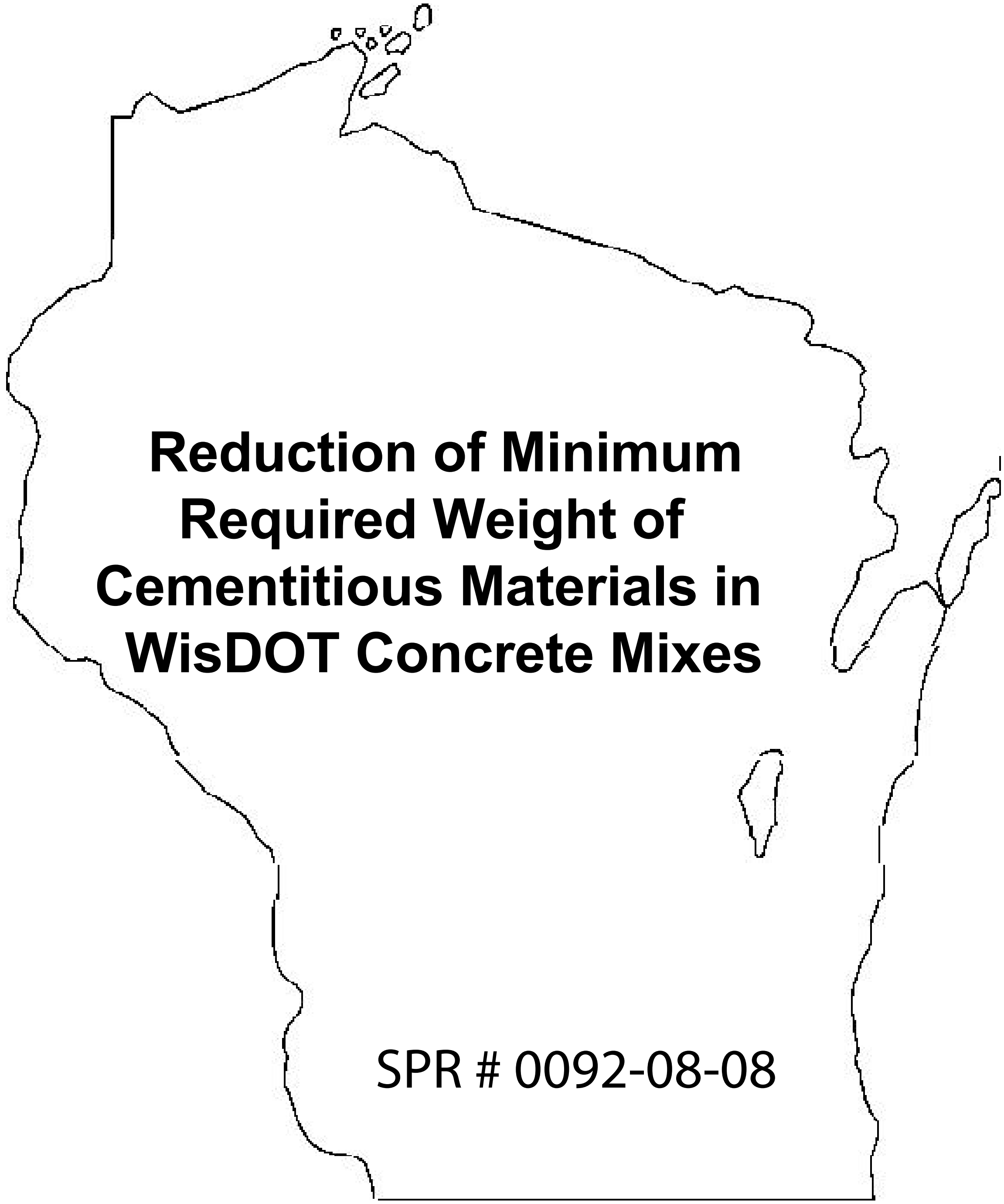
Wisconsin Highway Research Program



Reduction of Minimum Required Weight of Cementitious Materials in WisDOT Concrete Mixes

SPR # 0092-08-08

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16. Abstract

This project was designed to explore the feasibility of lowering the cementitious materials content (CMC) used in Wisconsin concrete pavement construction. The cementitious materials studied included portland cement, fly ash, and ground granulated blast furnace slag. For the first phase, mixtures were prepared using the current WisDOT aggregate grading specification. For the second phase, mixtures were prepared using an optimized (e.g. Shilstone) gradation. A variety of tests for fresh and hardened concrete were conducted to determine the viability of low CMC mixtures for use in concrete pavement.

The research resulted in several successful low CMC concrete mixtures in terms of workability, strength, and durability. Many unsuccessful low CMC concrete mixtures were also produced. The analysis of the data suggests a practical minimum CMC of 5.0 sacks/yd^3 for concrete. However, successful mixtures containing fly ash were achieved at the CMC levels of 4.0 sacks/yd^3 and 4.5 sacks/yd^3. The same minimum CMC limits were established in both the first and second phases of the research, regardless of the change in aggregate gradation.

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EXECUTIVE SUMMARY

This project was designed to explore the feasibility of reducing the amount of cementitious materials used in Wisconsin concrete pavement construction. The cementitious materials studied included portland cement, fly ash, and ground granulated blast furnace slag. Cementitious materials are the most expensive components in concrete pavement mixtures, so any reduction represents the potential for cost-savings, as long as there is no impact to the service-life of the concrete pavement. The production of portland cement, the primary cementitious component, is also very intensive in terms of CO_2 production. Using less portland cement translates directly into the reduction of greenhouse gases associated with concrete pavement construction.

Any reduction in the cementitious materials content (CMC) of a concrete mixture implies an increase in the aggregate content. Reductions in CMC also imply relatively lower volumes of cement paste in the concrete mixture. Generally, the more cement paste in a given concrete mixture, the better it will flow during placement. Therefore, without careful mixture design, concrete with a low CMC may be difficult to place.

Decades of research have been spent devising methods for finding optimum aggregate gradations that will allow for workable low CMC concrete mixtures. One of the most popular is the Shilstone method. However, aggregate sources, whether produced at a quarry or excavated from natural deposits, do not always meet gradations as dictated by the Shilstone method. The first phase of this research focused on producing workable low CMC concrete using aggregate that met only existing WisDOT gradation specifications. For the second phase, deviations from the current gradation limits were made in an effort to meet Shilstone criteria.

The research was conducted at the Michigan Technological University Department of Civil and Environmental Engineering Benedict Laboratory. For the first phase, 28 concrete mixes were produced over a period of five months, and testing of the concrete spanned a period eight months. For the second phase, nine concrete mixes were produced over a period of two months, and testing of the concrete spanned a period of six months. A variety of tests for fresh and hardened concrete were conducted to determine the viability of low CMC mixtures for use in concrete pavement.

The research resulted in several successful low CMC concrete mixtures in terms of workability, strength, and durability. Many unsuccessful low CMC concrete mixtures were also produced. The analysis of the data suggests a practical minimum CMC of 5.0 sacks/yd^3 for concrete. However, successful mixtures containing fly ash were achieved at the CMC levels of 4.0 sacks/yd^3 and 4.5 sacks/yd^3. The same minimum CMC limits were established in both the first and second phases of the research, regardless of the change in gradation.

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CHAPTER 1. INTRODUCTION

1.1 Problem Statement

The reduction of the cementitious material content (CMC) to the minimum level necessary to achieve both a workable mixture and a concrete pavement with the desired strength and performance can be a challenging problem for today's concrete producers. A reduction in portland cement, the most costly component of a concrete mixture, results in the obvious benefit of a reduction in the overall cost of the concrete. However, aspects other than cost are also important. The manufacture of portland cement is a major contributor to the production of greenhouse gases. Dramatic cuts in CO_2 emissions associated with concrete pavement construction can be achieved by reductions in the CMC, or by the partial substitution of portland cement by supplementary cementitious materials (SCMs) or a combination of both approaches. Enhanced performance of concrete pavement in terms of strength, permeability, and resistance to alkali-silica reactivity are also possible through the combined use of SCMs and reduced CMC. This project explores reduction in CMC from the standard level of 564 lbs/yd^3 down to 470 lbs/yd^3, 423 lbs/yd^3 and 376 lbs/yd^3. Optimizing gradation utilizing the Shilstone method is also explored. Most of the mixtures incorporate SCMs, resulting in a further reduction of the portland cement content of the concrete produced.

1.2 Objectives

The objectives of this research project are to make recommendation values for the minimum CMC to be used by WisDOT for future pavement mixes and to make recommendations to WisDOT for future work in this area.

1.3 Background

Any reduction in the CMC inherently implies an increase in the aggregate content of a concrete mixture. Generally, a greater CMC translates into a larger volume fraction of cement paste. A mixture with a higher volume fraction of cement paste will yield concrete that flows more easily than a similar mixture with a lower volume fraction of cement paste. The controlled gradation of the aggregate component can play an important role in the development of a successful, workable, and durable low CMC concrete pavement. Examples of state DOT specifications that pertain to the optimization of aggregate gradations include Iowa, Michigan, Minnesota, and Kansas [1,2]. However, it is often noted that the manipulation of aggregate gradations is not practical in the field, and thus gradations are often used as-produced by the pit or quarry [2-5]. In such situations, the only practical means for the manipulation of the final gradation of the aggregate is to vary the ratio of the coarse/fine aggregate blend in the concrete mixture. Methods for the analysis of aggregate gradation and the optimization of aggregate gradation are frequently employed; the most popular being the Shilstone method [2].

The Shilstone method visualizes the gradation of the blended coarse and fine aggregates using two charts. The first chart plots the weight percent retained on each sieve. The objective for an optimized gradation is to achieve a smooth line that plots within the upper and lower boundaries at eight and eighteen percent, as shown in Figure 1. The second type of chart plots the workability factor against the coarseness factor. The workability factor is simply the weight

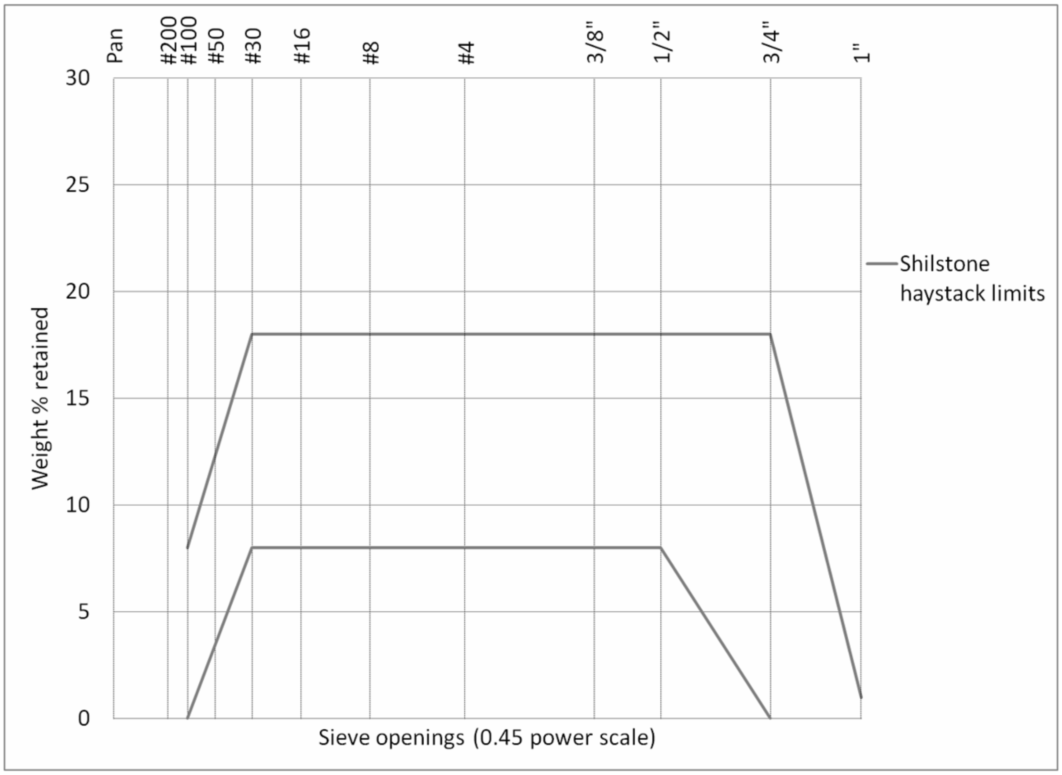

Figure 1: Shilstone "haystack" 8-18 plot.

percent passing the no. 8 sieve, but with a correction for the cement content, as shown in Equation 1.

$$WF = wt.\%\ passing\ the\ no.8\ sieve + wt.\%\ passing\ the\ no.8\ sieve \times 0.025 \times \left[\frac{c-564}{94}\right]$$

Equation 1

Where:

WF = Workability factor.

c = Cementitious content (in units of lbs/yd^3).

The coarseness factor is the ratio between the cumulative weight percent retained on the 3/8" sieve and the cumulative weight percent retained on the no. 8 sieve, as shown in Equation 2.

$$CF = \frac{cumulative\ wt.\%\ retained\ on\ the\ {}^{3}/_{8}"\ sieve}{cumulative\ wt.\%\ retained\ on\ the\ no.8\ sieve}$$

Equation 2

Where:

CF = Coarseness factor.

The coarseness and workability factors are related through the use of a chart that is separated into five zones as shown in Figure 2. Zone I represents difficult to work gap-graded mixtures susceptible to segregation. Zone II represents ideal conditions for most concrete paving mixtures. Zone III represents ideal conditions for concrete mixtures with a lower top size coarse aggregate. Zone IV represents over-sanded mixtures, and Zone V represents rocky mixtures. The region above Zone V is a transitional zone exhibiting generally good conditions for concrete mixtures.

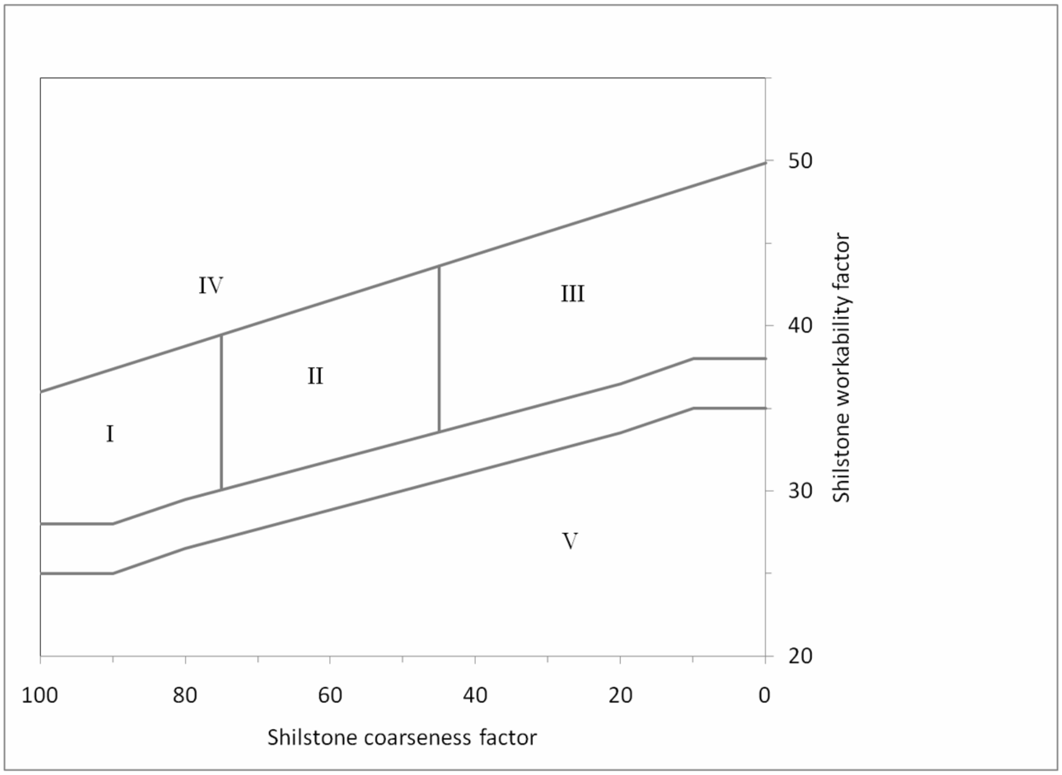

Figure 2: Shilstone coarseness/workability chart.

Figure 3 depicts several other schemes for optimizing gradation, several of which follow the general equation popularized by Fuller and Thompson [6]:

$$p = 100\left(\frac{d}{D}\right)^{n} \qquad \text{Equation 3}$$

Where:

p = Weight percentage of material passing the sieve.

d = Sieve opening size.

D = Maximum size aggregate.

n = A variable exponent.

The x-axis of the chart in Figure 3 is scaled to the 0.45 power. On this chart, the 0.45 power curve (n = 0.45) plots as a straight line starting at the origin, and ending at the maximum aggregate size present in the gradation. Figure 3 also includes curves derived from Equation 3 where the exponent = ½, and where the exponent = $^{1}/_{3}$.

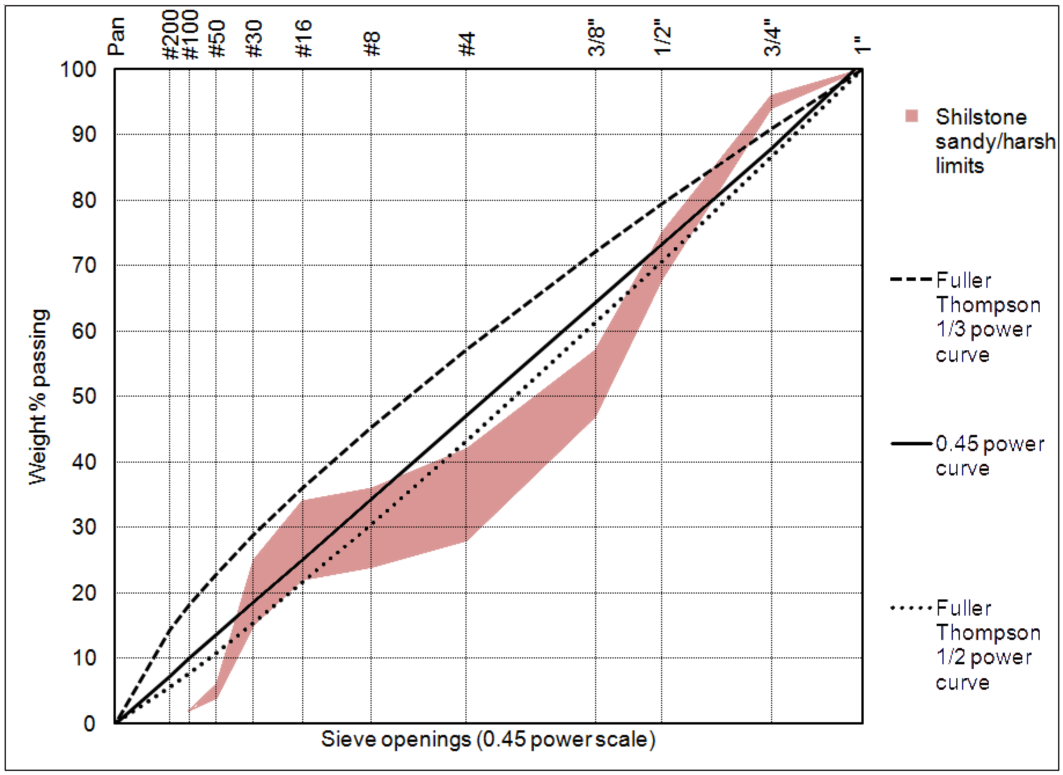

Figure 3: Theoretical maximum density curves, and Shilstone sandy/harsh limits for combined aggregate gradation.

Aggregate shape and texture also play a role in the workability of concrete mixtures. Aggregate that is angular and rough will result in harsher mixtures than aggregate that is smooth and rounded. However, the choice of aggregate is usually constrained to those that are geographically convenient, regardless of their shape or texture.

Aside from aggregate considerations, the workability of low CMC concrete mixtures can be influenced in a number of other ways, most notably through the use of admixtures, such as air entrainers or water reducers. Both of these admixtures essentially neutralize surface charges present on solids in the mixture, helping to prevent flocculation of particles and encourage dispersion of particles, which in turn yields more flowable mixtures. Some high-range water-reducers coat particles and impart a negative charge inducing them to repel each-other. Air entrainers have the added benefit of introducing numerous small spherical air voids, which help to reduce friction between the other mix components. As with the aggregate component, the gradation, shape, and texture of the portland cement or SCMs also influence workability. For example, small spherical SCMs such as fly ash tend to improve the workability of low CMC concrete mixtures in a manner similar to small entrained air voids. And finally, the water to cementitious ratio (*w/cm*) can influence workability; mixtures with a higher w/cm tend to be more workable.

CHAPTER 2. EXPERIMENT DESIGN

2.1 Materials

2.1.1 Aggregate Components

For the first phase of the project standard WisDOT aggregate gradations were used, and the ratio of the coarse/fine aggregate blend were varied depending on the CMC. Two coarse aggregate/fine aggregate pairs representative of northern and southern Wisconsin sources were used. The northern coarse aggregate source was a quarried granitic rock supplied by Milestone Materials, Mosinee, Wisconsin. The northern fine aggregate source was a siliceous natural sand supplied by Superior Sand & Gravel, Hancock, Michigan. The southern coarse aggregate source was a quarried carbonate rock supplied by Vulcan Materials, Sussex, Wisconsin. The southern fine aggregate source was a siliceous natural sand from Vulcan Materials, Oconomowoc, Wisconsin. The coarse aggregate sources were both sieved and recombined to meet the WisDOT gradation specification as shown in Figure 3. The fine aggregate sources both satisfied the WisDOT gradation specification and were used as-received as shown in Figure 4. Physical properties of the aggregate components are listed in Table 1.

For the second phase of the project, only the southern coarse aggregate/fine aggregate pair was used. The coarse aggregate was sieved and recombined to produce the gradation shown in Figure 4. The fine aggregate was used as-received as shown in Figure 5. Physical properties of the aggregate components are listed in Table 1.

Table 1: Physical properties of aggregate sources.

Geographical region	Aggregate supplier	Gradation type	Bulk specific gravity	Absorption (%)
Northern, Phase 1	Milestone Materials, Mosinee, Wisconsin	Coarse	2.67	0.57
	Superior Sand & Gravel, Hancock, Michigan	Fine	2.64	1.36
Southern, Phase 1	Vulcan Materials, Sussex, Wisconsin	Coarse	2.68	1.66
	Vulcan Materials, Oconomowoc, Wisconsin	Fine	2.61	1.57
Southern, Phase 2	Vulcan Materials, Sussex, Wisconsin	Coarse	2.72	1.90
	Vulcan Materials, Oconomowoc, Wisconsin	Fine	2.63	1.25

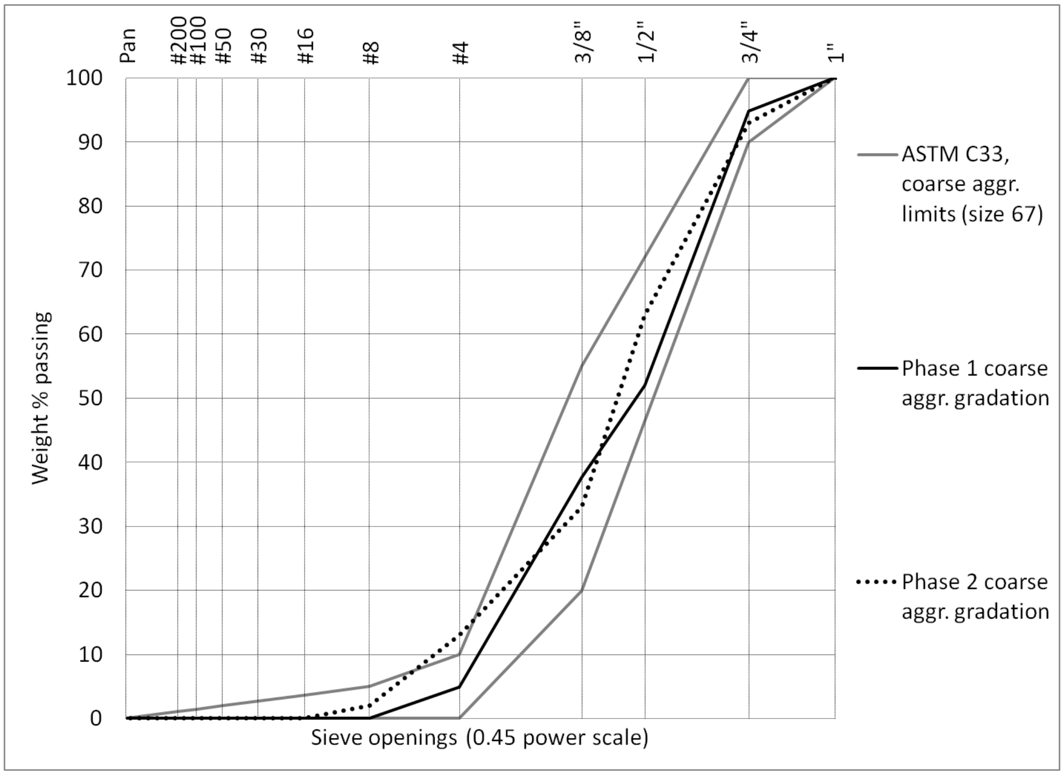

Figure 4: Manufactured coarse aggregate gradations.

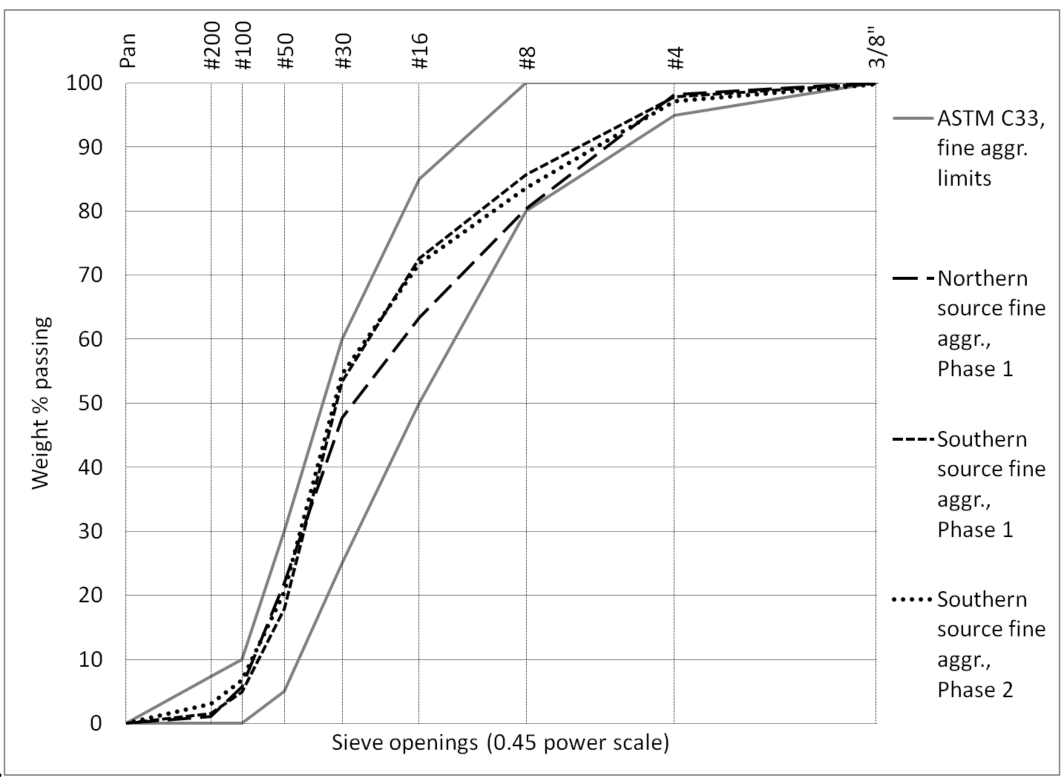

Figure 5: Fine aggregate gradations of material as-received.

2.1.2 Cementitious Components

Two sources of portland cement, two sources of fly ash, and one source of ground granulated blast furnace slag (GGBFS) were used as the cementitious components for the Phase 1 mixtures. The Type I portland cements were from the Lafarge plant near Alpena, Michigan, and the St Marys plant near Charlevoix, Michigan, (denoted cement 1 and cement 2 respectively). The Class C fly ashes were both supplied by Lafarge, and sourced from the Columbia coal-fired generation plant near Portage, Wisconsin, and the Weston coal-fired generation plant near Rothschild, Wisconsin, (denoted fly ash 1 and fly ash 2 respectively). The source of GGBFS was Holcim GranCem produced in Chicago, Illinois. The Phase 2 mixtures utilized only one source of cement (cement 2), one source of fly ash (fly ash 2), and the same slag source as Phase 1. Physical properties of the cementitious materials are included in Table 2.

Table 2: Physical properties of cementitious components.

Cementitious component	Source	Bulk specific gravity
Lafarge Type I portland cement (cement 1)	Alpena, Michigan	3.15
St Marys Type I portland cement (cement 2)	Charlevoix, Michigan	3.15
Lafarge Class C fly ash (fly ash 1)	Columbia plant, Portage, Wisconsin	2.58
Lafarge Class C fly ash (fly ash 2)	Weston plant, Rothschild, Wisconsin	2.63
Holcim GranCem grade 100 GGBFS	Chicago, Illinois	2.86

2.1.3 Admixtures

Two admixtures were used, an air entrainer, BASF Master Builders MB VR, and a water reducer BASF Master Builders Polyheed 1020.

2.2 Trial Batches

2.2.1 Phase 1 Trial Batches

The initial mix design criteria for Phase 1 were as follows:

- Two sources of coarse/fine aggregate pairs, both northern and southern.
- Three CMC levels: 564 lbs/yd^3, 470 lbs/yd^3, and 376 lbs/yd^3.

- SCM replacement levels of 30% for the fly ash mixtures, and 50% for the GGBFS mixtures.
- Air content of 6 ±1.5 percent.
- A constant coarse/fine aggregate weight ratio of 60/40.
- Water to cementitious (*w/cm*) ratio of 0.40.
- Slump of 3 ±1 inches.

Trial batches adhering to these criteria at the upper CMC level (564 lbs/yd^3) yielded fresh concrete with excessive slump values (on the order of 5-8”). Trial batches at the lower CMC level (376 lbs/yd^3) yielded unworkable concrete mixtures with negligible slump (on the order of 0-¼”). Additional trial batches were explored where the coarse/fine aggregate weight ratios were varied according to CMC level until reasonable slump values were achieved. To achieve workable fresh concrete at the upper CMC limit, it was found that lower values for the coarse/fine aggregate weight ratio (on the order of 55/45) were necessary. For trial batches made at the lower CMC limit the quantity of cement paste was often insufficient to coat the fine aggregate particles. By increasing the coarse/fine aggregate weight ratio to a value of 65/35, mixtures were produced where the cement paste adequately coated the fine aggregate particles; although these mixtures remained stiff and difficult to consolidate. Lower limit CMC trial batches exceeding the 65/35 ratio lacked sufficient mortar (cement paste + fine aggregate) to fill the spaces between the coarse aggregate particles, resulting in poorly consolidated mixtures.

2.2.2 Phase 2 Trial Batches

For the Phase 2 trial batches, both the coarse/fine aggregate weight ratios and the coarse aggregate gradation were varied. In spite of efforts to optimize the gradation, trial batches at the lower CMC limit were unworkable and difficult to consolidate, so the lower limit was raised from 376 lbs/yd^3 to 423 lbs/yd^3, and the *w/cm* ratio from 0.40 to 0.45. Figure 5 plots the locations of the trial batches produced at the 376 lbs/yd^3 and 423 lbs/yd^3 CMC levels on the Shilstone coarseness/workability chart in terms of SCM content and slump. Stiff yet workable mixtures were achieved at the 423 lbs/yd^3 CMC level. As shown in Figure 6, these workable low CMC mixtures plotted below Zone II, and well into the Zone V (rocky) region of Shilstone coarseness/workability space.

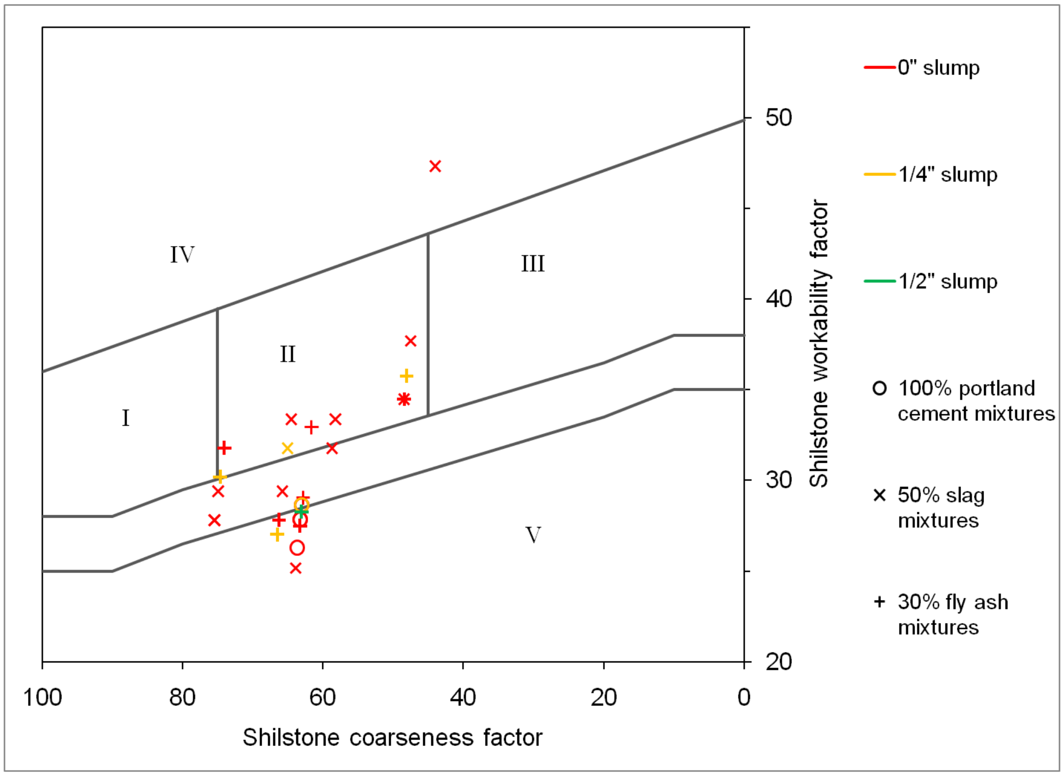

Figure 6: Locations of Phase 2 low CMC content trial batches as plotted on Shilstone coarseness/workability chart and color-coded according to slump.

2.3 Final Batch Experimental Matrix

2.3.1 Phase 1 Experimental Matrix

The mix design criteria selected for the final Phase 1 batches were as follows:

- Two sources of coarse/fine aggregate pairs: the southern coarse aggregate source from Vulcan Materials, Sussex, Wisconsin paired with the southern fine aggregate source from Vulcan Materials, Oconomowac Wisconsin, and the northern coarse aggregate source from Milestone Materials, Mosinee, Wisconsin paired with the northern fine aggregate source from Superior Sand & Gravel, Hancock, Michigan.
- Three CMC levels: 564 lbs/yd^3, 470 lbs/yd^3, and 376 lbs/yd^3 with corresponding coarse/fine aggregate weight ratios of 55/45, 60/40, and 65/35.
- SCM replacement levels of 30% for the fly ash mixtures, and 50% for the GGBFS mixtures.
- Target air content of 6 ±1.5 percent.
- Water to cementitious (*w/cm*) ratio of 0.40.
- Target slump of 3 ±1 inches.

Table 3 summarizes the mixture designs evaluated in the experimental matrix. Figure 7 plots the locations of the various mixtures on the Shilstone coarseness/workability chart. Figures 8 and 9 plot the combined gradations of the various mixtures on the Shilstone 8-18 chart. Figures 10 and 11 plot the combined gradations of the various mixtures on a 0.45 power curve.

2.3.2 Phase 2 Experimental Matrix

The mix design criteria selected for the final Phase 2 batches were as follows:

- The coarse/fine aggregate pair from the southern source (Vulcan Materials, Sussex and Oconomowac ,Wisconsin).
- Three CMC levels, 564 lbs/yd^3, 470 lbs/yd^3, and 423 lbs/yd^3.
- SCM replacement levels of 30% for the fly ash mixtures, and 50% for the GGBFS mixtures.
- At the upper CMC limit (564 lbs/yd^3) a coarse/fine aggregate weight ratio of 55/45 for the mixtures without fly ash, and a ratio of 40/60 for the mixture with fly ash.
- At the mid-range CMC level (470 lbs/yd^3) a coarse/fine aggregate weight ratio of 66/34 for all mixtures.
- At the lower CMC limit (423 lbs/yd^3) a coarse/fine aggregate weight ratio of 66/34 for the mixtures without fly ash, and a ratio of 67/33 for the mixture with fly ash.
- Target air content of 6 ±1.5 percent.
- Water to cementitious (*w/cm*) ratio of 0.45.
- Target slump of 3 ±1 inches.

Table 4 summarizes the mixture designs evaluated in the experimental matrix. Figure 12 plots the locations of the various mixtures on the Shilstone coarseness/workability chart. Figure 13 plots the combined gradations of the various mixtures on the Shilstone 8-18 chart. Figure 14 plots the combined gradations of the various mixtures on a 0.45 power curve.

Table 3: Phase 1 mix design experimental matrix.

Mix ID	Water	Admixtures: Air entrainer	Admixtures: Water reducer	Coarse aggregate: Northern source (N)	Coarse aggregate: Southern source (S)	Fine Aggregate: Northern source (N)	Fine Aggregate: Southern source (S)	Portland cement: Lafarge Type I (1)	Portland cement: St. Marys Type I (2)	Suppl. cementitious mat'ls: Columbia fly ash (FA1)	Suppl. cementitious mat'ls: Weston fly ash (FA2)	Suppl. cementitious mat'ls: Holcim GGBFS (SLG)	Cement-itious content	Cement-itious content (sacks/yd^3)
	Mix design (lbs/yd^3)													
6N1FA1	225.6	0.9	0.0	1705.5	0.0	1395.6	0.0	394.8	0.0	169.2	0.0	0.0	564	6
5N1FA1	188.0	1.2	1.2	1968.8	0.0	1315.0	0.0	329.0	0.0	141.0	0.0	0.0	470	5
4N1FA1	150.4	1.9	3.0	2251.6	0.0	1212.4	0.0	263.2	0.0	112.8	0.0	0.0	376	4
6N1FA2	225.6	0.9	0.0	1707.3	0.0	1397.2	0.0	394.8	0.0	0.0	169.2	0.0	564	6
5N1FA2	188.0	1.2	1.2	1971.9	0.0	1314.6	0.0	329.0	0.0	0.0	141.0	0.0	470	5
6N1SLG	225.6	1.4	2.5	1705.6	0.0	1395.5	0.0	282.0	0.0	0.0	0.0	282.0	564	6
5N1SLG	188.0	2.5	3.2	1968.9	0.0	1312.6	0.0	235.0	0.0	0.0	0.0	235.0	470	5
4N1SLG	150.4	2.6	3.0	2253.0	0.0	1214.1	0.0	188.0	0.0	0.0	0.0	188.0	376	4
6N2FA1	225.6	1.0	0.0	1706.0	0.0	1396.0	0.0	0.0	394.8	169.2	0.0	0.0	564	6
5N2FA1	188.0	1.1	1.2	1971.0	0.0	1314.0	0.0	0.0	329.0	141.0	0.0	0.0	470	5
6N2FA2	225.6	0.9	0.0	1708.0	0.0	1397.5	0.0	0.0	394.8	0.0	169.2	0.0	564	6
5N2FA2	188.0	1.2	1.2	1972.4	0.0	1315.0	0.0	0.0	329.0	0.0	141.0	0.0	470	5
6N2SLG	225.6	1.2	2.5	1704.3	0.0	1398.0	0.0	0.0	282.0	0.0	0.0	282.0	564	6
5N2SLG	188.0	1.8	3.2	1969.4	0.0	1314.6	0.0	0.0	235.0	0.0	0.0	235.0	470	5
6S1FA1	225.6	0.5	0.0	0.0	1699.6	0.0	1390.6	394.8	0.0	169.2	0.0	0.0	564	6
5S1FA1	188.0	0.8	0.0	0.0	1966.4	0.0	1311.2	329.0	0.0	141.0	0.0	0.0	470	5
4S1FA1	150.4	1.2	2.8	0.0	2247.8	0.0	1210.4	263.2	0.0	112.8	0.0	0.0	376	4
6S1FA2	225.6	0.5	0.0	0.0	1701.8	0.0	1391.7	394.8	0.0	0.0	169.2	0.0	564	6
5S1FA2	188.0	1.0	0.0	0.0	1967.4	0.0	1312.3	329.0	0.0	0.0	141.0	0.0	470	5
6S1SLG	225.6	1.2	1.1	0.0	1701.2	0.0	1392.1	282.0	0.0	0.0	0.0	282.0	564	6
5S1SLG	188.0	1.5	2.9	0.0	1963.3	0.0	1311.4	235.0	0.0	0.0	0.0	235.0	470	5
4S1SLG	150.4	1.2	2.8	0.0	2251.0	0.0	1212.1	188.0	0.0	0.0	0.0	188.0	376	4
6S2FA1	225.6	0.4	0.0	0.0	1700.3	0.0	1391.2	0.0	394.8	169.2	0.0	0.0	564	6
5S2FA1	188.0	0.8	0.0	0.0	1967.0	0.0	1311.3	0.0	329.0	141.0	0.0	0.0	470	5
6S2FA2	225.6	0.4	0.0	0.0	1702.3	0.0	1392.7	0.0	394.8	0.0	169.2	0.0	564	6
5S2FA2	188.0	0.8	0.0	0.0	1968.7	0.0	1312.5	0.0	329.0	0.0	141.0	0.0	470	5
6S2SLG	225.6	1.1	1.1	0.0	1700.1	0.0	1394.0	0.0	282.0	0.0	0.0	282.0	564	6
5S2SLG	188.0	1.3	2.4	0.0	1966.3	0.0	1310.8	0.0	235.0	0.0	0.0	235.0	470	5

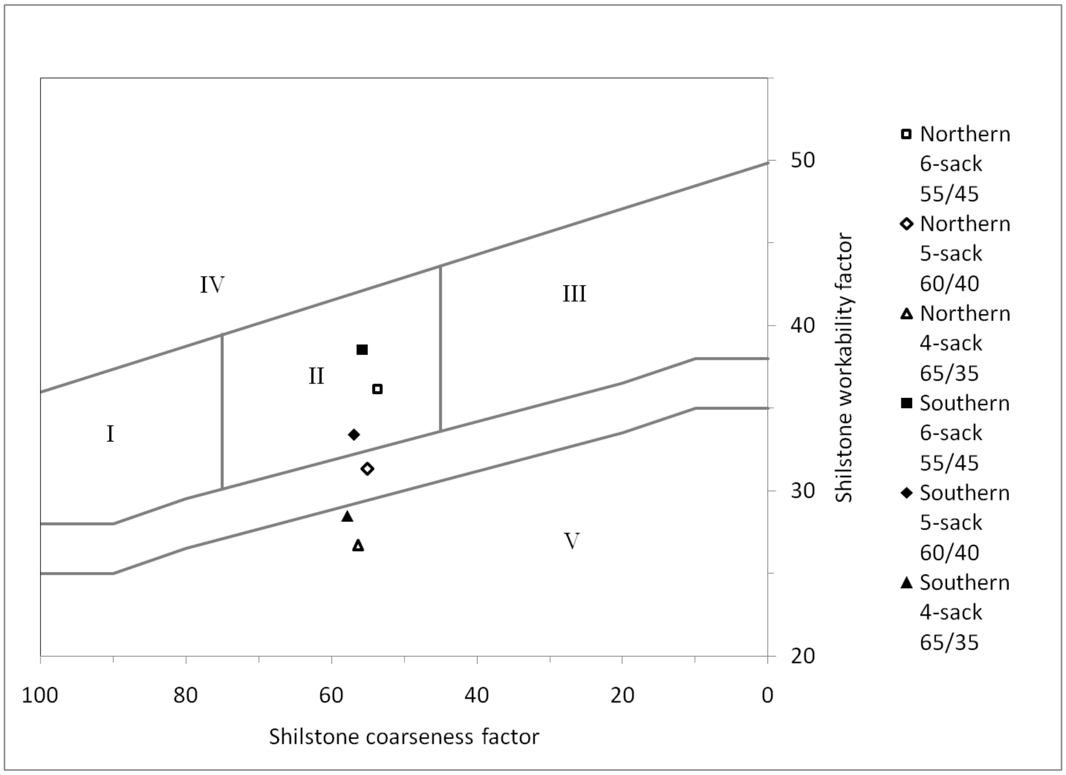

Figure 7: Shilstone coarseness/workability plot for final Phase 1 mix designs.

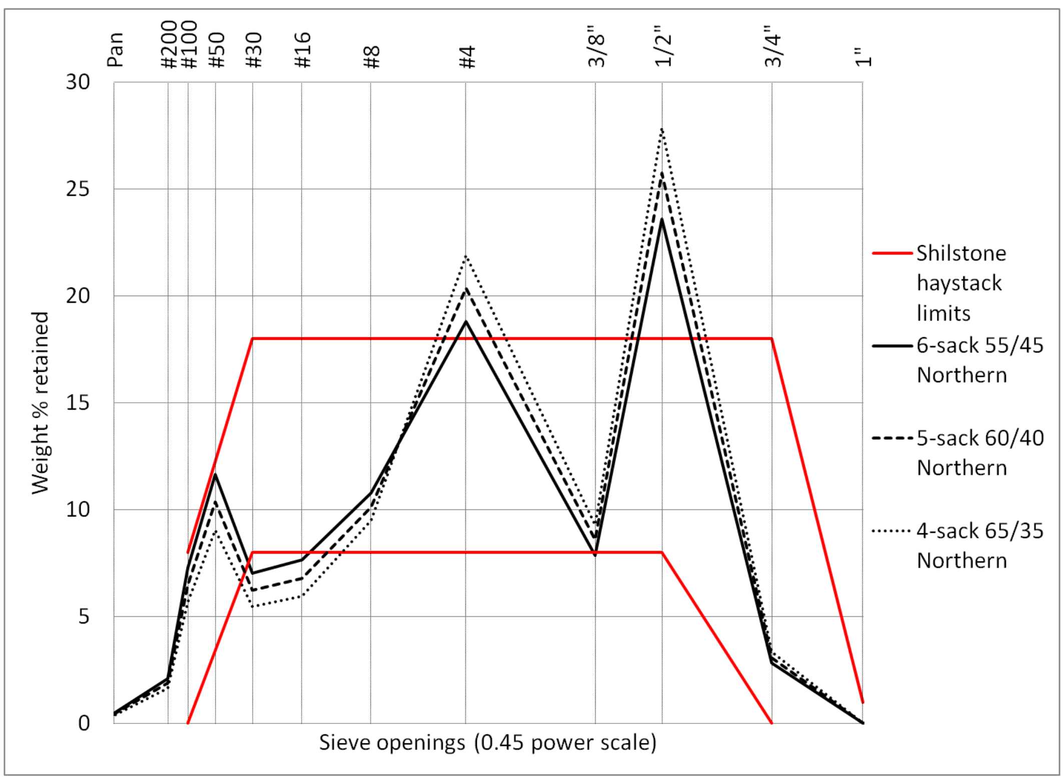

Figure 8: Shilstone "haystack" 8-18 plot for final Phase 1 mix designs with northern aggregate source.

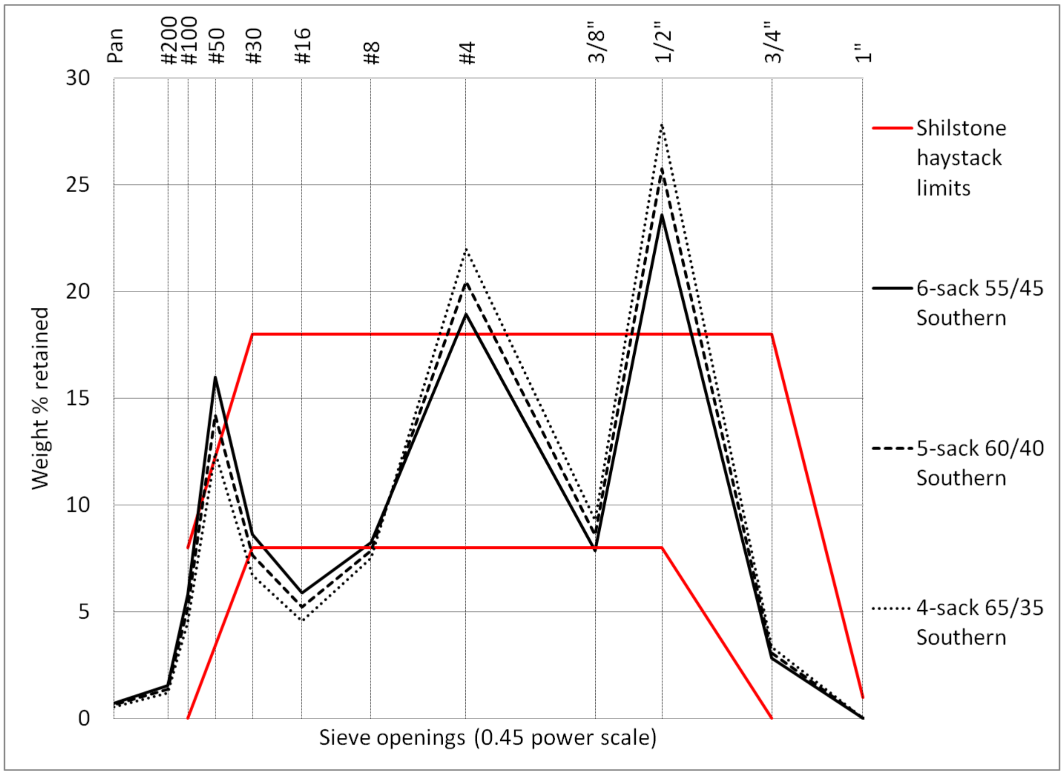

Figure 9: Shilstone "haystack" 8-18 plot for final Phase 1 mix designs with southern aggregate source.

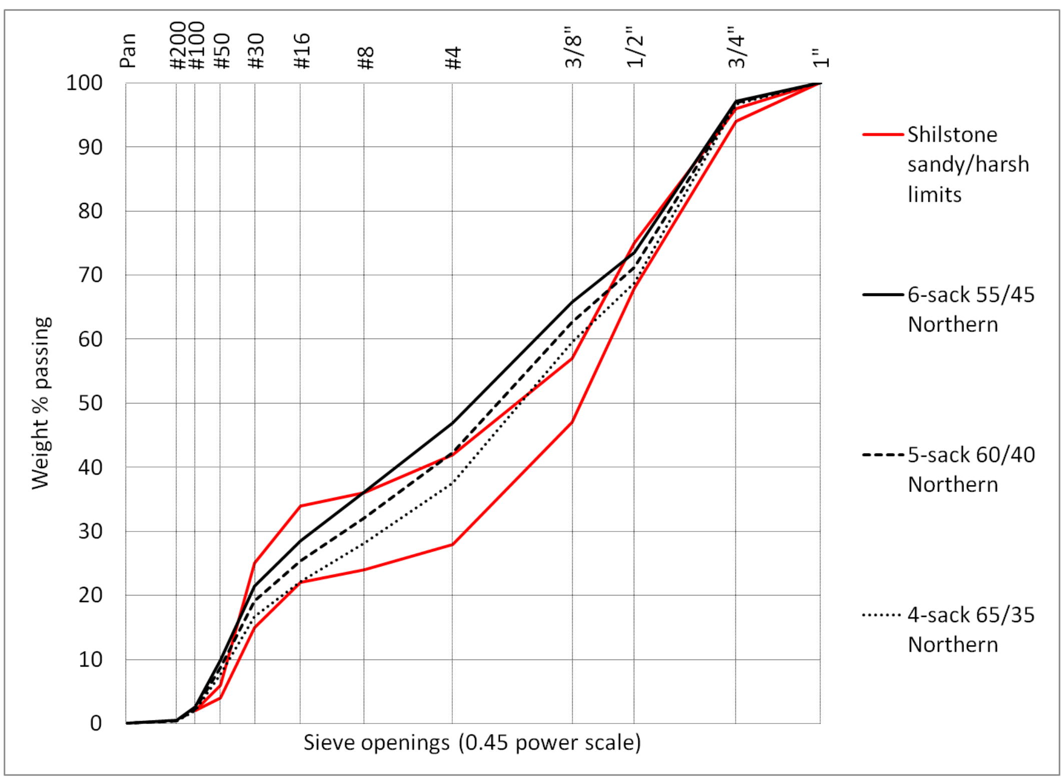

Figure 10: 0.45 power curve plot for final Phase 1 mix designs with northern aggregate source.

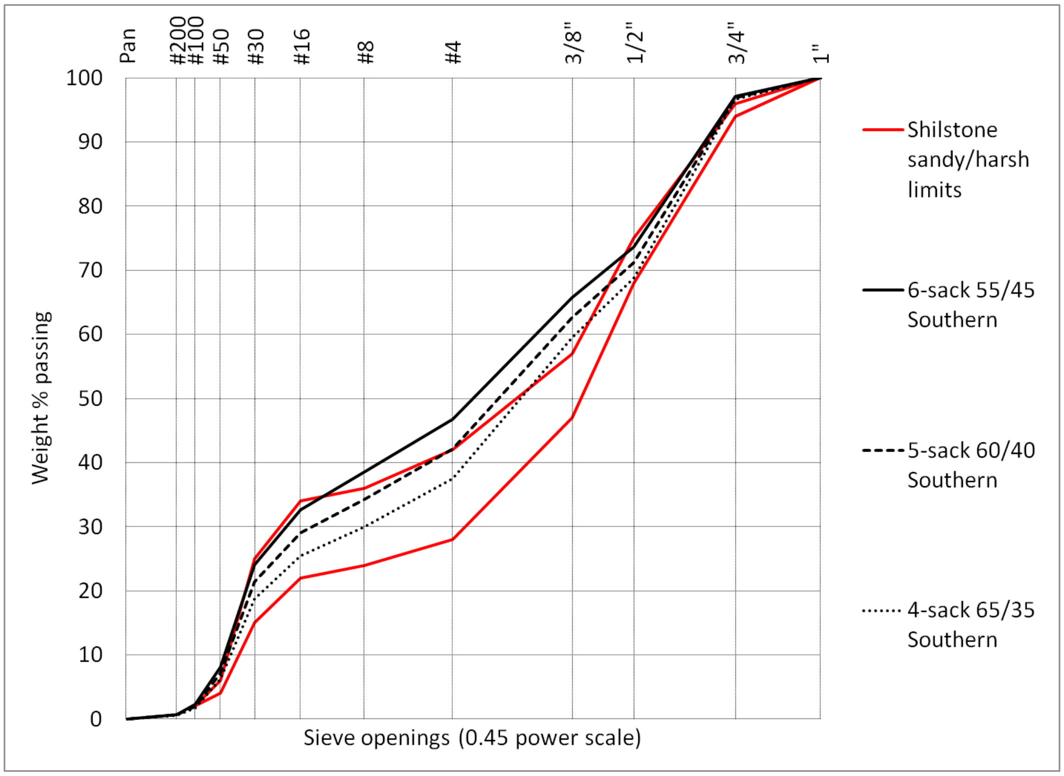

Figure 11: 0.45 power curve plot for final Phase 1 mix designs with southern aggregate source.

Table 4: Phase 2 mix design experimental matrix.

Mix ID	Mix design (lbs/yd³)												Cementitious content (sacks/yd³)
		Admixtures		Coarse aggregate		Fine Aggregate		Portland cement		Suppl. cementitious mat'ls			
	Water	Air entrainer	Water reducer	Northern source (N)	Southern source (S)	Northern source (N)	Southern source (S)	Lafarge Type I (1)	St. Marys Type I (2)	Columbia fly ash (FA1)	Weston fly ash (FA2)	Holcim GGBFS (SLG)	Cementitious content	
6S2-O	253.0	0.8	0.0	0.0	1696.6	0.0	1388.2	0.0	564.0	0.0	0.0	0.0	564.0	6.0
5S2-O	206.8	1.5	3.2	0.0	2197.2	0.0	1131.9	0.0	470.0	0.0	0.0	0.0	470.0	5.0
4.5S2-O	185.3	0.6	4.4	0.0	2225.3	0.0	1146.4	0.0	423.0	0.0	0.0	0.0	423.0	4.5
6S2FA2-O	253.5	0.3	0.0	0.0	1216.4	0.0	1824.6	0.0	394.8	0.0	169.2	0.0	564.0	6.0
5S2FA2-O	208.8	0.3	2.4	0.0	2156.1	0.0	1110.7	0.0	329.0	0.0	141.0	0.0	470.0	5.0
4.5S2FA2-O	184.6	1.1	4.7	0.0	2211.3	0.0	1139.1	0.0	296.1	0.0	126.9	0.0	423.0	4.5
6S2SLG-O	253.1	0.7	0.0	0.0	1709.2	0.0	1398.4	0.0	282.0	0.0	0.0	282.0	564.0	6.0
5S2SLG-O	206.6	0.9	3.9	0.0	2183.7	0.0	1124.9	0.0	235.0	0.0	0.0	235.0	470.0	5.0
4.5S2SLG-O	185.2	0.6	4.5	0.0	2213.3	0.0	1140.2	0.0	211.5	0.0	0.0	211.5	423.0	4.5

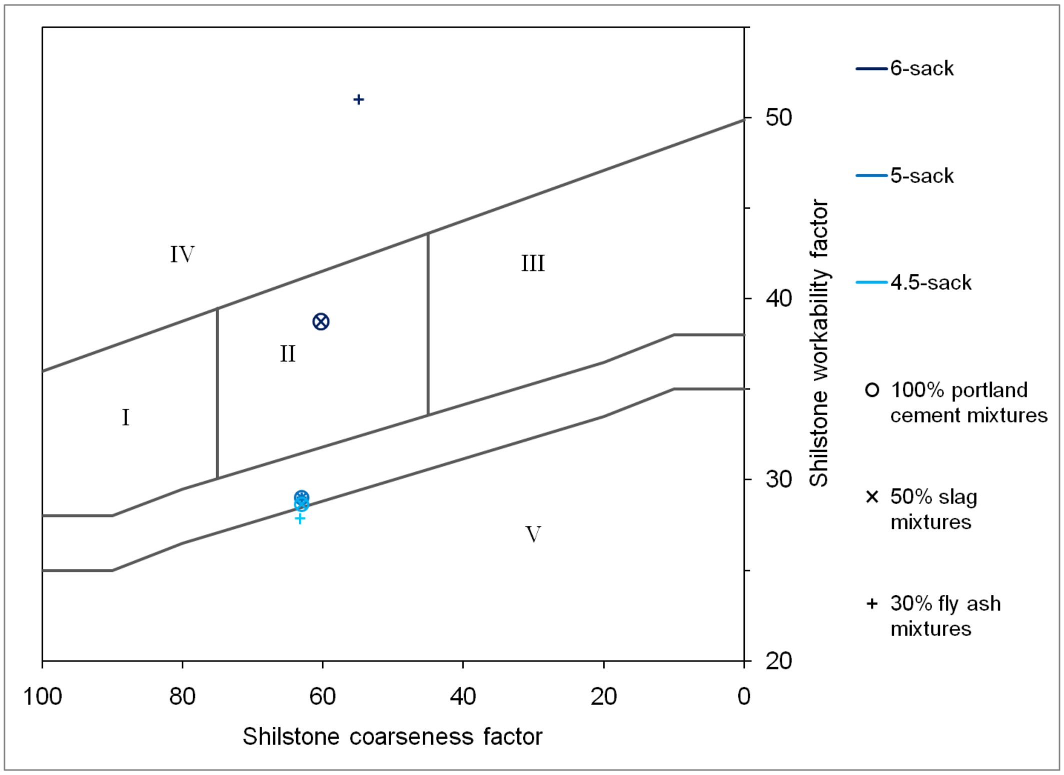

Figure 12: Shilstone coarseness/workability plot for final Phase 2 mix designs.

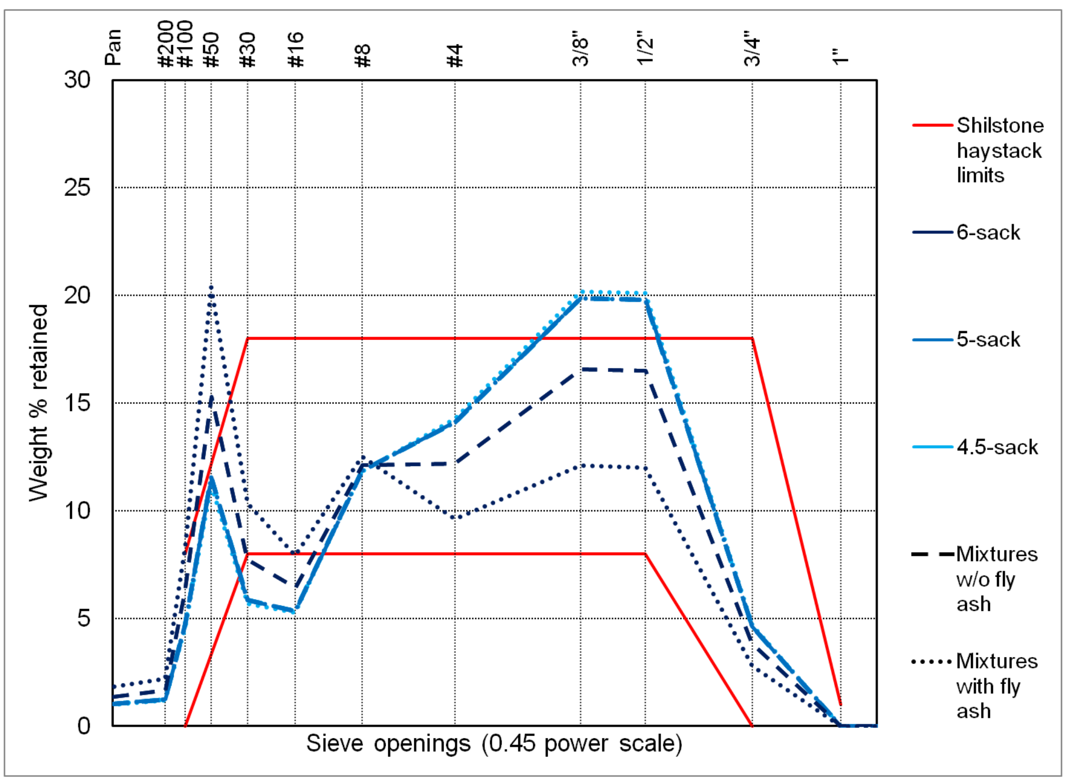

Figure 13: Shilstone "haystack" 8-18 plot for final Phase 2 mix designs.

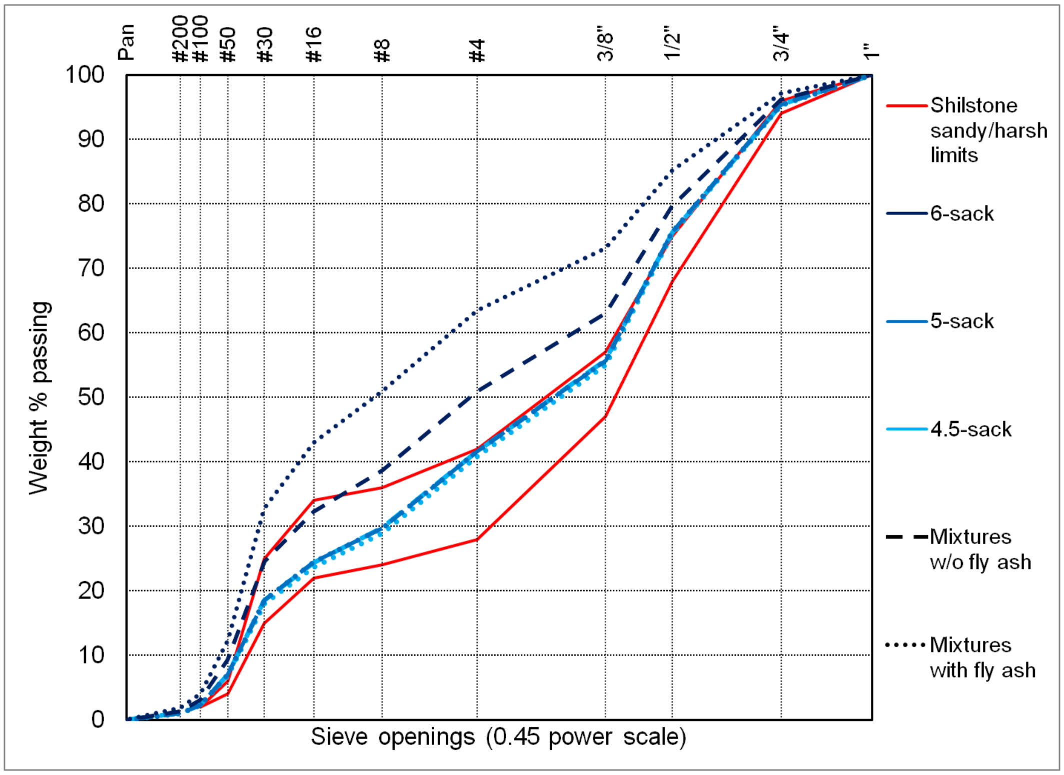

Figure 14: 0.45 power curve plot for final Phase 2 mix designs.

CHAPTER 3. RESULTS

3.1 Fresh Concrete Test Results

The following standard fresh concrete tests were performed for all of the mixtures, and the results summarized in Table 4:

- ASTM C1064 / C1064M - 08 Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete.
- ASTM C143 / C143M - 09 Standard Test Method for Slump of Hydraulic-Cement Concrete.
- ASTM C173 / C173M - 09 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.
- ASTM C231 - 09a Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.
- ASTM C138 / C138M - 09 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.

In addition to these standard tests, the air-void system parameters of mortar samples obtained from the fresh concrete were measured with a Germann Instruments AVA-3000, with the results included in Table 4, and semi-adiabatic calorimetry was performed using a Grace Adiacal™, with the results shown in Figures 15-17. Figures 18 and 19 compare relative slump values for the Phase 1 564 lbs/yd^3, 470 lbs/yd^3, and 376 lbs/yd^3 CMC batches. Slumps for the optimized gradation batches are shown in Figure 20.

Table 4: Fresh concrete test results.

Mix ID	Temp. (°F)	Slump (in.)	Unit wt. (lbs/yd^3)	Yield	Air volume (%)				AVA air-void parameters	
					Volu-metric meter	Pressure meter	Gravi-metric	AVA	Specific surface (mm^{-1})	Spacing factor (mm)
6N1FA1	69	2.00	149.7	0.97	5.5	6.4	3.1	6.8	54.5	0.067
5N1FA1	76	0.75	151.2	0.98	6.5	5.5	3.5	3.7*	30.4*	0.160*
4N1FA1	67	0.00	147.0	1.01	4.8	5.4	7.3	NA**	-	-
6N1FA2	69	2.00	149.6	0.97	5.3	5.8	3.3	5.4	52.7	0.085
5N1FA2	69	1.00	151.7	0.97	5.3	4.8	3.2	3.6	25.6	0.194
6N1SLG	68	2.75	149.6	0.97	4.8	4.5	3.2	2.8	17.0	0.351
5N1SLG	70	0.25	150.5	0.98	5.0	4.9	3.9	1.8*	19.8*	0.340*
4N1SLG	78	0.00	150.4	0.99	5.3	5.6	5.3	NA**	-	-
6N2FA1	68	2.00	145.9	1.00	7.3	7.5	5.6	4.6	35.2	0.135
5N2FA1	67	0.75	151.0	0.98	5.3	4.7	3.6	4.1*	49.9*	0.093*
6N2FA2	66	2.75	145.2	1.00	6.5	7.8	6.1	5.2	36.3	0.125
5N2FA2	66	0.50	150.1	0.98	5.8	5.4	4.2	3.4	23.8	0.212
6N2SLG	66	2.00	150.4	0.97	4.8	4.7	2.8	2.7	18.8	0.325
5N2SLG	68	1.50	152.7	0.97	5.8	5.1	2.6	5.1*	13.7*	0.282*
6S1FA1	69	4.50	148.5	0.98	6.8	7.0	4.1	4.7	29.8	0.159
5S1FA1	70	0.25	153.4	0.96	5.3	5.0	2.4	3.0	29.2	0.184
4S1FA1	66	1.00	153.8	0.98	6.3	5.4	3.5	3.7	16.8	0.265
6S1FA2	68	3.50	148.2	0.98	5.5	6.0	4.4	3.2	36.6	0.154
5S1FA2	70	0.25	152.1	0.97	5.3	4.8	3.3	5.5*	30.4*	0.124*
6S1SLG	67	1.25	151.7	0.96	4.8	4.6	2.2	2.7	21.4	0.285
5S1SLG	63	3.50	151.4	0.98	6.0	5.3	3.7	5.3*	48.4*	0.080*
4S1SLG	66	0.25	156.0	0.96	4.5	3.7	2.2	NA**	-	-
6S2FA1	68	4.00	147.1	0.99	6.8	6.6	5.0	4.0	26.9	0.190
5S2FA1	65	1.00	149.9	0.99	6.5	6.1	4.7	2.8	23.1	0.260
6S2FA2	68	3.50	147.8	0.99	6.0	5.5	4.7	3.4	23.2	0.237
5S2FA2	65	1.00	150.1	0.99	6.3	6.5	4.6	2.8	24.8	0.240
6S2SLG	66	1.25	149.6	0.98	5.0	4.5	3.5	5.1*	23.9*	0.191*
5S2SLG	67	1.75	149.5	0.99	7.5	7.0	5.0	4.6	19.3	0.229
6S2-O	65	3.00	144.5	0.99	7.8	7.8	7.2	0.1*	32.5*	0.811*
5S2-O	68	0.50	151.4	0.99	5.5	6.1	5.5	8.1	11.6	0.212
4.5S2-O	71	0.00	152.3	0.99	3.5	2.4	3.9	NA**	-	-
6S2FA2-O	60	4.50	143.5	0.99	7.5	7.6	6.7	1.2	9.7	0.822
5S2FA2-O	61	2.25	153.9	0.99	3.0	2.8	2.4	0.0*	-3522*	1.449*
4.5S2FA2-O	69	0.00	156.0	0.99	3.5	2.7	1.2	NA**	-	-
6S2SLG-O	67	1.25	147.5	0.99	5.8	5.2	5.8	4.2	15.3	0.297
5S2SLG-O	66	3.50	151.8	0.99	3.3	4.5	4.8	4.3	15.1	0.249
4.5S2SLG-O	74	0.00	155.6	0.99	3.5	2.6	1.3	NA**	-	-

* Irregularities during AVA magnetic stir-bar agitation of mortar sample.

** Not available because concrete mix was too harsh to obtain mortar fraction sample for AVA testing.

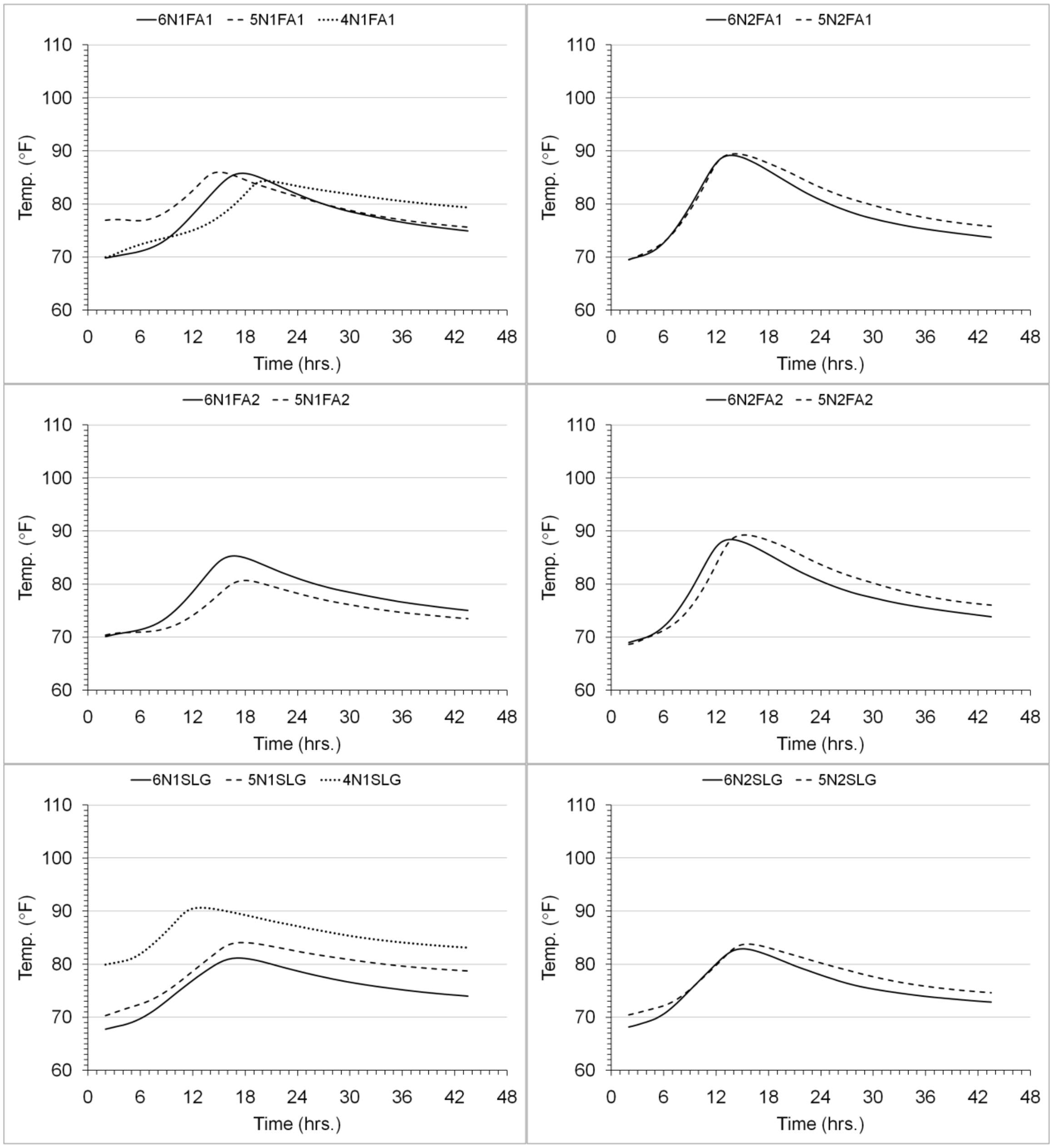

Figure 15: Calorimetry plots for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

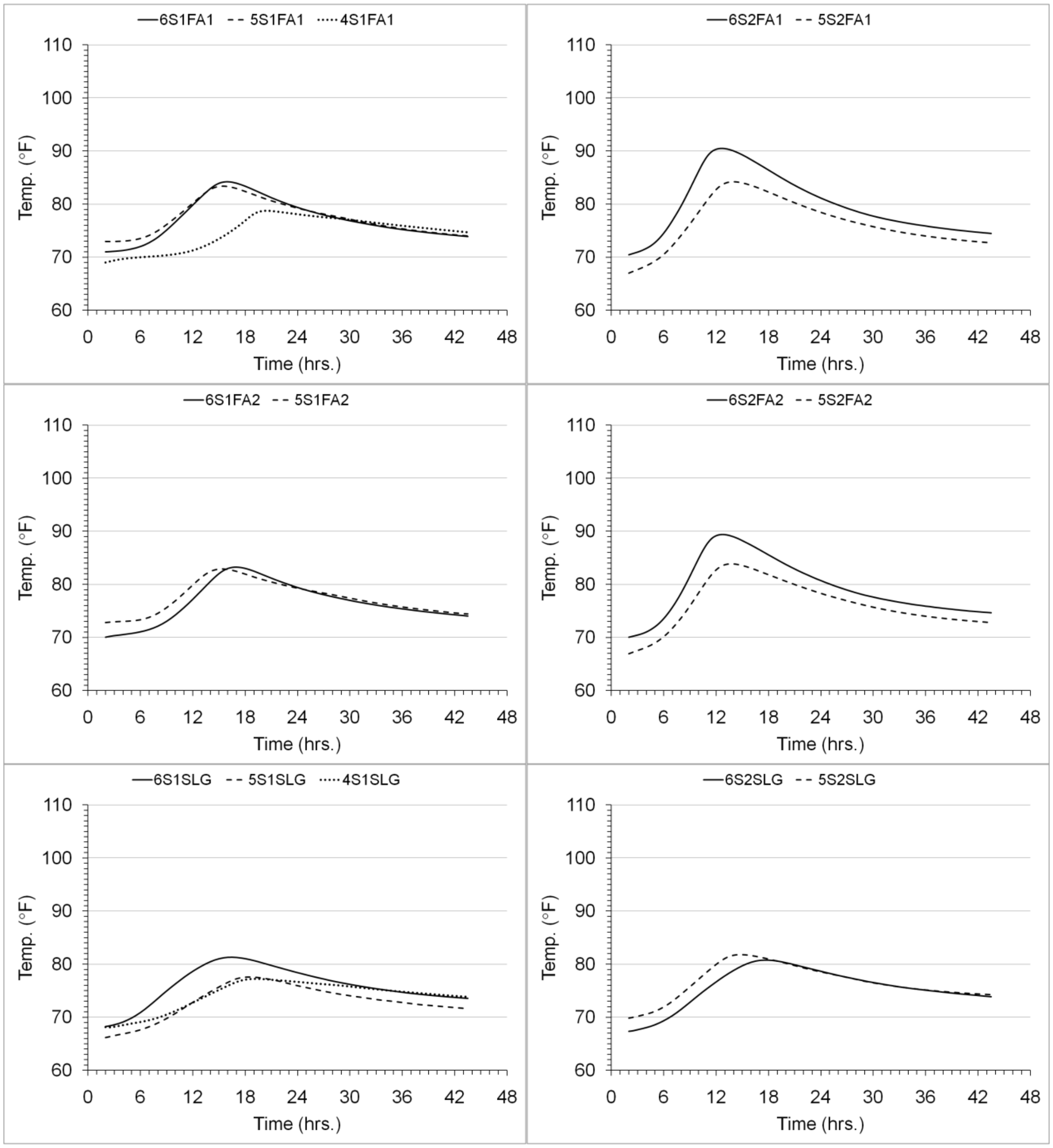

Figure 16: Calorimetry plots for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

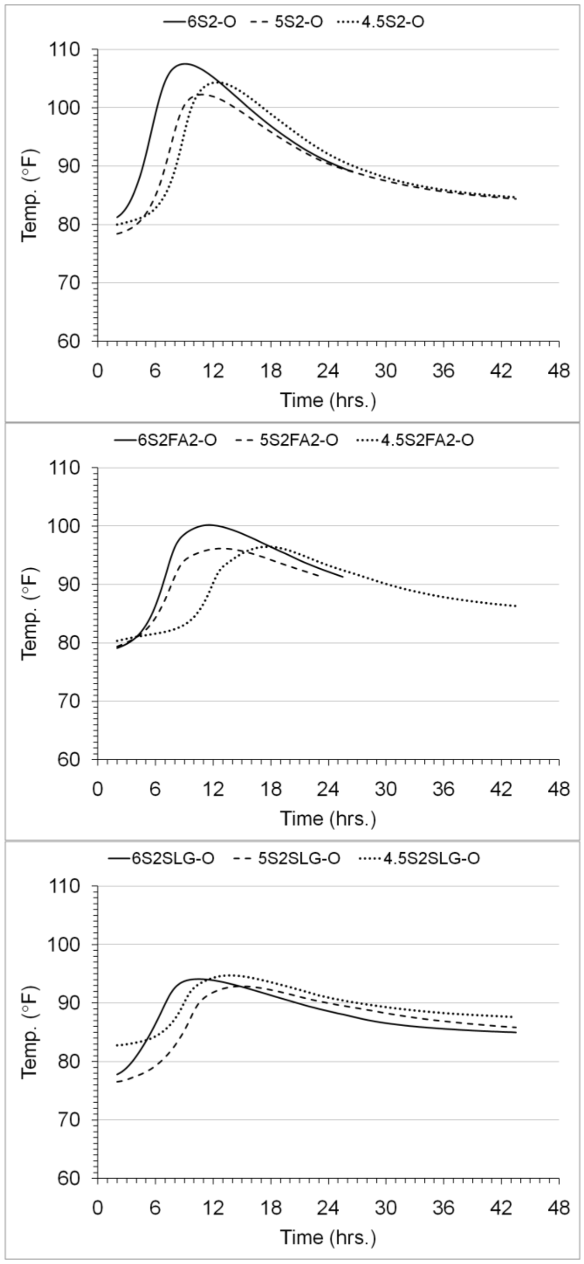

Figure 17: Calorimetry plots for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

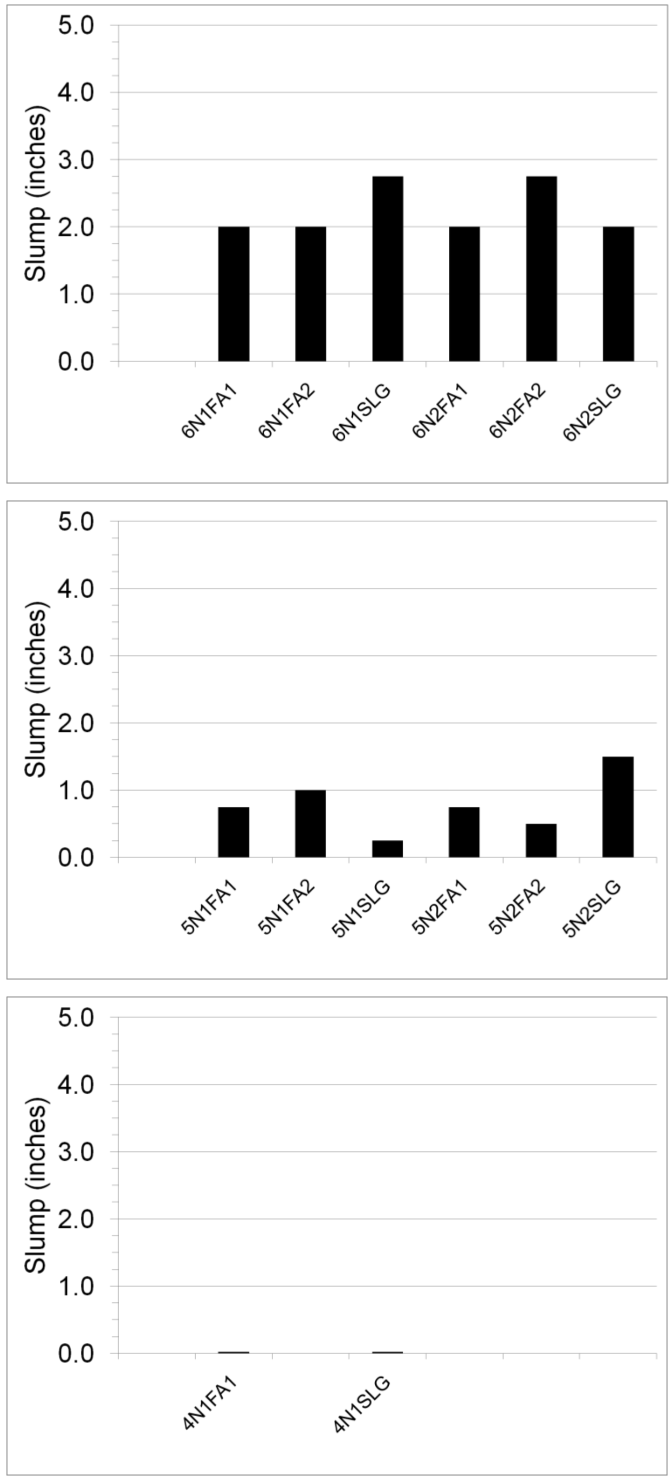

Figure 18: Slump test results from Phase 1 concrete made using northern aggregate source, from top to bottom, 564 lbs/yd^3, 470 lbs/yd^3, and 376 lbs/yd^3 CMC batches.

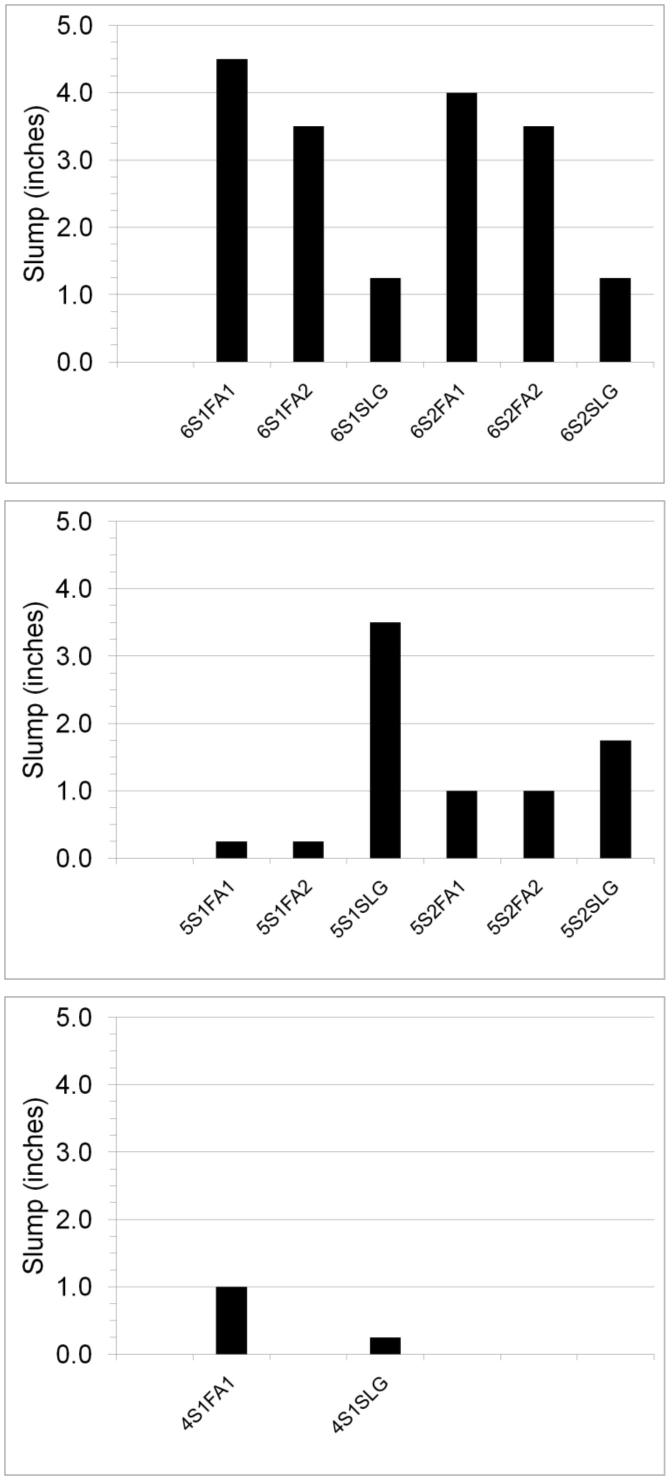

Figure 19: Slump test results from Phase 1 concrete made using southern aggregate source, from top to bottom, 564 lbs/yd^3, 470 lbs/yd^3, and 376 lbs/yd^3 CMC batches.

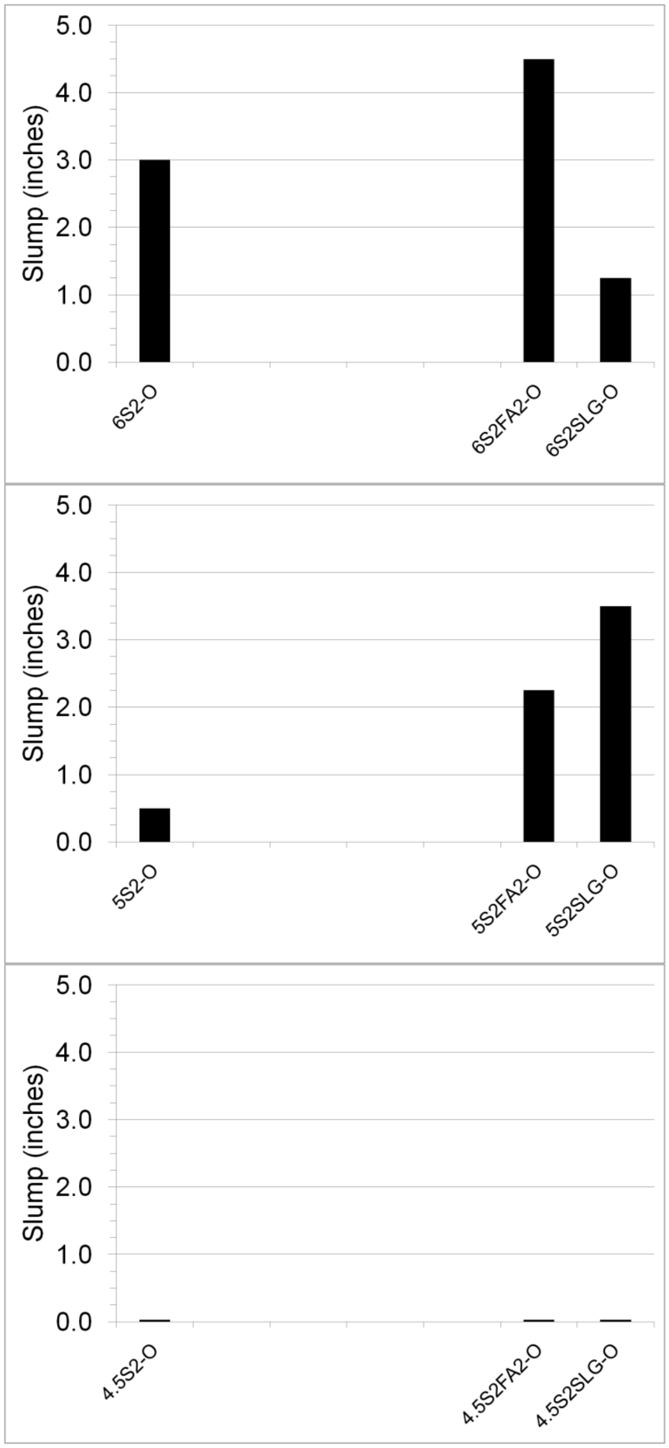

Figure 20: Slump test results from Phase 2 concrete made using southern aggregate source, from top to bottom, 564 lbs/yd^3, 470 lbs/yd^3, and 423 lbs/yd^3 CMC batches.

3.2 Hardened Concrete Test Results

The following hardened concrete tests were performed, and the results summarized in Tables 5-7:

- Modulus of elasticity and Poisson’s ratio at 28 days, (ASTM C469 - 02e1 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression).
- Split tensile strength at 3, 7, 28, and 90 days, (ASTM C496 / C496M - 04e1 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens).
- Compressive strength at 3, 7, 28, and 90 days, (ASTM C39 / C39M - 05e2 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens).
- Freeze-thaw testing of beams after 28 day moist cure and 28 days air cure, (ASTM C666 / C666M - 03(2008) Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure B).
- Shrinkage beams (ASTM C157 / C157M - 08 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete).
- Sorptivity, (ASTM C1585 - 04e1 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes).
- Rapid chloride permeability (ASTM C1202 - 09 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration).

Figures 21-35 show example photographs of cast cylinders representative of the concrete batches. Figures 36-41 plot compressive and tensile strength gain. Figures 42 through 44 plot drying shrinkage versus time, and Figures 45 through 47 plot sorptivity versus time. Figures 48 through 50 plot changes in the relative dynamic modulus of elasticity versus freeze-thaw cycles.

Table 5: Strength test results.

Mix ID	Compressive strength (psi)				Split tensile strength (psi)				Modulus of elasticity (lbs/in^2)	Poisson's ratio
	3 day	7 day	28 day	90 day	3 day	7 day	28 day	90 day		
6N1FA1	2921	4566	5979	7144	399	500	563	647	3700000	0.16
5N1FA1	3730	4956	6789	8083	475	550	649	708	3400000	0.14
4N1FA1	2488*	5277*	7359*	6811*	450	575	672*	700*	4250000	0.18
6N1FA2	3226	5187	6620	7773	423	550	633	678	3550000	0.18
5N1FA2	3610	5538	7248	8980	471	577	685	743	4600000	0.21
6N1SLG	3112	5245	8519	9740	422	527	757	786	3100000	0.16
5N1SLG	3082	5185	8755	9770	417	579	740	794	4350000	0.18
4N1SLG	2526*	3885*	5672*	6529*	394	540	698*	738	3400000	0.19
6N2FA1	2652	3527	5029	6041	377	403	561	578	3550000	0.21
5N2FA1	3796	4801	6613	7684	462	532	646	716	4000000	0.17
6N2FA2	2607	3515	5032	6005	356	441	527	580	3500000	0.18
5N2FA2	3586	4792	6641	7898	474	539	610	696	4050000	0.18
6N2SLG	2842	4659	8383	9182	369	542	734	734	3750000	0.21
5N2SLG	2467	3880	6843	8756	331	568	737	707	4000000	0.17
6S1FA1	2916	4484	5981	7474	397	505	597	704	3200000	0.20
5S1FA1	3924	4996	7028	7743	445	525	647	724	3500000	0.17
4S1FA1	3167	5381	6717	8782	455	597	620	697	4450000	0.21
6S1FA2	3381	5165	7380	8471	451	503	647	755	3550000	0.19
5S1FA2	3480	5250	6873	4415*	463	543	657	610*	4400000	0.19
6S1SLG	2930	4891	7629	9052	389	553	688	803	3800000	0.19
5S1SLG	2416	4512	7545	9246	369	557	658	746	3350000	0.17
4S1SLG	2733	4940	7747	8025*	402	549	739	792*	4650000	0.21
6S2FA1	3295	4410	6278	7670	416	457	609	641	4150000	0.22
5S2FA1	3486	4404	6367	7284	447	535	640	704	3600000	0.20
6S2FA2	3499	4396	6755	8201	395	470	645	639	3550000	0.19
5S2FA2	3196	4225	6615	7491	431	510	654	703	4550000	0.20
6S2SLG	2809	4748	7359	8342	370	533	694	719	3900000	0.19
5S2SLG	2660	3982	6314	7809	377	489	719	706	3450000	0.21
6S2-O	3040	3475	4205	4918	NA**	461	482	561	3000000	0.18
5S2-O	3105	4028	5639	6342	NA**	521	471	665	4000000	0.22
4.5S2-O	5849	6583	6062	5754	576	583	617	633	3700000	0.18
6S2FA2-O	3456	4225	5741	6824	NA**	509	502	704	3000000	0.19
5S2FA2-O	3995	5277	7218	8770	NA**	564	652	735	4500000	0.27
4.5S2FA2-O	3631	3920	8933	10996	536	520	662	856	4300000	0.20
6S2SLG-O	3024	4009	6042	6508	435	586	587	699	3000000	0.20
5S2SLG-O	3514	5492	8047	8498	NA**	567	606	805	3200000	0.17
4.5S2SLG-O	NA**	4759	8940	10058	NA**	644	721	811	3300000	0.24

*Test specimens exhibited visibly poor consolidation.

**Not available due to equipment failure

Table 6: Shrinkage test results.

	Length change (%)							
		Days air-drying						
Mix ID	Post 28 day soak	4	7	14	28	56	112	224
6N1FA1	0.012	-0.014	-0.021	-0.030	-0.033	-0.041	-0.040	
5N1FA1	0.003	-0.018	-0.020	-0.028	-0.033	-0.036	-0.037	
4N1FA1	0.001	-0.017	-0.018	-0.024	-0.033	-0.037		
6N1FA2	0.005	-0.022	-0.025	-0.036	-0.036	-0.043	-0.042	
5N1FA2	0.003	-0.016	-0.019	-0.027	-0.033	-0.038		
6N1SLG	0.010	-0.005	-0.009	-0.018	-0.017	-0.030	-0.033	
5N1SLG	0.010	0.000	-0.001	-0.007	-0.017	-0.024		
4N1SLG	0.003	-0.006	-0.011	-0.017	-0.021	-0.027		
6N2FA1	0.004	-0.026	-0.037	-0.041	-0.050	-0.055	-0.049	
5N2FA1	0.009	-0.019	-0.027	-0.035	-0.043	-0.044		
6N2FA2	0.003	-0.030	-0.040	-0.045	-0.051	-0.058	-0.052	
5N2FA2	0.012	-0.019	-0.025	-0.033	-0.040	-0.042		
6N2SLG	0.009	-0.006	-0.014	-0.020	-0.029	-0.035	-0.036	
5N2SLG	0.003	-0.011	-0.017	-0.029	-0.034	-0.037		
6S1FA1	0.003	-0.015	-0.023	-0.028	-0.039	-0.042	-0.044	
5S1FA1	0.002	-0.010	-0.013	-0.023	-0.031	-0.031	-0.034	
4S1FA1	0.003	-0.013	-0.014	-0.022	-0.029	-0.032		
6S1FA2	0.001	-0.013	-0.018	-0.027	-0.034	-0.035	-0.035	
5S1FA2	0.001	-0.012	-0.016	-0.025	-0.038	-0.031	-0.036	
6S1SLG	0.012	-0.001	-0.003	-0.009	-0.021	-0.027	-0.030	
5S1SLG	0.005	-0.003	-0.005	-0.006	-0.018	-0.025		
4S1SLG	0.007	0.001	0.004	-0.005	-0.015	-0.021		
6S2FA1	0.004	-0.008	-0.013	-0.024	-0.029	-0.036		
5S2FA1	0.006	-0.010	-0.014	-0.025	-0.024	-0.033		
6S2FA2	0.004	-0.007	-0.015	-0.029	-0.033	-0.041	-0.030	
5S2FA2	0.003	-0.013	-0.017	-0.025	-0.026	-0.034	-0.039	
6S2SLG	0.012	0.002	-0.003	-0.007	-0.018	-0.019	-0.022	
5S2SLG	0.014	0.007	-0.003	-0.008	-0.016	-0.020	-0.035	
6S2-O	-0.064*	-0.104*	-0.130*	-0.107*	-0.011*	0.010*	-0.003*	-0.013*
5S2-O	0.006*	0.024*	0.021*	0.132*	0.102*	0.094*	0.085*	0.079*
4.5S2-O	0.007*	-0.207*	0.092	0.118*		0.095*	0.093*	0.092
6S2FA2-O	-0.070*	-0.112*	-0.141*	-0.124*	-0.039*	-0.004*	-0.013*	-0.020*
5S2FA2-O	-0.096*	-0.137*	-0.166*	-0.144*	-0.044*	-0.020*	-0.028*	-0.030*
4S2FA2-O	0.039*	0.016*	0.087*	-0.112*	0.105*	0.104*	0.095*	0.093*
6S2SLG-O	0.039*	0.026*	0.039*	0.143*	0.175*	0.148*	0.133*	0.124*
5S2SLG-O	-0.058*	-0.036*	-0.036*	0.074*	0.046*	0.040*	0.031*	0.026*
4.5S2FA2-O	0.003*	-0.306*	0.075*	0.108*		0.090*	0.091*	0.093*

*Faulty test readings.

Table 7: Sorptivity, freeze-thaw, and rapid chloride permeability test results

Mix ID	Sorptivity (mm/sec$^{1/2}$)				Freeze-thaw at 300 cycles		Rapid chloride permeability	
	Initial slope	R	Secondary slope	R	Durability factor	Length change (%)	Charge passed (coulombs)	Penetrability rating
6N1FA1	8.95E-04	0.991	1.51E-04	0.965	102	-0.010	814	Very low
5N1FA1	9.34E-04	0.994	2.40E-04	0.988	102	0.006	589	Very low
4N1FA1	1.38E-03	0.960	3.49E-04*	0.995*	102	0.009	366	Very low
6N1FA2	7.58E-04	0.989	1.44E-04	0.957	102	0.003	878	Very low
5N1FA2	6.08E-04	0.977	1.01E-04	0.977	103	0.004	505	Very low
6N1SLG	6.08E-04	0.977	1.01E-04	0.977	100	0.016	425	Very low
5N1SLG	4.80E-04	0.990	1.15E-04*	0.981*	95	0.024	334	Very low
4N1SLG	1.54E-03	0.950	1.72E-04	0.988	88	0.051	317	Very low
6N2FA1	7.67E-04	0.987	1.88E-04	0.989	103	0.003	805	Very low
5N2FA1	8.65E-04	0.991	1.80E-04	0.976	104	0.010	580	Very low
6N2FA2	7.80E-04	0.975	1.50E-04	0.990	103	0.005	779	Very low
5N2FA2	8.56E-04	0.988	1.22E-04	0.983	105	0.009	572	Very low
6N2SLG	4.67E-04	0.977	7.88E-05	0.927	100	0.010	489	Very low
5N2SLG	5.49E-04	0.986	7.72E-05	0.915	101	0.016	326	Very low
6S1FA1	1.19E-03	0.990	2.89E-04	0.987	102	0.006	569	Very low
5S1FA1	6.55E-04	0.985	1.97E-04	0.988	101	0.001	493	Very low
4S1FA1	9.68E-04	0.991	2.30E-04	0.982	101	0.011	518	Very low
6S1FA2	1.11E-03	0.986	2.61E-04	0.995	102	0.003	530	Very low
5S1FA2	7.81E-04	0.986	2.06E-04	0.979	102	-0.003	484	Very low
6S1SLG	8.98E-04	0.983	1.15E-04	0.954	99	0.004	380	Very low
5S1SLG	6.66E-04	0.986	1.40E-04	0.987	99	0.006	343	Very low
4S1SLG	6.16E-04	0.984	6.20E-05	0.878	95	0.017	300	Very low
6S2FA1	9.31E-04	0.971	2.22E-04	0.987	102	0.011	556	Very low
5S2FA1	8.51E-04	0.984	1.86E-04	0.979	101	0.008	393	Very low
6S2FA2	1.14E-03	0.980	2.22E-04	0.978	103	0.006	537	Very low
5S2FA2	8.21E-04	0.983	1.86E-04	0.978	101	0.009	354	Very low
6S2SLG	9.05E-04	0.977	1.40E-04	0.943	99	0.003	448	Very low
5S2SLG	9.21E-04	0.988	1.37E-04	0.980	100	0.012	308	Very low
6S2-O	3.09E-04	0.869	1.46E-04	0.984	97	-0.020	2409	Moderate
5S2-O	5.94E-04	0.984	1.19E-04	0.979	97	0.025	2161	Moderate
4.5S2-O	2.95E-03	0.970	2.80E-04	0.977	82	0.197	1244	Low
6S2FA2-O	3.13E-04	0.839	1.44E-04	0.942	97	-0.017	1815	Low
5S2FA2-O	4.08E-04	0.890	3.78E-05	0.642	97	0.002	1557	Low
4.5S2FA2-O	1.26E-03	0.991	3.55E-04	0.983	95	0.068	946	Very low
6S2SLG-O	5.75E-04	0.981	1.68E-04	0.954	93	0.050	692	Very low
5S2SLG-O	6.10E-04	0.962	1.44E-04	0.731	90	-0.007	681	Very low
4.5S2SLG-O	2.61E-03	0.979	3.83E-04	0.993	85	0.114	485	Very low

*Sorptivity data at days seven and eight (last two collected data points) excluded from linear best fit.

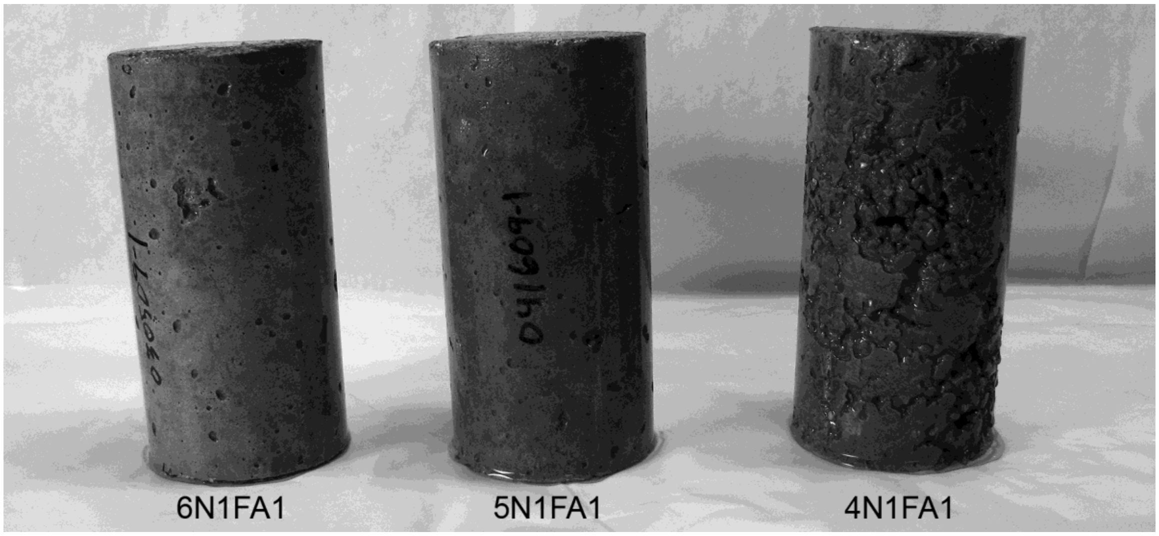

Figure 21: Cylinders to represent the 564, 470, and 376 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, Lafarge portland cement, and Columbia fly ash.

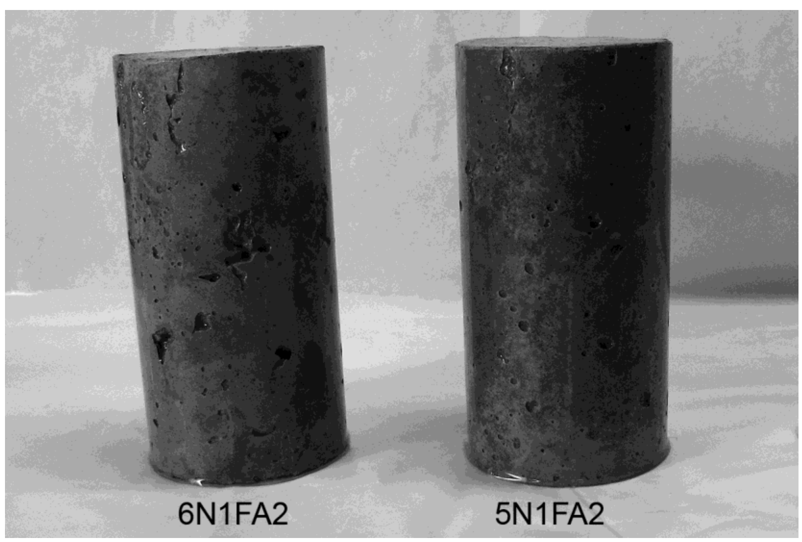

Figure 22: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, Lafarge portland cement, and Weston fly ash.

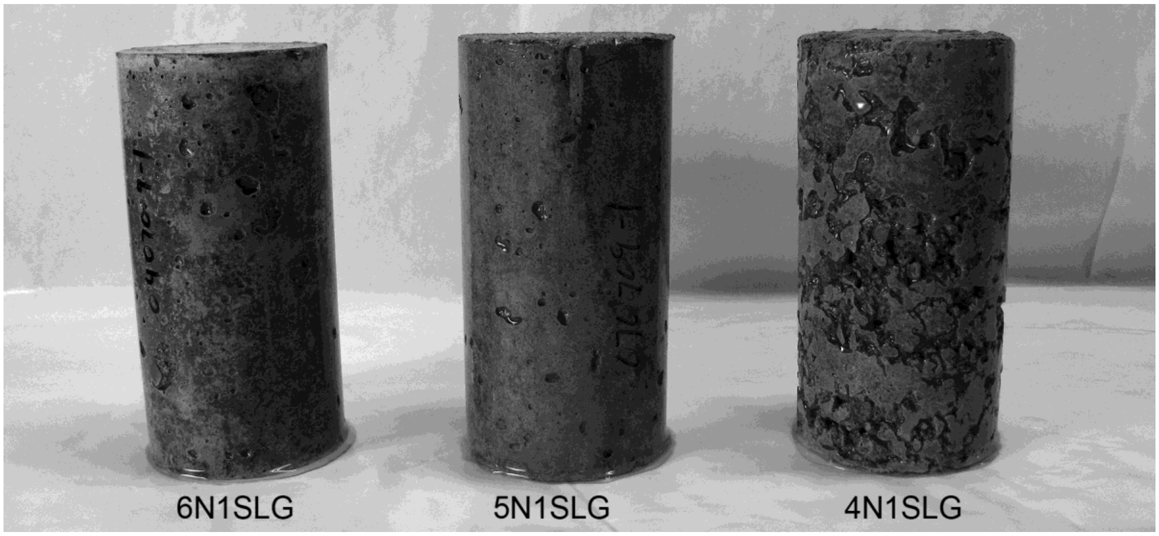

Figure 23: Cylinders to represent the 564, 470, and 376 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, Lafarge portland cement, and Holcim GGBFS.

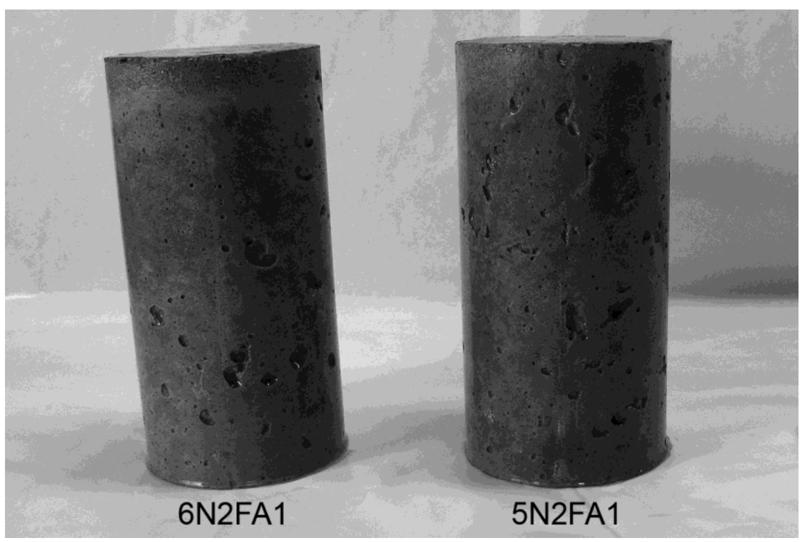

Figure 24: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, St Marys portland cement, and Columbia fly ash.

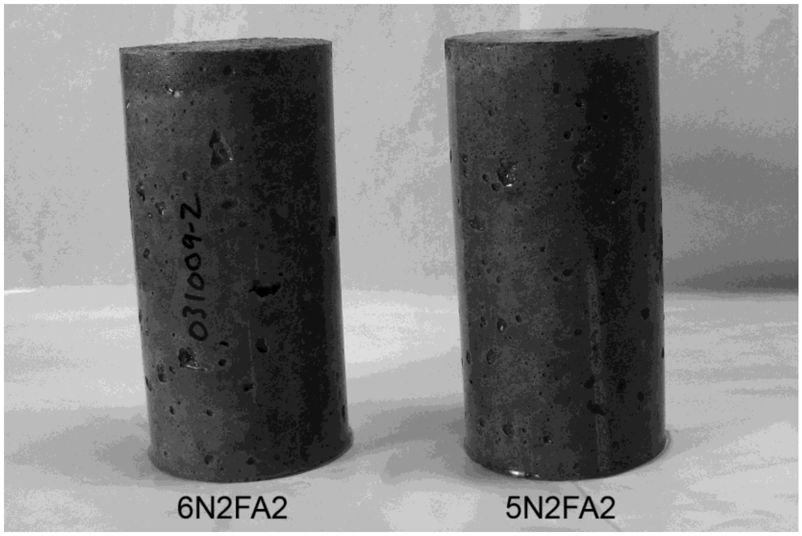

Figure 25: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, St Marys portland cement, and Weston fly ash

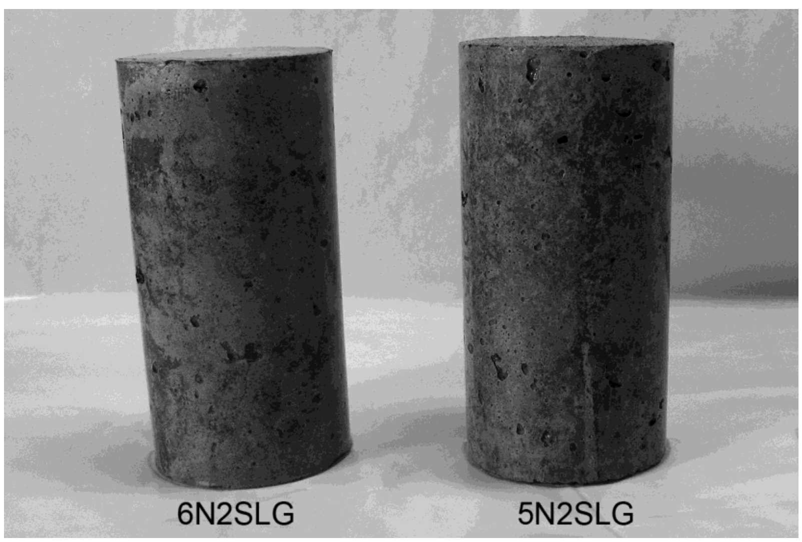

Figure 26: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Northern aggregate source, St Marys portland cement, and Holcim GGBFS.

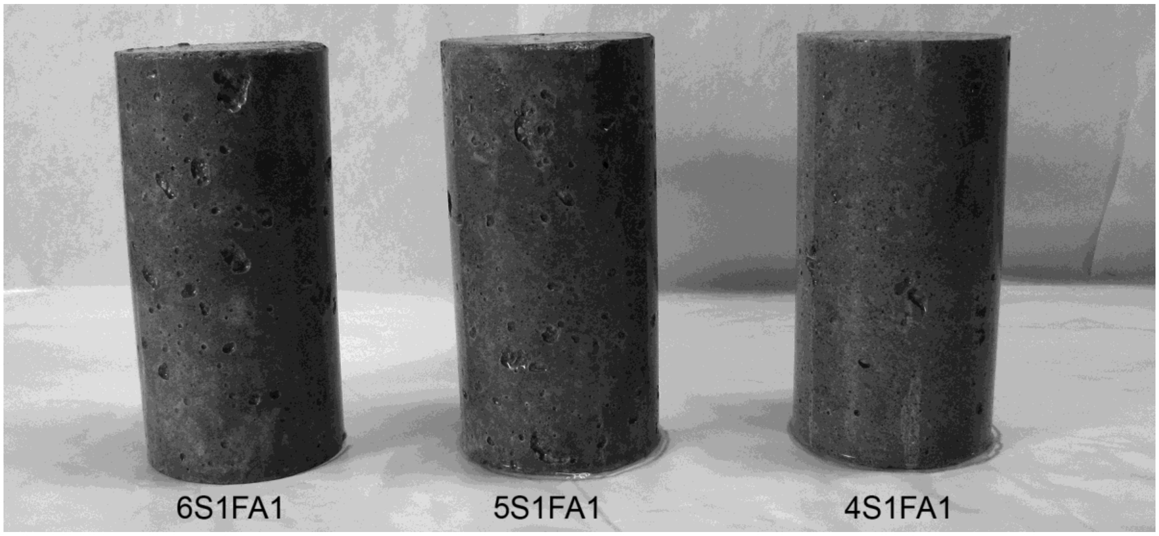

Figure 27: Cylinders to represent the 564, 470, and 376 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, Lafarge portland cement, and Columbia fly ash.

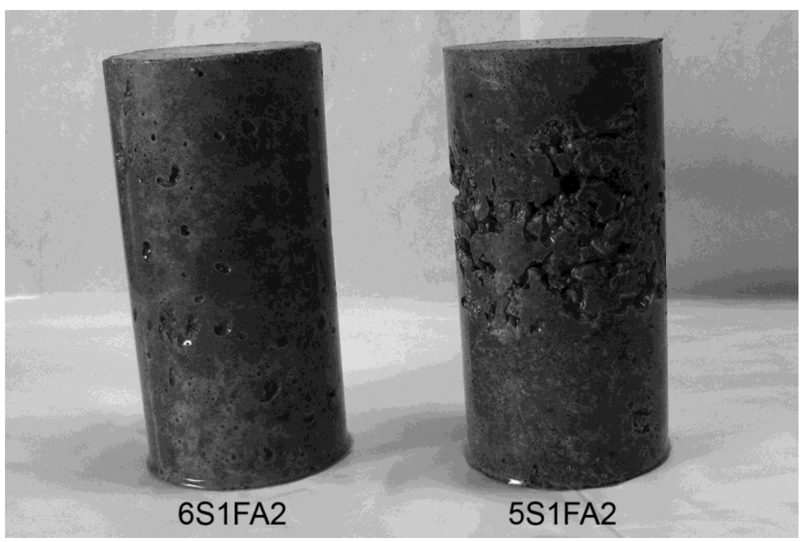

Figure 28: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, Lafarge portland cement, and Weston fly ash.

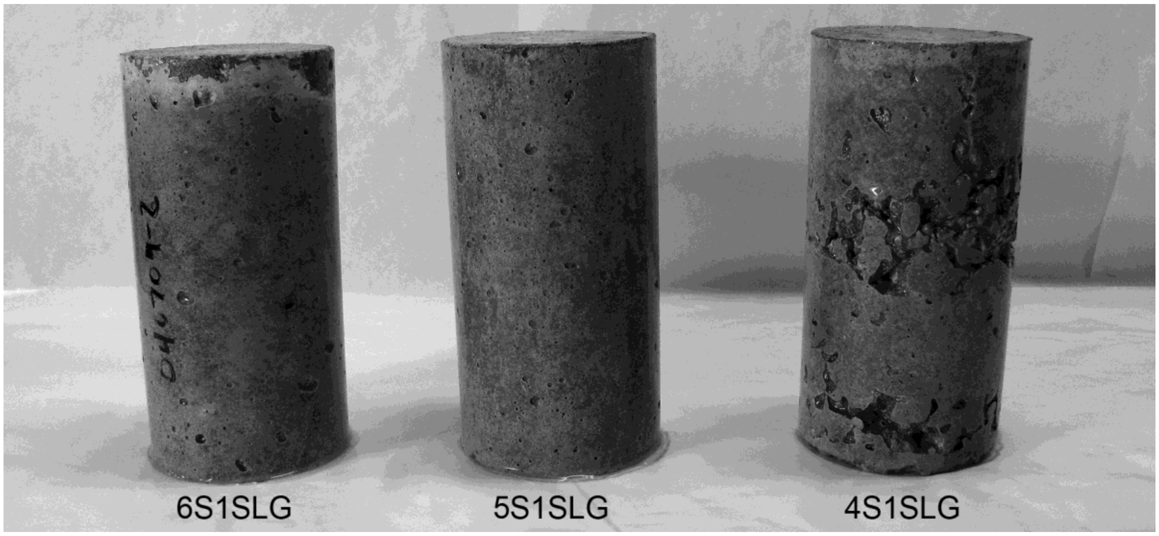

Figure 29: Cylinders to represent the 564, 470, and 376 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, Lafarge portland cement, and Holcim GGBFS.

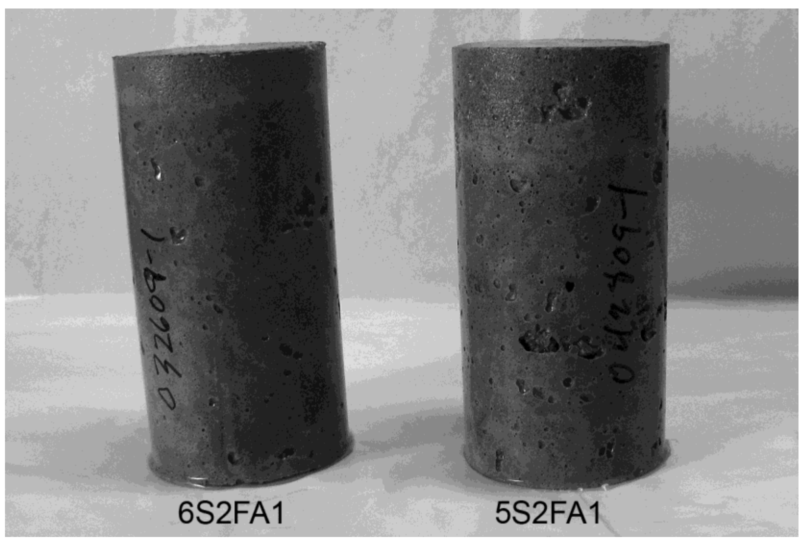

Figure 30: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, St Marys portland cement, and Columbia fly ash.

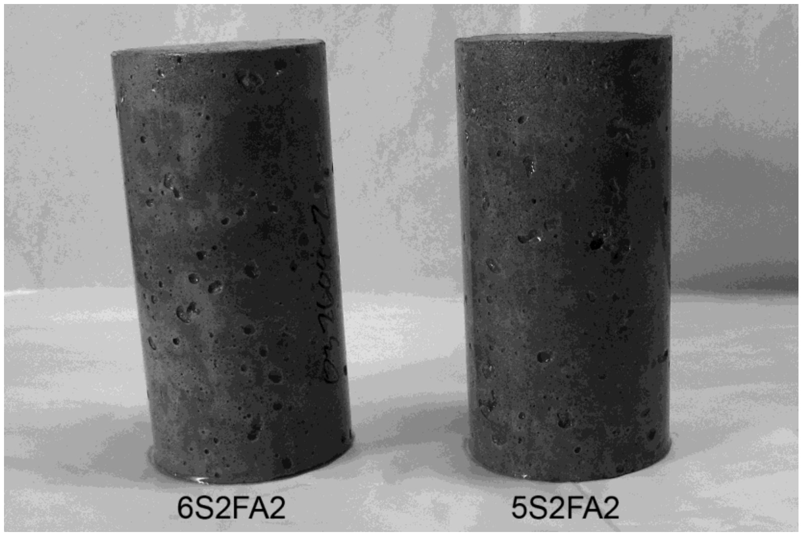

Figure 31: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, St Marys portland cement, and Weston fly ash.

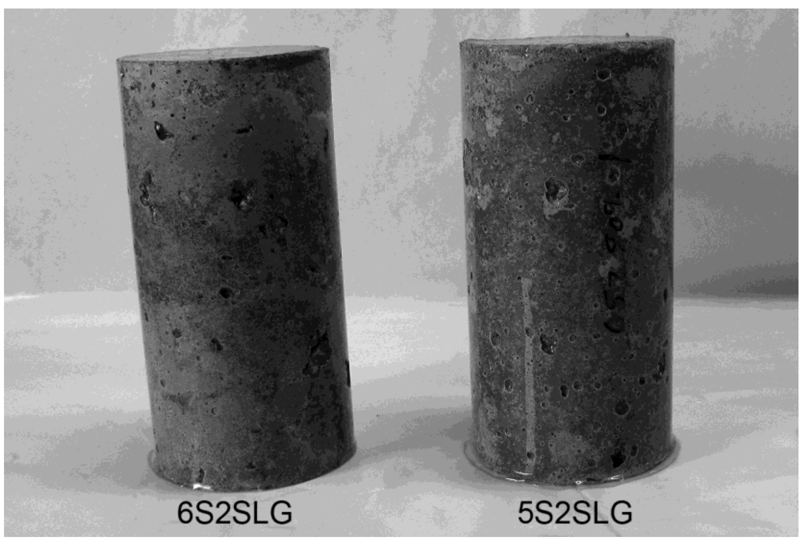

Figure 32: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 1 using the Southern aggregate source, St Marys portland cement, and Holcim GGBFS.

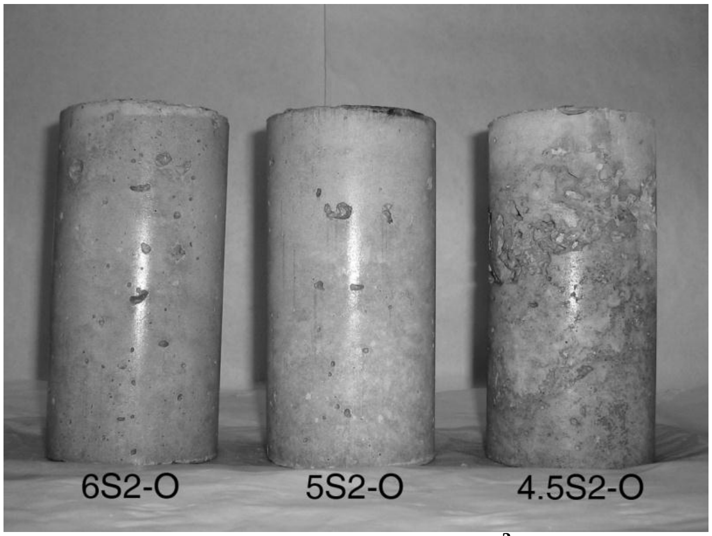

Figure 33: Cylinders to represent the 564, 470, and 423 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 2 using the Southern aggregate source, St Marys portland cement.

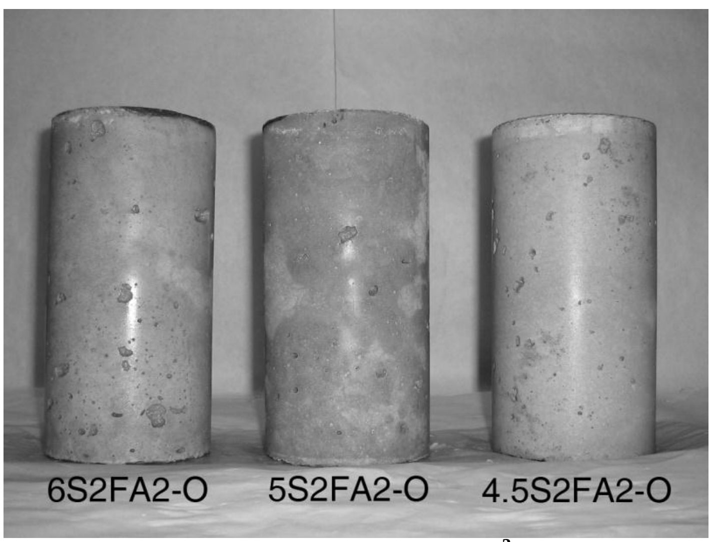

Figure 34: Cylinders to represent the 564, 470, and 423 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 2 using the Southern aggregate source, St Marys portland cement, and Weston fly ash.

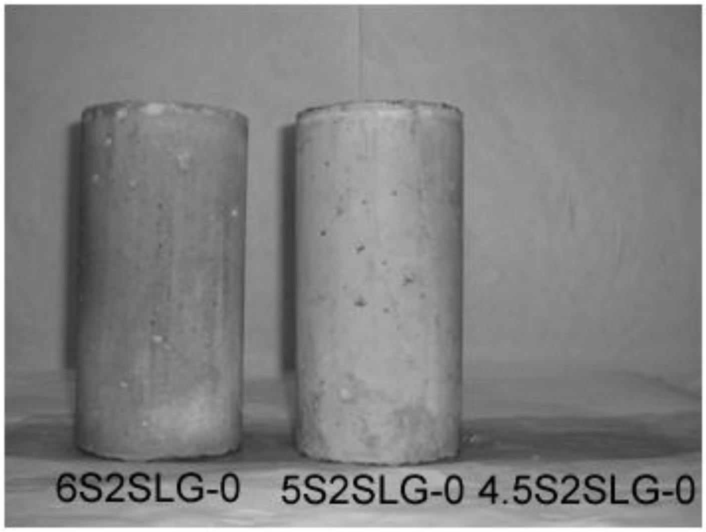

Figure 35: Cylinders to represent the 564 and 470 lbs/yd^3 cementitious content mixes (from left to right) produced during Phase 2 using the Southern aggregate source, St Marys portland cement, and Holcim GGBFS. The 423 lbs/yd^3 cylinder is not pictured.

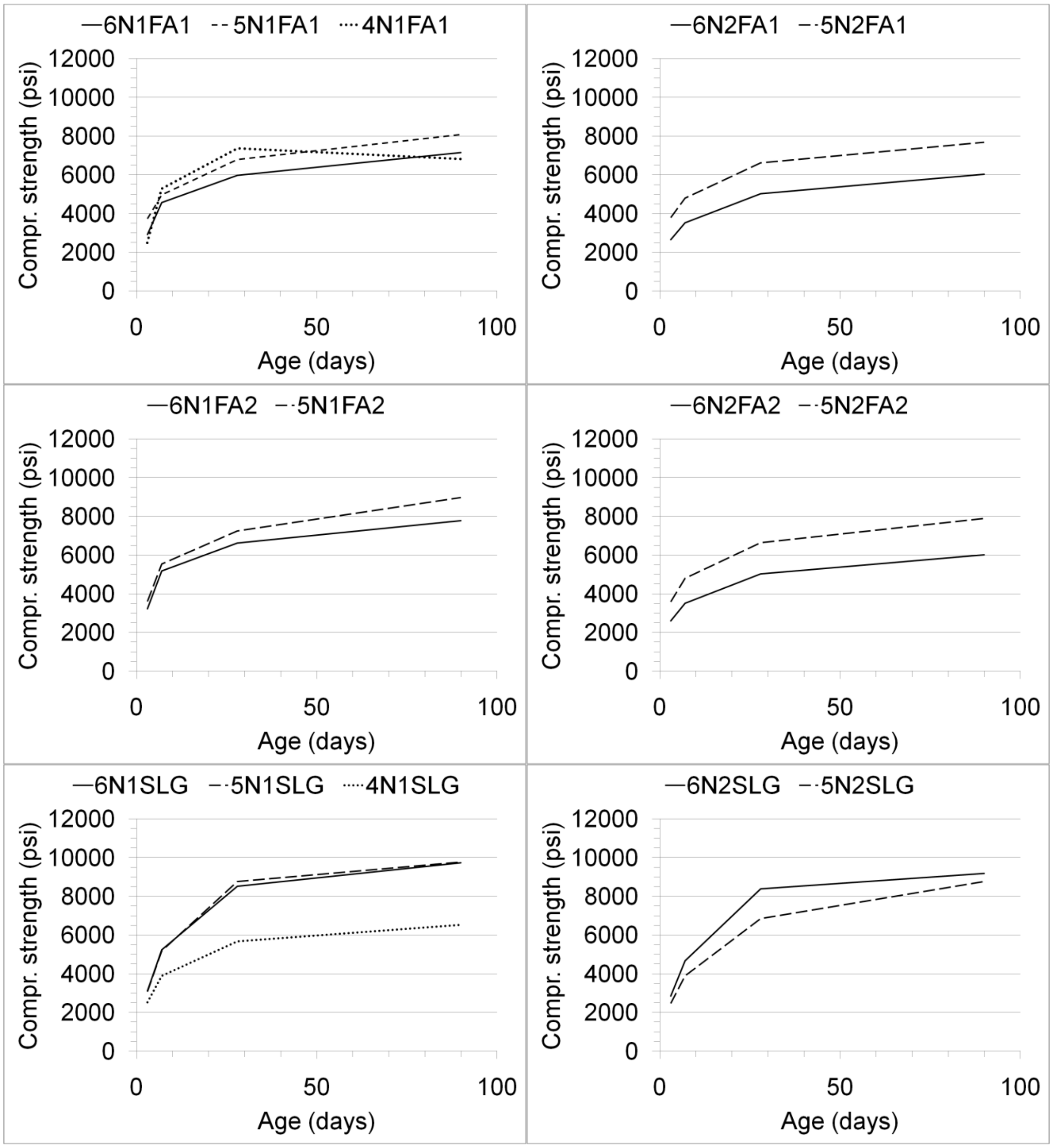

Figure 36: Compressive strength gain plots for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

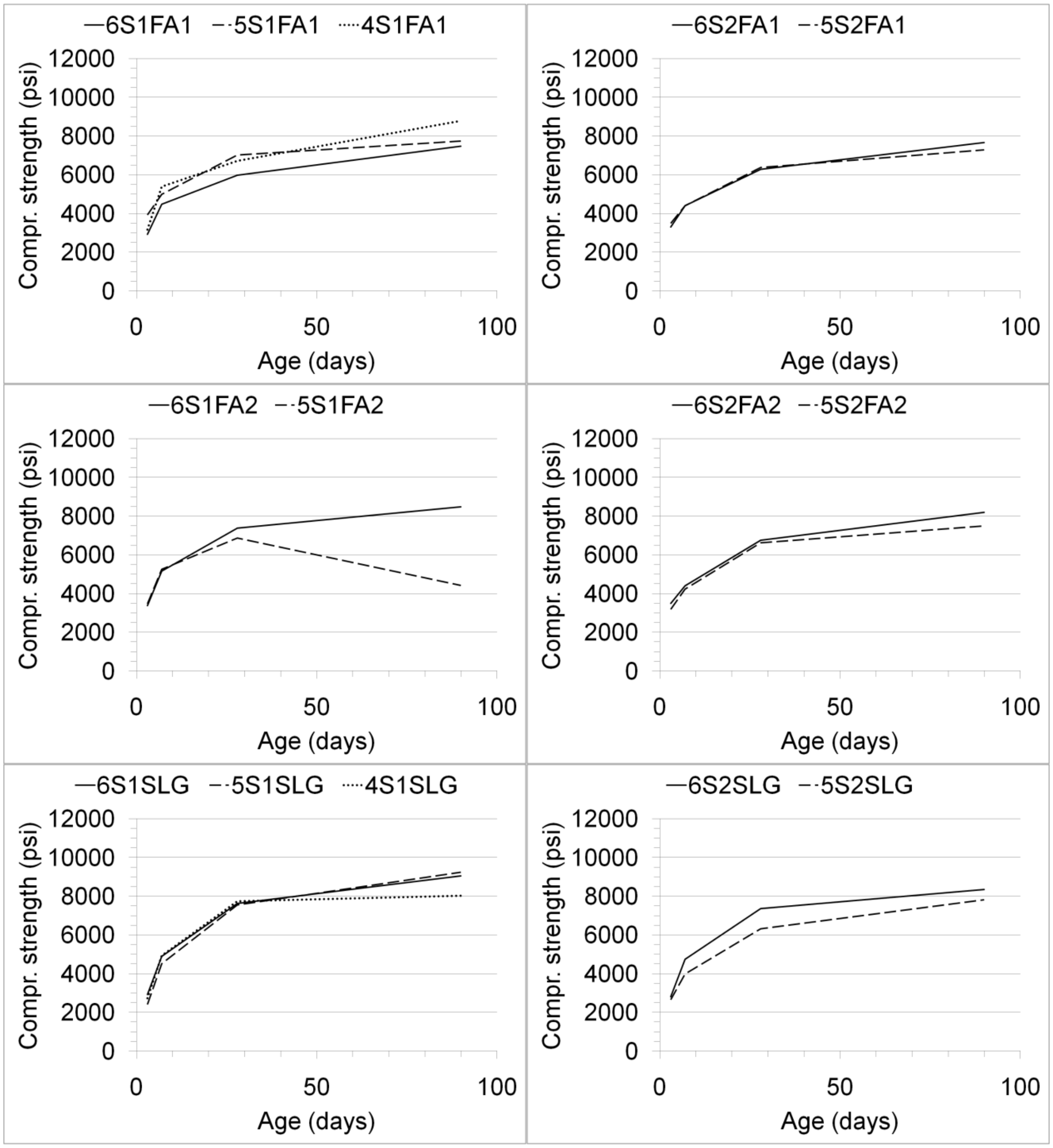

Figure 37: Compressive strength gain plots for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

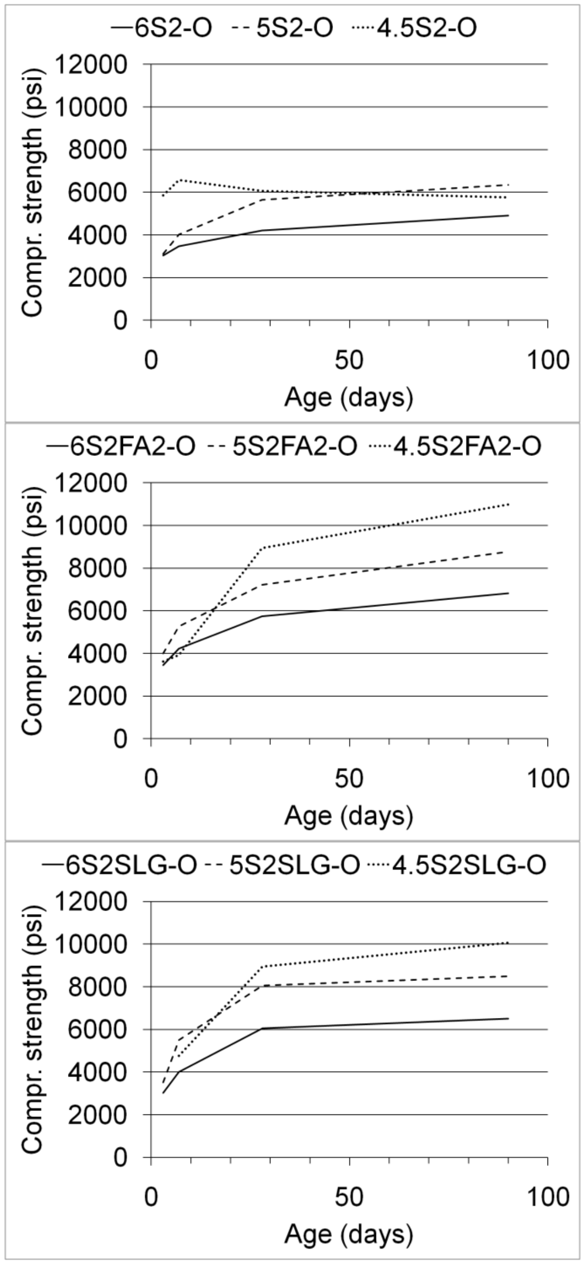

Figure 38: Compressive strength gain plots for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

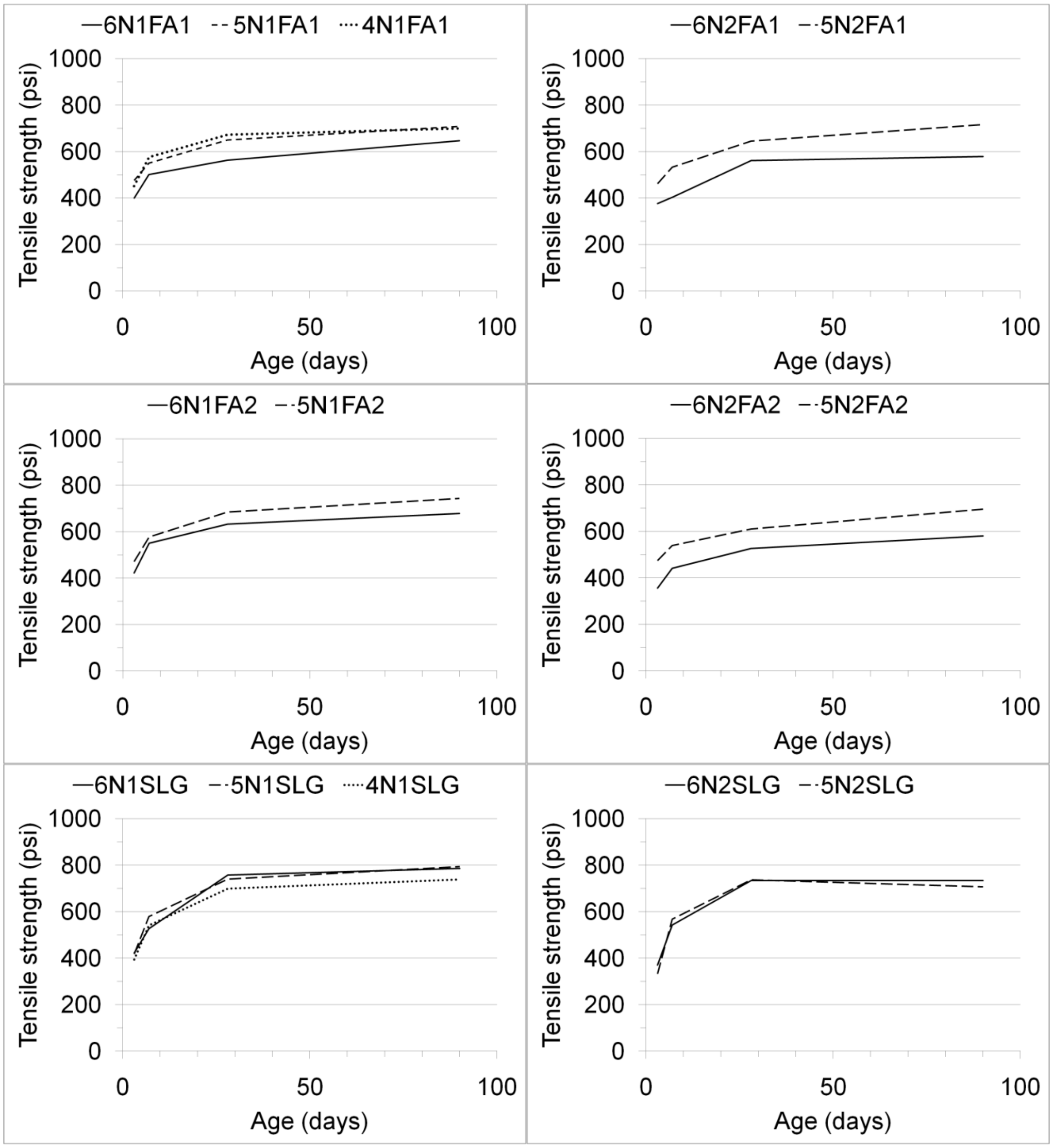

Figure 39: Tensile strength gain plots for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

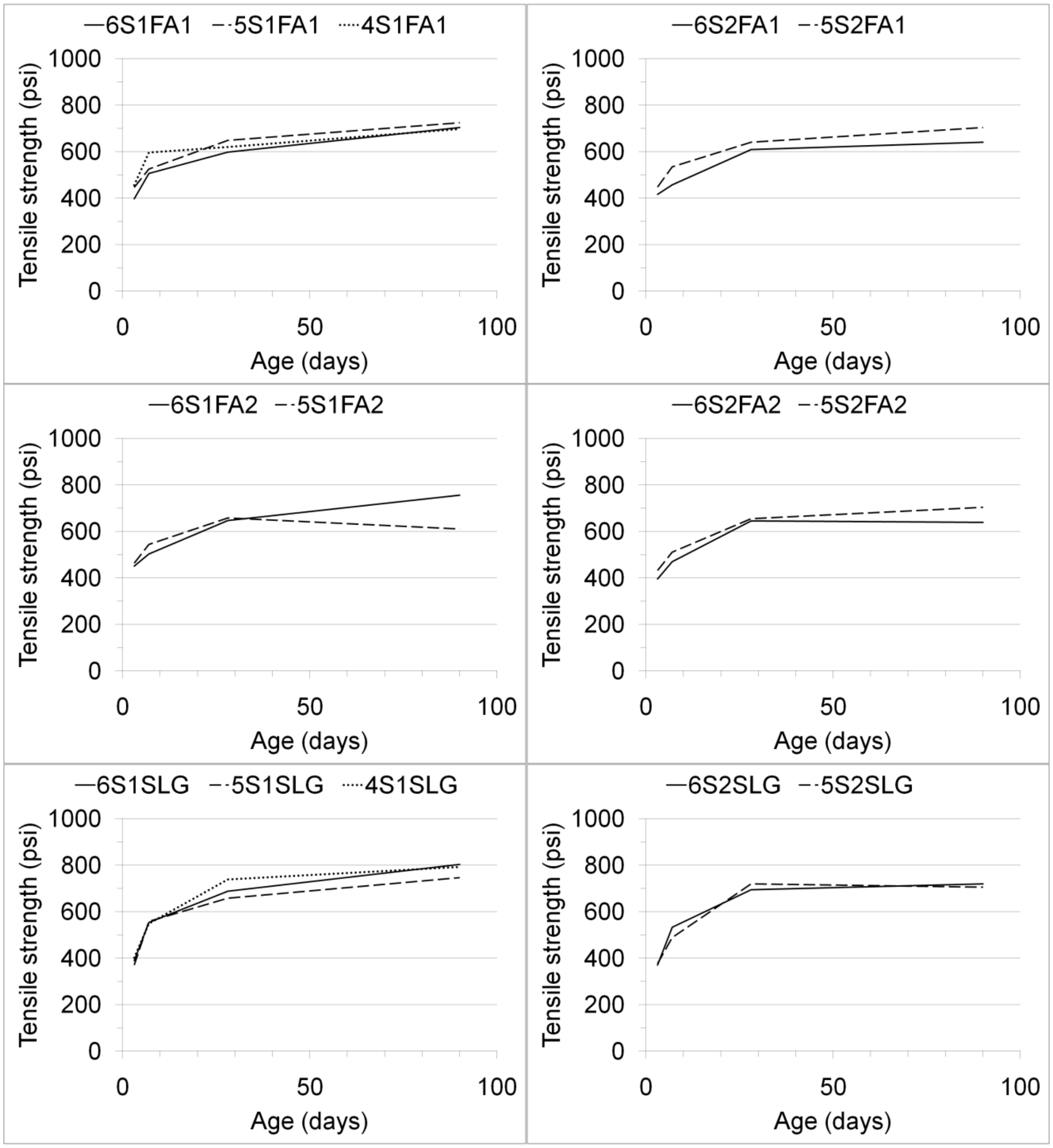

Figure 40: Tensile strength gain plots for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

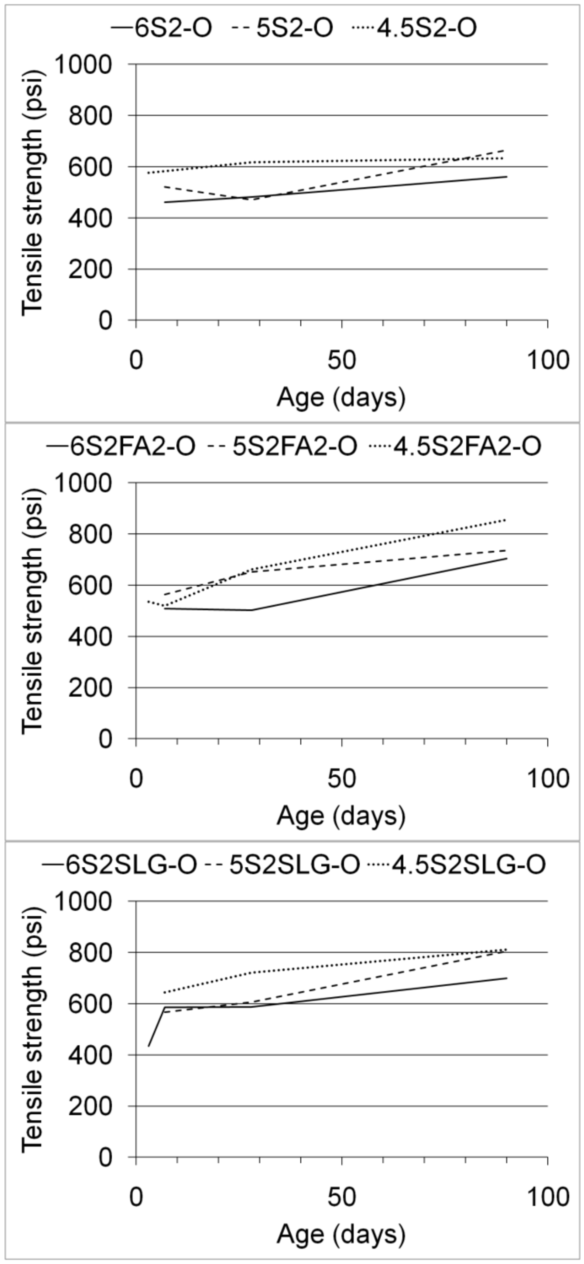

Figure 41: Tensile strength gain plots for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

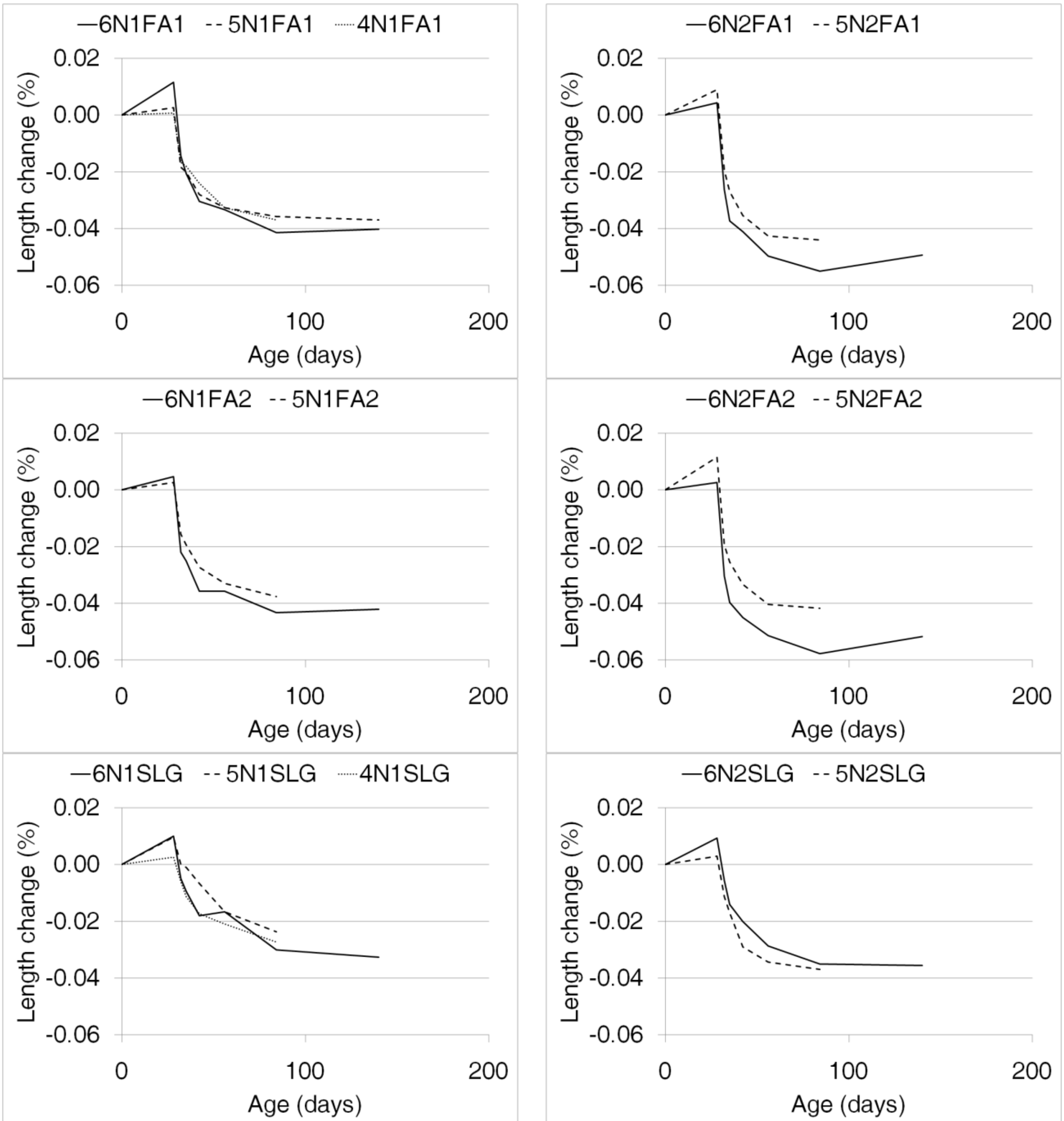

Figure 42: Shrinkage plots for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

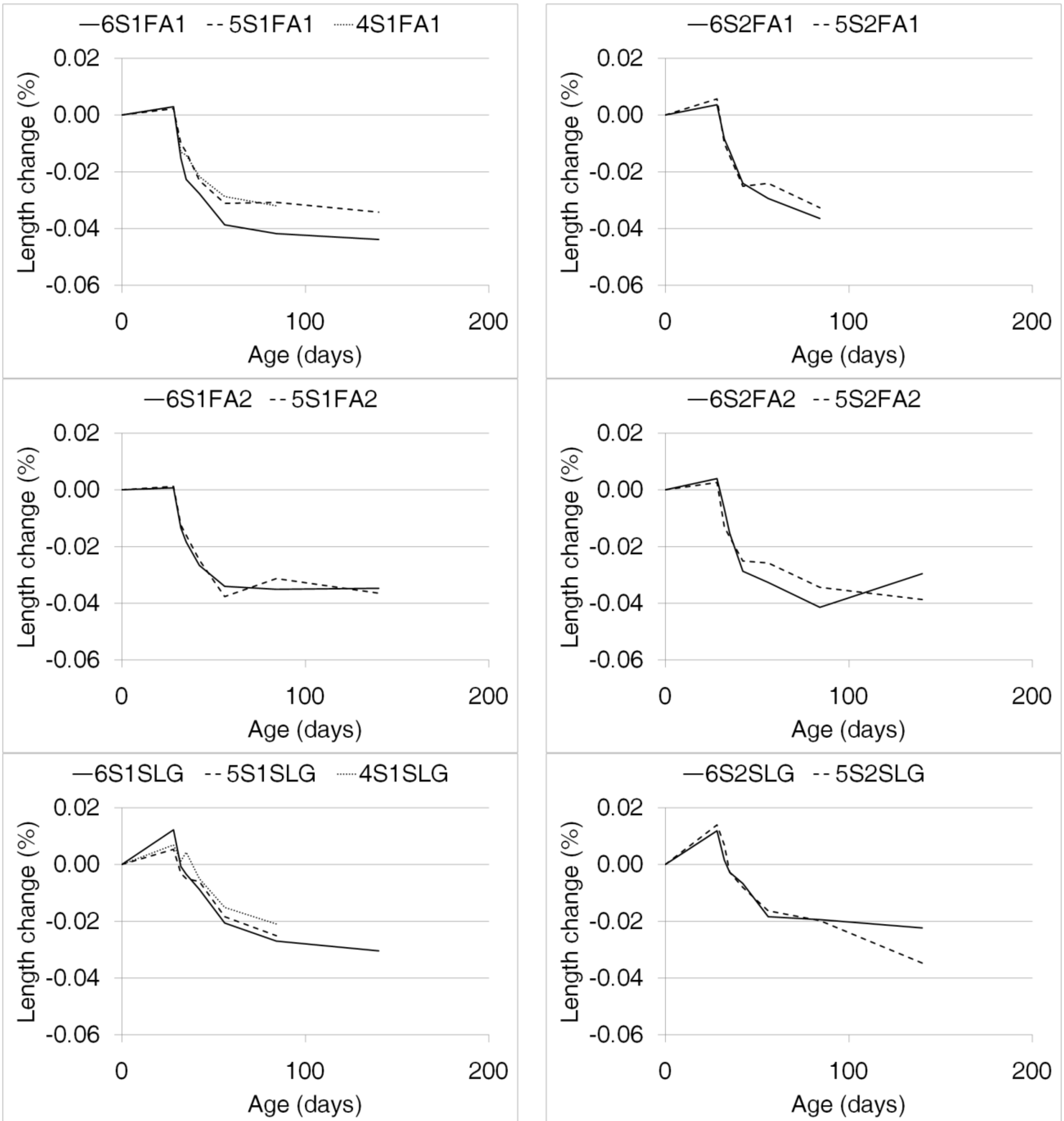

Figure 43: Shrinkage plots for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

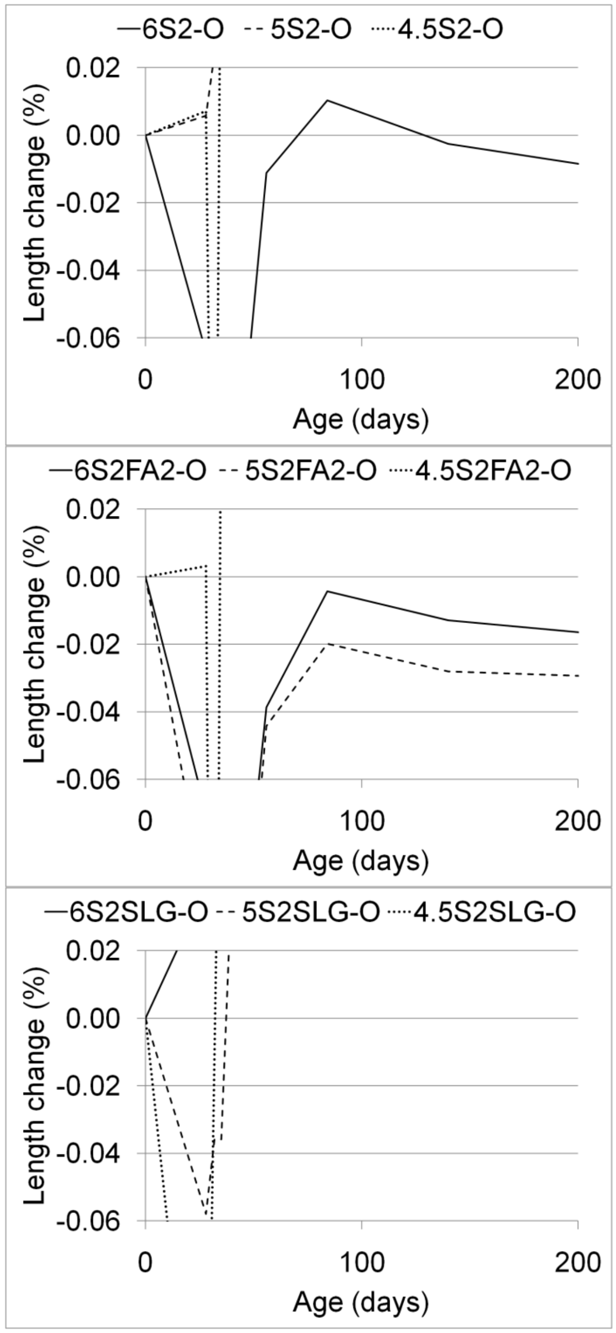

Figure 44: Faulty shrinkage plots for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

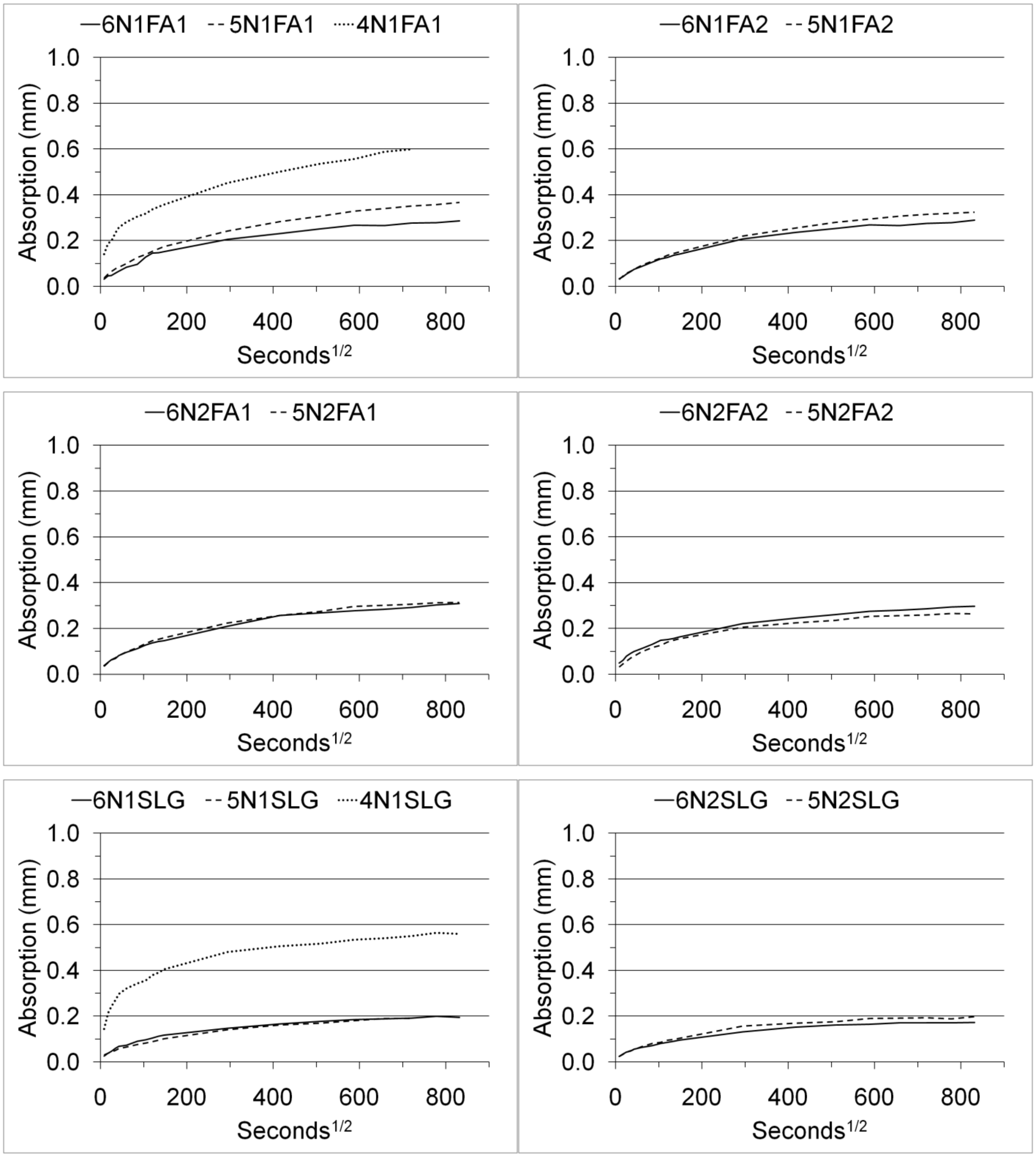

Figure 45: Sorptivity plots for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

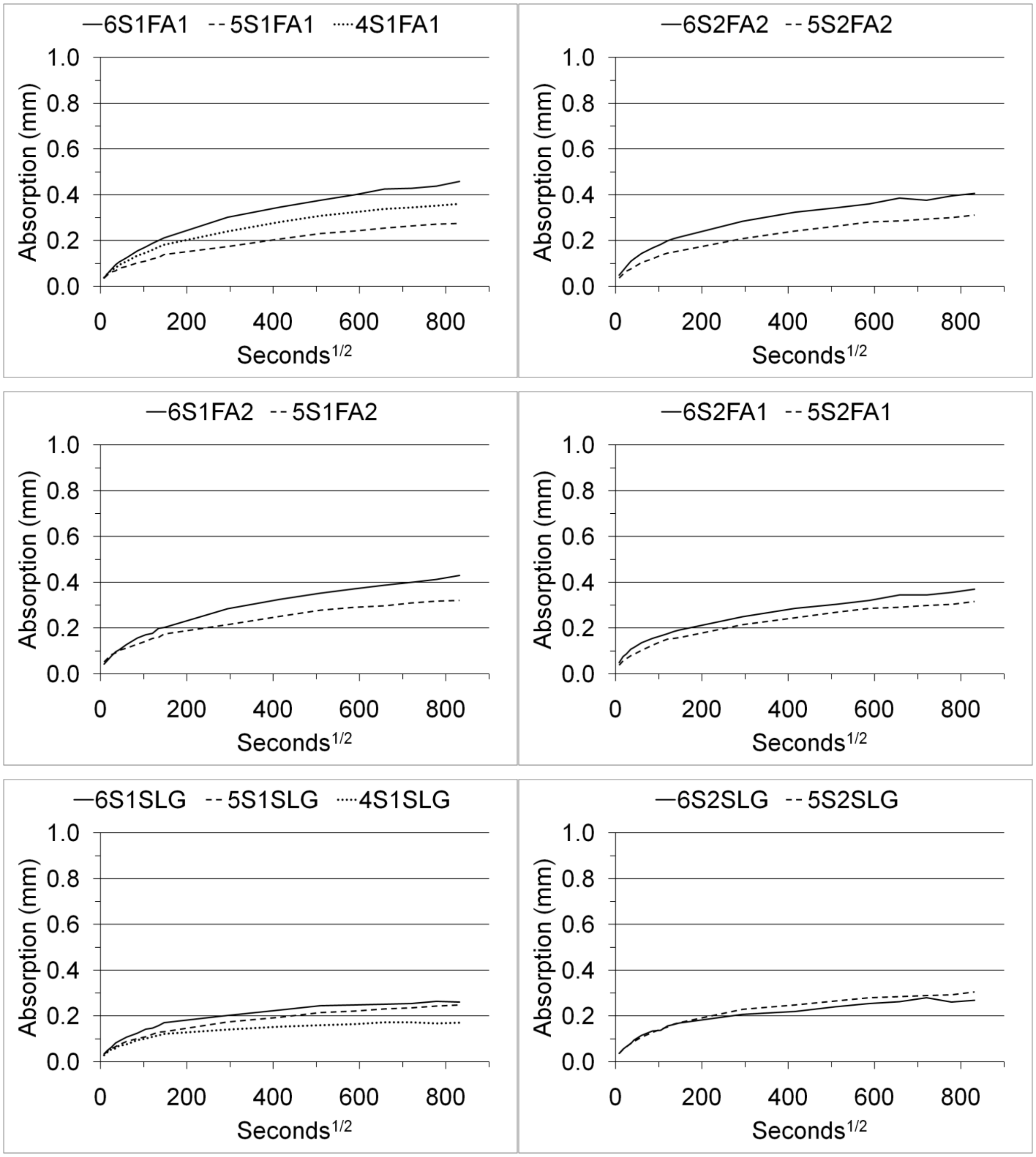

Figure 46: Sorptivity plots for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

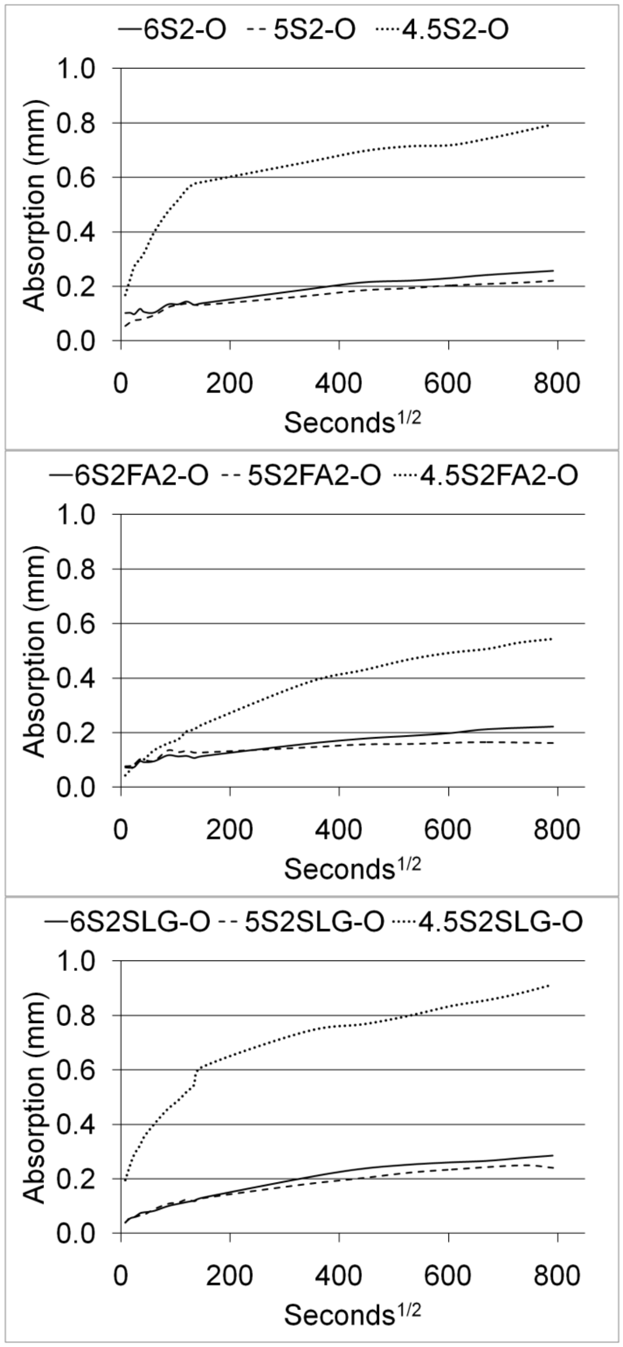

Figure 47: Sorptivity plots for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

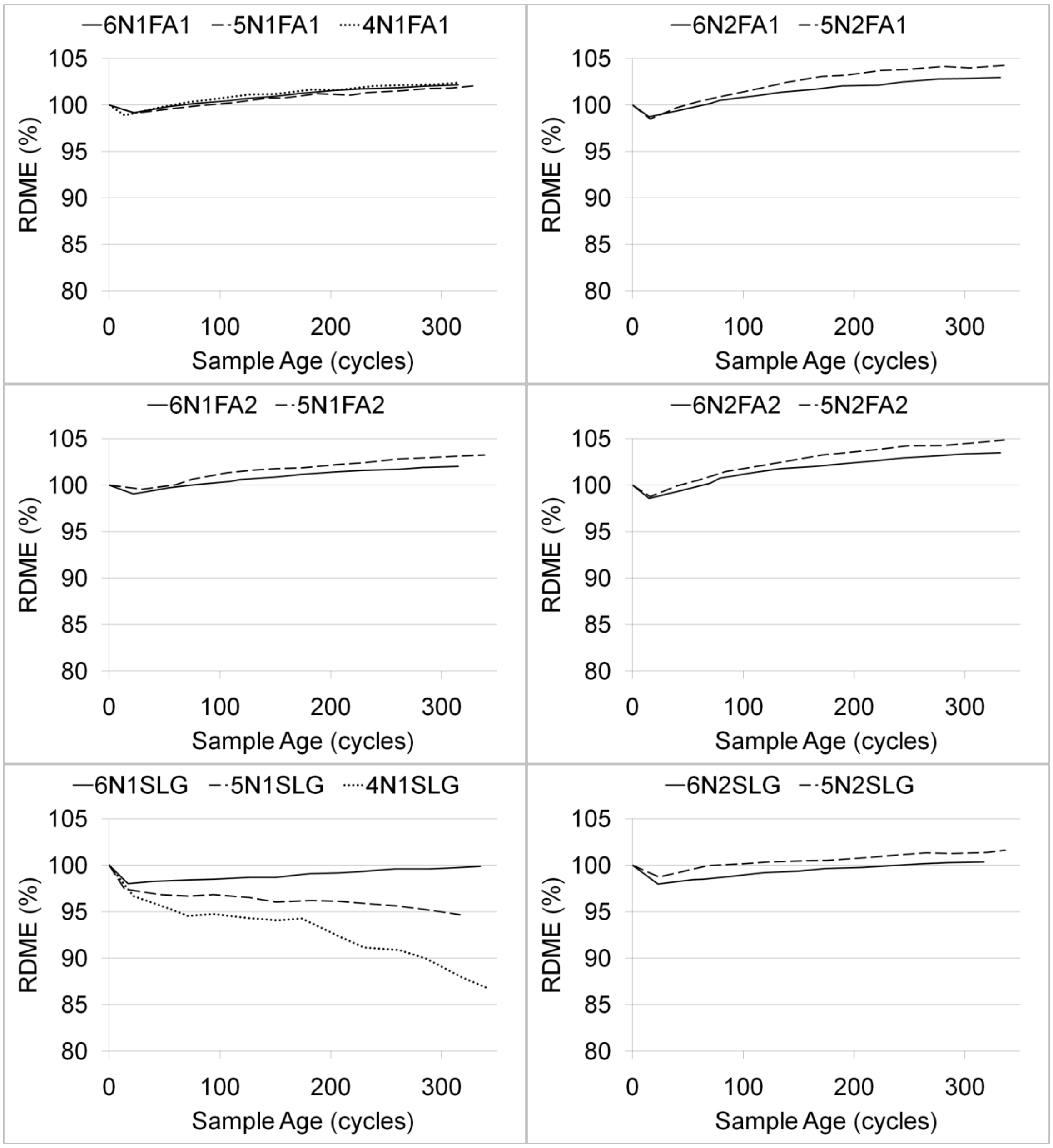

Figure 48: Plots to show changes in relative dynamic modulus of elasticity versus freeze-thaw cycles for the Phase 1 northern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

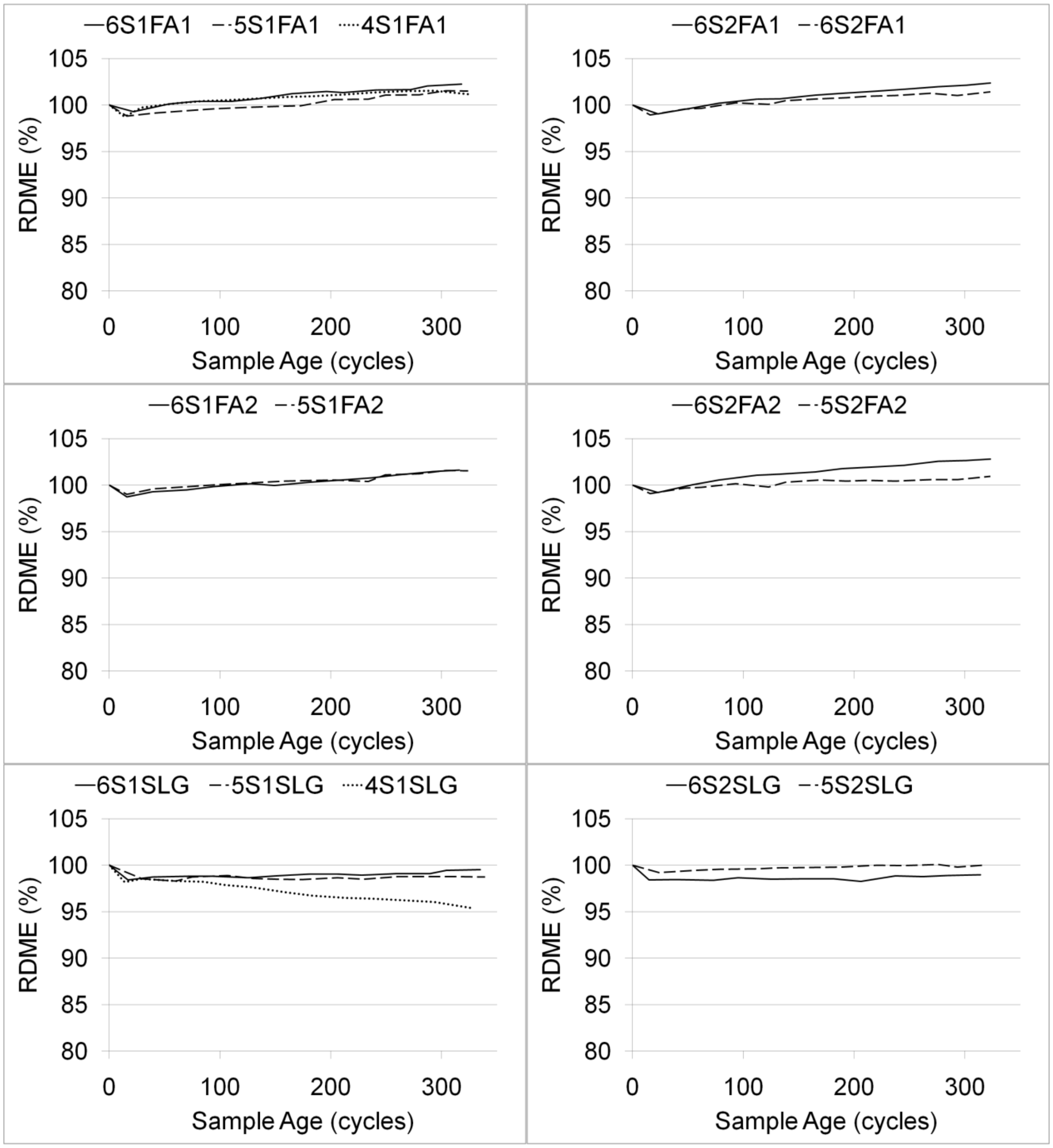

Figure 49: Plots to show changes in relative dynamic modulus of elasticity versus freeze-thaw cycles for the Phase 1 southern aggregate concrete mixtures. From left to right, mixtures with Lafarge and St Marys portland cement. From top to bottom, mixtures with Columbia fly ash, Weston fly ash, and GGBFS.

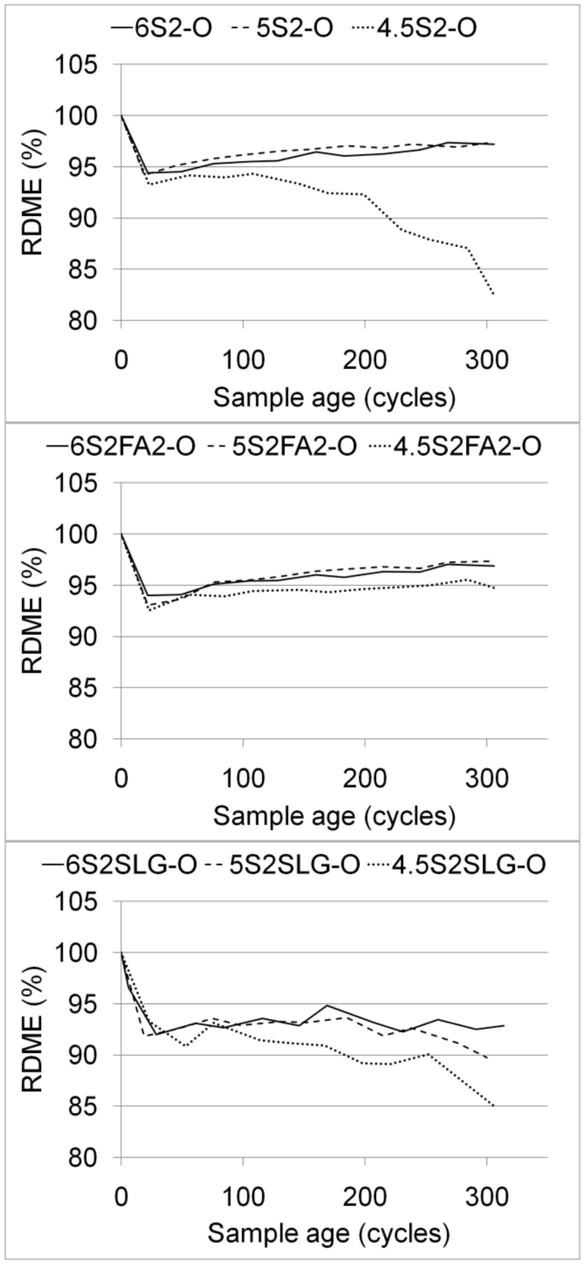

Figure 50: Plots to show changes in relative dynamic modulus of elasticity versus freeze-thaw cycles for the Phase 2 southern aggregate concrete mixtures. From top to bottom, mixtures with 100% St Marys portland cement, 30% Weston fly ash, and 50% GGBFS.

CHAPTER 4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Discussion and Conclusions

Workability issues were present in many of the reduced CMC (470 lbs/yd^3, 423 lbs/yd^3, and 376 lbs/yd^3) mixtures. The problem of harsh and difficult to consolidate mixtures at the lower CMC levels is evident in the slump test results of Table 4 and Figures 18-20, as well as in the test cylinder photos of Figures 21, 23, 28, 29, and 33. The effect of poor consolidation carried over into many of the hardened concrete tests. Reductions in compressive strength and tensile strength in Table 5 and Figures 36-38 and 40 can be attributed to the poor consolidation of test cylinders. Cylinders pulled for early age testing from batches that exhibited poor consolidation were selected based on the degree of observed consolidation issues: cylinders with fewer consolidation problems were tested first, cylinders with more pronounced consolidation issues were tested later. Batches with serious consolidation issues, such as the 376 lbs/yd^3 CMC batch containing northern aggregate, cement 1, and GGBFS (batch 4N1SLG) showed dramatically lower strengths than its higher-CMC counterpart.

The effects of poor consolidation also carried over into the test results for sorptivity and changes to the relative dynamic modulus of elasticity (RDME) versus freeze-thaw cycles, as shown in Figures 45, 47, 48 and 50. Sorptivity curves for batches with pronounced consolidation problems, specifically the Phase 1 batches with northern aggregate and cement 1 (batches 4N1FA1 and 4N1SLG) and the lower limit CMC Phase 2 batches (4.5S2-O, 4.5S2FA2, and 4.5S2SLG-0) exhibited much higher water uptake as shown in Figures 45 and 47. In spite of the consolidation issues, all of the batches performed adequately in terms of freeze-thaw durability, with durability factors (DF) greater than 80 at 300 cycles as listed in Table 7. Most of the mixtures maintained RDME values of 100% or greater as shown in Figures 48-50. Again, the mixtures with the worst consolidation problems, 4N1SLG and 4.5S2-O, both exhibited a considerable drop in RDME with increasing freeze-thaw cycles.

Consolidation issues also caused problems for the testing of air-void parameters of fresh concrete using the AVA. In several cases, fresh mortar samples from the harsh and difficult to work low-slump batches were impossible to obtain using the vibrating-cage sampling apparatus. Difficulties with the testing equipment were also experienced after inserting the mortar samples into the base of the AVA fluid-filled column. During proper operation, the magnetic stir-bar present at the base of the column disrupts the mortar, releasing air bubbles contained in the paste. In some cases, the magnetic stir bar had difficulty disrupting some of the stiffer mortars. In other cases, large air bubbles released from the mortar ascended the column and off-set the collection cup at the top, setting it askew, thereby allowing trapped air bubbles to escape the collection cup. The large air bubbles could also cause the collection cup to contact the side of the column, affecting the balance reading. Figure 51 plots spacing factor values from the successful AVA runs against DF. Although the trend is not very pronounced, the slope of the line is slightly negative, as would be expected, since higher values for spacing factor are associated with decreased F-T durability. Figure 52 plots the pressure meter air content values against DF. In Figure 52, the slope of the line is positive, but again the trend is not very pronounced. In Figure 52 it is interesting to note that the two worst performers in terms of DF also had the lowest air contents.

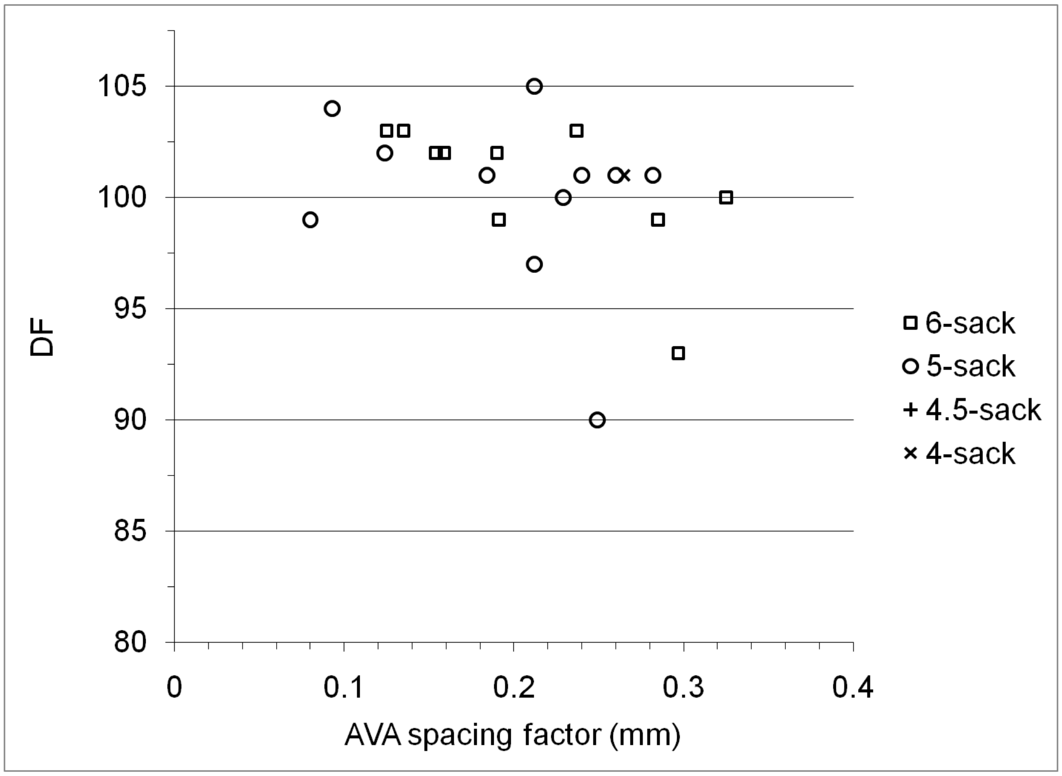

Figure 51: AVA spacing factor vs. DF.

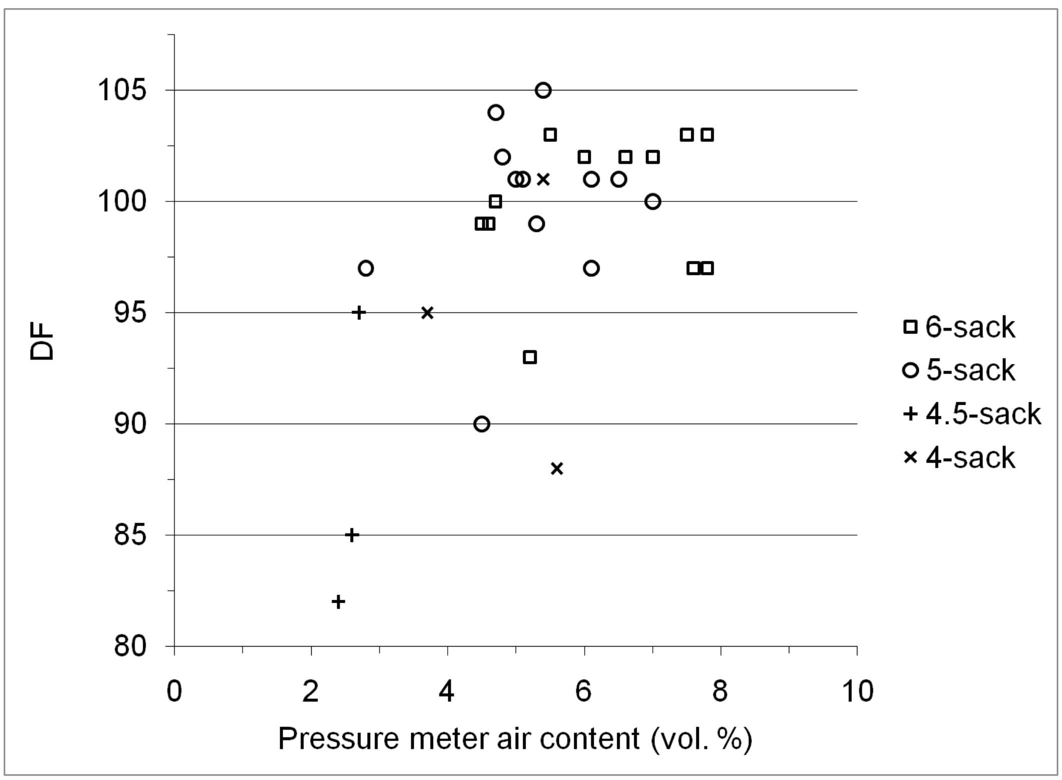

Figure 52: Pressure meter air content vs. DF.

Aside from consolidation issues, several other trends were observed. Using the 564 lbs/yd^3 CMC batches as a reference point, the 470 lbs/yd^3 CMC batches with northern aggregate and fly ash showed improvements in compressive and tensile strength on the order of 10-40% and 5-30% respectively, as is shown in Figures 36 and 39 and Table 5. This trend was also present for the southern aggregate batches, but not as pronounced in Phase 1, as shown in Figures 37, 38, 40, and 41. Again, using the 564 lbs/yd^3 CMC batches as a reference point, the 470 lbs/yd^3 CMC batches with GGBFS tended to show slight decreases in compressive and tensile strength. Exceptions to these trends were also observed, especially for batches with poor consolidation. Statements about trends for the 423 lbs/yd^3 and 376 lbs/yd^3 CMC mixtures are difficult to make since poor consolidation was a major influence in most cases. But, there was one very successful Phase 1 376 lbs/yd^3 CMC batch in terms of consolidation and strength: the southern aggregate, cement 1, fly ash 1 combination (batch 4S1FA1). There was also one successful Phase 2 423 lbs/yd^3 CMC batch in terms of consolidation and strength: the southern aggregate, cement 2, fly ash 2 combination (batch 4.5S2FA2-O). Although this Phase 2 batch measured 0" for slump, when vibrated, the mixture flowed and consolidated nicely.

In terms of drying shrinkage, with few exceptions, in Phase 1 the 564 lbs/yd^3 CMC batches experienced more shrinkage than the 470 lbs/yd^3 and 376 lbs/yd^3 CMC batches as shown in Figures 42 and 43. Furthermore, batches containing GGBFS tended to show less shrinkage than their fly ash batch counterparts. Similarly, as shown in Figures 46 and 47, the GGBFS batches experienced less water absorption during sorptivity tests as compared to their fly ash batch counterparts. For the southern aggregate batches, the 564 lbs/yd^3 CMC batches also tended to absorb more water during sorptivity tests as compared to the 470 lbs/yd^3 and 376 lbs/yd^3 CMC batches. However, this trend was not as evident in the northern aggregate batches. For Phase 2, the shrinkage data was faulty and unreliable, with wildly fluctuating length changes an order of magnitude higher than normal, as shown in Table 6 and Figure 44. In Phase 2, the differences between the sorptivity curves for the 100% portland cement, 30% fly ash, and 50% GGBFS mixtures were more subtle, but in all cases, the 423 lbs/yd^3 mixtures showed increased water absorption as compared to the 564 lbs/yd^3 and 470 lbs/yd^3 mixtures.

The semi-adiabatic calorimetry curves in Figures 16 and 17 indicated a slight delay in set for some of the low CMC mixtures. These delays could possibly be related to the elevated dosages of the water-reducing admixture used in these mixtures.

In conclusion, the research demonstrates that use of 470 lbs/yd^3 CMC mix designs can yield concrete mixtures that are workable and perform well in terms of strength and durability. For the most part, lower CMC levels (423 lbs/yd^3 and 376 lbs/yd^3) yielded difficult to consolidate concrete mixtures that did not perform well in terms of strength and durability, with the exception of two mixtures, both of which contained fly ash.

4.2 Recommendations

Based upon the results of this research it is recommended that the concrete proportions for WisDOT Grade A concrete be expanded to include mixtures with a CMC of 470 lbs/yd^3 (the current lower CMC limit for A3 concrete is 517 lbs/yd^3), and that additional categories be created for concrete containing fly ash and slag at the 470 lbs/yd^3 CMC level. Efforts to optimize or modify the coarse aggregate gradation beyond the prescribed WisDOT limits did not impart any benefits in terms of fresh concrete workability, therefore changes to the current coarse and fine aggregate WisDOT gradation limits are not recommended. The 470 lbs/yd^3 CMC mixtures produced in this study were within the current WisDOT recommended range of 30-40 for the percentage of fine aggregate (expressed as a percentage of the total weight of aggregate). The 470 lbs/yd^3 CMC mixtures produced in this study had a total aggregate weight, on average, of 3285 lbs/yd^3, and covered a range of 3267 to 3329 lbs/yd^3. The 470 lbs/yd^3 CMC mixtures produced in this study had an average design water content of 23.4 gal/yd^3, and covered a range of 22.6 to 25.4 gal/yd^3.

It is not recommended that the CMC be reduced further than 470 lbs/yd^3 given the potential for poor workability and lower durability in the 423 lbs/yd^3 and 376 lbs/yd^3 CMC concrete mixtures. However, successful 423 lbs/yd^3 and 376 lbs/yd^3 CMC concrete mixtures in terms of workability, strength, and durability were produced in this study, and are worthy of additional investigation.

Interpretations of the F-T performance of the concrete produced in this study were complicated due to incomplete information about the air-void parameters, as the harsh low CMC concretes were difficult to sample with the AVA equipment. An alternative approach utilizing ASTM C457 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" could provide the relevant spacing factor information that was missing for the 423 lbs/yd^3 and 376 lbs/yd^3 concrete mixtures.

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