# Optimizing Concrete Mixtures for Performance and Sustainability

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FINAL REPORT TO THE RMC RESEARCH & EDUCATION FOUNDATION

PROJECT 09-06

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## INTRODUCTION

Consensus-based industry standards in the U.S. do not include requirements for minimum cementitious materials content for concrete mixtures for the most part. There is no such requirement in the ACI 318-14. ACI 301-10 has minimum cementitious materials content requirements only for interior floor slabs (Table 1). The intent is to ensure adequate paste to facilitate finishability. A test slab placement is permitted as an alternative to the minimum cementitious content requirement. However, many project specifications invoke requirements of minimum cementitious (CM) contents for concrete mixtures. In the U.S. many state departments of transportation agencies (DOTs) and other agencies specify a minimum cement content between 550 and 600 lb/yd$^3$ for slip-form pavement mixtures (Rudy 2009). Most state highway agencies also establish classes of concrete for various elements in transportation construction projects and these classes of concrete are typically defined by minimum content of cementitious materials among other parameters.

Typically, specified minimum limits on cementitous materials exceed the quantity required for intended performance, such as workability, strength, and durability. This results in increased cost and higher carbon footprint of the concrete mixture. The performance implied or intended by the minimum cementitious material content may not be clear or enforceable. Minimum cementitious materials limits in specifications for concrete represent a significant restriction to a concrete producer towards optimizing concrete mixtures for performance and sustainability. Specifications that include these requirements do not provide any incentive for the concrete producer to invest in improved quality management systems and innovative technology. These requirements prevent the evolution to performance-based specifications. In many cases, the higher levels of cementitious content in fact result in lower performance. The primary focus of this project was to examine the relation between cementitious content and concrete performance at specific water-to-cementitious materials ratios (w/cm). Concrete performance was evaluated through laboratory tests on workability, strength, and durability. Based on the results of this study, the value of maintaining minimum cementitious content requirements in project specifications is questioned. A concrete mixture proportioning approach based on the combined aggregate void content is also suggested.

The study was conducted in three phases and these are discussed separately in this report.

## LITERATURE REVIEW

Wasserman et al. (2009) identified three possible reasons for specifying a minimum cementitious content:

1. It provides assurance that a low *w/cm* is attained, even if good control of the mixing water content is not exercised;
2. It ensures there is enough paste to fill the voids between the aggregates and provide adequate workability; and
3. It offers corrosion protection by chemically binding the chlorides and the carbon-dioxide that penetrate the concrete.

Wasserman et al. (2009) and Dhir et al. (2003) reported that at any given *w/cm*, increasing cement contents lead to similar compressive strengths and carbonation rates, but higher absorption and chloride penetration. A mixture with higher cement content had increased chloride threshold concentration to initiate corrosion but this benefit was offset by greater chloride penetration. Dhir et al. (2003) reported that for mixtures with similar *w/cm* values, increasing cement contents led to similar flexural strengths, modulus of elasticity, and levels of deicer salt scaling. However, increasing cement contents led to reduced sulfate resistance, increased chloride diffusion, greater air permeability, and higher length change due to shrinkage. These studies concluded that the minimum cementitious materials content should not be specified for concrete durability.

Several researchers that include Marquardsen (1929), Smith (1936), Katoh (1936), and Kennedy (1940) have proposed concrete mixture proportioning approaches based on the assumption that the consistency of concrete depends on two factors: the volume of the cement paste in excess of the amount required to fill the voids of the compacted combined aggregate, and the consistency of the paste as it impacts workability. Kennedy stated that for a given workability the excess paste increased as the w/c ratio decreased.

Powers (1968) categorized mixtures into three groups based on their aggregate-to-cement ratios

- lean mixtures with cement contents approximately below 450 lb/yd$^3$;
- normal mixtures with cement contents approximately between 450 and 650 lb/yd$^3$; and
- rich mixtures with cement contents approximately above 650 lb/yd$^3$.

It is important to note that these mixture evaluations were primarily portland cement mixtures without the use of water-reducing admixtures. Powers found that the water demand for a target consistency wAS more or less similar for the normal mixtures but increased for both the lean and rich mixtures. He showed experimentally and through models that optimized mixtures that had the lowest water demand for given workability in each category depended on different parameters. For rich mixtures, specific surface of the aggregates had to be minimized and this could be accomplished by reducing the quantity of fine aggregate content. For lean mixtures, the ratio of fine and coarse aggregate had to be selected so as to minimize the void content of the combined aggregate. For normal mixtures, since both specific surface of the aggregates and void content of the combined aggregates played a role, increase in cement content needed to be offset by reducing the fine aggregate content. To summarize, for the normal and rich mixtures, the optimum proportion of fine aggregate was somewhat lower than that resulting in the minimum void content of the combined aggregate. Powers showed through equations that the excess paste theory would lead to the same conclusion. This was consistent with past experimental observations by Abrams (1918) and Powers (1932).

Powers (1967) also showed experimentally and through models that the quantity of fine aggregate should be reduced when using a finer sand or for mixtures at a lower w/c. The ACI mixture proportioning approach (1991) is based on work done by Talbot and Richard (1923) and modified by Goldbeck and Gray (1949). The approach requires higher quantity of coarse aggregate when a fine aggregate with a finer sized, as characterized by a lower fineness modulus (FM) is used. Powers pointed out questionable aspects of Kennedy's approach, one of which was that correlations between excess paste volume and slump had to be developed at different w/c ratios.

Koehler and Fowler (2007) used an approach based on the excess paste theory to proportion self-consolidating concrete mixtures. NRMCA (2009) used an approach based on the excess paste theory to proportion pervious concrete mixtures. ACI has recently published guidance on proportioning normal-weight concrete mixtures based on the excess paste theory (ACI 211.6T, 2015). One of the primary differences appears to be the manner by which the excess paste quantity is selected.

# PHASE I

## Materials and Mixture Proportions

In Phase I, the evaluation focused on the implication of a minimum cementitious (CM) content requirement in concrete specifications on the performance of concrete. Non-air-entrained (NAE) concrete mixtures were evaluated in this phase. At fixed w/cm ratios concrete mixtures were prepared with different paste volumes. Change in paste volume at the specific w/cm was based on selected levels of CM content. The paste volumes were varied from less than the volume of voids in the combined aggregate to substantially greater.

The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (PC), NRMCA Lot number 8135
- ASTM C989 slag cement (SL), Lot 8209D;
- ASTM C618 Class F fly ash (FA), Lot 8314;
- ASTM C33 No. 57 crushed coarse aggregate, Lot 8209B;
- ASTM C33 natural sand with an FM=2.88, Lot 8209A;
- ASTM C494 Type F high range water reducing admixture, Lot 8209G; and
- A defoaming agent, Lot 8209J.

For all concrete mixtures in Phase I, the coarse aggregate absolute volume was set at 58.4% of the total aggregate absolute volume. This ensured that the combined aggregate grading and void content remained the same for all mixtures. The coarse aggregate volume of 58.4% was established based on proportioning mixtures according to ACI 211.1, assuming an average paste volume. Because of the fixed aggregate ratio, the paste volume was varied to maintain target yield, as opposed to varying the quantity of fine aggregate as in the ACI 211.1 approach. Paste volume is defined as the volume of cementitious materials, mixing water, and entrapped air, which was assumed to be 2%.

Combined aggregate void content was measured as outlined in ASTM C29. The quantity of oven dry coarse and fine aggregate was determined, so as to maintain the selected aggregate ratio. The coarse and fine aggregate were placed in a pan and blended together with a scoop. The blended combined aggregate was placed in three layers in a container of capacity 0.33 cubic foot, and each layer was rodded 25 times. The void content was calculated from the measured bulk density and the relative density of aggregate. The test was repeated three times with separate batches. The average void content of the combined aggregate was calculated as 25.4%.

In Phase I, 20 NAE concrete mixtures were evaluated. Of these, 12 mixtures contained slag cement at 40% by mass of the cementitious material. For these 12 mixtures, the water to cementitious materials ratio (w/cm) was varied at 0.40, 0.47 and 0.55. At each w/cm the paste volumes were varied at 24%, 26%, 29%, and 33% of total concrete volume. Four mixtures contained fly ash at 25% by mass of CM material and the remaining four mixtures were made with portland cement only. For these eight mixtures only one level of w/cm at 0.47 was used, with the paste volumes varied at 24%, 26%, 29%, and 33% of total concrete volume. Mixture designations were assigned by the w/cm followed by the SCM type and paste volume. Mixtures without SCM use the designation “PC”. For example, 0.40SL29 refers to mixture with a w/cm of 0.40, slag cement as part of the CM material and paste volume of 29%. In some plots the paste volume is not indicated in the mixture designation and as an example is reported as 0.40SL.

The concrete mixture variables are shown in Table 2. Detailed mixture proportions and test results of the 12 slag cement concrete mixtures are shown in Table 3. Detailed mixture proportions and test results of the remaining eight fly ash concrete and portland cement concrete mixtures are shown in Table 4. Calculated batch quantities are based on the measured density of fresh concrete. Slump was not controlled because of the constraints of the mixture proportions, but if the measured slump was below 1 in. a high range reducing admixture (HRWRA) was added to achieve a slump that exceeded 1 in. A small dosage of an anti-foaming agent was added because during trial batches, high entrapped air contents were measured, even in the absence of air-entraining admixtures.

## Procedures

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. Fresh concrete was tested for slump (C143), temperature (C1064), air content (C231), and density (C138). Time of setting of the concrete mixtures was estimated from the temperature profile measured using commercially available equipment that maintains specimens in insulated semi-adiabatic environment. The equipment contains four cells with time/temperature data loggers. Concrete was molded in 4 x 8 in. cylinders and placed in the equipment. The thermal signature was monitored and the initial and final setting times were estimated as the elapsed time corresponding to 21% and 42% of peak temperature, respectively. This only provides a relative comparison of estimated time of setting for the mixtures evaluated. It is noted that the estimated time of setting from the thermal signature curve will not be the same as that which would be measured using the penetration resistance method (ASTM C403).

Two types of specimen curing were followed:

- Standard curing when specimens were stored in a moist room at 73±3°F immediately after casting for the duration prior to testing; and
- Accelerated curing when specimens were subjected to seven days of standard curing followed by 21 days of curing in water at 100°F. Accelerated curing was only used for some of the rapid index test specimens as outlined below.

Compressive strength (C39) test was conducted using 4x8 in. standard cured cylindrical specimens. Reported strengths are the average of two specimens tested at ages of 1, 7 and 28 days. Length change (C157) was measured on three 3x3x11 ¼ in. prisms, with seven days standard curing followed by up to 90 days of air drying in a 70°F, 50% RH environment.

Rapid index tests to measure the transport characteristics of concrete mixtures included the rapid indication of chloride ion penetrability test (RCPT) (ASTM C1202), rapid migration test (RMT) (AASHTO TP 64), and the initial sorptivity test (ASTM C1585). The RCPT and RMT test specimens were subjected to accelerated curing and tested at an age of 28 days. The sorptivity test specimens were standard cured for 28 days prior to testing. After conditioning, the sorptivity test specimens were subject to water absorption only for six hours and therefore only the initial sorptivity result was measured. Results of rapid index tests were the average of two 4x8 in. cylindrical specimens for each test and test age. The specimens were cut and the top 2 in. from the finished surface was tested.

A modified chloride bulk diffusion test (ASTM C1556) was conducted. One 4x8 in. cylindrical specimens was cast for each mixture and standard cured for a period of 28 days. Following this curing period, the specimens were cut at 3 in. from the finished surface. All sides of the specimens except for the finished surface were coated with an epoxy and the specimens were immersed in an aqueous solution of sodium chloride for a period of about 45 months. This permits chloride penetration from the finished surface of the specimen. At the end of the exposure period the specimens were profiled in layers of 2 mm thickness. Chloride contents were measured at depths of 9, 11, 17, 19, and 73 mm and are reported in Table 3.

## Discussion

### *Slump*

Figure 1a shows the relation between the mixing water content and the measured slump prior to adding HRWRA (typically referred to as water slump) for the concrete mixtures containing slag cement. For certain concrete applications, such as slabs, it may be desirable to attain a water slump of 1 in. Figure 1a indicates that a mixing water content of 250-260 lb/yd$^3$ is needed to attain a water slump of 1 in. This corresponds to a CM content range of 455, 553 and 650 lb/yd$^3$ for w/cm of 0.55, 0.47, and 0.40, respectively. The corresponding yield adjusted paste volumes are 25.7%, 27.7%, and 29.8%. The paste-to-void ratio in Table 3 is the volume of paste to the measured void content of the combined aggregate, which was 25.4%. A paste-to-void ratio of 1.00 represents the volume of paste equal to the volume of voids in the combined aggregates. Figure 1b illustrates the measured water slump as a function of the paste-to-void ratio for the mixtures containing slag cement. For a water slump of 1 in. the required paste-to-void ratio were 1.01, 1.09, and 1.17 for the mixtures with w/cm of 0.55, 0.47, and 0.40 respectively. This validates that the volume of paste should exceed the void volume to attain a measureable water slump. The additional paste needed increases as the w/cm decreases. This is consistent with past observation (Kennedy 1940).

Figure 2 shows the relation between the mixing water content and the measured water slump for the portland cement and fly ash concrete mixtures. The minimum quantity of mixing water needed for a 1 in. water slump for these mixtures was 255 lb/yd$^3$ and 265 lb/yd$^3$ for the fly ash and portland cement concrete mixtures, respectively. Since the w/cm evaluated was 0.47 the corresponding paste volumes are 28.1% and 28% for the fly ash and portland cement concrete mixtures, respectively. The corresponding paste-to-void ratios are 1.11 and 1.10.

Interpolating between the lines in Figure 1a, if the mixing water content is at 285 lb/yd$^3$, at w/cm of 0.55, 0.47, 0.40 the CM content would be 517, 613, and 720 lb/yd$^3$, respectively. The estimated slump for these conditions would be 6.50, 4.75, and 2.50 in., respectively. As might be expected, at given mixing water content, a higher CM content results in a lower slump. If the mixing water content is 252 lb/yd$^3$, at w/cm of 0.55, 0.47, 0.40, the CM content would be 459, 534, and 627 lb/yd$^3$. The estimated slump would be 1.25, 0.75, and 0.25 in., respectively, which is a smaller range. This suggests that once the desired 1 in. water slump has been attained with a certain amount of mixing water, further increase in slump should be achieved with the use of a water reducing admixture, particularly for mixtures at a low w/cm, such as 0.40. If the mixing water content is increased to achieve slump, a higher CM content will be required to maintain the target w/cm and this in turn will increase the mixing water demand.

Tables 3 and 4 indicate the mixtures where there was no measureable slump with the quantity of mixing water used and HRWRA was needed to achieve a measureable slump. Observations on workability indicate that the mixtures appeared to be rocky, sticky and in one case (0.40SL26) because of the high slump the mixture sheared when performing the slump test. These mixtures had mixing water contents below 250 lb/yd$^3$ and paste-to-void ratios of 1.02 or lower. So if a water slump of 1 in. was not achieved, HRWRA could be added to attain target slump levels for all the mixtures. These mixtures had a yield adjusted paste volume as low as 23.7% which corresponds to a paste-to-void ratio of 0.93. Even though these mixtures attained the desired slumps their workability would have to be examined to see if it is satisfactory for the desired application.

### *Thermal Setting Time*

The initial and final setting times of the slag cement mixtures are plotted against total CM content in Figure 3. Also indicated on these charts is the dosage of HRWRA used to increase the slump of the mixtures. While it appears that at each w/cm when the CM content decreased the time of setting increased, this is attributed to the retarding effect of the HRWRA used. Mixtures with no HRWRA had similar setting times. Similar observations are made for the time of setting data for the fly ash and portland cement mixtures in Figure 4.

### *Compressive Strength*

The 1, 7, and 28 day compressive strengths of the mixtures containing slag cement are plotted against total CM content in Figure 5. As expected, strength at all ages increase with a reduction in w/cm from 0.55 to 0.40. Despite a wide range of CM content, of about 200 lb/yd$^3$, the compressive strengths are relatively similar. For the w/cm of 0.40 when the total CM content increased from 505 lb/yd$^3$ to 720 lb/yd$^3$ the 28 day compressive strength decreased from 8560 psi to 8100 psi. Compressive strength of the fly ash and the portland cement mixtures are plotted against total CM content in Figure 6. At a w/cm of 0.47 the compressive strengths were reasonably constant even though the CM content varied between 450 and 650 lb/yd$^3$. This does not mean that at any w/cm there would be no reduction in strength if the CM content and mixing water content were reduced consistently to even lower levels. Reducing the paste volume too much below the void content of the combined aggregate would increase the void content of the concrete as placed, thereby reducing strength and durability. However, the minimium CM requirements typically seen in project specifications do not get close to causing a deficiency of paste volume in concrete mixtures.

### *RCPT*

The RCPT results for all the mixtures are plotted against total CM content in Figure 7. For the mixtures containing slag cement (Figure 7a) at a given w/cm the charge passed in coulombs increased with an increase in the CM content. A higher charge passed is indicative of higher chloride ion penetrability. Since transport of chloride ions is through the paste, this is as expected that the charge passed increases as the paste volume increases, at a fixed w/cm. Figure 7b shows a similar trend of increasing charge passed with increase in CM content for the fly ash and portland cement concrete mixtures. As expected at the same w/cm, the charge passed is considerably lower for the mixtures containing slag cement and fly ash compared to the mixtures containing only portland cement.

The charge passed for concrete mixtures containing slag cement are plotted against mixing water content in Figure 8. It is interesting to observe that at any given mixing water content, regardless of the w/cm, the charge passed was the same. For example, at a mixing water content of 250 lb/yd$^3$ even when the CM content was varied between 455 to 650 lb/yd$^3$ (corresponding to w/cm varying between 0.55 and 0.40) the charge passed was about 750 coulombs. The 0.40 w/cm mixture with more CM content should have a tighter pore structure and therefore a lower charge passed indicative of a lower permeability. However, with increasing CM content, the paste volume increases which increases the charged passed. These effects offset each other, resulting in no change in charge passed.

### *RMT*

The RMT results, which represent the average depth of chloride ion penetration under an electrical current, of all the mixtures are plotted against total CM content in Figure 9. A higher RMT result indicates greater depth of penetration of chlorides. Reduced depth of penetration is observed for the mixtures with slag cement and fly ash compared to the portland cement mixtures. The RMT results of the mixtures containing slag cement are plotted against mixing water content in Figure 10. The observations are similar to that made for the RCPT results except that a unique relationship between mixing water content and RMT results regardless of w/cm was not observed (Figure 10). These results indicate the depth of chloride ion penetration is reduced with a reduction in w/cm (for the mixtures containing slag cement).

### *Initial Sorptivity*

The initial sorptivity results for all the mixtures are plotted against total CM content in Figure 11. The initial sorptivity results of the slag cement mixtures are plotted against mixing water content in Figure 12. A higher sorptivity result is indicative of greater rate of moisture ingress, and hence, potentially reduced durability. The observations are similar to those made for the RCPT results except that a unique relationship between mixing water content and initial sorptivity values with varying w/cm was not observed. In this set of results the higher paste volume is demonstrated to have caused a higher sorptivity result.

### *Chloride Penetration*

The chloride content of the slag cement mixtures at a depth of 18 mm from the surface exposed to chlorides are plotted against total CM content in Figure 13. The chloride content at 18 mm depth is the average of the measured chloride contents at depths of 17 and 19 mm. As the w/cm decreased from 0.55 to 0.40 the chloride penetration decreased as expected. For a given w/cm, as the cementitious content increased the chloride contents increased for the mixtures with a w/cm of 0.47 and 0.55, and was constant in the case of the 0.40 w/cm mixtures as the CM content varied. The chloride content of the mixtures containing slag cement at a depth of 18 mm are plotted against mixing water content in Figure 14. Unlike the RCPT results, at a given mixing water content, a lower w/cm reduced the penetration of chlorides (Figure 14).

### *Length Change Due to Drying Shrinkage*

The 90 day length change results of all the mixtures are plotted against paste volume in Figure 15. As the paste volume increases the average length change increases. This is as expected because, for a particular aggregate, concrete shrinkage is affected by paste volume. The 90 day length change results of all the mixtures are plotted against mixing water content in Figure 16. At any given mixing water content, regardless of the w/cm, the length change values of the mixtures containing slag cement were similar. For example at a mixing water content of 250 lb/yd$^3$ even when the CM content was varied between 455 to 650 lb/yd$^3$ the length change results varied over a narrow range between 0.039% and 0.046% (the mixture with the highest CM content and hence paste volume actually gave the lowest length change). The 90 day length change results of all the mixtures are plotted against CM content in Figure 17. At any given CM content, as the w/cm increases the length change results of the mixtures containing slag cement increased. For example, at a CM content of 550 lb/yd$^3$ when the mixing water content was varied between 220 to 300 lb/yd$^3$ (corresponding to a w/cm of 0.40 to 0.55) the length change values can be estimated to vary over a wider range, i.e. between 0.034% and 0.047%. To summarize, these observations indicate an increase in CM content and mixing water will increase drying shrinkage but a larger part of this increase is due to increase in mixing water content. Fly ash and straight cement mixtures had similar length changes at the same mixing water or CM content.

## Phase I Conclusions

For a given w/cm, increasing CM content, results in similar compressive strengths, but increase in permeability, as indicated by the higher charge passed, chloride penetration with an electrical current measured by RMT, chloride penetration due to diffusion, initial sorptivity, and greater length change due to drying shrinkage. The reduced concrete performance of the mixtures with higher CM contents at the same w/cm is due to the higher paste volumes. These results clearly show that at a given w/cm requiring a higher CM content is counterproductive as it leads to poorer concrete performance.

For the aggregates tested a mixing water content of 250-265 lb/yd$^3$ was needed to attain a slump of 1 in., without the use of a water-reducing admixture, and independent of the w/cm or composition of cementitious materials used. So the current ACI 211.1 mixture proportioning approach of assigning a target mixing water content for target slump seems reasonable. However, if the aggregates are changed, or if the concrete mixtures are air-entrained, these mixing water contents will change.

For a 1 in. water slump the required minimum paste volume varied from 25.7% to 29.8% which corresponds to a paste-to-void ratio of 1.01 to 1.17; Lower w/cm concrete mixtures required higher paste volumes which is consistent with past observation (Kennedy 1940). It appears that with a more fluid paste due to higher w/cm, the quantity of excess paste to impact concrete workability is lower. If a water slump of 1 in. was not achieved, and HRWRA could be added to attain target workability, a 23.7% paste volume which corresponds to a paste-to-void ratio of 0.93 provided adequate slump and hardened concrete performance.

## PHASE II

### Materials and Mixture Proportions

Phase II evaluated air-entrained (AE) concrete mixtures to validate some of the conclusions in Phase I. Slag cement and fine aggregate were the same as those used in Phase I.

The following materials were used for the concrete mixtures:

- ASTM C150 Type II portland cement (PC), Lot 8209C;
- ASTM C989 slag cement (SL), Lot 8209D;
- ASTM C33 No. 57 crushed coarse aggregate, Lot 8688;
- ASTM C33 natural sand with an FM=2.88, Lot 8209A;
- ASTM C260 air-entraining admixture, Lot 8638H; and
- ASTM C494 Type F high range water reducing admixture, Lot 8638I

For the Phase II concrete mixtures, the absolute volume of coarse aggregate was set at 58.4% of the total aggregate volume. Combined aggregate void content was measured based on ASTM C29 as described in Phase I and the average void content was calculated as 22.2%. The lower void content was likely because this lot of coarse aggregate was of a more spherical shape.

Four AE concrete mixtures were tested and the target air content was 5.5 to 6.5%. Slag cement was used in these mixtures at 40% by mass of cementitious material and a w/cm of 0.47. The paste volumes were varied at 24%, 26%, 29%, and 33% of total concrete volume. A target air content of 6% was included in the volume of the CM paste. This compared to the 2% entrapped air which was assumed as part of the CM paste in Phase I. Mixture designations included the letter A at the end to denote air entrainment. For example, 0.40SL29A refers to an air-entrained concrete mixture with a w/cm of 0.40, slag cement as part of the CM material and paste volume of 29% of total concrete volume. In some plots the paste volume is not indicated in the mixture designation and as an example is reported as 0.40SLA.

Detailed mixture proportions and test results of the concrete mixtures are shown in Table 5. Slump was not controlled, other than if the measured slump was less than 1 in. a HRWRA was added to increase slump to exceed 1 in.

### Procedures

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. Fresh concrete was tested for slump (C143), temperature (C1064), air content (C231), and density (C138).

All specimens were standard cured in accordance with ASTM C192 in a moist room at 73±3°F immediately after casting the specimens for the duration prior to testing.

Compressive strength (C39) was measured on 4x8 in. standard cured cylindrical specimens and tested at the age of 1, 7 and 28 days. Strength reported is the average of two specimens. The RCPT test was conducted on two 4x8 in. standard cured cylindrical specimens (at each age) and tested at an age of 90 days. The specimens were cut and the top 2 in. from the finished surface was tested.

## Discussion

### *Slump*

Figure 18a shows the relation between the mixing water content and the measured water slump for the air-entrained concrete mixtures. The plot indicates that a mixing water content of 240 lb/yd$^3$ is needed to attain a water slump of 1 in. This can be compared to 255 lb/yd$^3$ mixing water content needed for the 0.47 NAE concrete mixtures in Phase I. It is noted that the cement and coarse aggregate used in Phase I were different. This, however, illustrates that air entrainment reduces water demand for target slump of concrete. The corresponding yield-adjusted paste volume needed to attain a water slump of 1 in. was established as 29.7%. As noted earlier, the void content for this aggregate combination was 22.2% from which the paste-to-void ratio for the four mixtures can be determined. Figure 18b shows the relation between the paste-to-void ratio and the measured water slump for the AE concrete mixtures. This plot illustrates that the paste-to-void ratio required for a water slump of 1 in. is 1.34. This can be compared to the minimum paste-to-void ratio of 1.10 for NAE mixtures at a w/cm ratio of 0.47 in Phase I.

Figure 19a-g shows the visual appearance of all the mixtures when measuring the slump. The 0.47SL33A mixture had adequate workability without any HRWRA addition. The 0.47SL29A mixture appears to have adequate paste and workability prior to adding HRWRA. The 0.47SL26A mixture appears deficient in paste prior to adding HRWRA, however, after the addition of HRWRA the mixture workability was acceptable. So if a water slump of 1 in. was not achieved, and HRWRA could be added to attain target workability, even the 0.47SL26A mixture can be considered acceptable. This mixture had a yield adjusted paste volume of 25.8% which corresponds to a paste-to-void ratio of 1.16. Prior to the HRWRA addition the 0.47SL24A mixture visually appeared as rock particles coated with paste but following the addition of HRWRA the workability was reasonably adequate.

### *Compressive Strength*

The 1, 7, and 28 day compressive strengths of the AE concrete mixtures are plotted against total CM content in Figure 20. At the w/cm of 0.47 the compressive strengths did not vary much when the cementitous content was varied between 429 lb/yd$^3$ and 581 lb/yd$^3$. However, the 0.47SL24A mixture with the lowest CM content of 373 lb/yd$^3$ had a lower 7 and 28 day strength. The paste volume of the 0.47SL24A mixture was 23.7%, with a paste-to-void ratio of 1.07. Compressive strength at the level of the other mixtures was not achieved, despite the mixture having acceptable workability following the addition of HRWRA.

### *RCPT*

The RCPT results of all the mixtures are plotted against total CM content in Figure 21. At the same w/cm the RCPT values increased when the cementitous content was increased over the range of about 200 lb/yd$^3$. This trend is consistent with that observed in Phase I for the NAE mixtures.

## Phase II Conclusions

For a given w/cm, increasing CM content accompanied by increasing mixing water content, results in higher RCPT; compressive strengths were similar with the exception of the mixture with the lowest paste content, which had a lower strength. These results illustrate that at a given w/cm, increasing the content of cementitious materials will negatively impact concrete performance. Specifications that specify minimum CM quantities can therefore be counterproductive.

For the aggregates used in Phase II, a mixing water content of 240 lb/yd$^3$ was needed to attain a water slump of 1 in. For a 1 in. water slump the required minimum paste volume was 29.7% which corresponds to a paste-to-void ratio of 1.34. The required paste volume and paste-to-void ratios were higher than that for corresponding NAE concrete mixtures tested in Phase I which used a different coarse aggregate. When a water slump of 1 in. was not achieved, the use of a HRWRA achieved adequate workability and hardened concrete performance with a paste volume of 25.8%, corresponding to a paste-to-void ratio of 1.16. The mixture with lower paste volume at 23.7% had adequate workability but a lower compressive strength.

Other transport characteristic and length change due to drying shrinkage test methods were not conducted for the mixtures in Phase II. It is expected that similar trends would have been observed as in Phase I.

## PHASE III

In Phase I of this study it was observed that to attain a water slump of 1 in., a minimum paste-to-void ratio of 1.01 and 1.19 was needed for the concrete mixtures containing 40% slag cement with w/cm of 0.55, and 0.40, respectively. A paste-to-void ratio of 1.01 indicates a modest excess of paste to the aggregate void volume. However, for the mixture at a 0.40 w/cm, this paste-to-void ratio did not result in a water slump of 1 in. This is reviewed in Table 6. The first two rows in Table 6 show the calculated CM and mixing water contents for the required minimum paste-to-void ratio for the 0.55 and 0.40 w/cm mixtures, respectively. The third row shows that a 0.40 w/cm with paste-to-void ratio of 1.01 will have a mixing water content of only 220 lb/yd$^3$ and a total CM content of 550 lb/yd$^3$. A mixture with 40 lb/yd$^3$ less mixing water cannot yield the same slump if no HRWRA is added. This illustrates that a constant paste-to-void ratio cannot be used to proportion concrete mixtures for a water slump of 1 in. This is because when maintaining a constant paste volume for a target w/cm, increasing the volume of water will not have the same effect on slump as will decreasing an equivalent volume of cementitious materials. The question posed for Phase III was: if the paste consistency is improved by using a HRWRA, will a low w/cm achieve adequate workability with a low paste-to-void ratio? Table 3 shows that the 0.40SL26 mixture had a paste-to-void ratio of 1.01 and a w/cm of 0.40. The mixture had no initial water slump but the addition of HRWRA resulted in an 8 in. slump. While measuring slump, the concrete sheared off suggesting inadequate workability. The hardened properties of this mixture were acceptable. Evaluation in Phase III focused on whether the workability of these types of mixtures would improve if HRWRA was added with the initial mixing water.

### Materials and Mixture Proportions

The same materials used in Phase II were used. Fly ash was the same as that used in Phase I.

For all of the Phase III concrete mixtures, the absolute volume of coarse aggregate was set at 58.4% of the total aggregate volume. Void content of the combined aggregate was determined to be 22.2% in Phase II.

Eight NAE concrete mixtures were prepared. Three variables were evaluated:

- paste volume at 23% and 25.2%;
- w/cm at 0.40 and 0.55; and
- fly ash at 0% and 25% by mass of the CM material.

The paste volumes of 23% and 25.2% corresponded to paste-to-void ratio of 1.04 and 1.14, which are lower than the minimum ratio of 1.19 established in Phase I for the 0.40 w/cm mixture. An entrapped air content of 1.5% was assumed as part of the paste volume. Mixture designations are similar as those used in Phase I.

Detailed mixture proportions and test results of the concrete mixtures evaluated in Phase III are provided in Table 7.

### Procedures

Concrete mixtures were mixed in a revolving drum laboratory mixer in accordance with ASTM C192. For the 0.55 w/cm mixtures the mixing water was added during the mixing process in accordance with ASTM C192. During mixing, HRWRA was added so that slump exceeded 3 in.

For the 0.40 w/cm mixtures a small quantity of HRWRA was added with the the initial mixing water. Additional HRWRA was added as necessary during the mixing process to achieve a slump that exceeded 3 in. Fresh concrete was tested for slump (C143), temperature (C1064), air content (C231), and density (C138).

All specimens were standard cured in accordance with ASTM C192 in a moist room at 73±3°F immediately after casting the specimens for the duration prior to testing.

Compressive strength (C39) test was conducted on 4x8 in. cylindrical specimens standard cured and tested at the age of 1, 7 and 28 days. Strength reported is the average of two cylinders at each age. The RCPT test was conducted at an age of 90 days and involved casting two 4x8 in. cylindrical specimens for each test age. The top 2 in. from the finished surface was tested.

## Discussion

From Table 7 it can be seen that the measured air content varied between 2.5 and 4.9%, which exceeded the assumed value of 1.5%. This was an unintended consequence and defoaming agents were not used to reduce the air content. As a result of the higher air contents, the yield adjusted paste volumes for the target 23% paste was on average 25.1%; and for the target 25% paste was on average 26.6%. The corresponding average paste-to-void ratios were 1.14 and 1.20, respectively, compared to the targets of 1.04 and 1.14, respectively.

From Table 7 it can be seen that the measured slump for the 0.40 w/cm mixtures were similar to that of the 0.55 w/cm mixtures for both the PC and FA mixtures. However, the 0.40 w/cm mixtures required a significantly higher amount of HRWRA. The mixtures with a lower paste volume required a higher dosage of HRWRA than that for the mixtures with a higher paste volume to attain similar slumps. However mixtures with similar mixing water contents but different paste volumes required similar HRWRA dosages. This can be observed when comparing mixtures 0.55PC23 with 0.40PC25, and mixtures 0.55FA23 with 0.40FA25. Figure 22a-e illustrates the consistency of the concrete mixtures during the slump measurement. The 0.55PC23 mixture appears to be rocky prior to the addition of HRWRA. HRWRA addition improved the workability to an acceptable level. Addition of HRWRA to the 0.55FA23 mixture considerably improved the workability. The workability of the 0.55FA25, and 0.40PC25 mixtures were considered to be acceptable. In summary, when HRWRA was used, the required minimum paste-to-void ratio to attain a target workability level was relatively constant and independent of the w/cm.

As expected, mixtures with a lower w/cm had higher compressive strengths and lower RCPT results (Figures 23 and 24). Additionally, the mixtures containing fly ash had lower compressive strengths and RCPT results when compared to the PC mixtures. Consistent with Phase I and Phase II, the RCPT results for mixtures with a higher paste volume were slightly higher compared to the corresponding mixtures with a lower paste volume.

The data also reveals that the 28 day compressive strengths of the mixtures with a higher paste volume were modestly higher than the corresponding mixtures with a lower paste volume: 16% higher for the 0.55PC mixture, 4% higher for the 0.55FA mixture; 11% higher for the 0.40PC mixture, and 9% higher for the 0.40FA mixture. Some of these strength differences are attributed to differences in air content. For example, the strength of the fly ash concrete mixtures with a higher paste volume had lower measured air content compared to the mixtures with a higher paste volume. The air content for the PC mixtures were similar so strength comparisons can be made.

For this aggregate system, an average yield-adjusted paste volume of 27.1%, corresponding to a paste-to-void ratio of 1.22, was required for acceptable hardened concrete performance for the PC mixtures even though a paste-to-void ratio of 1.13 was acceptable for workability. The FA mixtures required an average yield-adjusted paste volume of 25.2%, corresponding to a paste-to-void ratio of 1.14 for acceptable workability and hardened concrete performance. In Phase I, the minimum paste-to-void ratio for acceptable workability and hardened concrete performance with the use of HRWRA was as low as 0.93. It appears that the minimum paste-to-void ratio depends on the coarse aggregate type. The combined aggregate void content of Phase I and Phase II were 25% and 22%, respectively. Generally lower combined aggregate void contents are indicative of a more spherical particle shape.

## Phase III Conclusions

HRWRA was effectively used to reduce the paste volume in concrete mixtures and achieve adequate workability. The minimum paste-to-void ratio seems to be independent of w/cm provided the paste achieves adequate consistency. Lower w/cm mixtures required the use of admixtures with the initial mix water. Reducing paste volume does reduce the permeability of concrete, but some reduction in strength was observed for the PC mixtures. When a water slump of 1 in. was not achieved, the use of a HRWRA achieved adequate workability and hardened concrete performance with a paste volume of 27.8%, corresponding to a paste-to-void ratio of 1.22 for PC mixtures. FA mixtures required a paste volume of 25.2% which corresponds to a paste-to-void ratio of 1.14.

## CONCLUSIONS FOR ALL 3 PHASES

### Applicability of the Paste-to-Void Ratio for Mixture Proportioning

Based on the findings of the three phases in this study, it can be surmised that a lower paste-to-void ratio results in improved concrete performance in terms of durability and reduced shrinkage. No significant impact on strength was observed unless the paste volume was reduced to less than an optimum level. HRWRA can be effectively used to facilitate improved workability with reduced paste volumes. This minimum paste-to-void ratio used in concrete mixtures at a set w/cm will establish the lowest cementitious materials content required for intended performance. When concrete mixtures are proportioned around this minimum paste-to-void ratio they will be optimized for performance, sustainability, and cost. The required minimum paste-to-void ratio for optimized concrete performance determined in the three phases is summarized in Table 8.

The following observations were made:

1. When mixtures are proportioned on the basis of achieving a water slump of 1 in., the minimum paste-to-void ratio for optimized performance increased with a reduction in the w/cm. This was observed in the Phase I results. When mixtures are not proportioned on the basis of achieving a water slump of 1 in. and HRWRA is used to impact the consistency of the paste, the minimum paste-to-void ratio for optimized performance appeared to be independent of w/cm. This was observed in Phase I and III results.
2. The type of coarse aggregate seems to have an effect on the minimum paste-to-void ratio required for optimized performance. The mixtures which were made with aggregates that had a lower combined aggregate void content required a higher minimum paste-to-void ratio. The coarse aggregate was changed in Phase III from that used in Phase I and the void content of the combined aggregate was determined to be 22.2% compared to 25.4%. As a result, the minimum paste-to-void ratio increased to between 1.11 and 1.22 from about 0.93.
3. With the same coarse aggregate used in Phase II and III of this study, it seems that air-entrained concrete mixtures have similar minimum paste-to-void ratio as NAE concrete mixtures for optimum performance. HRWRA was used in both phases. The volume of air is included in the paste volume.
4. It is not conclusive whether the combination of cementitious materials impacts the minimum paste-to-void ratio for optimized performance. In Phase I, with slag cement there did not seem to be an effect. In Phase III, it was observed that mixtures containing fly ash had lower minimum paste-to-void ratio than portland cement mixtures.
5. When mixtures are proportioned on the basis of achieving a water slump of 1 in. the minimum paste-to-void ratio for optimized performance varied between 1.01 and 1.34. The lower paste-to-void ratio was applicable to NAE concrete mixtures with a higher w/cm and with the coarse aggregate that resulted in higher void content of the combined aggregate.
6. When mixtures are not proportioned on the basis of achieving a water slump of 1 in. and HRWRA is used to impact the consistency of the paste, the minimum paste-to-void ratio for optimized performance was between 0.93 and 1.22. The lower paste-to-void ratio was applicable to the coarse aggregate that resulted in higher void content of combined aggregate. In this study, it was observed that preliminary addition of some

HRWRA with the initial mixing water was effective for mixtures with a low w/cm in achieving required workability of concrete with a lower paste-to-void ratio. Yurdakul (2013) proposed a paste-to-void ratio of 1.50 for optimum concrete performance. Applying that to the aggregates tested in Phase I of this study will result in a paste requirement of 38.1% which corresponds to a 0.40 w/cm ratio NAE concrete mixture with 1.5% entrapped air, portland cement content of 860 lb/yd$^3$ and mixing water content of 344 lb/yd$^3$. Based on the results of this study, a paste-to-void ratio of 1.50 appears excessive for good concrete performance.

## Proposed Mixture Proportioning Based on Paste-to-Void Content

The following methodology is suggested to arrive at trial mixture proportions for optimized paste volumes to achieve the required strength, workability and durability:

1. Establish a ratio of coarse to fine aggregate. The ACI 211.1 process of selecting the volume of dry rodded coarse aggregate per unit volume of concrete, based on nominal maximum size of coarse aggregate and the fineness modulus of the sand, can be used.
2. Combine and blend samples of the coarse and fine aggregate in the established ratio by volume and measure the void content of the combined aggregate in accordance with ASTM C29.
3. For concrete to be used in horizontal applications that have to be hand-finished, such as slabs and pavements, a water slump of at least 1 in. is desirable. Besides slump, finishability is important for these applications. Choose a paste volume that is equal to 1.2 x measured void content of the combined aggregate. For other concrete applications, choose a paste volume that is equal to 1.1 x void content of combined aggregate. The placement method, such as pumped concrete, may require a higher paste volume. Include volume of air in the paste volume.
4. Select w/cm for required strength and/or durability. The actual w/cm would depend on the local materials, and cementitious type and specification requirements for durability.
5. Calculate the total cementitious materials and mixing water contents from the selected paste volume and w/cm. Split the cementitious materials in the desired percentage of portland cement and supplementary cementitious materials.
6. Prepare a trial mixture in the laboratory in accordance with ASTM C192. For mixtures that do not yield a measureable water slump, add a small quantity of water reducing admixture with the initial mixing water followed by additional HRWRA during mixing as needed to attain target workability.
7. If workability of the trial batch is not adequate, where it appears to be deficient in paste, increase mixing water content and then recalculate CM content based on target w/cm in a new trial batch. HRWRA dosage may have to be reduced. If workability is too high, where the mixture appears to have excessive paste, reduce mixing water content and recalculate CM content based on target w/cm in a new trial batch.

It should be emphasized that, as with any procedure for mixture proportioning, trial batches should be prepared to evaluate the performance of fresh and hardened concrete and appropriate modifications made. The above approach is proposed to reduce and optimize the cementitious materials contents by using minimum paste volume to achieve concrete with the required strength, improved durability, and low shrinkage.

Different aggregate types with varying size, shape and texture, and aggregate gradings can be tried to reduce the combined aggregate void content. As discussed earlier, for the leaner mixtures the aggregate proportions that result in the lowest combined aggregate void content would require the lowest water demand for target workability. For normal and rich mixtures, the optimum proportion of fine aggregate should be somewhat lower than that giving minimum void content for the combined aggregate. This is due to the influence of the specific surface of the aggregate on water demand. Therefore, it is best to make trial mixtures with different levels of fine aggregate that are at or slightly lower than that resulting in the lowest void content of the combined aggregate.

This methodology is based on the measured void content of the combined aggregate. Some observations are made on the variability of this determination:

1. When the same sample was tested three times by the same operator the range of the measured void content was about 2%. It is suggested that the void content be measured at least three times on different portions of the combined aggregate sample and the average value used.
2. The minimum size of measure based on the nominal maximum size (NMS) of coarse aggregate as required in ASTM C29 was used in the test. For a 1 in. NMS coarse aggregate a measure of volume 1/3 cubic feet was used. Measures of volume 0.1 and 0.5 cubic feet were used and the combined aggregate void contents did not vary by more than 2%. No trends were observed as the volume of the measure was varied.
3. When two operators measured the void content of the same sample with two replicate measurements, the variation in the average combined aggregate void content was 1.5%. Individual operator procedures with scooping portions for the test sample vary and can result in a difference in the ratio of coarse to fine aggregate incorporated in the measure. Increase in fine aggregate will reduce the measured void content. If there is a question on the representative nature of the tested sample, the compacted aggregates in the measure can be sieved to check the coarse to fine aggregate ratio.

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**Table 1:** Minimum cementitious materials content requirements for floors (Table 4.2.2.1 in ACI 301-10)

| Nominal maximum size of aggregate, in. | Minimum cementitious materials content, lb/yd$^3$ |
|---|---|
| 1-1/2 | 470 |
| 1 | 520 |
| 3/4 | 540 |
| 3/8 | 610 |

**Table 2:** Concrete Mixture Variables – Phase I

| W/CM | CM type | Paste volume, % | Target CM content |
|---|---|---|---|
| 0.40 | 40% slag cement | 24 | 510 |
| | | 26 | 556 |
| | | 29 | 625 |
| | | 33 | 718 |
| 0.47 | 40% slag cement | 24 | 465 |
| | | 26 | 507 |
| | | 29 | 570 |
| | | 33 | 655 |
| 0.55 | 40% slag cement | 24 | 422 |
| | | 26 | 461 |
| | | 29 | 518 |
| | | 33 | 595 |
| 0.47 | 25% fly ash | 24 | 465 |
| | | 26 | 507 |
| | | 29 | 570 |
| | | 33 | 655 |
| 0.47 | PC* | 24 | 449 |
| | | 26 | 490 |
| | | 29 | 551 |
| | | 33 | 633 |

*PC = portland cement only mixture

**Table 3:** Yield Adjusted Mixture Proportions and Test Results for the Slag Cement Mixtures – Phase I

| **Mixture Designation** | **0.55SL33** | **0.55SL29** | **0.55SL26** | **0.55SL24** | **0.47SL33** | **0.47SL29** | **0.47SL26** | **0.47SL24** | **0.40SL33** | **0.40SL29** | **0.40SL26** | **0.40SL24** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Calculated Batch Quantities** | | | | | | | | | | | | |
| Total Cementitious, lb/yd$^3$ | 602 | 517 | 459 | 417 | 655 | 571 | 507 | 465 | 720 | 627 | 557 | 505 |
| Portland cement, lb/yd$^3$ | 361 | 310 | 275 | 250 | 393 | 343 | 304 | 279 | 432 | 376 | 334 | 303 |
| Slag cement, lb/yd$^3$ | 241 | 207 | 184 | 167 | 262 | 228 | 203 | 186 | 288 | 251 | 223 | 202 |
| SCM, % | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Coarse Aggregate, lb/yd$^3$ | 1929 | 2015 | 2095 | 2135 | 1905 | 2025 | 2102 | 2159 | 1910 | 2028 | 2107 | 2143 |
| Fine Aggregate, lb/yd$^3$ | 1245 | 1301 | 1353 | 1379 | 1230 | 1307 | 1357 | 1394 | 1233 | 1309 | 1360 | 1384 |
| Mixing Water, lb/yd$^3$ | 331 | 284 | 252 | 229 | 308 | 268 | 238 | 218 | 288 | 251 | 223 | 202 |
| w/cm | 0.55 | 0.55 | 0.55 | 0.55 | 0.47 | 0.47 | 0.47 | 0.47 | 0.40 | 0.40 | 0.40 | 0.40 |
| HRWRA, oz/cwt | 0.0 | 0.0 | 0.0 | 7.7 | 0.0 | 0.0 | 2.8 | 7.7 | 0.0 | 1.2 | 7.1 | 12.0 |
| Defoaming agent, ml | 17 | 17 | 17 | 15 | 17 | 17 | 15 | 15 | 10 | 10 | 15 | 15 |
| Yield Adjusted Paste Volume, % | 32.3 | 28.4 | 25.9 | 23.7 | 32.6 | 28.5 | 26.0 | 23.7 | 33.5 | 28.8 | 25.9 | 23.7 |
| Paste-To-Void Ratio | 1.27 | 1.12 | 1.02 | 0.93 | 1.28 | 1.12 | 1.02 | 0.93 | 1.32 | 1.13 | 1.02 | 0.93 |
| **Fresh Concrete Properties** | | | | | | | | | | | | |
| ASTM C143, Slump Before HRWRA, in. | 8.25 | 6.50 | 1.25 | 0.00 | 7.75 | 1.75 | 0.00 | 0.00 | 2.50 | 0.25 | 0.00 | 0.00 |
| ASTM C143, Slump After HRWRA, in. | | | | 2.00 | | | 1.50 | 3.50 | | 1.50 | 8.00 | 1.25 |
| Workability Observation | very fluid, some segregation | | | visually rocky | very workable no apparent segregation, lots of paste | just enough workability, not sticky | rocky | visually very sticky | | | final slump sheared on one side, handling medium to hard | |
| ASTM C231, Air, % | 1.0 | 1.5 | 2.0 | 2.0 | 1.6 | 1.5 | 2.0 | 1.7 | 2.4 | 1.7 | 1.8 | 1.9 |
| ASTM C138, Density, lb/ft$^3$ | 152.9 | 153.3 | 154.9 | 154.9 | 152.5 | 155.3 | 156.5 | 157.7 | 154.5 | 156.9 | 158.1 | 157.7 |
| ASTM C1064, Temperature, °F | 74 | 75 | 75 | 75 | 76 | 76 | 74 | 74 | 73 | 74 | 75 | 72 |
| Thermal Initial Setting, h:min | 3:26 | 3:25 | 3:28 | 4:48 | 3:29 | 3:22 | 3:44 | 5:32 | 3:27 | 2:51 | 5:01 | 8:01 |
| Thermal Final Setting, h:min | 4:55 | 5:02 | 5:03 | 6:22 | 4:59 | 4:55 | 5:09 | 7:11 | 4:57 | 4:13 | 6:42 | 9:55 |

| **Mixture Designation** | **0.55SL33** | **0.55SL29** | **0.55SL26** | **0.55SL24** | **0.47SL33** | **0.47SL29** | **0.47SL26** | **0.47SL24** | **0.40SL33** | **0.40SL29** | **0.40SL26** | **0.40SL24** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hardened Concrete Properties** | | | | | | | | | | | | |
| **ASTM C39, Compressive Strength, psi** | | | | | | | | | | | | |
| 1d | 1,040 | 720 | 860 | 900 | 1,270 | 1,250 | 1,360 | 1,280 | 1,770 | 1,890 | 2,150 | 1,690 |
| 7d | 2,980 | 2,860 | 2,830 | 3,160 | 3,840 | 4,040 | 4,240 | 4,510 | 5,170 | 5,480 | 6,260 | 5,820 |
| 28d | 6,300 | 5,700 | 5,450 | 6,010 | 6,850 | 7,170 | 7,480 | 7,800 | 8,100 | 8,780 | 8,800 | 8,560 |
| **ASTM C1202, RCPT, coulomb** | | | | | | | | | | | | |
| 28d ac | 1218 | 791 | 822 | 532 | 1079 | 803 | 785 | 547 | 908 | 709 | 484 | 465 |
| **AASHTO TP64, RMT, mm/V-hr** | | | | | | | | | | | | |
| 28d accelerated | 0.0163 | 0.0156 | 0.0139 | 0.0095 | 0.0126 | 0.0115 | 0.0115 | 0.0075 | 0.0098 | 0.0078 | 0.0069 | 0.0060 |
| **ASTM C157, Length Change, %** | | | | | | | | | | | | |
| 28d | 0.044 | 0.032 | 0.036 | 0.036 | 0.041 | 0.034 | 0.037 | 0.027 | 0.030 | 0.027 | 0.023 | 0.020 |
| 3 mo | 0.053 | 0.043 | 0.046 | 0.044 | 0.054 | 0.048 | 0.044 | 0.035 | 0.044 | 0.039 | 0.034 | 0.031 |
| **ASTM C 1585, Rate of Water Absorption (Sorptivity), x$10^{-4}$ mm/$s^{1/2}$** | | | | | | | | | | | | |
| Initial Sorptivity | 4.02 | | 1.89 | 1.93 | 3.42 | 2.53 | | 2.49 | 5.85 | | 2.13 | 1.87 |
| $r^2$ | 1.00 | | 0.98 | 0.97 | 0.99 | 1.00 | | 0.99 | 0.98 | | 1.00 | 0.98 |
| **ASTM C1556, Chloride Concentration at Different Depths, % by weight of concrete** | | | | | | | | | | | | |
| 9 mm | 1.040 | 0.964 | 0.710 | 0.567 | 1.193 | 0.750 | 1.012 | 0.881 | 1.039 | 0.655 | 0.559 | 0.602 |
| 11 mm | 0.994 | 0.929 | 0.579 | 0.545 | 0.916 | 0.707 | 0.794 | 0.750 | 0.758 | 0.601 | 0.506 | 0.494 |
| 17 mm | 0.513 | 0.633 | 0.398 | 0.435 | 0.624 | 0.433 | 0.311 | 0.372 | 0.326 | 0.332 | 0.313 | 0.275 |
| 19 mm | 0.430 | 0.579 | 0.409 | 0.368 | 0.573 | 0.347 | 0.277 | 0.312 | 0.191 | 0.203 | 0.194 | 0.205 |
| 73 mm | 0.007 | 0.012 | 0.015 | 0.023 | 0.006 | 0.007 | 0.048 | 0.009 | 0.059 | 0.005 | 0.040 | 0.015 |

**Table 4:** Yield Adjusted Mixture Proportions and Test Results for the Fly Ash and Portland Cement Concrete Mixtures – Phase I

| **Mixture Designation** | **0.47FA33** | **0.47FA29** | **0.47FA26** | **0.47FA24** | **0.47PC33** | **0.47PC29** | **0.47PC26** | **0.47PC24** |
|---|---|---|---|---|---|---|---|---|
| **Calculated Batch Quantities** | | | | | | | | |
| Total Cementitious, lb/yd$^3$ | 641 | 553 | 491 | 451 | 670 | 581 | 512 | 471 |
| Portland cement, lb/yd$^3$ | 481 | 415 | 368 | 338 | 670 | 581 | 512 | 471 |
| Slag cement, lb/yd$^3$ | | | | | | | | |
| Fly ash, lb/yd$^3$ | 160 | 138 | 123 | 113 | | | | |
| SCM, % | 25 | 25 | 25 | 25 | 0 | 0 | 0 | 0 |
| Coarse Aggregate, lb/yd$^3$ | 1930 | 2028 | 2109 | 2165 | 1924 | 2035 | 2097 | 2160 |
| Fine Aggregate, lb/yd$^3$ | 1246 | 1309 | 1362 | 1398 | 1242 | 1314 | 1354 | 1395 |
| Mixing Water, lb/yd$^3$ | 301 | 260 | 231 | 212 | 315 | 273 | 240 | 221 |
| w/cm | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| HRWRA, oz/cwt | 0.0 | 0.0 | 5.9 | 10.4 | 0.0 | 0.0 | 4.8 | 14.6 |
| Defoaming agent, ml | 0 | 0 | 17 | 17 | 17 | 17 | 17 | 17 |
| Yield Adjusted Paste Volume, % | 32.5% | 28.6% | 26.3% | 24.0% | 32.7% | 28.8% | 25.6% | 23.9% |
| Paste-To-Void Ratio | 1.28 | 1.12 | 1.03 | 0.94 | 1.29 | 1.13 | 1.01 | 0.94 |
| **Fresh Concrete Properties** | | | | | | | | |
| ASTM C143, Slump Before HRWRA, in. | 6.00 | 1.50 | 0.00 | 0.00 | 7.50 | 2.00 | 0.00 | 0.00 |
| ASTM C143, Slump After HRWRA, in. | | | 1.25 | 0.50 | | | 1.75 | 1.25 |
| ASTM C231, Air, % | 1.1 | 1.5 | 2.2 | 1.9 | 1.4 | 1.6 | 1.7 | 1.9 |
| ASTM C138, Density, lb/ft$^3$ | 153.3 | 154.5 | 156.1 | 157.3 | 154.5 | 156.5 | 156.5 | 158.1 |
| ASTM C1064, Temperature, °F | 78 | 77 | 78 | 78 | 78 | 78 | 85 | 83 |
| Thermal Initial Setting, h:min | | | 3:30 | 5:15 | 2:35 | 2:47 | 3:34 | 4:35 |
| Thermal Final Setting, h:min | | | 5:00 | 7:13 | 3:56 | 4:09 | 4:48 | 5:54 |
| **Hardened Concrete Properties** | | | | | | | | |
| **ASTM C39, Compressive Strength, psi** | | | | | | | | |
| 1d | 1,770 | 1,790 | 2,050 | 1,860 | 2,780 | 2,870 | 2,890 | 3,180 |
| 7d | 3,500 | 3,750 | 4,060 | 3,720 | 5,270 | 5,480 | 5,120 | 5,280 |
| 28d | 5,460 | 5,630 | 5,900 | 5,600 | 6,810 | 7,160 | 6,510 | 7,170 |
| **ASTM C1202, RCPT, coulomb** | | | | | | | | |
| 28d ac | 1367 | 1256 | 1027 | 959 | 3790 | 3317 | 2966 | 2602 |
| **AASHTO TP64, RMT, mm/V-hr** | | | | | | | | |
| 28d accelerated | 0.0279 | 0.0279 | 0.0271 | 0.0263 | 0.0408 | 0.0402 | 0.0386 | 0.0395 |
| **ASTM C157, Length Change, %** | | | | | | | | |
| 28d | 0.027 | 0.024 | 0.027 | 0.023 | 0.027 | 0.023 | 0.023 | 0.024 |
| 3 mo | 0.043 | 0.039 | 0.038 | 0.035 | 0.046 | 0.039 | 0.038 | 0.038 |
| **ASTM C 1585, Rate of Water Absorption (Sorptivity), x10$^{-4}$ mm/s$^{1/2}$** | | | | | | | | |
| Initial rate | 5.83 | 5.47 | 5.13 | 6.43 | 4.69 | NA | 4.79 | 4.47 |
| r$^2$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | NA | 1.00 | 0.99 |

**Table 5:** Yield Adjusted Mixture Proportions and Test Results for the Air-Entrained Concrete Mixtures – Phase II

| **Mixture Designation** | **0.47SL33A** | **0.47SL29A** | **0.47SL26A** | **0.47SL24A** |
|---|---|---|---|---|
| **Calculated Batch Quantities** | | | | |
| Total Cementitious, lb/yd$^3$ | 581 | 491 | 429 | 373 |
| Portland cement, lb/yd$^3$ | 349 | 295 | 258 | 224 |
| Slag cement, lb/yd$^3$ | 232 | 196 | 171 | 149 |
| Fly ash, lb/yd$^3$ | | | | |
| SCM, % | 40 | 40 | 40 | 40 |
| Coarse Aggregate, lb/yd$^3$ | 1892 | 1990 | 2084 | 2069 |
| Fine Aggregate, lb/yd$^3$ | 1251 | 1317 | 1379 | 1369 |
| Mixing Water, lb/yd$^3$ | 274 | 233 | 203 | 176 |
| w/cm | 0.47 | 0.47 | 0.47 | 0.47 |
| AEA, oz/cwt | 1.7 | 2.3 | 1.1 | 1.2 |
| HRWRA, oz/cwt | 0 | 2.0 | 4.5 | 7.4 |
| Yield Adjusted Paste Volume, % | 33.0% | 28.9% | 25.8% | 23.7% |
| Paste-To-Void Ratio | 1.49 | 1.30 | 1.16 | 1.07 |
| **Fresh Concrete Properties** | | | | |
| ASTM C143, Slump Before HRWRA, in. | 4.75 | 0.50 | 0 | 0 |
| ASTM C143, Slump After HRWRA, in. | | 2.00 | 2.50 | 4.50 |
| Workability Observation | creamy | sticky | just workable | very workable |
| ASTM C231, Air, % | 5.5 | 5.5 | 5.4 | 6.0 |
| ASTM C138, Density, lb/ft$^3$ | 148.1 | 149.3 | 151.7 | 147.7 |
| ASTM C1064, Temperature, °F | 72 | 73 | 73 | 72 |
| **Hardened Concrete Properties** | | | | |
| **ASTM C39, Compressive Strength, psi** | | | | |
| 1d | 600 | 440 | 420 | 570 |
| 7d | 3,090 | 3,610 | 3,550 | 2,730 |
| 28d | 4,880 | 4,810 | 4,910 | 3,960 |
| **ASTM C1202, RCPT, coulomb** | | | | |
| 90d | 978 | 552 | 478 | 468 |

**Table 6:** Calculated CM and Water Contents for the Required Minimum Paste-to-Void Ratio to attain a Water Slump of 1 in. for the 40% Slag Cement Mixtures Tested in Phase I

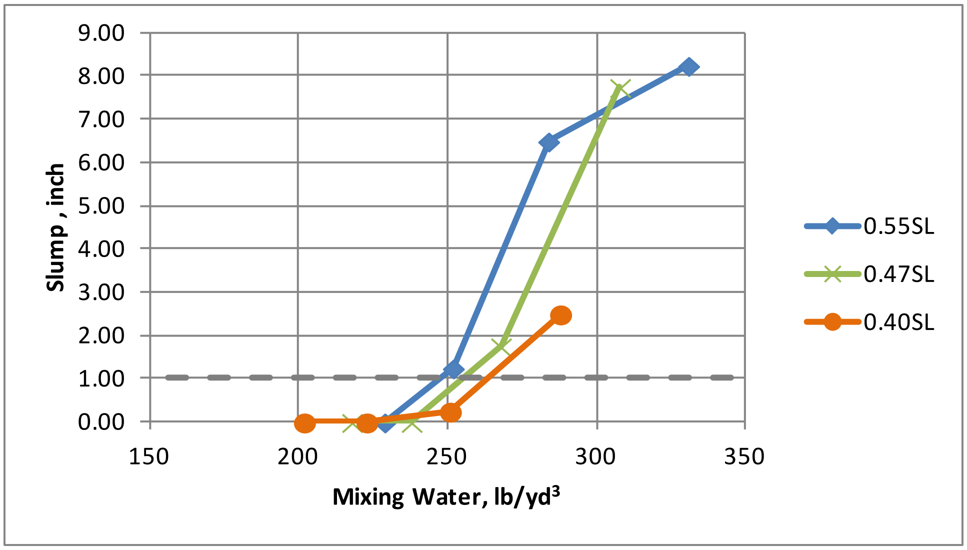
| Paste Volume, % | W/CM | CM Content, lb/yd$^3$ | Mixing Water, lb/yd$^3$ | Paste-to-void ratio |
|---|---|---|---|---|
| 25.7 | 0.55 | 455 | 250 | 1.01 |
| 30.1 | 0.40 | 650 | 260 | 1.19 |
| 25.7 | 0.40 | 550 | 220 | 1.01 |

**Table 7:** Yield Adjusted Mixture Proportions and Test Results for Fly ash and Portland Cement Concrete Mixtures – Phase III

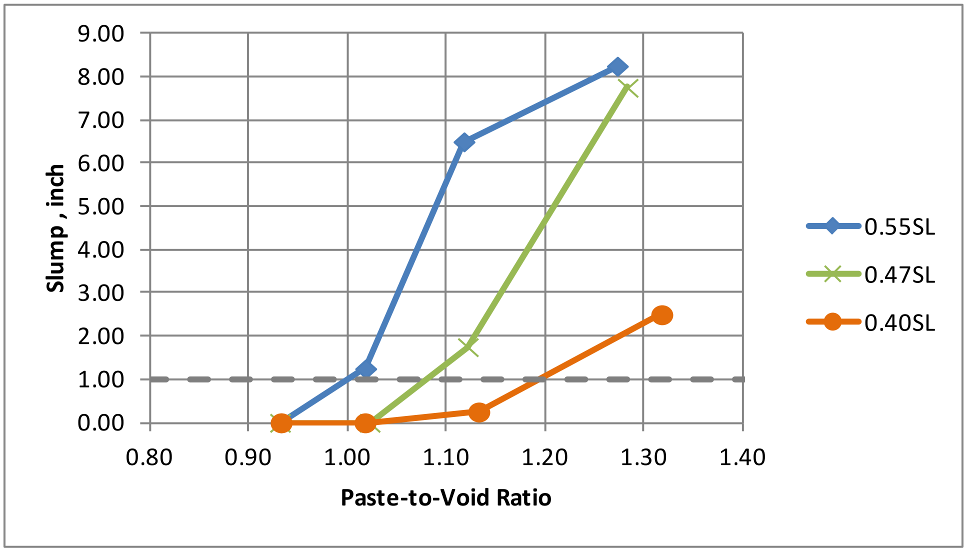
| **Mixture Designation** | **0.55PC23** | **0.55FA23** | **0.40PC23** | **0.40FA23** | **0.55PC25** | **0.55FA25** | **0.40PC25** | **0.40FA25** |
|---|---|---|---|---|---|---|---|---|
| **Calculated Batch Quantities** | | | | | | | | |
| Total Cementitious, lb/yd$^3$ | 401 | 395 | 490 | 464 | 449 | 436 | 543 | 531 |
| Portland cement, lb/yd$^3$ | 401 | 296 | 490 | 348 | 449 | 327 | 543 | 398 |
| Fly ash, lb/yd$^3$ | 0 | 99 | 0 | 116 | 0 | 109 | 0 | 133 |
| SCM, % | 0 | 25 | 0 | 25 | 0 | 25 | 0 | 25 |
| Coarse Aggregate, lb/yd$^3$ | 2064 | 2110 | 2072 | 2067 | 2026 | 2058 | 2032 | 2082 |
| Fine Aggregate, lb/yd$^3$ | 1365 | 1396 | 1371 | 1367 | 1341 | 1361 | 1345 | 1378 |
| Mixing Water, lb/yd$^3$ | 222 | 217 | 196 | 186 | 247 | 241 | 218 | 212 |
| w/cm | 0.55 | 0.55 | 0.40 | 0.40 | 0.55 | 0.55 | 0.40 | 0.40 |
| HRWRA, oz/cwt | 4.9 | 5.1 | 11.2 | 9.1 | 3.3 | 2.7 | 4.8 | 4.9 |
| Yield Adjusted Paste Volume, % | 25.2% | 24.7% | 24.9% | 25.7% | 27.1% | 26.0% | 27.1% | 26.3% |
| Paste-To-Void Ratio | 1.14 | 1.11 | 1.12 | 1.16 | 1.22 | 1.17 | 1.22 | 1.18 |
| **Fresh Concrete Properties** | | | | | | | | |
| ASTM C143, Slump After HRWRA, in. | 5.75 | 3.00 | 4.75 | 5.00 | 8.00 | 6.50 | 8.25 | 6.50 |
| Workability observation | runny | workable | sticky | sticky | very fluid, little segregation | fluid, very workable | workable, little sticky | workable, very sticky |
| ASTM C231, Air, % | 4.5 | 3.5 | 4.0 | 4.9 | 4.0 | 2.5 | 3.9 | 2.5 |
| ASTM C138, Density, lb/ft$^3$ | 150.1 | 152.5 | 152.9 | 151.3 | 150.5 | 151.7 | 153.3 | 155.7 |
| ASTM C1064, Temperature, °F | 73 | 73 | 73 | 73 | 75 | 75 | 75 | 75 |
| **Hardened Concrete Properties** | | | | | | | | |
| **ASTM C39, Compressive Strength, psi** | | | | | | | | |
| 1d | 810 | 370 | 1,530 | 1,300 | 960 | 530 | 2,180 | 1,550 |
| 7d | 3,030 | 2,140 | 5,580 | 4,830 | 3,710 | 2,240 | 6,030 | 4,870 |
| 28d | 4,060 | 3,430 | 6,690 | 6,260 | 4,700 | 3,580 | 7,440 | 6,800 |
| **ASTM C1202, RCPT, coulomb** | | | | | | | | |
| 90 d (standard cured) | 3484 | 1004 | 1538 | 724 | 3930 | 1208 | 2109 | 748 |

**Table 8:** Required Minimum Paste-to-Void Ratios for Optimized Performance for all Mixtures Tested

| Phase | Mixture Proportioning Preference | w/cm | CM type | Air content | Minimum paste-to-void ratio | Other remarks |
|---|---|---|---|---|---|---|
| I | Water slump of 1 in. (i.e. slump without any admixture added=1 in.) | 0.55 | 40% slag | 2.0% | 1.01 | Non-air-entrained concrete |
| | | 0.47 | 40% slag | 1.5% | 1.09 | |
| | | 0.40 | 40% slag | 1.7% | 1.17 | |
| | | 0.47 | PC | 1.6% | 1.10 | |
| | | 0.47 | 25% fly ash | 1.5% | 1.11 | |
| | No measurable water slump. HRWRA needed for workability | 0.55 | 40% slag | 2.0% | 0.93 | |
| | | 0.47 | 40% slag | 1.9% | 0.93 | |
| | | 0.40 | 40% slag | 1.7% | 0.93 | |
| | | 0.47 | PC | 1.9% | 0.94 | |
| | | 0.47 | 25% fly ash | 1.9% | 0.94 | |
| II | Water slump of 1 in. | 0.47 | 40% slag | 5.5% | 1.34 | Air-entrained concrete, Different coarse aggregate from Phase I |
| | No measurable water slump. HRWRA needed for workability | 0.47 | 40% slag | 5.5% | 1.16 | |
| III | No measurable water slump. HRWRA needed for workability (sometimes with head water) | 0.55 | PC | 4.0% | 1.22 | Non-air-entrained concrete, Same coarse aggregate as Phase II |
| | | 0.55 | 25% fly ash | 3.5% | 1.11 | |
| | | 0.40 | PC | 3.9% | 1.22 | |
| | | 0.40 | 25% fly ash | 4.9% | 1.16 | |



(a)



(b)

**Figure 1:** Phase I: Measured Slump for the Slag Cement Mixtures prior to adding any HRWRA vs (a) Mixing Water content (b) Paste-to-Void ratio

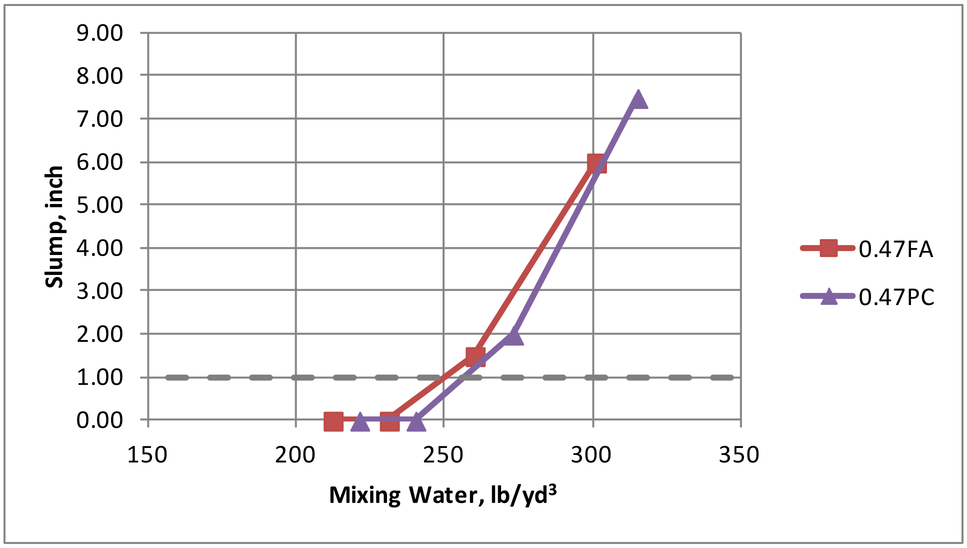
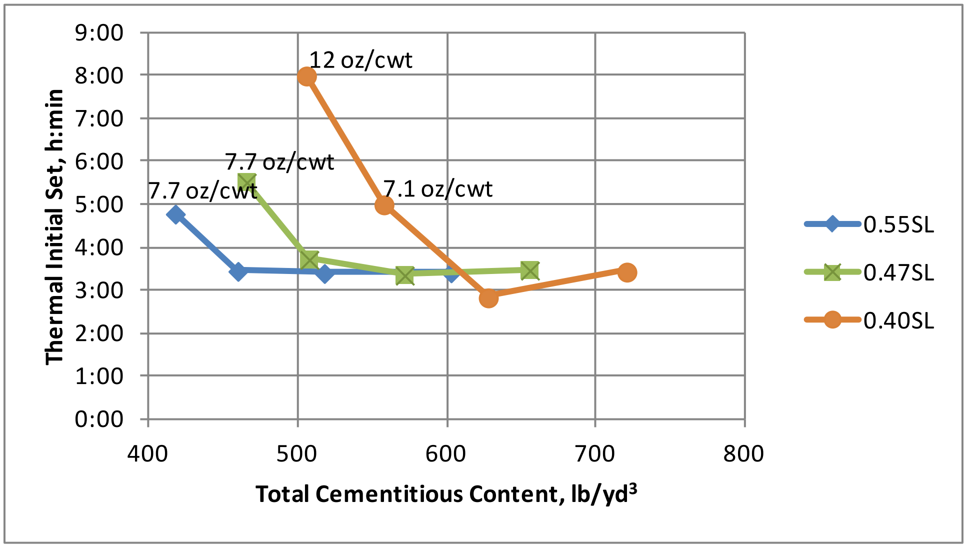


**Figure 2:** Phase I: Measured Slump for the Portland Cement and Fly Ash Mixtures prior to adding any HRWRA Vs Mixing Water Content



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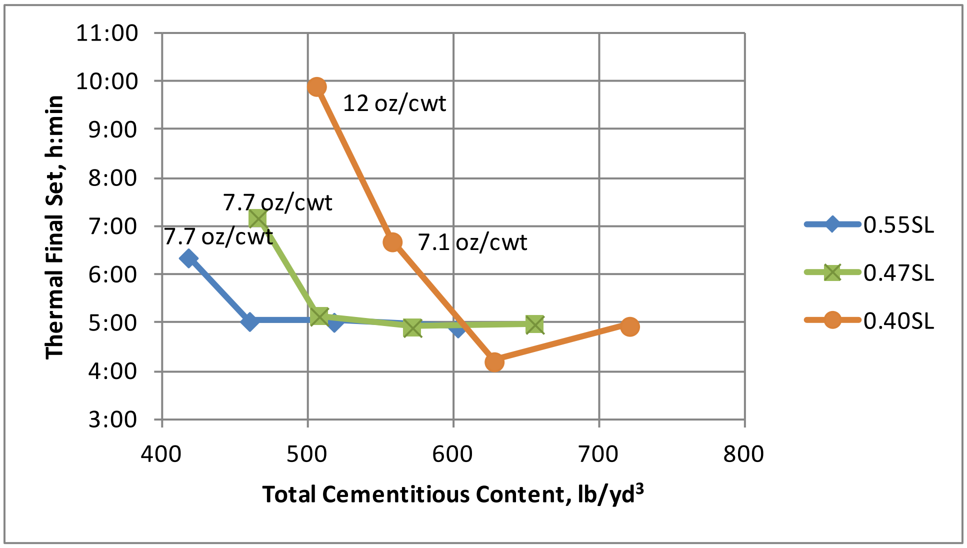
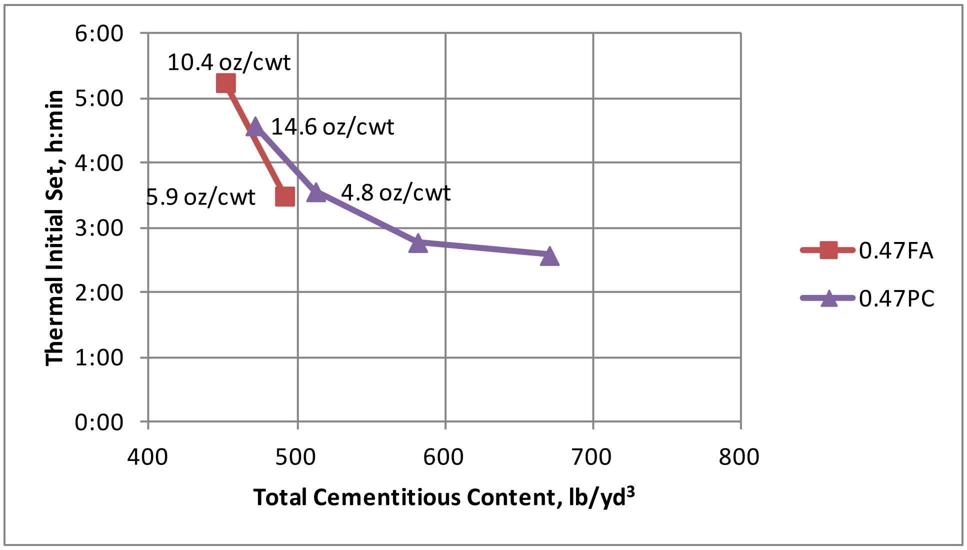


(b)

**Figure 3:** Phase I: Thermal Setting Times Vs Total Cementitious Content of the Slag Cement Mixtures (a) Initial Setting Time (b) Final Setting Time



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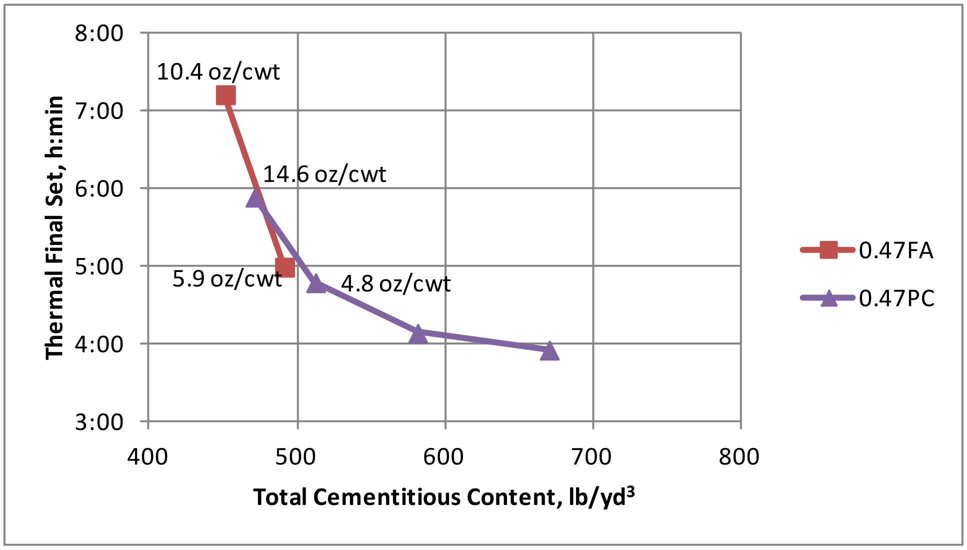
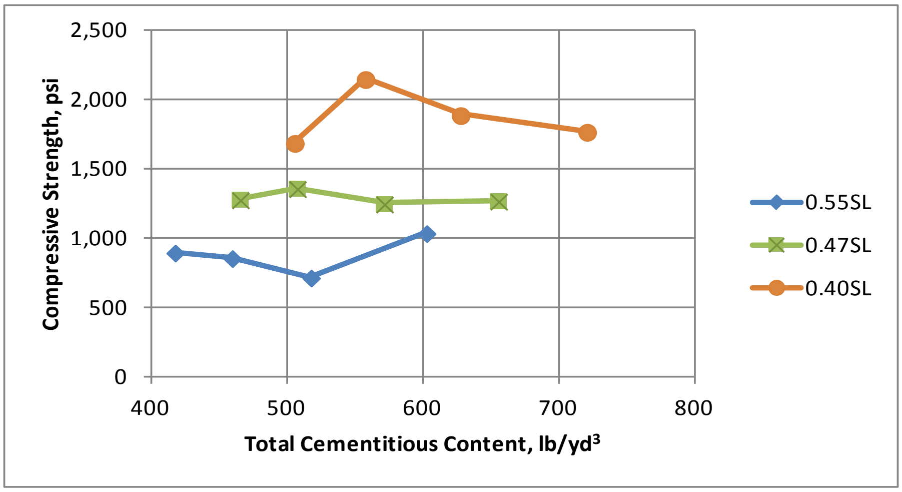


(b)

**Figure 4:** Phase I: Thermal Setting Times Vs Total Cementitious Content of the Portland Cement and Fly Ash Mixtures (a) Initial Setting Time (b) Final Setting Time



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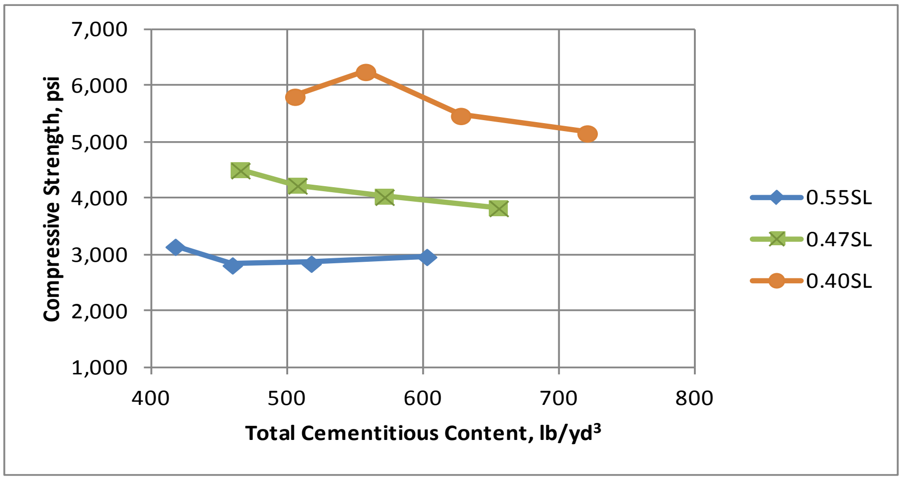
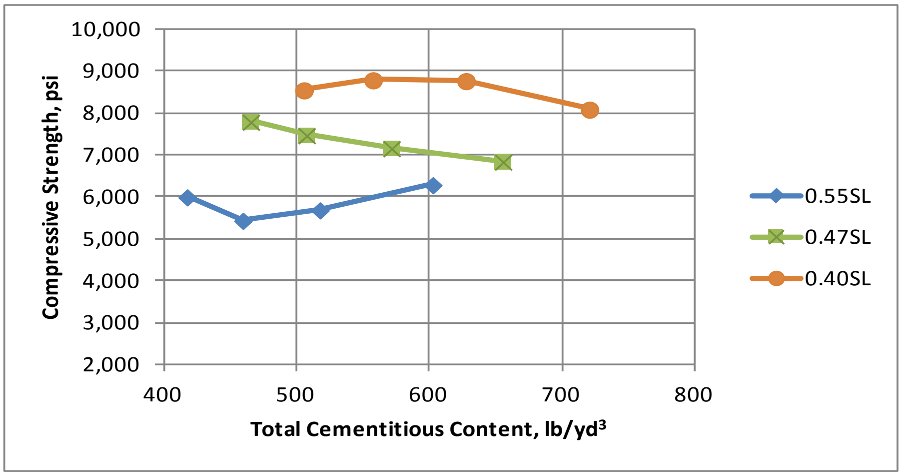
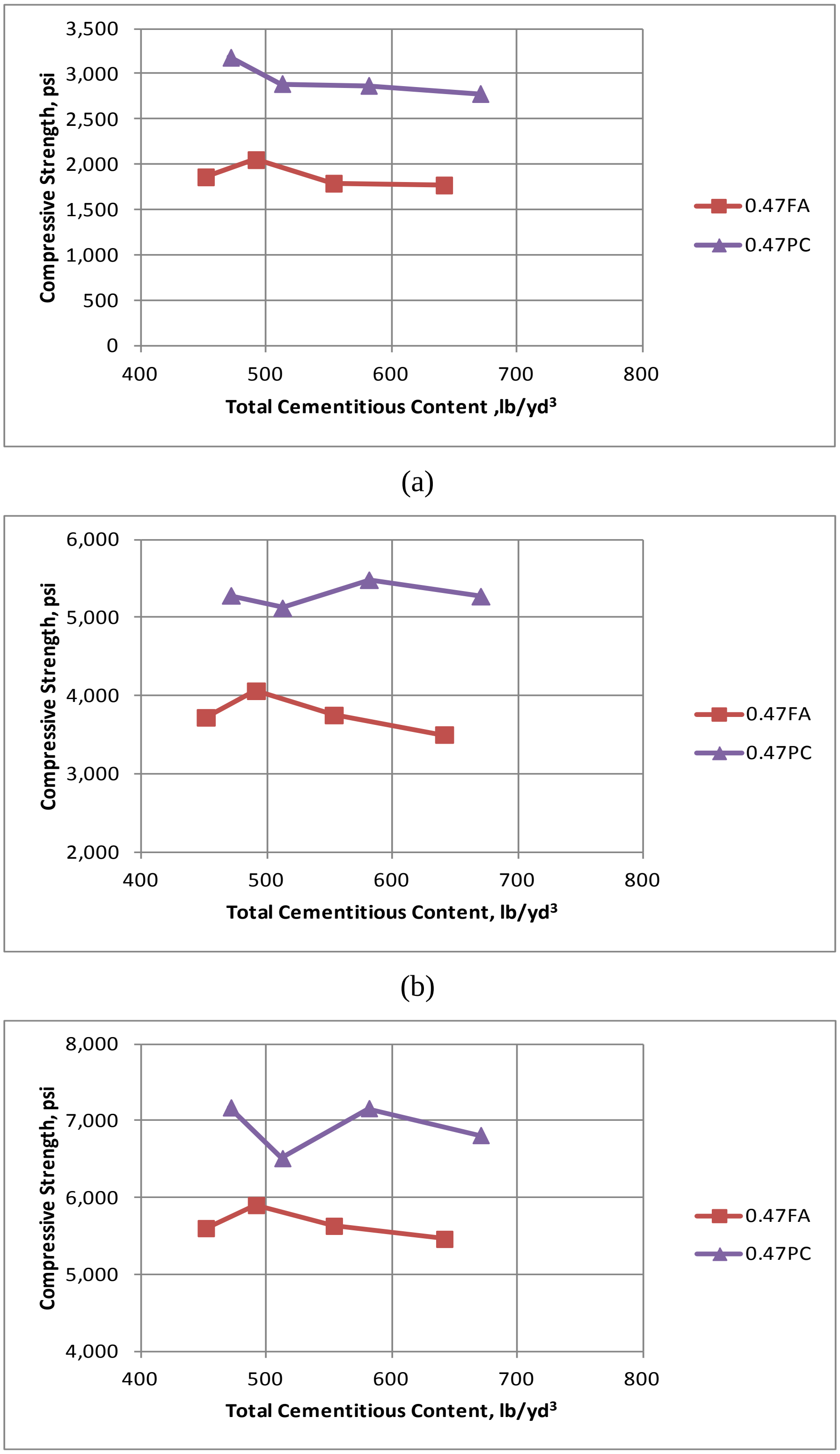


(b)



(c)

**Figure 5:** Phase I: Compressive Strength Vs Total Cementitious Content for the Slag Cement Mixtures (a) 1d Strength (b) 7d Strength (c) 28d Strength

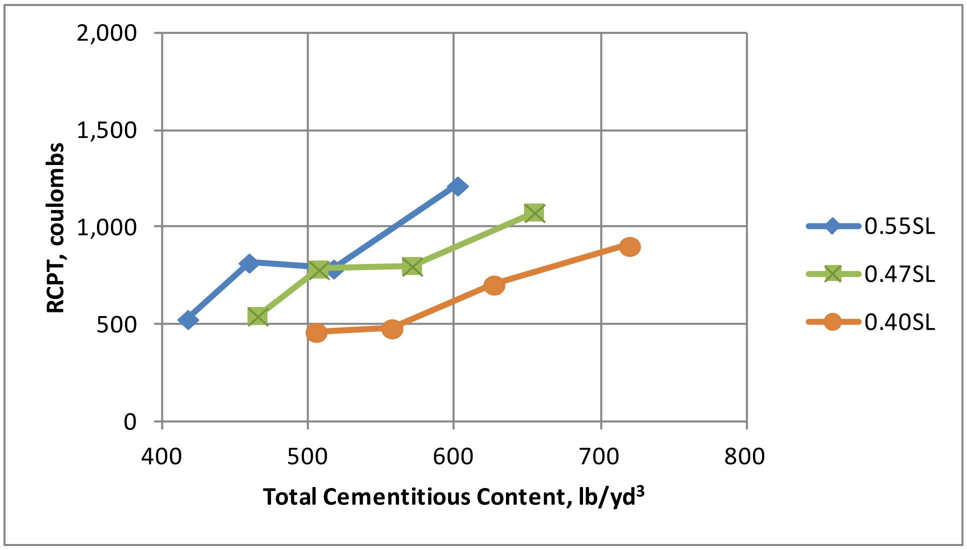


(a)

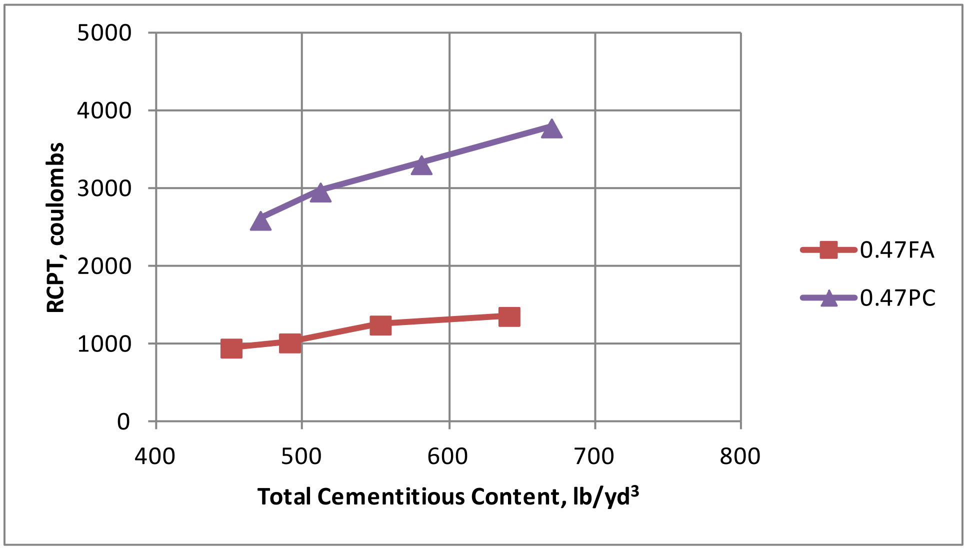
(b)

(c)

**Figure 6:** Phase I: Compressive Strength Vs Total Cementitious Content for the Portland Cement and Fly Ash Mixtures (a) 1d Strength (b) 7d Strength (c) 28d Strength



(a)



(b)

**Figure 7:** Phase I: RCPT Vs Total Cementitious Content for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures

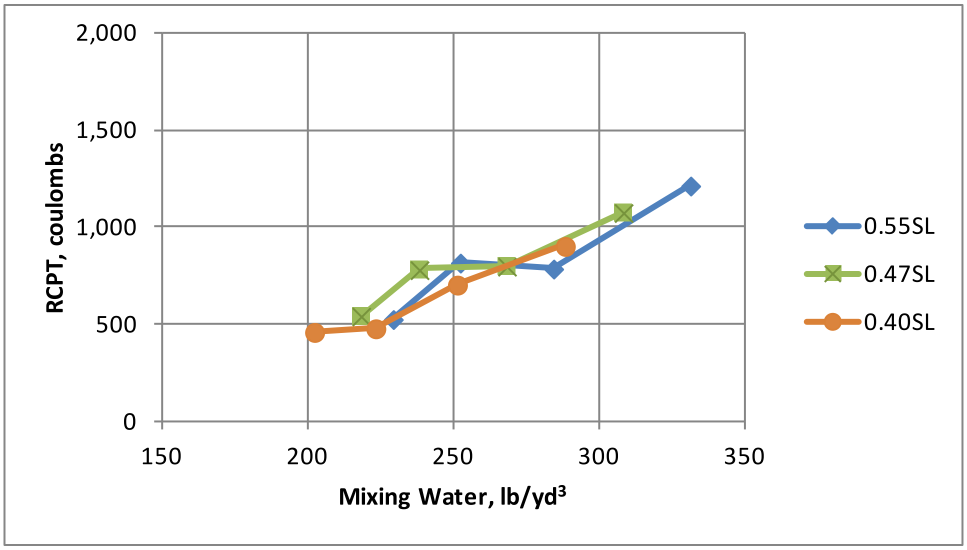
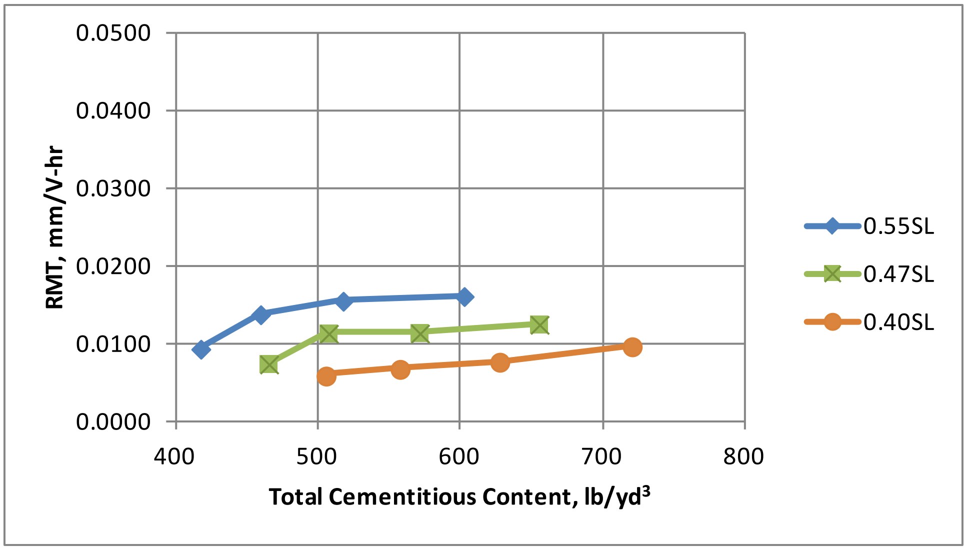


**Figure 8:** Phase I: RCPT Vs Mixing Water for the Slag Cement Mixtures



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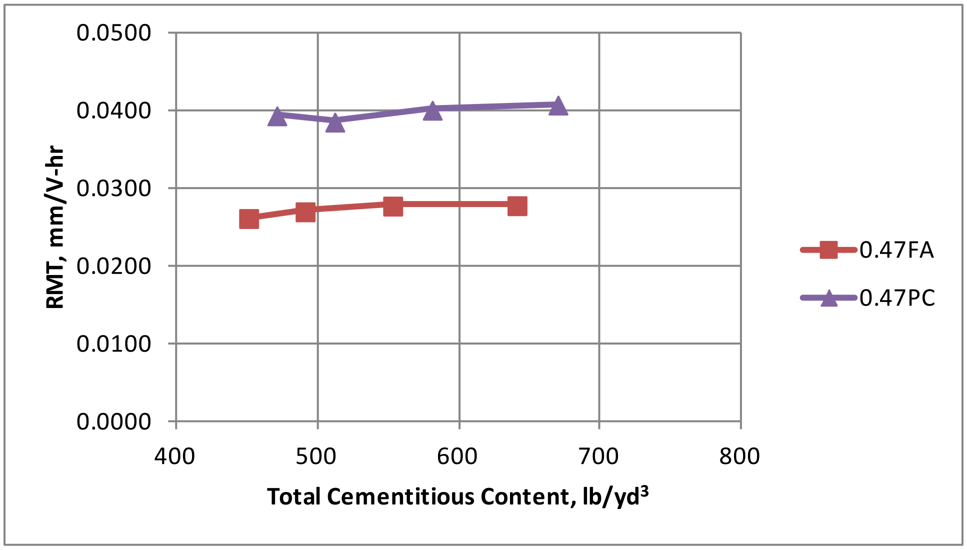


(b)

**Figure 9:** Phase I: RMT Vs Total Cementitious Content for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures

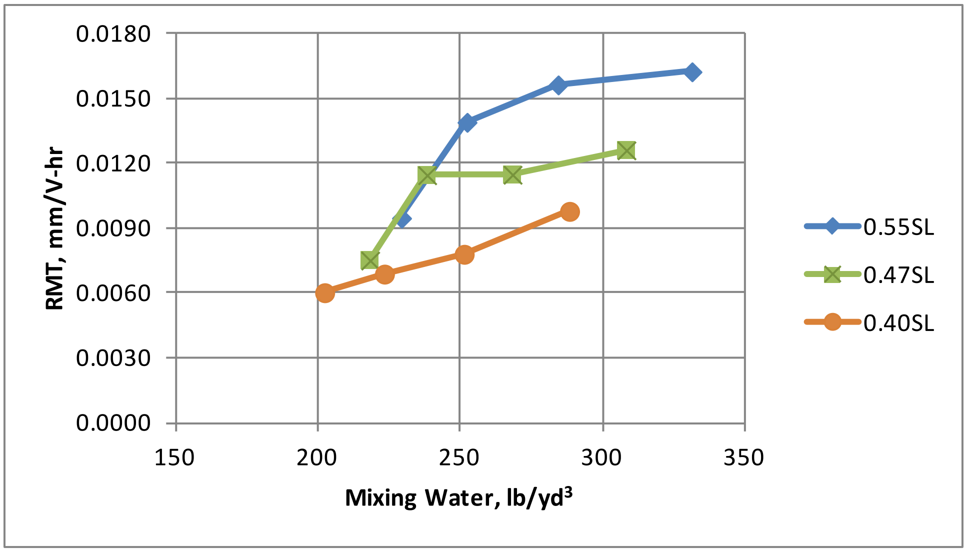
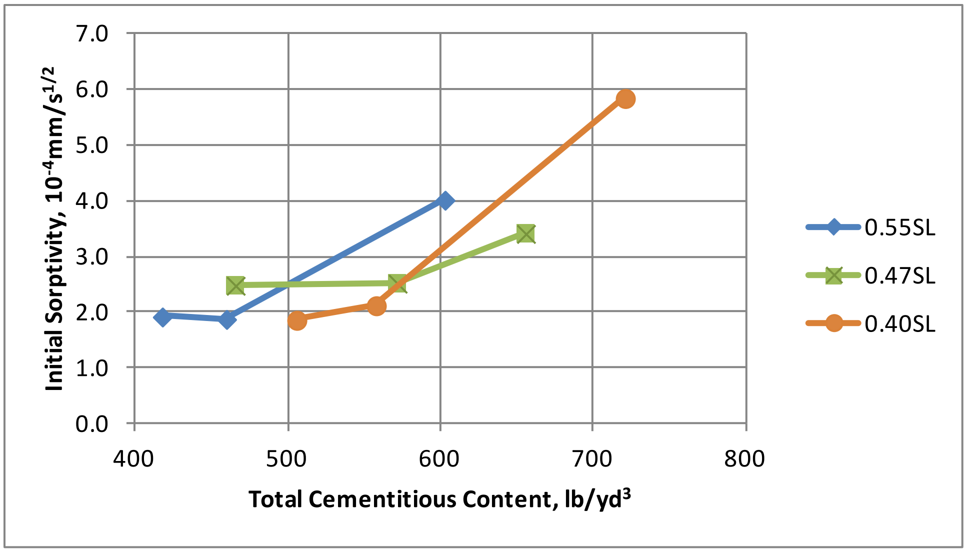
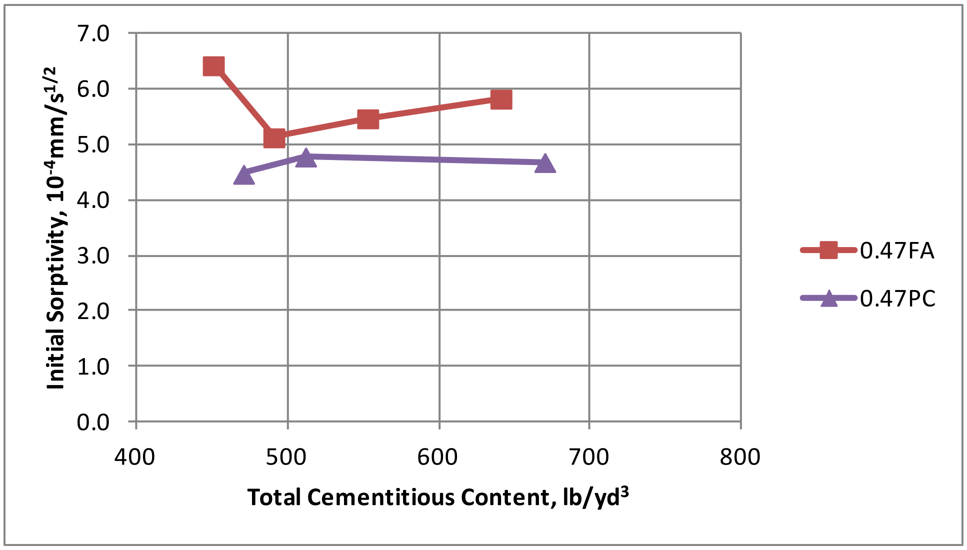


**Figure 10:** RMT Vs Mixing Water for the Slag Cement Mixtures



(a)



(b)

**Figure 11:** Phase I: Initial Sorptivity Value Vs Total Cementitious Content for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures

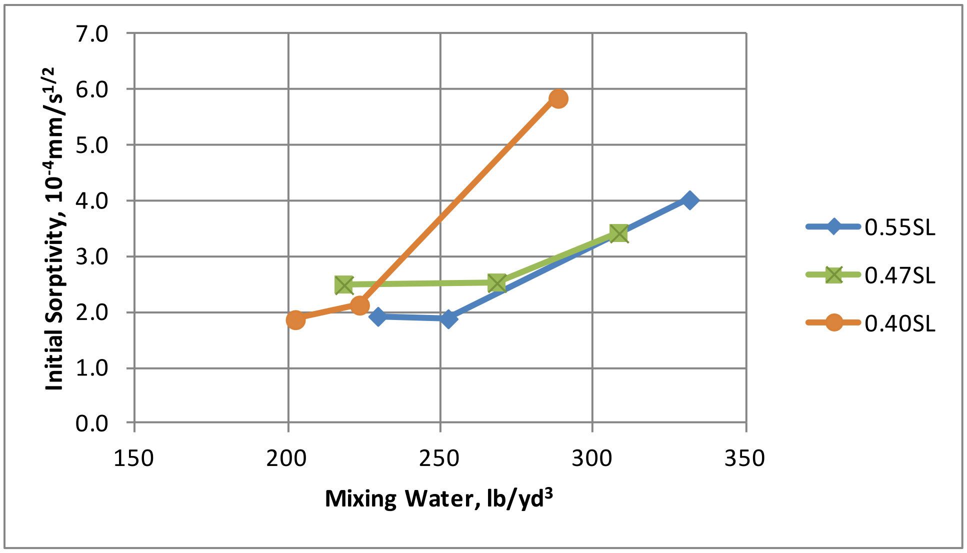


**Figure 12:** Phase I: Initial Sorptivity Value Vs Mixing Water for the Slag Cement Mixtures

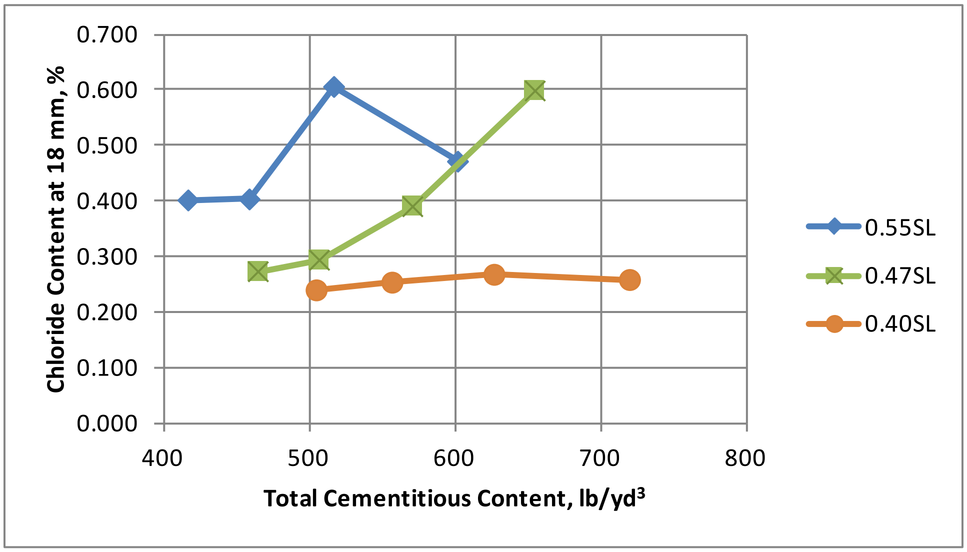


**Figure 13:** Phase I: Chloride Concentration at 18 mm depth Vs Total Cementitious Content

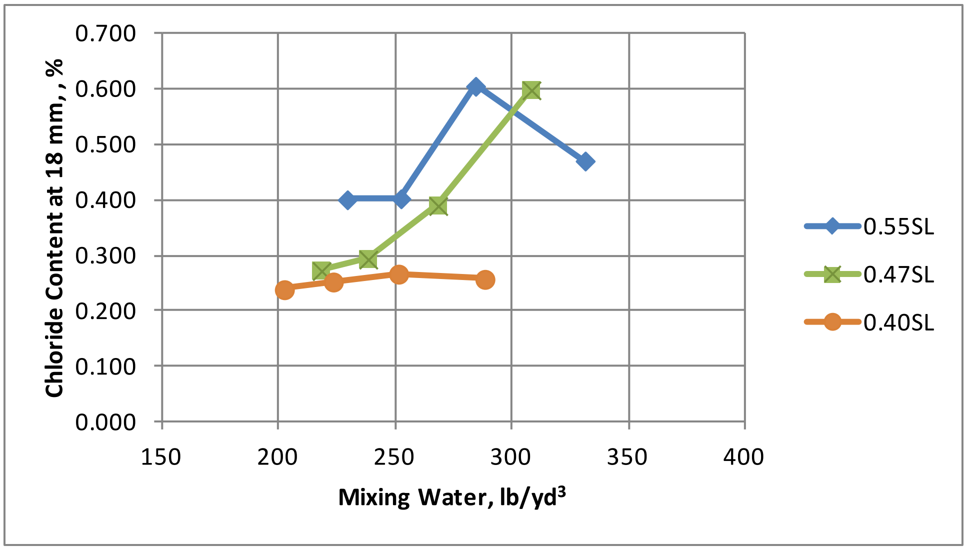
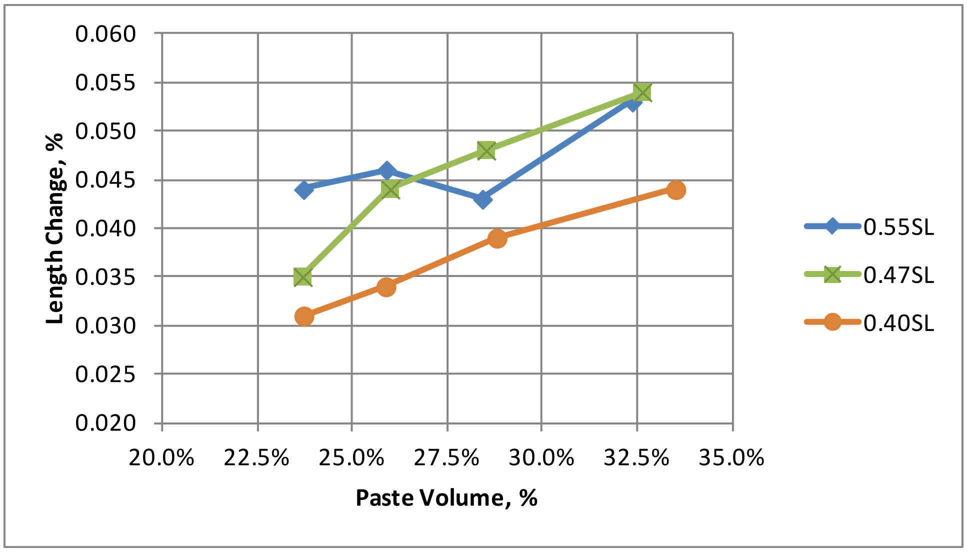
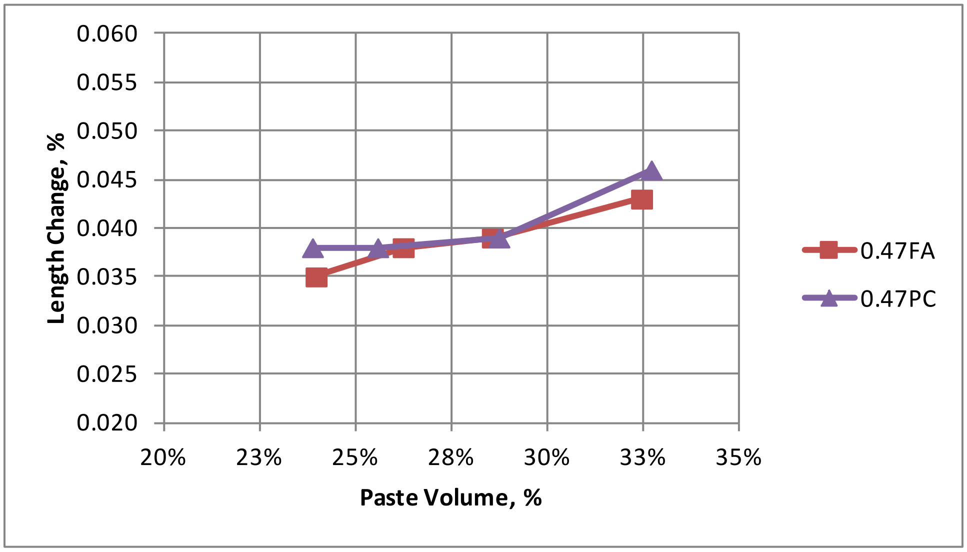


**Figure 14:** Phase I: Chloride Concentration at 18 mm depth Vs Mixing water content

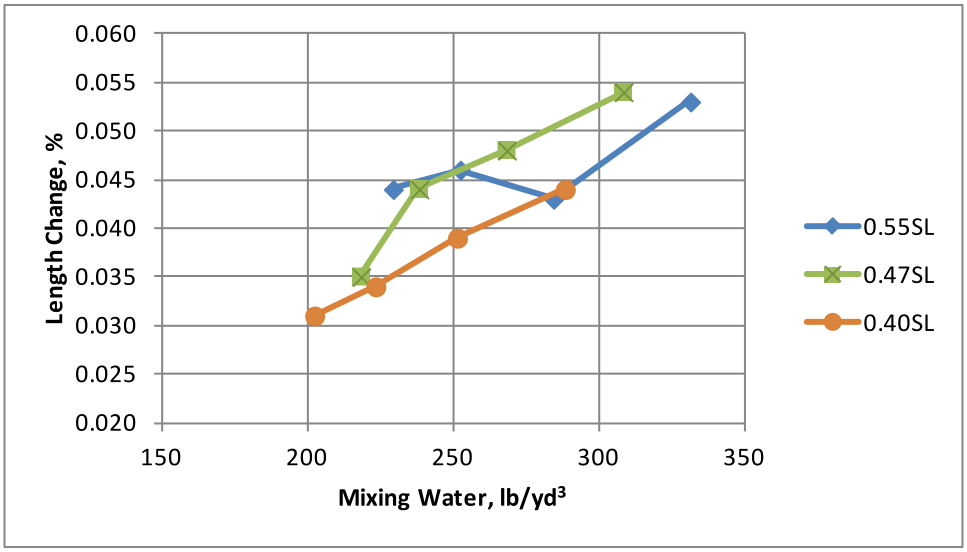


(a)



(b)

**Figure 15:** Phase I: Length Change Vs Paste Volume for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures



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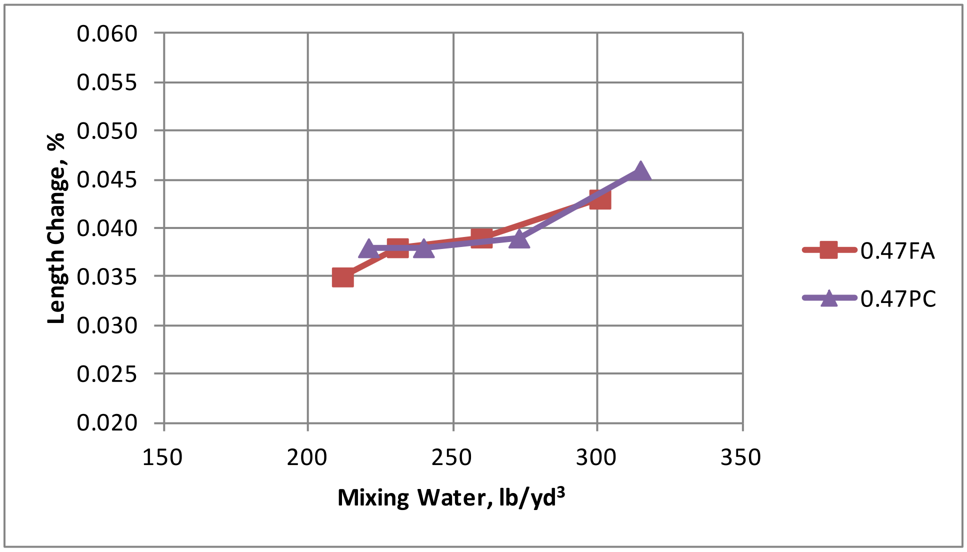
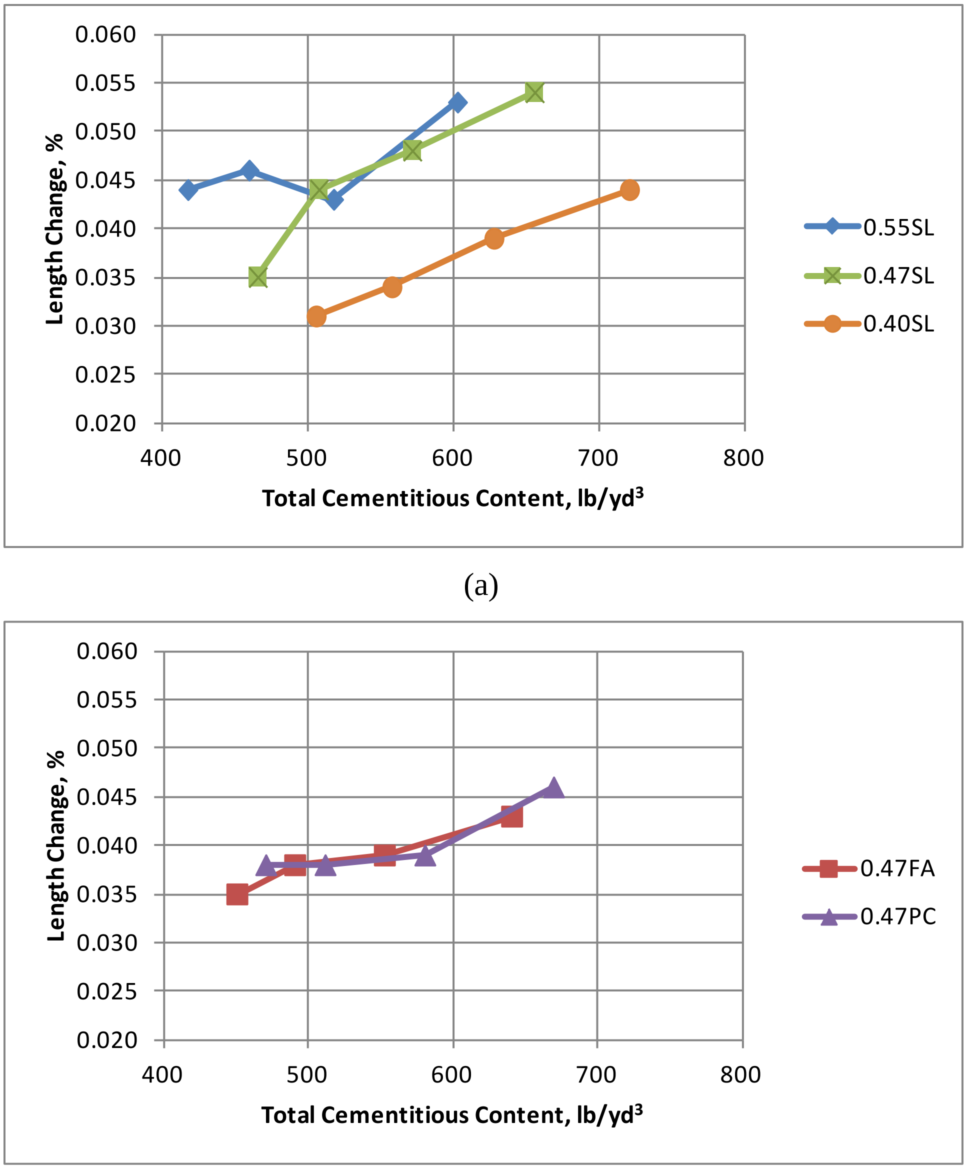


(b)

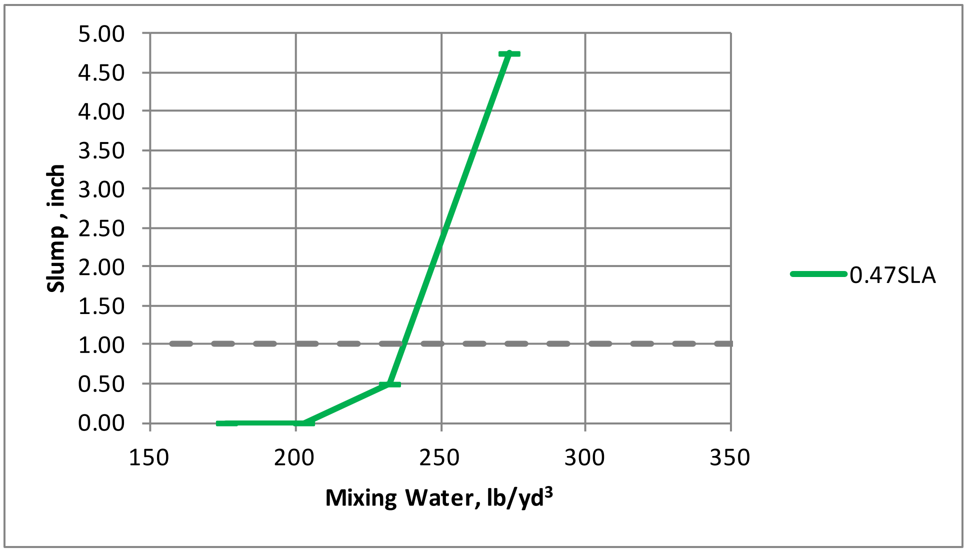
**Figure 16:** Phase I: Length Change Value Vs Mixing Water for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures



(a)

(b)

**Figure 17:** Phase I: Length Change Vs Total Cementitious Content for (a) Slag Cement Mixtures (b) Portland Cement and Fly Ash Mixtures



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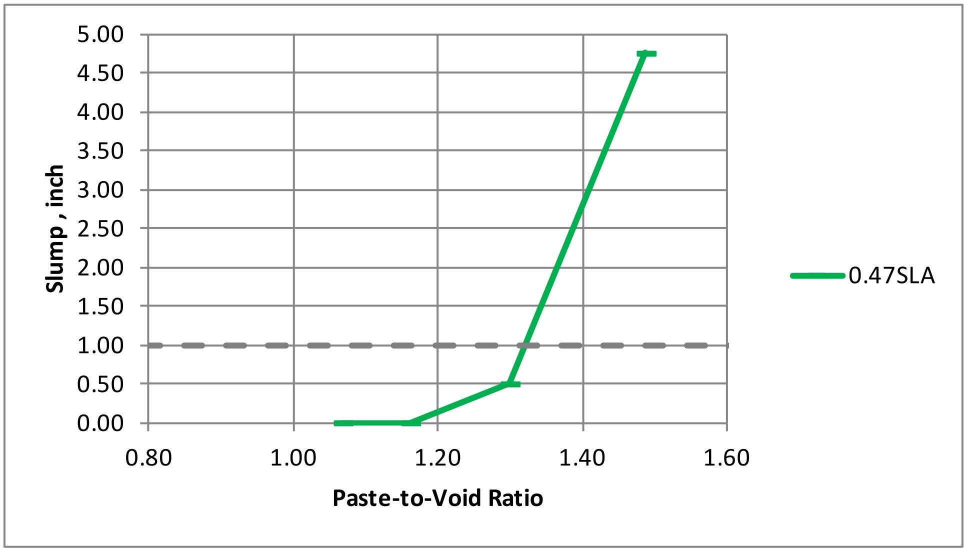

(b)

**Figure 18:** Phase II: Measured Slump for the Air-Entrained Concrete Mixtures prior to adding HRWRA Vs (a) Mixing Water content (b) Paste-to-Void ratio

Figure 19(a) 0.47SL33A Mixture before HRWRA addition

Figure 19(b) 0.47SL29A before HRWRA addition

Figure 19(c) 0.47SL29A after HRWRA addition

Figure 19(d) 0.47SL26A before HRWRA addition

Figure 19(e) 0.47SL26A after HRWRA addition

Figure 19(f) 0.47SL24A before HRWRA addition

Figure 19(g) 0.47SL24A after HRWRA addition

**Figure 19:** Phase II: Visual appearance of Mixtures (a) to (g)

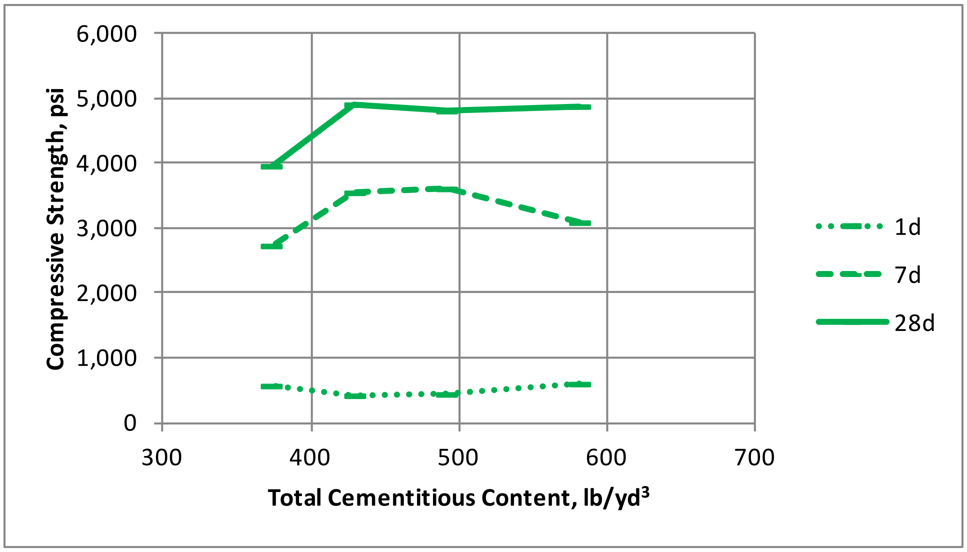

**Figure 20:** Phase II: Compressive Strength vs Total Cementitious Content for the Air-Entrained Concrete Mixtures

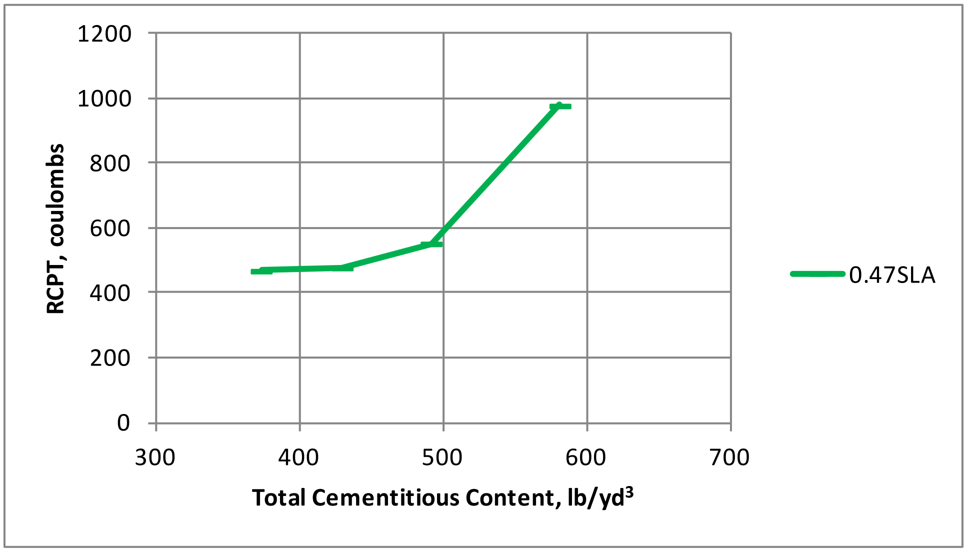

**Figure 21:** Phase II: RCPT vs Total Cementitious Content for the Air-Entrained Concrete Mixtures

Figure 22(a) 0.55PC23 before HRWRA addition

Figure 22(b) 0.55PC23 after HRWRA addition

Figure 22(c) 0.55FA23 after HRWRA addition

Figure 22(d) 0.55FA25 after HRWRA addition

Figure 22(e) 0.40PC25 after HRWRA addition

**Figure 22:** Phase III: Visual Appearance of Mixtures (a) – (e)

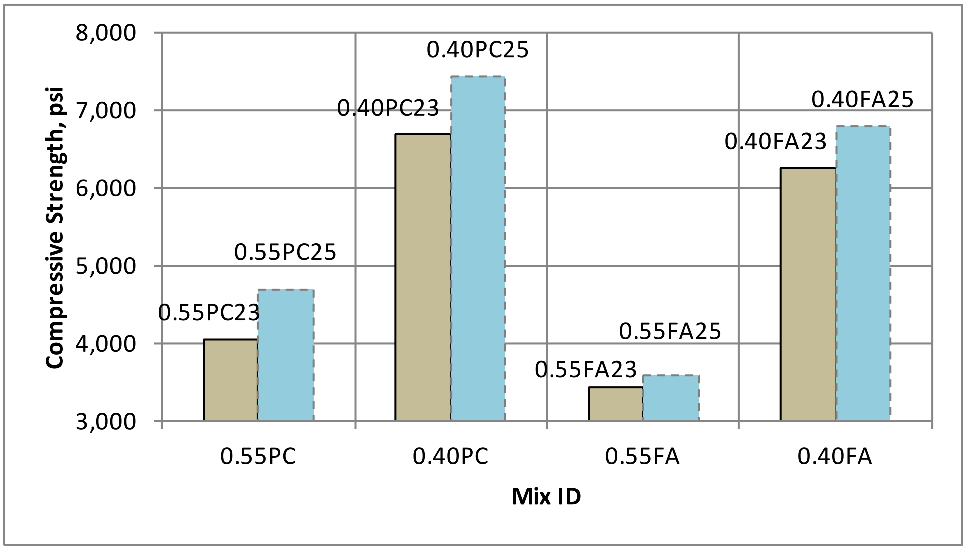

**Figure 23:** Phase III: 28d Compressive Strength of Different Mixtures

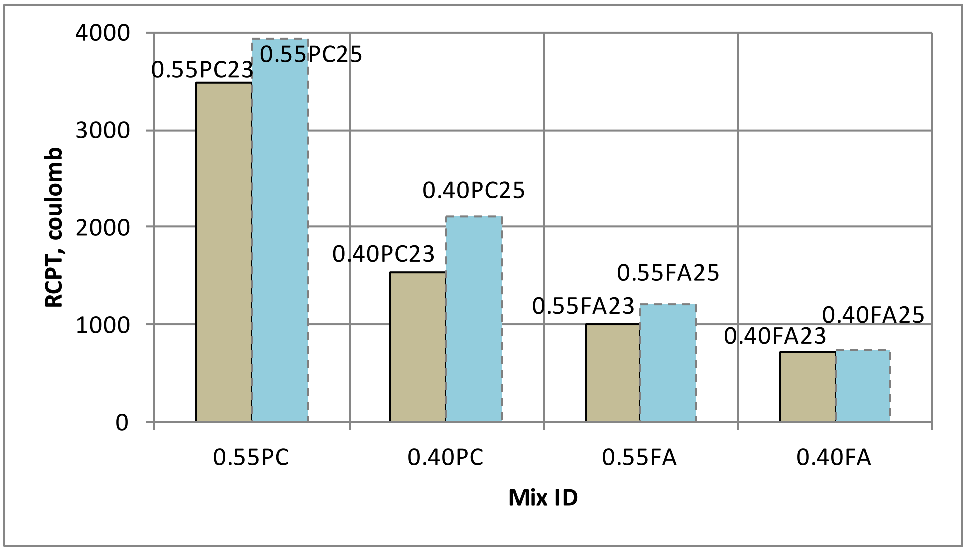

**Figure 24:** Phase III: RCPT of Different Mixtures