interaction with both AEAs.

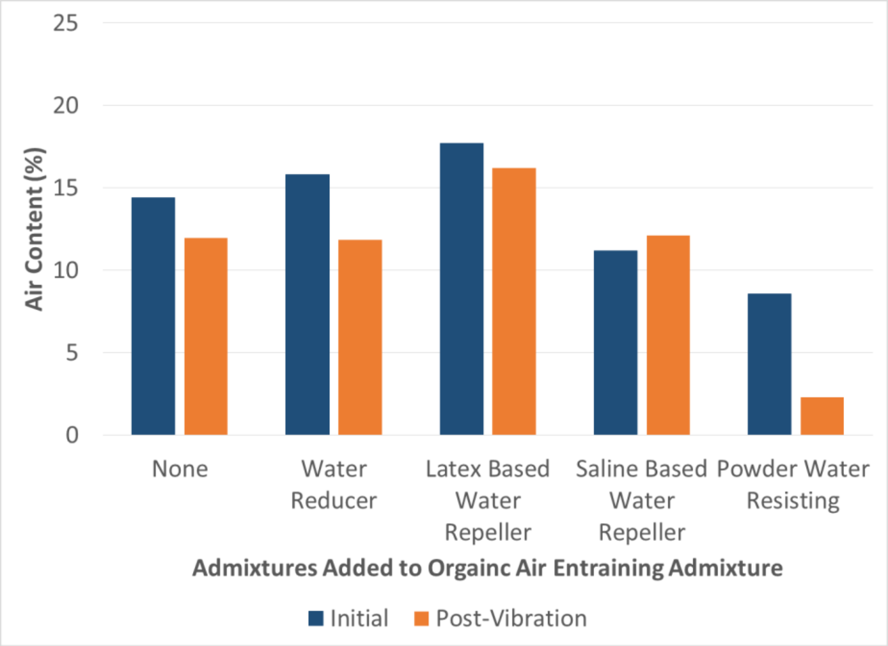

Figure 1. Average Air Content for Grout Containing Organic Air Entraining Admixture

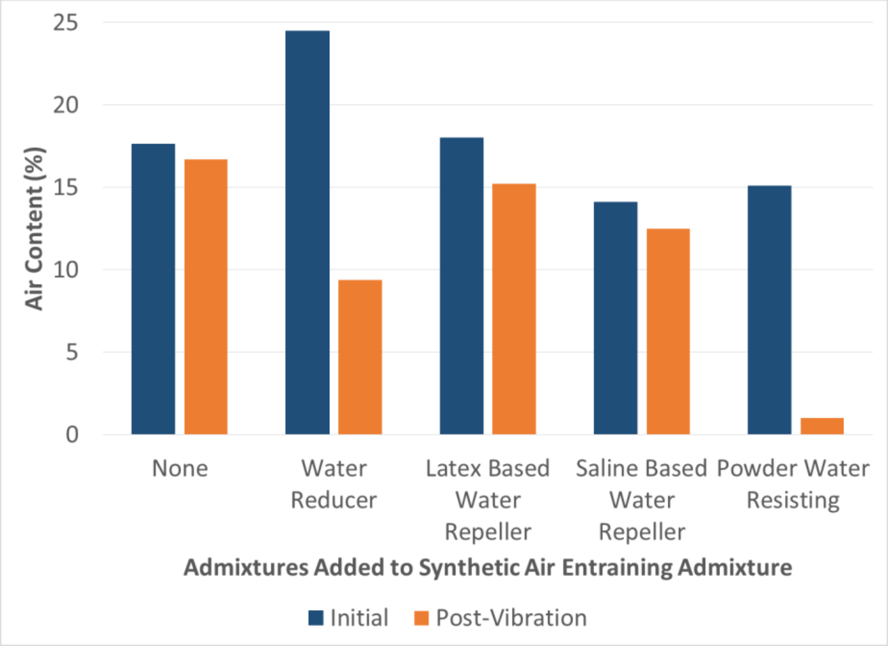

Figure 2. Average Air Content for Grout Containing Synthetic Air Entraining Admixture

3.2. Phase 2: Small Scale Laboratory GERCC

During Phase 2, properties of the grout, RCC, and GERCC were determined. For the grout, the flow times were recorded immediately after mixing and were typically within the same range of 26-38 seconds for all grouts, with the exception of the grout with the water reducing admixture, which had a significantly higher flow time. This may have been the result of the thixotropic nature of the grout when a WRA is added, which would result in a higher flow time when measured by the Marsh Funnel method. The bleed of the grout was also measured, and due to the high water to cement ratio, the amount of bleed was substantial. The average bleed of all the grouts was 82 mL, with the lowest being 42 mL from the grout containing the WRA, which is the result of a reduced water to cement ratio in this grout. The air content of the grout was measured immediately after mixing, after 30 minutes of rest and 1 minute of vibration, and after recirculation under pressure through the pump for 3 minutes. These results are shown in Figure 3.

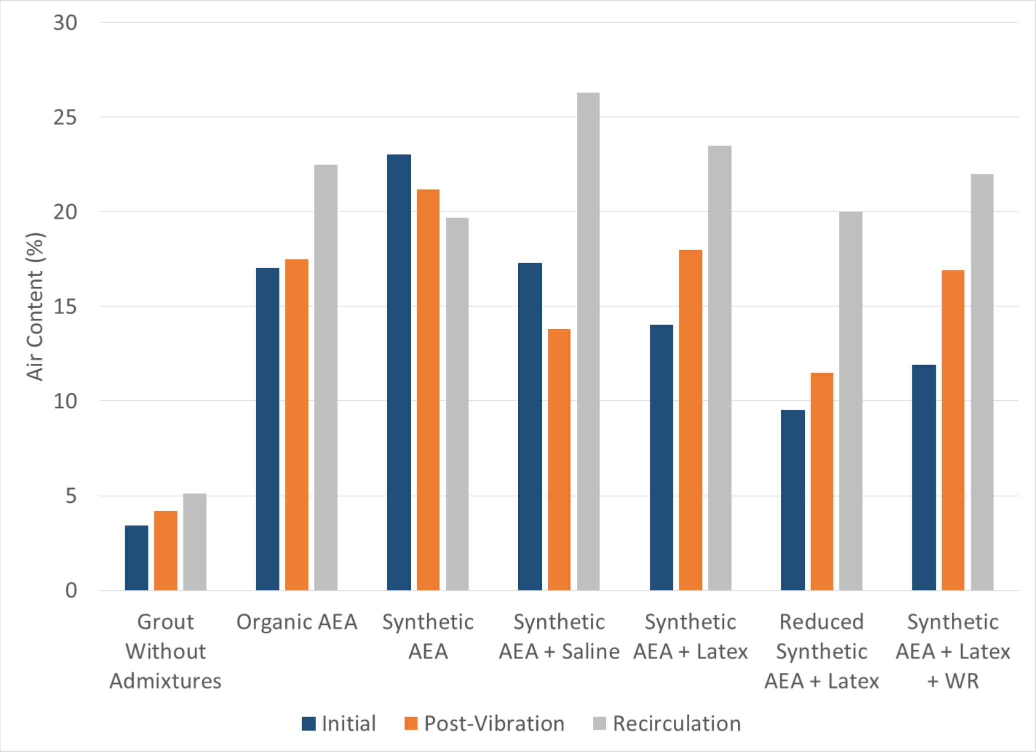

Figure 3. Grout Air Content during Large Scale Testing

Some interesting observations can be made from the air content data from Phase 2. The recirculation of the grout through the pump does not negatively affect the air content of the grout; in fact, for most materials, recirculation increased the air content. This is likely because after the grout was pumped under pressure, it was reintroduced into the holding tank containing the grout where it splashed around, allowing more air to be introduced into the grout. Additionally, the material for the initial air content was removed from the holding tank first, followed by the grout used to determine the 30 minute air content. The pump is setup so that it removes material from the bottom of the holding tank; therefore, if the lighter material with the higher air content rises to the top, it would be used for the recirculated air content and may be the reason for the higher air contents. The same justification could be used to explain why for many of the samples, the grout allowed to sit for 30 minutes and subjected to vibration has a slightly higher air content.

When comparing the different materials, the synthetic AEA exhibited the highest performance with the highest initial air content and produced air contents that were the most consistent, indicating an ability of the mixture to remain homogeneous. This was the primary justification for using the synthetic AEA for evaluating the other admixtures. The other admixtures generally had a negative effect on the initial air content, with the saline having the least effect. It should be noted that one sample, labeled as “Reduced Synthetic AEA + Latex,” had a reduced dose of AEA added to evaluate if the high air content of the grout was necessary to achieve acceptable freeze-thaw resistance.

The air content of the GERCC was also measured for each grout formulation and is shown in Figure 4. The air contents correlate well with the expected values calculated based on the measure air content of the grout and the dosage, and they also largely achieve the target of 4-5% that is needed for reasonable freeze-thaw resistance. The once exception is the grout with the water reducing admixture, where the measured air content was much higher than expected. One possible explanation for this anomaly is that, as indicated earlier, the grout with the water reducer had a significantly higher flow time, indicating it was less fluid than the other grouts. The meter used to measure the air will report the percent of all air within the meter, including any voids within the sample. So, if a less fluid grout resulted in a sample with poor compaction, the air content measured would be artificially high.

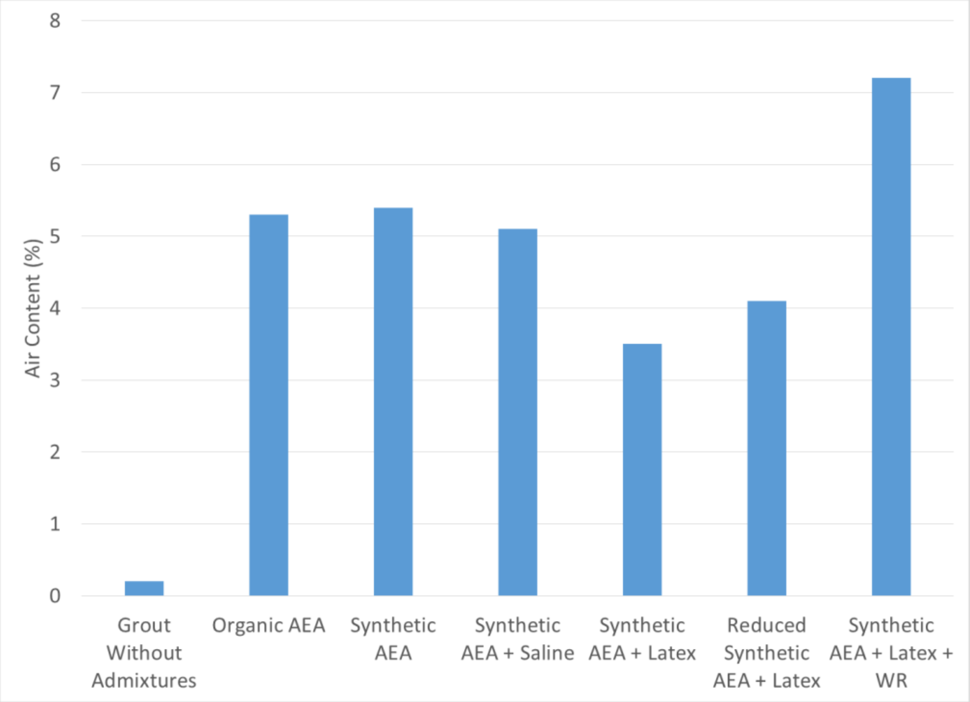

Figure 4. Air Content of GERCC

The results of the freeze-thaw tests are shown in Figures 5 and 6, as well as Table 1. Figure 5 shows the change in modulus of elasticity versus the number of freeze-thaw cycles. The only samples to fail the test (exhibit a drop in dynamic modulus below 60% of original) were the plain RCC samples shown in black and the grout without admixtures shown in light blue. All samples containing an AEA maintained at least 75% of their initial modulus. Table 1 shows the average mass loss and percent of original dynamic modulus for each set of samples. The samples with the highest freeze-thaw resistance were the synthetic AEA with the saline water repelling admixture, which retained 96.8% of its initial modulus. The remaining mixtures all preformed similarly and satisfactorily. Figure 6 shows the samples containing the synthetic AEA and saline water repelling admixtures as well as the corresponding RCC sample after 300 cycles and clearly shows the greatly improved durability when the air entrained grout is added.

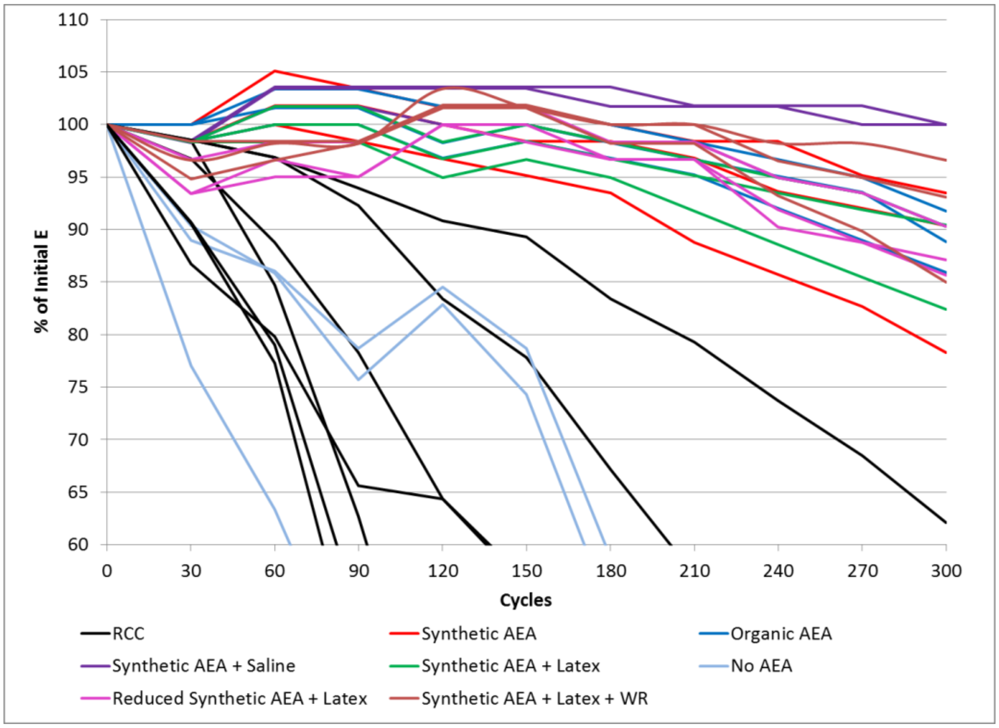

Figure 5. Freeze Thaw Resistance of GERCC

Table 1. Freeze Thaw Resistance of GERCC

GERCC	Average % of Original E After 300 Cycles	Average % of Mass Lost After 300 Cycles
Synthetic AEA + Saline	96.8	0.29
Synthetic AEA + Latex + WR	91.6	0.39
Organic AEA	88.8	0.49
Synthetic AEA + Latex	87.7	0.00
Reduced Synthetic AEA + Latex	87.7	0.48
Synthetic AEA	87.4	0.67
No AEA	12.9	3.76

Figure 6. Freeze Thaw Samples After 300 Cycles

4. CONCLUSIONS

Based on the results of the research program, the following conclusions can be drawn:

- Both the organic and synthetic air-entraining admixtures were capable of successfully achieving an air content between 15% and 25% when added at their respective maximum recommended dosages. The most successful air-entrainer with the most stable air content readings and superior freeze-thaw resistance was the synthetic air-entrainer.
- Although the water-reducing admixture was beneficial in reducing bleed and permeability, its addition resulted in a greater variance in air content. Therefore, the use of a water reducing admixture is not recommended for use in air entrained GERCC at this time.
- Both water-repelling and efflorescence controlling admixtures proved to be beneficial to the performance of air-entrained grout, with the saline-based admixture exhibiting superior freeze-thaw resistance. The powder water resisting admixture negatively impacted the air entrainment and is not recommended for use in air entrained GERCC.

The ongoing research is focused on evaluating different construction techniques and their effect on the distribution of grout within the RCC and the freeze-thaw resistance of the resulting air entrained GERCC with the goal of recommending a placement technique and vibration level that optimizes performance in these two competing criteria. Future research could evaluate these parameters for different RCC mixtures. Additionally, an automated process for grout placement, mixing of the grout with the RCC, and consolidation of the resulting mixture could be developed to improve the quality and consistency of the GERCC.

5. ACKNOWLEDGMENTS

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