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EFFECT OF PORTLAND CEMENT (CURRENT ASTM C150/AASHTO M85) WITH LIMESTONE AND PROCESS ADDITION (ASTM C465/AASHTO M327) ON THE PERFORMANCE OF CONCRETE FOR PAVEMENT AND BRIDGE DECKS

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Testing of Portland Cement (Current ASTM C150) with Limestone and Process Addition (ASTM C465)

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16. Abstract

The Illinois Department of Transportation (IDOT) is making several changes to concrete mix designs, using revisions to cement specification ASTM C150/AASHTO M85 and ASTM C465/AASHTO M327. These proposed revisions will enable the use of more sustainable materials for concrete pavements, overlays, and bridge decks. Accordingly, a study was conducted by the University of Illinois at Chicago (UIC) to test the performance of concrete mixes batched with cement comprising less (conventional) and more (modified) than 5% by weight of limestone and inorganic processing additions (IPA) specified in ASTM C465/AASHTO M327, and/or insoluble residue (IR) with quantity above the specified limit by ASTM C150.

Twenty-four concrete mixes with different cementitious combinations and aggregates were developed for this study. Each cement source was batched in a concrete mixture by replacing 30% of the total cement content with supplementary cementitious materials (SCMs), fly ash, or slag. Also, each cementitious combination was batched with fine aggregates (either natural or combined sand) and coarse aggregate (crushed limestone).

The study included measuring fresh properties such as the slump, air content, unit weight, and setting time. The hardened properties included measuring the strength and durability for each concrete mix combination. The strength results were measured in terms of compressive and flexural strength, and the durability results were measured in terms of rapid chloride penetration resistance (coulombs), water permeability (DIN 1048), chloride ion penetration, and freeze/thaw tests of the concrete mixes.

The study found similar performance in terms of strength and durability of concrete between the conventional and modified cements and demonstrated their performance with SCMs replacements and fine aggregate types.

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ABSTRACT

The Illinois Department of Transportation (IDOT) is making several changes to concrete mix designs, using revisions to cement specification ASTM C150/AASHTO M85 and ASTM C465/AASHTO M327. These proposed revisions will enable the use of more sustainable materials for concrete pavements, overlays, and bridge decks. Accordingly, a study was conducted by the University of Illinois at Chicago (UIC) to test the performance of concrete mixes batched with cement comprising less (conventional) and more (modified) than 5% by weight of limestone and inorganic processing additions (IPA) specified in ASTM C465/AASHTO M327, and/or insoluble residue (IR) with quantity above the specified limit by ASTM C150.

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ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of ICT-R27-112, **Effect of Portland Cement (Current ASTM C150) with Limestone and Process Addition (ASTM C465) on the Performance of Concrete for Pavement and Bridge Deck**. ICT-R27-112 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation, Division of Highways; and the U.S. Department of Transportation, Federal Highway Administration.

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EXECUTIVE SUMMARY

The addition of limestone and alternative raw materials to cement to reduce CO_2 emissions in the cement production and concrete industries has been used in Europe for decades, with quantities up to 35% replacement of cement by weight. The Canadian Standards Association (CSA A3000) recently approved the addition of limestone in cement up to 15% by weight. The success in modifying cement production in both Europe and Canada prompted the United States to move toward a more sustainable approach in the cement production and concrete industries. The current ASTM C150/AASHTO M85 and ASTM C465/AASHTO M327 specifications state that the maximum limestone and inorganic processing addition (IPA) of cement is limited to 5% by weight.

The Illinois Department of Transportation (IDOT) is pushing forward in its efforts to modify the ASTM specifications to approve the use of limestone and IPA with more than 5% replacement of cement by weight. If this modification is approved, it will have both an environmental and economic impact on the concrete industry in the United States.

From a sustainability standpoint, cement production is energy intensive and harmful to the environment because of the high temperatures required to burn the raw materials and also because of the emission of gaseous by-products in that process. On average, each ton of cement produced from a cement plant accounts for 0.92 tons of CO_2 emissions (Marceau et al. 2006).

The emission of CO_2 and other gases from cement production is attributed primarily to the calcination process of limestone and fuel combustion. Calcination is necessary in the process of cement production and now it accounts for more than 60% of total CO_2 emissions (Marceau et al. 2006). The process of crushing limestone rocks to produce aggregates and the ruins of demolished buildings produce materials that are classified as waste and considered a burden on the environment.

The addition of more than 5% limestone and IPA to cement, as proposed by IDOT, will mitigate some environmental problems by reducing the amount of raw materials burned to produce cement and to reduce the carbon footprint by at least 3% to 4% of total CO_2 emissions. The modification will also help reduce the depletion of natural resources and will offer a low-cost, efficient method to secure waste materials.

For this purpose, a study was conducted at the University of Illinois at Chicago (UIC) to test the performance of concrete mixes batched with cement comprising less than 5% as well as more than 5% by weight of limestone and IPA. In addition, the effect of insoluble residue (IR) was evaluated with cement comprising 0.75% and 1.5% of IR, respectively. The results of this study can be used to help ensure a broader pool of cement supplies, thereby enhancing competition and lowering costs. It is also hoped that Portland cement manufactured under the new ASTM C150/AASHTO M85 specifications will produce a “greener,” more environmentally friendly product. Accepting and optimizing the use of these cements in IDOT-specified concrete mixtures will help the department continue its implementation of the principles of the IDOT *Driving Towards Sustainability* program, which was introduced by then–IDOT Secretary Gary Hannig in 2010.

Two sources of cement were procured. Each cement source provided cement with less and more than 5% of limestone and IPA (Cem1 and Cem3) and in accordance with ASTM C465. Ground, granulated blast furnace slag was used as IPA for cement with more than 5% limestone and IPA. One cement source (Cem1) was blended with fly ash to produce cement (Cem2) with 0.75% and 1.5% IR, respectively.

Each cement source was batched in a concrete mixture by replacing 30% of the total cementitious materials content (CMC) with supplementary cementitious materials (SCMs), fly ash, or slag. Twenty-four concrete mixes with different cementitious combinations totaling 535 lb/yd^3 (375 lb/yd^3 cement and 160 lb/yd^3 slag or fly ash) and aggregates were developed for this study. Also, each cementitious combination was batched with fine aggregates (natural or combined sand) and coarse aggregate (crushed limestone).

The concrete mixes were batched according to ASTM C192/AASHTO T126. The 24 concrete mixes were proportioned using IDOT PCC Mix Design Version V2.1.2. based on 1 yd^3. Several trial batches of 1 to 3 ft^3 were made for each mix and were calibrated to yield 5 to 8% of air content and approximately 3.5 in. slump. Fresh properties were determined for each mix based on the measurement of slump, unit weight, and air content (pressure meter) as well as the setting of times, concrete- mix temperature, and ambient temperature. Hardened properties were also determined based on the evaluation of strength and durability. Each mix required 18 ft^3 of fresh concrete, divided into three batches of 6 ft^3, to produce cast specimens for studying strength and durability: The first batch produced cast specimens for compressive strength, the second batch produced cast specimens for flexural strength, and the third batch produced cast specimens for the durability study. The acceptance criteria for each batch were based on the specified values for air content and slump. The batches that did not meet any of the specified values were rejected and replaced with new ones.

Strength results were measured in terms of compressive and flexural strength, and durability results were measured in terms of rapid chloride penetration resistance (coulomb), water permeability (DIN 1048), chloride ion penetration, and freeze/thaw tests.

The compressive and flexural strength test results for the 24 concrete mixes exceeded IDOT's minimum target strength at 14 day. The water permeability and rapid chloride penetration tests were within acceptable limits. However, none of the concrete mixes met IDOT's minimum target for chloride ion concentration at 90 and 180 days based on the salt ponding test. Some specimens failed to pass the freeze/thaw test because of inadequate, hardened entrained air content.

Overall, the limestone and IPA added to cement and/or the increase in IR content showed acceptable performance in concrete. The compressive and flexural strength results for concrete mixes made with more or less than 5% by weight of limestone and IPA were similar and showed insignificant variation. The durability results for permeability and freeze/thaw were comparable regardless of the concrete mixes compliance with IDOT's specifications. Moreover, the results demonstrated the performance of the 24 concrete mixes with the SCMs and fine aggregate sources (natural or combined sand) used.

Recommendations were made regarding the level of CMC used in the concrete mix in order to maintain adequate strength at an early age (3 and 7 day) and to secure minimum, hardened entrained air content to resist the freeze/thaw attack.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

The Illinois Department of Transportation (IDOT) is making several changes to concrete mix designs, using revisions to cement specification ASTM C150/AASHTO M85 and ASTM C465/AASHTO M327 for the new IDOT Standard Specifications book. These proposed revisions may impact the department and the concrete industry. The addition of more than 5% limestone and IPA and the increase in IR content above the specified limit by ASTM C150 (current max. 0.75% IR) require strength and durability testing of concrete mixes using common cements with less than 5% and cements with more than 5% limestone and IPA, and/or with more than 0.75% IR. The results of the strength and durability testing, in terms of concrete compressive and flexural strength, rapid chloride penetration resistance (coulomb), water permeability, chloride penetration, and freeze/thaw tests, for both concrete mixes are compared and evaluated.

1.2 RESEARCH OBJECTIVES

This research project is conducted to develop economical concrete mixes for providing sustainable and durable concrete paving solutions to IDOT and the concrete industry. However, IDOT is concerned with the field performance of the new mix designs upon the addition of more than 5% IPA and limestone, and/or adding more than 0.75% of IR. Adequate strength and early strength gain are also considered a source of concern to the department. Because of the lack of experimental test data for concrete with IDOT mix designs using more than 5% limestone and IPA and/or more than 0.75% IR, an experimental investigation must be conducted to assess the strength gain, ultimate strength, and durability characteristics of concrete mixes containing Portland cements with more than 5% limestone and IPA, and/or with IR exceeding 0.75% in combination with SCMs. Therefore, the main objective of this project is to evaluate the strength and durability properties of the IDOT concrete mixes with 535 lb/yd^3 CMC when the Portland cement contains more than 5% limestone and IPA and/or more than 0.75% IR for the purpose of accepting and recognizing current ASTM C150/AASHTO M85 revisions and for ensuring that implementation of these revisions will not affect the performance of the economical concrete used by the department.

The concrete mix design contains 375 lb/yd^3 Portland cement which is the minimum content required, and 160 lb/yd^3 Grade 100 slag or 160 lb/yd^3 class C fly ash, 0.40 to 0.44 w/cm by weight, depending on the mix proportion, freeze/thaw-resistant aggregates, and a mortar factor of 0.88.

The selection of 375 lb/yd^3 of cement and 160 lb/yd^3 of Slag or Fly Ash are based on a ternary mix study conducted in April 15, 2008 at IDOT District 1, Schaumburg. Four concrete mixes with different cementitious combinations were batched by Meyer Material using Holcim Clarksville IS cement. The study included testing for the following:

- Slump (IL Modified AASHTO T119)
- Air Content (IL Modified AASHTO T152)
- Compressive Strength (IL Modified AASHTO T22)
- Flexural Strength (IL Modified AASHTO T177)
- Freeze/Thaw (IL Modified AASHTO T161 Procedure B)
- Salt Scaling (IL Modified ASTM C 672)

The concrete mix properties, with the test results are presented in Table 1-1 below.

Table 1-1 Mix Design and Test Results for District 1 Schaumburg Ternary Mix Study

Mix and Test Properties		**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**
Cement, lb/yd^3		428	364	364	344
Slag, lb/yd^3		107	91	91	86
Fly ash, lb/yd^3		—	80	120	110
Total CMC, lb/yd^3		**535**	**535**	**575**	**540**
W/CM		0.41	0.41	0.41	0.41
Slump, in.		1.75	3	6	3.5
Air Content, %		5.5	6.4	6.7	6.2
Compressive Strength, psi	**3 Day**	3810	3280	3053	3233
	7 Day	4467	4336	4402	4423
	14 Day	4950	5000	4963	5453
Flexural Strength, psi	**3 Day**	705	630	600	653
	7 Day	785	740	668	755
	14 Day	858	850	890	875
Durability Factor at 300 Cycles Freeze/Thaw (ASTM C666, Procedure B)		85	79.5	80.3	70.9
Salt Scaling (ASTM C672)		1.8	1.8	1.4	1.6

The measured parameters of this study are the fresh and hardened properties and durability aspects of the concrete mixes. The fresh properties of concrete are based on 2 to 4 in. (3.5 in.) slump, 5% to 8% (6.5%) air content, unit weight, initial and final setting time of concrete, concrete and ambient temperature, and humidity. The hardened properties of concrete, on the other hand, are based on compressive and flexural strength, hardened air void system parameters, cyclic freezing and thawing durability, rapid chloride ion permeability (coulomb permeability), salt ponding and penetration test, and water permeability test.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

The studies done on adding IPA to cement were very limited for this research. The only comprehensive work found was the NCHRP Report 607 (Specifications and Protocols for Acceptance Tests on Processing Additions in Cement Manufacturing). Therefore, the literature review focused on studies investigated the addition of limestone to cement by either blending or intergrinding.

This review incorporates the studies that were conducted to investigate the use of alternative raw materials, such as limestone, and industrial by-products, such as slag or fly ash, to replace cement. Most studies were conducted in Europe and Canada to document the performance of Portland cement when replaced by alternative materials having different quantities and different properties. Studies that were conducted in Canada were initiated after the Canadian Cementitious Materials Compendium CAN/CSA A 3000 adopted the use of up to 15% Portland-limestone cement.

This literature review documents the performance of added raw materials to cement in the fresh and hardened stage of cement paste and concrete. The fresh properties include the effect on workability, fresh air content, and setting time. The hardened properties include the effect on strength and durability.

2.2 EFFECT OF ADDING LIMESTONE AND ALTERNATIVE CEMENTITIOUS MATERIALS TO CEMENT ON THE FRESH PROPERTIES OF CONCRETE

This section provides a review on the effect of adding limestone to cement on the fresh properties of concrete mixtures. The fresh properties of the materials used in the project include the measurement of workability (slump) and setting time of concrete. The studies conducted in Canada and Europe revealed conflicting results because the results were influenced by the Blaine fineness of Portland-limestone cement, the method adopted to add limestone to cement, the amount of SCMs replacement, the type and gradation of aggregates, and the type of chemical admixtures used.

2.2.1 Workability

Studies show inconsistent results for the effect of limestone addition on the workability of cement and concrete. Most studies focus on the effect of the Blaine fineness of limestone and their particle size distribution with respect to the cement. Mathews (1994) observed that a higher water to cement ratio was needed to maintain the desired slump after the addition of the limestone. It was reported that an approximate 0.01 increase in w/cm ratio was needed for cement with less than 5% limestone addition while 0.02 increase in w/cm ratio was needed for cement with less than 25% limestone addition. Bonavetti et al. (2003) proved that the addition of limestone reduced workability as a result of administering more admixtures to get the desired slump. In contrast, Schmidt et al.(1993) found that the addition of limestone to cement with 13% to 17% content resulted in reducing the water cement ratio in comparison with regular Portland cement from 0.60 to 0.57.

Other studies failed to observe major changes in the slump as a result of limestone addition. Bucher et al. (2008) reported that concrete mixtures produced with conventional Portland cement and with cement containing 10% interground limestone showed insignificant changes in the slump reading. Hooton and Thomas (2009), who investigated concrete mixtures with regular cement content and with cement including 12% limestone content, reported that the mixtures did not show any difference in their fresh properties, including workability, bleeding, and finishing.

2.2.2 Setting Time

Most studies showed that the initial and final setting of cement are influenced by the fineness and amount of limestone added to cement.

Vuk et al. (2001) reported that initial and final set times decreased with the increase of fineness. Hooton et al. (2007) reported that cement with finer limestone set faster than regular cement. Tsivilis et al. (1999a) found that the addition of finer limestone resulted in decreasing the setting time. In contrast, the study conducted by Moir and Kelham (1997) showed that the replacement of cement by 20% limestone with increased fineness prolonged the setting time.

On the other hand, El-Didamony et al. (1995) reported that the addition of a low quantity (up to 5%) of limestone to cement increased the setting time while the addition of higher quantities of limestone resulted in decreasing the setting time. Heikal et al. (2000) reported that the replacement of cement with up to 20% limestone having the same Blaine fineness resulted in decreasing the setting time. Bucher et al. (2008) also observed a decrease in the time set in cement having 10% limestone content. Mounanga et al. (2010) observed that the addition of limestone as filler reduced the setting time for concrete containing fly ash and blast furnace slag. On the other hand, a study conducted by Tsivilis et al. (2000) showed an increase in set time as a result of an increase in limestone content. Ezziane et al. (2010) also reported that the blended addition of limestone to cement increased the set time in mortar. Other studies, such as Hooton and Thomas (2009), reported that no correlation was found between the addition of limestone to cement and the setting time of field concrete mixtures.

2.3 EFFECT OF ADDING LIMESTONE AND ALTERNATIVE CEMENTITIOUS MATERIALS TO CEMENT ON THE HARDENED PROPERTIES OF CONCRETE

2.3.1 Compressive and Flexural Strength

The effect of adding limestone to cement on the strength of concrete has been attributed to the quality and quantity of limestone used, production method, i.e. whether limestone was blended or interground with cement, distribution of cement particle size and shape, limestone and cement Blaine fineness, and addition of other cementitious and pozzolanic materials.

Studies investigating the addition of limestone to cement explored the strength of cement paste and concrete. Schiller and Ellerbrock (1992) conducted a study on cement containing 0, 10, and 20% limestone by mass. It was observed that in order to achieve 50 MPa (7250 psi) strength at 28 days with cement with limestone, the equivalent amount coarser than 30 μm for plain cement should be coarser than 26 μm for cement with 10% limestone and 14 μm for cement with 20% limestone. Sprung and Seibel (1991) found that replacing cement with limestone having up to 10% fineness would result in a strength increase because of improved particle distribution. The increase is noticed at early ages but will not improve long-term strength development. Sprung and Seibel (1991) also concluded that using large quantities of limestone would cause a reduction in strength because of the dilution effect; however, this setback could be compensated by increasing the fineness in the limestone cement. Similarly, Schmidt (1992a) concluded that cement with 5% to 10% limestone had little effect on strength reduction compared with regular cement. Another major study conducted by Tsivilis et al. (1999a) showed the results of compressive strength of cement produced from two different clinkers, with four different levels of Blaine fineness each and with limestone contents ranging from 5% to 35%. In this study, it was observed that cement with up to 10% limestone content having cement fineness up to a limit value showed insignificant strength reduction compared with pure cement while cement with higher limestone contents resulted in lower strength regardless of its fineness.

Kiattikomol et al. (2000) studied the effect of adding insoluble residue (IR) on the strength properties of concrete. Portland cement type I was prepared with 0%, 0.5%, 1.0%, 1.5%, 2.0%, 3.0%, 5.0%, and 7.0% replacement of IR by weight and with similar particle size distribution and shape of cement. Figure 2-1 shows a relationship between the compressive strength at different ages and the IR added to the cement. The results showed a strength drop ranging from 2% to 9.5% at 3 day, and 1.2% to 5.5% at 60 days for cement with 0.5% to 7% IR. It is therefore concluded that the higher the IR content, the lower the compressive strength. However, it was observed that the cement with the highest IR had a compressive strength exceeding the ASTM C150 limits at all ages, which limits the amount of IR to 0.75%.

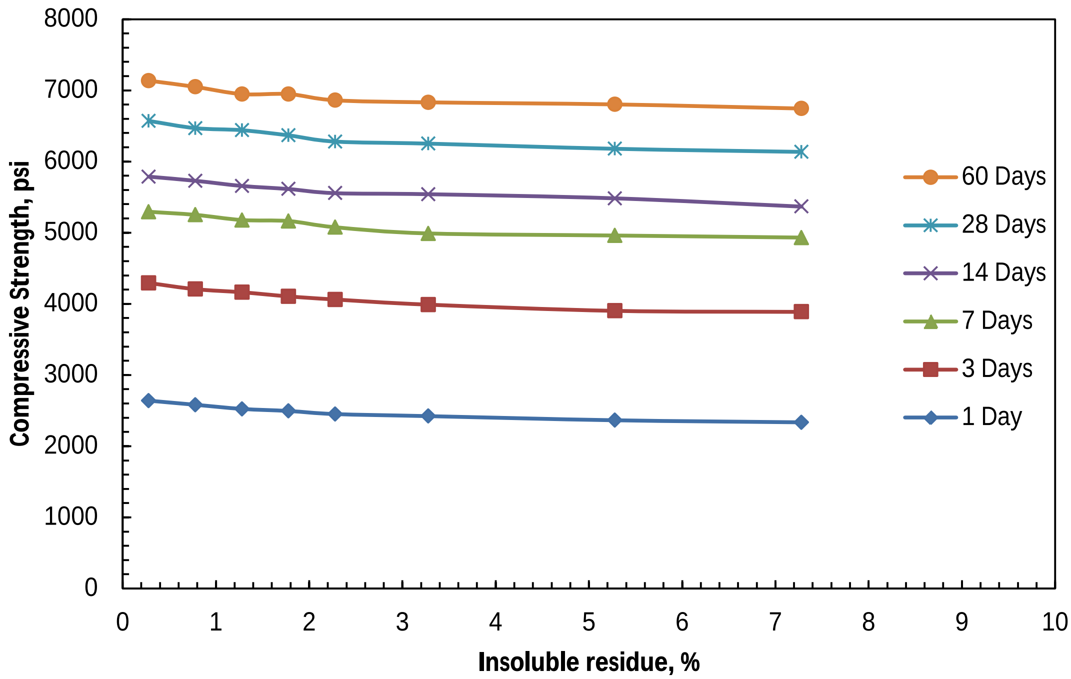

Figure 2-1 Effect of insoluble residue addition on compressive strength (Kiattikomol et al. 2000).

Studies showed a similar performance between strength development in concrete with limestone cement and strength development in cement paste with limestone. Bonavetti et al. (2003) observed that concrete with cement containing limestone showed better early strength than concrete made with plain cement at 7 days for cement with 10% limestone and 3 days for cement with 20% limestone, knowing that strength reduction was noticed after 28 day. Bonavetti et al. (2003) attributed the strength variation to the gel-space ratio concept: “The compressive strength of concrete depends on the effective w/cm ratio and the degree of hydration of cement. For the same Portland cement composition, the addition of filler creates changes in both gel–space ratio terms”. Irassar et al. (2001) tested the compressive strength of concrete mixtures with cement containing 0, 9, and 18% limestone by mass. The study showed that the limestone filler improved the early strength of the mixes, but reduced the long-term strength because of the high fineness of the limestone cement. It was also observed in the same study that the use of blast furnace slag (20 % replacement by mass) improved the long-term strength of concrete. Dhir et al. (2007) evaluated the use of Portland-limestone cement in concrete construction. The study showed that for every 10% limestone added to cement, a reduction of 0.08 in the w/cm ratio of concrete mix was needed to attain the same strength with respect to Portland cement.

In addition to the studies mentioned above, three major studies were recently published in Canada to study the effect of limestone addition on strength development in concrete. The studies, which were conducted by Thomas et al. (2010a), Thomas et al. (2010b), and Hooton et al. (2010), are discussed in Section 2.5.

Most studies focusing on the tensile and flexural strength showed strength variation and development similar to compressive strength because of the addition of limestone to cement.

2.4 EFFECT OF ADDING LIMESTONE AND ALTERNATIVE CEMENTITIOUS MATERIALS TO CEMENT ON THE DURABILITY PROPERTIES

2.4.1 Permeability

The permeability in concrete is mainly related to the pore structure, the size of pores, and the connectivity between pores in concrete. Deterioration of concrete structures is strongly related to its permeability. For example, corrosion in steel embedded in concrete is caused by the penetration of water, oxygen, and chloride ions. Freezing and thawing cycles are more hostile when concrete is saturated. Alkali-silica reactivity (ASR) and sulfate attack could be prevented by improving the porous structure and permeability in concrete. As a result, low permeability is required in aggressive environments to support longevity of concrete structures. Studies show that the effect of adding limestone and alternative materials to cement on permeability varies according to their particle size distribution and fineness and the addition of SCMs.

Moir and Kelham (1993) studied the permeability of oxygen in concrete with cement containing 0, 5, and 25% limestone. The results indicated a slight reduction in permeability caused by the addition of limestone. No difference was observed in the porosity and sorptivity for concrete with control and 5% limestone cement. Schmidt (1992b) used the water permeability test (DIN 1048) to study permeability in air-entrained concrete with and without limestone addition to cement. The results were comparable for concrete with both types of cement. Because of the limited number of studies, it is not confirmed whether the higher fineness of Portland-limestone cement contributes to lowering permeability or not.

Tsivilis et al. (1999b) investigated the effect of limestone addition to cement on air permeability, water absorption, and pore structure for concrete. In this study, cement was prepared from two clinkers with different chemical composition and strength development and with the addition of three different types of limestone. Tsivilis et al. (1999b) concluded that “limestone cement concrete, with optimum limestone content, can give lower gas permeability and water absorption rate as compared with pure cement concrete.” Tsivilis et al. (2003) also investigated air permeability, water permeability, sorptivity, and porosity of limestone cement concrete. The limestone was interground with the cement to give Portland-limestone cement (PLC). The cement properties used for the study are shown in Table 2-1. All specimens were cured for 28 days prior to testing. Table 2-2 shows the results of all tests. First, gas permeability, K_g, increased with the increase of limestone content, except for the concrete produced with 35% limestone which showed the lowest gas permeability value. On the other hand, water permeability, K_w, and sorptivity, S, were among the highest for concrete with control cement, and were among the lowest for concrete with 15% limestone cement. The results of porosity, P, were comparable with the control up to 15% limestone addition, but porosity increased with higher limestone content.

Table 2-1 Cement Properties (Tsivilis et al. 2003)

Sample	Composition (%)		Specific Surface (m^2/Kg)	Compressive Strength (psi)			
	Clinker	Limestone		1 Day	2 Day	7 Day	28 Day
LC1	100	0	260	1726	3089	5120	7411
LC2	90	10	340	1624	3031	5265	6947
LC3	85	15	366	1871	3292	5468	7034
LC4	80	20	470	2161	3524	5511	6976
LC5	80	20	325	1102	2495	4076	5773
LC6	75	25	380	1407	2582	4554	5802
LC7	65	35	530	1421	2466	3800	4772

Table 2-2 Permeability Test Results for PLC Concrete (Tsivilis et al. 2003)

Code	w/cm	Strength 28 Day (psi)	Limestone (%)	K_g (10^{-17} m^2)	K_w (10^{-12} m/s)	S ($mm/min^{0.5}$)	P (%)
LC1	0.70	4627	0	2.26	2.39	0.237	12.48
LC2	0.70	3974	10	2.65	2.3	0.238	12.3
LC3	0.70	3960	15	2.8	2.22	0.226	12.31
LC4	0.70	4061	20	2.95	2	0.22	13.14
LC5	0.62	4090	20	3.03	1.81	0.228	12.94
LC6	0.62	3843	25	2.82	2.07	0.229	13.62
LC7	0.62	3858	35	2.1	2.23	0.224	14.64
K_g: gas permeability K_w: water permeability				S: sorptivity P: porosity			

2.4.2. Chloride Penetration

Tezuka et al. (1992) used cement with 0, 5, and 10% limestone and Blaine fineness of 450 kg/m^2 to determine the chloride diffusion coefficient for mortar specimens. The diffusion coefficient for specimens with 5% limestone was the lowest, and the results for specimens with cement containing 0 and 10% limestone were also toward the low end. Moir (1993) reported tests on the chloride penetration for concrete with cement containing up to 5% limestone. He found that compressive strength is the best indicator of chloride concentration. It was concluded that the higher the compressive strength, the lower the chloride concentration. Mathews (1994) measured the chloride concentration of reinforced concrete prisms placed for 5 years in a tidal zone in a marine exposure site. Five different sources of Portland cement were used in these mixes. One source was blended with 30% fly ash while another was interground with 28% fly ash. In addition, one source was interground with 5 and 25% limestone while the rest were blended with 5 and 25% limestone. The chloride concentrations were measured up to 30mm depth and averaged for all mixes batched with the same amount of limestone or fly ash. The results were considerably lower for the fly ash mixes. Chloride concentrations were lower in concrete with cement containing 5% limestone compared with concrete with control cement; whereas, chloride concentrations were slightly higher in concrete with cement containing 25% limestone than in concrete with control cement. Alunno-Rosetti and Curcio (1997) used cement from two different plants, with and without 20% limestone, to test chloride concentration in concrete. The results, shown in Table 2-3, indicate that concrete with higher cement content has lower chloride penetration. However, the results for concrete with and without 20% limestone were inconsistent between the two sources of cement.

Table 2-3 Chloride Penetration in Concrete (Alunno-Rosetti and Curcio 1997)

	Total Cement Content, kg/m³	Limestone Content (%)	Chloride Penetration, mm	
			28 Days	60 Days
Plant B	270	0	43	63
		20	102	113
	330	0	38	49
		20	48	79
Plant G	270	0	212	281
		20	197	264
	330	0	115	183
		20	146	182

Rapid chloride permeability test (RCPT per ASTM C1202) was measured by Thomas et al. (2010a) in a comprehensive study on the effect of limestone and SCMs addition on the performance of concrete. Table 2-4 shows the mixture proportioning with the cementitious content, w/cm ratio, and the RCP test results of this study. The study showed that the older specimen and the use of SCMs reduced the coulombs charged, but exhibited no significant difference between the specimens made with Portland cement (PC) or Portland-limestone cement (PLC) with 12% limestone. In another study by Thomas et al. (2010b), RCPT was conducted to determine the diffusion coefficient for cores taken from cast-in-place slabs after 35 days. Cement properties, SCMs replacement levels (two parts slag and one part fly ash), RCPT results, and the diffusion coefficient (per ASTM C1556) are shown in Table 2-5. It is noticed that the charge passed reduced significantly with the addition of SCMs, but showed insignificant difference between the PC and the PLC with 12% limestone.

Table 2-4 Mix Proportions and RCP Test Results (Thomas et al. 2010a)

	w/cm	Mix Proportion				Total Cem. (lb/yd³)	RCPT (coulombs)	
		Cement Type	Limestone Content (%)	Fly Ash (%)	Slag (%)		28 Days	56 Days
Series C	0.40	PC	0	0	0	689	2030	1730
		PLC	12	0	0	696	2050	1910
Series B	0.45	PC	0	0	0	597	2570	2350
		PLC	12	0	0	603	2620	2360
		PC	0	0	35	599	1020	810
		PLC	12	0	35	600	940	710
		PC	0	20	0	603	1190	650
		PLC	12	20	0	604	1450	690

Table 2-5 RCP Test Results and Diffusion Coefficients (Thomas et al. 2010b)

Cement Type	Limestone Content (%)	RCPT Results (coulombs)				Da (10^{-12} m²/s)			
		SCM Replacement Level, %				SCM Replacement Level, %			
		0	25	40	50	0	25	40	50
PC	0	2400	1410	570	490	15.0	3.8	1.5	1.3
PLC	12	2350	1310	620	520	11.9	2.9	1.2	1.8

Irassar et al. (2001) measured the chloride concentration and determined the diffusion coefficient of concrete specimens immersed in 3% NaCl solution for a period of 45, 180, and 360 days. Table 2-6 shows the results for diffusion coefficient (Da) and surface chloride concentration (Cs) for concrete specimens with different amount of limestone in cement. It was observed that the higher the w/cm ratio and limestone content, the higher the diffusion coefficient. The increase is attributed to the minimal contribution of limestone cement to the hydration process. Thomas et al. (2010b) noted that the diffusion coefficients for cores immersed for 42 days in chloride solution, shown in Table 2-5,indicated inconsistent performance of concrete whether made with PC or PLC, but showed lower Da for concrete made with higher SCM content.

Table 2-6 Surface Chloride Concentration and Chloride Diffusion (Irassar et al. 2001)

Limestone Content in Cement (%)	**Cs** (%)			**Da** (10^{-12} m^2/s)		
	w/cm			**w/cm**		
	0.4	0.5	0.6	0.4	0.5	0.6
0	0.12	0.15	0.15	5	6.9	25.7
10	0.13	0.12	0.18	11.2	20.3	21.6
20	0.14	0.15	0.25	10.5	23.8	41.4

Cs: surface concentration (% by weight of concrete)
Da: diffusion coefficient

2.4.3 Freeze/Thaw

Early studies on the effect of limestone addition to Portland cement have shown conflicting results as far as the freeze/thaw damage to concrete. Sprung and Seibel (1991) used the “cube” method to test the resistance of concrete with total cement content of 300 kg/m3 (506 lb/yd^3) and w/cm ratio of 0.6 to frost damage. Siebel and Sprung (1991) also tested the frost resistance of concrete using the European round robin with three different Portland-limestone cements having 11%, 26%, and 12% limestone. Both studies concluded that the amount, quality, and strength of limestone used to replace the cement have a great effect on controlling frost damage to concrete. Albeck and Sutej (1991) reported that concrete made from Portland limestone could have the same frost resistance as concrete made from Portland cement as long as the organic materials in the limestone are less than 0.2% by mass. In contrast, Scmidt (1992b) showed that concrete specimens made from Portland-limestone cement with 13% to 17% limestone, showed similar or slightly better resistance to frost damage and de-icer scaling compared with concrete with Portland cement.

Section 2.5 discusses the effect of freeze/thaw on concrete made with PLC based on the studies conducted in Canada by Thomas el al. (2010a), Thomas et al. (2010b), and Hooton et al. (2010). The tests were conducted in accordance with ASTM C666 for freeze/thaw resistance and de-icer salt scaling (ASTM C672 or OPS LS-412). All three studies indicated adequate resistance to freeze/thaw for concrete specimens made with PLC and similar durability factors for concrete specimens made with PC.

Several investigations and long-term studies show a strong relation between cement fineness and cement freeze/thaw resistance. Mehta (1999) observed old concrete curbs and gutters that were in good condition despite being without air entrainment and exposed to severe concrete weathering (heating, cooling, wetting, and drying). This observation is supported by his model which indicates that concrete starts to deteriorate when weathering damages the microstructure, thereby increasing the concrete’s susceptibility to freeze/thaw attack. Burrows (1999) supports this correlation in his study of concrete specimens made from Portland cement with varying Blaine fineness that were tested to check their resistance to freeze/thaw cycles, as shown in Figure 2-2. The curves show the number of cycles needed to cause 25% mass loss in the concrete specimens. The blue curve indicates specimens stored indoors and the red-dashed curve indicates specimens stored indoors for 3 months and then outdoors in Denver Colorado for 9 months. Two conclusions were made: First, increased cement fineness reduces concrete resistance to frost damage by increasing the mass loss and, second, weathering drastically reduces resistance to frost damage for concrete made with higher Blaine fineness. These observations raise questions about the frost resistance of concrete made from Portland-limestone cement that has higher Blaine fineness than Portland cement.

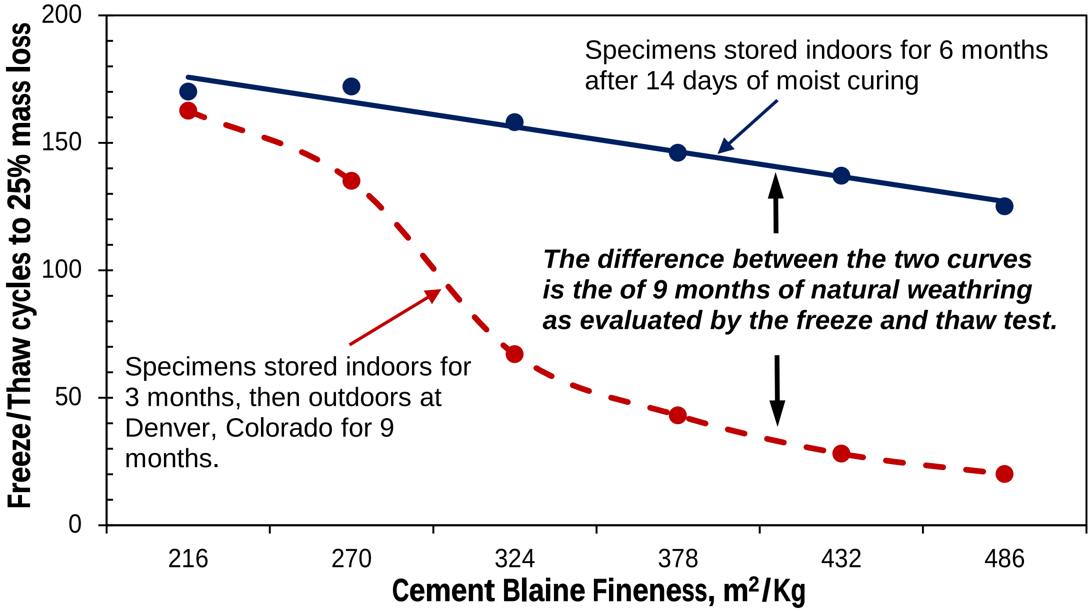

Figure 2-2 Effect of weathering on fineness of cement in concrete (Burrows 1999).

2.5 STUDIES CONDUCTED IN CANADA

The addition of up to 15% limestone to Portland cement was investigated in Canada in 2008. Extensive laboratory and field research have been conducted in Canada in recent years to compare the strength and durability of the PLC with that of PC. Three related laboratory and field trials that were documented in 2010 indicated comparable results in the strength and durability of PLC compared with PC. Two trials were conducted by the University of New Brunswick and Lafarge (Thomas et al.) while the third trial was conducted by the University of Toronto and Holcim (Hooton et al.):

- Equivalent Performance with Half the Clinker Content using PLC and SCM. (Thomas et al. 2010a)
- Field Trials of Concretes Produced with Portland-limestone cement. (Thomas et al. 2010b)
- Decreasing the Clinker Component in Cementing Materials: Performance of Portland-Limestone Cements in Concrete in Combination with SCMs. (Hooton et al. 2010)

2.5.1 Equivalent Performance with Half the Clinker Content Using PLC and SCM

Thomas et al. (2010a) examined the strength and durability of PLC with 12% limestone in comparison with PC with 3% to 4% limestone. Three series of mix proportions were prepared as shown in Table 2-7. Series A and C included pure PC (3% to 4% limestone) or PLC (12% limestone) cement with w/cm of 0.8 for Series A and 0.4 for Series C. Series B included PC and PLC mixes with w/cm of 0.45. The cement in Series B mixes was prepared with no SCMs, 20% fly ash replacement, and 30% slag replacement. The study tested the time of setting of concrete per ASTM C403, compressive strength per ASTM C39, rapid chloride penetration per ASTM C1202, resistance to rapid freezing and thawing per ASTM C666, Procedure A, and scaling resistance to de-icing chemicals per ASTM C672.

Table 2-7 Laboratory Mix Design (Thomas et al. 2010b)

Mix Proportion	Series A lb/yd^3		Series B lb/yd^3						Series C lb/yd^3	
w/cm	0.78	0.8	0.45	0.45	0.45	0.45	0.45	0.45	0.4	0.4
Cement Type	PC	PLC	PC	PLC	PC	PLC	PC	PLC	PC	PLC
Slag, %	na	na	na	na	35	35	na	na	na	na
Fly Ash, %	na	na	na	na	na	na	20	20	na	na
Total Cmt.	**396**	**396**	**597**	**603**	**599**	**600**	**603**	**604**	**689**	**696**
Water	310	317	268	271	270	270	271	271	276	278
Air, %	1.5	1.4	6.2	5.3	6	5.6	5.2	5	6.2	5.4
Slump, in.	4.75	4.5	4.75	4.75	4.25	4.25	5	4.25	5	4.5
Set Time, hrs:min	5:40	5:10	5:40	4:50	6:20	5:45	7:05	5:45	6:35	5:55

The setting time results shown in Table 2-7 indicate that PLC mixes set faster than similar PC mixes. The compressive strength of each mix was measured at 1, 7, 28, and 56 day. The results of this study show insignificant variation in the compressive strength between the mixes with PC and PLC cement type. In most cases, the compressive strength was higher for PLC mixes at an early stage compared with PC mixes.

A rapid chloride penetration test was conducted per ASTM C1202 on Series B and C mixes. The results showed no significant impact on replacing PC with PLC. However, a significant reduction in the charge passed in PC and PLC mixes with fly ash or slag content was observed.

The effect of limestone on the performance of concrete was inconsistent when the de-icer salt scaling test was conducted per ASTM C672. Mass loss increased with the increase of the amount of SCMs in PC and PLC mixes. All mixes showed great performance after 300 cycles in the freeze/thaw test per ASTM C666 with high durability factors ranging from 98% to 102%.

The laboratory tests in this study showed good performance for concrete mixes with PLC cement with up to 12% limestone in terms of strength and durability and comparable results for the mixes with PC cement. It was also noticed that SCMs improved the durability of concrete mixes with PLC and PC cement.

2.5.2 Field Trials of Concrete Produced with Portland-Limestone Cement

Thomas et al. (2010b) examined the strength and durability of PLC with 12 % limestone content in comparison with PC with 3% to 4% limestone content. Eight concrete mixes were batched with total cementitious material content of 600 lb/yd^3. Each batch contained either PC or PLC. For each type of cement, the SCM comprising two parts slag cement and one part fly ash by mass was used at replacement levels of 0%, 25%, 4%0, or 50%. The target air content was 6% and target slump was 4 in. The study tested the compressive strength per ASTM C39, rapid chloride penetration per ASTM C1202, apparent chloride diffusion coefficient per ASTM C1556, resistance to rapid freezing and thawing per ASTM C666, Procedure A, microscopic determination of air void system parameters per ASTM C457, and scaling resistance to de-icing chemicals per ASTM C672 and BNQ NQ 2621 Annex B.

The results for the compressive strength showed highest strengths for PC and PLC with 40 and 50% SCM; however, the concrete batched with PC and PLC showed insignificant variation. The rapid chloride penetration test showed that the charge passed in 6 hours decreased with the increase of SCM content, and that there was insignificant difference in performance between concretes produced with PC and PLC. Moreover, all mixtures with PC and PLC showed satisfactory air void parameters with excellent durability factors after 300 cycles of freezing and thawing per ASTM C666, Procedure A. The scaling resistance per ASTM C672 showed that the mass loss increased with the increase of SCM content in the mix, regardless of the type of mix.

The study showed that adding SCMs to concrete may increase its strength and resistance to chloride ion penetration, regardless whether PC or PLC are used, and that replacing cement by SCMs in the range of 40% to 50% results in better performance. The study also showed that the content of limestone in cement could be increased to 12% while maintaining equivalent strength and durability, and that replacing cement by SCMs in the range of 40% to 50% results in better performance.

2.5.3 Decreasing the Clinker Component in Cementing Materials: Performance of Portland-Limestone Cement in Concrete in Combination with SCMs

In a study by Hooten et al. (2010), Portland cement clinker with 12% C_3A was interground with different levels of limestone. Tests were conducted on three types of cements; Portland cement with 3.5% limestone (GU), 10% limestone (PLC10), and 15% limestone (PLC15). Each cement type was replaced with slag at 0, 30, and 50% of total cementitious content. The study tested the sulfate resistance per ASTM C1012 (sulfate-resistance expansion), alkali-silica reactivity test per ASTM C1567 (accelerated mortar bar test) and per ASTM C1293 (concrete prism test), and the following laboratory concrete tests: compressive strength per ASTM C39, de-icer salt scaling per OPS LS-412 similar to ASTM C672 and based on the Ontario Ministry of Transport provisional standard, drying shrinkage per ASTM C157, rapid chloride penetration test per ASTM C1202, and obvious chloride diffusion coefficient per ASTM C1556.

Laboratory concrete tests were conducted at w/cm = 0.4 and total cementitious materials of 360 kg/m^3 (607 lb/yd^3). Cement was replaced with slag at 0% and 30% of total cementitious content. The target air content was 5% to 8%, target compressive strength was 35 MPa (5080 psi) at 28 day, and target rapid chloride penetration was 1500 coulomb at 56 days.

Sulfate attack and alkali-silica reactivity are not part of the current project; however, it is important to show their effect on the performance of concrete with PLC.

In the sulfate-resistance test, mortar bars and cubes were cast and cured until their compressive strength reached 2850 psi. The bars were then immersed in a 50 g/l of sodium sulfate (Na_2SO_4) solution and their length change was measured periodically for 1 year. According to ASTM C1157 (Standard Performance Specification of Hydraulic Cement) and the Canadian Standard

Association, a cement is considered moderately sulfate resistant if the bar expansion is less than 0.1 % after 6 months and highly sulfate-resistant if the bar expansion is less than 0.05% after 6 months or 0.1% after 1 year. The results indicated that slag-free mixes failed to pass the test after 6 months, and that bar expansion increased with the increase in the amount of limestone. However, all mixes that contained 30 and 50% slag showed high sulfate resistance.

The accelerated mortar bar test per ASTM C1567 and the concrete prism test per ASTM C1293 were both conducted to study alkali-silica reactivity. For ASTM C1567, siliceous limestone aggregates from the Spratt quarry near Ottawa, Ontario, were crushed to sand size to meet the specified particle size distribution. Mortar bars (1 x 1 x 12 in.) were cast and cured, immersed in water, and heated in an oven at 80°C for 1 day. Then, the bars were immersed in sodium hydroxide solution and stored at 80°C. The length change was recorded periodically for 28 days in NaOH solution. According to the standard, expansion should be less than 0.1% at 14 days. All slag-free cements failed the test. The results indicated that mortar expansion was higher in PLCs than GU cement. On the other hand, the bar expansion for cements with slag failed at the 30% slag replacement, but all cements with 50% slag showed positive results.

The compressive strength results, shown in Table 2-8, were inconsistent compared with other studies where mixes with slag indicated higher strength. First, the compressive strength of mixes with PLC10 and PLC15 and for slag-free mixes was slightly higher than the compressive strength of GU mixes. However, a significant drop in the strength of all mixes with 30% slag replacement and a significant increase in the strength of PLC mixes were observed compared with to the GU mixes. Therefore, it was concluded that the reduction might be attributed to other factors, such as the air content in the concrete.

Table 2-8 Compressive Strength Results (Thomas et al. 2010b)

Concrete Mix	Compressive Strength (MPa)			
	7 Day	28 Day	56 Day	91 Day
GU 100%	5700	6860	7281	8485
PLC10 100%	6179	7353	8238	8731
PLC15 100%	5860	7165	8108	8137
GU 70% SLAG 30%	2814	4351	4786	4873
PLC10 70% SLAG 30%	4351	6179	6701	7745
PLC15 70% SLAG 30%	4554	6237	6788	7832

The results for drying shrinkage in this study showed no variation in the length change for the three types of cement with 0 and 30% slag replacement.

In the rapid chloride penetration test, the charge passed for all slag-free mixes was higher than the maximum requirement of 1500 coulombs at 56 days. However, the results were much lower with the 30% slag replacement. It was therefore concluded that there was no effect of limestone from both types of cement PLC10 and PLC15 when compared with GU cement.

The apparent chloride diffusion measurements were very compatible with the RCPT test results. The use of PLC cement in all mixes had no effect on chloride penetration, and the replacement of 30% slag reduced the percentage of chloride in all cements.

This study showed that the performance of PLC cement with up to 15% interground limestone is comparable to the performance of GU cement. It was also observed that slag improved the strength and durability of GU and PLC cements.

CHAPTER 3 ISSUES ADDRESSED IN THE PROJECT

3.1 EFFECT OF CHEMICAL ADMIXTURES ON THE AIR CONTENT STABILITY OF CONCRETE IN THE FRESH AND HARDENED STATE

3.1.1 Introduction

The early concrete mixes completed in this project have low hardened entrained air compared with their fresh air content. As a result, the concrete mixes failed to pass the freeze/thaw test of ASTM C666, procedure A. In order to check this inadequacy, a sensitivity study was conducted to investigate air stability in the fresh and hardened state. The study analyzed the effect of chemical admixtures on the air content of concrete mixes batched at the University of Illinois at Chicago (UIC). The results of the report provide a description of the effect of chemical admixtures on the rate of air loss in concrete mixes in the fresh stage. It also demonstrates the effect of admixtures on each other and on the slump and air readings.

3.1.2 Materials

Source Cem1 (Table 6-1) with less than 5% limestone and IPA was used in all mixes. Class C fly ash or Grade 100 slag was added to the mixes. Two types of fine aggregates were used; natural sand provided by Bluff City material, South Beloit, and combined sand, which contained natural sand and crushed limestone provided by MS Romeoville. The coarse aggregate used was a crushed limestone from Hanson MS Thornton quarry.

Three types of chemical admixtures were used in the concrete mixes: air-entraining agent (AEA) Daravair 1400 per ASTM C260, water-reducing admixture (WRA) WRDA 82 per ASTM C494 Type A and D, and high-range water reducer (HRWR) ADVA Cast 575 per ASTM C494 Type A and F.

Manufacturer’s guidelines were provided for all chemical admixtures with details about performance, addition rates, compatibility with other admixtures, and batching sequences.

The Daravair 1400 is chemically similar to vinsol-based products. The guideline of Daravair 1400 does not specify a standard addition rate. A typical Daravair 1400 addition rate ranges from 0.5 to 3 fl oz/cwt. The addition rate varies depending on several factors, including temperature, type of cement, sand gradation, and using extra fine materials such as fly ash and micro silica. It is, however, recommended to add Daravair 1400 to the concrete mix at the beginning of the batch sequence by dribbling on the sand to obtain optimum performance.

The WRDA 82 is an aqueous solution of modified lignosulfonates. The addition rate for the WRDA 82 ranges from 3 to 5 fl oz/cwt and from 2 to 10 fl oz/cwt if local testing shows acceptable performance. It is recommended to add WRDA 82 to the concrete mix near the end of the batch sequence and to avoid any contact between WRDA 82 and other admixtures before and during the batching process to obtain optimum performance. WRDA 82 is highly compatible with Daravair 1400 when both are used in the same mix. Using WRDA 82 in a concrete mix might reduce the quantity of air-entraining admixture by 25-50%.

The ADVA Cast 575 is a polycarboxylate-based high-range water reducer. The addition rate of the ADVA Cast 575 varies between 2 to 10 fl oz/cwt. The dosage requirement for ADVA Cast 575 might be affected by the mix proportions, cementitious content, and ambient conditions. It is not recommended to use ADVA Cast 575 in concrete mixes with naphthalene-based admixtures, including Daracem 19 and Daracem 100, and melamine-based admixtures, including Daracem ML 330 and Daracem 65. It is recommended to add ADVA 575 to the concrete mix near the end of the batch sequence to obtain optimum performance.

3.1.3 Mix Design

Four different mixes were prepared with cementitious materials containing 375 lb/yd^3 of cement and 160 lb/yd^3 of fly ash or slag. Each mix was batched with one type of fine aggregate, combined sand, or natural sand. Fly ash is designated by F, slag by S, combined sand by C, and natural sand by N. The four different mixes are listed below:

1. Combined sand with fly ash (CF)
2. Combined sand with slag (CS)
3. Natural sand with fly ash (NF)
4. Natural Sand with slag (NS)

The amount of WRDA 82 and ADVA Cast 575 varied depending on the workability of the mix and the ability to get the desired 3.5 in. slump without exceeding the maximum amount of chemical admixtures required per mix. Daravair-1400 was used to maintain the air at approximately 6.5% to 8% in the fresh state at approximately 1 in. slump level of the concrete mix. This project required a w/cm ratio of 0.42 for all mix types. The w/cm ratio was inadequate to maintain a 3.5 in. slump for mixes made with combined sand and slag with the use of WRDA 82 and ADVA 575. Therefore, the w/cm ratio was increased to 0.44 for all mixes made with combined sand and slag. On the other hand, mixes made with natural sand and fly ash experienced higher slump than desired and their w/cm ratio was, consequently, reduced to 0.40. The remaining mixes were prepared with w/cm ratio of 0.42.

3.1.4 Procedure

Two ft^3 concrete batches were prepared for mixing. Manufacturer's recommendations were followed in terms of the addition rate and the sequence of addition of chemical admixtures. The mixing sequence started with the addition of air entrainment with water in a 6 ft^3 drum mixer. The fine aggregate was then added, followed by the coarse aggregate and the cementitious materials. Finally, the water reducers were added at the end of the batch sequence. The batch was mixed for three minutes, left to rest for three minutes, and was then mixed for two additional minutes. For the majority of mixes, the slump was measured upon discharge and 12 minutes afterwards. The fresh air content was measured 12 minutes after discharging and at 1 in. slump level.

For each mix, 6 x 12 in. cylinders were molded to test the compressive strength of concrete in accordance with ASTM C39 at 3, 7, and 14 day, respectively. The specimens were unmolded after 24 hours and then secured into the moisture room for further curing.

3.1.5 Discussion of Test Results

The fresh air content, slump, and compressive strength readings and the amount of chemical admixtures used are shown in Table P-1 through Table P-4 in Appendix P. The rate of air loss is the difference between final and initial air readings divided by the time difference between them. The compressive strength was tested and recorded at 3, 7, and 14 day. Figure P-1 through Figure P-8 show plots for initial (12 minutes after discharge) or final (at 1 in. slump level) percentage of air versus the compressive strength in descending order at 14 days for each mix type.

The effect of admixtures on the mixes was consistent with the slump variation and depended on the variation of the dosage of WRDA 82 and ADVA 575. However, air content variations were only consistent in the mixes that had the same dosage of water reducers. The effect of water reducers WRDA 82 and ADVA Cast 575 on the concrete mixes, their interactive effect with the air entrainment Daravair 1400, and their effect on the percentage of air at different times were, therefore, concluded. Table P-1, showing concrete mixes with combined sand and fly ash, and Table P-4, showing natural sand and slag, indicate a slight change in the amount of air entrainment Daravair 1400. However, the air content variation in the initial and final readings was approximately 3% in Table P-1 and 1.5% in Table P-4. Because all mixes were batched from the same materials, the variation in air readings seems to be strongly related to the variation in the amount of water reducers WRDA 82 and ADVA Cast 575. Moreover, the results of the air loss showed that the readings became more inconsistent with the increase in the amount of water reducers in the mix. Mixes CS and CF required more water reducers than mixes NS and NF to bring the slump to the desired level. Table P-1, showing CF, and Table P-2, showing CS, indicate a high range of variation in air loss rates. For instance, Table P-2, showing mixes CS-44-16 and CS-44-17, has the same amount of admixtures but the rate of air loss (%/ min) in CS-44-16 is 0.063 and in CS-44-17 is 0.038. On the other hand, Table P-3, showing NF with little to no water reducers, indicates low variation in the rate of air loss.

Figure P-1 through Figure P-8 represent a strong correlation between the air content and compressive strength, on one hand, and the amount of water reducers used in the mixes, on the other hand. Figure P-1 and Figure P-2 show the compressive strength versus the initial air content (12 minutes after discharge) and final air content (at 1 in. slump) of concrete mixes containing combined sand and fly ash. Figure P-5 and Figure P-6 show the compressive strength versus the initial and final air content of concrete mixes containing natural sand and fly ash. The comparison was based on the fact that air content increases with the decrease of compressive strength. The readings of Figure P-1 for initial air were inconsistent with the readings of Figure P-2 for the final air of mixes CF. In contrast, the readings of Figure P-5 and Figure P-6 for mixes NF for initial and final air were consistent with the compressive strength reading. The inconsistency shown in Figure P-1 and Figure P-2 is attributed to the amount of water reducers used in mixes CF compared with mixes NF, which had little to no water reducers.

3.1.6 Conclusions

The WRDA 82, used in these mixes had a synergistic effect when it reacted with Daravair 1400. This reaction enhanced the air bubbles, but it increased the instability of air content in the mix and the variation in the rate of air loss. On the other hand, the addition of ADVA Cast 575 showed an adverse effect when used with Daravair 1400. ADVA Cast 575 reduced and stabilized the air content in the mix by eliminating the effect of combining WRDA 82 and Daravair 1400 on the air bubbles.

3.2 EFFECT OF COARSE AGGREGATE GRADATION ON WORKABILITY, AIR CONTENT, AND STRENGTH OF CONCRETE

Overcoming the inconsistency in calibrating the concrete mixtures that were influenced by the gradation of coarse aggregate was a major concern. The coarse aggregates used in this study are crushed limestone, selected specifically for bridge decks. The sources of coarse aggregate are shown in Table 4-1. IDOT specifications for bridge decks state that 45% to 60% of the coarse aggregate must pass 0.5 in. sieve. The coarse aggregate was provided by a local ready-mix concrete plant. In some cases, the gradation failed to meet IDOT specifications. For this purpose, a study was conducted at the UIC laboratory to test the effect of coarse aggregate gradation on the workability, fresh air content, and compressive strength of concrete.

The materials, mix proportioning, and batching and mixing procedures used were similar to the mixes used in the previous study. The slump was measured immediately and at 12 minutes after discharge. The air content was measured at 12 minutes after discharge and at 1 in. slump. For each concrete mix, 6 x 12 in. concrete cylinders were cast to test the compressive strength at 3, 7, and 14 days. The specimens were unmolded after 24 hours and were secured in the moisture room for further curing. Trial mixes were divided into three sets with different amounts of coarse aggregate passing 0.5 in. sieve; the three sets contained 25% to 35%, 35% to 45%, and 45% to 60% chips of the total coarse aggregate content, respectively.

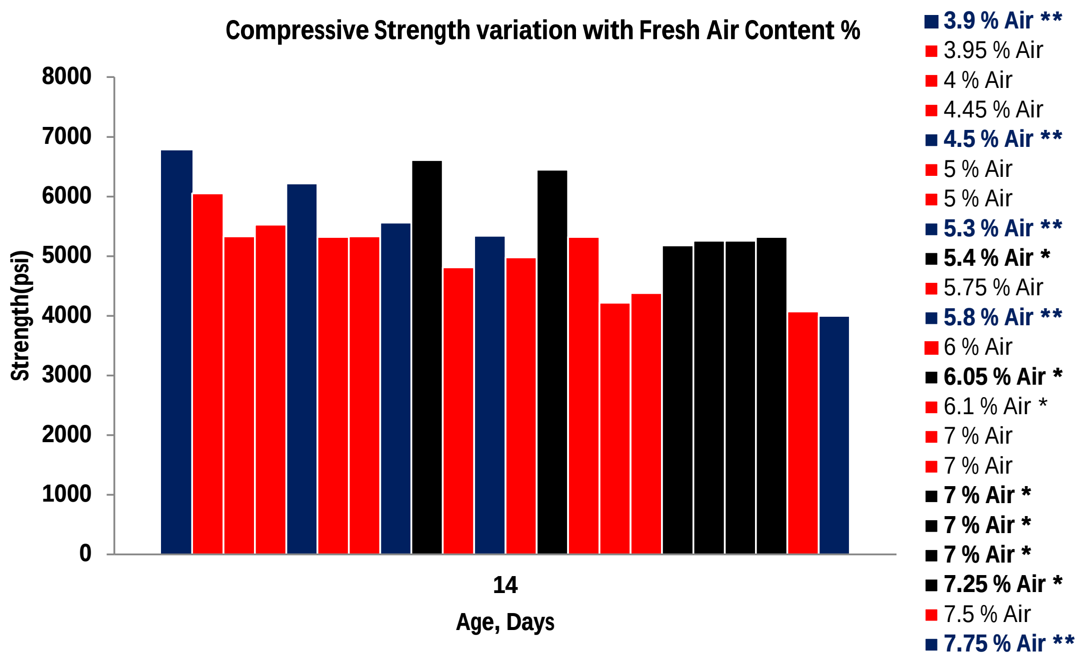

Figure 3-1 Compressive strength vs. air content for concrete mix with combined sand and slag.

The change in the coarse aggregate gradation demonstrated a great impact on the performance of concrete in the fresh and hardened states. In the fresh state, the higher amount of coarse aggregate passing 0.5 in. sieve required a higher amount of water reducer to reach the desired slump and a higher air-entraining agent to achieve the required air content, but it helped stabilize the air and reduced the rate of fresh air loss in the concrete mixtures. In the hardened state, the higher amount of chips contributed to the improvement of strength. Figure 3-1 shows a list of trial mixes with different coarse aggregate gradation. The histograms indicate the strength of the three different set of trial mixes at 14 days in ascending order with respect to the amount of fresh air content in the mix. The red, blue, and black histograms indicate the trial mixes made with coarse aggregate containing 25% to 35% chips, 35% to 45% chips, and 45% to 60% chips of the total coarse aggregate content, respectively. The graph shows that the higher the amount of coarse aggregate passing 0.5 in. sieve, the better the compressive strength.

3.3 FACTORS AFFECTING THE MARGINAL AIR CONTENT FOR FREEZE/THAW RESISTANCE

The factors affecting the concrete performance against freeze/thaw were investigated to achieve adequate freeze/thaw resistance. Voids in concrete are classified into four types: capillary voids, entrained air voids, entrapped air voids, and water pockets. Capillary voids occupy the space between the cement gels after hydration. They are irregularly shaped, are less than 5µm in size, and have no contribution to the air void system. Air-entrained voids are created by the addition of surfactants with stabilized foam (air-entraining admixture) to resist the cyclic attack of freezing and thawing. The Virginia Transportation Research Council (VTRC) define the air-entrained void as spherical in shape, larger than the capillary void, and smaller than 1mm when measured on a saw-cut lapped surface (Ozyildirim 1998). Entrapped air and water voids are usually larger in size than entrained air voids. Entrapped air voids are influenced by the physical properties of the aggregate and the workability and improper consolidation of the mix. Water pockets result from the water that fails to bleed to the surface because of an aggregate or hardening paste.

The current U.S. practice considers the total air content measures in a mixture an indication of the concrete's freeze/thaw resistance. IDOT requires 5% to 8% total air in the concrete mixture. However, it is not confirmed whether freeze/thaw resistance is attributed to the total air in the concrete or the hardened entrained air.

The quality of the air void system has a major impact on the concrete's resistance; for example, the size, number, spacing, and distribution of air bubbles contribute to the quality of the air void system. A UIC study on the hardened air content in concrete attributed the concrete's freeze/thaw resistance to the amount of hardened air entrainment (air bubble sizes ranged from 5 μm to 1 mm). In this study, concrete specimens with a total air content of 6% to 7% failed to achieve the required freeze/thaw resistance. Further testing showed that these specimens had only 3% to 4% entrained air, which rendered them susceptible to deterioration when exposed to repeated freeze/thaw cycles. Table 3-1 shows the fresh and hardened air content for the concrete mixes that failed the freeze/thaw test. The source of materials and mix design for these concrete mixes are shown in Table 4-1 and Table 4-2. The hardened air contents were measured at the UIC lab and Holcim Laboratories. The UIC lab considered measuring the hardened entrained air content using the linear traverse method per ASTM C457; whereas, Holcim Laboratories measured the total hardened air using image analysis. Consistent results were obtained for the fresh and hardened air content measured at Holcim Laboratories while a difference ranging from 2.2% to 3.8% was observed between the fresh air content and hardened entrained air at UIC lab. Although the total air content ranged between 5% and 8%, the specimens' failure to resist the freeze/thaw cycles was attributed primarily to the low hardened air entrainment.

Table 3-1 Fresh and Hardened Air Content for Mix 1–Mix 4 and Mix 9–Mix 12

Mix No.	Mix Design	Fresh Air Content UIC Lab[1] %	Hardened Air Entrainment Content UIC Lab[2] %	Difference between Fresh and Hardened Air %	Hardened Air Entrained and Entrapped Content Holcim Lab[3] %
1	Cem1 < 5% _F	6.5	4.34	2.16	4.48
2	Cem1 > 5% _F	7.0	3.13	3.87	6.03
3	Cem1 < 5% _S	6.5	4.06	2.44	5.66
4	Cem1 > 5% _S	6.5	3.66	2.84	6.12
9	Cem3 < 5% _F	6.6	3.76	2.84	6.06
10	Cem3 > 5% _F	6.5	3.92	2.58	6.36
11	Cem3 < 5% _S	6.6	3.9	2.70	6.30
12	Cem3 > 5% _S	6.3	3.72	2.58	6.18

Notes:

1. The fresh air content at UIC lab includes both entrapped and entrained air.
2. The hardened air content at UIC lab includes **entrained air** only.
3. The Holcim Concrete Lab Report Hardened air includes both entrapped and entrained air as stated in their **WAIVER of LIABILITY**: The results obtained from this testing are intended to provide guidance and it does not distinguish between entrapped and entrained voids.

CHAPTER 4 MATERIAL SELECTION AND MIX DESIGN

4.1 PROCURING SOURCES OF MATERIALS

The sources of materials procured for the study are: (a) two sources of cement, (b) one source of coarse aggregate, (c) two sources of fine aggregate, and (d) one source of class C fly ash and one source of Grade 100 slag. The sources and types of materials are presented in Table 4-1.

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Table 4-1 Materials Source and Type

Ingredients	Supplier	Designation
Three sources of cement	1st cement, Producer #1 **Cem1** has **6.7% IPA** more than the 5% limit **Cem1R** has **4.5% IPA** replaced **Cem1**	Cem1 Cem1R
	2nd cement, **choose 1st cement with limestone plus**: 1. **Low dose processing addition** using fly ash with LOI max 3% and IR Max 0.75%), and 2. **High dose processing addition** using fly ash with LOI max 3.5% and IR Max 1.5%)	Cem2
	3rd cement, Producer #3 **Cem3R** was received in January 2013 and it contains **1% more limestone** than **Cem3**	Cem3 Cem3R
Fly Ash	Pleasant Prairie, Type C	Fly Ash
GGBFS	Holcim Skyway, Slag Grade 100	Slag
One source of coarse aggregate	Hanson MS Thornton quarry The material is MS Thornton Aggregate Source: 50312-04 Material Code: CM 1101 BD.	CA_1
Two sources of fine aggregate	Bluff City material in South Beloit, natural sand Aggregate Source: 52010-20 Material Code: 027FM02	FA_1
	Hanson MS Romeoville, combined sand Aggregate Source: 51972-02 Material Code: 029FM20	FA_2
Type A Water Reducer, WRA	W.R. Grace WRDA 82 ADVA Cast 575	WRA
Air entrainment, AEA	W.R. Grace AEA Daravair 1400	AEA

Each cement source (Cem1 and Cem3) provided cement with limestone and IPA less than and exceeding 5% in accordance with ASTM C465. Ground, granulated blast furnace slag was used as IPA for cement with more than 5% limestone and IPA. Cem1 source was prepared by intergrinding limestone and partially intergrinding IPA at CTL laboratory in Skokie, Illinois. However, Cem1 source has IPA content of 6.7%, which exceeds the recommended limit (5%). As a result, cement producer #1 replaced Cem1 by Cem1R, which has 4.5% IPA. Cem3 was produced by intergrinding limestone and homogeneously blending IPA. Because of a shortage of Cem3, the producer delivered a new shipment labeled Cem3R because it has 0.8% limestone more than the original Cem3. The chemical and physical properties of the cement sources are detailed in Chapter 6. The insoluble residue (IR) content of ASTM C150 and AASHTO M85 Portland cements is limited per the specifications to a maximum of 0.75% by weight. Cem2 is made by blending Cem1R < 5% with fly ash with 0.49% and 32.41% IR, respectively, to give Cem2 < 5% with 0.75% IR and Cem2 > 5% with 1.5% IR, as shown in Appendix F.

Only aggregates demonstrating a history of good performance for durability concerns, such as D-Cracking and ASR, are used in this study. The coarse aggregate was provided by Hanson MS Thornton quarry with a minimum 45% passing the 0.5 in. sieve. The fine aggregate was provided by MS Romeoville and Bluff City material in South Beloit. According to IDOT's District 1, these aggregates have a good history of durability performance. The Grade 100 slag and Class C fly ash were provided by Holcim Skyway and Pleasant Prairie, respectively.

4.2 CONCRETE MIXES PREPARED AT THE UIC LABORATORY

Twenty-four concrete mix combinations were made for the above sources and types of materials, as shown in Table 4-2 and Table 4-3; Table 4-2 presents a combination of all cementitious materials batched with Hanson MS Thornton coarse aggregate and Bluff City natural sand fine aggregate; Table 4-3 presents the combination of all cementitious materials batched with Hanson MS Thornton coarse aggregate and Hanson MS Romeoville combined sand as fine aggregate. Mix 1–Mix 4 were then repeated after replacing Cem1 with Cem1R, and Mix 9–Mix 12 were repeated after receiving a new load of Cem3 with 0.8% more of limestone than the original Cem3. The repeated mixes were renamed Mix 1R–Mix 4R and Mix 9R–Mix 12R.

Table 4-2 Cements+CA_1 (Hanson MS Thornton)+FA_1 (Bluff City)+ AEA+WRA+HRWR

Mixture Designation	Mixture Combinations	CA_1 (Hanson MS Thornton)	FA_1 (Bluff City, Natural Sand)	AEA	WRA	HRWR
Mix 1	Cem1 < 5% _Fly ash	x	x	x		x
Mix 2	Cem1 > 5% _Fly ash	x	x	x		x
Mix 3	Cem1 < 5% _Slag	x	x	x	x	x
Mix 4	Cem1 > 5% _Slag	x	x	x	x	x
Mix 5	Cem2 < 5% _Fly ash	x	x	x		x
Mix 6	Cem2 > 5% _Fly ash	x	x	x		x
Mix 7	Cem2 < 5% _Slag	x	x	x	x	x
Mix 8	Cem2 > 5% _Slag	x	x	x	x	x
Mix 9	Cem3 < 5% _Fly ash	x	x	x		x
Mix 10	Cem3 > 5% _Fly ash	x	x	x		x
Mix 11	Cem3 < 5% _Slag	x	x	x	x	x
Mix 12	Cem3 > 5% _Slag	x	x	x	x	x

Table 4-3 Cements+CA_1 (Hanson MS Thornton)+FA_2 (MS Romeoville)+ AEA+WRA+HRWR

Mixture Designation	Mixture Combinations	CA_1 (Hanson MS Thornton)	FA_2 (MS Romeoville, Combined Sand)	AEA	WRA	HRWR
Mix 13	Cem1R < 5% _Fly ash	x	x	x	x	x
Mix 14	Cem1R > 5% _Fly ash	x	x	x	x	x
Mix 15	Cem1R < 5% _Slag	x	x	x	x	x
Mix 16	Cem1R > 5% _Slag	x	x	x	x	x
Mix 17	Cem2 < 5% _Fly ash	x	x	x	x	x
Mix 18	Cem2 > 5% _Fly ash	x	x	x	x	x
Mix 19	Cem2 < 5% _Slag	x	x	x	x	x
Mix 20	Cem2 > 5% _Slag	x	x	x	x	x
Mix 21	Cem3 < 5% _Fly ash	x	x	x	x	x
Mix 22	Cem3 > 5% _Fly ash	x	x	x	x	x
Mix 23	Cem3 < 5% _Slag	x	x	x	x	x
Mix 24	Cem3 > 5% _Slag	x	x	x	x	x

CHAPTER 5 LABORATORY TEST METHODS FOR FRESH AND HARDENED CONCRETE ACCORDING TO ASTM/AASHTO

The ASTM/AASHTO test methods for the fresh and hardened properties of concrete for strength and durability are applied to the 24 concrete mixes. The ASTM/AASHTO test methods and number of tests are presented in Table 5-1.

Table 5-1 ASTM/AASHTO Test Methods and Number of Tests for 24 Concrete Mixes

Test Method	Testing Times	Sample Size	Number of Samples		
			Per Test	Per Mix	Total
Slump ASTM C143/AASHTO T119	after mixing and 12 minutes after mixing	slump cone	1	2	48
Unit Weight ASTM C138/AASHTO T121	after mixing	cylindrical container, volume = 0.25 cubic ft	1	1	24
Air Content ASTM C231/AASHTO T121	after mixing and 12 minutes after mixing	measuring bowl	1	2	48
Initial Setting Time, ASTM C403 AASHTO T197	time to 1st reading (40 psi), hr. testing time then until initial set, (500 psi), hr.	measuring bowl with minimum diameter of 6²	1	1	24
Hardened air, ASTM C457	at 56 days	Concrete samples sliced vertically from 6" x 12" cylinder	2 runs	2	72
Rapid chloride ion permeability, ASTM C1202/AASHTO T277	at 56, 180, 360 days	4" x 2" discs sliced from 4" x 8" cylinders	3	9	216
Salt ponding test, AASHTO T259 ASTM C1543	Salt pond for 90 days but will continue for 360 days	12" x 12" x 3" slab	1	3	72
Chloride measure for salt ponding, AASHTO T260 ASTM C1151, ASTM C1218	at 90, 180, 360 days 2 drill holes/slab 5 depths/hole	Measure at 5, 15, 25, 35, 45, and 55 mm across the slab depth	12 runs	36	864
Freeze/Thaw, Procedure A, ASTM C666/AASHTO T161	Relative dynamic modulus (RDM) and mass loss readings every 30 cycles	3" x 4" x 16" prisms	5 runs	5	120
DIN 1048, Water permeability test	Measure penetration of water at 56, 180, and 360 days	8" x 8" x 5" cubes	3 runs	9	216
Compressive Strength ASTM C39/AASHTO T22	at 3, 7, 14, 28, and 56 days	6" x 12" cylinders	5	25	600
Flexural Strength, ASTM C78/AASHTO T97	at 3, 7, 14, 28, and 56 days	6" x 6" x 24" prisms	2	10	240

5.1 FRESH CONCRETE PROPERTIES

All concrete mixes are mixed according to ASTM C192/AASHTO T126. The IDOT PCC Mix Design Version V2.1.2 was used. The slump, unit weight, fresh air content (pressure meter), initial and final setting times, concrete mix temperature, ambient temperature, and humidity were measured for each mix.

5.2 HARDENED CONCRETE STRENGTH PROPERTIES

The compressive and flexural strength tests were conducted according to ASTM C39/ AASHTO T22 and ASTM C78/AASHTO T97, respectively, at 3, 7, 14, 28, and 56 days. The concrete was cast at the UIC laboratory. The compressive specimens were capped with plastic covers, and the flexural specimens were covered with wet burlaps and stored indoors under ambient temperature for 24 hours after casting. The specimens were then demolded and stored in the moisture room under a controlled temperature of 23°C (73°F) and 100% humidity (according to ASTM C511/AASHTO M 201) until the testing dates.

5.3 HARDENED CONCRETE DURABILITY PROPERTIES

Cyclic freezing and thawing, salt ponding, water permeability, rapid chloride ion permeability, and hardened air tests represented the primary characteristics for durability testing. The concrete must be air-entrained to provide resistance to cyclic freezing and thawing encountered in Illinois. Air entrainment provides void space in which ice crystals can expand without subjecting the concrete material to pressure and inducing cracking. The hardened air void parameters, including void spacing factors and specific surface, were measured. Air-entraining admixtures were evaluated in the testing program to ensure compatibility with other admixtures in the mixes. These standard laboratory tests were chosen because they predicted the overall behavior and durability of concrete. The ASTM/AASHTO testing program is presented in Table 5-2.

5.4 CYCLIC FREEZE/THAW TESTS (ASTM C666, PROCEDURE A/AASHTO T161)

Five 3 x 4 x16 in. specimens were cast for each concrete mix at the UIC laboratory for freeze/thaw testing. The beams were cured for 56 days of moisture room curing [temperature of 23°C (73°F) and 100% humidity] prior to testing. Testing was conducted until each specimen passed 300 cycles or until its relative dynamic modulus (RDM) reached 80% of the initial modulus , whichever occurred first. ASTM C494 (Standard Specification for Chemical admixtures for Concrete) states that when chemical admixtures are used in air-entrained concrete, the concrete RDM should be minimum 80% of the initial modulus after 300 cycles of freeze/thaw testing. The curing processes used in all durability tests were approved by IDOT before the testing program was initiated.

5.5 HARDENED AIR CONTENT, AIR VOID SPACING, AND SPECIFIC SURFACE

Two 6^{2}x12^{2} concrete cylinders of were cast for each concrete mix. The concrete cylinders were subject to curing in the moisture room for 28 days and were then left to dry for another 28 days in the laboratory before testing. Using a diamond blade saw, sample disks were cut from the top of the concrete cylinder and 8^{2}x5^{2} samples were cut from the concrete cylinder across its length. The specimens were then sanded and polished. Air void was determined in the specimens in accordance with ASTM C457, following the linear-transverse method, through an automated concrete analysis system (CAS 2000).

5.6 RAPID CHLORIDE PERMEABILITY TESTS (ASTM C1202/AASHTO T277)

Six 4 x 8 in. cylinders were cast for each concrete mix. The cylinders were divided into three sets. Each set was cured in the moisture room [23°C (73°F) and 100% humidity] for 28, 152, and 332 days, respectively, and was then subject to 28 days of dry curing before testing. Each concrete cylinder was cut using a diamond saw to obtain three 4 x 2 in. disks. The electrical conductivity of concrete was measured in accordance with ASTM C1202/AASHTO T277, which determines the electrical conductivity of concrete as an indicator of its resistance to the penetration of chloride ions. The test was conducted on each concrete mix at 56, 180, and 360 days.

5.7 SALT PONDING AND CHLORIDE ION PENETRATION TEST (AASHTO T259/T260)

Three concrete slabs of 12 x 12 x 3 in. were cast for each concrete mix. AASHTO T259 calls for 14 days moist curing followed by 28 days of drying, while ASTM C1543 specifies moist curing either until a specified strength is reached or 14 days, followed by 14 days of drying. Prior to ponding, the sides of ASTM C1543 slabs were sealed to prevent evaporation from those surfaces and to control the direction of chloride penetration. The ponded slabs were stored to allow air circulation around the slabs in a room at 50% relative humidity. A cover was placed over the solution pond to prevent water evaporation. AASHTO T259 calls for ponding period of 90 days. ASTM C1543 allows the user to select the ponding period based on the tested materials, recommending initial sampling at 90 days of salt ponding and subsequent sampling at 180 and 360 days according to AASHTO T260/ASTM C1218, ASTM C1151. After 28 days of wet curing and 28 days of dry curing, the specimens would be ponded in a 3% sodium chloride solution for 360 days.

5.8 WATER PERMEABILITY TEST, DIN 1048

Nine 8 x 8 x 5 in. prisms were cast for each concrete mix. The concrete prisms were divided into three sets. Each set was cured in the moisture room [23°C (73°F) and 100% humidity] for 28, 152, and 332 days, respectively, and was then subject to 28 days of dry curing before testing. The water permeability test was conducted at 56, 180, and 360 days. The prisms were assembled in the test cells, then a 100 kPa (1 bar) water pressure was applied by means of a water tank connected to an air compressor through a valve for the first 48 hours, followed by 300 kPa (3 bar) and 700 kPa (7 bar) pressures for 24 hours each.

The prisms were then removed from the cells, surface dried, and split in half perpendicular to the injected surface. The maximum depth of water penetration was measured on the two halves of the split specimen by means of a Vernier Caliper, and the average depth was deduced. The resulting values explained water permeability of concrete in terms of the depth of water penetration. Hedegaard and Hansen (1992) stated that concrete is “watertight” for all practical purposes when the penetration depth is less than 50 mm. Walz (1968) also reached the same conclusion after more than 50 years of experience with the DIN equipment in Germany.

Table 5-2 Standard Tests and Suggested Target Values

Tests	Suggested Values	Test Method
Fresh Properties		
Slump	2-4 in. **(3.5 in.)**	ASTM C143 AASHTO T 119
Yield unit weight		ASTM C138 AASHTO T121
Initial set time		ASTM C403 AASHTO T197
Total air content, plastic concrete	5%–8%, **(6.5%)**	ASTM C231 AASHTO T121
Hardened Durability Properties		
Hardened air void system Total air content, hardened concrete, (minimum surface area = 12 in^2)	**Curing**: 28 days moisture room/28 days dry. Start testing at 56 days 5%–8%, **(6.5%)**	ASTM C457
Maximum air void spacing factor	£0.010 in. (0.254 mm)	
Minimum air void specific surface	³ 500 $in.^{-1}$ (19.7 mm^{-1})	
Minimum void per in. (voids frequency)	³ 8 (315 per m)	
Cyclic Freezing and thawing tests, RDM and mass loss readings every 30 cycles	**Curing**: cure in moisture room for 56 days until testing time. start testing at 56 days	ASTM C666, Procedure A AASHTO T161
Rapid chloride ion permeability,	**Curing**: cure in moist room until 28 days prior to testing start testing at 56, 180 and 360 days	ASTM C1202 AASHTO T277
Salt ponding test and sampling chloride ion penetration.	**Curing**: 28 days moisture room/28 days dry Start ponding test at 56 days start testing at 90, 180 and 360 days	AASHTO T259/ ASTM C1543 AASHTO T260/ ASTM C1218 ASTM C1152
	0.5–1 in., < 0.03% Cl^- by wt. of concrete at 90 days 0.5–1 in., < 0.06% Cl^- by wt. of concrete at 6 months (1 year preferred)	
Water Permeability test (DIN 1048)	**Curing**: cure in moist room until 28 days prior to testing, Start testing at 56, 180, and 360 days	DIN 1048
Hardened Strength Properties		
3, 7, 14, 28, and 56-day compressive strength	**Curing**: moisture room until testing	ASTM C39, AASHTO T22
3, 7, 14, 28, and 56-day flexural strength	**Curing**: moisture room until testing	ASTM C78, AASHTO T97

CHAPTER 6 MATERIAL PROPERTIES

6.1 CEMENT SOURCES AND PROPERTIES

Cem1 source was used for Mix 1–Mix 4. Cem1 source had 6.7% IPA content, which exceeded the 5% limit; therefore, it was replaced by Cem1R. Mix 1–Mix 4 were repeated with Cem1R and were renamed Mix 1R–Mix 4R. In addition, Mix 13–Mix 16 were completed using Cem1R.

Cem2 was used for Mix 5–Mix 8 and Mix 17–Mix 20. Cem2 low and high IR levels were achieved by replacing a portion of Cem1R < 5% with fly ash and by blending them together with a mixer (see Figure 6-1) to reach the loss on ignition (LOI) and IR limits shown in Table 4-1. The preparation of Cem2 is explained in Appendix F.

Cem3 source was used for Mix 9–Mix 12 and Mix 21–Mix 24. Because of a shortage in Cem3, a new shipment was delivered and renamed Cem3R because it contained 0.8% limestone more than the original Cem3. Mix 9R–Mix 12R were completed using Cem3R.

As a result, **Cem1** and **Cem3** were produced to test the performance of concrete mixes with cement with more than 5% of limestone and IPA, and **Cem2** was prepared from Cem1R < 5% to test the performance of cement in concrete with higher amount of IR.

Figure 6-1 Preparing Cem2 by blending Cem1R with fly ash.

Cement specifications, including their chemical and physical properties, are shown in Appendix E. A summary of the chemical properties of cement, Blaine fineness, and amount of limestone plus IPA (Cem1 and Cem3) are shown in Table 6-1 and Table 6-2. The proportions of Cem1R < 5% needed to make Cem2 < 5% and Cem2 > 5% are shown in Appendix F.

Table 6-1 Chemical and Physical Properties of Cement

		Chemical Data, %										Blaine
Date	**Cement**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**C_3S**	**C_2S**	**C_3A**	**C_4AF**	**(m^2/Kg)**
Aug, 2011	Cem1 < 5%	20	4.7	2.7	63.3	2.8	2.5	56	15	8	8	378
Aug,2011	Cem1 > 5%	21	5.2	2.6	61.4	3.4	2.6	51	15	7	8	408
Oct,2011	Cem1**R <** 5%	19.8	4.8	2.8	63.1	2.6	2.6	55	15	8	8	380
Oct,2011	Cem1**R >** 5%	20.4	5.1	2.6	62.3	2.9	2.6	55	13	8	8	407
Aug,2011	Cem3 < 5%	19.2	4.7	2.7	62.1	3.8	3.9	56	13	8	8	385
Aug,2011	Cem3 > 5%	19.8	4.9	2.7	61.7	4	3.8	55	12	8	8	383
Jan,2013	Cem3R < 5%	19	4.8	2.7	61.7	3.5	3.9	53	14	8	8	378
Jan,2013	Cem3R > 5%	19.8	4.9	2.7	61.2	3.7	3.8	51	15	8	8	386

Note: Appendix E shows detailed report for the chemical and physical properties of cement and fly ash.

Table 6-2 Limestone and Inorganic Process Addition to Cement and IR Content

Cement	**Limestone, %**	**Inorganic Process Addition, %**		**Total**	**Insoluble Residue (IR), %**	**Loss on Ignition (LOI), %**
		Slag	**Fly Ash**			
Cem1 < 5%	3.8	0	0	**3.8**	na	2.3
Cem1 > 5%	3.2	6.7	0	**9.9**	na	2.0
Cem1**R** < 5%	4.2	0	0	**4.2**	0.49	2.54
Cem1**R** > 5%	3.8	4.5	0	**8.3**	0.50	2.32
Cem2 < 5%	4.2	0	0.81	5.01	**0.75**	2.54
Cem2 > 5%	4.2	0	3.17	7.37	**1.5**	2.55
Cem3 < 5%	2.6	0	0	**2.6**	0.20	1.5
Cem3 > 5%	2.5	3	0	**5.5**	0.18	1.4
Cem3**R** < 5%	3.4	0	0	**3.4**	0.21	1.9
Cem3**R** > 5%	3.1	3	0	**6.1**	0.15	1.7

Note: Cem2 < 5% and Cem2 > 5% were prepared by blending Cem1R < 5% and fly ash at UIC laboratory

6.2 FLY ASH PROPERTIES

The physical and chemical properties for fly ash are shown in Table 6-3.

Table 6-3 Physical and Chemical Properties of Fly Ash

Physical Properties		**Chemical Properties (%)**			
Fineness	Specific Gravity	$SiO_2 + Fe_2O_3$	SO_3	Moisture Content (%)	Loss on Ignition (LOI)
15.4	2.55	64.6	2.2	0.1	0.4

Note: Appendix E shows detailed report for the chemical and physical properties of cement and fly ash.

6.3 AGGREGATE PROPERTIES

The material properties for fine and coarse aggregates were analyzed in terms of specific gravities and water absorption, as shown in Table 6-4 and Table 6-5, respectively. Gradation samples for both aggregates were prepared and measured according to IDOT specifications. The coarse aggregate samples were prepared using a mechanical splitting device, as shown in Figure 6-2, while the fine aggregate samples were prepared by quartering the field sample, as shown in Figure 6-3. The gradation for fine and coarse aggregates was determined for each set of mix combinations. The sieve analysis and gradation curves are shown in Appendix B. The fine and coarse aggregate sieve analysis for Mix 1–Mix 4 and Mix 9–Mix 12 and their gradations are shown in Table B-1 and Table B-2, respectively. The fine and coarse aggregate sieve analysis for Mix 13–Mix 24 and their gradations are shown in Table B-3 and Table B-4, respectively. The fine and coarse aggregate sieve analysis for the remaining mixes and their gradations are shown in Table B-5 and Table B-6, respectively.

Fine aggregates, both natural and combined sand, were prepared and stored in sealed buckets with a moisture content ranging between 2% and 5%, as shown in Figure 6-4. Coarse aggregates were prepared to maintain saturated surface dry (SSD) condition. First, the coarse aggregates were soaked in water for at least 24 hours to ensure complete saturation. Second, the water was drained and the aggregates were spread on the ground until the SSD condition was reached. The coarse aggregates were then placed in sealed buckets as shown in Figure 6-5.

Table 6-4 Properties of Fine Aggregate

Aggregate Type	Source	Material Code	SSD Specific Gravity	Oven-Dried Specific Gravity	Water Absorption, %
Bluff City natural sand, South Beloit (FA_1)	52010-20	027FM02	2.642	2.613	1.1
Hanson Material Service, combined sand, Romeoville, (FA_2)	51972-02	029FM20	2.674	2.634	1.5

Table 6-5 Properties of Coarse Aggregate

Aggregate Type	Source	Material Code	SSD Specific Gravity	Oven-Dried Specific Gravity	Water Absorption, %
Hanson Material Service, Thornton, (CA_1)	50312-04	CM1101BD	2.697	2.654	1.6

Figure 6-2 Mechanical splitting device for coarse aggregate gradation sampling.

Figure 6-3 Quartering of fine aggregate for gradation sampling.

Figure 6-4 Aggregate stored in sealed buckets for maintaining the moisture content.

Figure 6-5 Coarse aggregate preparation for SSD condition.

CHAPTER 7 FRESH PROPERTIES OF CONCRETE

All concrete mixes were batched according to ASTM C192/AASHTO T126. IDOT PCC Mix Design Version V2.1.2 was used for proportioning the 24 concrete mixes. An example of the IDOT PCC Mix Design is shown in Appendix A. The mixture design proportioning was based on 1 yd^3. Several 1 to 3 ft^3 trial batches were made for each mix and were calibrated to yield an air content ranging between 5 and 8% and a slump of approximately 3.5 in. The fresh properties for each concrete mix were determined, including the measurement of slump, unit weight, air content (pressure meter), setting times, concrete mix temperature, and ambient temperature. The hardened properties included the evaluation of strength and durability. Each mix required 18 ft^3 of fresh concrete that was divided into three 6 ft^3 batches to cast the specimens for the strength and durability study. The first batch was used to cast the specimens for compressive strength, the second batch was used to cast the specimens for flexural strength, and the third batch was used to cast the required specimens for the durability study. The acceptance criteria for each batch were based on the specified values for air content and slump. The batches that failed to meet the specified values were rejected, and new batches were made. The mixer used in this study is shown in Figure 7-1.

Figure 7-1 Concrete mixer (7 ft^3 capacity).

A summary of the fresh properties for the 24 mixes is presented in Appendix D. The fresh properties measures are the fresh air content, unit weight of fresh concrete, ambient and concrete temperature and humidity, slump, and initial and final setting times of concrete.

7.1 FRESH AIR CONTENT

Mix 1–Mix 4 and Mix 9–Mix 12 concrete mixes were completed in summer 2011. Their fresh air contents, measured 12 minutes after discharging the mixture, ranged between 6.2% to 6.8%. The mixes experienced high air loss and their hardened entrained air content was at least 2% lower than the fresh air content. To limit air loss, the fresh air contents for the rest of the mixes were measured at 12 minutes after discharging at 1 in. slump. The final reported fresh air content was controlled to remain within the range of 7% to 8%. Some issues were encountered when the air content of the concrete mixes batched with MS Romeoville combined sand was controlled. These issues are reported in Chapter 3.

7.2 UNIT WEIGHT OF FRESH CONCRETE

The unit weights of fresh concrete mixes batched with natural sand (Mix 1–Mix 12) are shown in Table D-1 and the unit weights of the concrete mixes batched with combined sand (Mix 13–Mix 24) are shown in Table D-2. The values range between 143 and 148 pcf.

7.3 AMBIENT AND CONCRETE TEMPERATURE AND HUMIDITY

The ambient and concrete temperature and humidity for all mixtures, shown in Table D-1 and Table D-2, are subject to the environment of the concrete laboratory.

7.4 WORKABILITY

The slump was measured upon discharging of the concrete mix and 12 minutes afterwards. The concrete mixes were calibrated to achieve the desired slump and air content. The amount of plasticizers varied depending on the workability of the mix and the ability to get the desired 3.5 in. slump without exceeding the maximum amount of chemical admixtures recommended per mix. Once the desired slump and air content were met, the required samples were cast for each concrete mix. Figure 7-2 and Figure 7-3 show the slump versus the total amount of plasticizers added for concrete mixes batched with natural sand and combined sand, respectively.

Special attention was given to the effect of variables on the performance of concrete mixes when the concrete mixes were calibrated to reach the desired slump and air content. These variables included the cement source, addition of fly ash or slag, and sources of fine aggregates (natural or combined sand).

7.4.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

Concrete mixes with Cem < 5% were compared with concrete mixes having Cem > 5%; both mixes had the same material proportion and cement source. Most concrete mixes made with Cem > 5% required a less amount of admixtures to achieve a slump equivalent to mixes made with Cem < 5%. Figure 7-2, showing mixes batched with natural sand, indicates that the mixes made with Cem > 5% gave slightly higher slump, except for Mix 4R which required more admixture to retain a slump equivalent to Mix 3R. Figure 7-3, showing mixes batched with combined sand, indicates inconsistent variation between the slump and admixture dosage for mixes with Cem < 5% and Cem > 5%.

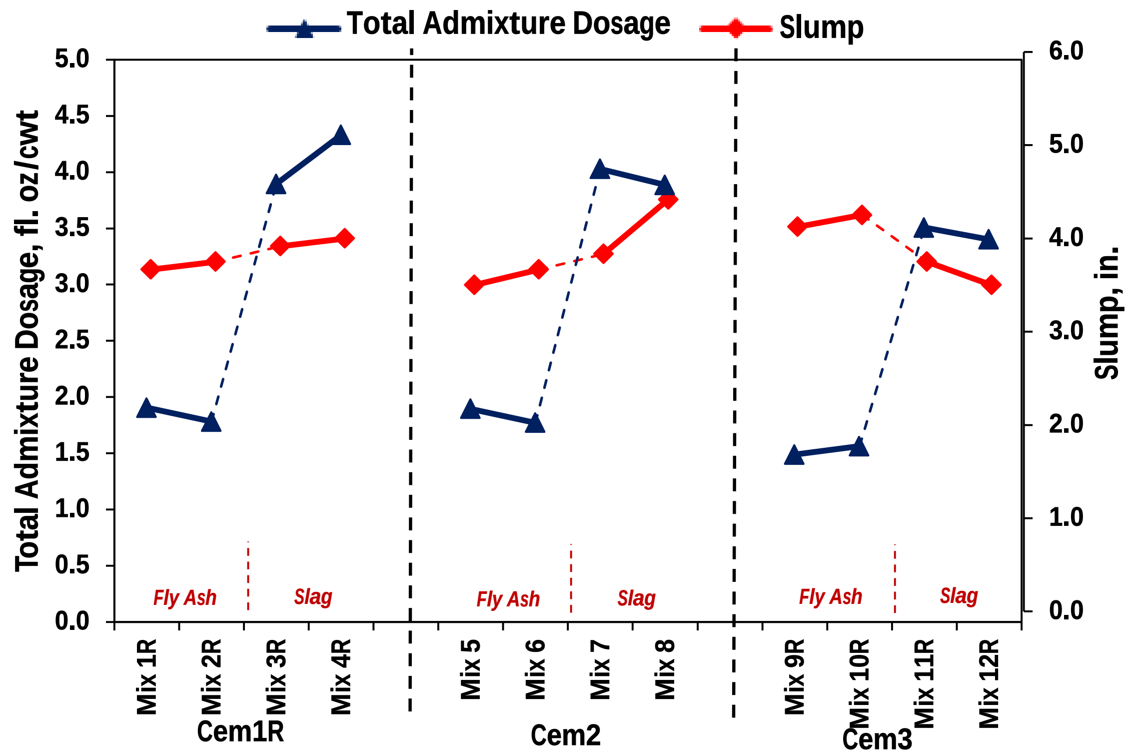

Figure 7-2 Total admixture dosage vs. slump for mixes with natural sand (Mix 1–Mix 12).

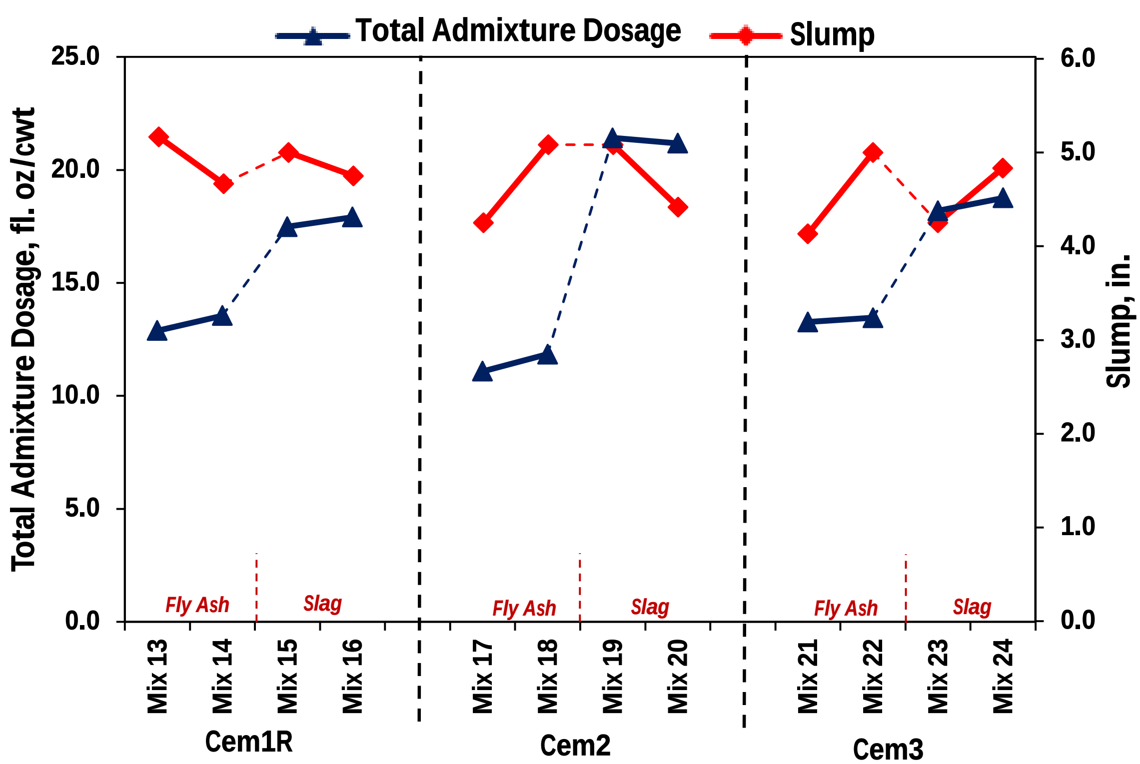

Figure 7-3 Total admixture dosage vs. slump for mixes with combined sand (Mix 13–Mix 24).

7.4.2 Effect of Fly Ash or Slag (SCMs)

The use of slag or fly ash affected the workability of concrete as shown in Figure 7-2 and Figure 7-3. Concrete mixes batched with fly ash had 0.02 w/cm less than concrete mixes batched with slag. Moreover, mixes with fly ash required fewer admixtures to maintain the desired slump in comparison to mixes batched with slag. The improved workability of using fly ash in comparison with slag is attributed to their different physical characteristics (specific surface area and surface texture). The specific surface area for fly ash is typically lower than slag, and the surface texture for fly ash is spherical in shape in comparison with slag, which has rough, angular-shaped grains (Kosmatka et al. 2011).

7.4.3 Effect of Fine Aggregate Source (Natural or Combined Sand)

Combined sand required a high dosage of HRWR and AEA to maintain workability. Consequently, the w/cm ratio increased to 0.44 for all mixes made with slag and batched with combined sand. On the other hand, the mixes made with fly ash and natural sand experienced higher slump than desired and the w/cm ratio was, therefore, reduced to 0.40.

7.5 INITIAL AND FINAL SETTING TIMES

Figure 7-4 Penetration resistance testing equipment, ASTM C403.

7.5.1 Testing Results

The setting time for the 24 concrete mixes was measured according to ASTM C403 (Time of concrete mixtures by penetration resistance). The apparatus used for this testing is shown in Figure 7-4. The initial and final setting times for mixes batched with natural sand and combined sand are shown in Table D-1 and Table D-2, respectively. Figure D-1 through Figure D-5 show the time setting plots for mixes made with Cem1 (Mix 1–Mix 4), Cem1R (Mix 1R–Mix 4R), Cem2 (Mix 5–Mix 8), Cem3 (Mix 9–Mix 12), and Cem3R (Mix 9R–Mix 12R), respectively, and batched with natural sand. Figure D-6 through Figure D-8 show the time setting plots for mixes made with Cem1R (Mix 13–Mix 16), Cem2 (Mix 17–Mix 20), and Cem3 (Mix 21–Mix 24), respectively, and batched with combined sand.

Initial and final setting results indicated ±5% difference for most concrete mixes having the same mix proportioning and cement source with Cem < 5% or Cem > 5%. However, Cem2 mixes with combined sand and fly ash showed a decrease in the initial set by 13% and final set by 8% for Mix 18 (Cem2 > 5%) with respect to Mix 17 (Cem2 < 5%).

7.5.2 Discussion of Test Results

The setting times were first tested for concrete mixes with Cem1 (Mix 1–Mix 4) and Cem3 (Mix 9–Mix 12) batched with natural sand. However, the results were excluded from the analysis because of inconsistency. The setting times for the remaining mixes having the same cement source were prepared and tested on the same day to avoid any inconsistency. The setting time results for the early mixes were replaced by mixes made with Cem1R (Mix 1R–Mix 4R) and Cem3R (Mix 9R–Mix 12R) batched with natural sand.

7.5.2.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

The setting time results for the 24 mixes indicated that the initial and final set times were slightly higher for concrete mixes with Cem > 5% than concrete mixes with Cem < 5%, knowing that both mixes had the same mix proportions. Table 7-1 shows the average setting time of different mix combinations and the difference in the setting time between mixes with Cem < 5% and Cem > 5%. Table 7-1 also compares using fly ash vs. slag and natural vs. combined sand. Most concrete mixes made with Cem > 5% experienced a slight increase in initial and final setting times. This increase is attributed to a slowdown in the hydration process between cement and water because of the addition of more limestone and IPA, and/or insoluble residue. These materials are considered inert and had negligible effect on the chemical reaction of cement paste.

7.5.2.2 Effect of Fly Ash or Slag (SCMs)

The addition of fly ash or slag to concrete mixes showed a significant difference in setting times. Fly ash prolonged initial and final set times in comparison with slag. As shown in Table 7-1, the average time needed to reach the initial and final set times for concrete mixes batched with fly ash and natural sand was, respectively, 37% and 31% longer than the set times for concrete mixes batched with slag and natural sand. In addition, the average time needed to reach the initial and final set times for concrete mixes batched with fly ash and combined sand was, respectively, 70% and 63% longer than the set times for concrete mixes batched with slag and combined sand.

7.5.2.3 Effect of Fine Aggregate Source (Natural or Combined Sand)

Natural sand resulted in quicker set time in concrete in comparison with combined sand. The initial and final set times for mixes made with Cem1R were significantly longer in the mixes batched with combined sand (Mix 13–Mix 16) than the mixes batched with natural sand (Mix 1R–Mix 4R). In addition, the performance of mixes made with Cem2 and Cem3 was similar to Cem1R mixes. As shown in Table 7-1, the average time needed to reach the initial and final set for concrete mixes batched with fly ash and combined sand was, respectively, 34% and 39% higher than the set times for concrete mixes batched with fly ash and natural sand. Moreover, the average time needed to reach the initial and final set times for concrete mixes batched with slag and combined sand was, respectively, 8% and 11% higher than the set times for concrete mixes batched with slag and natural sand.

Table 7-1 Average Setting Times for Different Mix Combinations and their Difference in %

Mix Combination			**Average Set Times, hr:min**		**Difference in the Average Set Time, %**					
					Cem > 5% vs. Cem < 5%		**Fly Ash vs. Slag**		**CS vs. NS**	
F.A.	**Cement**	**SCM**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
Natural Sand (NS)	**Cem < 5%**	**Fly Ash**	7:15	9:01	2.9	2.8	37.1	31.2	**with Fly Ash**	
	Cem > 5%		7:28	9:16					34.4	38.6
	Cem < 5%	**Slag**	5:20	6:52	1.1	2.7				
	Cem > 5%		5:24	7:04						
Combined Sand (CS)	**Cem < 5%**	**Fly Ash**	10:08	12:45	-4.7	-1.3	70.2	63.3	**with Slag**	
			(9:21)	(11:47)						
	Cem > 5%		9:40	12:35	(0.5)	(2.6)			8.2	11.3
			(9:24)	(12:06)						
	Cem < 5%	**Slag**	5:39	7:41	5.9	1.9				
	Cem > 5%		5:59	7:50						

For average of set time results for mixes with combined sand and fly ash excluding Mix 17 and Mix 18

CHAPTER 8 EXPERIMENTAL TEST RESULTS FOR COMPRESSIVE AND FLEXURAL STRENGTH OF HARDENED CONCRETE

Appendix C shows the hardened properties of concrete in terms of compressive and flexural strength for each mixture (Mix 1–Mix 24). The compressive and flexural strength results are presented in the charts and tables shown in Appendix G and Appendix H, respectively.

8.1 COMPRESSIVE AND FLEXURAL STRENGTH TEST RESULTS

The average compressive strength tables and charts for all concrete mixes are presented in Appendix G. Table G-1 shows the compressive strength test results for mixes batched with natural sand (Mix 1–Mix 12R), and Table G-2 shows the compressive strength test results for mixes batched with combined sand (Mix 13–Mix 24). The compressive strength tables also include fresh air content and unit weight values of each concrete mix. Air content variations between compression concrete mixes having the same cement source and fine aggregate type are less than 0.6%, as shown in Table G-1 and Table G-2. This gives a better understanding of the effect of replacing cement with limestone and IPA on the strength properties of concrete. Figure G-1 through Figure G-5 (for mixes batched with natural sand) show charts for mixes with Cem1 (Mix 1–Mix 4), Cem1R (Mix 1R–Mix 4R), Cem2 (Mix 5–Mix 8), Cem3 (Mix 9–Mix 12), and Cem3R (Mix 9R–Mix 12R), respectively. Figure G-6 through Figure G-8 (for mixes batched with combined sand) show charts for mixes with Cem1R (Mix 13–Mix 16), Cem2 (Mix 17–Mix 20), and Cem3 (Mix 21–Mix 24), respectively.

Flexural tests are extremely sensitive and test results are usually affected by the way the test is prepared, handled, cured, and conducted. Flexural specimens for all the concrete mixes were tested while wet because drying would yield lower strength. Average flexural strength tables and charts for all concrete mixes are presented in Appendix H. Table H-1 shows the flexural strength results for mixes batched with natural sand (Mix 1–Mix 12R), and Table H-2 shows the results for mixes batched with combined sand (Mix 13–Mix 24). The flexural strength tables also include fresh air content and unit weight values of each concrete mix. For the same cement source, the variation in the air content between each concrete mix for flexural beams batched with natural sand is less than 0.5%, as shown in Table H-1. However, concrete mixes for the flexural beams batched with combined sand were calibrated by dosing high amount of chemical admixtures, which caused a higher variation in air content as shown in Table H-2. Figure H-1 through Figure H-5 (for mixes bathed with natural sand) show charts for mixes with Cem1 (Mix 1–Mix 4), Cem1R (Mix 1R–Mix 4R), Cem2 (Mix 5–Mix 8), Cem3 (Mix 9–Mix 12), and Cem3R (Mix 9R–Mix 12R), respectively. Figure H-6 through Figure H-8 (for mixes batched with combined sand) show charts for mixes with Cem1R (Mix 13–Mix 16), Cem2 (Mix 17–Mix 20), and Cem3 (Mix 21–Mix 24), respectively.

It was observed that the average compressive and flexural strength for the 24 concrete mixes at 14 days exceeded the minimum target strength specified by IDOT of 3500 psi and 600 psi, respectively, except for the flexural strength for Mix 13 which had high air content.

8.2 DISCUSSION OF TEST RESULTS

Studies on the addition of limestone and IPA to concrete have shown that the strength properties of concrete are affected by the quality and quantity of limestone and IPA added, production method (i.e. blended or interground with cement), particle size distribution and shape, Blaine fineness, and the addition of SCMs. In this project, cements were prepared by intergrinding the limestone and adding IPA for Cem > 5% by partial intergrinding at CTL Group for Cem1 source and homogenous blending for Cem3 source. Cem2 was prepared from Cem1R < 5%, as shown in Appendix F. The Blaine fineness and strength properties of the cement sources used in this project are presented in Table 8-1. The Blaine fineness ranged between 378 and 408 m^2/Kg. The compressive strength properties were slightly higher with Cem > 5% in comparison with Cem < 5%, except for Cem3 which showed similar strength.

Figure 8-1 Test setup for compressive strength.

Table 8-1 Blaine Fineness and Strength Properties of Cement

Cement Source	% of Limestone and Inorganic Processing			Blaine Fineness (m^2/Kg)	Compressive Strength, psi			
	Limestone	Inorganic Process	Total		1 Day	3 Day	7 Day	28 Day
Cem1 < 5%	3.8	0	3.8	378		3470	4640	
Cem1 > 5%	3.2	6.7	9.9	408		3530	5020	
Cem1R < 5%	4.2	0	4.2	380	2070	3800	5020	6130
Cem1R > 5%	3.8	4.5	8.3	407	2010	3940	4650	6400
Cem3 < 5%	2.6	0	2.6	385	2960	4340	5070	
Cem3 > 5%	2.5	3	5.5	383	2920	4160	5020	
Cem3R < 5%	3.4	0	3.4	378	2910	4043	4648	5973
Cem3R > 5%	3.1	3	6.1	386	3183	4413	5220	6390
	1 MPa = 145.037 psi							

Note: The Cem1 > 5% has IPA of 6.7% which is more than 5%. As a result, Cem1 was reproduced to have an IPA of 4.5% which is smaller than 5%.

The comparison in the strength properties was based on concrete mixes having the same mix proportioning and batched with Cem < 5% or Cem > 5%. The effect of using SCMs (slag or fly ash) and fine aggregate source (natural or combined sand) on the strength properties of concrete was analyzed and discussed below.

8.2.1 Compressive Strength

Figure 8-2 and Figure 8-3 show plots for the compressive strength results for concrete mixes batched with natural sand and combined sand, respectively.

8.2.1.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

For the same cement source and mix proportioning, the compressive strength results for concrete mixes batched with natural sand showed that most mixes with Cem > 5% experienced slightly lower compressive strength at early curing age in comparison with mixes with Cem < 5%. However, most mixes with Cem > 5% demonstrated better strength gain over a 56 day curing period compared with Cem < 5% mixes.

Figure 8-2, showing mixes batched with natural sand (Mix 1–Mix 12), indicates that the 3 day compressive strength for mixes made with Cem1, Cem2, Cem3, and Cem3R > 5% was less than the compressive strength of mixes made with Cem1, Cem2, Cem3, and Cem3R < 5%, respectively. However, the 56 day compressive strength test results varied for each concrete mix. Thus, Mix 1R–Mix 4R with Cem1R was the only cement to yield better strength and strength gain at all ages for mixes made with Cem > 5% in comparison with mixes made with Cem < 5% and having the same mix proportion. In contrast, the compressive strength for mixes made with Cem2 > 5% was less at all ages than the strength for mixes made with Cem2 < 5% and having the same mix proportion. However, the mixes made with Cem2 > 5% demonstrated a slight strength gain compared with mixes made with Cem2 < 5% at all ages.

As shown in Figure 8-3, the compressive strength of concrete mixes batched with combined sand (Mix 13–24) showed similar trends in terms of strength gain to concrete mixes batched with natural sand. For mixes made with Cem1R, Mix 13 (Cem1R < 5% _fly ash) demonstrated better 3 day compressive strength and equivalent 56 day strength compared with Mix 14 (Cem1R > 5% _fly ash). Mix 15 (Cem1R < 5% _slag) demonstrated lower compressive strength than Mix 16 (Cem1R > 5% _slag) at all ages except at 56 day. Similarly, mixes with Cem3 > 5% resulted in higher compressive strength and strength gain at all ages in comparison with mixes with Cem3 < 5%, except for Mix 24 (Cem3 > 5% _slag) which gave lower 3 day compressive strength than Mix 23 (Cem3 < 5% _slag). Moreover, mixes made with Cem2 > 5% resulted in lower compressive strength at all ages than mixes with Cem2 < 5% having the same mix proportions.

This implies that the majority of concrete mixes made with Cem > 5% experienced slightly lower strength at early curing age (3 to 7 days) and better strength gain at long-term curing age (28 to 56 days) in comparison with Cem < 5% having the same cement source and mix proportions. The strength increase is also affected by the compressive strength properties of cement per ASTM C109, as shown in Table 8-1.

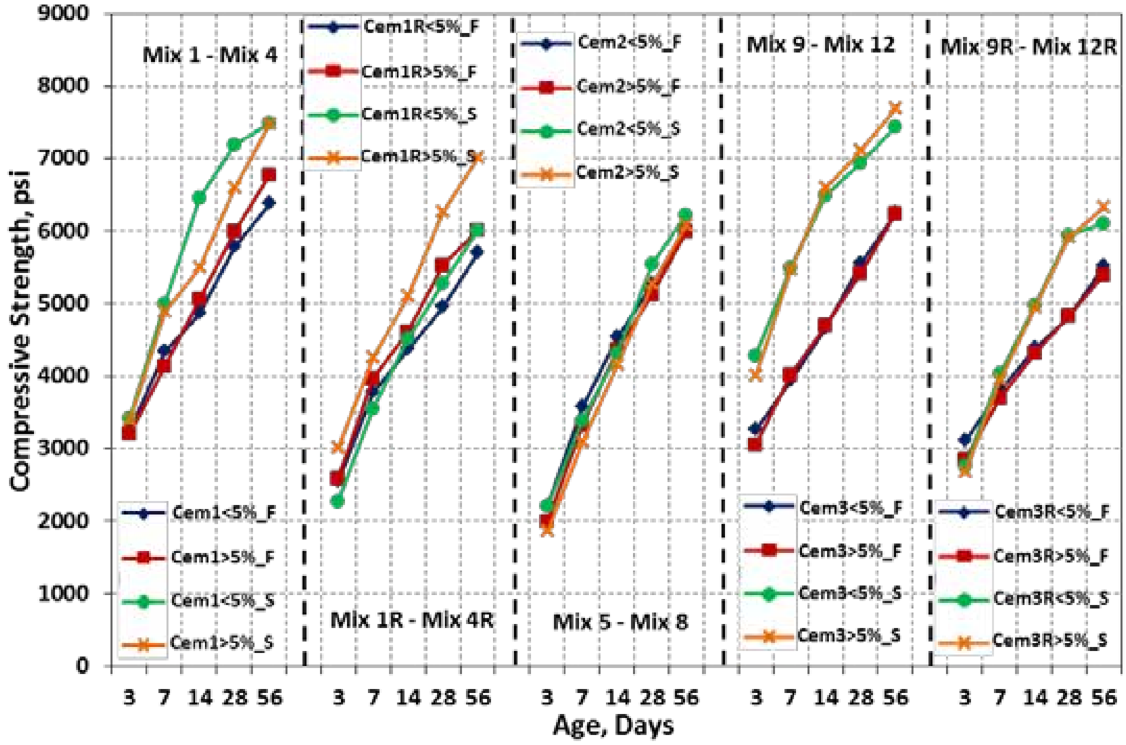

Figure 8-2 Compressive strength for mixes batched with natural sand (Mix 1–Mix 12R).

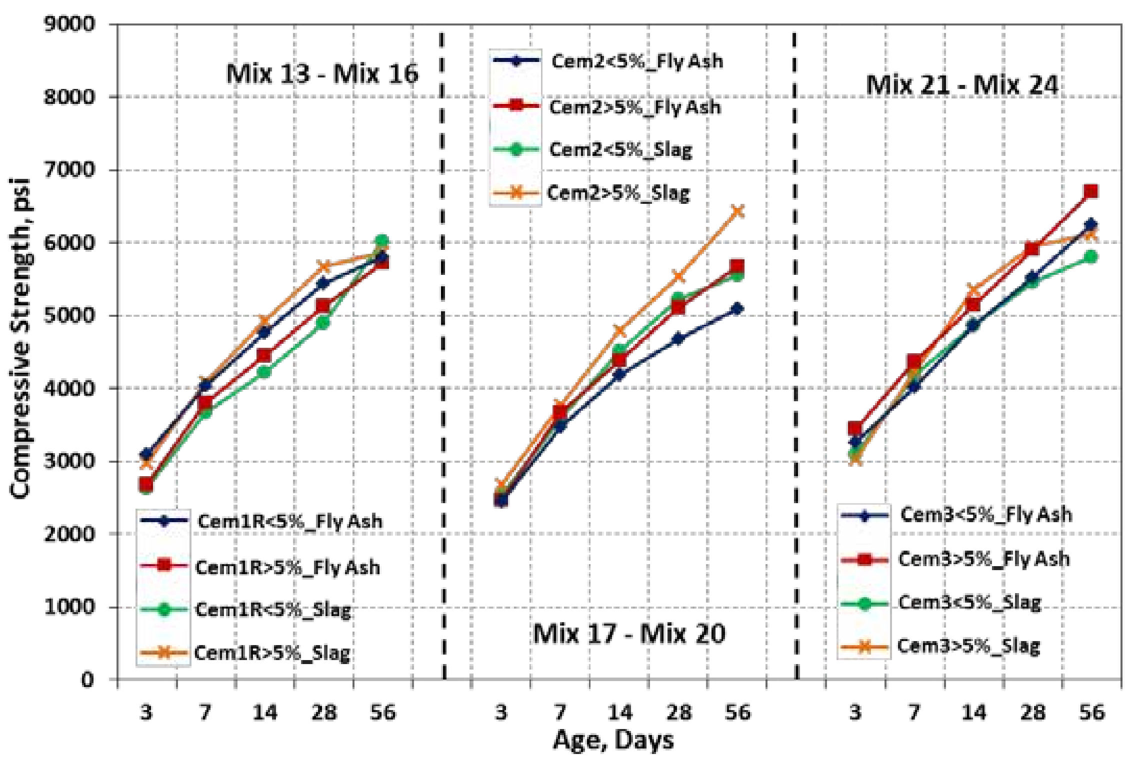

Figure 8-3 Compressive strength for mixes batched with combined sand (Mix 13–Mix 24).

8.2.1.2 Effect of Slag or Fly Ash (SCMs)

When slag was compared with fly ash for the same cement source and fine aggregate source, it was observed that the majority of concrete mixes batched with slag had better strength and strength gain than the mixes batched with fly ash. Figure 8-2 and Figure 8-3 show that, for the same cement source, concrete mixes made with slag gave better 56 day compressive strength than the mixes made with fly ash, except for mixes made with Cem3 and batched with combined sand (Mix 21–Mix 24); those mixes showed lower strength at all ages and lower strength development compared with the mixes made with fly ash. This strength drop was also affected by the high w/cm ratio used in mixes made with slag and combined sand (0.44) compared with the w/cm ratio used in the mixes made with fly ash and combined sand (0.42).

8.2.1.3 Effect of Fine Aggregate Sources (Natural or Combined Sand)

The source of fine aggregate used did not show significant effect on the compressive strength. Because of fresh air content and w/cm ratio variations between concrete mixes batched with natural sand and combined sand, it was hard to observe which type of fine aggregate had better effect on the compressive strength and strength gain.

8.2.2 Flexural Strength

Figure 8-3 and Figure 8-4 show plots for the flexural strength results for concrete mixes batched with natural sand and combined sand, respectively.

8.2.2.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

The flexural strength for the 24 concrete mixes, having the same cement source and mix proportioning, showed no favorable performance for any concrete mix with Cem > 5% or Cem < 5%, as shown in Figure 8-4. For concrete mixes batched with Cem1 and natural sand, the strength variation at different ages between Mix 1 (Cem1 < 5% _fly ash) and Mix 2 (Cem1 > 5% _fly ash) and between Mix 3 (Cem1 < 5% _slag) and Mix 4 (Cem1 > 5% _slag) was inconsistent. Similarly, for the same mix proportion, mixes made with Cem1R, Cem2, Cem3, and Cem3R and batched with natural sand showed inconsistent variation in the flexural strength.

The flexural strength for concrete mixes batched with combined sand (Mix 13–24), demonstrated similar performance compared with the results for mixes batched with natural sand, as shown in Figure 8-5. No favorable performance observed on whether Cem > 5% or Cem < 5% was used. For example, Mix 15 (Cem1R < 5% _slag) gave equivalent strength to Mix 16 (Cem1R > 5% _slag) at 3 and 28 days and better strength at 7, 14, and 28 day. However, Mix 19 (Cem2 < 5% _slag) gave higher strength than Mix 20 (Cem2 > 5% _slag) at 3 and 7 days and lower strength at 56 days. Therefore, using more than 5% of limestone and IPA, and increasing the insoluble residue content to 1.5% in cement in concrete did not cause significant changes in the flexural strength.

8.2.2.2 Effect of Fly Ash or Slag (SCMs)

When slag was compared with fly ash for the same cement source and fine aggregate type, it was observed that the majority of concrete mixes batched with slag had better strength gain than the mixes batched with fly ash. For the same cement source, concrete mixes batched with slag gave better 28 and 56 day flexural strength than the mixes batched with fly ash.

8.2.2.3 Effect of Fine Aggregate Sources (Natural or Combined Sand)

For the same cementitious combination, most concrete mixes batched with combined sand had better flexural strength than the mixes batched with natural sand from 3 to 14 days and lower flexural strength at 28 and 56 day. However, mixes made with Cem3 cement, showed favorable performances for concrete mixes batched with natural sand (Mix 9R–Mix 12R) at all ages than combined sand (Mix 21–Mix 24).

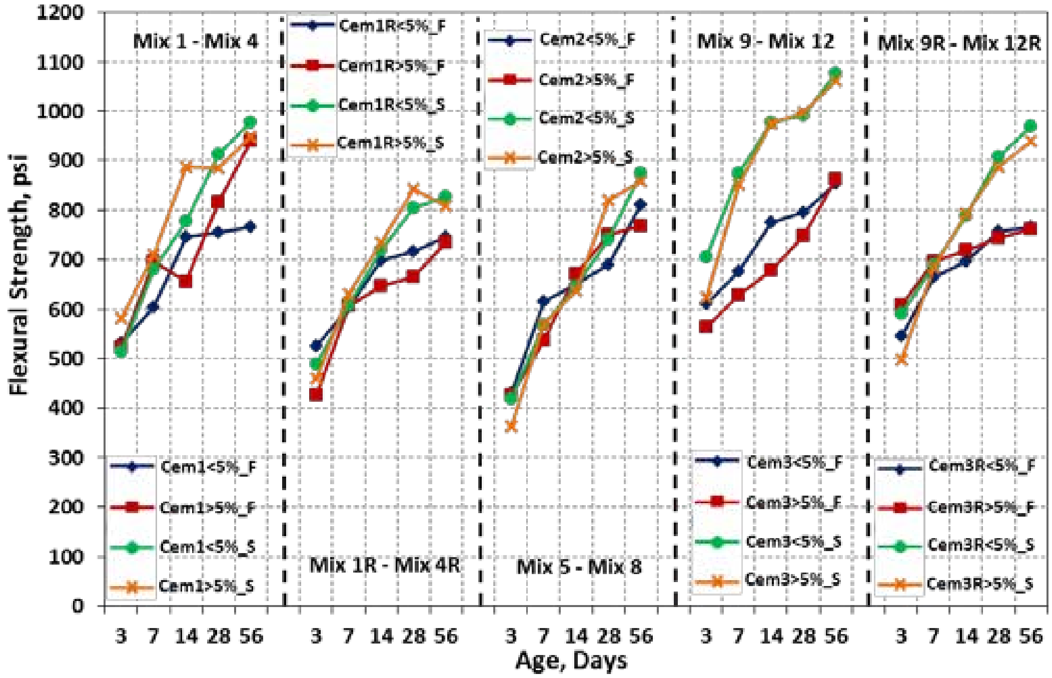

Figure 8-4 Flexural strength for mixes batched with natural sand (Mix 1–Mix 12R).

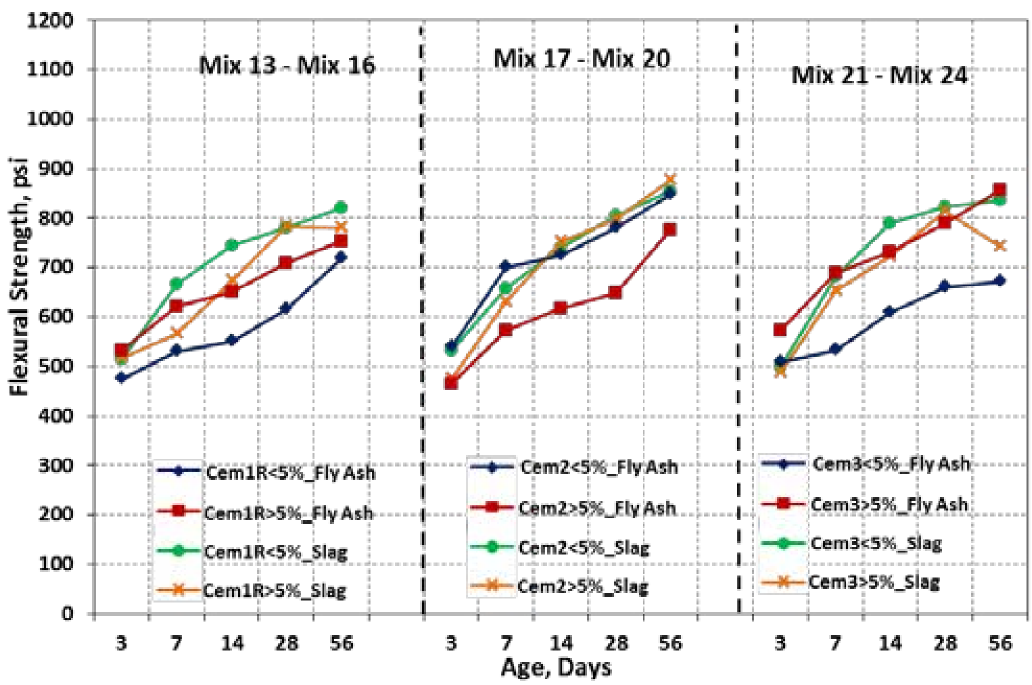

Figure 8-5 Flexural strength for mixes batched with combined sand (Mix 13–Mix 24).

CHAPTER 9 EXPERIMENTAL TEST RESULTS FOR DURABILITY OF HARDENED CONCRETE

The hardened properties of concrete include air void system parameters, freeze/thaw tests, rapid chloride penetration resistance (coulomb), water permeability (DIN 1048), and chloride penetration (salt ponding).

9.1 HARDENED AIR VOID SYSTEM PARAMETERS, ASTM C457

The specimens for this test were prepared in accordance with ASTM C457 (Microscopical Determination of Parameters of the Air Void System in Hardened Concrete). For each concrete mix, two 6 x1 in. concrete specimens were cut from 6 x 12 in. concrete cylinders using a diamond blade concrete saw. Specimens were then lapped on a sanding machine until a desired surface for microscopic determination was reached. The testing setup for the hardened air measurement is shown in Figure 9-1.

9.1.1 Testing Parameters and Results

The hardened air content was measured using the linear traverse method per ASTM C457. The test determines the amount and distribution of air bubbles within the concrete specimen. The amount, maximum size, and distribution of air bubbles are the major parameters affecting the resistance against freeze/thaw. Entrained air bubbles that are less than or equal to 1 mm in size were measured because studies showed that the size of air bubbles contributing to frost resistance ranges between 10 um to 1mm. Larger bubbles are classified as entrapped air and are less evenly distributed than entrained air. This type of bubbles hardly contributes to freeze/thaw resistance and has undesirable effect on the concrete strength.

The IDOT specification for air content in concrete is 5% to 8% for the fresh and hardened stages of concrete. The hardened entrained air results were recorded according to the following parameters:

- Void frequency (1/in.) or void per unit length, which represents the number of air voids intercepted by a traverse line divided by the length of that line. It is suggested to have 8 per in. minimum void frequency.
- Specific surface (1/in.), which is the surface area of the air voids divided by their volume. It gives an indirect indication of the size and distribution of air bubbles in the specimen. It is suggested to have 500 1/in. minimum specific surface.
- Spacing factor, which designates the distance needed for water to travel from the cement paste to the periphery of the air void. It is suggested to have a maximum spacing factor <0.01 in.

The criteria for minimum void frequency, minimum specific surface, and maximum spacing factor are the same as those recommended for Wacker Drive Viaduct Reconstruction (Evaluation of HPC Mixes for Performance and Durability Characteristics).

The hardened entrained air results for the 24 concrete mixes and the repeated ones are presented in Appendix L. Table L-1 through Table L-5 show the hardened air results for mixes batched with natural sand and made with Cem1 (Mix 1–Mix 4), Cem1R (Mix 1R–Mix 4R), Cem2 (Mix 5–Mix 8), Cem3 (Mix 9–Mix 12), and Cem3R (Mix 9R–Mix 12R), respectively. Table L-6 through Table L-8 show the hardened air results for concrete mixes batched with combined sand and made with Cem1R (Mix 13–Mix 16), Cem2 (Mix 17–Mix 20), and Cem3 (Mix 21–Mix 24), respectively.

Table 9-1 and Tale 9-2 show a summary of the hardened entrained air results and a comparison of the fresh and hardened air content for concrete mixes batched with natural sand (Mix 1–Mix12) and for mixes batched with combined sand (Mix 13–Mix 24), respectively. The red cells indicate that the specimen failed to meet IDOT specifications.

For mixes batched with natural sand, the amount of air voids in the fresh and hardened concrete ranged from losing 3% in Mix 10R to gaining 0.6% in Mix 4R, as shown in Table 9-1. The average air change between the fresh and hardened stages was estimated at 1.8% air loss with 1.21% standard deviation. For mixes batched with combined sand, the amount of air voids in fresh and hardened concrete ranged from losing 3.7% for Mix 15 to gaining 1.9% for Mix 21R, as shown in Table 9-2. The average air change in the fresh and hardened stages was estimated at 1.5% air loss with 1.28% standard deviation. The difference between fresh and hardened air indicated the amount of entrapped and water pockets in the concrete mixes because only entrained air was measured in the hardened stage. Table 9-1 and Table 9-2 show the material properties and mix proportion has insignificant effect on air change in concrete in the fresh and hardened stages.

The hardened air content for Mix 1–Mix 4 and Mix 9–Mix 12, shown in Table 9-1, and Mixes 13, 15, and 16, shown in Table 9-2, failed to meet IDOT minimum air content condition of 5%. In addition, the freeze/thaw specimens related to these mixes failed, as will be discussed in the following section. On the other hand, some mixes such as Mix4R, Mix 9R, 11R, and 12R, shown in Table 9-1, and Mix 23, shown in Table 9-2, had adequate hardened air content; however, those mixes failed to pass the freeze/thaw test as well.

Figure 9-1 Microscopic determination of air void system parameters (ASTM C457).

Table 9-1 Air Void System Parameters of Hardened Concrete for Mixes with Natural Sand

Mix No.	Mix Design	Air Content %		Difference between Fresh and Hardened Air (%)	Hardened Air (ASTM C457)			Freeze/Thaw after 300 Cycles (ASTM C666)
		Fresh	Hardened Entrained		Voids per Inch (>8)	Specific Surface, 1/in (>500)	Spacing Factor, in. (<0.01)	
1	Cem1 < 5% _F	6.5	4.34	2.16	11.26	1036.4	0.0046	FAIL
2	Cem1 > 5% _F	7.0	3.13	3.87	6.88	880.3	0.0063	FAIL
3	Cem1 < 5% _S	6.5	4.06	2.44	6.41	632.1	0.0079	FAIL
4	Cem1 > 5% _S	6.5	3.66	2.84	6.10	665.9	0.0079	FAIL
1R	Cem1R < 5% _F	7.8	8.04	-0.24	16.82	835.9	0.0035	PASS
2R	Cem1R > 5% _F	7.5	7.26	0.25	15.03	829.2	0.0039	PASS
3R	Cem1R < 5% _S	7.5	7.47	0.04	13.41	718.4	0.0045	PASS
4R	Cem1R > 5% _S	7.3	7.92	-0.62	16.26	821.3	0.0037	FAIL
5	Cem2 < 5% _F	7.9	6.09	1.81	12.03	793.3	0.0049	PASS
6	Cem2 > 5% _F	8.1	6.91	1.20	12.58	729.2	0.0047	PASS
7	Cem2 < 5% _S	8.0	7.13	0.87	11.70	657.2	0.0051	PASS
8	Cem2 > 5% _S	8.0	5.90	2.10	10.25	694.0	0.0059	PASS
9	Cem3 < 5% _F	6.6	3.76	2.84	7.58	806.4	0.0063	FAIL
10	Cem3 > 5% _F	6.5	3.92	2.58	9.41	960.8	0.0052	FAIL
11	Cem3 < 5% _S	6.6	3.9	2.7	6.48	664.3	0.0077	FAIL
12	Cem3 > 5% _S	6.3	3.72	2.58	7.61	818.6	0.0064	FAIL
9R	Cem3R < 5% _F	8.0	5.29	2.72	8.10	612.9	0.0072	FAIL
10R	Cem3R > 5% _F	7.5	4.50	3.00	6.05	538.4	0.0088	PASS
11R	Cem3R < 5% _S	8.1	7.17	0.93	14.06	784.4	0.0042	FAIL
12R	Cem3R > 5% _S	8.0	5.75	2.26	10.12	704.2	0.0059	FAIL

Table 9-2 Air Void System Parameters of Hardened Concrete for Mixes with Combined Sand

Mix No.	Mix Design	Air Content %		Difference between Fresh and Hardened Air (%)	Hardened Air (ASTM C457)			Freeze/Thaw after 300 Cycles (ASTM C666)
		Fresh	Hardened Entrained		Voids per Inch (>8)	Specific Surface, 1/in (>500)	Spacing Factor, in. (<0.01)	
13	Cem1R < 5% _F	6.9	4.06	2.84	7.62	750.8	0.0067	FAIL
13R	Cem1R < 5% _F	8	9.08	-1.08	20.50	902.9	0.0030	PASS
14	Cem1R > 5% _F	7.4	5.99	1.41	10.33	691.6	0.0059	PASS
15	Cem1R < 5% _S	8.1	4.34	3.76	6.14	565.3	0.0087	FAIL
15R	Cem1R < 5% _S	7.8	5.88	1.92	11.77	798.2	0.0052	PASS
16	Cem1R > 5% _S	6.9	4.99	1.91	6.97	558.5	0.0082	FAIL
16R	Cem1R > 5% _S	8.0	6.50	1.51	12.83	799.9	0.0047	PASS
17	Cem2 < 5% _F	7.9	5.95	1.95	14.89	999.9	0.0041	PASS
18	Cem2 > 5% _F	8	5.80	2.21	14.01	969.4	0.0043	PASS
19	Cem2 < 5% _S	7.5	5.91	1.60	13.97	942.6	0.0044	PASS
20	Cem2 > 5% _S	7.8	6.05	1.76	11.70	773.6	0.0052	PASS
21	Cem3 < 5% _F	6.6	5.39	1.22	6.78	503.5	0.0088	PASS
22	Cem3 > 5% _F	7.2	6.46	0.74	11.38	705.9	0.0053	PASS
23	Cem3 < 5% _S	7.8	6.21	1.60	8.78	565.9	0.0069	FAIL
23R	Cem3R < 5% _S	7.1	4.70	2.40	10.43	890.7	0.0045	PASS
24	Cem3 > 5% _S	7.3	5.92	1.38	7.35	495.9	0.0083	PASS

9.2 FREEZE/THAW TEST

9.2.1 Testing Procedure

The freeze/thaw test is conducted in accordance with ASTM C666, Procedure A, and is performed over 300 cycles. Each cycle ranged between 3 and 3.5 hours with 2 to 2.5 hours freezing and 1 hour thawing. The setup for the freeze/thaw test is shown in Figure 9-2.

The damage assessment caused by freeze/thaw was performed in accordance with ASTM C215. The method assesses deterioration in the concrete specimen based on its dynamic response or resonant frequency. Figure 9-3 shows a specimen with the test setup to measure the transverse frequency. An accelerometer is attached at one end of the specimen to record the frequency through exciting vibration by using impact hammer. Testing was repeated at regular intervals ranging between 30 and 36 cycles and the RDM and durability factor (DF) were recorded at each interval and after 300 cycles, respectively. The percentage of RDM is calculated as follows:

$$P_c = \frac{n_c^2}{n^2} \times 100$$

where P_c is the RDM after c cycles, n_c is the resonant frequency after c cycles, and n is the initial resonant frequency.

The DF is calculated as follows:

$$DF = \frac{N}{M} \times 100$$

where N is the number of completed cycles and M is the duration of the test, which is 300 cycles.

Figure 9-2 Freeze/thaw test cabinet, ASTM C666, procedure A.

Figure 9-3 DK-5000 dynamic resonance frequency tester, ASTM C215.

9.2.2 Freeze/Thaw Test Results

Appendix M includes the RDM and DF results for all the freeze/thaw specimens of the 24 concrete mixes and the repeated mixes. Table M-1 through Table M-5 show the freeze/thaw results for concrete specimens made with Cem1, Cem1R, Cem2, Cem3, and Cem3R, respectively, and batched with natural sand (Mix 1–Mix 12). Table M-6 through Table M-8 show the freeze/thaw results for concrete specimens made with Cem1R, Cem2, and Cem3, respectively, and batched with combined sand (Mix 13–Mix 24). ASTM C494 (Standard Specification for Chemical admixtures for Concrete) states that when chemical admixtures are used in air-entrained concrete, the concrete DF should be minimum 80% after 300 cycles of freeze/thaw testing.

Mix 1–Mix 4 (Cem1) and Mix 9–Mix 12 (Cem3), which were batched with natural sand, were the first set of concrete specimens tested for freeze/thaw. As shown in Table M-1, Mix 1–Mix 4 showed a DF less than 80% after 300 cycles. The mixes fresh air contents ranged between 6.0% and 7.0% (average of 6.5%), and their hardened air content (entrained air) ranged between 3.13% for Mix 2 and 4.34% for Mix 1. The mixes hardened air contents were less than IDOT’s recommended air content of 5.0% to 8.0% (average of 6.5%).

Table M-4 shows the specimens results for Mix 9–Mix 12. These specimens experienced a DF less than 80% after 300 cycles. Their fresh air content ranged between 6.3% and 6.6% and their hardened air content (entrained air) were in the range of 3.72% for Mix 12 and 3.92% for Mix 10. The mixes hardened air contents were less than IDOT’s recommended air content of 5.0% to 8.0% (average of 6.5%).

The freeze/thaw results for Mix 1–Mix 4 and Mix 9–Mix 12 show that the freeze/thaw specimens failed because of the inadequate amount of hardened entrained air measured under the microscopic air void system. To verify this inadequacy, the hardened air specimens for those mixes were sent to Holcim Laboratories where image analysis was performed to determine the total hardened air content.

A comparison of hardened air results between UIC and Holcim is presented in Section 3.3. The results indicate a large gap between total air and entrained air. For that reason, a sensitivity study was conducted to maintain air stability in the fresh and hardened states. The study was based on the effect of chemical admixtures, provided by W.R. Grace, and the effect of coarse aggregate gradation on the air content of concrete mixes. More than one hundred of trial concrete mixes, 2 ft^3 in size, were performed to study and determine the admixture dosage needed to control the air loss and maintain air stability between the fresh and hardened states. Fresh air was measured at 12 and 30 minutes after discharge and at a slump level of 1in. or after filling all concrete casts. In addition, cylinders were cast and the compressive strength was measured for each trial mix to establish a correlation between the recorded fresh air content and strength. It was concluded that fresh air content should range between 7% and 8% at 1in. slump in order to have adequate hardened air (entrained air) for the frost resistance per ASTM C666, Procedure A.

The freeze/thaw tests were repeated for Mix 1–Mix 4 and Mix 9–Mix 12 using Cem1R (Mix 1R–Mix 4R) and Cem3R (Mix 9R–Mix 12R). Fresh air content ranged between 7% and 8% and hardened entrained air exceeded 5%, as shown in Table 9-1. The results of Cem1R mixes (Mix 1R–Mix 4R) and Cem3R mixes (Mix 9R–Mix 12R) are shown in Table M-2 and in Table M-5, respectively. Cem1R mixes exceeded the 80% DF after 300 cycles, except for Mix 4R which had enough air content, but nevertheless failed the freeze/thaw test. The fresh air content for Cem1R mixes ranged between 7.3% for Mix 4R and 7.8% for Mix 1R and their hardened air content ranged between 7.26% for Mix 2R and 8.04% for Mix 1R. For Cem3R mixes, Mix 10R, which had the lowest hardened entrained air parameters (4.5% air voids, 6.05 voids frequency, and 0.0088 in. specific surface) in comparison with Mixes 9R, 11R, and 12R, was the only mix to pass the freeze/thaw test after 300 cycles. The fresh air content for Cem3R mixes ranged between 7.5% for Mix 10R and 8.1% for Mix 11R and their hardened air content ranged between 4.5% for Mix 10R and 7.17% for Mix 11R. The unexpected failure for Cem1R mixes (Mix 4R) and Cem3R mixes (Mix 9R, 11R, and 12R) was related to failure in the coarse aggregates at early freeze/thaw cycles.

Mix 13–Mix 16 (Cem1R) and Mix 21–Mix 24 (Cem3), which were batched with combined sand, were the second set for concrete specimens tested for freeze/thaw. These mixes contained higher amount of fresh air content to compensate for the air loss and to preserve a higher amount of entrained air in the hardened state.

Table M-6 shows the freeze/thaw results for Mix 13–Mix 16 specimens. The fresh air content for Mix 13–Mix 16 ranged between 6.9% for Mix 16 and 8% for Mixes 13R and 16R, and their hardened air content ranged between 4.34% for Mix 15 and 9.08% for Mix 13R. Mix14 (Cem1R > 5%_ fly ash) demonstrated good DF results. However, the DF values for Mixes 13 (Cem1R < 5%_fly ash), and 15 and 16 (Cem1R and slag) were below 80% after 300 cycles although the mixes had adequate fresh air content. This failure was attributed to the low hardened air content (entrained air) of the three mixes compared with Mix 14, which had an acceptable amount of hardened air. The low hardened air content in Mixes 13, 15, and 16 might be attributed to a high rate of air loss in the fresh stage and to a time difference between measuring the fresh air content and filling the freeze/thaw specimens. Freeze/thaw tests for Mixes 13, 15 and 16 were repeated with Mixes 13R, 15R, and 16R. The repeated mixes had adequate hardened air and showed good DF after 300 cycles, as shown in Table M-6.

Mix 23 (Cem3 < 5%_slag), shown in Table M-8, is the only mix that experienced DF below 80% after 300 cycles. The fresh air content for Mix 21–Mix 24 ranged between 6.6% for Mix 21 and 7.8% for Mix 23 and their hardened air content (entrained air) ranged between 4.7% for Mix 23R and 6.46% for Mix 22, with 6.21% for Mix 23. Although Mix 23 had an acceptable amount of air, it failed to reach a DF above 80% after 300 cycles. The failure of Mix 23 is similar to the failure of Mix 9R, 11R, and 12R, where signs of aggregate pop-outs appeared at early freeze/thaw cycles. The freeze/thaw test for Mix 23 was repeated with Mix 23R. The hardened air content for Mix 23R was 4.7% but it gave an excellent DF after 300 cycles as shown in Table M-8.

The third set of concrete specimens tested for freeze/thaw were Mix 5–Mix 8 (Cem2 and natural sand) and Mix 17–Mix 20 (Cem2 and combined sand). These mixes gave the best performance in terms of DF when compared with the previous mixes.

Table M-3 shows the freeze/thaw results for Mix 5–Mix 8. The fresh air content was well controlled and ranged between 7.9% and 8.1%. The hardened entrained air content ranged between 5.9% for Mix 8 and 7.13% for Mix 7. The four mixes showed proper resistance to the freeze/thaw test with DF values ranging between 87% and 95%.

Table M-7 shows the freeze/thaw results for Mix 17–Mix 20. The fresh air content for these mixes ranged between 7.5% and 8.0% and their hardened air content ranged between 5.8% for Mix 18 and 6.05% for Mix 20. These mixes passed the freeze/thaw test after 300 cycles with excellent DF ranging between 92.9% and 94.7%.

The performance of the third set of concrete mixes proved that the amount of air content, specifically the entrained air, is the main contributor to resistance against freeze/thaw attacks. Moreover, the freeze/thaw results highlight the basic requirements for the spacing factor, specific surface, and voids frequency. Most of the concrete specimens that failed to pass the freeze/thaw test met the requirements for specific surface, spacing factor, and void frequency per ASTM C457. For example, the spacing factors for the first set of mixes (Mix 1–Mix 4 and Mix 9–Mix 12), were acceptable at less than 0.01 in., as shown in Table 9-1, but the entrained air was insufficient for the freeze/thaw resistance. Similarly, the spacing factors for the second set of mixes (Mix 13–Mix 16 and Mix 21–Mix 24) were less than 0.01 in., as shown in Table 9-2. However, Mix 15 and Mix 16, which had the lowest hardened air of 4.34% and 4.99%, respectively, showed the two lowest durability factors and failed to pass the freeze/thaw test. As a result, further investigation is recommended to optimize the hardened air parameters per ASTM C457 for the best performance of the concrete mixes in this project against the freeze/thaw attack.

9.2.3 Discussion of Freeze/Thaw Test Results

Table 9-3 and Table 9-4 present a summary of the test results for the durability factor and mass loss after 300 cycles of freeze/thaw specimens for concrete mixes batched with natural sand (Mix 1–Mix 12) and combined sand (Mix 13–Mix 24), respectively. The performance of concrete specimens subjected to freeze/thaw cycles were assessed by two types of deteriorations: The internal micro cracking observed by the DF after 300 cycles and the surface scaling examined by visual inspection and mass loss.

9.2.3.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

Several factors were involved in calibrating air content in a fresh concrete mix to preserve adequate amount of entrained air in the hardened state. Cem1 and Cem3 mixes, shown in Table 9-3, failed to pass the freeze/thaw test after 300 cycles because of insufficient entrained air; whereas, Cem2 mixes demonstrated good performance because the higher amount of entrained air. However, the DF results did not show significant differences or consistent changes between specimens of the same mix proportion and cement source with Cem < 5% or Cem > 5%, regardless of passing or failing the test. For example, DF for Mix 3 (Cem1 < 5% _slag) was slightly higher than DF for Mix 4 (Cem1 > 5% _slag); whereas, DF for Mix 9 (Cem3 < 5% _slag), which had the same mix proportion as Mix 3 andCem3 source cement, was lower than DF for Mix 10 (Cem3 > 5% _slag). In addition, the DF values for Cem2 mixes and natural sand (Mix 5–Mix 8) exhibited similar performance between Mix 5 (Cem2 <5%_fly ash) and Mix 6 (Cem2 > 5%_fly ash) and between Mix 7 (Cem2 < 5%_slag) and Mix 8 (Cem2 > 5%_slag) .Moreover, Table 9-4 for DF of mixes batched with combined sand (Mix 13–Mix 24) shows an inconsistent variation in performance based on the use of Cem < 5% or Cem > 5%. The variation in DF was primarily attributed to the amount of entrained air in the mix. For example, Mix 13R and Mix 14 of Cem1R and fly ash passed the freeze/thaw test with a DF slightly higher for Mix 13R than Mix 14, while Mix 13 failed the freeze/thaw test because of its inadequate hardened entrained air. However, Mix 15 and Mix 16 of Cem1R and slag failed to pass the freeze/thaw test because of the insufficient amount of entrained air with a DF slightly higher for Mix16 than Mix 15. Moreover, Cem3 mixes (Mix 21–Mix 24) showed variable and inconsistent DF results. In contrast, all Cem2 mixes (Mix 17–Mix 20) were very close in range and gave excellent DF results. Similarly, a comparison of mass loss between mixes with Cem < 5% and mixes with Cem > 5% specimens showed insignificant differences and failed to indicate signs of high level of spalling and bad scaling.

The DF test results for the 24 concrete mix combinations proved that the addition of limestone and IPA, and the increase in IR content in cement gave equivalent performance to Cem < 5% for freeze/thaw resistance in concrete.

Table 9-3 Summary of F/T Results for Mixes Batched with Natural Sand (Mix 1–Mix 12)

Mix No.	Mix Design	Air Content, %		ASTM C457	Durability Factor		% of Mass Loss after 300 Cycles
		Fresh	Hard.	Voids per Inch, (>8)	After 300 Cycles	Condition	
1	Cem1 < 5% _F	6.5	4.34	11.26	**68.67**	**Failed after 240 Cycles**	0.078
2	Cem1 > 5% _F	7.0	3.13	6.88	**58.24**	**Failed after 210 Cycles**	0.192
3	Cem1 < 5% _S	6.5	4.06	6.41	**46.30**	**Failed after 180 Cycles**	0.190
4	Cem1 > 5% _S	6.5	3.66	6.10	**43.94**	**Failed after 150 Cycles**	0.006
1R	Cem1R < 5% _F	7.8	8.04	16.82	**80.18**	**PASS**	0.158
2R	Cem1R > 5% _F	7.5	7.26	15.03	**85.84**	**PASS**	0.843
3R	Cem1R < 5% _S	7.5	7.47	13.41	**80.48**	**PASS**	0.03
4R	Cem1R > 5% _S	7.3	7.92	16.26	**71.44**	**Failed after 275 Cycles**	0.00
5	Cem2 < 5% _F	7.9	6.09	12.03	**93.57**	**PASS**	1.126
6	Cem2 > 5% _F	8.1	6.91	12.58	**95.13**	**PASS**	0.879
7	Cem2 < 5% _S	8.0	7.13	11.70	**89.48**	**PASS**	0.900
8	Cem2 > 5% _S	8.0	5.90	10.25	**87.74**	**PASS**	1.158
9	Cem3 < 5% _F	6.6	3.76	7.58	**62.70**	**Failed after 270 Cycles**	0.143
10	Cem3 > 5% _F	6.5	3.92	9.41	**51.67**	**Failed after 240 Cycles**	0.541
11	Cem3 < 5% _S	6.6	3.90	6.48	**55.92**	**Failed after 270 Cycles**	0.000
12	Cem3 > 5% _S	6.3	3.72	7.61	**66.06**	**Failed after 270 Cycles**	0.121
9R	Cem3R < 5% _F	8.0	5.29	8.10	**45.89**	**Failed after 175 Cycles**	0.466
10R	Cem3R > 5% _F	7.5	4.50	6.05	**87.57**	**PASS**	0.516
11R	Cem3R < 5% _S	8.1	7.17	14.06	**64.22**	**Failed after 210 Cycles**	0.073
12R	Cem3R > 5% _S	8.0	5.75	10.12	**50.64**	**Failed after 210 Cycles**	0.00

Note: Mix 4R, 9R, 11R, and 12R failed because of early coarse aggregate pop-out

Table 9-4 Summary of F/T Results for Mixes Batched with Combined Sand (Mix 13–Mix 24)

Mix No.	Mix Design	Air Content, %		ASTM C457	Durability Factor		% of Mass Loss after 300 Cycles
		Fresh	Hard.	Voids per Inch, (>8)	After 300 Cycles	Condition*	
13	Cem1R < 5%_F	7.2	4.06	7.62	**69.75**	**Failed after 175 Cycles**	0.198
13R	Cem1R < 5% _F	8	9.08	20.50	**90.02**	**PASS**	0.176
14	Cem1R > 5% _F	7.4	5.99	10.33	**84.10**	**PASS**	0.153
15	Cem1R < 5% _S	8.1	4.34	6.14	**60.47**	**Failed after 175 Cycles**	0.073
15R	Cem1R < 5% _S	7.8	5.88	11.77	**90.27**	**PASS**	0.167
16	Cem1R > 5% _S	6.9	4.99	6.97	**69.95**	**Failed after 245 Cycles**	0.088
16R	Cem1R > 5% _S	7.3	6.50	12.83	**88.76**	**PASS**	0.002
17	Cem2 < 5% _F	7.9	5.95	14.89	**92.89**	**PASS**	1.471
18	Cem2 > 5% _F	8	5.80	14.01	**94.16**	**PASS**	0.783
19	Cem2 < 5% _S	7.5	5.91	13.97	**93.43**	**PASS**	0.266
20	Cem2 > 5% _S	7.8	6.05	11.70	**94.70**	**PASS**	0.000
21	Cem3 < 5% _F	7.2	5.39	6.78	**81.38**	**PASS**	0.000
22	Cem3 > 5% _F	7.2	6.46	11.38	**81.22**	**PASS**	0.071
23	Cem3 < 5% _S	7.8	6.21	8.78	**72.76**	**Failed after 245 Cycles**	0.000
23R	Cem3R < 5% _S	7.1	4.70	10.43	**94.40**	**PASS**	0.196
24	Cem3 > 5% _S	7.3	5.92	7.35	**89.98**	**PASS**	0.126

Note: Mix 23 failed because of early coarse aggregate pop-out

9.2.3.2 Effect of Fly Ash or Slag (SCMs)

The use of slag or fly ash as a replacement to cement showed inconsistent variation in the DF results for concrete mixes made with the same cement source and batched with the same sand source. However, it was visually observed the concrete mixes with fly ash experienced more surface scaling than mixes made with slag as verified by the percentage of mass loss after 300 cycles. Therefore, for the same cement source, most of the concrete mixes made with fly ash experienced greater mass loss than concrete mixes made with slag.

9.2.3.3 Effect of Fine Aggregate Sources (Natural or Combined Sand)

The testing results also showed that using combined sand in concrete provided better freeze/thaw performance than using natural sand. Only eight of the 20 concrete mixes batched with natural sand passed the freeze/thaw test with DF greater than 80% after 300 cycles. However, 12 out of the 16 concrete mixes batched with combined sand passed the freeze/thaw test with DF greater than 80% after 300 cycles. Moreover, the percentage of mass loss was greater for concrete mixes batched with natural sand than combined sand. For example, mixes made with Cem2 and natural sand (Mix 5–Mix 8) experienced greater mass loss than mixes made with Cem2 and combined sand (Mix 17–Mix 20). Similarly, mixes made with Cem3 and natural sand (Mix 9–Mix 12, Mix 9R–Mix 12R) experienced greater mass loss in comparison with Cem3 and combined sand mixes (Mix 21–Mix 24).

9.3 SURFACE RATING OF FREEZE/THAW SPECIMENS BASED ON ASTM C672

Appendix O includes photos for the 24 mixes Mix 1–Mix 24 after 300 cycles. Specimens of each mix were evaluated in accordance with ASTM C672. The evaluation was based on the surface ratings provided in Table 9-5, the number and size of pop-outs, and degree of spalling and scaling on the surface. Appendix N includes the description of the specimens' condition after 300 cycles of freezing and thawing. Table N-1 and Table N-2 report the specimens' condition after 300 cycles for mixes batched with natural sand (Mix 1–Mix 12), and Table N-3 and Table N-4 report the specimens' condition after 300 cycles for mixes batched with combined sand (Mix 13–Mix 24).

Table 9-5 Surface Rating Criteria Based on ASTM C672

Surface Rating	Condition of Surface
0	no scaling
1	very slight scaling (3 mm [1⁄8 in.] depth, max, no coarse aggregate visible)
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	severe scaling (coarse aggregate visible over entire surface)

Note: The surface ratings for the freeze/thaw samples for Mix 1–Mix 4 are presented in Appendix M based on their resistance to scaling in accordance to ASTM C672.

The following sample (Figure 9-4) shows Mix 15 after 300 cycles of freezing and thawing. Please see Appendix O for samples photos.

Figure 9-4 Mix15 Specimen #3 (DF = 64.63%, fresh air = 8%, hardened entrained air = 4.34%).

9.4 CHLORIDE PENETRATION TEST (ACID-SOLUBLE METHOD, AASHTO T260)

9.4.1 Concrete Sampling

The samples were prepared in accordance with AASHTO T259 (Resistance of concrete to chloride ion penetration). Chloride concentrations in the concrete samples were tested following AASHTO T260 (Sampling and testing for chloride ion in concrete and concrete raw materials). For each mix, three 12 x 12 x 3 in. slabs were cast, moist-cured for 28 days, and placed in a drying room for 28 days. Then, the slabs were subjected to continuous ponding with 3% sodium chloride solution at a minimum depth of approximately 0.5 in., as shown in Figure 9-5. Chloride concentrations were tested after 90, 180, and 360 days of salt ponding.

Figure 9-5 Salt ponding test, (chloride content across the slab depth).

9.4.2 Sample Preparation Procedure

Five samples were collected from each slab by drilling at least two holes in the slab using a drill press. The drill press setup is shown in Figure 9-6. The samples were collected from depths ranging from 0 to 0.5 in. to 2 to 2 .5 in. The acid-soluble and water-soluble methods were both followed for measuring the chloride concentration in the concrete.

9.4.2.1 Acid-Soluble Method

Three grams of the drilled sample were measured and placed in a beaker with 10 mL distilled water. The sample was stirred thoroughly to bring the powder into suspension, then 3 mL of nitric acid HNO_3 was added to the beaker and the solution was diluted with hot H_2O up to 50 mL. Three mL of hydrogen peroxide H_2O_2 and five drops of methyl orange indicator were added to samples with blast furnace slag. More HNO_3 drops were added to the solution, which showed yellow/orange color, until a permanent pink/ red color was seen. The beaker was covered with a watch glass and was heated to boiling on a hot-plate/magnetic stirrer using a small magnet. The mixture was boiled for five minutes and was then allowed to stand for 24 hours in an HCl fume-free atmosphere. The clear supernatant liquid was filtered through double filter paper (Whatman No. 41 over No. 40, or equivalent) into a 250 mL beaker. The filter papers and the funnel were washed with hot distilled water until a total volume of 125 to 150 ml was maintained in the beaker. Figure 9-7 shows the test apparatus.

9.4.2.2 Water-Soluble Method

Three grams of the drilled sample were placed in a beaker and 60 to 70 mL of distilled water was added to the beaker. The beaker was kept in a HCl fume-free atmosphere for 24 hours, then it was heated to boiling for five minutes on a hot-plate/magnetic stirrer. The sample beaker was filtered using double filter paper (Whatman No. 41 over No. 40, or equivalent) and was placed on a magnetic stirrer. While stirring the solution, one to two drops of methyl orange indicator were added, followed by drops of HNO_3 until a permanent pink to red color was seen. A total of 3 mL of H_2O_2 were added to samples containing blast furnace slag.

9.4.3 Potentiometric Titration

The electrode was calibrated with the solutions recommended by the manufacturer. A total of 4.00 mL of 0.01 N NaCI was added to the cooled sample beaker while swirling. The electrode was removed from the beaker of distilled water and was wiped with absorbent paper. The electrode was then immersed into the sample solution. The beaker-electrode assembly was placed on a magnetic stirrer and gently stirred. Using a calibrated buret, a standard 0.01 N $AgNO_3$ solution was added in 0.10 mL increments and a millivoltmeter reading was recorded after each addition. As the equivalence point was approached, equal additions of $AgNO_3$ solution caused increasingly larger changes in the millivolt reading. These changes decreased once the equivalence point passed. The titration procedure continued until the millivoltmeter reading was at least 40 mv past the approximate equivalence point. The end point of titration, usually near the approximate equivalence point in distilled water, was determined by plotting the volume of AgN03 solution added versus the millivoltmeter readings.

9.4.4 Calculations

The endpoint of titration was determined by plotting the volume of $AgNO_3$ solution versus the millivolt reading. This end point corresponds to the inflection point of the resultant smooth curve. The percentage of chloride ions was calculated according to the following equation:

$$Cl^- \% = 3.5453\ (V_1N_1 - V_2N_2) / W$$

where V_1 is the end point of $AgNO_3$ in mL, V_2 is the volume of NaCI solution added in mL, N_1 is the normality of AgNO3, N_2 is the normality of NaCI solution, and W is the weight of original concrete sample in grams.

Figure 9-6 Drilling press used to collect powdered concrete samples.

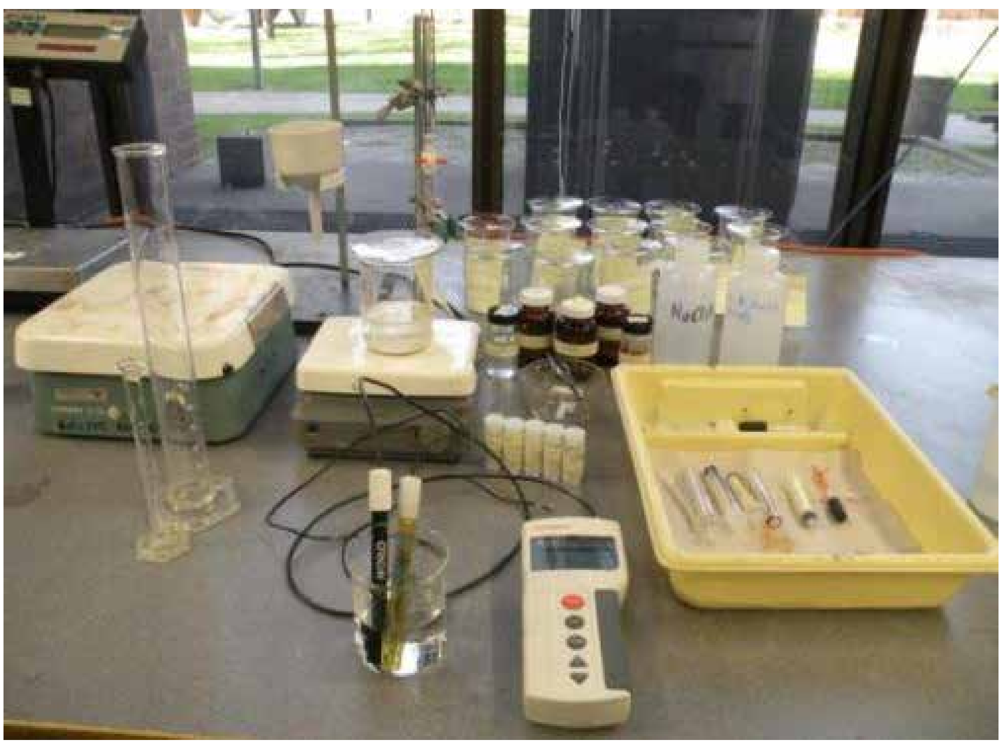

Figure 9-7 Apparatus for testing chloride concentration.

9.4.5 Results and Discussion

Appendix K includes the test results for the chloride concentration results for acid- and water-soluble at five different depths in concrete, from 0 to 0.5 in. to 2 to 2.5 in. Acid-soluble chloride reflects the total chloride content in concrete; whereas, water-soluble chloride represents the chloride ions that could be leached by water such as the sodium chloride.

Table K-1 through Table K-4 report the chloride concentration results for acid- and water-soluble for concrete mixes batched with natural sand. These tables include the test results at 90, 180, and 360 days salt ponding for mixes made with Cem1 (Mix 1–Mix 4), Cem1R (Mix 1R–Mix 4R), Cem2 (Mix 5–Mix 8), and Cem3 (Mix 9–Mix 12), respectively. Because of time restriction, chloride concentration results for mixes made with Cem1R (Mix 1R–Mix 4R) were measured at 315 days rather than 360 days salt ponding.

Table K-5 through Table K-7 report the chloride concentration results for acid- and water-soluble for concrete mixes batched with combined sand. These tables include the test results at 90, 180, and 360 days salt ponding for mixes made with Cem1R (Mix 13–Mix 16), Cem2 (Mix 17–Mix 20), and Cem3 (Mix 21–Mix 24), respectively.

The above-mentioned tables show the effect of the duration of salt ponding on chloride concentration and penetration depth. At 90 and 180 days of salt ponding, the majority of mixes showed significant chloride change up to 1 in. in depth, followed by a constant chloride concentration at lower depth ranging between 0.04% and 0.06%, which is observed as the initial chloride level in concrete. At 360 days of salt ponding, the majority of mixes showed chloride penetration change up to 1.5 in. in depth, followed by a constant chloride concentration at lower levels.

The specification states that the chloride content must be less than 0.03% chloride by weight of concrete at 0.5 to 1 in. depth after 90 days and less than 0.06% at the same depth after 180 days. The minimum acid-soluble chloride contents observed at 0.5 to 1 in. depth after 90 days were 0.083% (acid-soluble) and 0.077% (water-soluble) for Mix 12 and 0.083% (acid- and water-soluble) for Mix 11 after 180 days. These results indicate that none of the concrete mixes met the specification whether made with Cem < 5% or Cem > 5%.

Studies on chloride penetration in concrete show varying results regarding the addition of limestone and IPA to cement in concrete. Some studies indicate increasing chloride penetration with increasing limestone content while others show inconsistent change with limestone and IPA addition.

9.4.5.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

Figure 9-8 to Figure 9-11 show acid-soluble chloride versus depth in concrete for mixes batched with natural sand. Figure 9-8 shows that the percentage of chloride in mixes made with Cem1 (Mix 1–Mix 4) at 0.5 to 1 in. depth were lowest for Mix 2 (0.133%) at 90 days, Mix 4 (0.138%) at 180 days, and Mix 3 (0.251%) at 360 days, but were highest for Mix 1 (0.168% and 0.39%) at 90 and 360 days and Mix 3 (0.216%) at 180 days. Figure 9-9 shows that the percentage of chloride in mixes made with Cem1R (Mix 1R–Mix 4R) at 0.5 to 1 in. depth were lowest for Mix 2R (0.092%) at 90 days, Mix 3R (0.136%) at 180 days, and Mix 1R (0.18%) at 315 days, but were highest for Mix 1R (0.145%) at 90 days, Mix 4R (0.189%) at 180 days, and Mix 3R (0.295) at 315 days. Figure 9-10 shows that the percentage of chloride in mixes made with Cem2 (Mix 5–Mix 8) at 0.5 to 1 in. depth were lowest for Mix 6 (0.1% and 0.142%) at 90 and 180 days, and Mix 5 (0.174%) at 360 days, but were highest for Mix 8 (0.127% and 0.208%) at 90 and 180 days, and Mix 7 (0.275%) at 360 days. Figure 9-11 shows that the percentage of chloride in mixes made with Cem3 (Mix 9–Mix 12) at 0.5 to 1 in. depth were lowest for Mix 12 (0.083%) at 90 days and Mix 11 (0.083% and 0.177%) at 180 and 360 days and highest for Mix 9 (0.121%) at 90 days, Mix 10 (0.13%) at 180, and Mix 12 (0.331%) at 360 days. These results indicate the inconsistency of chloride concentration at different depths in concrete mixes made with Cem < 5% and Cem > 5% and batched with natural sand.

Figure 9-12 through Figure 9-14 show acid-soluble chloride versus depth in concrete for mixes batched with combined sand. Figure 9-12 shows that the percentage of chloride in mixes made with Cem1R (Mix 13–Mix 16) at 0.5 to 1 in. depth were lowest for Mix 16 (0.139% and 0.083%) at 90 and 180 days, and Mix 14 (0.213%) at 360 days, but were highest for Mix 13 (0.154% and 0.207%) at 90 and 180, and Mix 15 (0.278%) at 360 days. Similarly, the inconsistent variation in the chloride levels in concrete was also observed in mixes made with Cem2 (Mix 17–Mix 20) and Cem3 (Mix 21–Mix 24), as shown in Figure 9-13 and Figure 9-14, respectively. The inconsistency of these results is yet another indication that limestone and IPA, and the IR levels in cement have a negligible effect on chloride penetration in concrete mixes batched with combined sand.

Therefore, adding Cem < 5% or Cem > 5%to the concrete mixes measured for chloride concentration did not result in any significant variations.

9.4.5.2 Effect of Fly Ash or Slag (SCMs)

The results failed to indicate a significant variation or consistent trend in the chloride penetration at 90, 180, and 360 days between mixes with same cement source, but blended with fly ash or slag. The comparison was based on concrete mixes of the same cement source and fine aggregate, but made with slag or fly ash.

9.4.5.3 Effect of Fine Aggregate Sources (Natural or Combined Sand)

Similarly, no major difference was observed in chloride levels between concrete mixes batched with natural sand and combined sand. The comparison was based on concrete mixes made with same cement source and cementitious combination, but batched with either natural or combined sand. The acid-soluble and water-soluble results showed slightly lower chloride concentration for concrete mixes batched with natural sand because the initial chloride levels in concrete mixes batched with combined sand (~0.06%) were higher than natural sand (~0.04%).

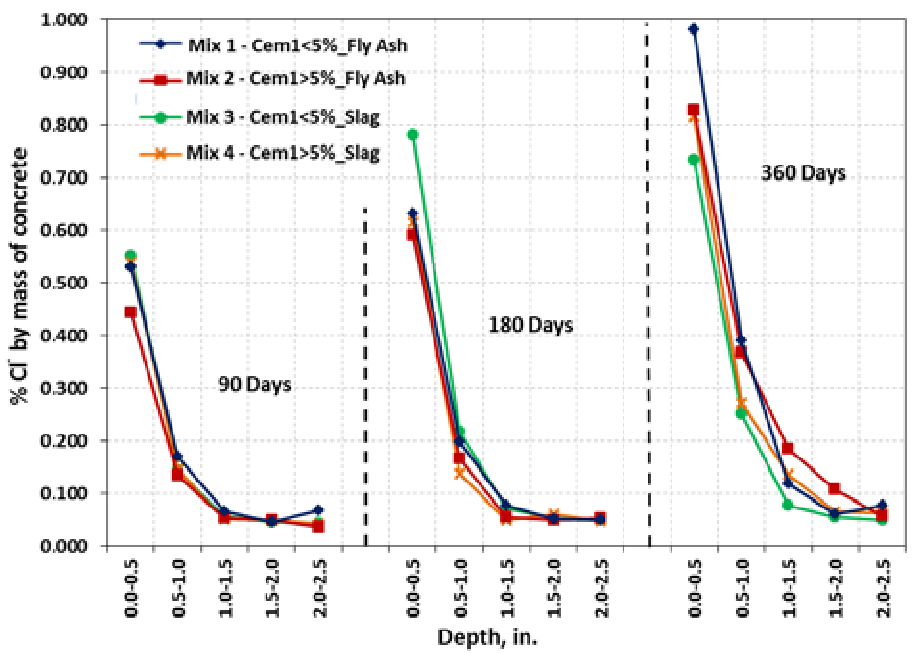

Figure 9-8 Acid-soluble chloride for mixes with Cem1 and natural sand (Mix 1–Mix 4).

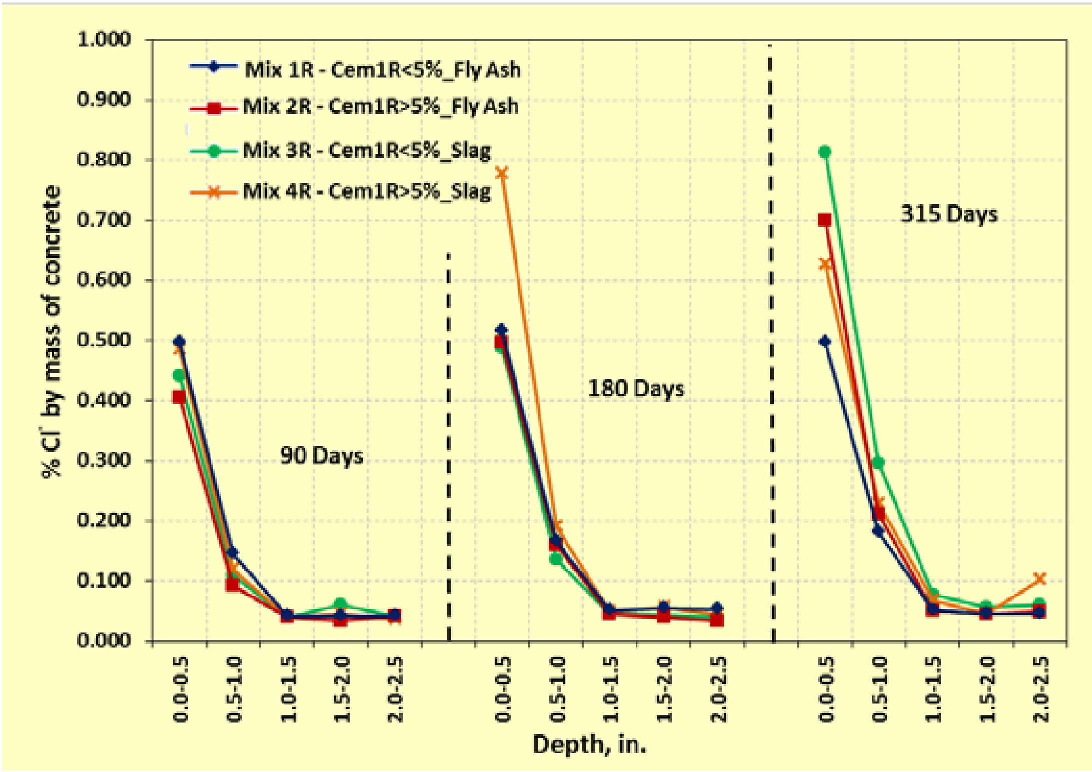

Figure 9-9 Acid-soluble chloride for mixes with Cem1R and natural sand (Mix 1R–Mix 4R).

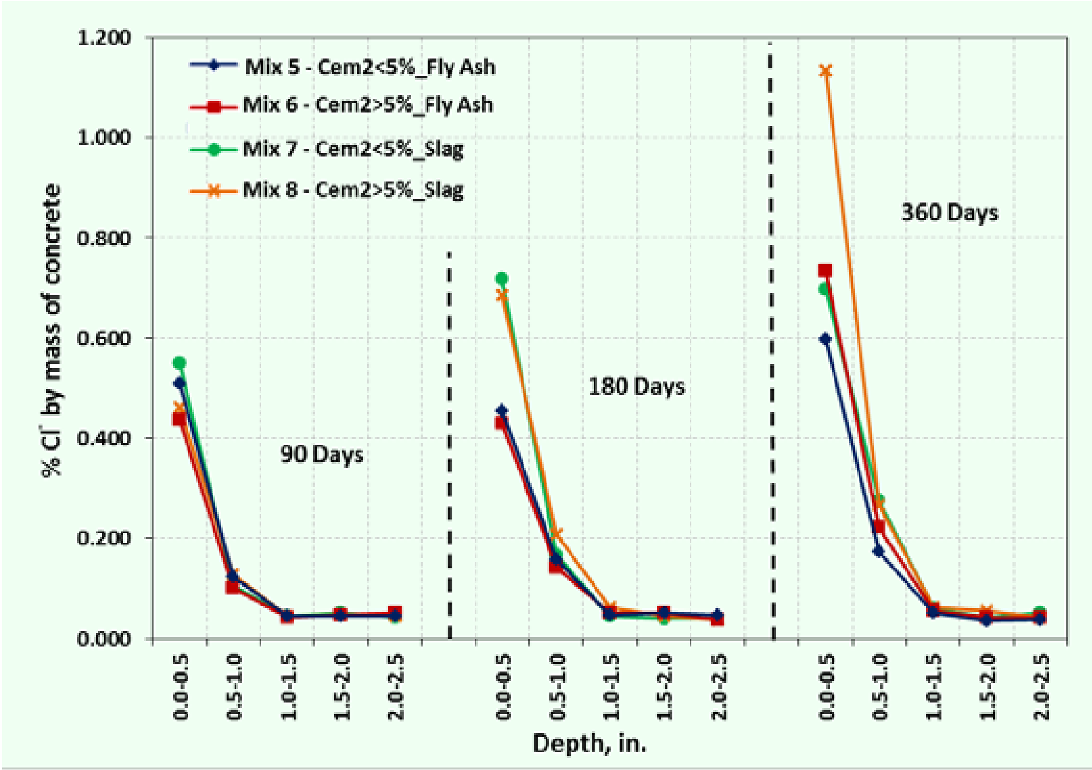

Figure 9-10 Acid-soluble chloride for mixes with Cem2 and natural sand (Mix 5–Mix 8).

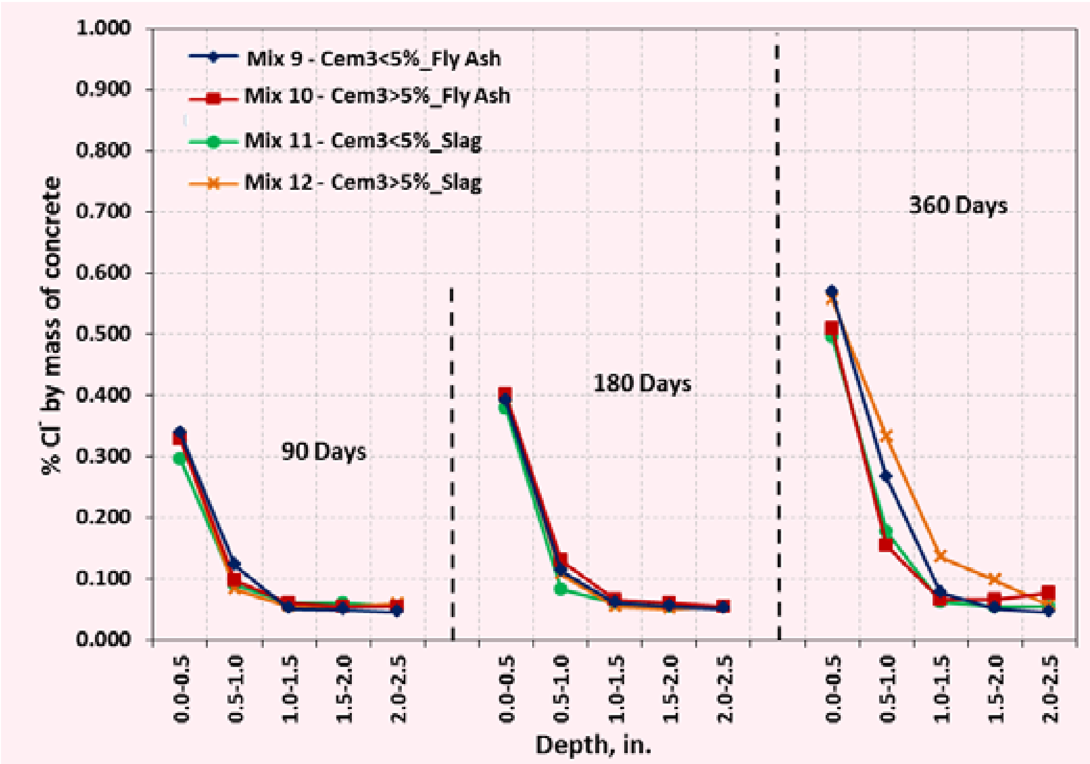

Figure 9-11 Acid-soluble chloride for mixes with Cem3 and natural sand (Mix 9–Mix 12).

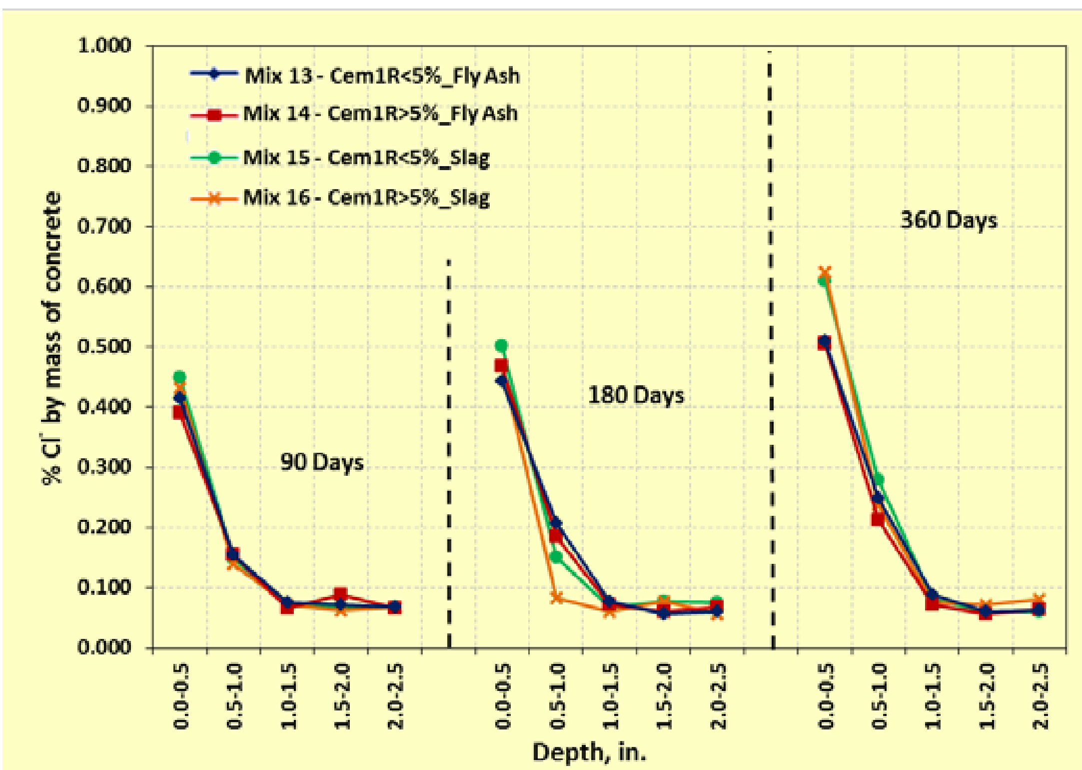

Figure 9-12 Acid-soluble chloride for mixes with Cem1R and combined sand (Mix 13–Mix 16).

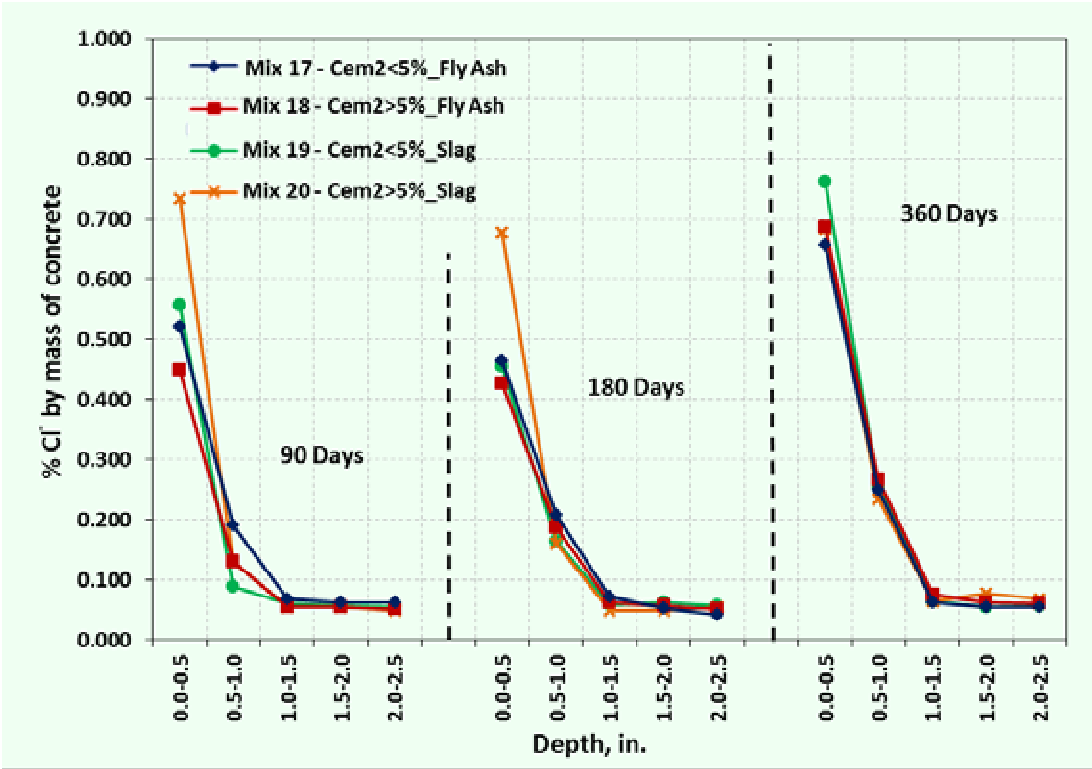

Figure 9-13 Acid-soluble chloride for mixes with Cem2 and combined sand (Mix 17–Mix 20).

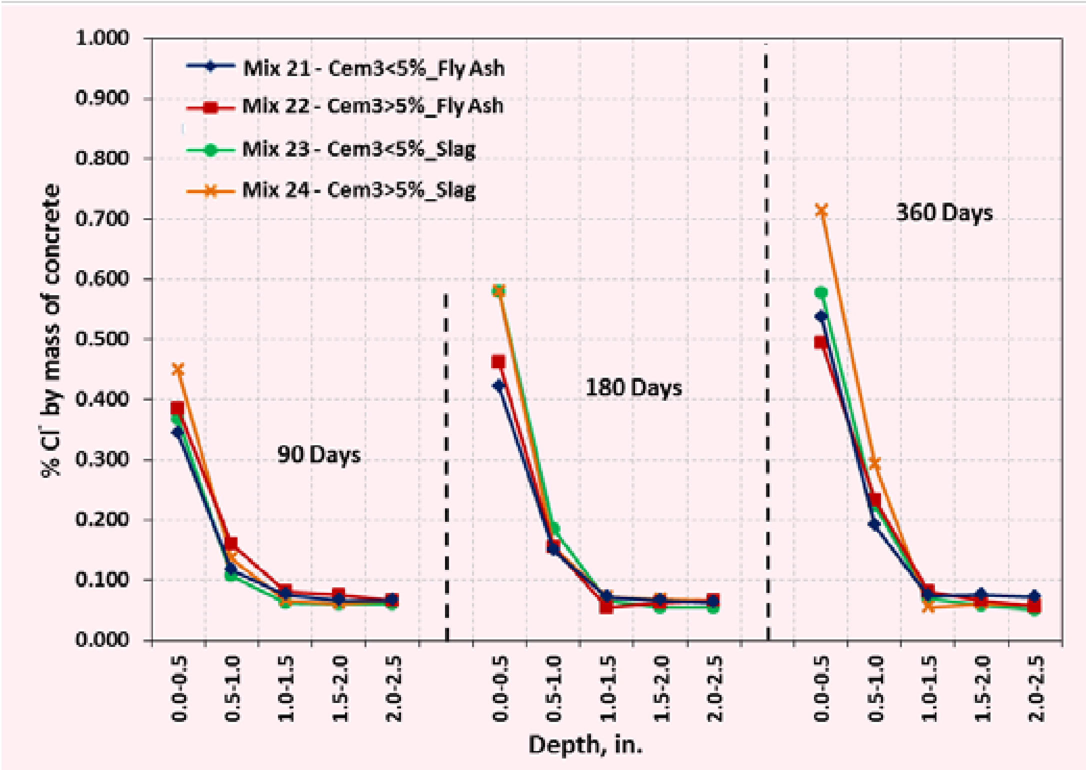

Figure 9-14 Acid-soluble chloride for mixes with Cem3 and combined sand (Mix 21–Mix 24).

9.5 WATER PERMEABILITY TEST, DIN 1048

9.5.1 Testing Procedure

The test is conducted in accordance with German standard DIN 1048. Water pressure is applied by means of a water tank connected to an air compressor through a valve, as shown in Figure 9-15. After water pressure was applied for a specific amount of time, the prisms were removed from the cells, surface dried, and split in half perpendicular to the injected surface. The maximum depth of water penetration was measured for the two halves of the specimen by means of a Vernier Caliper, and the average depth was recorded. These values indicated the water permeability of concrete in terms of the depth of water penetration. According to Hedegaard and Hansen (1992), concrete is “watertight” for all practical purposes whenever penetration depth is less than 50 mm. Walz (1968) reached the same conclusion after more than 50 years of experienced DIN experimentations in Germany.

For each concrete mix, 3 specimens were tested for DIN 1048 water permeability at each curing period. The depth of penetration was considered the average maximum depth of each specimen. Figure 9-16 shows Mix 12 specimens after 56, 180, and 360 days of curing. It was observed that penetration depth was lower in specimens cured for longer periods.

Figure 9-15 Water permeability test setup, DIN 1048.

Figure 9-16 Depth of penetration in Mix 12 specimens.

9.5.2 Discussion of Test Results

The permeability results for each concrete mix are shown in Appendix I; Table I-1 shows the results for concrete mixes batched with natural sand (Mix 1–Mix 12) and Table I-2 shows the results for concrete mixes batched with combined sand (Mix 13–Mix 24). Figure 9-17 and Figure 9-18 present the average water permeability for concrete mixes batched with natural sand and combined sand, respectively. All readings indicate less than 50 mm water penetration into concrete at all curing ages. The results in both tables show inconsistent variation in the depth of water permeability in mixes with Cem < 5% or Cem > 5%.

9.5.2.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

The permeability results for concrete mixes batched with natural sand, shown in Figure 9-17, indicate no significant variation between mixes with the same cement source. For example, for Cem1 mixes and natural sand (Mix 1–Mix 4), the measured permeability depths of Mix 1 (Cem1 < 5% _fly ash) were higher than those of Mix 2 (Cem1 > 5% _fly ash) at all ages; whereas, the depth of permeability in Mix 3 (Cem1 < 5% _slag) prisms was lower than that in Mix 4 (Cem1 > 5% _slag) at all ages. For Cem3 mixes, the permeability depth for Mix 9 was higher at 56 and lower at 360 days than Mix 10. This inconsistency is also apparent in the permeability results for concrete mixes batched with combined sand at 56, 180, and 360 days for Cem1R mixes (Mix 13–Mix 16), Cem2 mixes (Mix 5–Mix 8), and Cem3 mixes (Mix 21–Mix 24), as shown in Figure 9-18.

9.5.2.2 Effect of Fly Ash or Slag (SCMs)

Moreover, the results did not show any significant variation or consistent trend in the permeability depth between mixes with the same cement source, but blended with fly ash or slag. For instance, for Cem1 and natural sand mixes, Mixes 1 and 2, which were blended with fly ash, gave higher permeability results than Mixes 3 and 4, which were blended with slag. In contrast, for Cem3 and combined sand mixes, Mixes 21 and 22, which were blended with fly ash, gave lower permeability results than Mixes 23 and 24, which were blended with slag.

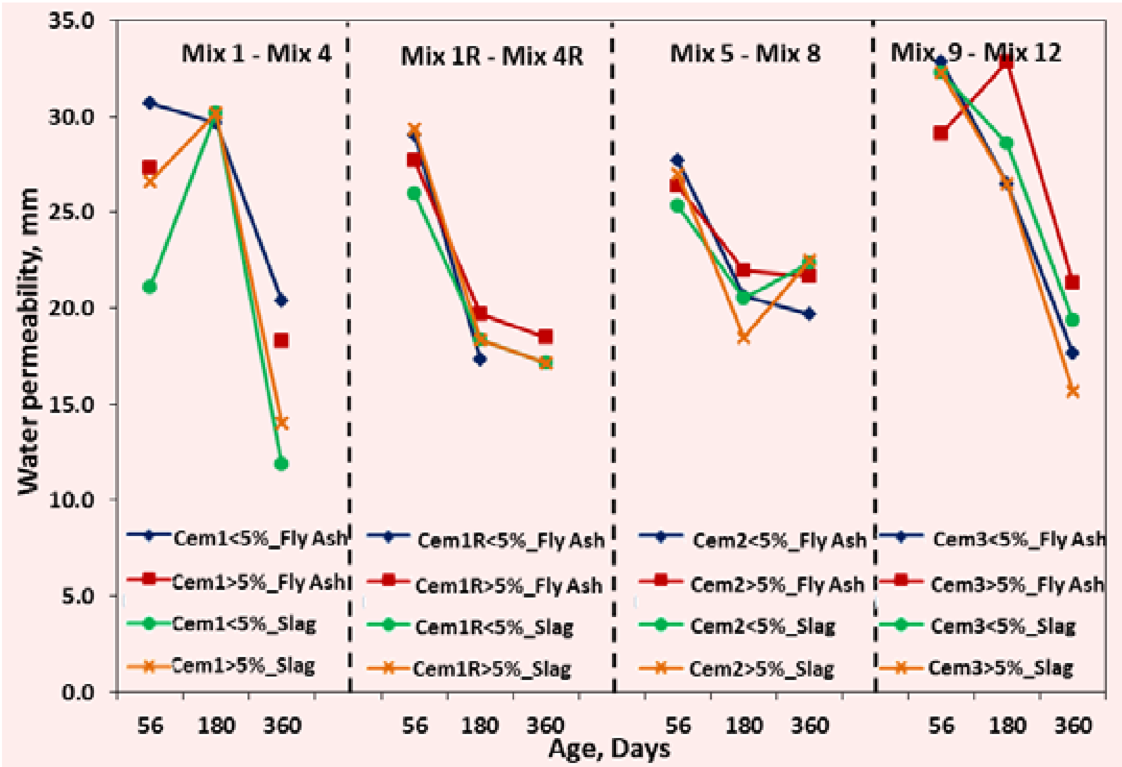

Figure 9-17 DIN 1048 results for mixes with natural sand (Mix 1–Mix 12).

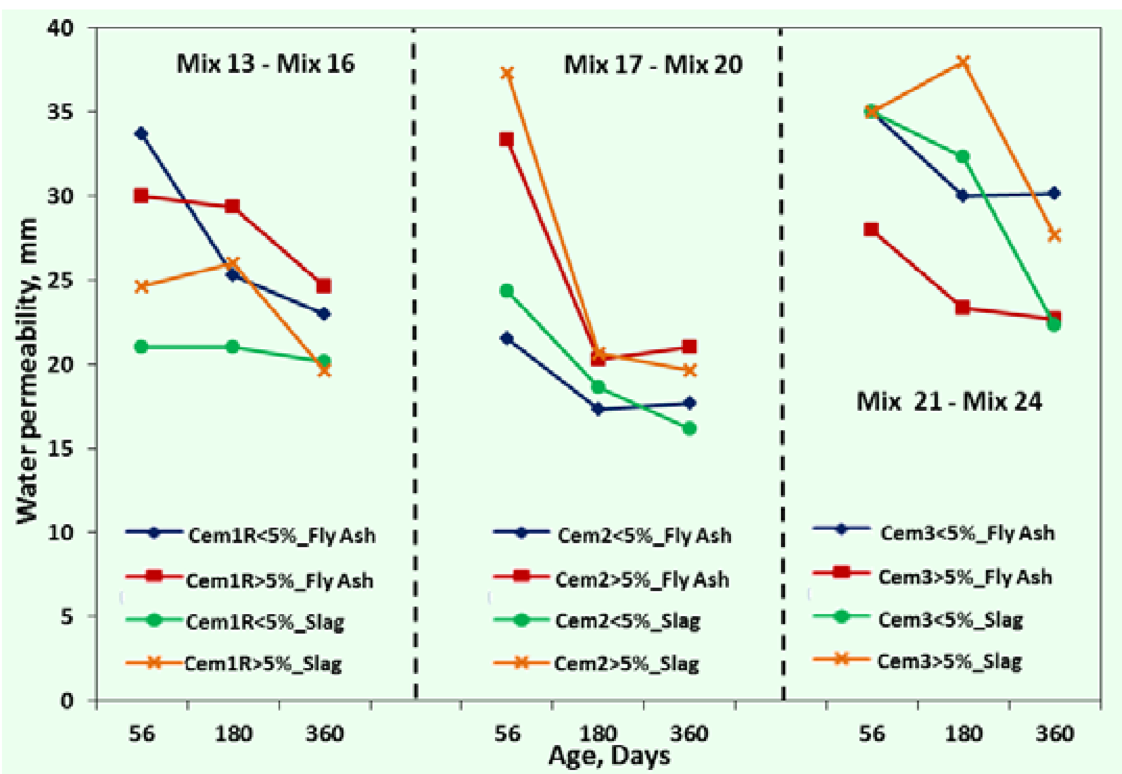

Figure 9-18 DIN 1048 results for mixes with combined sand (Mix 13–Mix 24).

9.5.2.3 Effect of Fine Aggregate Source (Natural or Combined Sand)

The type of fine aggregate had less influence on the DIN 1048 test than the AASHTO T260 test for chloride penetration in concrete. Concrete resistance to water penetration per DIN 1048 demonstrated a slight improvement in concrete mixes batched with natural sand compared with the mixes batched with combined sand at 56, 180, and 360 days. Table 9-6 shows a comparison of DIN 1048 results between concrete mixes made with the same cement source and cementitious combination, but batched with natural or combined sand. Most concrete mixes made with Cem1R and Cem3 showed better results for natural sand while Cem2 mixes showed a slightly improved performance for mixes batched with combined sand.

Table 9-6 Comparison in DIN 1048 Results Between Concrete Mixes Batched with Natural and Combined Sand

DIN 1048, Water Permeability Test					
Mix Design	**Mixes batched with NS**	**Comparison between Concrete Mixes with CS and NS**			**Mixes batched with CS**
		56 Days	**180 Days**	**360 Days**	
Cem1R < 5%_Fly ash	Mix 1R	**LESS**	**LESS**		Mix 13
Cem1R > 5%_Fly ash	Mix 2R	**LESS**	**LESS**	**LESS**	Mix 14
Cem1R < 5%_Slag	Mix 3R	**GREATER**	**LESS**	**LESS**	Mix 15
Cem1R > 5%_Slag	Mix 4R	**GREATER**	**LESS**	**LESS**	Mix 16
Cem2 < 5%_Fly ash	Mix 5	**GREATER**	**GREATER**	**GREATER**	Mix 17
Cem2 > 5%_Fly ash	Mix 6	**LESS**	**GREATER**	**GREATER**	Mix 18
Cem2 < 5%_Slag	Mix 7	**GREATER**	**GREATER**	**GREATER**	Mix 19
Cem2 > 5%_Slag	Mix 8	**LESS**	**LESS**	**GREATER**	Mix 20
Cem3 < 5%_Fly ash	Mix 9	**LESS**	**LESS**	**LESS**	Mix 21
Cem3 > 5%_Fly ash	Mix 10	**GREATER**	**GREATER**	**LESS**	Mix 22
Cem3 < 5%_Slag	Mix 11	**LESS**	**LESS**	**LESS**	Mix 23
Cem3 > 5%_Slag	Mix 12	**LESS**	**LESS**	**LESS**	Mix 24
NS: Natural Sand CS: Combined Sand					

9.6 RAPID CHLORIDE PERMEABILITY TEST

9.6.1 Testing Procedure

Electrical resistance was tested in accordance with ASTM C1202, which determines the electrical conductance of concrete to rapidly indicate its resistance to the penetration of chloride ions. The chloride permeability test was conducted on concrete at ages of 56, 180, and 360 days. For each concrete mix, two 4 x 8 in. cylinders were cut using a diamond saw to get four 4 x 2 in. disks. These disks were vacuum-saturated prior to testing. First, the specimens were placed in the vacuum desiccator bowl and were vacuum-pumped for three hours before adding de-aerated water through a suction opening. The specimens were then run under vacuum for another hour. The vacuum pump was turned off, and the specimens were allowed to soak in water for another 18 ± 2 hours. Once the conditioned, the specimens were placed in the test cells and were connected to the "Prove It" apparatus. Each test cell has two reservoirs on both sides. One of the test cell reservoirs was filled with 0.3N NaOH and the other with 3% NaCl solution. The RCPT was then conducted by means of a 60 volt electric connector to allow the migration of chloride ion through the concrete specimen from the negative terminal, which was connected to the NaCl reservoir's electrode, and then from the positive terminal, which was connected to the NaOH reservoir. A typical test setup is shown in Figure 9-19. The total charge passing was measured in coulombs. It was concluded that that the larger the number of coulombs, the greater the permeability of the sample.

Figure 9-19 Rapid chloride permeability test, ASTM C1202/AASHTO T277.

9.6.2 Results and Discussion

The coulomb values of each specimen are presented in Appendix J; Table J-1 shows the values for concrete mixes batched with natural sand (Mix 1–Mix 12) and Table J-2 shows the values for concrete mixes batched with combined sand (Mix 13–Mix 24). A summary of average RCPT results for concrete mixes batched with natural sand and combined sand is shown in Table 9-8 and Table 9-9, respectively.

Table 9-7 provides a correlation between the level of chloride ion penetration and the charge passed. The table, copied from ASTM C1202, is used as a base for determining the validity of the concrete mix against chloride penetration. The average charge for the 24 concrete mixes and the repeated ones ranged between low to moderate at 56 days, very low to low at 180 days, and very low at 360 days, with few exceptions.

Table 9-7 Chloride Ion Penetrability Based on Charge Passed

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
1000–1,000	Very Low
< 100	Negligible

9.6.2.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

The RCPT results shown in the tables below, which contradict DIN 1048 and AASHTO T260 results, indicate that most concrete mixes made with Cem > 5% had slightly higher rapid chloride coulomb charge compared with concrete mixes made with Cem < 5% at 56 and 180 days. First, for concrete mixes batched with natural sand (Mix 1–Mix 12), the RCPT results for mixes made with Cem > 5% were greater or equivalent to those made with Cem < 5% at 56 and 180 days, except for Mix 4 (Cem1 > 5% _slag), which had lower charge than Mix 3 (Cem1 < 5% _slag) at 56 and 180 days. For mixes batched with combined sand, all concrete mixes made with Cem > 5% had slightly higher charge than those made with Cem < 5% at 180 days but varied at 56 days. At 360 days, all mixes indicated very low permeability with similar coulombs charge between Cem > 5% and Cem < 5%.

9.6.2.2 Effect of Fly Ash or Slag (SCMs)

Moreover, the effect of slag on concrete mixes exceeded the effect of fly ash on reducing the coulombs charge at 56 and 180 days. The comparison was based on concrete mixes of the same cement source and fine aggregate, but made with slag or fly ash. For mixes batched with natural sand, the charge readings for concrete mixes made with slag were lower than all mixes made with fly ash at 56 days and most mixes made with fly ash at 180 days. Similarly, concrete mixes batched with combined sand showed the same trend at 56 and 180 days for mixes made with slag compared with mixes made with fly ash. At 360 days, no notable difference was observed in the coulombs charge.

9.6.2.3 Effect of Fine Aggregate Sources (Natural or Combined Sand)

In contrast, the effect of the type of fine aggregate used on the coulombs charge was conflicting and irrelevant. Table 9-10 shows a comparison of RCPT results between concrete mixes batched with natural sand and mixes batched with combined sand. For mixes made with Cem3, the majority of RCPT results after 56 days curing for mixes batched with natural sand were greater than the results for mixes batched with combined sand. However, the majority of RCPT results after 180 days curing for mixes batched with natural sand were less than the results for mixes batched with combined sand. Accordingly, RCPT results show that combined sand had a better effect on the coulombs charge than natural sand at 56 days while the effect of natural sand was better at 180 days. At 360 days, the difference was irrelevant and inconsistent. This indicates that the fine aggregate type in concrete had negligible effect on the coulombs charge as it was concluded in the chloride ion penetration test.

Table 9-8 RCPT Results for Concrete Mixes Batched with Natural Sand (Mix 1–Mix 12)

Mix No.	Mix Design	56 Days		180 Days		360 Days	
		Coulombs	Permeability	Coulombs	Permeability	Coulombs	Permeability
Mix 1	Cem1 < 5%_Fly ash	2111	***Moderate***	701	***Very Low***	516	***Very Low***
Mix 2	Cem1 > 5%_Fly ash	2121	***Moderate***	712	***Very Low***	491	***Very Low***
Mix 3	Cem1 < 5%_Slag	1280	***Low***	482	***Very Low***	568	***Very Low***
Mix 4	Cem1 > 5%_Slag	1218	***Low***	369	***Very Low***	581	***Very Low***
Mix 1R	Cem1R < 5%_Fly ash	1615	***Low***	1060	***Low***	533	***Very Low***
Mix 2R	Cem1R > 5%_Fly ash	1742	***Low***	1060	***Low***	458	***Very Low***
Mix 3R	Cem1R < 5%_Slag	1315	***Low***	925	***Very Low***	571	***Very Low***
Mix 4R	Cem1R > 5%_Slag	1682	***Low***	903	***Very Low***	573	***Very Low***
Mix 5	Cem2 < 5%_Fly ash	1184	***Low***	558	***Very Low***	571	***Very Low***
Mix 6	Cem2 > 5%_Fly ash	1778	***Low***	1132	***Low***	554	***Very Low***
Mix 7	Cem2 < 5%_Slag	1077	***Low***	790	***Very Low***	533	***Very Low***
Mix 8	Cem2 > 5%_Slag	1225	***Low***	955	***Very Low***	711	***Very Low***
Mix 9	Cem3 < 5%_Fly ash	1879	***Low***	445	***Very Low***	585	***Very Low***
Mix 10	Cem3 > 5%_Fly ash	2529	***Moderate***	635	***Very Low***	512	***Very Low***
Mix 11	Cem3 < 5%_Slag	1231	***Low***	608	***Very Low***	495	***Very Low***
Mix 12	Cem3 > 5%_Slag	1339	***Low***	585	***Very Low***	512	***Very Low***

Table 9-9 RCPT Results for Concrete Mixes Batched with Combined Sand (Mix 13–Mix 24)

Mix No.	Mix Design	56 Days		180 Days		360 Days	
		Coulombs	Permeability	Coulombs	Permeability	Coulombs	Permeability
Mix 13	Cem1R < 5%_Fly ash	2546	***Moderate***	882	***Very Low***	479	***Very Low***
Mix 14	Cem1R > 5%_Fly ash	2128	***Moderate***	994	***Very Low***	523	***Very Low***
Mix 15	Cem1R < 5%_Slag	1229	***Low***	688	***Very Low***	611	***Very Low***
Mix 16	Cem1R > 5%_Slag	1040	***Low***	897	***Very Low***	607	***Very Low***
Mix 17	Cem2 < 5%_Fly ash	3558	***Moderate***	1853	***Low***	576	***Very Low***
Mix 18	Cem2 > 5%_Fly ash	3801	***Moderate***	1936	***Low***	708	***Very Low***
Mix 19	Cem2 < 5%_Slag	1329	***Low***	1020	***Low***	662	***Very Low***
Mix 20	Cem2 > 5%_Slag	978	***Very Low***	1040	***Low***	641	***Very Low***
Mix 21	Cem3 < 5%_Fly ash	1396	***Low***	678	***Very Low***	367	***Very Low***
Mix 22	Cem3 > 5%_Fly ash	2144	***Moderate***	717	***Very Low***	365	***Very Low***
Mix 23	Cem3 < 5%_Slag	964	***Very Low***	701	***Very Low***	495	***Very Low***
Mix 24	Cem3 > 5%_Slag	1061	***Low***	735	***Very Low***	504	***Very Low***

Table 9-10 Comparison of ASTM C1202-RCPT Results between Concrete Mixes Batched with Natural Sand and Mixes Batched with Combined Sand

ASTM C1202, Rapid Chloride Permeability Test					
Mix Design	Mixes batched with NS	Comparison between Concrete Mixes with CS and NS			Mixes batched with CS
		56 Days	180 Days	360 Days	
Cem1R < 5%_Fly ash	Mix 1R	**LESS**	**GREATER**	**GREATER**	Mix 13
Cem1R > 5%_Fly ash	Mix 2R	**LESS**	**GREATER**	**LESS**	Mix 14
Cem1R < 5%_Slag	Mix 3R	**GREATER**	**GREATER**	**LESS**	Mix 15
Cem1R > 5%_Slag	Mix 4R	**GREATER**	**EQUAL**	**LESS**	Mix 16
Cem2 < 5%_Fly ash	Mix 5	**LESS**	**LESS**	**EQUAL**	Mix 17
Cem2 > 5%_Fly ash	Mix 6	**LESS**	**LESS**	**LESS**	Mix 18
Cem2 < 5%_Slag	Mix 7	**LESS**	**LESS**	**LESS**	Mix 19
Cem2 > 5%_Slag	Mix 8	**GREATER**	**LESS**	**GREATER**	Mix 20
Cem3 < 5%_Fly ash	Mix 9	**GREATER**	**LESS**	**GREATER**	Mix 21
Cem3 > 5%_Fly ash	Mix 10	**GREATER**	**LESS**	**GREATER**	Mix 22
Cem3 < 5%_Slag	Mix 11	**GREATER**	**LESS**	**EQUAL**	Mix 23
Cem3 > 5%_Slag	Mix 12	**GREATER**	**LESS**	**EQUAL**	Mix 24
NS: Natural Sand CS: Combined Sand					

CHAPTER 10 CONCLUSION AND RECOMMENDATIONS

10.1 RESEARCH SUMMARY

This research was conducted to evaluate the performance of concrete made with Cem < 5% and Cem > 5% by weight of limestone and IPA, and/or with cement with 0.75 and 1.5% IR. Implementing Cem > 5% in concrete will lead to great environmental benefits for the IDOT and the concrete industry. Strength and durability properties of hardened concrete were the main focus of the project. Securing the right materials, calibrating the concrete mixture combinations, meeting IDOT specifications, and developing a testing program that provided accurate and consistent results were the major challenges faced by the researchers who exerted all possible efforts to set up the program, complete the project on time, and most importantly, provide experienced manpower to ensure excellent workmanship and successful outcomes.

A total of 24 concrete mix combinations were prepared for testing. Two sources of cement were used, with less or exceeding 5% of limestone and IPA each (Cem1 and Cem3). A third source was introduced by blending Cem1R (replacement to Cem1), having less than 5% of limestone and IPA, with fly ash to produce Cem2 with 0.75 and 1.5% IR levels. In addition, each cement source was replaced by slag or fly ash with 30% replacement of CMC levels by weight. The mixes were batched with one source of coarse aggregate (crushed limestone) and two sources of fine aggregates (natural or combined sand).

The concrete mixes were batched according to ASTM C192/AASHTO T126. The IDOT PCC Mix Design Version V2.1.2 was used to select the mix proportioning for each mix combination. Trial batches were made to calibrate each concrete mix to yield 5% to 8% air content and approximately 3.5 in. slump. Each concrete mix combination needed 18 ft^3 of fresh concrete divided into three batches of 6 ft^3 to cast the specimens for strength and durability. The batches were used to cast the specimens for compressive strength, flexural strength, and durability, respectively.

The fresh properties, including the measurement of slump, unit weight, air content (pressure meter), setting times, concrete mix temperature, ambient temperature, and humidity, were successfully determined. The researchers encountered difficulties to reach the desired slump and air content using WRDA 82. The w/cm ratio specified for the concrete mixes was 0.42. However, the w/cm ratio was increased to 0.44 for concrete mixes batched with slag and combined sand and decreased to 0.40 for concrete mixes batched with fly ash and natural sand. The concrete setting times were consistent, but they varied depending on the mix proportion and materials source.

The strength properties were tested for both compressive and flexural strengths. The compressive and flexural strengths for the 24 concrete mix combinations indicated acceptable results and exceeded the minimum target of 3500 and 600psi at 14 day. The early strength and strength gain were desirable per IDOT specs and the concrete industry. As a result, the strength properties of the concrete mixes yielded the following:

For compressive strength:

- 100% exceeded 3500 psi at 14 days
- 94% exceeded 3500 psi at 7 days
- 6% exceeded 3500 psi at 3 days

For flexural strength:

- 100% exceeded 600 psi at 14 days
- 78% exceeded 600 psi at 7 days
- 12% exceeded 600 psi at 3 days

The durability properties included the measurement of the freeze/thaw test, hardened air content parameters, chloride ion penetration in concrete, water permeability (DIN 1048), and rapid chloride penetration test (RCPT).

The hardened air content parameters were determined for each concrete mix combination with the freeze/thaw test. The freeze/thaw results showed that the entrained air, air bubbles less than 1mm in size, was the main contributor to resistance against freeze/thaw.

The performance of the concrete mixes against freeze/thaw varied depending on the hardened entrained air content. Some concrete mixes had sufficient hardened entrained air but failed to pass the freeze/thaw test. The unexpected failure of these mixes was because of coarse aggregate pop-outs at early freeze thaw cycles. A total of 36 concrete mixes were tested for freeze/thaw. The test results are summarized as follows:

- 57% of the concrete mixes retained an average DF above 80%
- 40% of the concrete mixes batched with natural sand retained an average DF above 80%
- 73% of the concrete mixes batched with combined sand retained an average DF above 80%
- Mix 1–Mix 4 (Cem1 and natural sand) and Mix 9–Mix 12 (Cem3 and natural sand) failed the freeze/thaw test because of the low hardened entrained air content
- Mixes made with Cem2 (Mix 5–Mix 8 and Mix 17–Mix 20) exhibited the best DF, but experienced the highest rate of mass loss
- Mix 4R, 9R, 11R, 12R, and 23 had sufficient hardened air, but failed to pass the freeze/thaw test. Their failure is attributed to coarse aggregate pop-outs.

The findings of the freeze/thaw test denoted the basic requirements for the spacing factor, specific surface, and voids frequency for hardened air parameters. Most concrete specimens that failed the freeze/thaw test satisfied the requirements for specific surface, spacing factor, and void frequency per ASTM C457. As a result, further investigation is recommended in order to optimize the hardened air parameters per ASTM C457 for the best performance of the concrete mixes in this project against the freeze/thaw attack.

The chloride penetration results were determined for each concrete mix combination at 90, 180, and 360 days salt ponding. The results were determined at five different depths from 0 to 0.5 in. to 2 to 2.5 in. For the 90 and 180 days salt ponding, most mixes showed significant chloride increase up to 1 in. depth, followed by an unchanged chloride level at lower depths ranging between 0.05% and 0.07%. This is observed as the initial chloride content in concrete. For the 360 days of salt ponding, the increase in chloride concentration was observed up to 1.5 in. depth, followed by a constant chloride concentration at lower depths.

The specification states that the chloride content must be less than 0.03% chloride by weight of concrete at 0.5 to 1 in. depth after 90 days and less than 0.06% after 180 days. The minimum chloride content observed at 0.5 to 1 in. depth after 90 days was 0.083% (acid-soluble) and 0.077% (water-soluble) for Mix 12 and after 180 days was 0.083% (acid- and water-soluble) for Mix 11. These results indicated that none of the concrete mixes met the IDOT specification at 0.5 to 1 in. depth. However, for practical application, the minimum concrete cover required for steel reinforcement for cast-in-place concrete is 1.5 in. At the 1.5 in. depth and below, the concrete did not experience any change in the chloride concentration.

The water permeability (DIN 1048) and rapid chloride penetration results were tested at 56, 180, and 360 days. The water permeability results indicated that all the specimens experienced less than 50 mm water penetration into concrete at all curing ages. These results are supported by Hedegaard and Hansen (1992) who consider concrete as "watertight" for all practical purposes whenever the penetration depth is less than 50 mm.

The RCPT results were within the acceptable range of ASTM C1202. The average coulombs charge for the 24 concrete mixes and the repeated ones ranged between low to moderate at 56 days, very low to low at 180 days, and very low at 360 days.

10.1.1 Effect of Limestone and Inorganic Processing, and Insoluble Residue

The results of this study showed that increasing the amount of limestone and IPA in cement in quantities exceeding 5% by weight, and the increase of IR to 1.5% had negligible effect on the strength and durability properties of concrete. The performance of concrete mixes with Cem > 5% is summarized as follows:

- Improved the workability in concrete but slightly prolonged its initial and final setting times
- Had comparable compressive and flexural strength properties to concrete mixes with Cem < 5%
- The performance against freezing and thawing was comparable to the concrete specimens with Cem < 5%
- The permeability and chloride ion penetration properties were more or less the same as mixes with Cem < 5%

10.1.2 Effect of Fly Ash and Slag (SCMs)

The effect of slag and fly ash replacements is summarized as follows:

- The use of fly ash improved the workability of the concrete mix, but extended the initial and final setting periods for concrete
- A comparison of the strength properties of the 24 concrete mix combinations showed better compressive and flexure strength for mixes with slag compared with mixes with fly ash
- Concrete mixes made with slag experienced less surface scaling and mass loss than mixes made with fly ash under a freeze/thaw attack

10.1.1 Effect of Fine Aggregate Sources (Natural or Combined Sand)

The effect of fine aggregate sources was significantly different in the fresh and hardened properties of concrete. Following is a summary of the results of the effect of fine aggregate source:

- Concrete mixes batched with natural sand required much less admixture dosage for workability and reached the initial and final sets earlier than mixes batched with combined sand
- The permeability and chloride penetration were less for mixes batched with natural sand than combined sand
- Concrete mixes batched with combined sand had better resistance against freeze/thaw than natural sand

10.2 RECOMMENDATIONS

Several factors presented challenges to the fresh and hardened properties of concrete. These factors were mainly attributed to the type of materials used, total CMC, w/cm ratio, SCM source (slag or fly ash), coarse aggregate gradation, and the type of chemical admixtures used.

The calibration of concrete mixes to reach 2 to 4 in. slump and 5% to 8% fresh air content required careful consideration of the admixture dosage, coarse aggregate gradation, and the different combinations between the SCMs (slag or fly ash) and fine aggregate sources.

10.2.1 Effect of Chemical Admixtures on the Fresh Properties of Concrete Mixes

The lignosulfonate based WRA used in these mixes (WRDA 82) caused a synergistic effect when it reacted with the air-entraining agent (Daravair 1400). Although the admixture enhanced the air bubbles, it increased the instability of the mix's air content and variation in the rate of air loss. On the other hand, the addition of ADVA Cast 575 (HRWR) showed an adverse effect when used with Daravair 1400. ADVA Cast 575 reduced the air content in the mix, but it also stabilized the air content by killing the combined effect on air bubbles caused by combining WRDA 82 and Daravair 1400.

Concrete mixes batched with combined sand (specifically combined sand and slag) were very harsh and required adding high dosage of chemical admixtures to reach a good slump. Adding WRDA 82 in large quantities resulted in a high rate of air loss. As a result, it is recommended to limit the use of WRDA 82 to 3 to 4 fl oz/cwt of CMC and increase the amount of Daravair 1400, and ADVA Cast 575 in order to stabilize the air and limit air loss with the slump.

10.2.2 Effect of Lignosulfonate Based WRA (WRDA 82) on the Freeze/Thaw Durability

Ley et al. (2012) suggested that concrete mixes with higher lignosulfonate based WRA will need about 1% more air content in the concrete in order to overcome its negative effect on freeze/thaw. Many of the concrete mixes conducted in this project using lignosulfonate based product (WRDA 82) experienced unexpected early failure against freeze/thaw testing.

The WRDA 82 content varied depending on the mixture proportion, cementitious combination and fine aggregate type. Natural sand mixes were dosed with different quantities of WRDA 82 depending on the cementitious combination (fly ash or slag). Figure 10-1 shows DF results for concrete mixes batched with natural sand versus the amount of WRDA 82 used. Each square diamond symbol on the plot indicates the DF of a concrete mix with respect to the amount of WRDA 82 added. The red line indicates the minimum specified DF of 80%. Figure 10-1 shows a decreasing trend in the DF with increasing WRDA 82 content. Mixes that were made without WRDA 82 were above the red line except for one mix. The increase in WRDA 82 content showed clearly a decrease in the number of mixes above the red line.

Concrete mixes batched with combined sand (specifically combined sand and slag) were very harsh and required adding high dosage of chemical admixtures to retain a good slump. Adding WRDA 82 in large quantities resulted in high rate of air loss for these mixes. As a result, the WRDA 82 for these mixes was limited and ranged between 3 and 4.5 fl oz/cwt. Figure 10-2 shows DF results for concrete mixes batched with combined sand versus the amount of WRDA 82 added. Each square diamond symbol on the plot indicates the DF of a concrete mix with respect to the amount of WRDA 82 added. The red line indicates the minimum specified DF of 80%. The plot shows that the DF for most mixes were above the red line and the WRDA 82 content ranged between 3 and 4.5 fl oz/cwt.

In conclusion, regardless of the hardened entrained air retained, higher WRDA 82 dosage in concrete mixes lead to a lower DF result and reduced performance against freeze/thaw. Moreover, WRDA 82 showed higher influence on concrete mixes batched with natural sand than combined sand. Mixes batched with natural sand showed acceptable performance for most mixes batched without adding WRDA 82. As a result, it is recommended to eliminate the use of WRDA 82 for concrete mixes batched with natural sand and to use a maximum of 4.5 fl oz/cwt for concrete mixes batched with combined sand.

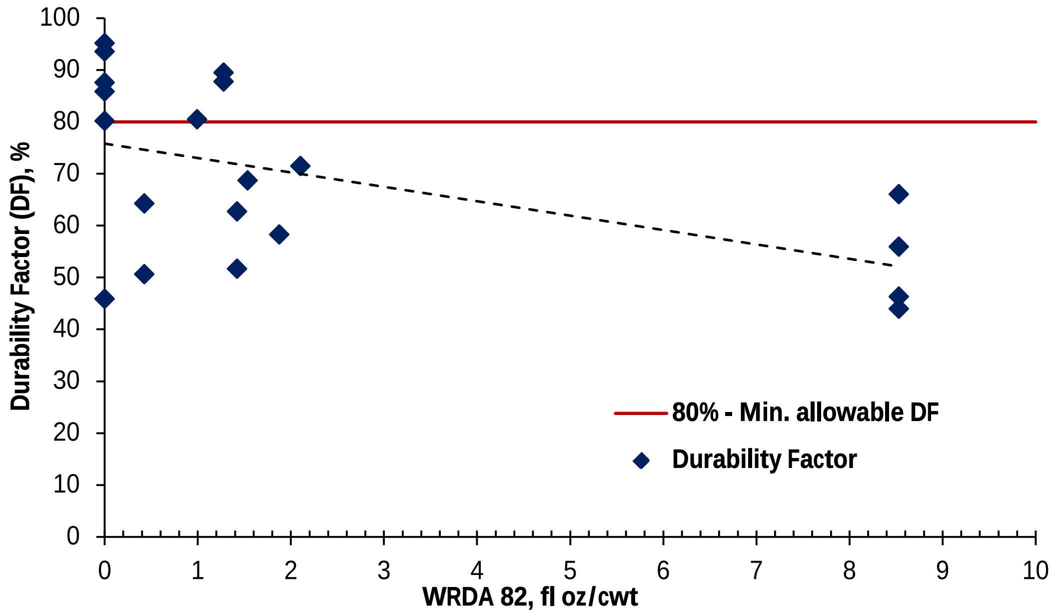

Figure 10-1 Effect of WRDA 82 on DF results for mixes batched with natural sand (Mix 1–Mix 12).

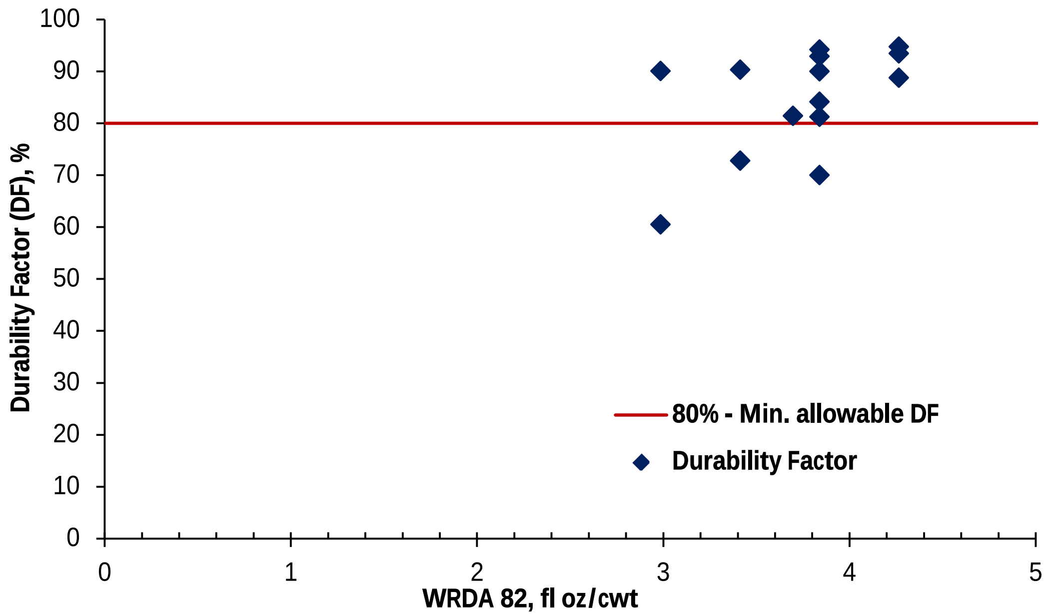

Figure 10-2 Effect of WRDA 82 on DF results for mixes batched with combined sand (Mix 13–Mix 24).

10.2.3 Effect of Coarse Aggregate Gradation on the Slump, Air Content, and Strength of Concrete

The coarse aggregate used in this study was crushed limestone, selected specifically for bridge decks. The IDOT specifications for bridge decks state that 45% to 60% of the coarse aggregate must pass 0.5 in. sieve. This coarse aggregate, provided to us from a nearby ready-mix concrete plant or quarry, often failed to meet the IDOT specification mentioned above.

The change in the coarse aggregate gradation exhibited great impact on the concrete performance in the fresh and hardened states. In the fresh state, a higher amount of coarse aggregate passing 0.5 in. sieve required a higher amount of water reducer to reach the desired slump and a higher air-entraining agent to achieve the required air content; nevertheless, it helped stabilize the air content and reduced the rate of fresh air loss in the concrete mixtures. In the hardened state, a higher amount of chips contributed to better strength. Figure 3-1 shows a list of trial mixes with different coarse aggregate gradations. The histograms indicate the 14 day strength for the three different set of trial mixes mentioned above which are sorted in ascending order with respect to the amount of fresh air content in the mix. The red, blue, and black histograms represent the trial mixes made with coarse aggregate containing 25% to 35% chips, 35% to 45% chips, and 45% to 60% chips, of the total coarse aggregate content, respectively. The graph shows that the strength increase in the concrete mixes with more than 45% chips ranged between 10% to 20% compared with mixes with 25% and 35% chips.

10.2.3 Effect of the Cementitious Materials Content (CMC) on the Performance of Concrete Mixes

The design of the 24 concrete mixes was based on a CMC of 535 lb/yd^3,which is the minimum CMC recommended by IDOT. Cement constituted 375 lb/yd^3 of the total CMC while slag or fly ash accounted for the remaining 160 lb/yd^3. When studying the fresh properties of mixes batched with combined sand and the hardened properties for strength and freeze/thaw evaluation.

The minimum target strength specified by IDOT is 3500 psi for compressive strength and 600 psi for flexural strength. The strength of the 24 concrete mixes exceeded the specification at 14 day. The 3 and 7 day strength properties for the 24 concrete mixes were not very promising. The 7 day compressive strength for 94% of the concrete mixes exceeded 3500 psi. However, all concrete mixes that failed the freeze/thaw test had a strength exceeding 3500 psi, and 80% of those mixes had a strength exceeding 4000 psi at 7 day. Therefore, it was concluded that a reduction in the air content would improve the concrete strength, but it would have adverse effect on its resistance to freeze/thaw.

Moreover, the study of the freeze/thaw led to analyzing the mix design and its performance. ASTM C666, Procedure A was conducted on the 24 concrete mixes to evaluate their freeze/thaw performance. Table 9-3 shows that most of the mixes batched with natural sand failed to pass the freeze/thaw test although some of the mixes retained enough hardened air content. However, only four mixes batched with combined sand failed the freeze/thaw test as shown in Table 9-4.

The most recent studies conducted in Canada by Thomas et al. (2010a) and (2010b) and Hooton et al. (2010) on the addition of limestone to cement in concrete used a minimum CMC level of 600 lb/yd^3 and included SCMs with different levels of replacements. The raw materials (limestone) added in cement at different levels were interground to higher fineness rather than blended. Consequently, early strength gains increased through nucleation and the dilution effect caused by the addition of limestone was overcome.

Thomas et al. (2010b) measured the hardened air and conducted the freeze/thaw test (ASTM C666, Procedure A) on concrete mixes. The hardened air per ASTM C457 ranged between 4.9% and 6.6% and gave DF results ranging between 100% and 104%. A comparison of the results between the current project and Thomas et al. (2010b) showed that the increased cement content in the mixes of

Thomas et al. (2010b) provided excellent DF results, better than all of the current project's DF results. Moreover, the total air content of the mixes of Thomas et al. (2010b) was equivalent to the air content in most of the mixes in this project, which failed to maintain a DF above 80%.

It is not easy to achieve adequate strength and strength gain and enough resistance against freeze/thaw attacks when using low CMC levels. The 535 lb/yd^3 CMC level resulted in achieving the strength requirements at the expense of the freeze/thaw resistance and vice versa. Only 330 to 340 lb/yd^3 of the modified cement were straight cement and the rest was limestone and IPA along with 30% SCMs of the total CMC level 535 lb/yd^3.

Increasing the CMC level is under consideration. However, this will raise speculation of the need to increase economy of concrete mixes and implement greener and more environmentally friendly products. Accordingly, increasing the CMC level will increase the cost of the mix and reduce environmental benefits, which are the focus of this project. However, the challenges and difficulties posed as a result of using a low CMC level of 535 lb/yd^3 put the industry at stake between maintaining adequate strength and good strength gain, on one hand, and maintaining adequate hardened entrained air content to resist the freeze/thaw, on the other hand. Thus, increasing the CMC level will encourage to the industry to provide adequate air for concrete mixes without sacrificing the strength. This will also improve the performance of the industry and save the time wasted because of failing to meet the concrete mixes' specified performance criteria.

In conclusion, increasing the CMC up to a determined level will improve the strength and strength gain and will help reduce the time needed to achieve the minimum target strength. In addition, it will improve resistance against the freeze/thaw by increasing the paste volume in concrete, which will help stabilize the fresh air and reduce its rate of loss and allow better distribution of hardened entrained air.

Therefore, based on the results of this study and the studies conducted in Canada, it is recommended to raise the cementitious contents as follows:

1. Cement content of 405 to 425 lb/yd^3
2. Class C fly ash or Grade 100 slag of 175 to 185 lb/yd^3

This increase will result in total CMC level ranging between 580 and 610 lb/yd^3.

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APPENDIX A SAMPLE MIXTURE PROPORTION FOR MIX 13

Sample Mixture proportion for Mix 13 (Cem1 < 5%_Fly ash)

DTT03110 PCC MIX DESIGN Version 2.1.2

PCC MIX #: MIX 13-CEM1<5% MATERIAL: 21605 CONCRETE PC ASH EFFECTIVE:
REF MIX#: UIC CLASS: PV LAST YR USED: TERMINATED:
RESP: 91 DISTRICT 1 LAB: IP Independent Plant Site REVIEWED BY: DFLAG:

BATCH CU YD	ADX	H2O% RED	FINE MOD	% AIR	VOIDS	(Z) CEMENT	MORTAR FACTOR	{TYPE} ASH	{TYPE} FA	{GAL/CWT} FA	{GAL/CWT} CA	{ABS. VOL} CA,B	{ABS. VOL} FA,A
1.00	W	8.0		6.5	0.41	5.35	0.88	C	B	5.3	0.200	0.401	0.291

MATERIAL	PROD NO	PROD NAME	SP G	% BLEND	%MOIST / REPL	[LBS / CU YD] SSD	[LBS / CU YD] ADJ	[KG / CU M] ADJ
022CA11	50312-04	MS THORNTON, (CA)	2.70	100.0		1823	1823	1082
029FM02	52010-20	NATURAL SAND (BLUFF CITY)	2.64					
029FM20	51972-02	HANSON MS ROMEOVILLE(CS)	2.67	100.0	1.70	1308	1331	790
37801	52403-02	LAFARGE PLEASANT PRAIRIE, WI	2.53	29.9		160	160	95
37601		ST MARY, CEM3	3.15	70.1		375	375	225
37821	544-07	HOLCIM SKYWAY, SLAG GR. 100	2.90					
					ADJ. H2O (gal : lbs)	24.5	204	121
					TOTAL BATCH WT (lbs)		3893	2310
					THEO. H2O (gal : lbs)	27.1	226	

{FA + CA} MIX-H2O: 5.50 W/C RATIO: 0.42
RED MIX-H2O: 5.06
TOTAL CEMENTITIOUS MATL: 5.35

PRODUCER: 1234-56 PROD NAME: PCC PAVING CO.
REMARKS: CONTRACT
REMARKS: ICT Project

ADDITIONAL INFORMATION: Lab: UIC CONCRETE LAB Location: CHICAGO
Designer: M. ISSA Created: 07/010/12

Adx(s): Matl Code	Type	Product	Remarks
42147	AEA	W.R. GRACE DARAVAIR 1400	2 oz/cwt
43709	A	W.R. GRACE WRDA 82	4 oz/cwt

	Target	Actual
Slump (in.)	3.5	
Air (%)	6.5	
Strength (psi) 1.	3500	Comp. 14 day
2.	600	Flex. 14 day
3.		
4.		

Printed 8/16/2012

Note: All other mixes can be made by changing the cement source and Indicating weather slag or fly ash is used.

APPENDIX B COARSE AND FINE AGGREGATE GRADATION TABLES AND CURVES

Table A-1 Sieve Analysis of (FA_1) Natural Sand for Mix 1–Mix 4 and Mix 9–Mix 12

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
3/8 in	9.5	0	0	1141.9	0.0	100.0
No. 4	4.75	33.3	33.3	1108.6	2.9	97.1
No. 8	2.36	99.2	132.5	1009.4	11.6	88.4
No.16	1.18	109.5	242	899.9	21.2	78.8
No. 30	0.60	215.2	457.2	684.7	40.0	60.0
No.50	0.3	482.2	939.4	202.5	82.3	17.7
No.100	0.15	182.3	1121.7	20.2	98.2	1.8
Pan		20.2	1141.9	0	100.0	0.0
Total		**1141.9**	**Fineness Modulus=**		**2.56**	

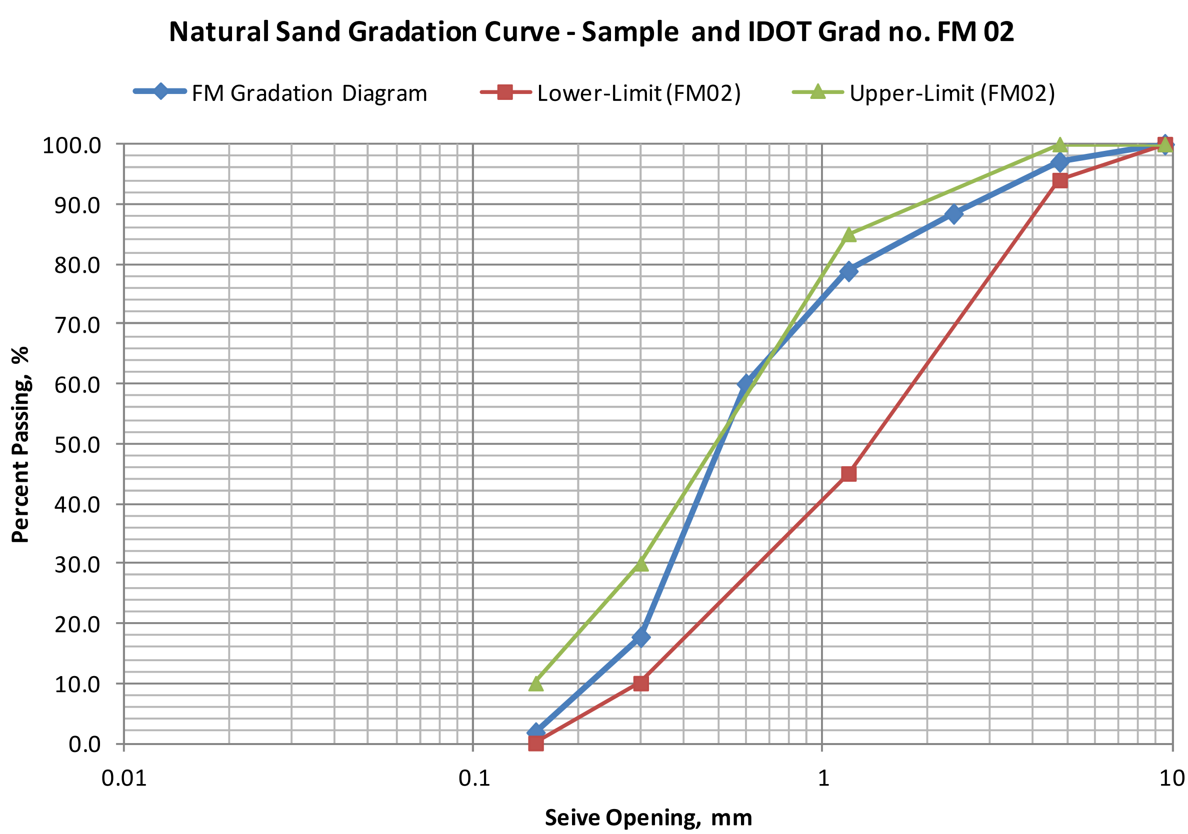

Figure A-1 Gradation of (FA_1) natural sand for Mix 1–Mix 4 and Mix 9–Mix 12.

Table A-2 Sieve Analysis of Coarse Aggregate for Mix 1–Mix 4 and Mix 9–Mix 12

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
1.0 in	25	0.0	0.0	6152.7	0.0	100.0
¾ in.	19	880.9	880.9	5271.8	14.3	85.7
½ in.	12.5	2580.9	3461.8	2690.9	56.3	43.7
3/8 in.	9.5	1036.4	4498.2	1654.5	73.1	26.9
No. 4	4.75	1248.2	5746.4	406.4	93.4	6.6
Pan		406.4	6152.7	0.0	100.0	0.0
Total		**6153**				

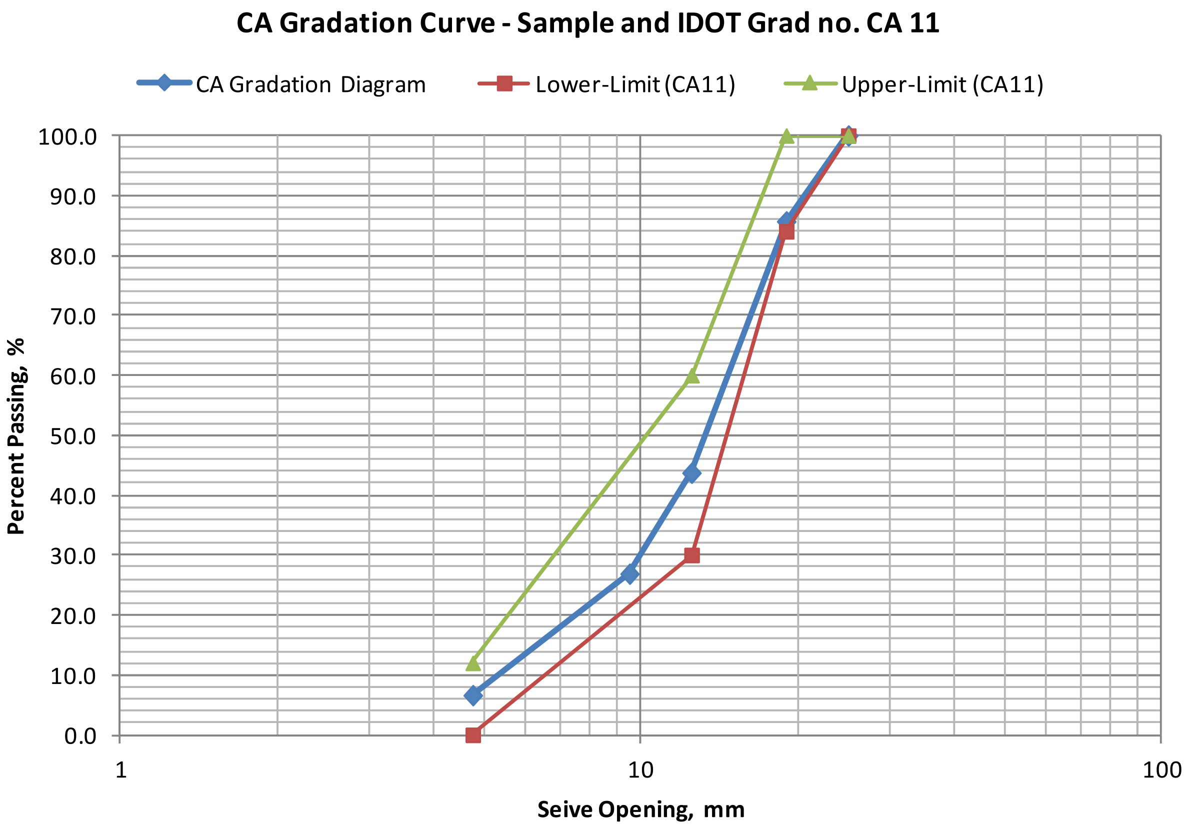

Figure A-2 Gradation of coarse aggregate for Mix 1–Mix 4 and Mix 9–Mix 12.

Table A-3 Sieve Analysis of (FA_2) Combined Sand for Mix 13–Mix 24

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
3/8 in	9.5	0	0	1377.5	0.0	100.0
No. 4	4.75	7	7	1370.5	0.5	99.5
No. 8	2.36	193	200	1177.5	14.5	85.5
No.16	1.18	334	534	843.5	38.8	61.2
No. 30	0.60	255.5	789.5	588	57.3	42.7
No.50	0.3	293	1082.5	295	78.6	21.4
No.100	0.15	251	1333.5	44	96.8	3.2
No.200	0.075	40.5	1374	3.5	99.7	0.3
Pan		44	1377.5	0	100.0	0.0
Total		**1418**	**Fineness Modulus=**		**2.86**	

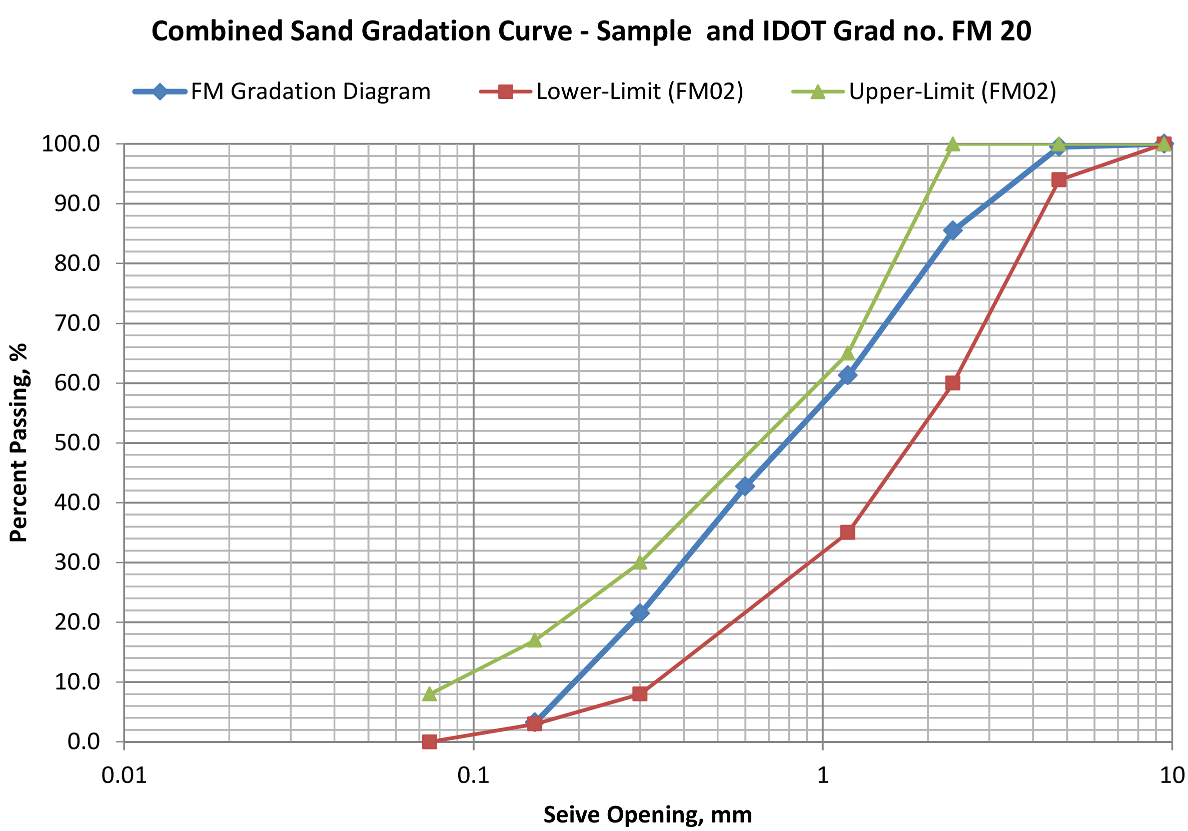

Figure A-3 Gradation of (FA_2) combined sand for Mix 13–Mix 24.

Table A-4 Sieve Analysis of Coarse Aggregate for Mix 13–Mix 24

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
1.0 in	25	0	0	4639	0.0	100.0
¾ in.	19	691.5	691.5	3947.5	14.9	85.1
½ in.	12.5	1703.5	2395	2244	51.6	48.4
3/8 in.	9.5	705	3100	1539	66.8	33.2
¼ in.	6.3	766.5	3866.5	772.5	83.3	16.7
No. 4	4.75	361	4227.5	411.5	91.1	8.9
No.16	1.18	361.5	4589	50	98.9	1.1
No.200	0.075	23.5	4612.5	26.5	99.4	0.6
Pan		26.5	4639	0	100.0	0.0
Total		**4639**				

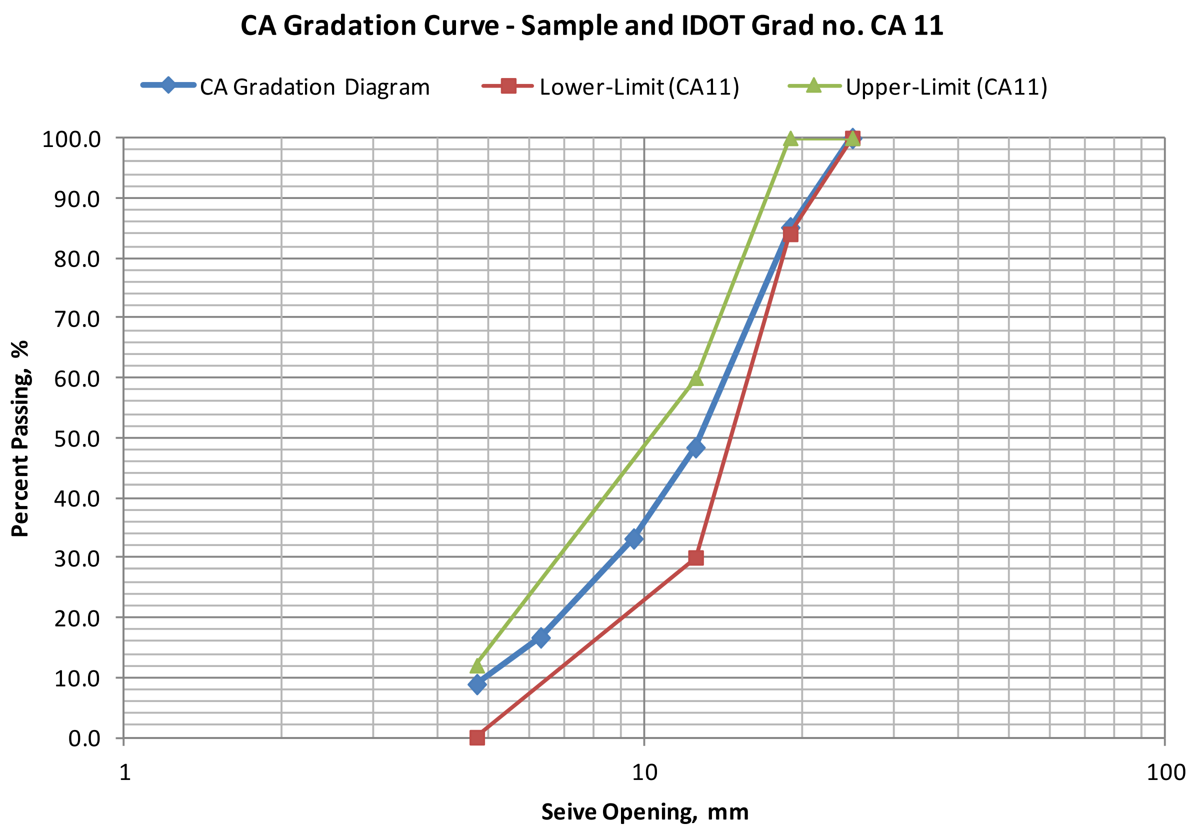

Figure A-4 Gradation of coarse aggregate for Mix 13–Mix 24.

Table A-5 Sieve Analysis of (FA_1) Natural Sand for Mix 5–Mix 8, Mix 1R–Mix 4R, and Mix 9R–Mix 12R

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
3/8 in	9.5	0	0	1930	0.0	100.0
No. 4	4.75	60	60	1870	3.1	96.9
No. 8	2.36	135	195	1735	10.1	89.9
No.16	1.18	305.5	500.5	1429.5	25.9	74.1
No. 30	0.60	296	796.5	1133.5	41.3	58.7
No.50	0.3	904	1700.5	229.5	88.1	11.9
No.100	0.15	203	1903.5	26.5	98.6	1.4
Pan		26.5	1930	0	100.0	0.0
Total		**1930**	**Fineness Modulus=**		**2.67**	

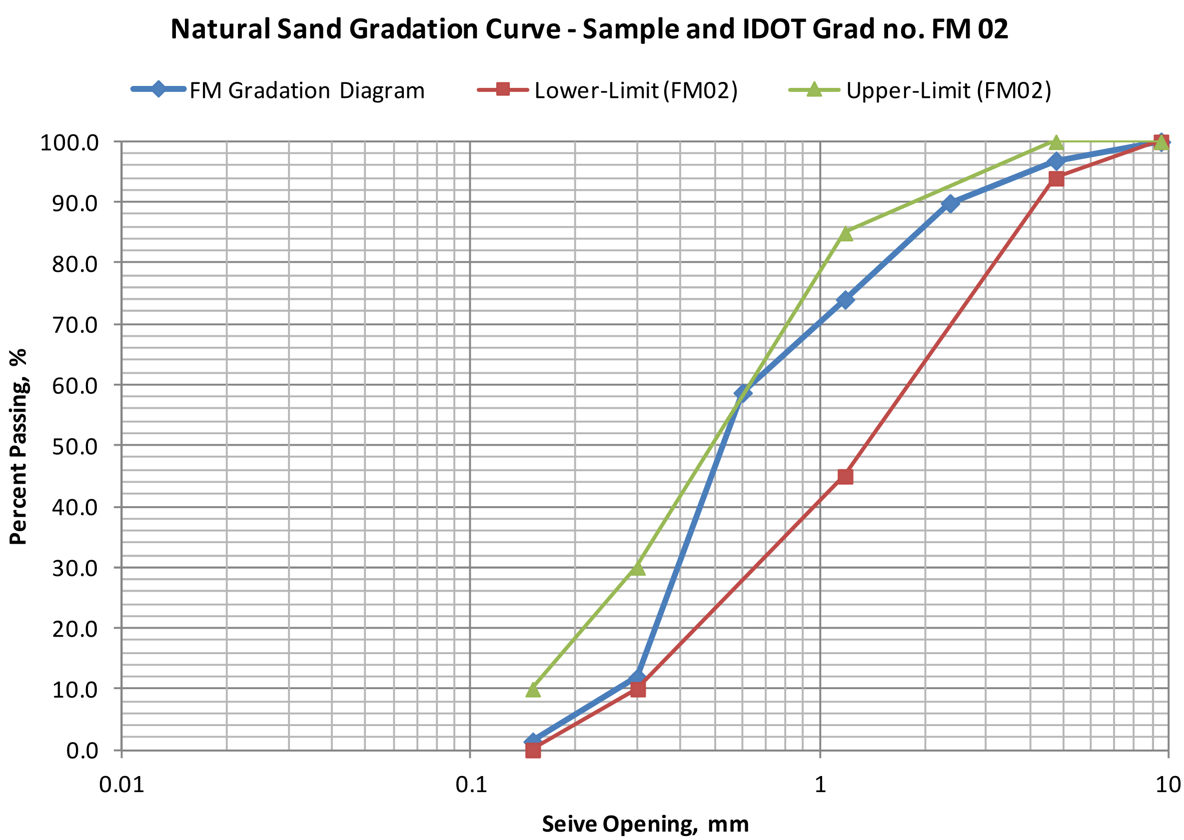

Figure A-5 Gradation of (FA_1) natural sand for Mix 5–Mix 8, Mix 1R–Mix 4R, and Mix 9R–Mix 12R.

Table A-6 Sieve Analysis of Coarse Aggregate for Mix 5–Mix 8, Mix 1R–Mix 4R, and Mix 9R–Mix 12R

Sieve No.	Opening Size (mm)	Retained (g)	Cumulative Retained (g)	Cumulative Passed (g)	Cumulative Retained %	Cumulative Passing %
1.0 in	25	0	0	5156	0.0	100.0
¾ in.	19	517.5	517.5	4638.5	10.0	90.0
½ in.	12.5	1875.5	2393	2763	46.4	53.6
3/8 in.	9.5	892.5	3285.5	1870.5	63.7	36.3
¼ in.	6.3	869	4154.5	1001.5	80.6	19.4
No. 4	4.75	452	4606.5	549.5	89.3	10.7
No.16	1.18	443	5049.5	106.5	97.9	2.1
No.200	0.075	35.5	5085	71	98.6	1.4
Pan		71	5156	0	100.0	0.0
Total		**5156**				

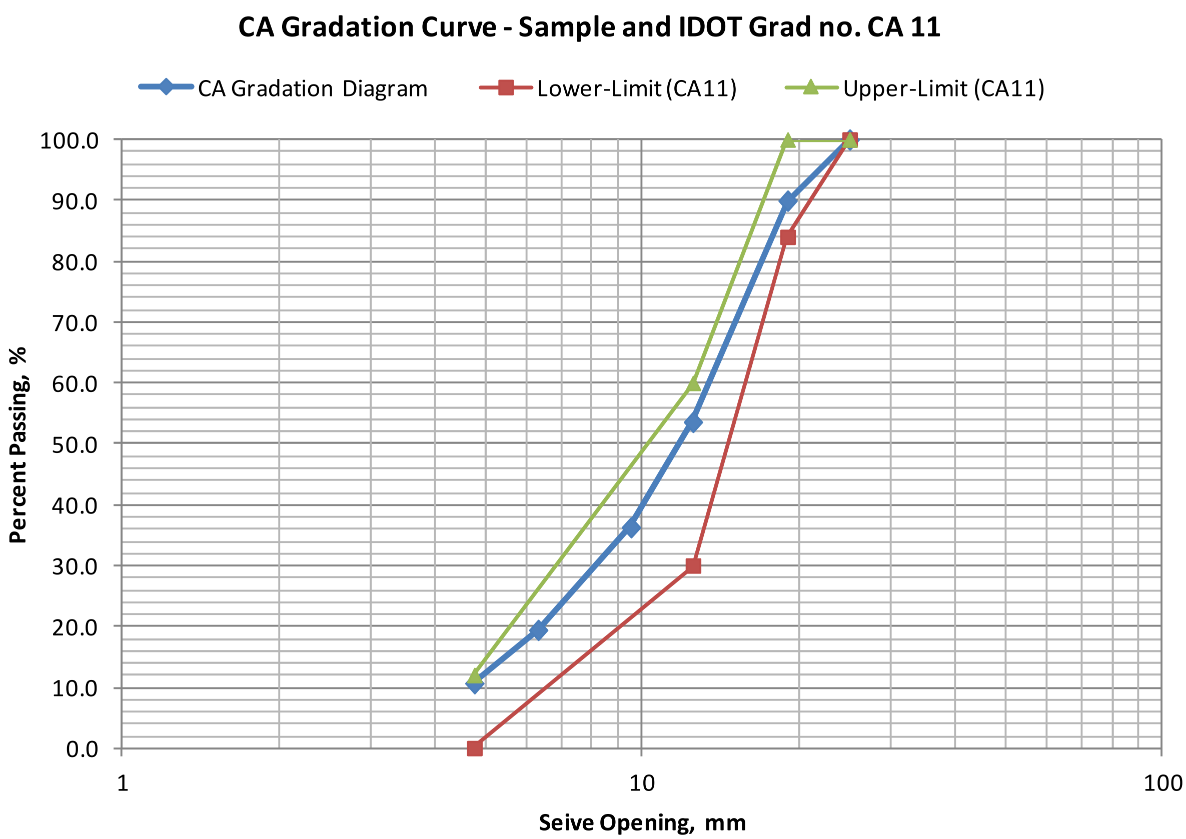

Figure A-6 Gradation of coarse aggregate Mix 5–Mix 8, Mix 1R–Mix 4R, and Mix 9R–Mix 12R.

APPENDIX C FRESH AND STRENGTH PROPERTIES OF CONCRETE MIXTURES

Mix 1–24
Mix 1R–4R
Mix 9R–12R

Properties of Fresh and Hardened Concrete
Mix Design # 1 - Main Mix
Cement 1 < 5% with Fly ash and Natural Sand (6 cu-ft batches)

Material	Source	7/31/2011 Flexural	7/30/2011 Compressive	7/19/2011 Durability
	Mix Date / Batch	*7/31/2011* / *Flexural*	*7/30/2011* / *Compressive*	*7/19/2011* / *Durability*
CA_1, lb	Hanson MS Thornton quarry	397.6	397.6	396.6
FA_1, lb	Bluff City Material (Natural)	300.2	300.2	292.88
Cement, lb	Cem1	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		47.1	47.1	51.78
WRDA, ml	W.R. Grace, Type A - 82	45	45	54
AEA, ml	W.R. Grace, Daravair 1400	29	31	31.2
FRESH PROPERTIES				
Slump, in		3.5	3.5	3.7
Air Content, %		6.6	6.5	6.5
wt concrete + bucket, lb		45.107	45.095	44.865
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.607	36.595	36.365
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.43**	**146.38**	**145.46**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		75	74	78
Lab Humidity, %		70	67	71
Concrete Temp, °F		75	75	78

HARDENED PROPERTIES

	3 Day	7 Day	14 Day	28 Day	56 Day
Compressive Strength, f_c'	8/2/2011	8/6/2011	8/13/2011	8/27/2011	9/24/2011
	3250	4300	4890	5930	6630
	3240	4360	4860	5680	6230
	3260	4310	4840	5730	6260
Average, psi	***3250***	***4323***	***4863***	***5780***	***6373***
Flexural Strength	3 Day	7 Day	14 Day	28 Day	56 Day
	8/3/2011	8/7/2011	8/14/2011	8/28/2011	9/25/2011
	530	588	753	755	761
	535	620	737	755	770
Average, psi	***533***	***604***	***745***	***755***	***766***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 2 - Main Mix
Cement 1 > 5% with Fly ash and Natural Sand (6 cu-ft batches)

	Mix Date	*7/31/2011*	*7/30/2011*	*7/20/2011*
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.6	397.6	396.6
FA_1, lb	Bluff City Material (Natural)	300.2	300.2	292.88
Cement, lb	Cem1	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C	35.56	35.56	35.56
Slag, lb	Holcim Skyway, Grade 100			
Water, lb*		47.1	47.1	51.78
WRDA, ml	W.R. Grace, Type A - 82	66	66	66
AEA, ml	W.R. Grace, Daravair 1400	29	32	33
FRESH PROPERTIES				
Slump, in		3.5	3.75	4
Air Content, %		6.5	6.7	7
wt concrete + bucket, lb		44.995	44.995	44.785
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.495	36.495	36.285
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.98**	**145.98**	**145.14**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		75	74	79
Lab Humidity, %		71	67	72
Concrete Temp, °F		75	74	79

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/2/2011	7 Day 8/6/2011	14 Day 8/13/2011	28 Day 8/27/2011	56 Day 9/24/2011
	3130	4180	5150	5800	7010
	3260	4090	5010	5940	6520
	3220	-	5020	6220	6760
Average, psi	***3203***	***4135***	***5060***	***5987***	***6763***

Flexural Strength	3 Day 8/3/2011	7 Day 8/7/2011	14 Day 8/14/2011	28 Day 8/28/2011	56 Day 9/25/2011
	505	690	686	844	993
	539	702	625	787	884
Average, psi	***522***	***696***	***656***	***816***	***939***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 3 - Main Mix
Cement 1 < 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date	*7/28/2011*	*7/28/2011*	*7/27/2011*
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.6	397.6	397.6
FA_1, lb	Bluff City Material (Natural)	305.1	305.1	305.1
Cement, lb	Cem1	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C			
Slag, lb	Holcim Skyway, Grade 100	35.56	35.56	35.56
Water, lb*		46.88	46.88	46.88
WRDA, ml	W.R. Grace, Type A - 82	300	300	300
AEA, ml	W.R. Grace, Daravair 1400	10	10	10.5
FRESH PROPERTIES				
Slump, in		3.50	3.00	3.25
Air Content, %		6.5	6.2	6.5
wt concrete + bucket, lb		45.11	45.275	45.1
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.61	36.775	36.6
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.44**	**147.1**	**146.4**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		74	74	73
Lab Humidity, %		73	72	67
Concrete Temp, °F		74	74	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/31/2011	7 Day 8/4/2011	14 Day 8/11/2011	28 Day 8/25/2011	56 Day 9/22/2011
	3340	4840	6470	6970	7530
	3420	5150	6430	7390	7160
	3500	-	6490	6750	7750
				7210	
Average, psi	***3420***	***4995***	***6463***	***7080***	***7480***

Flexural Strength	3 Day 7/31/2011	7 Day 8/4/2011	14 Day 8/11/2011	28 Day 8/25/2011	56 Day 9/22/2011
	499	664	782	904	981
	529	695	772	921	974
Average, psi	***514***	***680***	***777***	***913***	***978***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 4 - Main Mix
Cement 1 > 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date / Batch	*7/28/2011* *Flexural*	*7/28/2011* *Compressive*	*7/27/2011* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.6	397.6	397.6
FA_1, lb	Bluff City Material (Natural)	305.1	305.1	305.1
Cement,lb	Cem1	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C			
Slag, lb	Holcim Skyway, Grade 100	35.56	35.56	35.56
Water, lb*		46.88	46.88	46.88
WRDA, ml	W.R. Grace, Type A - 82	300	300	300
AEA, ml	W.R. Grace, Daravair 1400	10.5	11	13
FRESH PROPERTIES				
Slump, in		3.50	3.50	4.00
Air Content, %		6.5	6.6	6.5
wt concrete + bucket, lb		45.24	45.08	45.11
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.74	36.58	36.61
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.96**	**146.32**	**146.44**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		75	75	74
Lab Humidity, %		73	73	71
Concrete Temp, °F		75	75	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/31/2011	7 Day 8/4/2011	14 Day 8/11/2011	28 Day 8/25/2011	56 Day 9/22/2011
	3300	4960	5620	6620	7690
	3350	4960	5530	6530	7470
	3480	4690	5350	6590	7240
				6620	
Average, psi	***3377***	***4870***	***5500***	***6590***	***7467***
Flexural Strength	3 Day 7/31/2011	7 Day 8/4/2011	14 Day 8/11/2011	28 Day 8/25/2011	56 Day 9/22/2011
	535	707	867	844	961
	626	710	908	927	935
Average, psi	***581***	***709***	***888***	***886***	***948***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 5 - Main Mix
Cement 2 < 5% with Fly Ash and Natural Sand (6 cu-ft batches)

		Mix Date	*11/24/2012*	*11/24/2012*	*11/7/2012*
		Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**				
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)		297.6	297.6	297.6
Cement, lb	Cem2		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			44.44	44.44	44.44
WRDA 82, ml	W.R. Grace, WRA Type A&D		0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		35	35	45
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		25	30	30
FRESH PROPERTIES					
Slump, in			3.5	3.5	3.5
Air Content, %			7.5	7	7.9
wt concrete + bucket, lb			44.83	45.05	44.73
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.33	36.55	36.23
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.32**	**146.2**	**144.92**
W/CM			0.4	0.4	0.4
Lab Temperature, °F			67	67	70
Lab Humidity, %			35	34	34
Concrete Temp, °F			66	66	71

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 11/27/2012	7 Day 12/1/2012	14 Day 12/8/2012	28 Day 12/22/2012	56 Day 1/19/2013
	2200	3570	4470	5280	6120
	2220	3520	4510	5280	6020
	2190	3620	4610	5240	5940
Average, psi	***2203***	***3570***	***4530***	***5267***	***6027***

Flexural Strength	3 Day 11/27/2012	7 Day 12/1/2012	14 Day 12/8/2012	28 Day 12/22/2012	56 Day 1/19/2013
	458	605	612	710	829
	405	625	689	669	795
Average, psi	***432***	***615***	***651***	***690***	***812***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 6 - Main Mix
Cement 2 > 5% with Fly Ash and Natural Sand (6 cu-ft batches)

	Mix Date / Batch	11/26/2012 *Flexural*	11/26/2012 *Compressive*	11/7/2012 *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)	297.6	297.6	297.6
Cement, lb	Cem2	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		44.44	44.44	44.44
WRDA 82, ml	W.R. Grace, WRA Type A&D	0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	33	33	45
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	23	23	30
FRESH PROPERTIES				
Slump, in		3.75	3.5	3.75
Air Content, %		7.1	7.2	8.1
wt concrete + bucket, lb		44.93	44.88	44.59
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.43	36.38	36.09
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.72**	**145.52**	**144.36**
W/CM		0.4	0.4	0.4
Lab Temperature, °F		68	68	71
Lab Humidity, %		37	37	36
Concrete Temp, °F		67	67	71

HARDENED PROPERTIES

	3 Day 11/29/2012	7 Day 12/3/2012	14 Day 12/10/2012	28 Day 12/24/2012	56 Day 1/21/2013
Compressive Strength, f_c'					
	2020	3230	4320	5090	6040
	1973	3360	4380	5110	6020
	1975	3340	4410	5200	5890
Average, psi	***1989***	***3310***	***4370***	***5133***	***5983***

	3 Day 11/29/2012	7 Day 12/3/2012	14 Day 12/10/2012	28 Day 12/24/2012	56 Day 1/21/2013
Flexural Strength					
	453	525	646	606	768
	398	549	697	751	695
Average, psi	***426***	***537***	***672***	***751***	***768***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 7 - Main Mix
Cement 2 < 5% with Slag and Natural Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*11/23/2012* *Flexural*	*11/23/2012* *Compressive*	*10/31/2012* *Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)		295.56	295.56	295.56
Cement, lb	Cem2		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)				
Slag, lb	Holcim Skyway (Grade 100)		35.56	35.56	35.56
Water, lb*			47.11	47.11	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D		30	30	45
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		60	60	75
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		35	35	55
FRESH PROPERTIES					
Slump, in			3.5	3.5	4.5
Air Content, %			7.3	7.2	8
wt concrete + bucket, lb			44.96	45.05	44.68
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.46	36.55	36.18
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.84**	**146.2**	**144.72**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			67	67	70
Lab Humidity, %			30	30	26
Concrete Temp, °F			66	66	69

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 11/26/2012	7 Day 11/30/2012	14 Day 12/7/2012	28 Day 12/21/2012	56 Day 1/18/2013
	2230	3390	4380	5720	6320
	2160	3340	4340	5330	6250
	2230	3430	4240	5600	6110
Average, psi	***2207***	***3387***	***4320***	***5550***	***6227***

Flexural Strength	3 Day 11/26/2012	7 Day 11/30/2012	14 Day 12/7/2012	28 Day 12/21/2012	56 Day 1/18/2013
	457	574	649	757	901
	380	561	642	727	848
Average, psi	***419***	***568***	***646***	***742***	***875***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 8 - Main Mix
Cement 2 > 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date	*11/23/2012*	*11/23/2012*	*10/31/2012*
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)	295.56	295.56	295.56
Cement, lb	Cem2	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	35.56
Water, lb*		47.11	47.11	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D	30	30	45
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	55	55	75
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	35	35	50
FRESH PROPERTIES				
Slump, in		3.75	3.75	5.75
Air Content, %		7.4	7.3	4
wt concrete + bucket, lb		44.85	45	44.68
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.35	36.5	36.18
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.4**	**146**	**144.72**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		68	68	71
Lab Humidity, %		30	30	30
Concrete Temp, °F		67	67	70

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 11/26/2012	7 Day 11/30/2012	14 Day 12/7/2012	28 Day 12/21/2012	56 Day 1/18/2013
	1817	3100	4030	5250	6070
	1841	3090	4190	5270	6050
	1896	3040	4220	5280	6080
Average, psi	***1851***	***3077***	***4147***	***5267***	***6067***
Flexural Strength	3 Day 11/26/2012	7 Day 11/30/2012	14 Day 12/7/2012	28 Day 12/21/2012	56 Day 1/18/2013
	360	579	636	809	859
	366	559	639	833	
Average, psi	***363***	***569***	***638***	***821***	***859***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 9 - Main Mix
Cement 3 < 5% with Fly ash and Natural Sand (6 cu-ft batches)

	Mix Date / Batch	*8/9/2011* *Flexural*	*8/9/2011* *Compressive*	*8/10/2011* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.7	397.7	397.7
FA_1, lb	Bluff City Material (Natural)	300.4	300.4	300.4
Cement, lb	Cem3	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C	35.56	35.56	35.56
Slag, lb	Holcim Skyway, Grade 100			
Water, lb*		46.66	46.66	46.66
WRDA, ml	W.R. Grace, Type A - 82	50	50	50
AEA, ml	W.R. Grace, Daravair 1400	25	26	24
FRESH PROPERTIES				
Slump, in		3.50	3.70	3.75
Air Content, %		6.8	6.7	6.6
wt concrete + bucket, lb		45.075	45.005	45.05
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.575	36.505	36.55
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.3**	**146.02**	**146.2**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		73	73	71
Lab Humidity, %		66	70	57
Concrete Temp, °F		74	74	73

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/12/2011	7 Day 8/16/2011	14 Day 8/23/2011	28 Day 9/6/2011	56 Day 10/4/2011
	3340	3900	4680	5560	6100
	3230	3980	4690	5720	6500
	3170	3930	4640	5340	6170
					6170
Average, psi	***3247***	***3937***	***4670***	***5540***	***6235***

Flexural Strength	3 Day 8/12/2011	7 Day 8/16/2011	14 Day 8/23/2011	28 Day 9/6/2011	56 Day 10/4/2011
	573	652	810	793	805
	649	700	741	796	902
Average, psi	***611***	***676***	***776***	***795***	***854***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 10 - Main Mix
Cement 3 > 5% with Fly ash and Natural Sand (6 cu-ft batches)

	Mix Date Batch	8/9/2011 *Flexural*	8/9/2011 *Compressive*	8/10/2011 *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.7	397.7	397.7
FA_1, lb	Bluff City Material (Natural)	300.4	300.4	300.4
Cement, lb	Cem3	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C	35.56	35.56	35.56
Slag, lb	Holcim Skyway, Grade 100			
Water, lb*		46.66	46.66	46.66
WRDA, ml	W.R. Grace, Type A - 82	50	50	50
AEA, ml	W.R. Grace, Daravair 1400	25	26	22
FRESH PROPERTIES				
Slump, in		3.25	3.00	3.50
Air Content, %		6.5	6.5	6.5
wt concrete + bucket, lb		45.135	45.065	45.052
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.635	36.565	36.552
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.54**	**146.26**	**146.208**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		73	73	71
Lab Humidity, %		66	67	60
Concrete Temp, °F		74	74	73

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/12/2011	7 Day 8/16/2011	14 Day 8/23/2011	28 Day 9/6/2011	56 Day 10/4/2011
	3000	4060	4690	5460	6170
	3110	3980	4760	5300	6140
	3040	3990	4630	5480	6380
					6250
Average, psi	***3050***	***4010***	***4693***	***5413***	***6235***

Flexural Strength	3 Day 8/12/2011	7 Day 8/16/2011	14 Day 8/23/2011	28 Day 9/6/2011	56 Day 10/4/2011
	529	609	682	735	883
	597	649	675	760	842
Average, psi	***563***	***629***	***679***	***748***	***863***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 11 - Main Mix
Cement 3 < 5% with Slag and Natural Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*8/12/2011* *Flexural*	*8/12/2011* *Compressive*	*8/12/2011* *Durability*
CA_1, lb	Hanson MS Thornton quarry		397.6	397.6	397.6
FA_1, lb	Bluff City Material (Natural)		305.6	305.6	305.6
Cement, lb	Cem3		83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C				
Slag, lb	Holcim Skyway, Grade 100		35.56	35.56	35.56
Water, lb*			46.44	46.44	46.44
WRDA, ml	W.R. Grace, Type A - 82		300	300	300
AEA, ml	W.R. Grace, Daravair 1400		3.5	1.5	5
FRESH PROPERTIES					
Slump, in			3.25	3.60	3.50
Air Content, %			6.6	6.4	6.6
wt concrete + bucket, lb			44.875	44.6	45.05
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.375	36.1	36.55
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.5**	**144.4**	**146.2**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			71	71	71
Lab Humidity, %			64	65	64
Concrete Temp, °F			73	73	73

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/15/2011	7 Day 8/19/2011	14 Day 8/26/2011	28 Day 9/9/2011	56 Day 10/7/2011
	4200	5510	6410	6900	7530
	4260	5480	6550	6770	7340
	4360	5590	6720	6110**	8160**
		5400	6290	7130	
Average, psi	***4273***	***5495***	***6493***	***6933***	***7435***

Flexural Strength	3 Day 8/15/2011	7 Day 8/19/2011	14 Day 8/26/2011	28 Day 9/9/2011	56 Day 10/7/2011
	738	825	944	974	1081
	671	922	1009	1010	968**
					1073
Average, psi	***705***	***874***	***977***	***992***	***1077***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 12 - Main Mix
Cement 3 > 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date Batch	*8/12/2011* *Flexural*	*8/12/2011* *Compressive*	*8/12/2011* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	397.6	397.6	397.6
FA_1, lb	Bluff City Material (Natural)	305.6	305.6	305.6
Cement, lb	Cem3	83.3	83.3	83.3
Fly ash, lb	Pleasant Prairie, Type C			
Slag, lb	Holcim Skyway, Grade 100	35.56	35.56	35.56
Water, lb*		46.44	46.44	46.44
WRDA, ml	W.R. Grace, Type A - 82	300	300	300
AEA, ml	W.R. Grace, Daravair 1400	1.5	1.5	3
FRESH PROPERTIES				
Slump, in		3.50	3.50	4.00
Air Content, %		6.3	6.5	6.3
wt concrete + bucket, lb		45.48	45.03	45.323
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.98	36.53	36.823
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**147.92**	**146.12**	**147.292**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		71	71	71
Lab Humidity, %		64	65	65
Concrete Temp, F°		73	73	72

HARDENED PROPERTIES

	3 Day 8/15/2011	7 Day 8/19/2011	14 Day 8/26/2011	28 Day 9/9/2011	56 Day 10/7/2011
Compressive Strength, f_c'					
	4080	5400	6610	7050	7050**
	4020	5520	6690	7390	7620
	3900	5480	6480	6890	7680
				6620**	7740
Average, psi	***4000***	***5467***	***6593***	***7110***	***7680***
Flexural Strength	3 Day 8/15/2011	7 Day 8/19/2011	14 Day 8/26/2011	28 Day 9/9/2011	56 Day 10/7/2011
	644	904	941	983	1053
	606	798	1011	1012	1052
					1077
Average, psi	***625***	***851***	***976***	***998***	***1061***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing

** Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 13 - Main Mix
Cement 1R < 5% with Fly Ash and Combined Sand (6 cu-ft batches)

		Mix Date	*7/19/2012*	*7/17/2012*	*7/10/2012*
		Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**				
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		295.56	295.77	295.56
Cement, lb	Cem1R		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			45.33	45.33	45.33
WRDA 82, ml	W.R. Grace, WRA Type A&D		120	120	105
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		120	120	135
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		215	215	210
FRESH PROPERTIES					
Slump, in			5	5.25	5.25
Air Content, %			8.25	8	6.9
wt concrete + bucket, lb			44.29	44.4	45.21
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			35.79	35.9	36.71
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**143.16**	**143.6**	**146.84**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			77	78	79
Lab Humidity, %			69	68	70
Concrete Temp, °F			76	76	78

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/20/2012	7 Day 7/24/2012	14 Day 7/31/2012	28 Day 8/14/2012	56 Day• 9/11/2012
	3110	4080	4570	5470	5750
	3130	3980	4810	5330	5750
	3050	4030	4920	5510	5920
Average, psi	***3097***	***4030***	***4767***	***5437***	***5807***
Flexural Strength	3 Day 7/22/2012	7 Day 7/26/2012	14 Day 8/2/2012	28 Day 8/16/2012	56 Day 9/13/2012
	505	527	562	620	715
	443	535	541	610	723
Average, psi	***474***	***531***	***552***	***615***	***719***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
•Tested at 57 Days
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 14 - Main Mix
Cement 1R > 5% with Fly Ash and Combined Sand (6 cu-ft batches)

		Mix Date Batch	*7/23/2012* *Flexural*	*7/19/2012* *Compressive*	*7/11/2012* *Durability*
Material	**Source**				
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		295.77	295.77	295.56
Cement, lb	Cem1R		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			45.33	45.33	45.33
WRDA 82, ml	W.R. Grace, WRA Type A&D		135	135	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		125	120	120
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		220	220	220
FRESH PROPERTIES					
Slump, in			4.5	4.75	4.75
Air Content, %			7.3	8	7.4
wt concrete + bucket, lb			44.95	44.45	44.75
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.45	35.95	36.25
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.8**	**143.8**	**145**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			78	78	79
Lab Humidity, %			64	69	70
Concrete Temp, °F			78	78	78
HARDENED PROPERTIES					
Compressive Strength, f_c'	3 Day 7/22/2012	7 Day 7/26/2012	14 Day 8/2/2012	28 Day 8/16/2012	56 Day 9/13/2012
	2750	3700	4320	5260	5560
	2680	3790	4500	5040	5640
	2630	3930	4510	5110	5970
Average, psi	***2687***	***3807***	***4443***	***5137***	***5723***
Flexural Strength	3 Day 7/26/2012	7 Day 7/30/2012	14 Day 8/6/2012	28 Day 8/20/2012	56 Day 9/17/2012
	555	557	648	750	754
	511	688	653	670	658•
Average, psi	***533***	***623***	***651***	***710***	***754***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi
•Machine turned off while testing

Properties of Fresh and Hardened Concrete
Mix Design # 15 - Main Mix
Cement 1R < 5% with Slag and Combined Sand (6 cu-ft batches)

	Mix Date	*6/28/2012*	*6/28/2012*	*6/28/2012*
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	294.7	294.7	294.7
Cement, lb	Cem1R	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	35.56
Water, lb*		47.33	47.33	47.33
WRDA 82, ml	W.R. Grace, WRA Type A&D	105	150	105
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	135	135	135
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	360	360	360
FRESH PROPERTIES				
Slump, in		4.5	6	4.5
Air Content, %		8	8	8.1
wt concrete + bucket, lb		44.44	44.48	44.4
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		35.94	35.98	35.9
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**143.76**	**143.92**	**143.6**
W/CM		0.44	0.44	0.44
Lab Temperature, °F		76	75	77
Lab Humidity, %		70	67	71
Concrete Temp, °F		76	74	76

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/1/2012	7 Day 7/5/2012	14 Day 7/12/2012	28 Day 7/26/2012	56 Day 8/23/2012
	2490	3830	4170	4820	5960
	2780	3830	3970	4970	6540
	2620	3350	4510	4900	5580
Average, psi	***2630***	***3670***	***4217***	***4897***	***6027***
Flexural Strength	3 Day 7/1/2012	7 Day 7/5/2012	14 Day 7/12/2012	28 Day 7/26/2012	56 Day 8/23/2012
	501	713	762	766	837
	528	623	727	795	806
Average, psi	***515***	***668***	***745***	***781***	***822***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 16 - Main Mix
Cement 1R > 5% with Slag and Combined Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*7/6/2012* *Flexural*	*7/6/2012* *Compressive*	*7/2/2012* *Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		294.7	294.7	294.7
Cement, lb	Cem1R		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)				
Slag, lb	Holcim Skyway (Grade 100)		35.56	35.56	35.56
Water, lb*			47.33	47.33	47.33
WRDA 82, ml	W.R. Grace, WRA Type A&D		135	135	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		135	135	135
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		360	360	360
FRESH PROPERTIES					
Slump, in			4.5	4.25	5.5
Air Content, %			8	7.6	6.9
wt concrete + bucket, lb			44.52	44.76	45.01
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.02	36.26	36.51
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**144.08**	**145.04**	**146.04**
W/CM			0.44	0.44	0.44
Lab Temperature, °F			77	77	75
Lab Humidity, %			72	72	67
Concrete Temp, °F			78	78	76

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/9/2012	7 Day 7/13/2012	14 Day 7/20/2012	28 Day 8/3/2012	56 Day 8/31/2012
	3120	4120	5110	5340	5630
	2820	3890	4630	5910	6300
	3000	4240	5070	5760	5710
Average, psi	***2980***	***4083***	***4937***	***5670***	***5880***

Flexural Strength	3 Day 7/9/2012	7 Day 7/13/2012	14 Day 7/20/2012	28 Day 8/3/2012	56 Day 8/31/2012
	533	533	701	781	759
	501	602	645	786	803
Average, psi	***517***	***568***	***673***	***784***	***781***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 17 - Main Mix
Cement 2 < 5% with Fly Ash and Combined Sand (6 cu-ft batches)

	Mix Date Batch	*10/24/2012* *Flexural*	*10/17/2012* *Compressive*	*10/18/2012* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	294	294	294
Cement, lb	Cem2	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		47.11	47.11	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D	120	135	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	165	165	155
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	5	140	150
FRESH PROPERTIES				
Slump, in		3.75	5	4
Air Content, %		6.8	8	7.9
wt concrete + bucket, lb		44.95	44.39	44.54
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.45	35.89	36.04
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.8**	**143.56**	**144.16**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		72	73	72
Lab Humidity, %		39	53	42
Concrete Temp, °F		71	72	71

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 10/20/2012	7 Day 10/24/2012	14 Day 10/31/2012	28 Day 11/14/2012	56 Day 12/12/2012
	2440	3430	4150	4760	5090
	2510	3530	4130	4590	5180
	2410	3450	4260	4710	5010
Average, psi	***2453***	***3470***	***4180***	***4687***	***5093***
Flexural Strength	3 Day 10/27/2012	7 Day 10/31/2012	14 Day 11/7/2012	28 Day 11/21/2012	56 Day 12/19/2012
	542	711	717	758	797
	539	688	734	803	900
Average, psi	***541***	***700***	***726***	***781***	***849***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 18 - Main Mix
Cement 2 > 5% with Fly Ash and Combined Sand (6 cu-ft batches)

	Mix Date	10/19/2012	10/19/2012	10/19/2012
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	294	294	294
Cement, lb	Cem2	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		47.11	47.11	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D	120	135	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	165	165	165
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	95	120	150
FRESH PROPERTIES				
Slump, in		4.75	5.5	5
Air Content, %		7.5	8	8
wt concrete + bucket, lb		44.73	44.51	44.58
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.23	36.01	36.08
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**144.92**	**144.04**	**144.32**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		71	71	70
Lab Humidity, %		41	41	42
Concrete Temp, °F		72	72	71

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 10/22/2012	7 Day 10/26/2012	14 Day 11/2/2012	28 Day 11/16/2012	56 Day 12/14/2012
	2450	3790	4460	5180	5670
	2470	3670	4380	5170	5610
	2500	3540	4330	5010	5760
Average, psi	***2473***	***3667***	***4390***	***5120***	***5680***
Flexural Strength	3 Day 10/22/2012	7 Day 10/26/2012	14 Day 11/2/2012	28 Day 11/16/2012	56 Day 12/14/2012
	463	536	635	670	736
	469	610	602	627	818
Average, psi	***466***	***573***	***619***	***649***	***777***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 19 - Main Mix
Cement 2 < 5% with Slag and Combined Sand (6 cu-ft batches)

		Mix Date	*10/15/2012*	*10/11/2012*	*10/11/2012*
		Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**				
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		293.1	293.1	293.1
Cement, lb	Cem2		48.67	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)				
Slag, lb	Holcim Skyway (Grade 100)		35.56	35.56	35.56
Water, lb*			48.89	48.89	48.89
WRDA 82, ml	W.R. Grace, WRA Type A&D		150	150	150
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		180	180	180
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		410	425	435
FRESH PROPERTIES					
Slump, in			5	5	5.25
Air Content, %			8	8	7.5
wt concrete + bucket, lb			44.43	44.4	44.7
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			35.93	35.9	36.2
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**143.72**	**143.6**	**144.8**
W/CM			0.44	0.44	0.44
Lab Temperature, °F			74	74	75
Lab Humidity, %			37	29	28
Concrete Temp, °F			74	72	73

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 10/14/2012	7 Day 10/18/2012	14 Day 10/25/2012	28 Day 11/8/2012	56 Day 12/6/2012
	2510	3600	4450	5060	5630
	2590	3580	4510	5410	5500
	2480	3570	4600	5220	4980
Average, psi	***2527***	***3583***	***4520***	***5230***	***5565***
Flexural Strength	3 Day 10/18/2012	7 Day 10/22/2012	14 Day 10/29/2012	28 Day 11/12/2012	56 Day 12/10/2012
	560	661	787	813	861
	504	654	693	798	847
Average, psi	***532***	***658***	***740***	***806***	***854***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 20 - Main Mix
Cement 2 > 5% with Slag and Combined Sand (6 cu-ft batches)

	Mix Date Batch	10/15/2012 *Flexural*	10/15/2012 *Compressive*	10/11/2012 *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	293.1	293.1	293.1
Cement, lb	Cem2	83.4	83.4	83.4
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	35.56
Water, lb*		48.89	48.89	48.89
WRDA 82, ml	W.R. Grace, WRA Type A&D	150	150	150
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	170	165	165
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	420	420	445
FRESH PROPERTIES				
Slump, in		5	3.5	4.75
Air Content, %		7.5	8	7.8
wt concrete + bucket, lb		44.6	44.53	44.68
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.1	36.03	36.18
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**144.4**	**144.12**	**144.72**
W/CM		0.44	0.44	0.44
Lab Temperature, °F		74	76	75
Lab Humidity, %		37	34	29
Concrete Temp, °F		75	76	72

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 10/18/2012	7 Day 10/22/2012	14 Day 10/29/2012	28 Day 11/12/2012	56 Day 12/10/2012
	2660	3780	4760	5530	6310
	2730	3800	4850	5570	6520
	2660	3730	4760		6460
Average, psi	***2683***	***3770***	***4790***	***5550***	***6430***

Flexural Strength	3 Day 10/18/2012	7 Day 10/22/2012	14 Day 10/29/2012	28 Day 11/12/2012	56 Day 12/10/2012
	471	615	713	804	851
	480	646	792	792	901
Average, psi	***476***	***631***	***753***	***798***	***876***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 21 - Main Mix
Cement 3 < 5% with Fly Ash and Combined Sand (6 cu-ft batches)

	Mix Date	*7/19/2012*	*7/17/2012*	*7/11/2012*
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	295.56	295.77	295.56
Cement, lb	Cem3	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		45.33	45.33	45.33
WRDA 82, ml	W.R. Grace, WRA Type A&D	130	130	130
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	110	110	120
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	225	225	220
FRESH PROPERTIES				
Slump, in		4.25	3.9	4.25
Air Content, %		8.2	7.2	6.6
wt concrete + bucket, lb		44.36	44.86	45.38
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		35.86	36.36	36.88
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**143.44**	**145.44**	**147.52**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		78	78	79
Lab Humidity, %		69	68	70
Concrete Temp, °F		78	77	78

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/20/2012	7 Day 7/24/2012	14 Day 7/31/2012	28 Day 8/14/2012	57 Day• 9/11/2012
	3180	4020	4700	5460	6240
	3300	4200	5090	5690	6350
	3320	3860	4790	5420	6190
Average, psi	***3267***	***4027***	***4860***	***5523***	***6260***
Flexural Strength	3 Day 7/22/2012	7 Day 7/26/2012	14 Day 8/2/2012	28 Day 8/16/2012	56 Day 9/13/2012
	526	490	619	650	683
	489	578	601	671	662
Average, psi	***508***	***534***	***610***	***661***	***673***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
•Tested at 57 Days
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 22 - Main Mix
Cement 3 > 5% with Fly Ash and Combined Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*7/23/2012 Flexural*	*7/20/2012 Compressive*	*7/11/2012 Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		295.77	295.77	295.56
Cement, lb	Cem3		83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			45.33	45.33	45.33
WRDA 82, ml	W.R. Grace, WRA Type A&D		120	120	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		140	140	115
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		210	210	230
FRESH PROPERTIES					
Slump, in			5	4.5	5.5
Air Content, %			6.7	7	7.2
wt concrete + bucket, lb			45.17	45.01	45.06
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.67	36.51	36.56
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**146.68**	**146.04**	**146.24**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			78	76	79
Lab Humidity, %			64	63	70
Concrete Temp, °F			78	76	78

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 7/23/2012	7 Day 7/27/2012	14 Day 8/3/2012	28 Day 8/17/2012	56 Day 9/14/2012
	3430	4370	5080	6140	6720
	3390	4240	5180	5610	6660
	3490	4500	5160	5950	6740
Average, psi	***3437***	***4370***	***5140***	***5900***	***6707***
Flexural Strength	3 Day 7/26/2012	7 Day 7/30/2012	14 Day 8/6/2012	28 Day 8/20/2012	56 Day 9/17/2012
	565	724	710	764	869
	580	653	754	818	846
Average, psi	***573***	***689***	***732***	***791***	***858***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 23 - Main Mix
Cement 3 < 5% with Slag and Combined Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*8/15/2012* *Flexural*	*7/30/2012* *Compressive*	*7/2/2012* *Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)		293.3	294.7	294.7
Cement, lb	Cem3		48.67	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)				
Slag, lb	Holcim Skyway (Grade 100)		35.56	35.56	35.56
Water, lb*			48.67	47.33	47.33
WRDA 82, ml	W.R. Grace, WRA Type A&D		140	120	120
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		140	140	135
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		365	400	360
FRESH PROPERTIES					
Slump, in			5	3.5	4.25
Air Content, %			7.3	7.6	7.8
wt concrete + bucket, lb			44.93	44.93	44.74
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.43	36.43	36.24
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.72**	**145.72**	**144.96**
W/CM			0.44	0.44	0.44
Lab Temperature, °F			76	75	77
Lab Humidity, %			69	68	67
Concrete Temp, °F			75	74	76

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/2/2012	7 Day 8/6/2012	14 Day 8/13/2012	28 Day 8/27/2012	56 Day 9/24/2012
	3030	4120	4950	5500	5630
	3090	4100	4660	5090	6260
	3190	4350	4980	5810	5550
Average, psi	***3103***	***4190***	***4863***	***5467***	***5813***

Flexural Strength	3 Day 8/18/2012	7 Day 8/22/2012	14 Day 8/29/2012	28 Day 9/12/2012	38 Day• 10/10/2012
	511	668	791	814	830
	486	698	NA	831	844
Average, psi	***499***	***683***	***791***	***823***	***837***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 24 - Main Mix
Cement 3 > 5% with Slag and Combined Sand (6 cu-ft batches)

	Mix Date / Batch	7/30/2012 *Flexural*	8/6/2012 *Compressive*	7/2/2012 *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Hanson MS Romeoville (CS)	294.7	294.7	294.7
Cement, lb	Cem3	83.4	83.4	83.4
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	35.56
Water, lb*		47.33	47.33	47.33
WRDA 82, ml	W.R. Grace, WRA Type A&D	145	145	135
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	135	150	135
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	395	380	360
FRESH PROPERTIES				
Slump, in		4.75	5.75	4
Air Content, %		7.9	7.3	6.8
wt concrete + bucket, lb		44.68	44.95	45.2
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.18	36.45	36.7
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**144.72**	**145.8**	**146.8**
W/CM		0.44	0.44	0.44
Lab Temperature, °F		75	76	77
Lab Humidity, %		67	69	67
Concrete Temp, °F		74	75	76

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 8/9/2012	7 Day 8/13/2012	14 Day 8/20/2012	28 Day 9/3/2012	56 Day 10/1/2012
	3160	4220	5280	5920	5660
	2990	4230	5300	6070	6130
	2930	4280	5490	5890	6560
Average, psi	***3027***	***4243***	***5357***	***5960***	***6117***

Flexural Strength	3 Day 8/2/2012	7 Day 8/6/2012	14 Day 8/13/2012	28 Day 8/27/2012	49 Day• 9/24/2012
	486	656	744	841	768
	492	653	704	790	718
Average, psi	***489***	***655***	***724***	***816***	***743***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi
•Tested at 49 Days

Properties of Fresh and Hardened Concrete
Mix Design # 1R - Main Mix
Cement 1R < 5% with Fly Ash and Natural Sand (6 cu-ft batches)

	Mix Date	1/11/2013	1/11/2013	12/15/2012
	Batch	*Flexural*	*Compressive*	*Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)	296.5	296.5	297.6
Cement, lb	Cem1	83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		45.56	45.56	44.44
WRDA 82, ml	W.R. Grace, WRA Type A&D	0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	43	43	35
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	25	25	30
FRESH PROPERTIES				
Slump, in		3.75	3.75	3.5
Air Content, %		7.3	7.6	7.8
wt concrete + bucket, lb		44.89	44.7	44.68
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.39	36.2	36.18
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.56**	**144.8**	**144.72**
W/CM		0.4	0.4	0.4
Lab Temperature, °F		77	77	73
Lab Humidity, %		39	39	40
Concrete Temp, °F		74	74	72

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 1/14/2013	7 Day 1/18/2013	14 Day 1/25/2013	28 Day 2/8/2013	56 Day 3/8/2013
	2590	3830	4340	4960	5760
	2480	3900	4370	4880	5670
	2520	3560	4370	4980	5640
Average, psi	***2530***	***3763***	***4360***	***4940***	***5690***

Flexural Strength	3 Day 1/14/2013	7 Day 1/18/2013	14 Day 1/25/2013	28 Day 2/8/2013	56 Day 3/8/2013
	561	622	662	681	711
	490	587	733	753	781
Average, psi	***526***	***605***	***698***	***717***	***746***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 2R - Main Mix
Cement 1R > 5% with Fly Ash and Natural Sand (6 cu-ft batches)

		Mix Date	*2/22/2013*	*2/22/2013*	*12/18/2012*
		Batch	*Flexure*	*Compression*	*Durability*
Material	**Source**				
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)		303.6	303.6	297.6
Cement, lb	Cem1		83.3	83.3	83.34
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	35.56
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			38.44	38.44	44.44
WRDA 82, ml	W.R. Grace, WRA Type A&D		0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		30	33	43
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		26	26	30
FRESH PROPERTIES					
Slump, in			3.75	4	3.5
Air Content, %			7.8	7.5	7.5
wt concrete + bucket, lb			44.75	44.85	44.77
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.25	36.35	36.27
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145**	**145.4**	**145.08**
W/CM			0.4	0.4	0.4
Lab Temperature, °F			75	76	73
Lab Humidity, %			30	30	38
Concrete Temp, °F			72	72	73
HARDENED PROPERTIES					
Compressive Strength, f_c'	3 Day 2/25/2013	7 Day 3/1/2013	14 Day 3/8/2013	28 Day 3/22/2013	56 Day 4/19/2013
	2600	3910	4540	5690	5830
	2590	4010	4470	5350	5900
	2580	3980	4840	5520	6270
Average, psi	***2590***	***3967***	***4617***	***5520***	***6000***
Flexural Strength	3 Day 2/25/2013	7 Day 3/1/2013	14 Day 3/8/2013	28 Day 3/22/2013	56 Day 4/19/2013
	438	596	652	655	722
	414	618	639	674	747
Average, psi	***426***	***607***	***646***	***665***	***735***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 3R - Main Mix
Cement 1R < 5% with Slag and Natural Sand (6 cu-ft batches)

Material	Source		Mix Date / Batch	1/8/2013 *Flexural*	1/8/2013 *Compressive*	12/15/2012 *Durability*
CA_1, lb	Hanson MS Thornton quarry			405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)			294.4	294.4	295.56
Cement, lb	Cem1			83.34	83.34	83.34
Fly ash, lb	Pleasant Prairie (Type C)					
Slag, lb	Holcim Skyway (Grade 100)			35.56	35.56	35.56
Water, lb*				48.22	48.22	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D			35	35	35
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F			63	63	65
Daravair 1400, ml	W.R. Grace, AEA ASTM C260			35	40	40
FRESH PROPERTIES						
Slump, in				4.25	4	3.5
Air Content, %				7.7	8	7.5
wt concrete + bucket, lb				44.65	44.54	44.77
wt bucket, lb				8.5	8.5	8.5
wt concrete, lb				36.15	36.04	36.27
V, ft^3				0.25	0.25	0.25
Unit Weight, lb/ft^3				**144.6**	**144.16**	**145.08**
W/CM				0.42	0.42	0.42
Lab Temperature, °F				78	77	73
Lab Humidity, %				41	40	41
Concrete Temp, °F				73	74	72
HARDENED PROPERTIES						
Compressive Strength, f_c'	3 Day 1/11/2013	7 Day 1/15/2013		14 Day 1/22/2013	28 Day 2/5/2013	56 Day 3/5/2013
	2260	3600		4490	5140	6120
	2270	3420		4550	5430	5870
	2300	3610		4500	5240	6010
Average, psi	***2277***	***3543***		***4513***	***5270***	***6000***
Flexural Strength	3 Day 1/11/2013	7 Day 1/15/2013		14 Day 1/22/2013	28 Day 2/5/2013	56 Day 3/5/2013
	509	628		698	785	844
	468	587		740	825	809
Average, psi	***489***	***608***		***719***	***805***	***827***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 4R - Main Mix
Cement 1R > 5% with Slag and Natural Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*2/20/2013* *Flexure*	*2/21/2013* *Compression*	*12/15/2012* *Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	405.1
FA_1, lb	Bluff City Material (Natural)		301.6	301.6	295.56
Cement, lb	Cem1		83.33	83.33	83.34
Fly ash, lb	Pleasant Prairie (Type C)				
Slag, lb	Holcim Skyway (Grade 100)		35.56	35.56	35.56
Water, lb*			41.11	41.11	47.11
WRDA 82, ml	W.R. Grace, WRA Type A&D		50	45	30
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		80	70	55
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		46	36	45
FRESH PROPERTIES					
Slump, in			5	3.75	3.25
Air Content, %			7.4	7.3	7.3
wt concrete + bucket, lb			44.94	44.95	44.97
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.44	36.25	36.47
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.76**	**145**	**145.88**
W/CM			0.42	0.42	0.42
Lab Temperature, °F			76	76	74
Lab Humidity, %			36	36	40
Concrete Temp, °F			73	73	72

HARDENED PROPERTIES					
Compressive Strength, f_c'	3 Day 2/24/2013	7 Day 2/28/2013	14 Day 3/7/2013	28 Day 3/21/2013	56 Day 4/18/2013
	2990	4260	4970	6470	7260
	3030	4230	5200	6320	6860
	2970	4260	5090	5980	6900
Average, psi	***2997***	***4250***	***5087***	***6257***	***7007***
Flexural Strength	3 Day 2/23/2013	7 Day 2/27/2013	14 Day 3/6/2013	28 Day 3/20/2013	56 Day 4/17/2013
	478	618	759	864	831
	443	644	708	820	787
Average, psi	***461***	***631***	***734***	***842***	***809***

Note: *Amount of water depends on the moisture condition of the aggregate at the time of mixing
** Not included in the average
Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 9R - Main Mix
Cement 3R < 5% with Fly ash and Natural Sand (6 cu-ft batches)

Material	Source	Mix Date / Batch	*1/9/2013 Flexural*	*1/9/2013 Compressive*	*1/31/2013 Durability*
CA_1, lb	Hanson MS Thornton quarry		405.1	405.1	135
FA_1, lb	Bluff City Material (Natural)		296.5	296.5	101.2
Cement, lb	Cem1		83.34	83.34	27.8
Fly ash, lb	Pleasant Prairie (Type C)		35.56	35.56	11.85
Slag, lb	Holcim Skyway (Grade 100)				
Water, lb*			45.56	45.56	12.81
WRDA 82, ml	W.R. Grace, WRA Type A&D		0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F		40	40	15
Daravair 1400, ml	W.R. Grace, AEA ASTM C260		22	25	15
FRESH PROPERTIES					
Slump, in			4.50	3.75	3.50
Air Content, %			7.3	7.2	8.0
wt concrete + bucket, lb			44.89	44.96	44.55
wt bucket, lb			8.5	8.5	8.5
wt concrete, lb			36.39	36.46	36.05
V, ft^3			0.25	0.25	0.25
Unit Weight, lb/ft^3			**145.56**	**145.84**	**144.2**
W/CM			0.4	0.4	0.4
Lab Temperature, °F			77	77	75
Lab Humidity, %			39	36	33
Concrete Temp, °F			74	74	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 1/12/2013	7 Day 1/16/2013	14 Day 1/23/2013	28 Day 2/6/2013	56 Day 3/6/2013
	3020	3650	4440	4960	5440
	3150	3940	4410	4610	5550
	3130	3800	4270	4850	5550
Average, psi	***3100***	***3797***	***4373***	***4807***	***5513***

Flexural Strength	3 Day 1/12/2013	7 Day 1/16/2013	14 Day 1/23/2013	28 Day 2/6/2013	56 Day 3/6/2013
	565	676	706	754	732
	525	655	687	762	801
Average, psi	***545***	***666***	***697***	***758***	***767***

Note: The size of durability mix was 2 ft^3 and included only Freeze and Thaw specimens and hardened air cylinders

*Amount of water depends on the moisture condition of the aggregate at the time of mixing

**Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 10R - Main Mix
Cement 3R > 5% with Fly ash and Natural Sand (6 cu-ft batches)

	Mix Date / Batch	*1/11/2013* *Flexural*	*1/9/2013* *Compressive*	*1/31/2013* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	135
FA_1, lb	Bluff City Material (Natural)	296.5	296.5	101.2
Cement, lb	Cem1	83.34	83.34	27.8
Fly ash, lb	Pleasant Prairie (Type C)	35.56	35.56	11.85
Slag, lb	Holcim Skyway (Grade 100)			
Water, lb*		45.56	45.56	12.81
WRDA 82, ml	W.R. Grace, WRA Type A&D	0	0	0
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	55	38	15
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	22	23	12
FRESH PROPERTIES				
Slump, in		4.00	4.50	3.50
Air Content, %		7.1	7.7	7.5
wt concrete + bucket, lb		45.06	44.76	44.84
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.56	36.26	36.34
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146.24**	**145.04**	**145.36**
W/CM		0.4	0.4	0.4
Lab Temperature, °F		77	77	75
Lab Humidity, %		38	37	32
Concrete Temp, °F		75	74	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 1/12/2013	7 Day 1/16/2013	14 Day 1/23/2013	28 Day 2/6/2013	56 Day 3/6/2013
	2980	3680	4320	4960	5430
	2870	3710	4270	4520	5340
	2730	3720	4360	5010	
Average, psi	***2860***	***3703***	***4317***	***4830***	***5385***

Flexural Strength	3 Day 1/14/2013	7 Day 1/18/2013	14 Day 1/25/2013	28 Day 2/8/2013	56 Day 3/8/2013
	604	665	718	706	808
	614	725		783	715
Average, psi	***609***	***695***	***718***	***745***	***762***

Note: The size of durability mix was 2 ft^3 and included only Freeze and Thaw specimens and hardened air cylinders

*Amount of water depends on the moisture condition of the aggregate at the time of mixing

**Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 11R - Main Mix
Cement 3R < 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date / Batch	*2/21/2013* *Flexural*	*1/7/2013* *Compressive*	*1/31/2013* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	135
FA_1, lb	Bluff City Material (Natural)	301.6	294.4	100.5
Cement, lb	Cem1	83.34	83.34	27.8
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	11.85
Water, lb*		41.1	48.22	13.7
WRDA 82, ml	W.R. Grace, WRA Type A&D	45	40	15
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	65	70	20
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	41	40	40
FRESH PROPERTIES				
Slump, in		4.25	3.50	3.75
Air Content, %		7.1	7.2	8.1
wt concrete + bucket, lb		45	45.05	44.5
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.5	36.55	36
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**146**	**146.2**	**144**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		76	76	76
Lab Humidity, %		36	33	33
Concrete Temp, °F		73	74	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 1/10/2013	7 Day 1/14/2013	14 Day 1/21/2013	28 Day 2/4/2013	56 Day 3/4/2013
	2830	3950	5000	6080	5900
	2830	4110	4990	5810	6160
	2600	4010	4940	5940	6270
Average, psi	***2753***	***4023***	***4977***	***5943***	***6110***
Flexural Strength	3 Day 2/24/2013	7 Day 2/28/2013	14 Day 3/7/2013	28 Day 3/21/2013	56 Day 4/18/2013
	613	650	785	890	922
	624	678	847	851	940
Average, psi	***619***	***664***	***816***	***871***	***931***

Note: The size of durability mix was 2 ft^3 and included only Freeze and Thaw specimens and hardened air cylinders

*Amount of water depends on the moisture condition of the aggregate at the time of mixing

**Not included in the average

Compressive strength calculated to the nearest 10 psi

Properties of Fresh and Hardened Concrete
Mix Design # 12R - Main Mix
Cement 3R > 5% with Slag and Natural Sand (6 cu-ft batches)

	Mix Date Batch	*1/7/2013* *Flexural*	*1/7/2013* *Compressive*	*1/31/2013* *Durability*
Material	**Source**			
CA_1, lb	Hanson MS Thornton quarry	405.1	405.1	135
FA_1, lb	Bluff City Material (Natural)	294.4	294.4	100.5
Cement, lb	Cem1	83.34	83.34	27.8
Fly ash, lb	Pleasant Prairie (Type C)			
Slag, lb	Holcim Skyway (Grade 100)	35.56	35.56	11.85
Water, lb*		48.22	48.22	13.7
WRDA 82, ml	W.R. Grace, WRA Type A&D	38	38	15
ADVA Cast 575, ml	W.R. Grace, HRWR Type A&F	65	68	20
Daravair 1400, ml	W.R. Grace, AEA ASTM C260	40	40	35
FRESH PROPERTIES				
Slump, in		3.50	3.50	3.50
Air Content, %		7.4	7.5	8.0
wt concrete + bucket, lb		44.86	44.75	44.61
wt bucket, lb		8.5	8.5	8.5
wt concrete, lb		36.36	36.25	36.11
V, ft^3		0.25	0.25	0.25
Unit Weight, lb/ft^3		**145.44**	**145**	**144.44**
W/CM		0.42	0.42	0.42
Lab Temperature, °F		76	77	75
Lab Humidity, %		73	74	33
Concrete Temp, F°		41	40	74

HARDENED PROPERTIES

Compressive Strength, f_c'	3 Day 1/10/2013	7 Day 1/14/2013	14 Day 1/21/2013	28 Day 2/4/2013	56 Day 3/4/2013
	2690	3900	4980	5870	6300
	2650	3980	4960	5850	6390
	2670	3950	4880	6010	6270
Average, psi	***2670***	***3943***	***4940***	***5910***	***6320***

Flexural Strength	3 Day 1/10/2013	7 Day 1/14/2013	14 Day 1/21/2013	28 Day 2/4/2013	56 Day 3/4/2013
	512	658	769	896	978
	485	711	816	878	902
Average, psi	***499***	***685***	***793***	***887***	***940***

Note: The size of durability mix was 2 ft^3 and included only Freeze and Thaw specimens and hardened air cylinders

*Amount of water depends on the moisture condition of the aggregate at the time of mixing

**Not included in the average

Compressive strength calculated to the nearest 10 psi

APPENDIX D FRESH PROPERTIES AND SETTING TIME CURVES FOR CONCRETE MIXES

Table A-7 Fresh Properties for Concrete Mixes Batched with Natural Sand (Mix 1–Mix 12, Mix 1R–4R, & Mix 9R–12R)

Mix No.	Mix Design	Batch Set	Air Content %	Slump in.	Unit Wt. lb/ft^3	Conc. Temp. °F	Lab Temp. °F	Lab Hum. %	Setting Time hrs : min	
									Initial	Final
1	Cem1 < 5% _Fly ash	Durability	6.5	3.70	145.5	78	78	71	7:38	9:38
		Compression	6.5	3.50	146.4	75	78	67		
		Flexural	6.6	3.50	146.4	75	74	70		
2	Cem1 > 5%_Fly ash	Durability	7.0	4.00	145.1	79	79	72	7:58	10:21
		Compression	6.7	3.75	146.0	74	79	67		
		Flexural	6.5	3.50	146.0	75	74	71		
3	Cem1 < 5%_Slag	Durability	6.5	3.25	146.4	74	73	67	9:22	11:41
		Compression	6.2	3.00	147.1	74	73	72		
		Flexural	6.5	3.50	146.4	74	74	73		
4	Cem1 > 5%_Slag	Durability	6.5	4.00	146.4	74	74	71	9:14	11:20
		Compression	6.6	3.50	146.3	75	74	73		
		Flexural	6.5	3.50	147.0	75	75	73		
1R	Cem1R < 5%_Fly ash	Durability	7.8	3.50	144.7	40	73	72	8:32	10:25
		Compression	7.6	3.75	144.8	39	77	74		
		Flexural	7.3	3.75	145.6	39	77	74		
2R	Cem1R > 5%_Fly ash	Durability	7.5	3.50	145.1	38	73	73	9:20	11:00
		Compression	8.0	4.00	144.4	30	76	72		
		Flexural	7.8	3.75	145.0	30	75	72		
3R	Cem1R < 5%_Slag	Durability	7.5	3.50	145.1	41	73	72	5:48	7:20
		Compression	8.0	4.00	144.2	40	77	74		
		Flexural	7.7	4.25	144.6	41	78	73		
4R	Cem1R > 5%_Slag	Durability	7.3	3.25	145.9	40	74	72	5:31	7:10
		Compression	7.6	3.75	145.0	36	76	73		
		Flexural	7.4	5.00	145.8	36	76	73		
5	Cem2 < 5%_Fly ash	Durability	7.9	3.50	144.9	71	70	34	7:16	9:09
		Compression	7.0	3.50	146.2	66	67	34		
		Flexural	7.5	3.50	145.3	66	67	35		
6	Cem2 > 5%_Fly ash	Durability	8.1	3.75	144.4	71	71	36	7:28	9:29
		Compression	7.2	3.50	145.5	67	68	37		
		Flexural	7.1	3.75	145.7	67	68	37		
7	Cem2 < 5%_Slag	Durability	8.0	4.50	144.7	69	70	26	5:23	7:06
		Compression	7.2	3.50	146.2	66	67	30		
		Flexural	7.3	3.50	145.8	66	67	30		
8	Cem2 > 5%_Slag	Durability	8.0	5.75	144.7	70	71	30	5:25	7:15
		Compression	7.3	3.75	146.0	67	68	30		
		Flexural	7.4	3.75	145.4	67	68	30		
9	Cem3 < 5%_Fly ash	Durability	6.6	3.75	146.2	73	71	57	5:55	7:41
		Compression	6.7	3.70	146.0	74	71	70		
		Flexural	6.8	3.50	146.3	74	73	66		
10	Cem3 > 5%_Fly ash	Durability	6.5	3.50	146.2	73	71	60	5:52	7:37
		Compression	6.5	3.00	146.3	74	71	67		
		Flexural	6.5	3.25	146.5	74	73	66		
11	Cem3 < 5%_Slag	Durability	6.6	3.50	146.2	73	71	64	7:13	9:08
		Compression	6.4	3.60	144.4	73	71	65		
		Flexural	6.6	3.25	145.5	73	71	64		
12	Cem3 > 5%_Slag	Durability	6.3	4.00	147.3	72	71	65	8:17	9:37
		Compression	6.5	3.50	146.1	73	71	65		
		Flexural	6.3	3.50	147.9	73	71	64		
9R	Cem3R < 5%_Fly ash	Compression	7.2	3.75	145.8	36	77	74	5:59	7:30
		Flexural	7.3	4.50	145.6	39	77	74		
10R	Cem3R > 5%_Fly ash	Compression	7.7	4.50	145.0	37	77	74	5:37	7:20
		Flexural	7.1	4.00	146.2	38	77	75		
11R	Cem3R < 5%_Slag	Compression	7.2	3.50	146.2	33	76	74	4:51	6:12
		Flexural	6.6	4.00	146.8	31	77	75		
12R	Cem3R > 5%_Slag	Compression	7.5	3.50	145.0	40	77	74	5:17	6:47
		Flexural	7.4	3.50	145.4	41	76	73		

Table A-8 Fresh Properties for Concrete Mixes Batched with Combined Sand (Mix 13–Mix 24)

Mix No.	Mix Design	Batch Set	Air Content %	Slump in.	Unit Wt. lb/ft^3	Conc. Temp. °F	Lab Temp. °F	Lab Hum. %	Setting Time hrs:min	
									Initial	Final
13	Cem1R < 5%_Fly ash	Durability	6.9	5.25	146.84	78	79	70	11:16	13:42
		Compression	8.0	5.25	143.6	76	78	68		
		Flexural	8.3	5.00	143.16	76	77	69		
14	Cem1R > 5%_Fly ash	Durability	7.4	4.75	145	78	79	70	11:06	14:07
		Compression	8.0	4.75	143.8	78	78	69		
		Flexural	7.3	4.50	145.8	78	78	64		
15	Cem1R < 5%_Slag	Durability	8.1	4.50	143.6	76	77	71	6:07	8:24
		Compression	8.0	6.00	143.92	74	75	67		
		Flexural	8.0	4.50	143.76	76	76	70		
16	Cem1R > 5%_Slag	Durability	6.9	5.50	146.04	76	75	67	6:49	8:42
		Compression	7.6	4.25	145.04	78	77	72		
		Flexural	8.0	4.50	144.08	78	77	72		
17	Cem2 < 5%_Fly ash	Durability	7.9	4.00	144.16	71	72	42	11:42	14:41
		Compression	8.0	5.00	143.56	72	73	53		
		Flexural	6.8	3.75	145.8	71	72	39		
18	Cem2 > 5%_Fly ash	Durability	8.0	5.00	144.32	71	70	42	10:11	13:35
		Compression	8.0	5.50	144.04	72	71	41		
		Flexural	7.5	4.75	144.92	72	71	41		
19	Cem2 < 5%_Slag	Durability	7.5	5.25	144.8	73	75	28	5:25	7:20
		Compression	8.0	5.00	143.6	72	74	29		
		Flexural	8.0	5.00	143.72	74	74	37		
20	Cem2 > 5%_Slag	Durability	7.8	4.75	144.72	72	75	29	5:34	7:24
		Compression	8.0	3.50	144.12	76	76	34		
		Flexural	7.5	5.00	144.4	75	74	37		
21	Cem3 < 5%_Fly ash	Durability	6.6	4.25	147.52	78	79	70	7:27	9:53
		Compression	7.2	3.90	145.44	77	78	68		
		Flexural	8.2	4.25	143.44	78	78	69		
22	Cem3 > 5%_Fly ash	Durability	7.2	5.50	146.24	78	79	70	7:43	10:05
		Compression	7.0	4.50	146.04	76	76	63		
		Flexural	6.7	5.00	146.68	78	78	64		
23	Cem3 < 5%_Slag	Durability	7.8	4.25	144.96	76	77	67	5:25	7:20
		Compression	7.6	3.50	145.72	74	75	68		
		Flexural	7.3	5.00	145.72	75	76	69		
24	Cem3 > 5%_Slag	Durability	6.8	4.00	146.8	76	77	67	5:34	7:24
		Compression	7.3	5.75	145.8	75	76	69		
		Flexural	7.9	4.75	144.72	74	75	67		

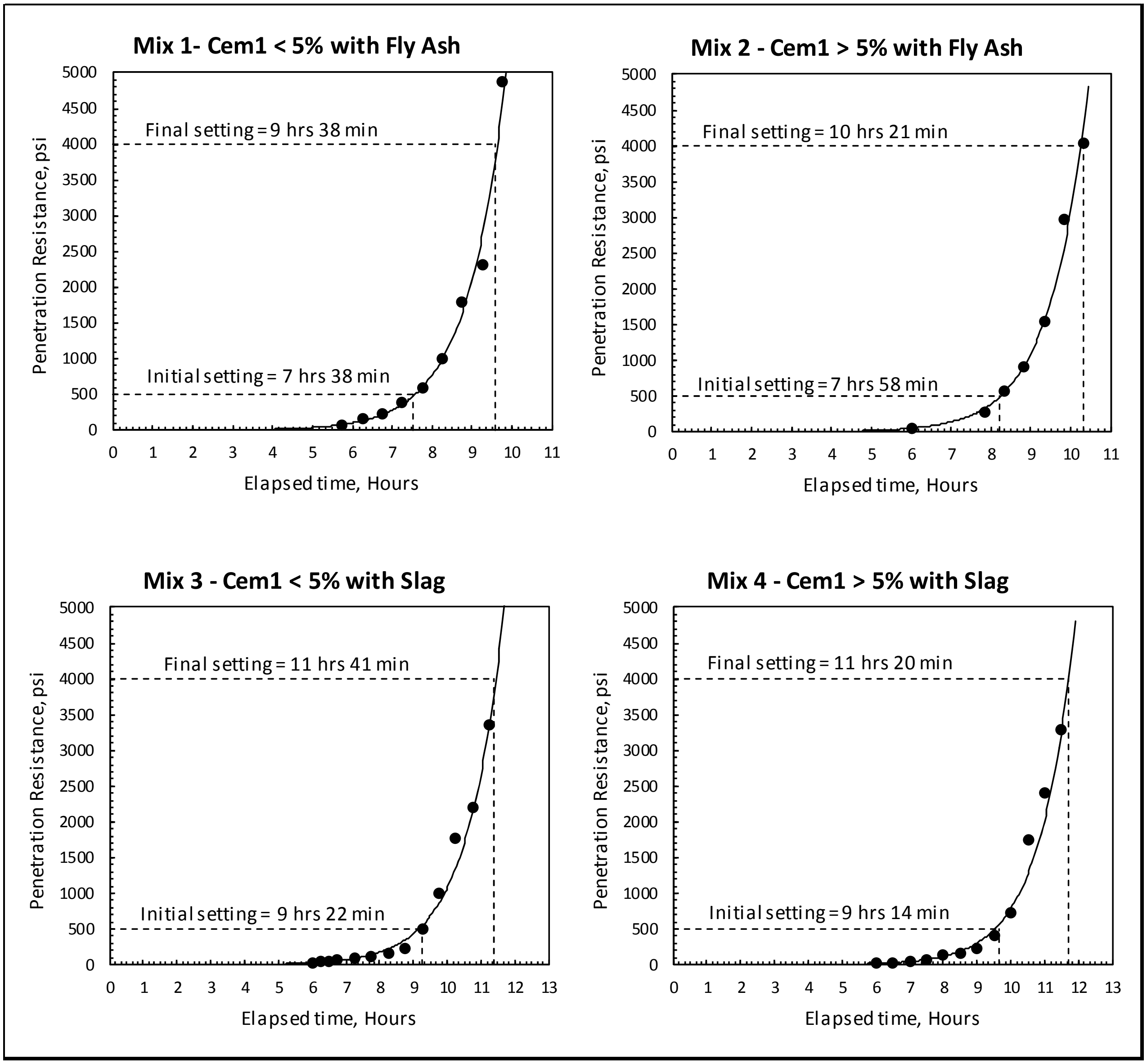

Figure A-7 Penetration pressure vs. time for concrete with Cem1 and natural sand (Mix 1–Mix 4).

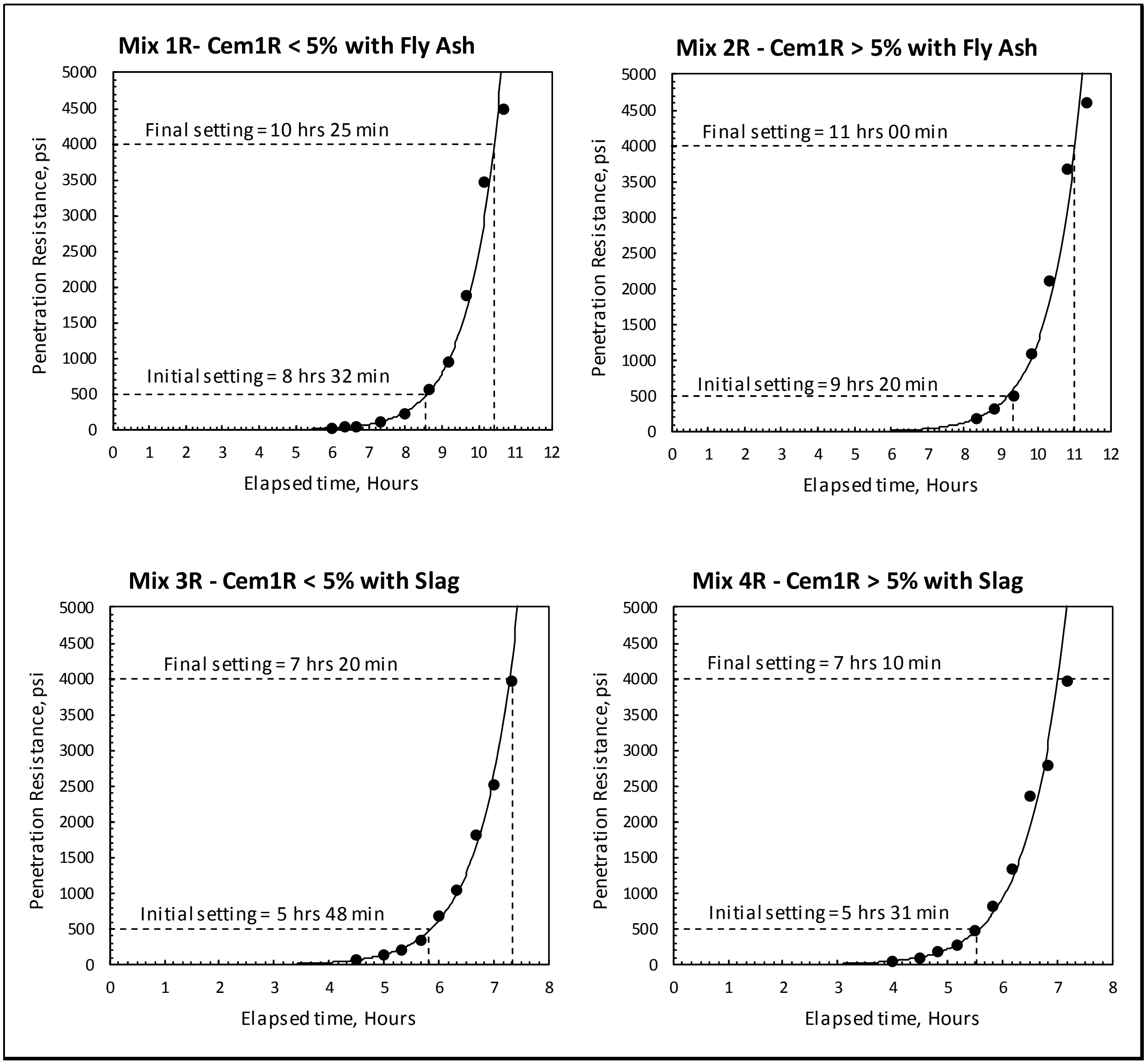

Figure A-8 Penetration pressure vs. time for concrete with Cem1R and natural sand (Mix 1R–Mix 4R).

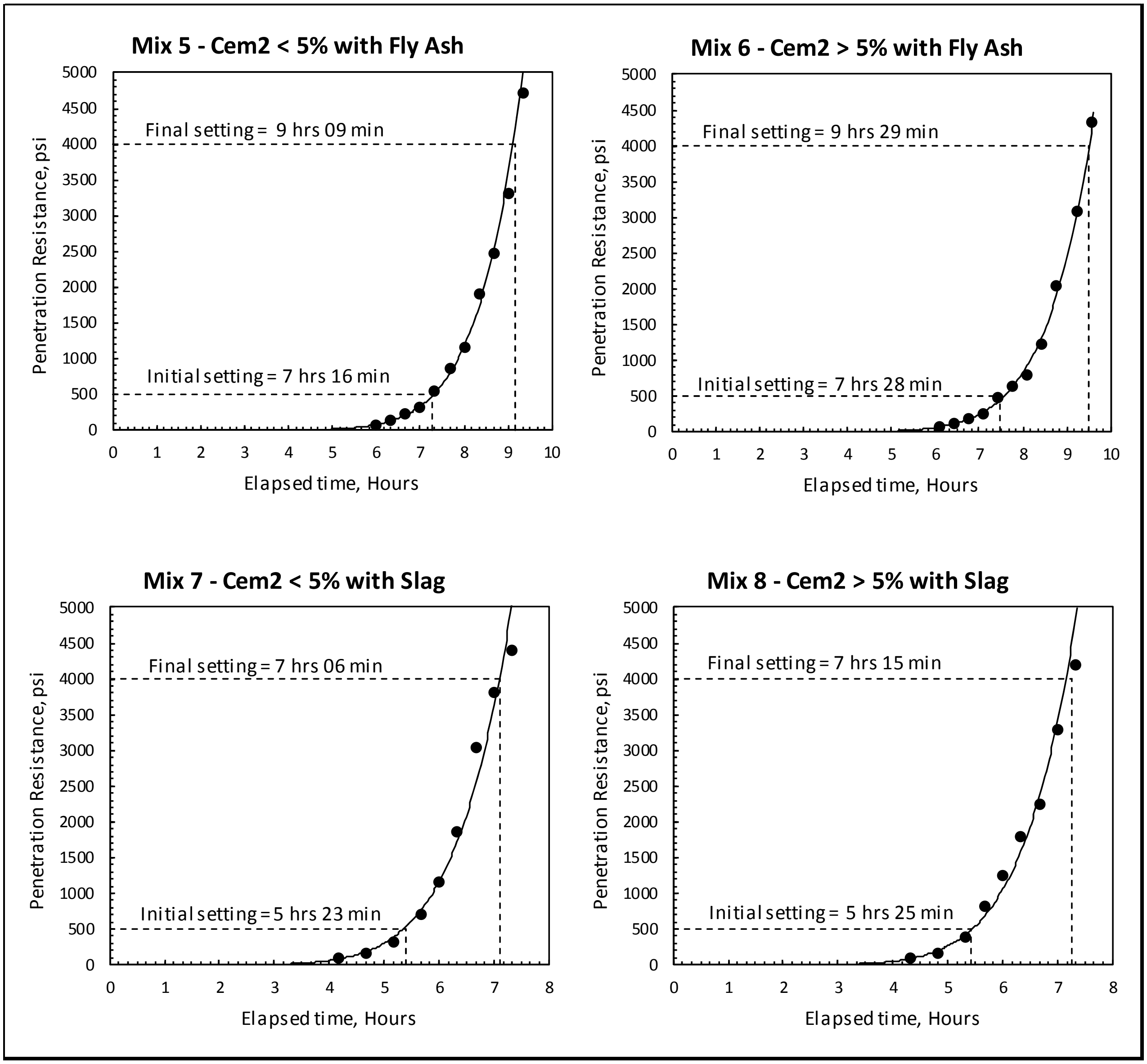

Figure A-9 Penetration pressure vs. time for concrete with Cem2 and natural sand (Mix 5–Mix 8).

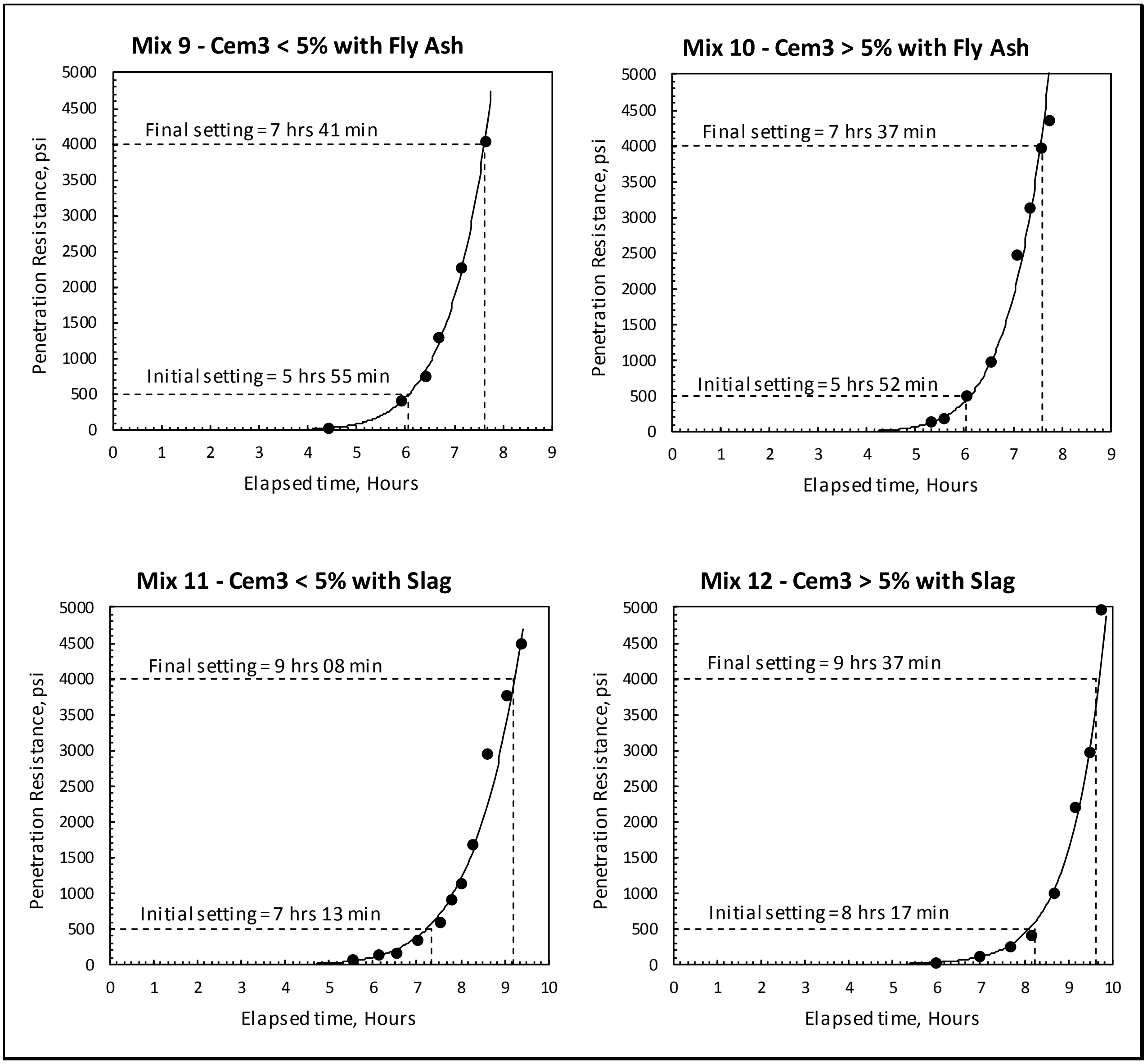

Figure A-10 Penetration pressure vs. time for concrete with Cem3 and natural sand (Mix 9–Mix 12).

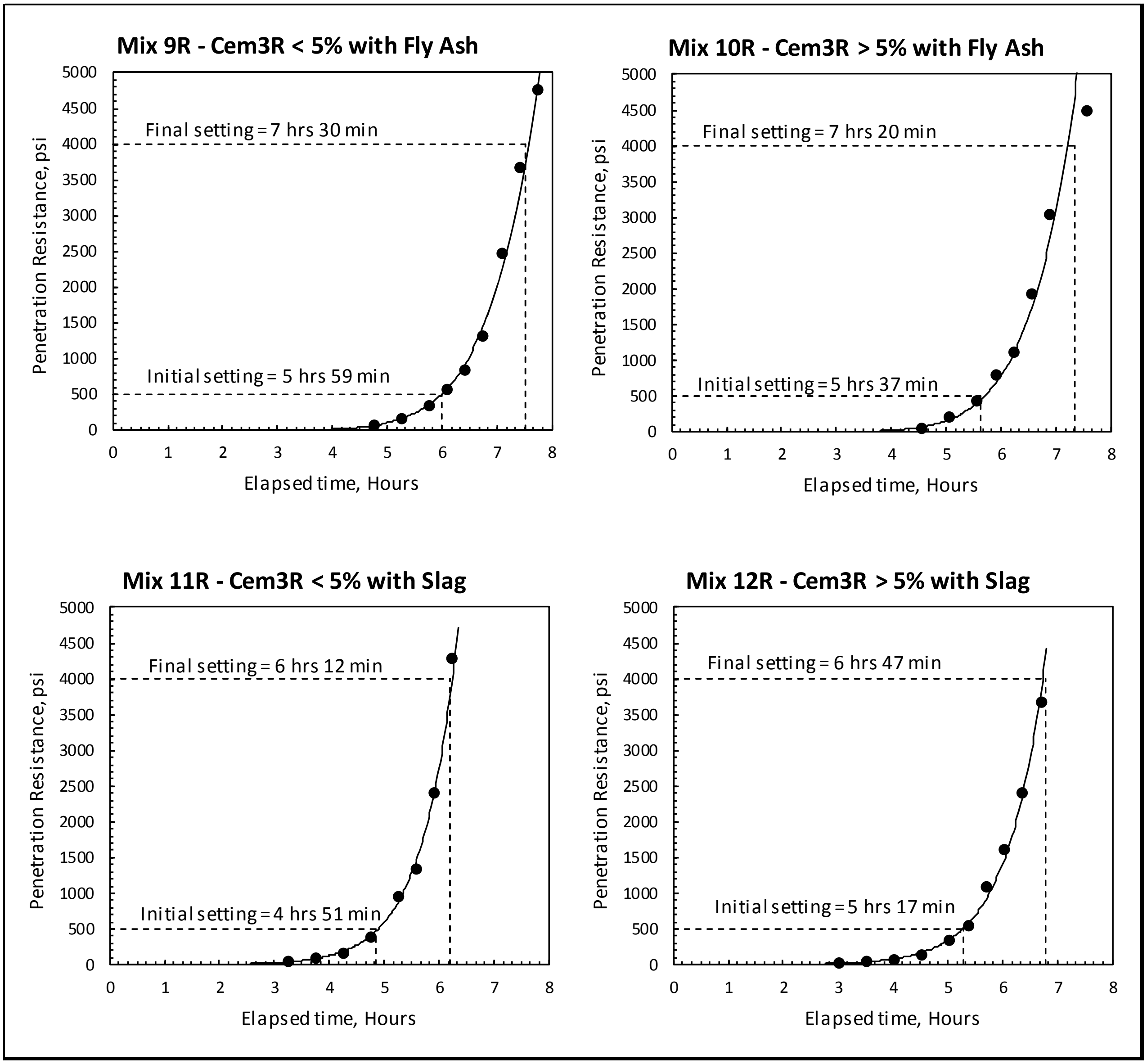

Figure A-11 Penetration pressure vs. time for concrete with Cem3R and natural sand (Mix 9R–Mix 12R).

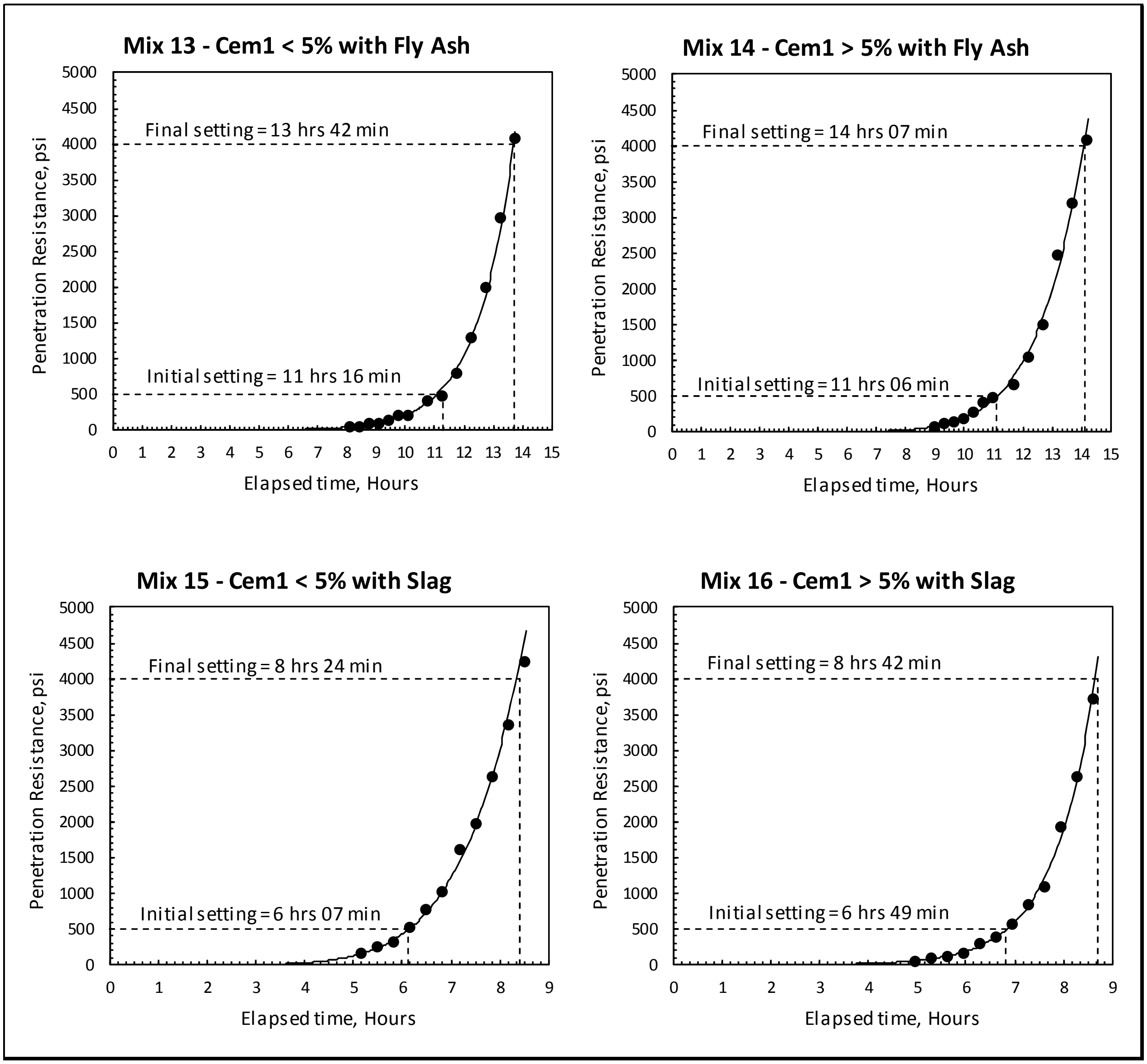

Figure A-12 Penetration pressure vs. time for concrete with Cem1R and combined sand (Mix 13–Mix 16).

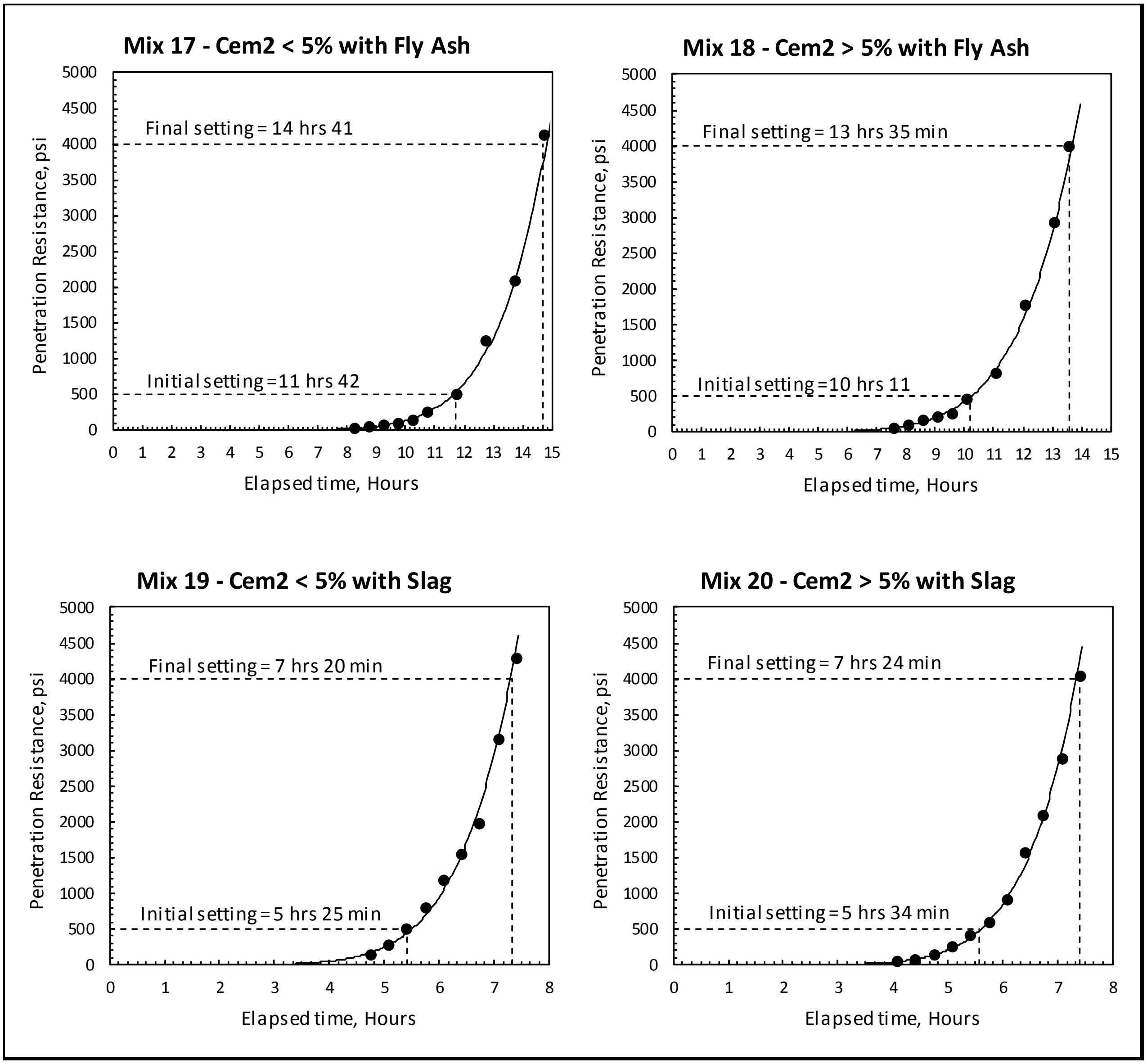

Figure A-13 Penetration pressure vs. time for concrete with Cem2 and combined sand (Mix 17–Mix 20).

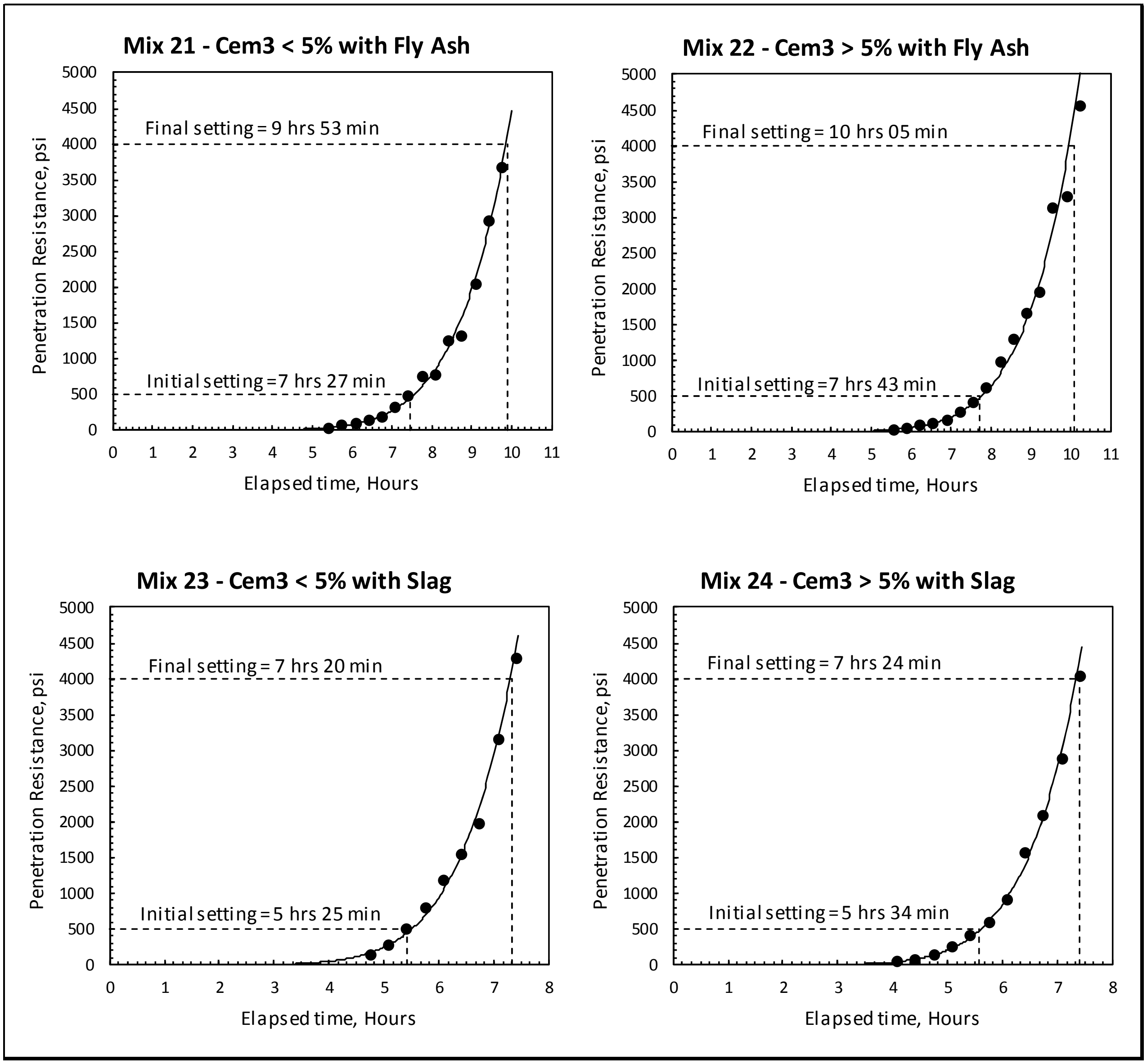

Figure A-14 Penetration pressure vs. time for concrete with Cem3 and combined sand (Mix 21–Mix 24).

APPENDIX E CHEMICAL AND PHYSICAL PROPERTIES OF CEMENTITIOUS MATERIALS

LAFARGE NORTH AMERICA

CEMENT MILL TEST REPORT

Cement

CONSIGNEE:		Date:	August '11
		Cement Type:	Type I-II Cem 1 < 5%
		Manufacture Period:	July '11

PHYSICAL DATA		CHEMICAL DATA (C114)	Percent
Specific Surface (Blaine) (C204)		Silicon Dioxide (SiO_2).................	20.0
(sq. cm./gm.)................................	3780		
(sq. m./kg.).................................	378	Aluminum Oxide (Al_2O_3)...........	4.7
Normal Consistency	25.5	Ferric Oxide (Fe_2O_3).....................	2.7
Compressive Strength (psi) (C109)		Calcium Oxide (CaO)....................	63.3
Mortar Cubes		Magnesium Oxide (MgO)............	2.8
3 day..............................	3470		
7 day..............................	4640	Sulphur Trioxide (SO_3)...............	2.5
28 day			
		Insoluble Residue (%)	
Gilmore Initial (min.)........................	145	Ignition Loss (%).........................	2.3
Gilmore Final (min.).........................	270		
Vicat Setting Time (C-191)		Tricalcium Silicate (C_3S)..............	56
Initial (min.)................................	110		
Final (min.)................................	210	Dicalcium Silicate (C_2S)..............	15
Air Content (%) (C185)................	6.5	Tricalcium Aluminate (C_3A)........	8
Autoclave Expansion (%) (C151)..	0.016	(C_4AF)........	8
False Set	61	Equivalent Alkalis (%)................	0.55

LIMESTONE PERCENTAGE

CO_2 (%) (C114)......................	1.5
$CaCO_3$ in Limestone (%)...............	94
Limestone (%) (C-150)...............	3.8

We hereby certify that this cement complies with current ASTM C150 specification.

Web: www.lafargenorthamerica.com

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Figure E-1 Cem1 < 5%, physical and chemical properties (old).

LAFARGE
NORTH AMERICA

Cement

CEMENT MILL TEST REPORT

Additional Data

	Base Cement Phase Composition
C_3S (%)	58
C_2S (%)	15
C_3A (%)	8
C_4AF (%)	9

Lafarge Contact: Kenneth G. Kazanis, Regional Technical Director
Phone: 248-594-1991

Figure E-2 Cem1 < 5%, base cement phase composition (old).

LAFARGE
NORTH AMERICA

CEMENT MILL TEST REPORT

Cement

CONSIGNEE:		Date:	August '11
		Cement Type:	**Cem 1 > 5%** (w/Limestone and Slag)
		Manufacture Period:	July '11

PHYSICAL DATA		CHEMICAL DATA (C114)	Percent
Specific Surface (Blaine) (C204)		Silicon Dioxide (SiO_2)	21.0
(sq. cm./gm.)	4080		
(sq. m./kg.)	408	Aluminum Oxide (Al_2O_3)	5.2
Normal Consistency	25.8	Ferric Oxide (Fe_2O_3)	2.6
Compressive Strength (psi) (C109)		Calcium Oxide (CaO)	61.4
Mortar Cubes		Magnesium Oxide (MgO)	3.4
3 day	3530		
7 day	5020	Sulphur Trioxide (SO_3)	2.6
28 day			
		Insoluble Residue (%)	
Gilmore Initial (min.)	150	Ignition Loss (%)	2.0
Gilmore Final (min.)	260		
Vicat Setting Time (C191)		Tricalcium Silicate (C_3S)	51
Initial (min.)	115		
Final (min.)	220	Dicalcium Silicate (C_2S)	15
Air Content (%) (C185)	6.0	Tricalcium Aluminate (C_3A)	7
Autoclave Expansion (%) (C151)	0.023	(C_4AF)	8
False Set	69	Equivalent Alkalies (%)	0.57

LIMESTONE PERCENTAGE

CO_2 (%) (C-114)	1.3
$CaCO_3$ in Limestone (%)	94
Limestone (%) (C-150)	3.2

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Figure E-3 Cem1 > 5%, physical and chemical properties (old).

LAFARGE NORTH AMERICA

Cement

CEMENT MILL TEST REPORT

Additional Data

Inorganic Processing Addition Data

Type	Ground, granulated blast furnace slag
Amount (%)	6.7
SiO_2 (%)	33.3
Al_2O_3 (%)	10.5
Fe_2O_3 (%)	0.2
CaO (%)	35.7
SO_3 (%)	2.6

Base Cement Phase Composition

C_3S (%)	57
C_2S (%)	16
C_3A (%)	8
C_4AF (%)	9

Lafarge Contact: Kenneth G. Kazanis, Regional Technical Director
Phone: 248-594-1991

Figure E-4 Cem1 > 5%, inorganic processing addition and base cement phase composition (old).

CTLGROUP

Client:	**Lafarge North America**	**CTL Project No.:**	**052079**
Project:	**Chemical Analysis**	**CTL Proj. Mgr.:**	**Ben Birch**
		Analyst:	**Naamane, Vaiyda**
Contact:	**Brian Borowski**	**Approved:**	***R W Stevenson***
Submitter:	**Brian Borowski**	**Date Analyzed:**	**October 18, 2011**
Date Received:	**October 12, 2011**	**Date Reported:**	**October 18, 2011**

ASTM C150-11 STANDARD CHEMICAL REQUIREMENTS — Test Results

	Cement Type I / IA	II / IIA	MH) / II(MH	III / IIIA	IV	V	Client ID: / CTL ID:	Limestone	Calculated Base	**Cem1R<5% 2961108 RT**
Silicon dioxide (SiO_2), min.%	---	---	---	---	---	---		2.75	20.5	**19.8**
Aluminum oxide (Al_2O_3), max. %	---	6.0	6.0	---	---	---		0.55	5.0	**4.8**
Ferric oxide (Fe_2O_3), max. %	---	$6.0^{A,B}$	$6.0^{A,B}$	---	6.5	---		0.47	2.9	**2.8**
Calcium oxide (CaO)	---	---	---	---	---	---		52.10	63.6	**63.1**
Magnesium oxide (MgO), max. %	6.0	6.0	6.0	6.0	6.0	6.0				**2.6**
Sulfur trioxide (SO_3)										
When (C_3A) is 8% or less, max. %	3.0	3.0	3.0	3.5	2.3	2.3		0.80	2.7	**2.6**
When (C_3A) is more than 8%, max. %	3.5	---	---	4.5	---	---				
Sodium oxide (Na_2O)	---	---	---	---	---	---				**0.21**
Potassium oxide (K_2O)	---	---	---	---	---	---				**0.51**
Titanium oxide (TiO_2)	---	---	---	---	---	---				**0.24**
Phosphorus pentoxide (P_2O_5)	---	---	---	---	---	---				**0.11**
Manganic oxide (Mn_2O_3)	---	---	---	---	---	---				**0.15**
Strontium oxide (SrO)	---	---	---	---	---	---				**0.07**
Chromic oxide (Cr_2O_3)	---	---	---	---	---	---				**0.02**
Zinc oxide (ZnO)	---	---	---	---	---	---				**0.05**
Loss on ignition (550°C), %	---	---	---	---	---	---				**0.84**
Loss on ignition (950°C), max. %	3.0	3.0	3.0	3.0	2.5	3.0		40.3		**2.54**
Total										**99.65**
Limestone % (based on client supplied limestone chemistry)										
Equivalent alkalies ($Na_2O+0.658K_2O$)	---	---	---	---	---	---				**0.54**
Insoluble residue, max. %	0.75	0.75	0.75	0.75	0.75	0.75				**0.49**
Free calcium oxide	---	---	---	---	---	---				**---**
Calculated Compounds per ASTM C 150-11										
Tricalcium silicate (C_3S), max. %	---	---	---	---	35^{A}	---			57	**55**
Dicalcium silicate (C_2S), min. %	---	---	---	---	40^{A}	---			16	**15**
Tricalcium aluminate (C_3A), max. %	---	8	8	15	7^{A}	5^{B}			8	**8**
Tetracalcium alumino ferrite (C_4AF)	---	---	---	---	---	---			9	**8**
ss(C4AF + C2F) or (C4AF + 2(C3A)) as applicable	---	---	---	---	---	25^{B}				**---**
% Limestone (Client supplied LOI 40.3)	5.0	5.0	5.0	5.0	5.0	5.0				**4.2**
$C_3S + 4.75\ C_3A$	---	---	100^{C}	---	---	---			97	**93**

A: Does not apply when heat of hydration limit of ASTM C150-11 - Table 4 is specified.

B: Does not apply when sulfate resistance limit of ASTM C150-11 - Table 4 is specified.

C.The 7 day heat of hydration shall be conducted and reported for informational purposes at least once every six months.

OPTIONAL CHEMICAL REQUIREMENTS *	I	II	III	IV	V
C_3A - for moderate sulfate resistance	---	---	8	---	---
C_3A - for high sulfate resistance	---	---	5	---	---
For Low Alkali - ($Na_2O+0.658K_2O$), max. %	0.60	0.60	0.60	0.60	0.60

* see Table 2 of ASTM C150-09 for additional information

Notes:

1. This analysis represents specifically the sample submitted.
2. Oxide analysis by X-ray fluorescence spectrometry. Sample fused at 1000°C with $Li_2B_4O_7$. X-Ray Fluorescence oxide analysis meets the precision and accuracy requirements for rapid methods per ASTM C114-11a. Most recent re-qualification date is 05-May-2011. Insoluble residue and free calcium oxide tested in accordance with ASTM C114-11a.
3. Compound calculation by base cement derivation based on client supplied limestone chemistry.
4. This report may not be reproduced except in its entirety.

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Figure E-5 Cem1R < 5%, chemical properties.

CTLGroup

Client:	Lafarge North America	CTL Project No.:	052079
Project:	ASTM C150	CTL Proj. Mgr.:	Ben Birch
		Analyst:	DD, PS, CW
Contact:	Brian Borowski	Approved:	Xiuping Feng
Submitter:	Brian Borowski	Date Analyzed:	10/13/11-11/11/11
Date Received:	October 12, 2011	Date Reported:	January 11, 2012

ASTM C150-11 STANDARD PHYSICAL REQUIREMENTS

	Cement Type						Test Results
	I	II	II(MH)	III	IV	V	Client ID: **Cem1R<5%** CTL ID: **2961108**
Air content of mortar, volume %:							
maximum:	12	12	12	12	12	12	**10**
minimum:	---	---	---	---	---	---	
Fineness, specific surface :							
Turbidimeter minimum, m^2/kg	150	150	150	---	150	150	
maximum, m^2/kg	---	---	245^{++}	---	245	---	
Air permeability minimum, m2/kg	260	260	260	---	260	260	**380**
maximum, m^2/kg	---	---	430^{++}	---	430	---	
No. 325 sieve, % passing	---	---	---	---	---	---	**96.5**
Autoclave expansion, max. %:	0.80	0.80	0.80	0.80	0.80	0.80	**0.00**
Strength, compression**, min., MPa (psi)							
1 day	---	---	---	12.0 (1740)	---	---	**14.3** **(2070)**
3 days	12.0 (1740)	10.0 (1450)	10.0 (1450) 7.0^{+} (1020)$^{+}$	24.0 (3480)	--- ---	8.0 (1160)	**26.2** **(3800)**
7 days	19.0 (2760)	17.0 (2470)	17.0 (2470) 12.0^{+} (1740)$^{+}$	---	7.0 (1020)	15.0 (2180)	**34.6** **(5020)**
28 days	---	---	---	---	17.0 (2470)	21.0 (3050)	**42.3** **(6130)**
Time of setting:							
Vicat test:*							
Initial set, minimum minutes:	45	45	45	45	45	45	**155**
Initial set, maximum minutes:	375	375	375	375	375	375	
Final set, minutes:	---	---	---	---	---	---	**235**

\+ When the optional heat of hydration limit in Table 4 of ASTM C150-09 is specified.

* The time of setting is that described as initial setting time in Method C191. Test conducted using Method B of ASTM C191-08.

++ The maximum fineness limits do not apply if the sum of $C_3S + 4.75C_3A$ is less than or equal to 90.

** The strength at any specified test age shall be not less than that attained at any previous specified test age.

QLT 38-001
Revision 1.0

Corporate Office and Laboratory: 5400 Old Orchard Road Skokie, Illinois 60077-1030

Figure E-6 Cem1R < 5%, physical properties.

Client:	Lafarge North America		CTL Project No.:	052079
Project:	Chemical Analysis		CTL Proj. Mgr.:	Ben Birch
			Analyst:	Naamane, Vaiyda
Contact:	Brian Borowski		Approved:	R W Stevenson
Submitter:	Brian Borowski		Date Analyzed:	October 18, 2011
Date Received:	October 12, 2011		Date Reported:	October 18, 2011

ASTM C150-11 STANDARD CHEMICAL REQUIREMENTS

	Cement Type I / IA	II / IIA	MH) / II(MH	III / IIIA	IV	V	Client ID: / CTL ID: Slag	Limestone	Calculated Base From Sample As Tested	Test Results Cem1R->5% 2996307 RT
Silicon dioxide (SiO_2), min.%	---	---	---	---	---	---	33.3	2.8	20.5	20.4
Aluminum oxide (Al_2O_3), max. %	---	6.0	6.0	---	---	---	10.5	0.6	5.0	5.1
Ferric oxide (Fe_2O_3), max. %	---	6.0[A,D]	6.0[A,D]	---	6.5	---	0.2	0.5	2.8	2.6
Calcium oxide (CaO)	---	---	---	---	---	---	35.7	52.1	64.1	62.3
Magnesium oxide (MgO), max. %	6.0	6.0	6.0	6.0	6.0	6.0				2.9
Sulfur trioxide (SO_3)										
When (C_3A) is 8% or less, max. %	3.0	3.0	3.0	3.5	2.3	2.3	2.6	0.8	2.6	2.6
When (C_3A) is more than 8%, max. %	3.5	---	---	4.5	---	---				
Sodium oxide (Na_2O)	---	---	---	---	---	---				0.21
Potassium oxide (K_2O)	---	---	---	---	---	---				0.44
Titanium oxide (TiO_2)	---	---	---	---	---	---				0.25
Phosphorus pentoxide (P_2O_5)	---	---	---	---	---	---				0.10
Manganic oxide (Mn_2O_3)	---	---	---	---	---	---				0.16
Strontium oxide (SrO)	---	---	---	---	---	---				0.06
Chromic oxide (Cr_2O_3)	---	---	---	---	---	---				0.01
Zinc oxide (ZnO)	---	---	---	---	---	---				<0.01
Loss on ignition (550°C), %	---	---	---	---	---	---				0.81
Loss on ignition (950°C), max. %	3.0	3.0	3.0	3.0	2.5	3.0		40.3		2.32
Total										99.54
Limestone % (based on client supplied limestone chemistry)										
Equivalent alkalies ($Na_2O+0.658K_2O$)	---	---	---	---	---	---				0.55
Insoluble residue, max. %	0.75	0.75	0.75	0.75	0.75	0.75				0.50
Free calcium oxide	---	---	---	---	---	---				---
Calculated Compounds per ASTM C 150-11										
Tricalcium silicate (C_3S), max. %	---	---	---	---	35[A]	---			60	55
Dicalcium silicate (C_2S), min. %	---	---	---	---	40[A]	---			14	13
Tricalcium aluminate (C_3A), max. %	---	8	8	15	7[A]	5[B]			9	8
Tetracalcium alumino ferrite (C_4AF)	---	---	---	---	---	---			9	8
ss(C4AF + C2F) or (C4AF + 2(C3A)) as applicable	---	---	---	---	---	25[B]				---
C_3S + 4.75 C_3A	---	---	100[C]	---	---	---			100	92
% Limestone (Client supplied LOI 40.3)	5.0	5.0	5.0	5.0	5.0	5.0		3.8		3.8
% Inorganic Processing Addition (reported by client : 4.5%)	5.0	5.0	5.0	5.0	5.0	5.0	4.5			4.5
% Base cement (calculated)									91.7	91.7

A: Does not apply when heat of hydration limit of ASTM C150-11 - Table 4 is specified.
B: Does not apply when sulfate resistance limit of ASTM C150-11 - Table 4 is specified.
C.The 7 day heat of hydration shall be conducted and reported for informational purposes at least once every six months.

OPTIONAL CHEMICAL REQUIREMENTS *	I	II	III	IV	V
C_3A - for moderate sulfate resistance	---	---	8	---	---
C_3A - for high sulfate resistance	---	---	5	---	---
For Low Alkali - ($Na_2O+0.658K_2O$), max. %	0.60	0.60	0.60	0.60	0.60

* see Table 2 of ASTM C150-09 for additional information

Notes:
1. This analysis represents specifically the sample submitted.
2. Oxide analysis by X-ray fluorescence spectrometry. Sample fused at 1000°C with $Li_2B_4O_7$. X-Ray Fluorescence oxide analysis meets the precision and accuracy requirements for rapid methods per ASTM C114-11a. Most recent re-qualification date is 05-May-2011. Insoluble residue and free calcium oxide tested in accordance with ASTM C114-11a.
3. Compound calculation by base cement derivation based on client supplied limestone chemistry.
4. This report may not be reproduced except in its entirety.

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Figure E-7 Cem1R > 5%, chemical properties.

CTLGROUP

Client:	Lafarge North America	CTL Project No.:	052079
Project:	Lafarge Blended Cement Testing	CTL Proj. Mgr.:	B. Birch
		Analyst:	SH, DD, PS, WD, CW
Contact:	Mr. Brian Borowski	Approved:	X. Feng
Submitter:	Mr. Brian Borowski	Date Analyzed:	12/6/11 - 1/3/12
Date Received:	November 28, 2011	Date Reported:	January 5, 2012

ASTM C150-11 STANDARD PHYSICAL REQUIREMENTS

	Cement Type						Test Results
	I	II	II(MH)	III	IV	V	Client ID: **Cem1R>5%** CTL ID: **2996307**
Air content of mortar, volume %:							
maximum:	12	12	12	12	12	12	**9**
minimum:	---	---	---	---	---	---	
Fineness, specific surface :							
Turbidimeter minimum, m^2/kg	150	150	150	---	150	150	
maximum, m^2/kg	---	---	245++	---	245	---	
Air permeability minimum, m2/kg	260	260	260	---	260	260	**407**
maximum, m^2/kg	---	---	430++	---	430	---	
No. 325 sieve, % passing	---	---	---	---	---	---	
Autoclave expansion, max. %:	0.80	0.80	0.80	0.80	0.80	0.80	**0.02**
Strength, compression**, min., MPa (psi)							
1 day	---	---	---	12.0 (1740)	---	---	**13.9 (2010)**
3 days	12.0 (1740)	10.0 (1450)	10.0 (1450) 7.0+ (1020)+	24.0 (3480)	---	8.0 (1160)	**27.2 (3940)**
7 days	19.0 (2760)	17.0 (2470)	17.0 (2470) 12.0+ (1740)+	---	7.0 (1020)	15.0 (2180)	**32.1 (4650)**
28 days	---	---	---	---	17.0 (2470)	21.0 (3050)	**44.1 (6400)**
Time of setting:							
Vicat test:*							
Initial set, minimum minutes:	45	45	45	45	45	45	**155**
Initial set, maximum minutes:	375	375	375	375	375	375	
Final set, minutes:	---	---	---	---	---	---	**235**

\+ When the optional heat of hydration limit in Table 4 of ASTM C150-09 is specified.

* The time of setting is that described as initial setting time in Method C191. Test conducted using Method B of ASTM C191-08.

++ The maximum fineness limits do not apply if the sum of $C_3S + 4.75C_3A$ is less than or equal to 90.

** The strength at any specified test age shall be not less than that attained at any previous specified test age.

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Corporate Office and Laboratory: 5400 Old Orchard Road Skokie, Illinois 60077-1030

Figure E-8 Cem1R > 5%, physical properties.

St. Marys Cement

ST MARYS

Great Lakes Region
Charlevoix Plant
1600 Bells Bay Road

Charlevoix, MI 49720
Phone: (231) 547-9971
Fax: (231) 547-6202

TEST REPORT - Portland Type I/II

Sample: Cement # 3 - Less that 5% Inorganic Processing Additions and Limestone

STANDARD REQUIREMENTS ASTM C150/C150M-09 Tables 1 and 2					
CHEMICAL			**PHYSICAL**		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
SiO_2 (%)	*- (1)*	19.2	Air Content of mortar (volume %)	12 max	8
Al_2O_3 (%)	-	4.7	Blaine fineness (m^2/kg)	280 min	385
Fe_2O_3 %	-	2.7		430 max	
CaO (%)	-	62.1	Retained on No. 325 Sieve (%)	-	3.0
MgO (%)	*6.0 max*	3.8	Autoclave expansion (%)	0.80 max	0.12
SO_3 (%)	*- (2)*	3.9	Normal Consistency (%)		26.6
Ignition Loss (%)	*3.0 max*	1.5	Compressive strength (MPa):		
Na_2O (%)	-	0.19	1 day	-	20.4
K_2O (%)	-	1.13	3 days	12.0 min	29.9
Insoluble Residue (%)	*0.75 max*	0.20	7 days	19.0 min	34.9
CO_2 (%)	-	1.1	28 days *(previous month)*	-	
Limestone (%)	*5.0 max*	2.6	Compressive strength (psi):		
$CaCO_3$ in limestone (%)	*70 min*	95	1 day	-	2960
Inorganic processing addition	*5.0 max*	*0.0*	3 days	1740 min	4340
Potential phase composition			7 days	-	5070
C_3S (%)	-	56	28 days *(previous month)*	2760 min	
C_2S (%)	-	13	Time of setting (minutes)		
C_3A (%)	-	8	(Vicat) Initial	45 min	90
C_4AF (%)	-	8	(Vicat) Not more than	375 max	205
$C_4AF + 2(C_3A)$ (%)	-	24	Test Method C1038		
$C_3S + 4.75(C_3A)$ (%)	-	110	Mortar Bar Expansion (%)	0.020 max	

OPTIONAL REQUIREMENTS ASTM C150/C150M-09 Tables 2 and 4					
CHEMICAL			**PHYSICAL**		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
Equivalent alkalies (%)	-	0.92	False Set	50 min	75

Additional Data - Inorganic Additions					
	Limestone	**Slag**	**BASE CEMENT COMPOSITION**		
SiO_2 (%)	2.2	40.3	C_3S (%)	-	57
Al_2O_3 (%)	0.7	7.6	C_2S (%)	-	13
Fe_2O_3 %	1.1	0.9	C_3A (%)	-	8
CaO (%)	50.2	37.9	C_4AF (%)	-	8
SO_3 (%)	0.7	2.0			

(1) : Not applicable   Obs: LIMS # 5021
(2) : Charlevoix Cement meets standard ASTM C1038

Quality Manager: Claudio Urrutia
E-mail: crurrutia@vcsmc.com

Figure E-9 Cem3 < 5%, physical and chemical properties.

ST MARYS

St. Marys Cement

Great Lakes Region
Charlevoix Plant
1600 Bells Bay Road

Charlevoix, MI 49720
Phone: (231) 547-9971
Fax: (231) 547-6202

TEST REPORT - Portland Type I/II

Sample: Cement # 3 - Greater than 5% Inorganic Processing Additions and Limestone

STANDARD REQUIREMENTS ASTM C150/C150M-09 Tables 1 and 2

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
SiO_2 (%)	*- (1)*	19.8	Air Content of mortar (volume %)	12 max	8
Al_2O_3 (%)	-	4.9	Blaine fineness (m^2/kg)	280 min	383
Fe_2O_3 %	-	2.7		430 max	
CaO (%)	-	61.7	Retained on No. 325 Sieve (%)	-	2.9
MgO (%)	*6.0 max*	4.0	Autoclave expansion (%)	0.80 max	0.10
SO_3 (%)	*- (2)*	3.8	Normal Consistency (%)		26.8
Ignition Loss (%)	*3.0 max*	1.4	Compressive strength (MPa):		
Na_2O (%)	-	0.18	1 day	-	20.1
K_2O (%)	-	1.12	3 days	12.0 min	28.7
Insoluble Residue (%)	*0.75 max*	0.18	7 days	19.0 min	34.6
CO_2 (%)	-	1.0	28 days *(previous month)*	-	
Limestone (%)	*5.0 max*	2.5	Compressive strength (psi):		
$CaCO_3$ in limestone (%)	*70 min*	95	1 day	-	2920
Inorganic processing addition	*5.0 max*	*3.0*	3 days	1740 min	4160
Potential phase composition			7 days	-	5020
C_3S (%)	-	55	28 days *(previous month)*	2760 min	
C_2S (%)	-	12	Time of setting (minutes)		
C_3A (%)	-	8	(Vicat) Initial	45 min	95
C_4AF (%)	-	8	(Vicat) Not more than	375 max	215
$C_4AF + 2(C_3A)$ (%)	-	24	Test Method C1038		
$C_3S + 4.75(C_3A)$ (%)	-	108	Mortar Bar Expansion (%)	0.020 max	

OPTIONAL REQUIREMENTS ASTM C150/C150M-09 Tables 2 and 4

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
Equivalent alkalies (%)	-	0.92	False Set	50 min	81

Additional Data - Inorganic Additions

	Limestone	**Slag**	**BASE CEMENT COMPOSITION**		
SiO_2 (%)	2.2	40.3	C_3S (%)	-	58
Al_2O_3 (%)	0.7	7.6	C_2S (%)	-	12
Fe_2O_3 %	1.1	0.9	C_3A (%)	-	8
CaO (%)	50.2	37.9	C_4AF (%)	-	9
SO_3 (%)	0.7	2.0			

(1) : Not applicable — Obs: LIMS # 5022
(2) : Charlevoix Cement meets standard ASTM C1038

Quality Manager: Claudio Urrutia
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Figure E-10 Cem3 > 5%, physical and chemical properties.

St. Marys Cement

ST MARYS

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Charlevoix Plant
1600 Bells Bay Road

Charlevoix, MI 49720
Phone: (231) 547-9971
Fax: (231) 547-6202

TEST REPORT - Portland Type I/II

Sample: Cement # 3 - Less that 5% Inorganic Processing Additions and Limestone

STANDARD REQUIREMENTS ASTM C150/C150M-09 Tables 1 and 2

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
SiO_2 (%)	*- (1)*	19.0	Air Content of mortar (volume %)	12 max	9
Al_2O_3 (%)	-	4.8	Blaine fineness (m^2/kg)	280 min	378
Fe_2O_3 %	-	2.7		430 max	
CaO (%)	-	61.7	Retained on No. 325 Sieve (%)	-	2.6
MgO (%)	*6.0 max*	3.5	Autoclave expansion (%)	0.80 max	0.12
SO_3 (%)	*- (2)*	3.9	Normal Consistency (%)		27.4
Ignition Loss (%)	*3.0 max*	1.9	Compressive strength (MPa):		
Na_2O (%)	-	0.16	1 day	-	20.0
K_2O (%)	-	1.17	3 days	12.0 min	27.9
Insoluble Residue (%)	*0.75 max*	0.21	7 days	19.0 min	32.0
CO_2 (%)	-	1.4	28 days	-	41.2
Limestone (%)	*5.0 max*	3.4	Compressive strength (psi):		
$CaCO_3$ in limestone (%)	*70 min*	95	1 day	-	2910
Inorganic processing addition	*5.0 max*	*0.0*	3 days	1740 min	4043
Potential phase composition			7 days	2760 min	4648
C_3S (%)	-	53	28 days	-	5973
C_2S (%)	-	14	Time of setting (minutes)		
C_3A (%)	-	8	(Vicat) Initial	45 min	135
C_4AF (%)	-	8	(Vicat) Not more than	375 max	220
$C_4AF + 2(C_3A)$ (%)	-	25	Test Method C1038		
$C_3S + 4.75(C_3A)$ (%)	-	92	Mortar Bar Expansion (%)	0.020 max	0.009

OPTIONAL REQUIREMENTS ASTM C150/C150M-09 Tables 2 and 4

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
Equivalent alkalies (%)	-	0.93	False Set	50 min	74

Additional Data - Inorganic Additions

	Limestone	**Slag**	**BASE CEMENT COMPOSITION**		
SiO_2 (%)	2.2	38.2	C_3S (%)	-	55
Al_2O_3 (%)	0.7	8.7	C_2S (%)	-	*14*
Fe_2O_3 %	1.1	0.6	C_3A (%)	-	*8*
CaO (%)	50.2	38.4	C_4AF (%)	-	9
SO_3 (%)	0.7	2.6			

(1) : Not applicable Obs: LIMS # 6092
(2) : Charlevoix Cement meets standard ASTM C1038

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Figure E-11 Cem3R < 5%, physical and chemical properties (2nd Sample).

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1600 Bells Bay Road

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Fax: (231) 547-6202

TEST REPORT - Portland Type I/II

Sample: Cement # 3 - Greater than 5% Inorganic Processing Additions and Limestone

STANDARD REQUIREMENTS ASTM C150/C150M-09 Tables 1 and 2

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
SiO_2 (%)	*- (1)*	19.8	Air Content of mortar (volume %)	12 max	8
Al_2O_3 (%)	-	4.9	Blaine fineness (m^2/kg)	280 min	386
Fe_2O_3 %	-	2.7		430 max	
CaO (%)	-	61.2	Retained on No. 325 Sieve (%)	-	2.2
MgO (%)	*6.0 max*	3.7	Autoclave expansion (%)	0.80 max	0.08
SO_3 (%)	*- (2)*	3.8	Normal Consistency (%)		27.2
Ignition Loss (%)	*3.0 max*	1.7	Compressive strength (MPa):		
Na_2O (%)	-	0.17	1 day	-	21.9
K_2O (%)	-	1.16	3 days	12.0 min	30.4
Insoluble Residue (%)	*0.75 max*	0.15	7 days	19.0 min	36.0
CO_2 (%)	-	1.3	28 days	-	44.1
Limestone (%)	*5.0 max*	3.1	Compressive strength (psi):		
$CaCO_3$ in limestone (%)	*70 min*	95	1 day	-	3183
Inorganic processing addition	*5.0 max*	*3.0*	3 days	1740 min	4413
Potential phase composition			7 days	2760 min	5220
C_3S (%)	-	51	28 days	-	6390
C_2S (%)	-	15	Time of setting (minutes)		
C_3A (%)	-	8	(Vicat) Initial	45 min	124
C_4AF (%)	-	8	(Vicat) Not more than	375 max	225
$C_4AF + 2(C_3A)$ (%)	-	24	Test Method C1038		
$C_3S + 4.75(C_3A)$ (%)	-	88	Mortar Bar Expansion (%)	0.020 max	0.003

OPTIONAL REQUIREMENTS ASTM C150/C150M-09 Tables 2 and 4

CHEMICAL			PHYSICAL		
Item	**Spec. Limit**	**Test Result**	**Item**	**Spec. Limit**	**Test Result**
Equivalent alkalies (%)	-	0.93	False Set	50 min	67

Additional Data - Inorganic Additions

	Limestone	**Slag**	**BASE CEMENT COMPOSITION**		
SiO_2 (%)	2.2	38.2	C_3S (%)	-	54
Al_2O_3 (%)	0.7	8.7	C_2S (%)	-	*16*
Fe_2O_3 %	1.1	0.6	C_3A (%)	-	*8*
CaO (%)	50.2	38.4	C_4AF (%)	-	9
SO_3 (%)	0.7	2.6			

(1) : Not applicable Obs: LIMS # 6093
(2) : Charlevoix Cement meets standard ASTM C1038

Quality Manager Claudio Urrutia
E-mail: crurrutia@vcsmc.com

Figure E-12 Cem3R > 5%, physical and chemical properties (2nd Sample).

CTLGROUP

Client:	**Lafarge North America**	CTL Project No.:	**052079**
Project:	**Chemical Analysis**	CTL Proj. Mgr.:	**Ben Birch**
		Analyst:	**R. Kelly**
Contact:	**Brian Borowski**	Approved:	*R W Stevenson*
Submitter:	**Brian Borowski**	Date Analyzed:	**December 14, 2011**
Date Received:	**November 16, 2011**	Date Reported:	**December 14, 2011**

REPORT OF CHEMICAL ANALYSIS

Client's Sample ID:	Lafarge PP.4 Ash 10-06-11
Material type:	Fly Ash
CTL Sample ID:	2988301

Analyte	Weight %
SiO_2	38.70
Al_2O_3	20.32
Fe_2O_3	5.62
CaO	22.91
MgO	4.01
SO_3	2.23
Na_2O	1.52
K_2O	0.57
TiO_2	1.43
P_2O_5	1.12
Mn_2O_3	0.02
SrO	0.40
Cr_2O_3	0.01
ZnO	0.01
BaO	0.87
L.O.I. (950° C)[2]	0.40
Total	100.14
Alkalies as Na_2O	1.90
Insoluble Residue[6]	32.4

Thermogravimetric Analysis - As Received Basis (C311-11a)	
Free moisture (Ambient-105° C)	0.09
L.O.I. (105° C - 750° C)	0.37
L.O.I. (750° C - 950° C)	0.02

Calculations per ASTM C618-08a	
$SiO_2+Al_2O_3+Fe_2O_3$	64.6
L.O.I. 750° C (dry 105° C basis)	0.37

Notes:

1. This analysis represents specifically the sample submitted.
2. Results reported on an oven dry (105°C) basis.
3. Oxide analysis by X-ray fluorescence spectrometry. Samples fused at 1000°C with $Li_2B_4O_7/LiBO_2$.
4. Elemental sulfur and sulfide sulfur may be lost during high temperature ignition and fusion.
5. Analysis conducted in accordance with test methods referenced in ASTM C618-08a.
6. Insoluble residue reported is the average of three tests.
7. This report may not be reproduced except in its entirety.

QLT 40-002
Revision 1.0

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Figure E-13 Fly ash, chemical analysis report.

CTLGROUP

Client:	Lafarge North America	CTL Project No:	052079
Project:	C618	CTL Project Mgr.:	B. Birch
		Analyst:	WD, DD, PS
Contact:	Mr. Brian Borowski	Approved:	X. Feng
Submitter:	Mr. Brian Borowski	Date Prepared:	November 21, 2011
Date Received:	November 16, 2011	Date Reported:	January 11, 2012

Report of Analysis - ASTM C 618-08a Standard Chemical and Physical Requirements

Sample Identification:

CTL ID 2988301

Client ID Lafarge PP.4 Ash 10-06-11

Standard Physical Requirements	Mineral Admixture Class N	Mineral Admixture Class F	Mineral Admixture Class C	Test Results
Fineness:				
Amount retained when wet sieved on No. 325 (45μ) sieve, maximum %	34	34	34	**15.4**
Specific Gravity, g/cc	—	—	—	**2.55**
Strength Activity Index: [A]				
With portland cement,				
at 7 days, minimum percent of control	75[B]	75[B]	75[B]	**94**
at 28 days, minimum percent of control	75[B]	75[B]	75[B]	**103**
Water requirement, maximum percent of control	115	105	105	**96**
Soundness: [C]				
Autoclave expansion or contraction, maximum %	0.80	0.80	0.80	**0.02**

Standard Chemical Requirements	Mineral Admixture Class N	Mineral Admixture Class F	Mineral Admixture Class C	Test Results
Silicon dioxide (SiO2) plus aluminum oxide (Al2O3) plus iron oxide (Fe2O3), minimum %	70.0	70.0	50.0	**64.6**
Sulfur trioxide (SO3), maximum %	4.0	5.0	5.0	**2.2**
Moisture content, maximum %	3.0	3.0	3.0	**0.1**
Loss on ignition, maximum %	10.0	6.0*	6.0	**0.4**

*The use of Class F pozzolan containing up to 12.0% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Notes:

A The strength activity index with portland cement is not to be considered a measure of compressive strength of concrete containing the mineral admixture. For more information see note A in ASTM C 618-08a, 'Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Concrete.'

B Meeting the 7 or 28 day strength activity index will indicate specification compliance.

C If the mineral admixture will constitute more than 20 % by weight of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage. For more information see note C in 'ASTM C 618-08a, 'Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Concrete.'

D Testing performed using a control portland cement supplied by the client.

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Figure E-14 Fly ash, physical and chemical properties.

APPENDIX F SOURCE II CEMENT SPECIFICATION (CEM2)

Cement Specification Limit Calculations for Fly Ash as an Inorganic Processing Addition

The provisions of ASTM C150 and AASHTO M85 both permit up to 5% inorganic processing additions (IPA) to be used as ingredients in portland cement. Such materials must be qualified through testing by ASTM C465 (or AASHTO M 327) and the finished cement must meet all of the other chemical and physical requirements of C150/M85. The chemical limits often provide a secondary limit on the amount of inorganic processing additions.

As an example, the insoluble residue (IR) content of ASTM C150 and AASHTO M85 portland cements is limited by the specifications to a maximum of 0.75% by mass. For Cem1R < 5% and the fly ash used in this project, the IR contents are 0.49% and 32.41% respectively. The maximum level of fly ash that can be used as an IPA would be as follows:

If **x** is the amount of fly ash in the finished cement that would result in an **IR** of **0.75%**, then

$$0.75 = (1-x)\ 0.49 + 32.4\ x$$
$$x = 0.81\%$$

The Canadian specification CSA A3001 does not limit the amount of inorganic processing additions used in portland to 5%. It does require that, when processing additions are used in amounts greater than 1%, the manufacturer identify and report the amount used. While the insoluble residue for other types of portland cement is limited to 0.75%, CSA A3001 permits a maximum insoluble residue of 1.5% for GU (general use) and HE (high early) portland cements. For Cem1R < 5% and the fly ash used in this project, the maximum level of fly ash that can be used would be as follows:

If **x** is the amount of fly ash in the finished cement that would result in an **IR** of **1.5%**, then

$$1.5 = (1-x)\ 0.49 + 32.4\ x$$
$$x = 3.17$$

APPENDIX G EXPERIMENTAL RESULTS FOR COMPRESSIVE STRENGTH FOR MIX 1–24

Table A-9 Average Compressive Strength for Mixes with Natural Sand (Mix 1–Mix 12, Mix 1R–4R, Mix 9R–12R), psi

Mix No.	Mix Design	w/cm Ratio	Unit Weight lb/ft^3	Air Content %	Average Compressive Strength, psi				
					3 Day	7 Day	14 Day	28 Day	56 Day
1	Cem1 < 5%_F	0.42	146.38	6.5	3250	4323	4863	5780	6373
2	Cem1 > 5%_F	0.42	145.98	6.7	3203	4135	5060	5987	6763
3	Cem1 < 5%_S	0.42	147.10	6.2	3420	4995	6463	7190	7480
4	Cem1 > 5%_S	0.42	146.32	6.6	3377	4870	5500	6590	7467
1R	Cem1R < 5%_F	0.40	144.80	7.6	2530	3763	4360	4940	5690
2R	Cem1R > 5%_F	0.40	144.40	8.0	2590	3967	4617	5520	6000
3R	Cem1R < 5%_S	0.42	144.16	8.0	2277	3543	4513	5270	6000
4R	Cem1R > 5%_S	0.42	145.00	7.6	2997	4250	5087	6257	7007
5	Cem2 < 5%_F	0.40	146.20	7.0	2203	3570	4530	5267	6027
6	Cem2 > 5%_F	0.40	145.52	7.2	1989	3310	4370	5133	5983
7	Cem2 < 5%_S	0.42	146.20	7.2	2207	3387	4320	5550	6227
8	Cem2 > 5%_S	0.42	146.00	7.3	1851	3077	4147	5267	6067
9	Cem3 < 5%_F	0.42	146.02	6.7	3247	3937	4670	5540	6235
10	Cem3 > 5%_F	0.42	146.26	6.5	3050	4010	4693	5413	6235
11	Cem3 < 5%_S	0.42	144.40	6.4	4273	5495	6493	6933	7435
12	Cem3 > 5%_S	0.42	146.12	6.5	4000	5467	6593	7110	7680
9R	Cem3R < 5%_F	0.40	145.84	7.2	3100	3797	4373	4807	5513
10R	Cem3R > 5%_F	0.40	145.04	7.7	2860	3703	4317	4830	5385
11R	Cem3R < 5%_S	0.42	146.20	7.2	2753	4023	4977	5943	6110
12R	Cem3R > 5%_S	0.42	145.00	7.5	2670	3943	4940	5910	6320

Table A-10 Average Compressive Strength for Mixes with Combined Sand (Mix 13–Mix 24), psi

Mix No.	Mix Design	w/cm Ratio	Unit Weight lb/ft^3	Air Content %	Average Compressive Strength, psi				
					3 Day	7 Day	14 Day	28 Day	56 Day
13	Cem1R < 5%_F	0.42	143.60	8.0	3097	4030	4767	5437	5807
14	Cem1R > 5%_F	0.42	143.80	8.0	2687	3807	4443	5137	5723
15	Cem1R < 5%_S	0.42	143.92	8.0	2630	3670	4217	4897	6027
16	Cem1R > 5%_S	0.42	145.04	7.6	2980	4083	4937	5670	5880
17	Cem2 < 5%_F	0.42	143.56	8.0	2453	3470	4180	4687	5093
18	Cem2 > 5%_F	0.42	144.04	8.0	2473	3667	4390	5120	5680
19	Cem2 < 5%_S	0.44	143.60	8.0	2527	3583	4520	5230	5565
20	Cem2 > 5%_S	0.44	144.12	8.0	2683	3770	4790	5550	6430
21	Cem3 < 5%_F	0.42	145.44	7.2	3267	4027	4860	5523	6260
22	Cem3 > 5%_F	0.42	146.04	7.0	3437	4370	5140	5900	6707
23	Cem3 < 5%_S	0.44	145.72	7.6	3103	4190	4863	5467	5813
24	Cem3 > 5%_S	0.44	145.80	7.3	3027	4243	5357	5960	6117

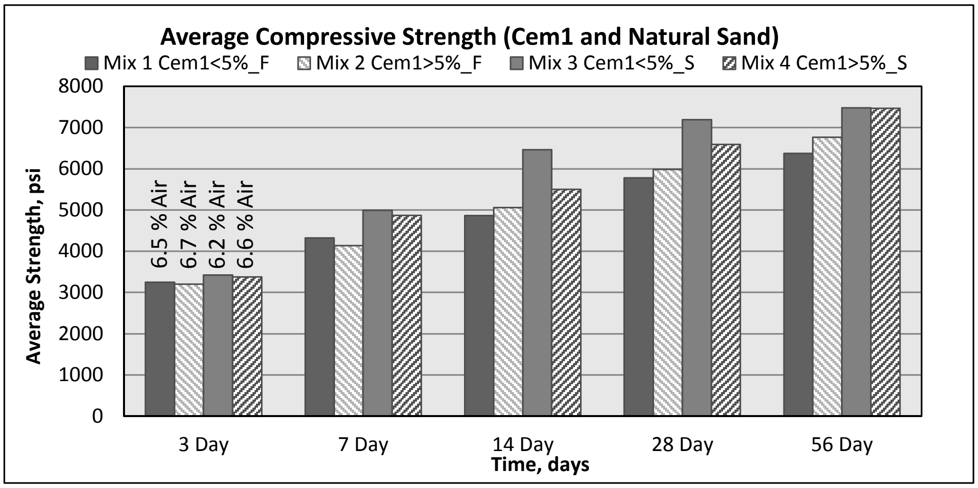

Figure A-15 Average compressive strength for Mix 1–Mix 4 (Cem1 and NS), psi.

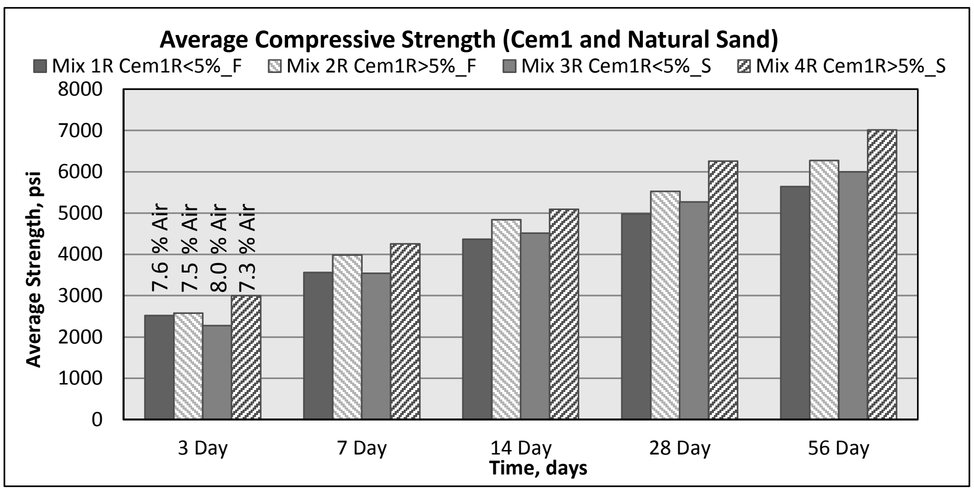

Figure A-16 Average compressive strength for Mix 1R–Mix 4R (Cem1R and NS), psi.

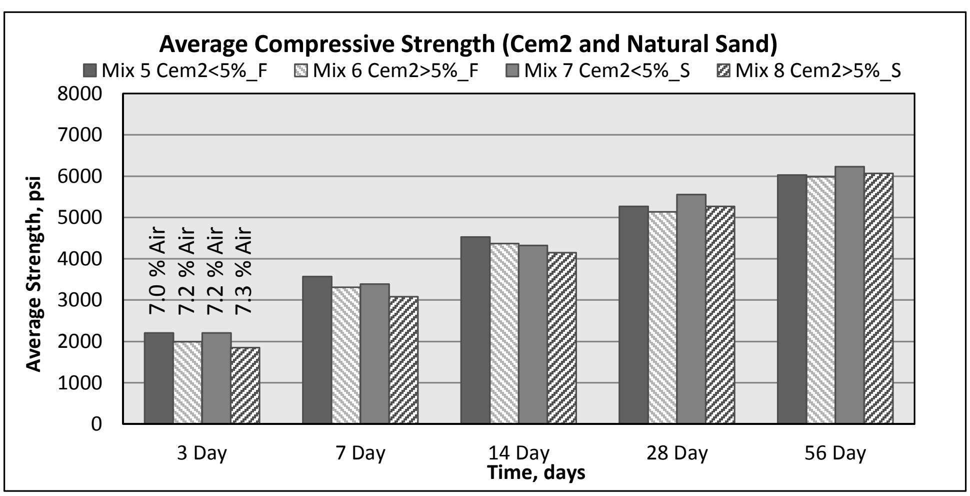

Figure A-17 Average compressive strength for Mix 5–Mix 8 (Cem2 and NS), psi.

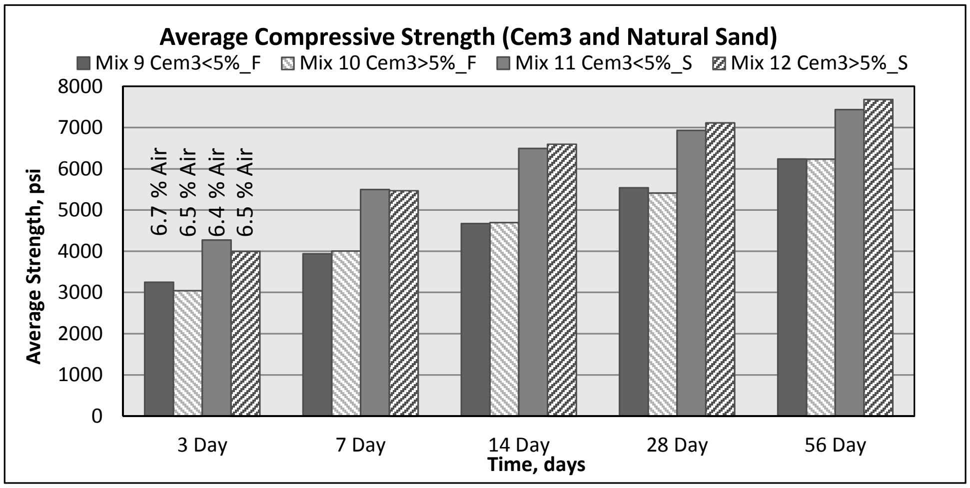

Figure A-18 Average compressive strength for Mix 9–Mix 12 (Cem3 and NS), psi.

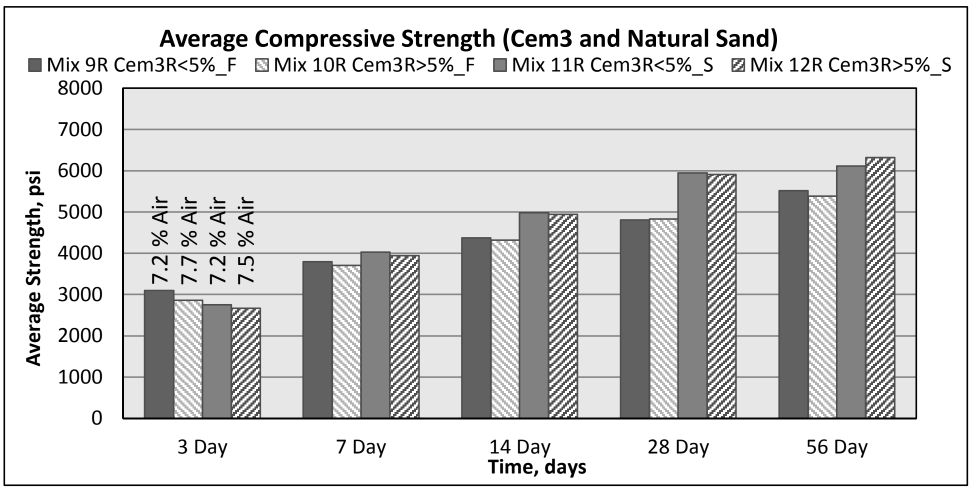

Figure A-19 Average compressive strength for Mix 9R–Mix 12R (Cem3R and NS), psi.

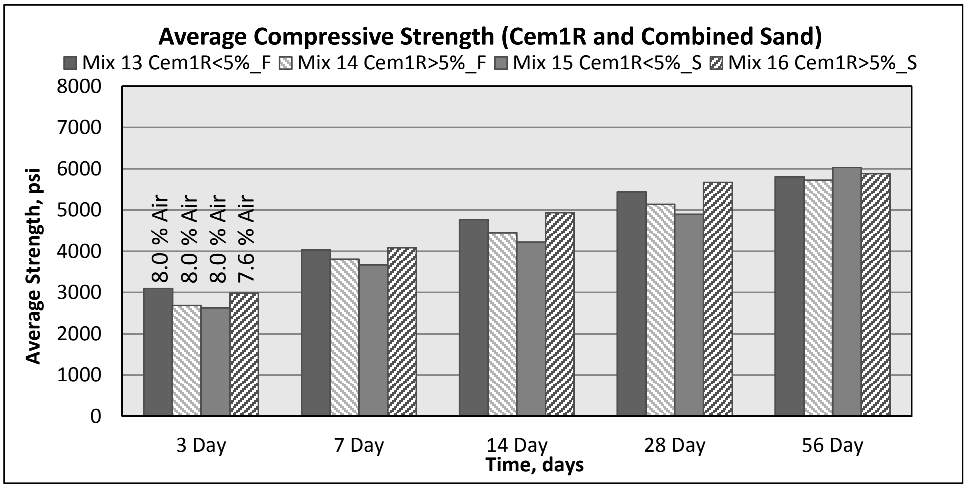

Figure A-20 Average compressive strength for Mix 13–Mix 16 (Cem1R and CS), psi.

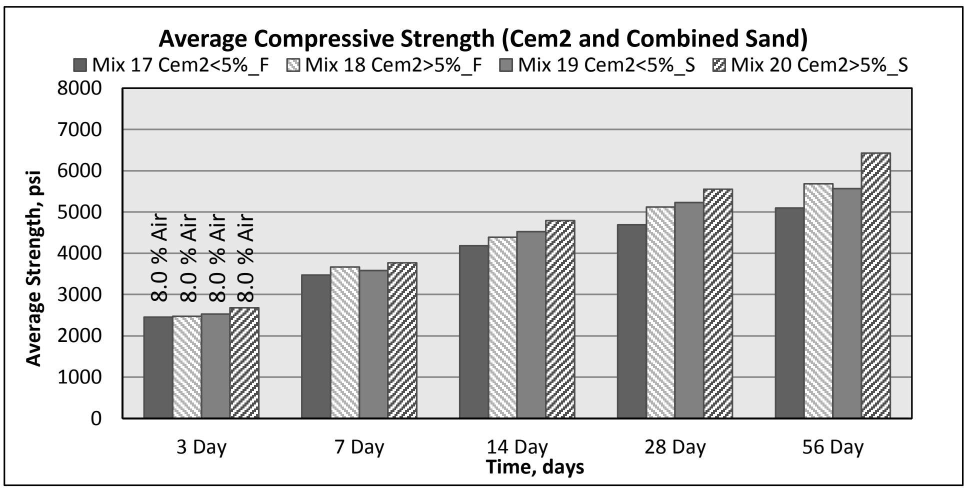

Figure A-21 Average compressive strength for Mix 17–Mix 20 (Cem2 and CS), psi.

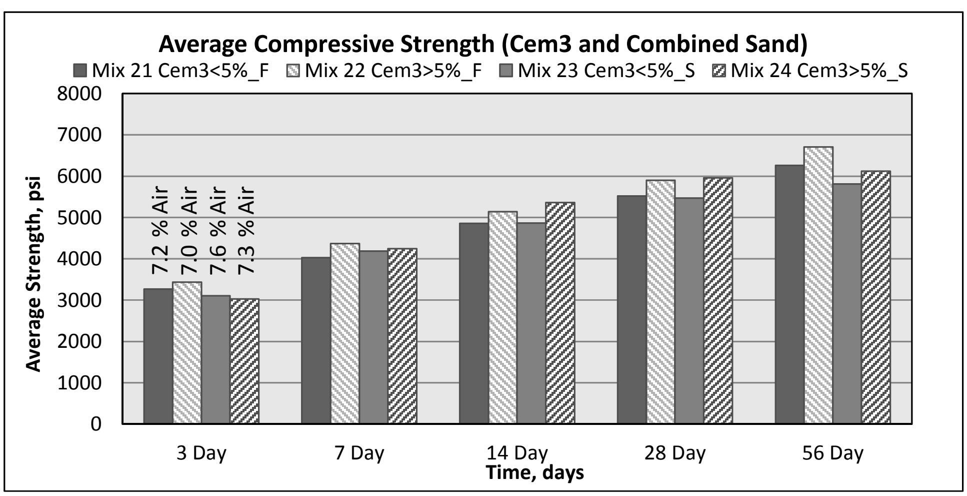

Figure A-22 Average compressive strength for Mix 21–Mix 24 (Cem3 and CS), psi.

APPENDIX H EXPERIMENTAL RESULTS FOR FLEXURAL STRENGTH FOR MIX 1–24

Table A-11 Average Flexural Strength for Mixes with Natural Sand (Mix 1–Mix 12, Mix 1R–4R, 9R–12R), psi

Mix No.	Mix Design	w/cm Ratio	Unit Weight lb/ft^3	Air Content %	Average Flexural Strength, psi				
					3 Day	7 Day	14 Day	28 Day	56 Day
1	Cem1 < 5%_F	0.42	146.43	6.6	533	604	745	755	766
2	Cem1 > 5%_F	0.42	145.98	6.5	522	696	656	816	939
3	Cem1 < 5%_S	0.42	146.44	6.5	514	680	777	913	978
4	Cem1 > 5%_S	0.42	146.96	6.5	581	709	888	886	948
1R	Cem1R < 5%_F	0.40	145.56	7.3	526	605	698	717	746
2R	Cem1R > 5%_F	0.40	145.00	7.8	426	607	646	665	735
3R	Cem1R < 5%_S	0.42	144.60	7.7	489	608	719	805	827
4R	Cem1R > 5%_S	0.42	145.76	7.4	461	631	734	842	809
5	Cem2 < 5%_F	0.40	145.32	7.5	432	615	651	690	812
6	Cem2 > 5%_F	0.40	145.72	7.1	426	537	672	751	768
7	Cem2 < 5%_S	0.42	145.84	7.3	419	568	646	742	875
8	Cem2 > 5%_S	0.42	145.40	7.4	363	569	638	821	859
9	Cem3 < 5%_F	0.42	146.30	6.8	611	676	776	795	854
10	Cem3 > 5%_F	0.42	146.54	6.5	563	629	679	748	863
11	Cem3 < 5%_S	0.42	145.50	6.6	705	874	977	992	1077
12	Cem3 > 5%_S	0.42	147.92	6.3	625	851	976	998	1061
9R	Cem3R < 5%_F	0.40	145.56	7.3	545	666	697	758	767
10R	Cem3R > 5%_F	0.40	146.24	7.1	609	695	718	745	762
11R	Cem3R < 5%_S	0.42	146.80	6.6	591	689	789	908	968
12R	Cem3R > 5%_S	0.42	145.44	7.4	499	685	793	887	940

Table A-12 Average Flexural Strength for Mixes with Combined Sand (Mix 13–Mix 24), psi

Mix No.	Mix Design	w/cm Ratio	Unit Weight lb/ft^3	Air Content %	Average Flexural Strength, psi				
					3 Day	7 Day	14 Day	28 Day	56 Day
13	Cem1R < 5%_F	0.42	143.16	8.3	474	531	552	615	719
14	Cem1R > 5%_F	0.42	145.80	7.3	533	623	651	710	754
15	Cem1R < 5%_S	0.42	143.76	8.0	515	668	745	781	822
16	Cem1R > 5%_S	0.42	144.08	8.0	517	568	673	784	781
17	Cem2 < 5%_F	0.42	145.80	6.8	541	700	726	781	849
18	Cem2 > 5%_F	0.42	144.92	7.5	466	573	619	649	777
19	Cem2 < 5%_S	0.44	143.72	8.0	532	658	740	806	854
20	Cem2 > 5%_S	0.44	144.40	7.5	476	631	753	798	876
21	Cem3 < 5%_F	0.42	143.44	8.2	508	534	610	661	673
22	Cem3 > 5%_F	0.42	146.68	6.7	573	689	732	791	858
23	Cem3 < 5%_S	0.44	145.72	7.3	499	683	791	823	837
24	Cem3 > 5%_S	0.44	144.72	7.9	489	655	724	816	743

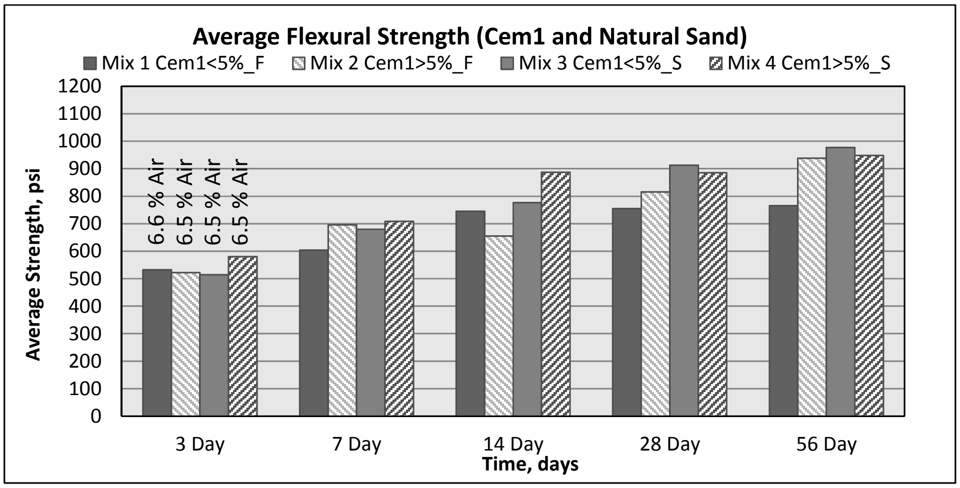

Figure A-23 Average flexural strength for Mix 1–Mix 4 (Cem1 and NS), psi.

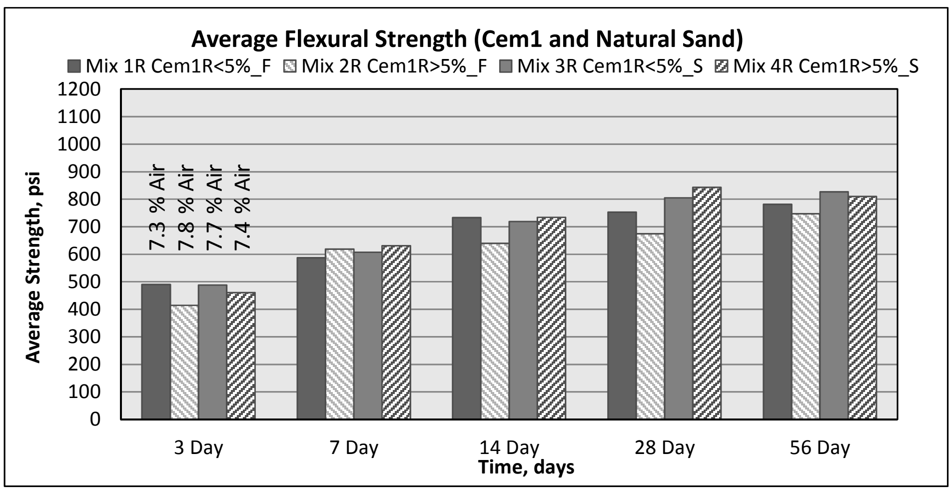

Figure A-24 Average flexural strength for Mix 1R–Mix 4R (Cem1R and NS), psi.

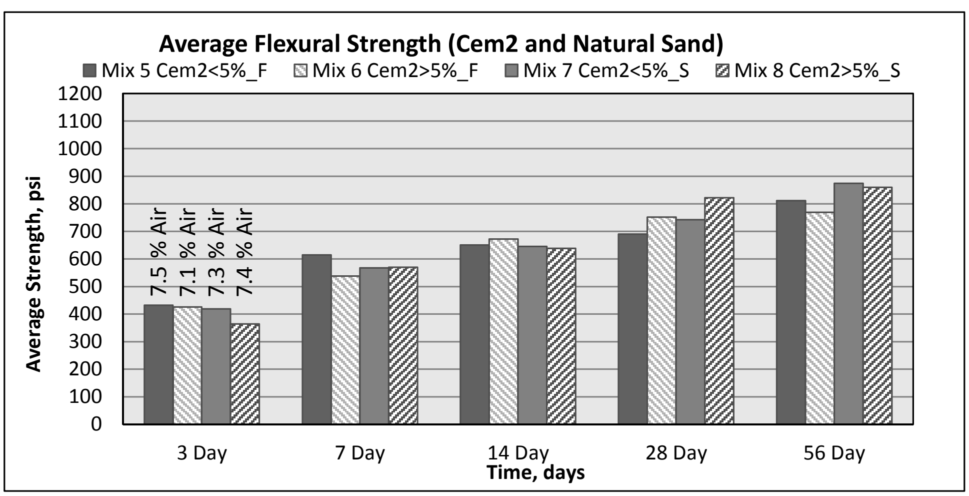

Figure A-25 Average flexural strength for Mix 5–Mix 8 (Cem2 and NS), psi.

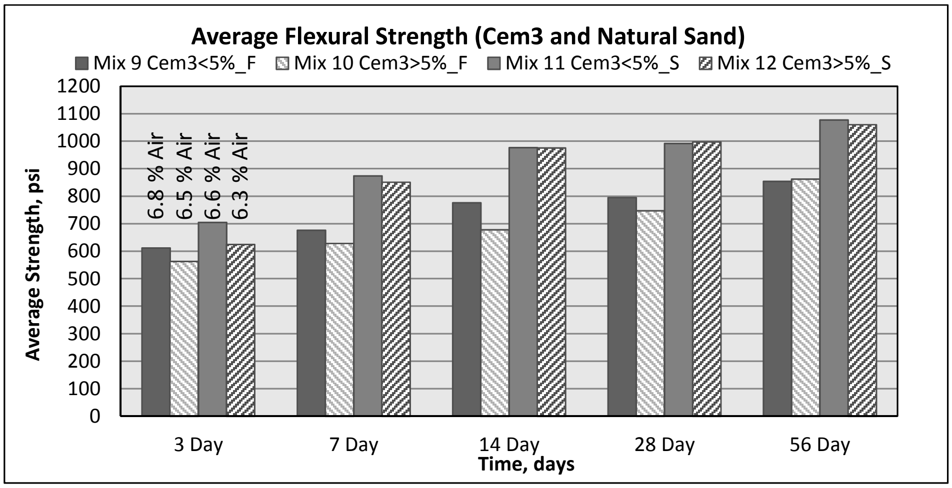

Figure A-26 Average flexural strength for Mix 9–Mix 12 (Cem3 and NS), psi.

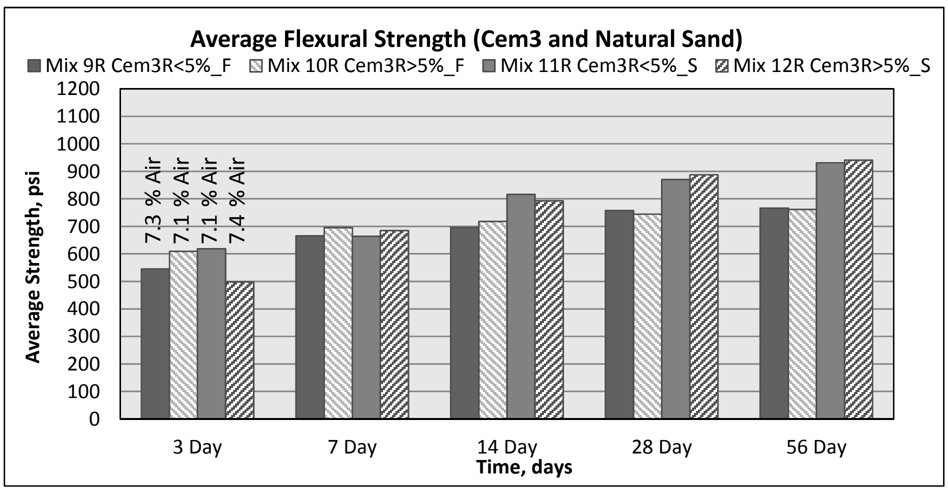

Figure A-27 Average flexural strength for Mix 9R–Mix 12R (Cem3R and NS), psi.

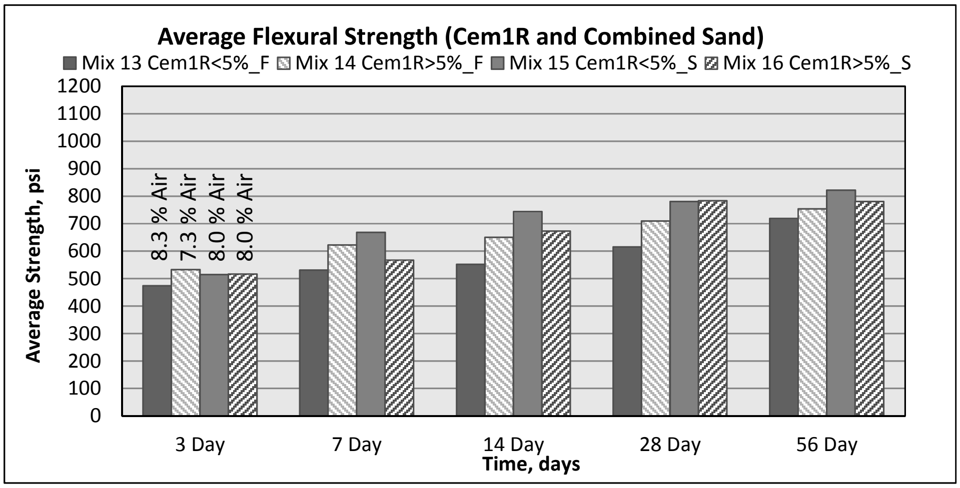

Figure A-28 Average flexural strength for Mix 13–Mix 16 (Cem1R and CS), psi.

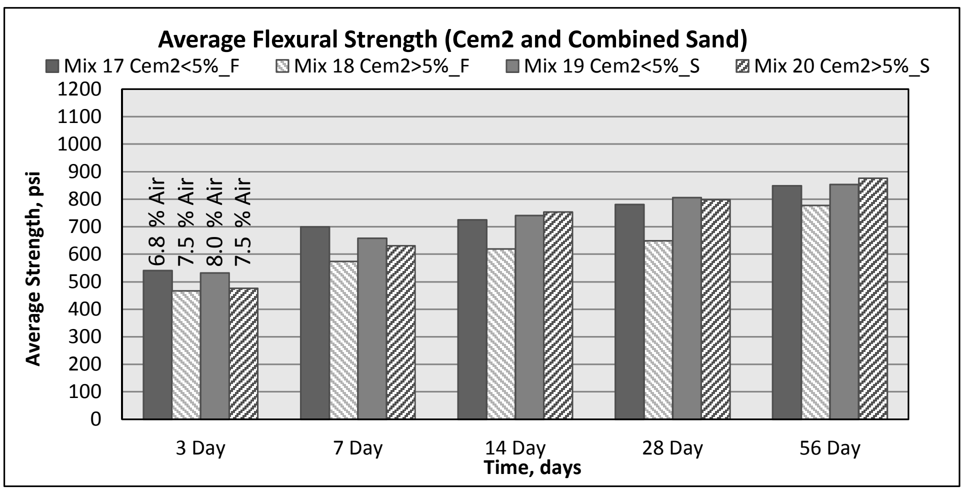

Figure A-29 Average flexural strength for Mix 17–Mix 20 (Cem2 and CS), psi.

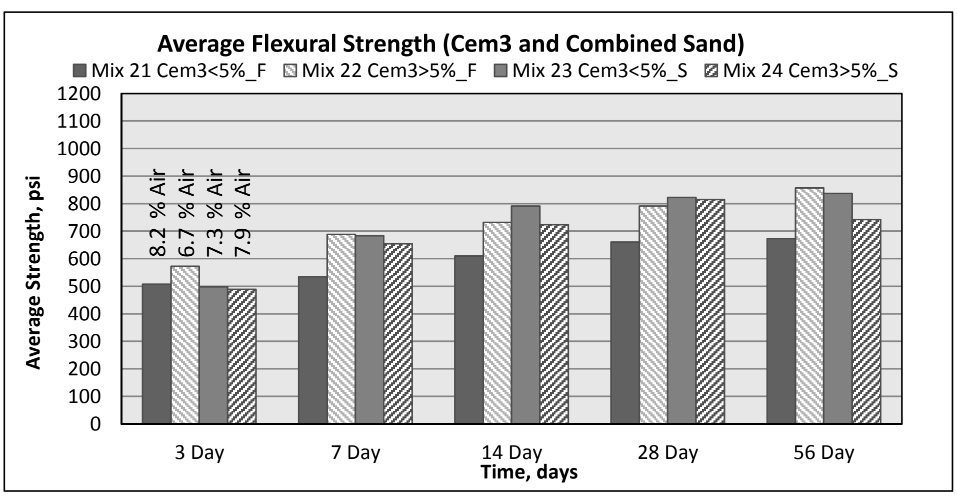

Figure A-30 Average flexural strength for Mix 21–Mix 24 (Cem3 and CS), psi.

APPENDIX I WATER PERMEABILITY TEST RESULTS PER DIN 1048

Table A-13 Water Permeability Test Results for Mixes Batched with Natural Sand (Mix 1–Mix 12 and Mix 1R–4R)

DIN 1048 - Water Permeability Test					
Mix No.	Mix Design	Sample No.	Maximum Water Permeability Depth, mm		
			56 Days	180 Days	360 Days
Mix 1	Cem1 < 5%_Fly ash	1	29.0	25.4	18.3
		2	34.4	31.8	13.5
		3	28.6	31.8	29.4
		Average	**30.7**	**29.6**	**20.4**
Mix 2	Cem1 > 5%_Fly ash	1	23.7	46.0	16.7
		2	25.6	30.2	23.0
		3	32.6	34.9	15.1
		Average	**27.3**	**37.0**	**18.3**
Mix 3	Cem1 < 5%_Slag	1	21.8	34.9	14.0
		2	20.3	28.6	11.0
		3	21.1	27.0	10.5
		Average	**21.1**	**30.2**	**11.8**
Mix 4	Cem1 > 5%_Slag	1	27.2	34.9	16.0
		2	28.5	28.6	14.0
		3	24.2	27.0	12.0
		Average	**26.6**	**30.2**	**14.0**
Mix 1R	Cem1R < 5%_Fly ash	1	32.0	15.0	
		2	28.0	20.0	
		3	27.0	17.0	
		Average	**29.0**	**17.3**	
Mix 2R	Cem1R > 5%_Fly ash	1	22.0	23.0	
		2	30.0	15.5	
		3	31.0	20.5	
		Average	**27.7**	**19.7**	
Mix 3R	Cem1R < 5%_Slag	1	24.0	19.5	
		2	28.0	14.5	
		3		21.0	
		Average	**26.0**	**18.3**	
Mix 4R	Cem1R > 5%_Slag	1	27.0	19.0	
		2	30.0	20.5	
		3	31.0	15.5	
		Average	**29.3**	**18.3**	
Mix 5	Cem2 < 5%_Fly ash	1	25.0	15.0	
		2	29.0	24.0	
		3	29.0	23.0	
		Average	**27.7**	**20.7**	
Mix 6	Cem2 > 5%_Fly ash	1	24.0	17.0	
		2	25.0	23.0	
		3	30.0	26.0	
		Average	**26.3**	**22.0**	
Mix 7	Cem2 < 5%_Slag	1	35.0	15.0	16.0
		2	21.0	23.5	25.0
		3	20.0	23.0	26.0
		Average	**25.3**	**20.5**	**22.3**
Mix 8	Cem2 > 5%_Slag	1	23.0	17.0	22.0
		2	24.0	18.0	22.5
		3	34.0	20.5	23.0
		Average	**27.0**	**18.5**	**22.5**
Mix 9	Cem3 < 5%_Fly ash	1	31.8	22.4	18.0
		2	33.3	33.0	19.0
		3	33.3	24.1	16.0
		Average	**32.8**	**26.5**	**17.7**
Mix 10	Cem3 > 5%_Fly ash	1	30.2	36.5	21.0
		2	31.8	33.3	21.0
		3	25.4	28.6	22.0
		Average	**29.1**	**32.8**	**21.3**
Mix 11	Cem3 < 5%_Slag	1	27.0	27.0	19.0
		2	34.9	27.0	19.0
		3	34.9	31.8	20.0
		Average	**32.3**	**28.6**	**19.3**
Mix 12	Cem3 > 5%_Slag	1	31.8	30.2	12.0
		2	34.9	19.1	17.0
		3	30.2	30.2	18.0
		Average	**32.3**	**26.5**	**15.7**

Table A-14 Water Permeability Test Results for Mixes Batched with Combined Sand (Mix 13–Mix 24)

DIN 1048 - Water Permeability Test					
Mix No.	**Mix Design**	**Sample No.**	**Maximum Water Permeability Depth, mm**		
			56 Days	**180 Days**	**360 Days**
Mix 13	Cem1R < 5%_Fly ash	1	39.0	27.0	23.5
		2	37.0	24.0	23.0
		3	25.0	25.0	22.5
		Average	**33.7**	**25.3**	**23.0**
Mix 14	Cem1R > 5%_Fly ash	1	29.0	26.0	25.0
		2	29.0	31.0	23.0
		3	32.0	31.0	26.0
		Average	**30.0**	**29.3**	**24.7**
Mix 15	Cem1R < 5%_Slag	1	17.0	19.0	21.0
		2	20.0	22.0	20.0
		3	26.0	22.0	19.5
		Average	**21.0**	**21.0**	**20.2**
Mix 16	Cem1R > 5%_Slag	1	19.0	24.0	18.5
		2	27.0	24.0	19.0
		3	28.0	30.0	21.5
		Average	**24.7**	**26.0**	**19.7**
Mix 17	Cem2 < 5%_Fly ash	1	24.0	18.0	13.0
		2	25.5	16.5	17.0
		3	15.0	17.5	23.0
		Average	**21.5**	**17.3**	**17.7**
Mix 18	Cem2 > 5%_Fly ash	1	31.0	22.5	20.5
		2	29.0	18.0	20.0
		3	40.0	20.5	22.5
		Average	**33.3**	**20.3**	**21.0**
Mix 19	Cem2 < 5%_Slag	1	26.0	16.0	20.5
		2	24.0	20.0	18.0
		3	23.0	20.0	10.0
		Average	**24.3**	**18.7**	**16.2**
Mix 20	Cem2 > 5%_Slag	1	39.0	19.0	21.5
		2	42.0	20.0	17.5
		3	31.0	23.0	20.0
		Average	**37.3**	**20.7**	**19.7**
Mix 21	Cem3 < 5%_Fly ash	1	31.0	27.0	33.0
		2	36.0	29.0	27.0
		3	38.0	34.0	30.5
		Average	**35.0**	**30.0**	**30.2**
Mix 22	Cem3 > 5%_Fly ash	1	24.0	21.0	21.5
		2	26.0	26.0	22.0
		3	34.0	23.0	24.5
		Average	**28.0**	**23.3**	**22.7**
Mix 23	Cem3 < 5%_Slag	1	29.0	40.0	21.0
		2	31.0	28.0	22.5
		3	45.0	29.0	23.5
		Average	**35.0**	**32.3**	**22.3**
Mix 24	Cem3 > 5%_Slag	1	41.0	40.0	19.5
		2	35.0	37.0	24.0
		3	29.0	37.0	39.5
		Average	**35.0**	**38.0**	**27.7**

APPENDIX J RAPID CHLORIDE PENETRATION TEST RESULTS PER ASTM C1202

Table A-15 RCPT Results for Mixes Batched with Natural Sand (Mix 1–Mix 12 and Mix 1R–Mix 4R)

ASTM C1202–Rapid Chloride Permeability Test								
Mix No.	**Mix Design**	**Sample No.**	**56 Days**		**180 Days**		**360 Days**	
			Coulombs	**Permeability**	**Coulombs**	**Permeability**	**Coulombs**	**Permeability**
Mix 1	Cem1 < 5% Fly ash	1	2176	**Moderate**	559	**Very Low**	561	**Very Low**
		2	2079		680		434	
		3	2079		864		554	
		Avg	**2111**		**701**		**516**	
Mix 2	Cem1 > 5% Fly ash	1	2162	**Moderate**	764	**Very Low**	470	**Very Low**
		2	2082		605		487	
		3	2119		766		516	
		Avg	**2121**		**712**		**491**	
Mix 3	Cem1 < 5% Slag	1	1308	**Low**	464	**Very Low**	481	**Very Low**
		2	1471		546		588	
		3	1061		437		635	
		Avg	**1280**		**482**		**568**	
Mix 4	Cem1 > 5% Slag	1	1158	**Low**	383	**Very Low**	599	**Very Low**
		2	1204		387		578	
		3	1291		337		565	
		Avg	**1218**		**369**		**581**	
Mix 1R	Cem1R < 5% Fly ash	1	1089	**Low**	1044	**Low**	601	**Very Low**
		2	1352		1100		498	
		3	2404		1085			
		4			1012		498	
		Avg	**1615**		**1060**		**533**	
Mix 2R	Cem1R > 5% Fly ash	1	1884	**Low**	923	**Low**	429	**Very Low**
		2			1149		521	
		3			1094		425	
		4	1600		1075			
		Avg	**1742**		**1060**		**458**	
Mix 3R	Cem1R < 5% Slag	1		**Low**		**Very Low**	569	**Very Low**
		2	1127		802		601	
		3	1717		1042		542	
		4	1101		933			
		Avg	**1315**		**925**		**571**	
Mix 4R	Cem1R > 5% Slag	1		**Low**	856	**Very Low**	557	**Very Low**
		2	1793		1056		685	
		3			907		520	
		4	1571		794		532	
		Avg	**1682**		**903**		**573**	
Mix 5	Cem2 < 5% Fly ash	1	1364	**Low**	450	**Very Low**	566	**Very Low**
		2	1134		439			
		3			665		677	
		4	1054				470	
		Avg	**1184**		**558**		**571**	
Mix 6	Cem2 > 5% Fly ash	1	1795	**Low**	901	**Low**	707	**Very Low**
		2			1039		563	
		3	1879		1363		419	
		4	1660				527	
		Avg	**1778**		**1132**		**554**	
Mix 7	Cem2 < 5% Slag	1		**Low**		**Very Low**	566	**Very Low**
		2	1151		708		534	
		3	1150		959		551	
		4	930		702		482	
		Avg	**1077**		**790**		**533**	
Mix 8	Cem2 > 5% Slag	1	1267	**Low**	945	**Very Low**	637	**Very Low**
		2					889	
		3	1187		1023		608	
		4	1219		898			
		Avg	**1225**		**955**		**711**	
Mix 9	Cem3 < 5% Fly ash	1	1786	**Low**	416	**Very Low**	628	**Very Low**
		2	1785		448		553	
		3	2068		471		573	
		Avg	**1879**		**445**		**585**	
Mix 10	Cem3 > 5% Fly ash	1	2181	**Moderate**	755	**Very Low**	517	**Very Low**
		2	2542		579		502	
		3	2862		572		517	
		Avg	**2529**		**635**		**512**	
Mix 11	Cem3 < 5% Slag	1	1274	**Low**	656	**Very Low**	574	**Very Low**
		2	1167		593		367	
		3	1251		574		545	
		Avg	**1231**		**608**		**495**	
Mix 12	Cem3 > 5% Slag	1	1488	**Low**	613	**Very Low**	565	**Very Low**
		2	1314		533		507	
		3	1214		608		464	
		Avg	**1339**		**585**		**512**	

Table A-16 RCPT Results for Mixes Batched with Combined Sand (Mix 13–Mix 24)

ASTM C1202–Rapid Chloride Permeability Test								
Mix No.	Mix Design	Sample No.	56 Days		180 Days		360 Days	
			Coulombs	Permeability	Coulombs	Permeability	Coulombs	Permeability
Mix 13	Cem1R < 5% Fly ash	1	2513	Moderate	707	Very Low	459	Very Low
		2	2554		803		483	
		3	2571		1061		486	
		4			957		489	
		Avg	**2546**		**882**		**479**	
Mix 14	Cem1R > 5% Fly ash	1	1960	Moderate	1038	Very Low	498	Very Low
		2	2236				518	
		3	2189		987		552	
		4			956			
		Avg	**2128**		**994**		**523**	
Mix 15	Cem1R < 5% Slag	1	1293	Low		Very Low	608	Very Low
		2	1305		544		586	
		3	1090		829		648	
		4			690		601	
		Avg	**1229**		**688**		**611**	
Mix 16	Cem1R > 5% Slag	1	972	Low		Very Low	600	Very Low
		2	1037		1031			
		3	1110		837		593	
		4			824		628	
		Avg	**1040**		**897**		**607**	
Mix 17	Cem2 < 5% Fly ash	1	3808	Moderate		Low	573	Very Low
		2	3324		1737			
		3	3542		2007		656	
		4			1815		498	
		Avg	**3558**		**1853**		**576**	
Mix 18	Cem2 > 5% Fly ash	1	3523	Moderate	1978	Low		Very Low
		2			2113		869	
		3	3962		1717		620	
		4	3919				634	
		Avg	**3801**		**1936**		**708**	
Mix 19	Cem2 < 5% Slag	1	1383	Low	686	Low	671	Very Low
		2	1324		976		641	
		3	1310		1161		748	
		4	1301		1258		588	
		Avg	**1329**		**1020**		**662**	
Mix 20	Cem2 > 5% Slag	1	860	Very Low	885	Low	573	Very Low
		2	880		1263		744	
		3			1051		597	
		4	1194		960		650	
		Avg	**978**		**1040**		**641**	
Mix 21	Cem3 < 5% Fly ash	1	1494	Low	539	Very Low	375	Very Low
		2	1396		668		356	
		3	1298		826		370	
		Avg	**1396**		**678**		**367**	
Mix 22	Cem3 > 5% Fly ash	1	1868	Moderate	650	Very Low	328	Very Low
		2	2298		925		411	
		3	2265		664		330	
		4			628		390	
		Avg	**2144**		**717**		**365**	
Mix 23	Cem3 < 5% Slag	1	1224	Very Low	728	Very Low	497	Very Low
		2	822		766		511	
		3	847		702		501	
		4			609		471	
		Avg	**964**		**701**		**495**	
Mix 24	Cem3 > 5% Slag	1	1159	Low	701	Very Low	497	Very Low
		2	997		734		533	
		3	1026		751		481	
		4			755			
		Avg	**1061**		**735**		**504**	

APPENDIX K CHLORIDE CONCENTRATION VERSUS DEPTH PER AASHTO T260

Table K-17 Chloride Concentration for Concrete Mixes with Cem1 and Natural Sand (Mix 1–Mix 4)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl$^-$ by Mass of Concrete								
Mix No.	Mix Design	Ponding Duration	Titration Method	Depth (d) from Outer Surface (in.)				
				0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5
Mix 1	Cem1 < 5% Fly ash with Natural Sand	90 Days	AS	0.529	0.168	0.065	0.044	0.067
			WS	0.567	0.165	0.065	0.041	0.062
		180 Days	AS	0.632	0.198	0.077	0.050	0.047
			WS	0.620	0.195	0.062	0.050	0.044
		360 Days	AS	0.981	0.390	0.118	0.059	0.077
			WS	0.731	0.425	0.149	0.080	0.077
Mix 2	Cem1 > 5% Fly ash with Natural Sand	90 Days	AS	0.443	0.133	0.051	0.047	0.035
			WS	0.449	0.124	0.047	0.050	0.044
		180 Days	AS	0.591	0.165	0.053	0.047	0.051
			WS	0.579	0.168	0.044	0.041	0.041
		360 Days	AS	0.827	0.366	0.183	0.106	0.055
			WS	0.827	0.366	0.068	0.095	0.055
Mix 3	Cem1 < 5% Slag with Natural Sand	90 Days	AS	0.550	0.142	0.055	0.044	0.043
			WS	0.550	0.142	0.047	0.041	0.041
		180 Days	AS	0.780	0.216	0.071	0.053	0.047
			WS	0.756	0.201	0.071	0.047	0.035
		360 Days	AS	0.733	0.251	0.077	0.053	0.047
			WS	0.674	0.225	0.065	0.047	0.044
Mix 4	Cem1 > 5% Slag with Natural Sand	90 Days	AS	0.539	0.145	0.050	0.047	0.041
			WS	0.532	0.139	0.044	0.050	0.044
		180 Days	AS	0.615	0.138	0.047	0.059	0.046
			WS	0.579	0.118	0.047	0.050	0.041
		360 Days	AS	0.815	0.272	0.136	0.065	0.062
			WS	0.745	0.248	0.118	0.053	0.056
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-18 Chloride Concentration for Concrete Mixes with Cem1R and Natural Sand (Mix 1R–Mix 4R)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl$^-$ by Mass of Concrete								
Mix No.	Mix Design	Ponding Duration	Titration Method	Depth (d) from Outer Surface (in.)				
				0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5
Mix 1R	Cem1R < 5% Fly Ash with Natural Sand	90 Days	AS	0.496	0.145	0.041	0.041	0.041
			WS	0.470	0.133	0.032		
		180 Day	AS	0.514	0.165	0.050	0.053	0.051
			WS	0.476	0.151	0.035		
		315 Days	AS	0.496	0.180	0.050	0.044	0.044
			WS	0.473	0.162	0.037		
Mix 2R	Cem1R > 5% Fly Ash with Natural Sand	90 Days	AS	0.405	0.092	0.038	0.033	0.041
			WS	0.369	0.080	0.032		
		180 Days	AS	0.496	0.160	0.044	0.038	0.034
			WS	0.479	0.142	0.034		
		315 Days	AS	0.700	0.210	0.050	0.044	0.047
			WS	0.656	0.192	0.035		
Mix 3R	Cem1R < 5% Slag with Natural Sand	90 Days	AS	0.440	0.109	0.038	0.059	0.041
			WS	0.422	0.097	0.032		
		180 Days	AS	0.487	0.136	0.044	0.043	0.039
			WS	0.467	0.130	0.035		
		315 Days	AS	0.812	0.295	0.077	0.056	0.059
			WS	0.792	0.278	0.068		
Mix 4R	Cem1R > 5% Slag with Natural Sand	90 Days	AS	0.485	0.118	0.038	0.044	0.035
			WS	0.470	0.109	0.032		
		180 Days	AS	0.777	0.189	0.047	0.056	0.043
			WS	0.756	0.167	0.038		
		315 Days	AS	0.626	0.227	0.068	0.044	0.100
			WS	0.597	0.202	0.056		
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-3 Chloride Concentration for Concrete Mixes with Cem2 and Natural Sand (Mix 5–Mix 8)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl^- by Mass of Concrete								
Mix No.	**Mix Design**	**Ponding Duration**	**Titration Method**	**Depth (d) from Outer Surface (in.)**				
				0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**
Mix 5	Cem2 < 5% Fly ash with Natural Sand	90 Days	AS	0.508	0.124	0.044	0.044	0.044
			WS	0.508	0.115	0.038	0.038	0.038
		180 Days	AS	0.455	0.157	0.047	0.050	0.045
			WS	0.421	0.138	0.032		
		360 Days	AS	0.597	0.174	0.050	0.034	0.038
			WS	0.555	0.154	0.038		
Mix 6	Cem2 > 5% Fly ash with Natural Sand	90 Days	AS	0.437	0.100	0.041	0.047	0.050
			WS	0.437	0.124	0.035	0.038	0.041
		180 Days	AS	0.428	0.142	0.050	0.050	0.038
			WS	0.402	0.130	0.038		
		360 Days	AS	0.733	0.222	0.056	0.043	0.041
			WS	0.688	0.204	0.044		
Mix 7	Cem2 < 5% Slag with Natural Sand	90 Days	AS	0.550	0.106	0.044	0.050	0.041
			WS	0.508	0.103	0.038	0.044	0.035
		180 Days	AS	0.718	0.165	0.044	0.040	0.040
			WS	0.653	0.151	0.030		
		360 Days	AS	0.697	0.275	0.060	0.041	0.050
			WS	0.691	0.256	0.050		
Mix 8	Cem2 > 5% Slag with Natural Sand	90 Days	AS	0.461	0.127	0.044	0.047	0.044
			WS	0.449	0.124	0.047	0.041	0.038
		180 Days	AS	0.685	0.208	0.062	0.044	0.038
			WS	0.659	0.192	0.050		
		360 Days	AS	1.134	0.267	0.062	0.056	0.042
			WS	1.105	-0.249	0.053		
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-4 Chloride Concentration for Concrete Mixes with Cem3 and Natural Sand (Mix 9–Mix 12)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl⁻ by Mass of Concrete								
Mix No.	**Mix Design**	**Ponding Duration**	**Titration Method**	**Depth (d) from Outer Surface (in.)**				
				0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**
Mix 9	Cem3 < 5% Fly ash with Natural Sand	90 Days	AS	0.337	0.121	0.050	0.048	0.044
			WS	0.343	0.124	0.050	0.044	0.047
		180 Days	AS	0.390	0.112	0.059	0.053	0.050
			WS	0.384	0.106	0.050	0.047	0.044
		360 Days	AS	0.567	0.266	0.077	0.050	0.044
			WS	0.272	0.239	0.089	0.047	0.041
Mix 10	Cem3 > 5% Fly ash with Natural Sand	90 Days	AS	0.329	0.097	0.059	0.054	0.054
			WS	0.307	0.089	0.053	0.080	0.053
		180 Days	AS	0.402	0.130	0.065	0.059	0.053
			WS	0.390	0.115	0.053	0.056	0.044
		360 Days	AS	0.508	0.154	0.065	0.065	0.077
			WS	0.514	0.154	0.065	0.065	0.077
Mix 11	Cem3 < 5% Slag with Natural Sand	90 Days	AS	0.295	0.090	0.059	0.059	0.053
			WS	0.301	0.083	0.053	0.051	0.041
		180 Days	AS	0.378	0.083	0.059	0.053	0.053
			WS	0.414	0.083	0.062	0.050	0.053
		360 Days	AS	0.496	0.177	0.062	0.053	0.053
			WS	0.496	0.165	0.059	0.059	0.050
Mix 12	Cem3 > 5% Slag with Natural Sand	90 Days	AS	0.331	0.083	0.053	0.054	0.057
			WS	0.331	0.077	0.047	0.047	0.041
		180 Days	AS	0.396	0.106	0.053	0.050	0.053
			WS	0.425	0.109	0.053	0.047	0.059
		360 Days	AS	0.555	0.331	0.136	0.097	0.055
			WS	0.573	0.260	0.106	0.157	0.055
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-5 Chloride Concentration for Concrete Mixes with Cem1R and Combined Sand (Mix 13–Mix 16)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl⁻ by Mass of Concrete								
Mix No.	**Mix Design**	**Ponding Duration**	**Titration Method**	**Depth (d) from Outer Surface (in.)**				
				0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**
Mix 13	Cem1R < 5% Fly ash with Combined Sand	90 Days	AS	0.414	0.154	0.074	0.071	0.068
			WS	0.402	0.154	0.068	0.065	0.068
		180 Days	AS	0.443	0.207	0.077	0.056	0.059
			WS	0.437	0.201	0.077	0.053	0.053
		360 Days	AS	0.508	0.248	0.089	0.059	0.062
			WS	0.476	0.219	0.069		
Mix 14	Cem1R > 5% Fly ash with Combined Sand	90 Days	AS	0.390	0.154	0.065	0.089	0.065
			WS	0.402	0.154	0.065	0.065	0.065
		180 Days	AS	0.467	0.183	0.071	0.059	0.068
			WS	0.467	0.207	0.071	0.065	0.065
		360 Days	AS	0.505	0.213	0.071	0.056	0.063
			WS	0.479	0.186	0.053		
Mix 15	Cem1R < 5% Slag with Combined Sand	90 Days	AS	0.449	0.148	0.071	0.068	0.068
			WS	0.414	0.151	0.071	0.071	0.071
		180 Days	AS	0.502	0.151	0.068	0.077	0.074
			WS	0.473	0.151	0.059	0.059	0.062
		360 Days	AS	0.609	0.278	0.080	0.059	0.059
			WS	0.588	0.251	0.059		
Mix 16	Cem1R > 5% Slag with Combined Sand	90 Days	AS	0.431	0.139	0.071	0.062	0.068
			WS	0.425	0.136	0.071	0.059	0.065
		180 Days	AS	0.467	0.083	0.059	0.077	0.056
			WS	0.449	0.118	0.050	0.062	0.047
		360 Days	AS	0.624	0.236	0.074	0.071	0.080
			WS	0.615	0.213	0.059		
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-6 Chloride Concentration for Concrete Mixes with Cem2 and Combined Sand (Mix 17–Mix 20)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl⁻ by Mass of Concrete								
Mix No.	Mix Design	Ponding Duration	Titration Method	Depth (d) from Outer Surface (in.)				
				0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5
Mix 17	Cem2 < 5% Fly ash with Combined Sand	90 Days	AS	0.520	0.189	0.068	0.062	0.062
			WS	0.502	0.177	0.056	0.050	0.050
		180 Days	AS	0.464	0.207	0.071	0.052	0.041
			WS	0.420	0.194	0.056		
		360 Days	AS	0.656	0.248	0.062	0.053	0.053
			WS	0.615	0.225	0.044		
Mix 18	Cem2 > 5% Fly ash with Combined Sand	90 Days	AS	0.449	0.130	0.053	0.053	0.050
			WS	0.437	0.136	0.047	0.041	0.038
		180 Days	AS	0.425	0.187	0.062	0.056	0.051
			WS	0.408	0.171	0.044		
		360 Days	AS	0.685	0.266	0.074	0.062	0.059
			WS	0.637	0.236	0.059		
Mix 19	Cem2 < 5% Slag with Combined Sand	90 Days	AS	0.555	0.089	0.059	0.056	0.053
			WS	0.555	0.106	0.047	0.047	0.044
		180 Days	AS	0.455	0.162	0.057	0.062	0.056
			WS	0.428	0.148	0.043		
		360 Days	AS	0.762	0.254	0.063	0.053	0.056
			WS	0.729	0.232	0.050		
Mix 20	Cem2 > 5% Slag with Combined Sand	90 Days	AS	0.733	0.130	0.053	0.053	0.047
			WS	0.721	0.124	0.044	0.044	0.047
		180 Days	AS	0.677	0.160	0.048	0.047	0.053
			WS	0.625	0.143	0.033		
		360 Days	AS	0.682	0.233	0.064	0.077	0.067
			WS	0.635	0.234	0.067		
AS: Acid soluble chloride method WS: Water soluble chloride method								

Table A-7 Chloride Concentration for Concrete Mixes with Cem3 and Combined Sand (Mix 21–Mix 24)

AASHTO T260–Testing for Chloride Ion in Concrete								
% Cl^- by Mass of Concrete								
Mix No.	**Mix Design**	**Ponding Duration**	**Titration Method**	**Depth (d) from Outer Surface (in.)**				
				0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**
Mix 21	Cem3 < 5% Fly ash with Combined Sand	90 Days	AS	0.343	0.115	0.074	0.065	0.065
			WS	0.331	0.106	0.071	0.065	0.068
		180 Days	AS	0.420	0.148	0.071	0.065	0.062
			WS	0.408	0.136	0.056	0.050	0.050
		360 Days	AS	0.535	0.189	0.073	0.074	0.071
			WS	0.485	0.157	0.057		
Mix 22	Cem3 > 5% Fly ash with Combined Sand	90 Days	AS	0.384	0.160	0.080	0.074	0.065
			WS	0.390	0.142	0.077	0.077	0.068
		180 Days	AS	0.461	0.154	0.053	0.062	0.065
			WS	0.437	0.142	0.047	0.047	0.047
		360 Days	AS	0.493	0.233	0.080	0.065	0.056
			WS	0.473	0.210	0.065		
Mix 23	Cem3 < 5% Slag with Combined Sand	90 Days	AS	0.366	0.106	0.062	0.059	0.059
			WS	0.378	0.112	0.065	0.062	0.062
		180 Days	AS	0.579	0.183	0.065	0.053	0.053
			WS	0.567	0.136	0.053	0.041	0.041
		360 Days	AS	0.576	0.225	0.069	0.057	0.050
			WS	0.567	0.210	0.054		
Mix 24	Cem3 > 5% Slag with Combined Sand	90 Days	AS	0.449	0.136	0.065	0.059	0.065
			WS	0.461	0.130	0.065	0.065	0.056
		180 Days	AS	0.579	0.154	0.071	0.068	0.065
			WS	0.615	0.142	0.059	0.059	0.047
		360 Days	AS	0.712	0.292	0.053	0.059	0.057
			WS	0.674	0.271	0.076		
AS: Acid soluble chloride method WS: Water soluble chloride method								

APPENDIX L HARDENED ENTRAINED AIR RESULTS PER ASTM C457 (LINEAR TRAVERSE METHOD)

Table A-19 Hardened Entrained Air Results for Concrete Mixes with Cem1 and Natural Sand (Mix 1–Mix 4)

Air Void Parameters per ASTM C457 (Linear Traverse Method)							
Mix No.	**Mix Design**	**Air Content (Fresh Concrete), %**	**Air Content (Hardened Concrete), %**	**Voids per Inch (>8)**	**Specific Surface, 1/in (>500)**	**Spacing Factor, in (<0.01)**	**Comment**
1	Cem1 < 5% & Fly ash	6.5	4.34	11.26	1036.4	0.0046	-
2	Cem1 > 5% & Fly ash	7.0	3.13	6.88	880.3	0.0063	Void frequency failed
3	Cem1 < 5% & Slag	6.5	4.06	6.41	632.1	0.0079	Void frequency failed
4	Cem1 > 5% & Slag	6.5	3.66	6.1	665.9	0.0079	Void frequency failed

Table A-20 Hardened Entrained Air Results for Concrete Mixes with Cem1R and Natural Sand (Mix 1R–Mix 4R)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
1R	Cem1R < 5% & Fly ash	1	Top Middle	A	7.93	15.86	799.4	0.004
		2	Top Middle		8.15	17.77	872.4	0.0033
		Average	**Top Middle**		**8.04**	**16.82**	**835.9**	**0.0035**
2R	Cem1R > 5% & Fly ash	1	Top Middle	A	7.13	15.44	866.3	0.0038
		2	Top Middle		7.38	14.61	792.1	0.0040
		Average	**Top Middle**		**7.26**	**15.03**	**829.2**	**0.0039**
3R	Cem1R < 5% & Slag	1	Top Middle	A	7.48	14.58	779.6	0.0041
		2	Top Middle		7.45	12.23	657.1	0.0049
		Average	**Top Middle**		**7.47**	**13.41**	**718.4**	**0.0045**
4R	Cem1R > 5% & Slag	1	Top Middle	A	8.00	17.23	861.3	0.0034
		2	Top Middle		7.83	15.29	781.3	0.0039
		Average	**Top Middle**		**7.92**	**16.26**	**821.3**	**0.0037**

Table A-21 Hardened Entrained Air Results for Concrete Mixes with Cem2 and Natural Sand (Mix 5–Mix 8)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
5	Cem2 < 5% & Fly ash	1	Top Middle	A	6.43	11.88	739.0	0.005
		2	Top Middle		5.75	12.18	847.6	0.0048
		Average	**Top Middle**		**6.09**	**12.03**	**793.3**	**0.0049**
6	Cem2 > 5% & Fly ash	1	Top Middle	A	6.41	11.91	742.8	0.0049
		2	Top Middle		7.40	13.24	715.6	0.0044
		Average	**Top Middle**		**6.91**	**12.58**	**729.2**	**0.0047**
7	Cem2 < 5% & Slag	1	Top Middle	A	7.23	11.21	620.3	0.0053
		2	Top Middle		7.03	12.19	694.0	0.0049
		Average	**Top Middle**		**7.13**	**11.70**	**657.2**	**0.0051**
8	Cem2 > 5% & Slag	1	Top Middle	A	6.12	11.04	722.0	0.0054
		2	Top Middle		5.68	9.46	666.0	0.0063
		Average	**Top Middle**		**5.90**	**10.25**	**694.0**	**0.0059**

Table A-22 Hardened Entrained Air Results for Concrete Mixes with Cem3 and Natural Sand (Mix 9–Mix 12)

Air Void Parameters per ASTM C457 (Linear Traverse Method)							
Mix No.	**Mix Design**	**Air Content (Fresh Concrete), %**	**Air Content (Hardened Concrete), %**	**Voids per Inch (>8)**	**Specific Surface, 1/in (>500)**	**Spacing Factor, in (<0.01)**	**Comment**
9	Cem3 < 5% & Fly ash	6.6	3.76	7.58	806.4	0.0063	Void frequency failed
10	Cem3 > 5% & Fly ash	6.5	3.92	9.41	960.8	0.0052	-
11	Cem3 < 5% & Slag	6.6	3.9	6.48	664.3	0.0077	Void frequency failed
12	Cem3 > 5% & Slag	6.3	3.72	7.61	818.6	0.0064	Void frequency failed

Table A-23 Hardened Entrained Air Results for Concrete Mixes with Cem3R and Natural Sand (Mix 9R–Mix 12R)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
9R	Cem3R < 5% & Fly ash	1	Top Middle	A	5.09	7.72	607.0	0.007
		2	Top Middle		5.48	8.48	618.7	0.0069
		Average	**Top Middle**		**5.29**	**8.10**	**612.9**	**0.0072**
10R	Cem3R > 5% & Fly ash	1	Top Middle	A	4.61	6.03	523.4	0.0089
		2	Top Middle		4.39	6.07	553.3	0.0086
		Average	**Top Middle**		**4.50**	**6.05**	**538.4**	**0.0088**
11R	Cem3R < 5% & Slag	1	Top Middle	A	7.25	14.41	795.4	0.0041
		2	Top Middle		7.09	13.71	773.3	0.0043
		Average	**Top Middle**		**7.17**	**14.06**	**784.4**	**0.0042**
12R	Cem3R > 5% & Slag	1	Top Middle	A	5.97	10.46	701.0	0.0057
		2	Top Middle		5.52	9.77	707.4	0.0061
		Average	**Top Middle**		**5.75**	**10.12**	**704.2**	**0.0059**

Table A-6 Hardened Entrained Air Results for Concrete Mixes with Cem1R and Combined Sand (Mix 13–Mix 16)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
13	Cem1R < 5% & Fly ash	1	Top	B	3.72	7.01	753.7	0.0069
		2			4.40	8.23	747.8	0.0065
		Average	**Top**		**4.06**	**7.62**	**750.8**	**0.0067**
13R	Cem1R < 5% & Fly ash	1	Top	B	9.08	20.50	902.9	0.0030
		2	Middle					
		Average	**Top**		**9.08**	**20.50**	**902.9**	**0.0030**
			Middle					
14	Cem1R > 5% & Fly ash	1	Top	A	5.84	10.60	726.4	0.0057
				B	5.82	11.13	765.5	0.0054
			Middle	A	5.29	7.97	601.9	0.0074
		2	Top	A	6.18	9.37	606.2	0.0065
				B	6.13	10.23	668.1	0.0059
			Middle					
		Average	**Top**		**5.99**	**10.33**	**691.6**	**0.0059**
			Middle		**5.29**	**7.97**	**601.9**	**0.0074**
15	Cem1R < 5% & Slag	1	Top	A	4.41	7.12	646.5	0.0075
		2	Top	A	4.55	5.86	514.4	0.0093
				B	4.06	5.43	535.1	0.0094
			Middle					
		Average	**Top**		**4.34**	**6.14**	**565.3**	**0.0087**
15R	Cem1R < 5% & Slag	1	Top	A	6.33	13.17	832.3	0.0046
		2			5.43	10.37	764.1	0.0058
		Average	**Top**		**5.88**	**11.77**	**798.2**	**0.0052**
16	Cem1R > 5% & Slag	1	Top	A	5.05	6.98	552.9	0.0082
				B	4.93	7.24	587.5	0.0078
		2	Top	A	5.00	6.69	535.0	0.0085
				B	5.36	6.84	510.3	0.0087
			Middle					
		Average	**Top**		**5.09**	**6.94**	**546.4**	**0.0083**
16R	Cem1R > 5% & Slag	1	Top	A	6.42	12.83	799.9	0.0047
		2		B	6.57	12.83	799.9	0.0047
		Average	**Top**		**6.50**	**12.83**	**799.9**	**0.0047**

Table A-24 Hardened Entrained Air Results for Concrete Mixes with Cem2 and Combined Sand (Mix 17–Mix 20)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
17	Cem2 < 5% & Fly ash	1	Top Middle	A	6.48	16.30	1005.5	0.0037
		2	Top Middle		5.42	13.47	994.3	0.0044
		Average	**Top Middle**		**5.95**	**14.89**	**999.9**	**0.0041**
18	Cem2 > 5% & Fly ash	1	Top Middle	A	6.11	14.14	926.6	0.0043
		2	Top Middle		5.48	13.88	1012.1	0.0043
		Average	**Top Middle**		**5.80**	**14.01**	**969.4**	**0.0043**
19	Cem2 < 5% & Slag	1	Top Middle	A	6.27	15.62	997.0	0.0039
		2	Top Middle		5.54	12.31	888.1	0.0049
		Average	**Top Middle**		**5.91**	**13.97**	**942.6**	**0.0044**
20	Cem2 > 5% & Slag	1	Top Middle	A	5.92	11.09	749.3	0.0055
		2	Top Middle		6.17	12.31	797.8	0.0049
		Average	**Top Middle**		**6.05**	**11.70**	**773.6**	**0.0052**

Table A-25 Hardened Entrained Air Results for Concrete Mixes with Cem3 and Combined Sand (Mix 21–Mix 24)

Air Void Parameters per ASTM C457 (Linear Traverse Method)								
Mix No.	**Mix Design**	**Sample No.**	**Location**	**Operator**	**Entrained Air %**	**Voids per in.**	**Specific Surface (1/in)**	**Spacing Factor (in.)**
21	Cem3 < 5% & Fly ash	1	Top	A	5.32	6.33	476.4	0.0093
		2			5.45	7.22	530.5	0.0083
		Average	**Top**		**5.39**	**6.78**	**503.5**	**0.0088**
21R	Cem3 < 5% & Fly ash	1	Top	A	9.02	15.08	668.8	0.0040
				B	9.17	15.63	681.8	0.0039
			Middle	B	7.97	8.90	446.9	0.0068
		2	Top	A	9.37	15.79	673.8	0.0038
			Middle					
		Average	**Top**		**9.19**	**15.5**	**674.8**	**0.0039**
			Middle		**7.97**	**8.90**	**446.9**	**0.0068**
22	Cem3 > 5% & Fly ash	1	Top	B	6.17	11.42	740.1	0.0053
			Middle					
		2	Top	A	6.78	11.06	652.1	0.0055
				B	6.75	11.33	671.7	0.0053
			Middle	A	9.07	11.29	498.0	0.0054
		Average	**Top**		**6.57**	**11.27**	**688.0**	**0.0054**
			Middle		**9.07**	**11.29**	**498.0**	**0.0054**
23	Cem3 < 5% & Slag	1	Top	A	6.19	8.80	568.8	0.0069
				B	6.22	8.76	562.9	0.0069
		2	Top	A	6.94	9.00	518.6	0.0068
			Middle					
		Average	**Top**		**6.73**	**8.85**	**529.7**	**0.0069**
23R	Cem3 < 5% & Slag	1	Top	A	4.38	10.18	930.2	0.0043
		2			5.02	10.68	851.1	0.0047
		Average	**Top**		**4.70**	**10.43**	**890.7**	**0.0045**
24	Cem3 > 5% & Slag	1	Top	A	5.97	7.31	489.7	0.0083
				B	5.81	6.48	446.1	0.0094
		2	Top	A	5.99	8.27	552.0	0.0073
			Middle					
		Average	**Top**		**5.92**	**7.35**	**495.9**	**0.0083**

APPENDIX M RAPID DYNAMIC MODULUS AND DURABILITY FACTOR RESULTS AFTER 300 CYCLES OF CONTINUOUS FREEZING AND THAWING

Table A-26 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem1 and Natural Sand (Mix 1–Mix 4)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles											Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	30	60	90	120	150	180	210	240	270	300			Fresh	Hard.	
Mix 1	Cem1 < 5% & Fly ash	1	100	94.12	92.45	95.37	93.68	89.49	86.72	83.81	81.96	77.87	70.42	*70.42*	*0.000*	6.5	4.34	0.0046
		2	100	93.39	93.43	94.69	92.97	89.47	85.92	82.95	81.09	78.80	71.37	*71.37*	*0.145*			
		3	100	94.04	92.37	93.56	91.86	86.50	82.91	79.96	76.25	71.95	64.22	*64.22*	*0.089*			
		AVG	**100**	**93.8**	**92.7**	**94.5**	**92.8**	**88.5**	**85.2**	**82.2**	**79.8**	**76.2**	**68.7**	**68.67**	**0.078**			
Mix 2	Cem1 > 5% & Fly ash	1	100	91.72	91.73	92.97	89.55	84.23	80.62	75.79	64.58	59.99	50.06	*50.06*	*0.201*	7	3.13	0.0063
		2	100	93.40	91.74	94.69	91.27	87.76	84.20	81.34	73.92	71.45	63.79	*63.79*	*0.154*			
		3	100	93.43	90.06	93.01	89.57	84.17	82.32	79.12	73.53	71.00	67.26	*67.26*	*0.505*			
		4	100	91.71	91.76	93.03	87.88	84.39	78.95	74.16	62.91	56.37	44.32	*44.32*	*0.000*			
		5	100	93.42	91.74	94.61	92.93	87.87	85.99	81.18	73.90	73.33	65.76	*65.76*	*0.100*			
		AVG	**100**	**92.7**	**91.4**	**93.7**	**90.2**	**85.7**	**82.4**	**78.3**	**69.8**	**66.4**	**58.2**	**58.24**	**0.192**			
Mix 3	Cem1 < 5% & Slag	1	100	90.97	89.29	88.85	85.31	81.79	76.45	66.21	64.34	58.10	50.29	*50.29*	*0.023*	6.5	4.06	0.0079
		2	100	92.64	91.00	88.84	83.59	78.23	72.79	64.30	52.94	46.39	30.24	*30.24*	*0.070*			
		3	100	91.05	89.40	90.60	88.81	85.32	80.11	73.63	66.39	58.38	46.73	*46.73*	*0.154*			
		4	100	92.68	90.81	91.91	90.11	88.41	83.28	80.29	73.22	67.29	57.94	*57.94*	*0.515*			
		AVG	**100**	**91.8**	**90.1**	**90.0**	**87.0**	**83.4**	**78.2**	**71.1**	**64.2**	**57.5**	**46.3**	**46.30**	**0.190**			
Mix 4	Cem1 > 5% & Slag	1	100	92.55	90.88	93.83	93.83	92.12	88.00	85.80	82.32	78.36	68.53	*68.53*	*0.000*	6.5	3.66	0.0079
		2	100	92.51	90.88	92.11	90.38	86.86	79.84	75.07	65.86	59.58	45.87	*45.87*	*0.028*			
		3	100	92.57	90.91	90.44	88.75	83.50	72.69	66.06	61.19	52.68	45.89	*45.89*	*0.000*			
		4	100	90.88	85.81	79.95	70.74	53.51	42.67	46.99	38.56	30.07	23.41	*23.41*	*0.000*			
		5	100	90.98	87.65	88.80	85.41	76.53	61.78	60.85	55.35	47.33	36.00	*36.00*	*0.000*			
		AVG	**100**	**91.9**	**89.2**	**89.0**	**85.8**	**78.5**	**69.0**	**67.0**	**60.7**	**53.6**	**43.9**	**43.94**	**0.006**			

Table A-27 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem1R and Natural Sand (Mix 1R–Mix 4R)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles										Durability Factor DF,	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	36	67	103	138	173	210	245	275	300			Fresh	Hard.	
Mix 1R	Cem1R < 5% & Fly ash	1	100	94.81	93.11	94.81	93.11	91.42	89.75	89.75	89.75	84.83	*84.83*	*0.000*	7.8	8.04	0.0035
		2	100	96.49	94.76	94.76	93.05	89.66	86.34	84.71	78.32	68.89	*68.89*	*0.000*			
		3	100	94.85	93.16	93.16	93.16	91.49	88.20	88.20	86.57	80.22	*80.22*	*0.448*			
		4	100	94.94	93.28	94.94	93.28	93.28	91.64	91.64	90.01	86.79	*86.79*	*0.183*			
		AVG	**100**	**95.3**	**93.6**	**94.4**	**93.1**	**91.5**	**89.0**	**88.6**	**86.2**	**80.2**	**80.18**	**0.158**			
Mix 2R	Cem1R > 5% & Fly ash	1	100	94.81	94.81	94.81	94.81	93.11	91.42	91.42	91.42	89.75	*89.75*	*0.631*	7.5	7.26	0.0039
		2	100	96.55	94.85	94.85	94.85	94.85	94.85	94.85	94.85	93.16	*93.16*	*0.612*			
		3	100	94.85	91.49	91.49	91.49	89.84	86.57	86.57	83.37	78.67	*78.67*	*0.980*			
		4	100	93.16	91.49	91.49	89.84	88.20	84.96	86.57	84.96	81.78	*81.78*	*1.150*			
		AVG	**100**	**94.8**	**93.2**	**93.2**	**92.7**	**91.5**	**89.5**	**89.9**	**88.6**	**85.8**	**85.84**	**0.843**			
Mix 3R	Cem1R < 5% & Slag	1	100	93.22	93.22	93.22	91.56	88.30	85.08	83.50	69.92	--	*--*	*0.120*	7.5	7.47	0.0045
		2	100	91.64	91.64	91.64	91.64	88.39	85.21	83.64	79.01	76.00	*76.00*	*0.000*			
		3	100	94.85	93.16	94.85	93.16	89.84	84.96	83.37	80.22	80.22	*80.22*	*0.000*			
		4	100	94.94	94.94	94.94	93.28	91.64	90.01	86.79	86.79	85.21	*85.21*	*0.000*			
		AVG	**100**	**93.7**	**93.2**	**93.7**	**92.4**	**89.5**	**86.3**	**84.3**	**79**	**80.48**	**80.48**	**0.030**			
Mix 4R	Cem1R > 5% & Slag	1	100	93.16	93.16	91.49	89.84	86.57	86.57	86.57	84.96	83.37	*83.37*	*0.000*	7.3	7.92	0.00365
		2	100	91.77	90.17	90.17	90.17	87.01	83.90	82.37	76.38	63.73	*63.73*	*0.000*			
		3	100	91.84	91.84	90.25	91.84	88.67	87.11	82.51	78.03	68.06	*68.06*	*0.000*			
		4	100	95.02	91.77	91.77	91.77	88.58	83.90	82.37	77.85	70.62	*70.62*	*0.000*			
		AVG	**100**	**92.9**	**91.7**	**90.9**	**90.9**	**87.7**	**85.4**	**83.5**	**79.3**	**71.4**	**71.44**	**0.000**			

Table A-28 Relative Dynamic Modulus and Durability Factor (DF) for specimens with Cem2 and Natural Sand (Mix 5–Mix 8)

Mix No.	Mix ID	Sample No.	Number of Free/Thaw Cycles										Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	35	70	105	140	175	210	245	275	300			Fresh	Hard.	
Mix 5	Cem2 < 5% & Fly ash	1	100	94.85	94.85	94.85	94.85	94.85	94.85	94.85	94.85	94.85	*94.85*	*1.361*	7.9	6.09	0.0049
		2	100	94.85	96.55	94.85	94.85	94.85	94.85	94.85	94.85	93.16	*93.16*	*0.965*			
		3	100	94.85	94.85	93.16	93.16	93.16	93.16	93.16	93.16	91.49	*91.49*	*1.226*			
		4	100	96.49	96.49	96.49	94.76	96.49	96.49	96.49	96.49	94.76	*94.76*	*0.953*			
		AVG	**100**	**95.3**	**95.7**	**94.8**	**94.4**	**94.8**	**94.8**	**94.8**	**94.8**	**93.6**	**93.57**	**1.126**			
Mix 6	Cem2 > 5% & Fly ash	1	100	94.85	94.85	94.85	94.85	93.16	93.16	94.85	94.85	93.16	*93.16*	*0.967*	8.1	6.91	0.0047
		2	100	96.49	96.49	96.49	94.76	94.76	94.76	94.76	93.05	93.05	*93.05*	*1.060*			
		3	100	96.49	96.49	96.49	96.49	96.49	96.49	96.49	96.49	96.49	*96.49*	*0.869*			
		4	100	96.49	96.49	96.49	96.49	94.76	94.76	96.49	96.49	96.49	*96.49*	*0.716*			
		5	100	96.46	96.46	96.46	96.46	96.46	96.46	96.46	96.46	96.46	*96.46*	*0.780*			
		AVG	**100.0**	**96.2**	**96.2**	**96.2**	**95.8**	**95.1**	**95.1**	**95.8**	**95.5**	**95.1**	**95.13**	**0.879**			
Mix 7	Cem2 < 5% & Slag	1	100	94.85	94.85	93.16	93.16	93.16	93.16	94.85	93.16	91.49	*91.49*	*1.142*	8.0	7.13	0.0051
		2	100	94.85	94.85	93.16	93.16	89.84	89.84	89.84	84.96	81.78	*81.78*	*1.064*			
		3	100	94.85	94.85	94.85	94.85	93.16	93.16	93.16	91.49	91.49	*91.49*	*0.452*			
		4	100	94.85	96.55	94.85	94.85	93.16	93.16	93.16	93.16	93.16	*93.16*	*0.941*			
		AVG	**100.0**	**94.9**	**95.3**	**94.0**	**94.0**	**92.3**	**92.3**	**92.8**	**90.7**	**89.5**	**89.48**	**0.900**			
Mix 8	Cem2 > 5% & Slag	1	100	93.16	93.16	91.49	91.49	89.84	88.20	88.20	88.20	88.20	*88.20*	*1.521*	8.0	5.9	0.0059
		2	100	94.81	94.81	93.11	93.11	91.42	91.42	91.42	89.75	88.10	*88.10*	*1.385*			
		3	100	94.81	94.81	93.11	91.42	89.75	88.10	89.75	88.10	86.46	*86.46*	*1.440*			
		4	100	93.16	93.16	91.49	91.49	89.84	89.84	89.84	89.84	88.20	*88.20*	*1.372*			
		AVG	**100**	**94.0**	**94.0**	**92.3**	**91.9**	**90.2**	**89.4**	**89.8**	**89.0**	**87.7**	**87.74**	**1.429**			

Table A-29 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem3 and Natural Sand (Mix 9–Mix 12)

Mix No.	Mix ID	Sample No.	Number of Freeze and Thaw Cycle											Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	30	60	90	120	150	180	210	240	270	300			Fresh	Hard.	
Mix 9	Cem3 < 5% & Fly ash	1	100	98.12	95.35	96.32	97.07	94.65	93.62	90.04	86.43	71.31	59.31	*59.31*	*0.162*	6.6	3.76	0.0063
		2	100	98.98	95.48	97.19	95.52	93.84	92.12	90.34	92.13	77.62	66.09	*66.09*	*0.124*			
		3	100	97.99	96.15	96.17	96.19	89.21	85.65	80.11	81.96	BROKEN		*0.00*				
		AVG	**100**	**98.4**	**95.7**	**96.6**	**96.3**	**92.6**	**90.5**	**86.8**	**86.8**	**74.5**	**62.7**	**62.70**	**0.143**			
Mix 10	Cem3 > 5% & Fly ash	1	100	98.56	96.80	96.79	96.83	95.05	89.60	85.88	81.18	55.91	-	*50.32*	*0.664*	6.5	3.92	0.0052
		2	100	95.27	93.49	95.26	93.55	88.15	84.43	72.87	41.49	-	-	*33.20*	*0.566*			
		3	100	97.09	95.31	96.30	95.36	93.59	91.66	87.98	80.43	60.79	50.62	*50.62*	*0.699*			
		4	100	97.03	97.00	96.89	95.26	91.72	88.04	88.01	80.57	50.58	-	*45.52*	*0.409*			
		5	100	97.11	95.30	96.98	97.10	93.59	91.80	91.80	89.96	78.68	70.98	*78.68*	*0.364*			
		AVG	**100**	**97.0**	**95.6**	**96.4**	**95.6**	**92.4**	**89.1**	**85.3**	**74.7**	**61.5**	**60.8**	**51.67**	**0.541**			
Mix 11	Cem3 < 5% & Slag	1	100	97.13	97.09	97.09	95.38	91.89	89.41	86.54	79.23	65.73	51.80	*51.80*	*0.000*	6.6	3.9	0.0077
		2	100	97.96	94.49	95.73	94.52	91.04	85.69	80.27	70.87	50.98	44.86	*44.86*	*0.000*			
		3	100	96.29	92.81	92.82	89.30	82.11	80.28	57.13	-	-	-	*39.99*	*0.000*			
		4	100	99.05	97.35	99.04	97.29	95.63	95.50	93.95	92.27	88.67	87.04	*87.04*	*0.000*			
		AVG	**100**	**97.6**	**95.4**	**96.2**	**94.1**	**90.2**	**87.7**	**79.5**	**80.8**	**68.5**	**61.2**	**55.92**	**0.000**			
Mix 12	Cem3 > 5% & Slag	1	100	98.94	94.62	94.73	95.50	90.25	86.72	83.11	69.97	54.04	-	*48.64*	*0.000*	6.3	3.72	0.0064
		2	100	98.95	97.21	97.23	97.21	95.47	95.35	93.72	93.77	90.07	80.84	*80.84*	*0.297*			
		3	100	97.18	97.16	96.34	97.02	93.53	91.81	84.69	82.92	65.82	39.33	*39.33*	*0.000*			
		4	100	98.87	95.32	96.99	96.93	95.16	95.17	93.38	93.39	89.78	84.31	*84.31*	*0.303*			
		5	100	98.21	97.15	97.15	97.08	93.59	95.35	90.04	90.04	86.39	77.17	*77.17*	*0.214*			
		AVG	**100**	**98.4**	**96.3**	**96.5**	**96.7**	**93.6**	**92.9**	**89.0**	**86.0**	**77.2**	**70.4**	**66.06**	**0.163**			

Table A-30 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem3R and Natural Sand (Mix 9R–Mix 12R)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles										Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	35	70	105	140	175	210	245	275	300			Fresh	Hard.	
Mix 9R	Cem3R < 5% & Fly ash	1	100	89.92	86.68	83.50	77.32	74.32	60.20	54.96	56.25	42.93	*42.93*	*0.186*	8	5.29	0.0072
		2	100	91.70	88.49	83.77	83.77	83.77	74.72	63.46	58.17	43.69	*43.69*	*0.000*			
		3	100	91.77	90.17	87.01	87.01	82.37	67.82	63.73	63.73	48.65	*48.65*	*0.000*			
		4	100	88.49	85.33	85.33	80.69	74.72	63.46	58.17	56.89	48.29	*48.29*	*1.677*			
		AVG	**100**	**90.5**	**87.7**	**84.9**	**82.2**	**78.8**	**66.5**	**60.1**	**58.8**	**45.9**	**45.89**	**0.466**			
Mix 10R	Cem3R > 5% & Fly ash	1	100	92.10	92.10	92.10	92.10	90.56	87.51	87.51	90.56	90.56	*90.56*	*0.952*	7.5	4.5	0.0088
		2	100	93.44	91.84	90.25	90.25	87.11	84.03	84.03	85.56	85.56	*85.56*	*0.238*			
		3	100	95.02	91.77	91.77	90.17	88.58	85.45	82.37	87.01	83.90	*83.90*	*0.441*			
		4	100	93.44	93.44	91.84	91.84	90.25	87.11	87.11	90.25	90.25	*90.25*	*0.435*			
		AVG	**100**	**93.5**	**92.3**	**91.5**	**91.1**	**89.1**	**86.0**	**85.3**	**88.3**	**87.6**	**87.57**	**0.516**			
Mix 11R	Cem3R < 5% & Slag	1	100	91.64	90.01	85.21	82.08	77.50	70.16	67.32	70.16	63.18	*63.18*	*0.293*	8.1	7.17	0.0042
		2	100	90.09	88.49	86.90	85.33	82.22	74.72	70.39	70.39	62.12	*62.12*	*0.000*			
		3	100	90.17	87.01	85.45	80.85	79.34	72.04	70.62	69.21	63.73	*63.73*	*0.000*			
		4	100	91.49	89.84	88.20	84.96	83.37	77.13	71.15	72.62	66.81	*66.81*	*0.000*			
		AVG	**100**	**90.8**	**88.8**	**86.4**	**83.3**	**80.6**	**73.5**	**69.9**	**70.6**	**63.96**	**64.22**	**0.073**			
Mix 12R	Cem3R > 5% & Slag	1	100	93.33	91.70	90.09	88.49	85.33	76.19	68.97	68.97	59.47	*59.47*	*0.000*	8	5.75	0.0059
		2	100	89.92	86.68	80.38	74.32	65.67	49.97	39.60	38.53	24.15	*24.15*	*0.000*			
		3	100	93.55	91.97	91.97	90.41	87.32	81.30	76.92	76.92	74.07	*74.07*	*0.000*			
		4	100	93.22	91.56	89.92	86.68	81.93	71.37	64.28	62.90	53.69	*53.69*	*0.000*			
		AVG	**100**	**92.5**	**90.5**	**88.1**	**85.0**	**80.1**	**69.7**	**62.4**	**61.8**	**52.8**	**50.64**	**0.000**			

Table A-31 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem1R and Combined Sand (Mix 13–Mix 16)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles										Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	35	70	105	140	175	210	245	275	300			Fresh	Hard.	
Mix 13	Cem1R < 5% & Fly ash	1	100	94.52	94.52	94.52	92.73	92.67	90.87	87.34	87.31	87.32	*87.32*	*0.155*	8	9.08	0.003
		2	100	94.47	92.66	94.58	92.85	92.87	92.93	91.05	89.32	89.34	*89.34*	*0.000*			
		3	100	96.30	94.47	96.23	94.39	94.36	94.37	92.42	92.44	94.16	*94.16*	*0.330*			
		4	100	94.67	92.92	94.63	92.84	91.08	91.11	87.60	89.30	89.28	*89.28*	*0.221*			
		AVG	**100**	**95.0**	**93.6**	**95.0**	**93.2**	**92.7**	**92.3**	**89.6**	**89.6**	**90.0**	**90.02**	**0.176**			
Mix 14	Cem1R > 5% & Fly ash	1	100	94.52	92.73	92.86	92.87	91.08	91.12	87.57	85.88	85.84	*85.84*	*0.000*	7.4	5.99	0.0059
		2	100	94.57	92.79	92.87	91.06	89.26	85.88	79.16	79.19	77.49	*77.49*	*0.102*			
		3	100	94.57	92.79	91.09	89.32	87.58	85.83	82.37	82.38	82.34	*82.34*	*0.189*			
		4	100	94.57	94.57	94.53	92.77	92.73	92.72	90.85	90.84	90.74	*90.74*	*0.320*			
		AVG	**100**	**94.6**	**93.2**	**92.8**	**91.5**	**90.2**	**88.9**	**85.0**	**84.6**	**84.1**	**84.10**	**0.153**			
Mix 15	Cem1R < 5% & Slag	1	100	92.53	88.90	85.47	78.52	70.22	59.51	49.61	49.59	45.59	*45.59*	*0.293*	8.1	4.34	0.0087
		2	100	90.70	87.11	85.55	82.04	78.60	73.68	68.76	65.64	65.58	*65.58*	*0.000*			
		3	100	90.87	87.34	87.56	82.35	75.68	74.08	66.16	64.67	64.63	*64.63*	*0.000*			
		4	100	94.15	90.34	90.63	85.12	81.46	76.19	71.11	69.43	66.10	*66.10*	*0.000*			
		AVG	**100**	**92.1**	**88.4**	**87.3**	**82.0**	**76.5**	**70.9**	**63.9**	**62.3**	**60.5**	**60.47**	**0.073**			
Mix 15R	Cem1R < 5% & Slag	1	100	96.55	96.55	94.85	94.85	93.16	93.16	91.49	89.84	88.20	*88.20*	*0.211*	7.8	5.88	0.0052
		2	100	93.11	93.11	93.11	94.81	93.11	91.42	91.42	89.75	89.75	*89.75*	*0.341*			
		3	100	94.94	94.94	94.94	94.94	93.28	93.28	94.94	93.28	93.28	*93.28*	*0.059*			
		4	100	94.85	94.85	94.85	94.85	93.16	93.16	93.16	91.49	89.84	*89.84*	*0.056*			
		AVG	**100**	**94.9**	**94.9**	**94.4**	**94.9**	**93.2**	**92.8**	**92.8**	**91.1**	**90.3**	**90.27**	**0.167**			
Mix 16	Cem1R > 5% & Slag	1	100	92.79	91.04	90.99	89.19	87.43	84.11	80.70	77.49	77.47	*77.47*	*0.133*	6.9	4.99	0.0082
		2	100	91.19	89.48	89.55	86.03	81.10	79.48	73.13	71.59	68.54	*68.54*	*0.232*			
		3	100	92.73	90.95	90.94	87.43	84.05	80.78	72.67	71.09	69.55	*69.55*	*0.000*			
		4	100	90.87	89.10	87.45	83.94	82.23	78.92	73.99	72.43	70.79	*70.79*	*0.000*			
		5	100	90.95	89.20	89.14	85.58	82.20	82.28	75.69	74.13	70.94	*70.94*	*0.074*			
		AVG	**100**	**91.7**	**90.0**	**89.6**	**86.4**	**83.4**	**81.1**	**75.2**	**73.3**	**71.5**	**69.95**	**0.088**			
Mix 16R	Cem1R > 5% & Slag	1	100	93.28	93.28	93.28	94.94	91.64	91.64	91.64	88.39	88.39	*88.39*	*0.000*	7.3	6.5	0.0047
		2	100	93.28	93.28	94.94	94.94	93.28	93.28	93.28	91.64	91.64	*91.64*	*0.000*			
		3	100	93.28	93.28	93.28	93.28	91.64	91.64	91.64	90.01	88.39	*88.39*	*0.000*			
		4	100	94.85	93.16	93.16	93.16	93.16	93.16	93.16	91.49	91.49	*91.49*	*0.012*			
		5	100	94.89	93.22	93.22	93.22	91.56	89.92	89.92	86.68	83.50	*83.50*	*0.000*			
		AVG	**100**	**93.9**	**93.2**	**93.6**	**93.9**	**92.3**	**91.9**	**91.9**	**89.6**	**88.7**	**88.76**	**0.002**			

Table A-32 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem2 and Combined Sand (Mix 17– Mix 20)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles										Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	35	70	105	140	175	210	245	275	300			Fresh	Hard.	
Mix 17	Cem2 < 5% & Fly ash	1	100	94.67	94.67	94.67	92.92	92.92	92.92	92.92	92.92	92.92	*92.92*	*1.660*	7.9	5.95	0.0041
		2	100	94.62	94.62	94.62	92.86	94.62	94.62	94.62	92.86	92.86	*92.86*	*1.570*			
		3	100	94.67	94.67	94.67	94.67	94.67	92.92	92.92	92.92	92.92	*92.92*	*1.411*			
		4	100	94.62	94.62	94.62	92.86	94.62	92.86	94.62	92.86	92.86	*92.86*	*1.242*			
		AVG	**100**	**94.6**	**94.6**	**94.6**	**93.3**	**94.2**	**93.3**	**93.8**	**92.9**	**92.9**	**92.89**	**1.471**			
Mix 18	Cem2 > 5% & Fly ash	1	100	96.43	96.43	96.43	96.43	94.67	96.43	96.43	96.43	94.67	*94.67*	*0.723*	8.0	5.8	0.0043
		2	100	94.62	96.40	96.40	94.62	94.62	96.40	94.62	94.62	94.62	*94.62*	*0.594*			
		3	100	96.36	96.36	96.36	96.36	96.36	96.36	96.36	96.36	94.57	*94.57*	*0.424*			
		4	100	96.36	96.36	94.57	94.57	94.57	94.57	94.57	94.57	92.79	*92.79*	*1.391*			
		AVG	**100**	**95.9**	**96.4**	**95.9**	**95.5**	**95.1**	**95.9**	**95.5**	**95.5**	**94.2**	**94.16**	**0.783**			
Mix 19	Cem2 < 5% & Slag	1	100	96.49	96.49	96.49	94.76	94.76	94.76	94.76	94.76	93.05	*93.05*	*0.384*	7.5	5.91	0.0044
		2	100	96.46	96.46	96.46	96.46	94.71	94.71	94.71	94.71	92.99	*92.99*	*0.419*			
		3	100	94.71	96.46	96.46	96.46	94.71	94.71	94.71	94.71	92.99	*92.99*	*0.148*			
		4	100	94.71	94.71	94.71	94.71	94.71	94.71	96.46	94.71	94.71	*94.71*	*0.113*			
		AVG	**100**	**95.6**	**96.0**	**96.0**	**95.6**	**94.7**	**94.7**	**95.2**	**94.7**	**93.4**	**93.43**	**0.266**			
Mix 20	Cem2 > 5% & Slag	1	100	96.43	96.43	94.67	94.67	94.67	94.67	94.67	94.67	94.67	*94.67*	*0.000*	7.8	6.05	0.0052
		2	100	94.71	94.71	94.71	94.71	94.71	94.71	94.71	94.71	94.71	*94.71*	*0.000*			
		3	100	94.71	94.71	94.71	94.71	94.71	94.71	94.71	94.71	94.71	*94.71*	*0.000*			
		4	100	96.43	96.43	96.43	96.43	94.67	94.67	96.43	94.67	94.67	*94.67*	*0.000*			
		5	100	96.46	96.46	96.46	96.46	94.71	96.46	96.46	96.46	94.71	*94.71*	*0.000*			
		AVG	**100**	**95.7**	**95.7**	**95.4**	**95.4**	**94.7**	**95.0**	**95.4**	**95.0**	**94.7**	**94.70**	**0.000**			

Table A-33 Relative Dynamic Modulus and Durability Factor (DF) for Specimens with Cem3 and Combined Sand (Mix 21– Mix 24)

Mix No.	Mix ID	Sample No.	Number of Freeze/Thaw Cycles										Durability Factor, DF	% of Mass Loss after 300 Cycles	Air Content %		Spacing Factor
			0	35	70	105	140	175	210	245	275	300			Fresh	Hard.	
Mix 21	Cem3 < 5% & Fly ash	1	100	94.76	91.35	89.66	87.99	84.71	84.71	86.34	83.08	76.76	*76.76*	*0.000*	7.2	5.39	0.0088
		2	100	94.81	93.11	91.42	93.11	91.42	89.75	88.10	84.83	83.23	*83.23*	*0.000*			
		3	100	94.62	94.62	94.62	94.62	91.12	91.12	91.12	89.39	85.98	*85.98*	*0.000*			
		4	100	92.92	91.19	92.92	91.19	87.78	86.11	84.44	79.55	79.55	*79.55*	*0.000*			
		AVG	**100**	**94.3**	**92.6**	**92.2**	**91.7**	**88.8**	**87.9**	**87.5**	**84.2**	**81.4**	**81.38**	**0.000**			
Mix 22	Cem3 > 5% & Fly ash	1	100	94.67	92.92	92.92	92.92	91.19	91.19	89.48	89.48	86.11	*86.11*	*0.000*	7.2	6.46	0.0053
		2	100	94.62	92.86	92.86	91.12	85.98	84.31	72.98	71.48	59.71	*59.71*	*0.000*			
		3	100	94.76	94.76	94.76	94.76	93.05	93.05	93.05	91.35	89.66	*89.66*	*0.284*			
		4	100	94.62	92.86	92.86	92.86	92.86	91.12	89.39	89.39	89.39	*89.39*	*0.000*			
		AVG	**100**	**94.7**	**93.4**	**93.4**	**92.9**	**90.8**	**89.9**	**86.2**	**85.4**	**81.2**	**81.22**	**0.071**			
Mix 23	Cem3 < 5% & Slag	1	100	90.70	90.70	90.70	88.90	85.34	83.59	80.15	80.15	78.45	*78.45*	*0.000*	7.8	6.21	0.0069
		2	100	90.44	88.58	86.75	83.13	72.75	66.21	64.63	66.21	63.06	*63.06*	*0.000*			
		3	100	92.60	92.60	90.79	87.23	82.02	82.02	76.98	75.33	24.06	*24.06*	*0.000*			
		4	100	92.53	90.70	88.90	87.11	85.34	87.11	85.34	80.15	76.77	*76.77*	*0.000*			
		AVG	**100**	**91.6**	**90.6**	**89.3**	**86.6**	**81.4**	**79.7**	**76.8**	**75.5**	**60.6**	**72.76**	**0.000**			
Mix 23R	Cem3R < 5% Slag & CS	1	100	94.94	93.28	93.28	94.94	94.94	93.28	93.28	93.28	93.28	*93.28*	*0.151*	7.1	4.7	0.0045
		2	100	94.89	94.89	94.89	94.89	94.89	93.22	93.22	94.89	94.89	*94.89*	*0.496*			
		3	100	94.89	93.22	93.22	94.89	93.22	91.56	93.22	93.22	93.22	*93.22*	*0.117*			
		4	100	96.67	95.02	95.02	95.02	95.02	93.39	93.39	96.67	95.02	*95.02*	*0.021*			
		AVG	**100**	**95.3**	**94.1**	**94.1**	**94.9**	**94.5**	**92.9**	**93.3**	**94.5**	**94.1**	**94.40**	**0.196**			
Mix 24	Cem3 > 5% & Slag	1	100	93.05	93.05	93.05	94.76	93.05	93.05	91.35	91.35	91.35	*91.35*	*0.172*	7.3	5.92	0.0083
		2	100	92.99	92.99	92.99	92.99	91.27	91.27	89.57	89.57	87.89	*87.89*	*0.041*			
		3	100	94.67	92.92	94.67	94.67	92.92	92.92	92.92	92.92	91.19	*91.19*	*0.193*			
		4	100	94.67	94.67	94.67	94.67	92.92	92.92	91.19	91.19	89.48	*89.48*	*0.000*			
		5	100	92.92	92.92	91.19	91.19	86.11	84.44	79.55	77.95	76.37	*76.37*	*0.271*			
		AVG	**100**	**93.7**	**93.3**	**93.3**	**93.7**	**91.3**	**90.9**	**88.9**	**88.6**	**87.3**	**89.98**	**0.126**			

APPENDIX N DESCRIPTION OF SPECIMENS CONDITION AFTER 300 CYCLES OF CONTINUOUS FREEZING AND THAWING PER ASTM C672

Table A-34 Mix 1–Mix 4 Specimen Condition after 300 Cycles

Specimen No.	Surface Rating	Width of Pop-outs		Comments
		<1/4 in.	>1/4 in.	
Mix 1 - S1	4 (Bottom) 3 (Sides)	*	9	Paste and coarse aggregate pop-outs Aggregate broken or cracked Moderate scaling on the bottom and sides
Mix 1 - S2	3 (Bottom) 3 (Sides)	*	*	Paste pop-outs Aggregate broken or cracked Moderate scaling on the bottom and sides
Mix 1 - S3	3 (Bottom) 4 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 2 - S1	4 (Bottom) 4 (Sides)	9	7	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 2 - S2	4 (Bottom) 3 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate cracked Moderate to severe scaling on the bottom and sides
Mix 2 - S3	4 (Bottom) 4 (Sides)	6	*	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 2 - S4	3 (Bottom) 4 (Sides)	4	12	Paste pop-outs Moderate scaling on the bottom Moderate to severe scaling on the sides
Mix 2 - S5	3 (Bottom) 3 (Sides)	8	12	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom & sides
Mix 3 - S1	3 (Bottom) 3 (Sides)	10	2	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 3 - S2	3 (Bottom) 2 (Sides)	6	5	Paste and coarse aggregate pop-outs Moderate scaling on the bottom and sides
Mix 3 - S3	3 (Bottom) 3 (Sides)	5	10	Paste and coarse aggregate pop-outs A coarse aggregate particle crushed Slight to moderate scaling on the bottom and sides
Mix 3 - S4	3 (Bottom) 3 (Sides)	10	3	Paste and coarse aggregate pop-outs Moderate scaling on the bottom and sides
Mix 4 - S1	3 (Bottom) 4 (Sides)	15	3	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 4 - S2	4 (Bottom) 4 (Sides)	8	*	Paste and coarse aggregate pop-outs Aggregate broken Moderate & sever scaling on the bottom and sides
Mix 4 - S3	3 (Bottom) 4 (Sides)	10	6	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 4 - S4	3 (Bottom) 3 (Sides)	7	10	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 4 - S5	3 (Bottom) 3 (Sides)	8	6	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides

Table A-35 Mix 9–Mix 12 Specimen Condition after 300 Cycles

Specimen No.	Surface Rating	Width of Pop-outs		Comments
		<1/4 in.	>1/4 in.	
Mix 9 - S1	3 (Bottom) 3 (Sides)	2	8	Paste and coarse aggregate pop-outs Aggregate broken or cracked Moderate scaling on the bottom and sides
Mix 9 - S2	3 (Bottom) 3 (Sides)	1	2	Paste pop-outs Aggregate broken or cracked Some swellings Moderate scaling on the bottom and sides
Mix 10 - S1	4 (Bottom) 4 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 10 - S2	4 (Bottom) 4 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate broken Moderate to severe scaling on the bottom and sides
Mix 10 - S3	4 (Bottom) 4 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate cracked Moderate to severe scaling on the bottom and sides
Mix 10 - S4	4 (Bottom) 4 (Sides)	*	*	Paste and coarse aggregate pop-outs Aggregate cracked Moderate to severe scaling on the bottom and sides
Mix 10 - S5	3 (Bottom) 4 (Sides)	*	*	Paste pop-outs Moderate scaling on the bottom Moderate to severe scaling on the sides
Mix 11 - S1	4 (Bottom) 3 (Sides)	13	3	Paste and coarse aggregate pop-outs Aggregate broken The specimen is cracked at one end Moderate to severe scaling on the bottom Moderate scaling on the sides
Mix 11 - S2	3 (Bottom) 3 (Sides)	11	3	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 11 - S3	3 (Bottom) 3 (Sides)	10	5	Paste and coarse aggregate pop-outs A large-size coarse aggregate particle crushed Moderate scaling on the bottom and sides
Mix 11 - S4	2 (Bottom) 2 (Sides)	11	6	Paste and coarse aggregate pop-outs A coarse aggregate particle crushed Slight to moderate scaling on the bottom and sides
Mix 12 - S1	3 (Bottom) 3 (Sides)	11	2	Paste and coarse aggregate pop-outs Moderate scaling on the bottom and sides
Mix 12 - S2	3 (Bottom) 3 (Sides)	14	2	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 12 - S3	3 (Bottom) 3 (Sides)	9	3	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 12 - S4	3 (Bottom) 3 (Sides)	11	4	Paste and coarse aggregate pop-outs Aggregate broken Moderate scaling on the bottom and sides
Mix 12 - S5	3 (Bottom) 3 (Sides)	7	6	Paste and coarse aggregate pop-outs Moderate scaling on the bottom and sides Aggregate broken

Table A-36 Mix 13–Mix 16 Specimen Condition after 300 Cycles

Specimen No.	Surface Rating	Width of Pop-outs		Comments
		<1/4 in.	>1/4 in.	
Mix 13R - S1	3 (Sides) 4 (Bottom)	3	4	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs Aggregate broken or cracked
Mix 13R - S2	3 (Sides) 3 (Bottom)	4	3	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs
Mix 13R - S3	3 (Sides) 3 (Bottom)	5	3	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs Corner scaling and spalling
Mix 13R - S4	3 (Sides) 3 (Bottom)	7	4	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs Corner scaling and spalling
Mix 14 - S1	4 (Sides) 3 (Bottom)	4	4	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs
Mix 14 - S2	4 (Sides) 3 (Bottom)	5	3	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs Corner scaling and spalling
Mix 14 - S3	4 (Sides) 4 (Bottom)	3	1	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs
Mix 14 - S4	3 (Sides) 3 (Bottom)	3	2	Moderate scaling on the sides bottom Minor paste and coarse aggregate pop-outs Paste cracking
Mix 15 - S1	4 (Sides) 4 (Bottom)	6	4	Minor cracks visible across the depth of the specimen Moderate scaling on the sides and severe on the bottom Paste and coarse aggregate pop-outs Aggregate broken or cracked
Mix 15 - S2	3 (Sides) 4-5 (Bottom)	6	3	Moderate scaling on the sides and severe on the bottom Paste and coarse aggregate pop-outs
Mix 15 - S3	4 (Sides) 4 (Bottom)	3	4	Moderate to severe scaling on the sides and bottom Corner scaling and spalling Paste and coarse aggregate pop-outs
Mix 15 - S4	4 (Sides) 4-5 (Bottom)	2	1	Moderate to severe scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 16 - S1	3-4 (Sides) 4 (Bottom)	4	3	Moderate scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 16 - S2	4 (Sides) 5 (Bottom)	4	4	Moderate to severe scaling on the sides and bottom Paste and coarse aggregate pop-outs Corner scaling and spalling Aggregate broken or cracked
Mix 16 - S3	4 (Sides) 4-5 (Bottom)	5	2	Moderate to severe scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 16 - S4	3 (Sides) 4 (Bottom)	3	4	Moderate scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 16 - S5	4 (Sides) 5 (Bottom)	2	3	Moderate to severe scaling on the sides and bottom Paste and coarse aggregate pop-outs

Table A-37 Mix 21–Mix 24 Specimen Condition after 300 cycles

Specimen No.	Surface Rating	Width of Pop-outs		Comments
		<1/4 in.	>1/4 in.	
Mix 21R - S1	2 (Sides) 3 (Bottom)	3	2	Moderate scaling on the sides and bottom Paste and coarse aggregate pop-outs Corner scaling and spalling
Mix 21R - S2	3 (Sides) 3 (Bottom)	2	2	Moderate scaling on the sides and bottom Paste and coarse aggregate pop-outs Corner scaling with cracked aggregate
Mix 21R - S3	3 (Sides) 3 (Bottom)	2	3	Moderate scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 21R - S4	3 (Sides) 3 (Bottom)	6	4	Moderate scaling on the sides and bottom Minor paste and coarse aggregate pop-outs Aggregate broken or cracked
Mix 22 - S1	3 (Sides) 2 (Bottom)	3	2	Minor scaling on the sides bottom Slight paste and coarse aggregate pop-outs Aggregate broken or cracked
Mix 22 - S2	3 (Sides) 2 (Bottom)	2	1	Slight scaling on the sides bottom Minor paste and coarse aggregate pop-outs
Mix 22 - S3	3 (Sides) 2 (Bottom)	3	2	Slight scaling on the sides bottom Minor paste and coarse aggregate pop-outs
Mix 22 - S4	3 (Sides) 2 (Bottom)	3	3	Slight scaling on the sides bottom Minor paste and coarse aggregate pop-outs Aggregate broken or cracked
Mix 23 - S1	4 (Sides) 3 (Bottom)	3	4	Moderate scaling on the sides and severe on the Paste and coarse aggregate pop-outs
Mix 23 - S2	4 (Sides) 3 (Bottom)	6	5	Moderate scaling on the sides and severe on the Aggregate broken or cracked Paste and coarse aggregate pop-outs
Mix 23 - S3	4 (Sides) 3 (Bottom)	3	2	Moderate to severe scaling on the sides and bottom Aggregate broken or cracked Major crack visible across the depth of the specimen Paste and coarse aggregate pop-outs
Mix 23 - S4	4 (Sides) 3 (Bottom)	3	2	Moderate to severe scaling on the sides and bottom Aggregate broken or cracked Paste and coarse aggregate pop-outs
Mix 24 - S1	3 (Sides) 3 (Bottom)	2	1	Slight scaling on the sides and bottom slight scaling and spalling on the corners Paste and coarse aggregate pop-outs
Mix 24 - S2	3 (Sides) 3 (Bottom)	4	2	Slight scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 24 - S3	3 (Sides) 3 (Bottom)	3	1	Minor scaling on the sides and bottom Paste and coarse aggregate pop-outs
Mix 24 - S4	3 (Sides) 3 (Bottom)	2	1	Minor scaling on the sides and bottom Aggregate broken or cracked Slight paste and coarse aggregate pop-outs
Mix 24 - S5	5(Sides) 4 (Bottom)	3	5	Moderate scaling on the sides and bottom Aggregate broken or cracked Paste and coarse aggregate pop-outs

APPENDIX O FREEZE/THAW PHOTOS AFTER 300 CYCLES

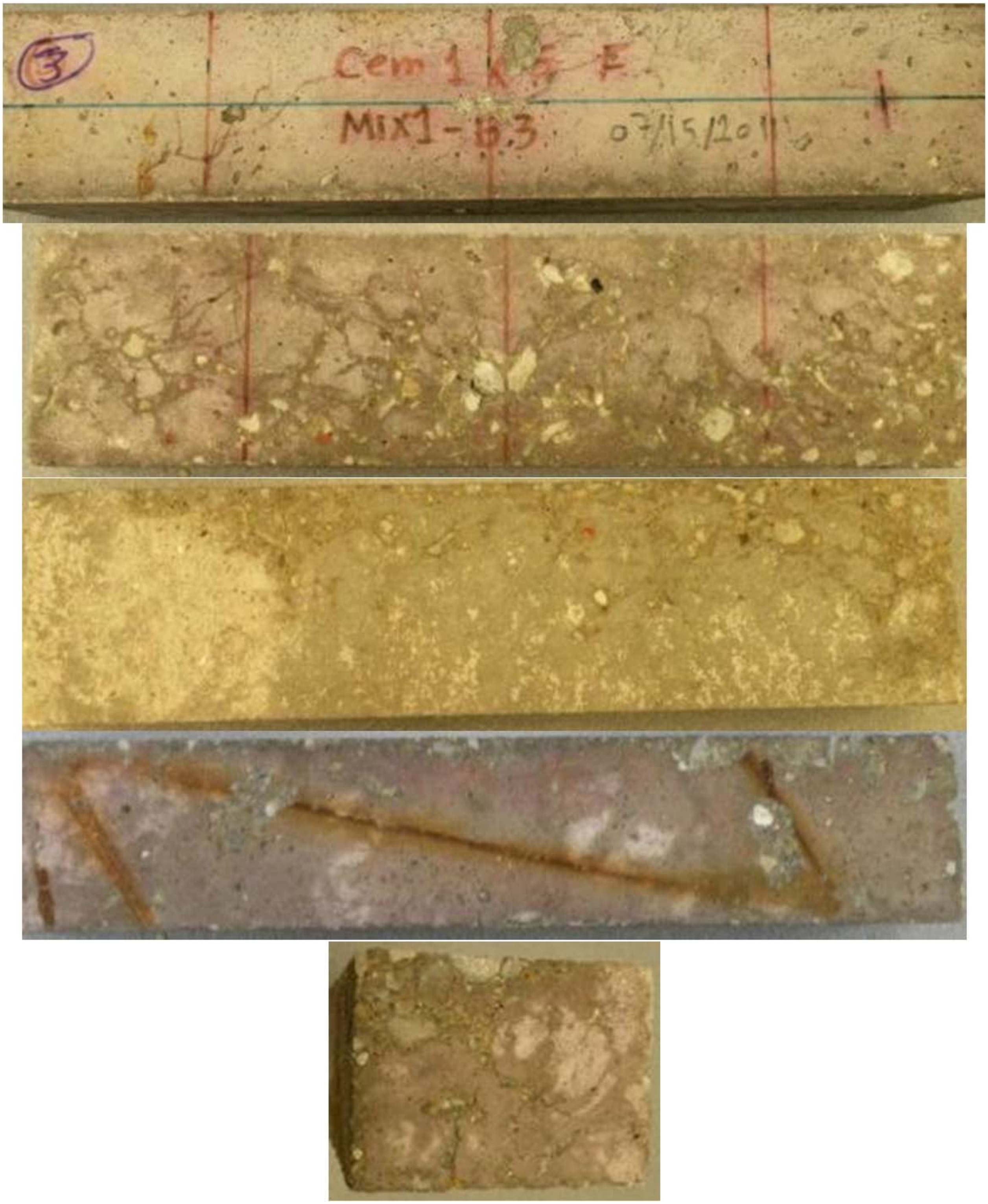

Figure O-1 Mix 1–Specimen #3
(DF = 64.22, Fresh Air = 6.5%, Hardened Entrained Air = 4.34%)

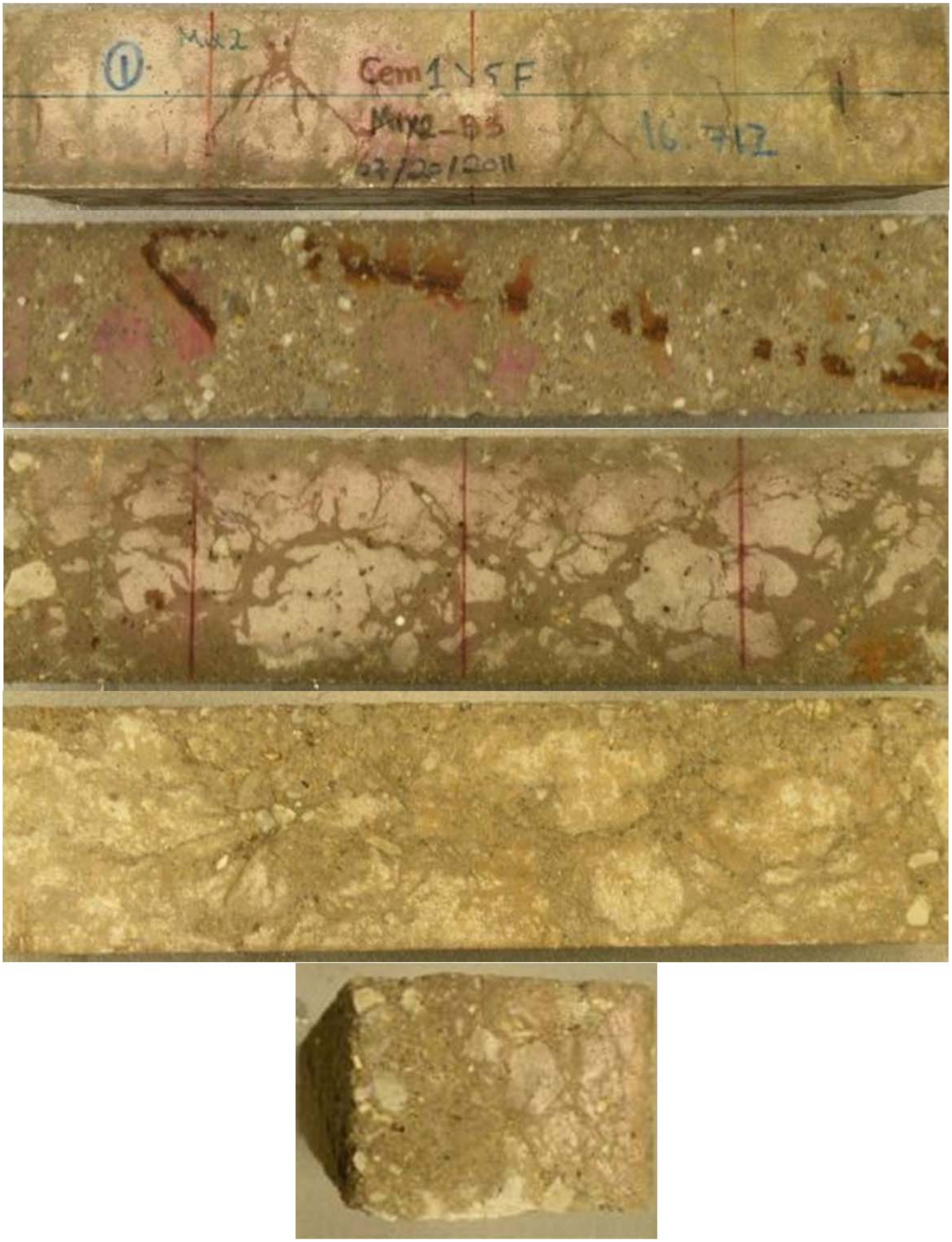

Figure O-2 Mix 2–Specimen #1
(DF = 50.06, Fresh Air = 7%, Hardened Entrained Air = 3.03%)

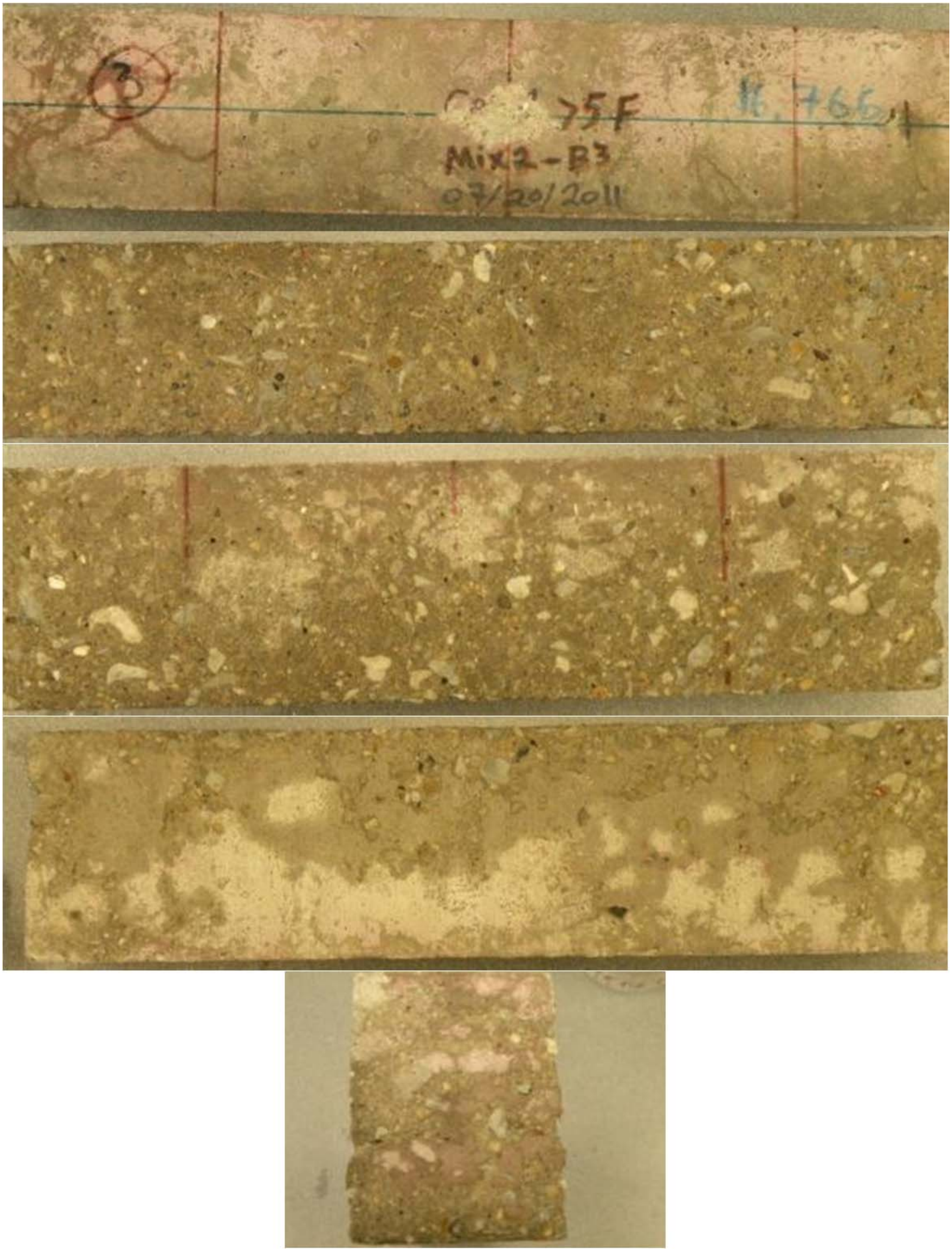

Figure O-3 Mix 2–Specimen #3
(DF = 67.26, Fresh Air = 7.0%, Hardened Entrained Air = 3.03%)

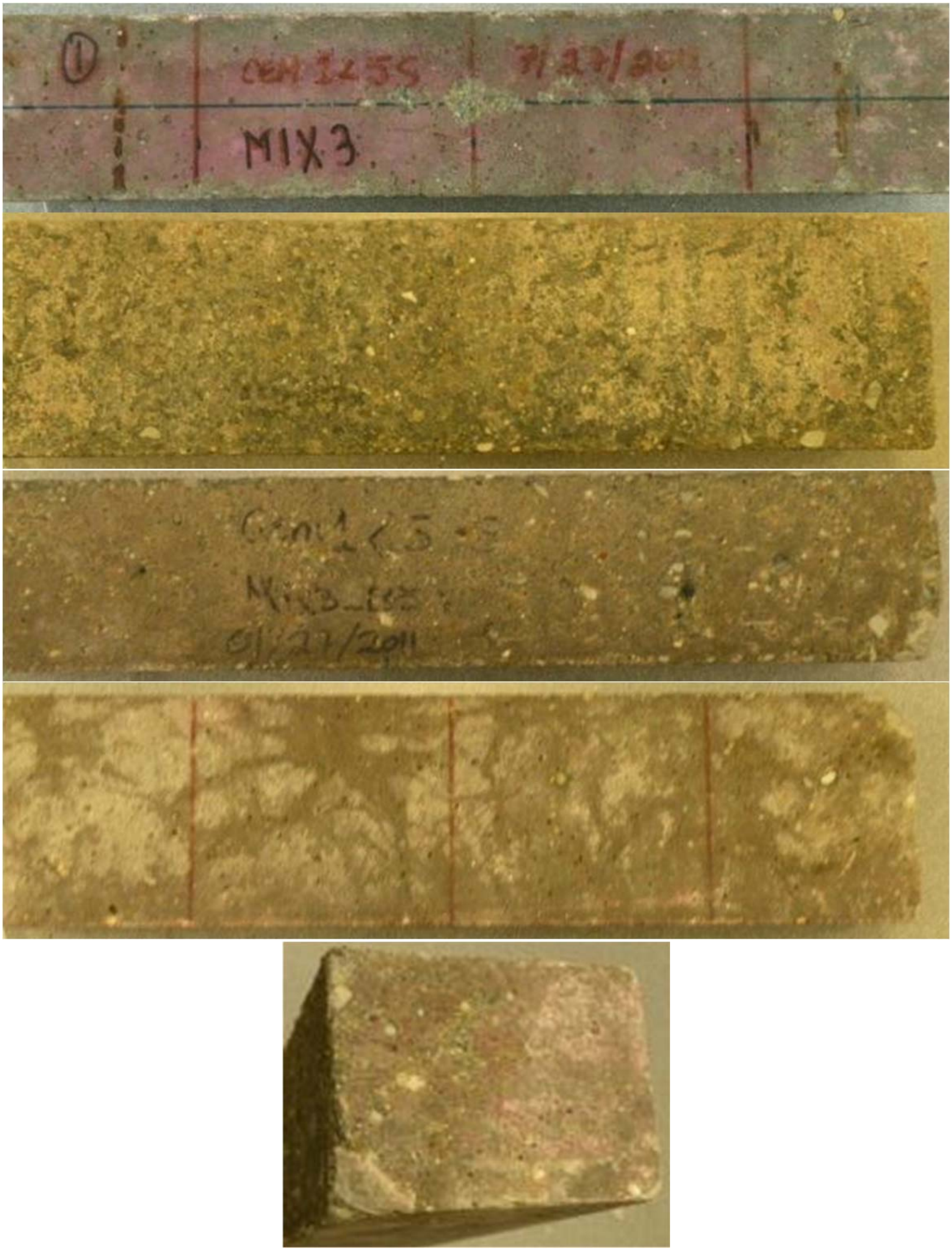

Figure O-4 Mix 3–Specimen #1
(DF = 50.29, Fresh Air = 6.5%, Hardened Entrained Air = 4.06%)

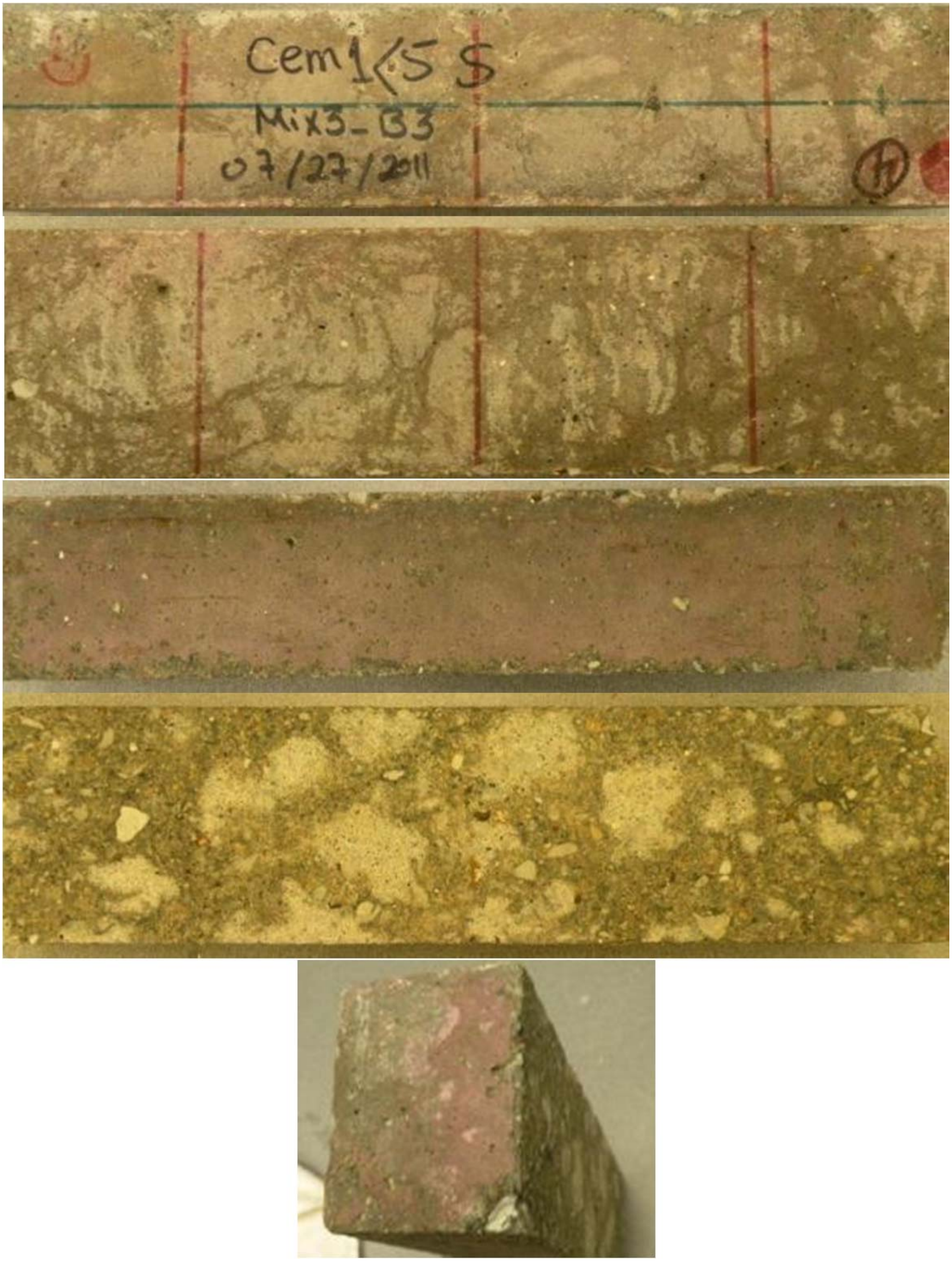

Figure O-5 Mix3–Specimen #4
(DF = 57.94, Fresh Air = 6.5%, Hardened Entrained Air = 4.06%)

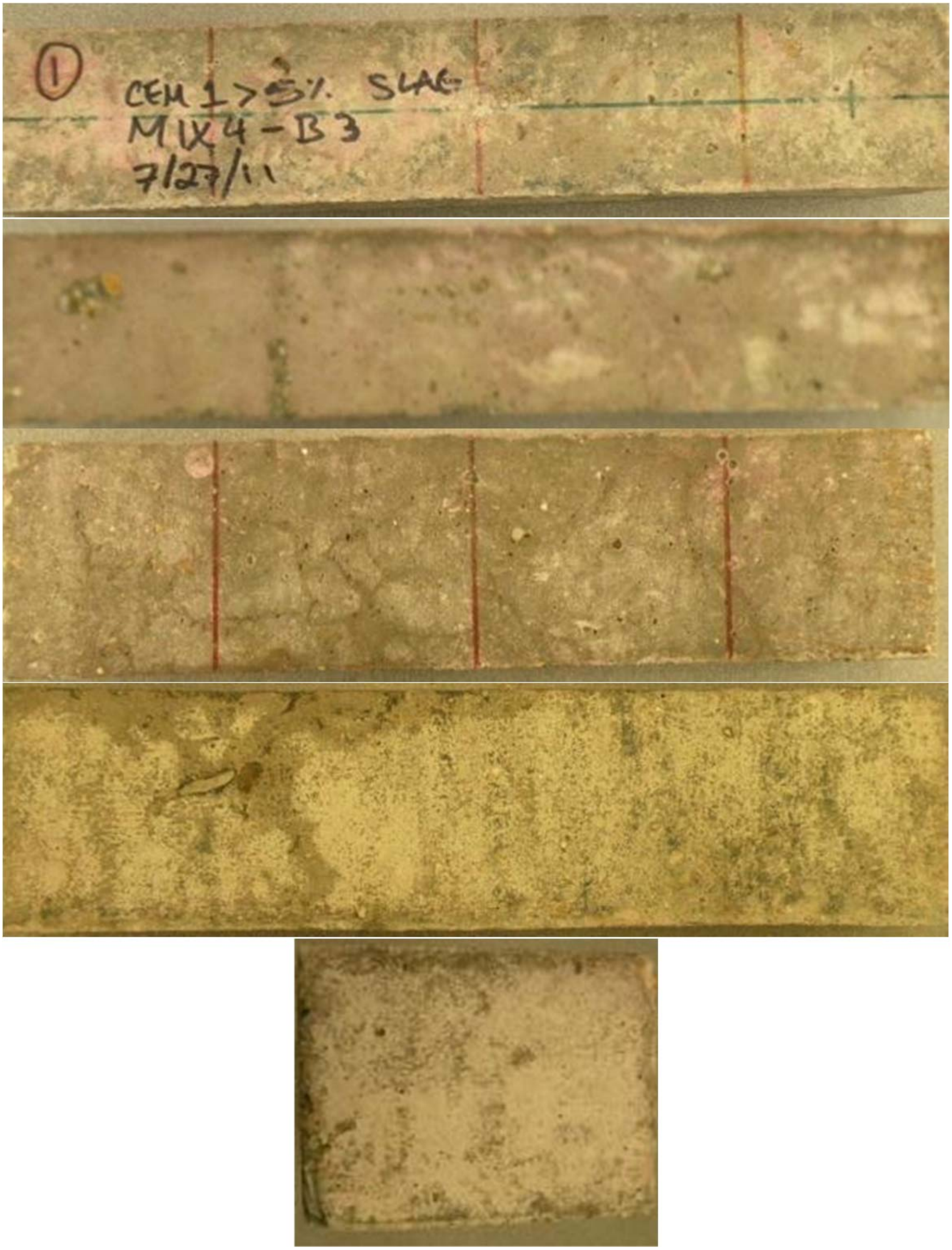

Figure O-6 Mix 4–Specimen #1
(DF = 68.53, Fresh Air = 6.5%, Hardened Entrained Air = 3.66%)

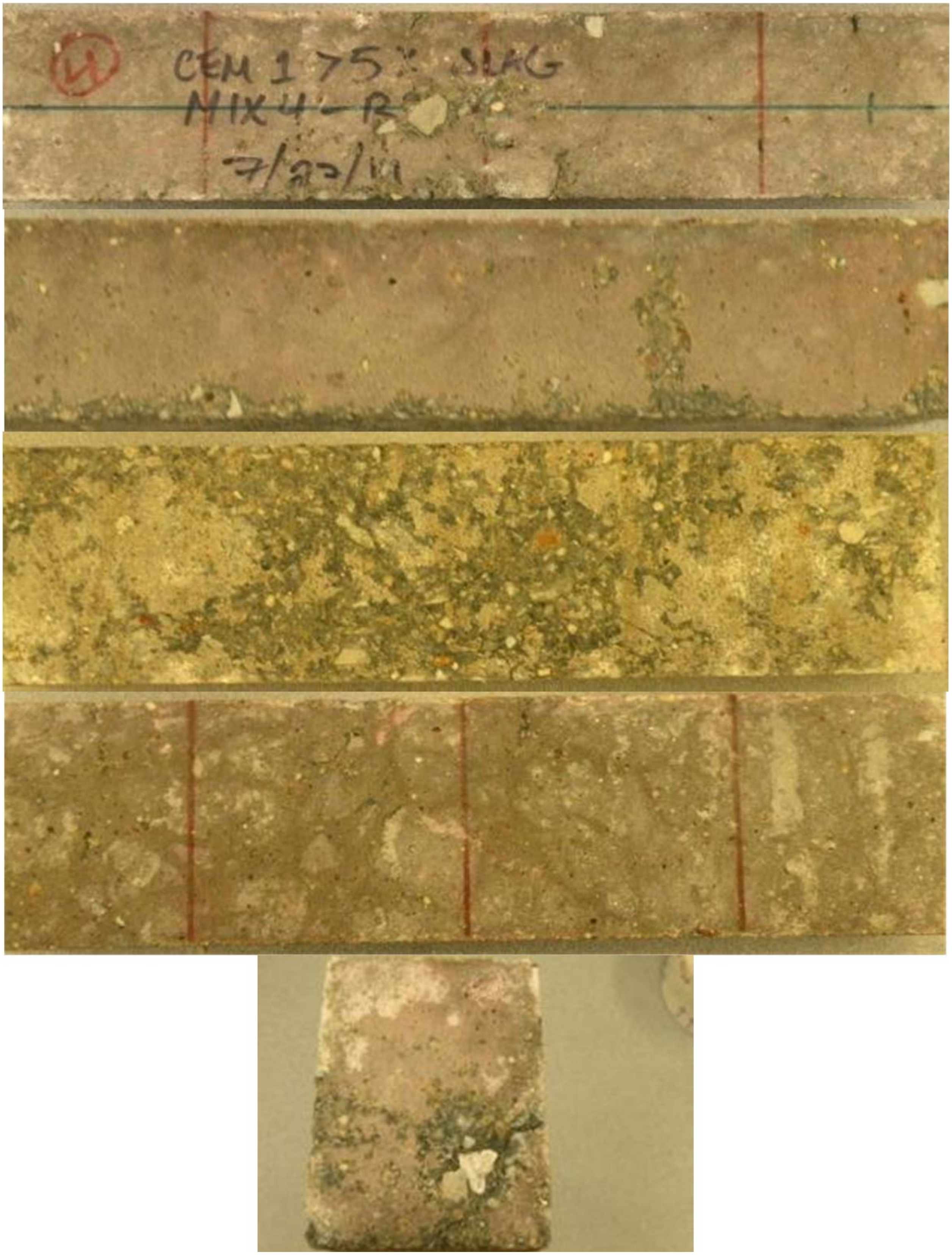

Figure O-7 Mix4–Specimen #4
(DF = 23.41, Fresh Air = 6.5%, Hardened Entrained Air = 3.66%)

Figure O-8 Mix 1R–Specimen #2
(DF = 68.89, Fresh Air = 7.8%, Hardened Entrained Air = 8.04%)

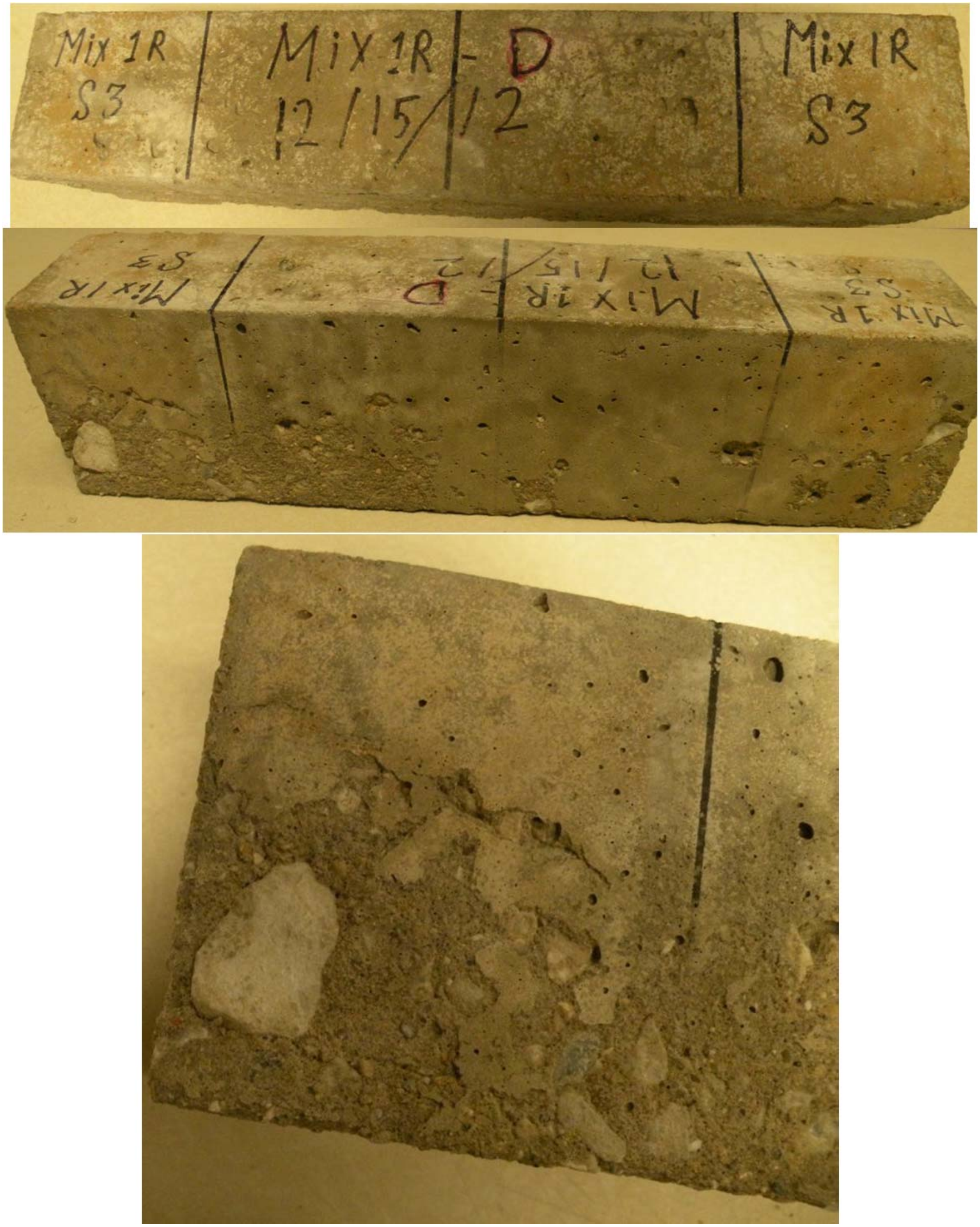

Figure O-9 Mix 1R–Specimen #3
(DF = 80.22, Fresh Air = 7.8%, Hardened Entrained Air = 8.04%)

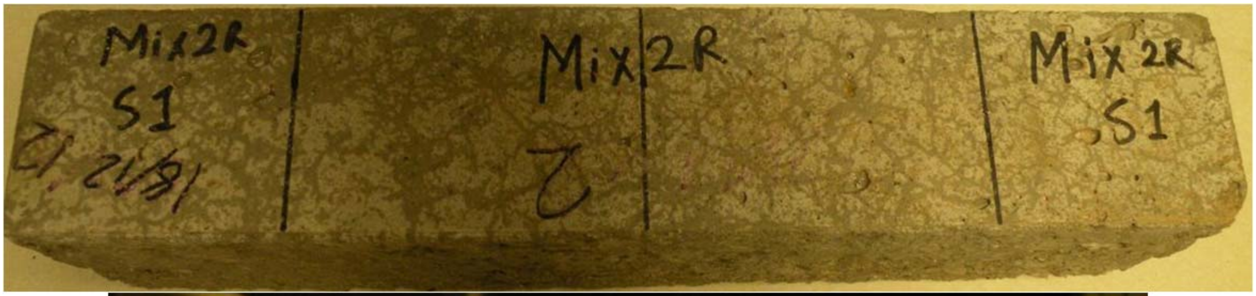

Figure O-10 Mix 2R–Specimen #1
(DF = 89.75, Fresh Air = 7.5%, Hardened Entrained Air = 7.26%)

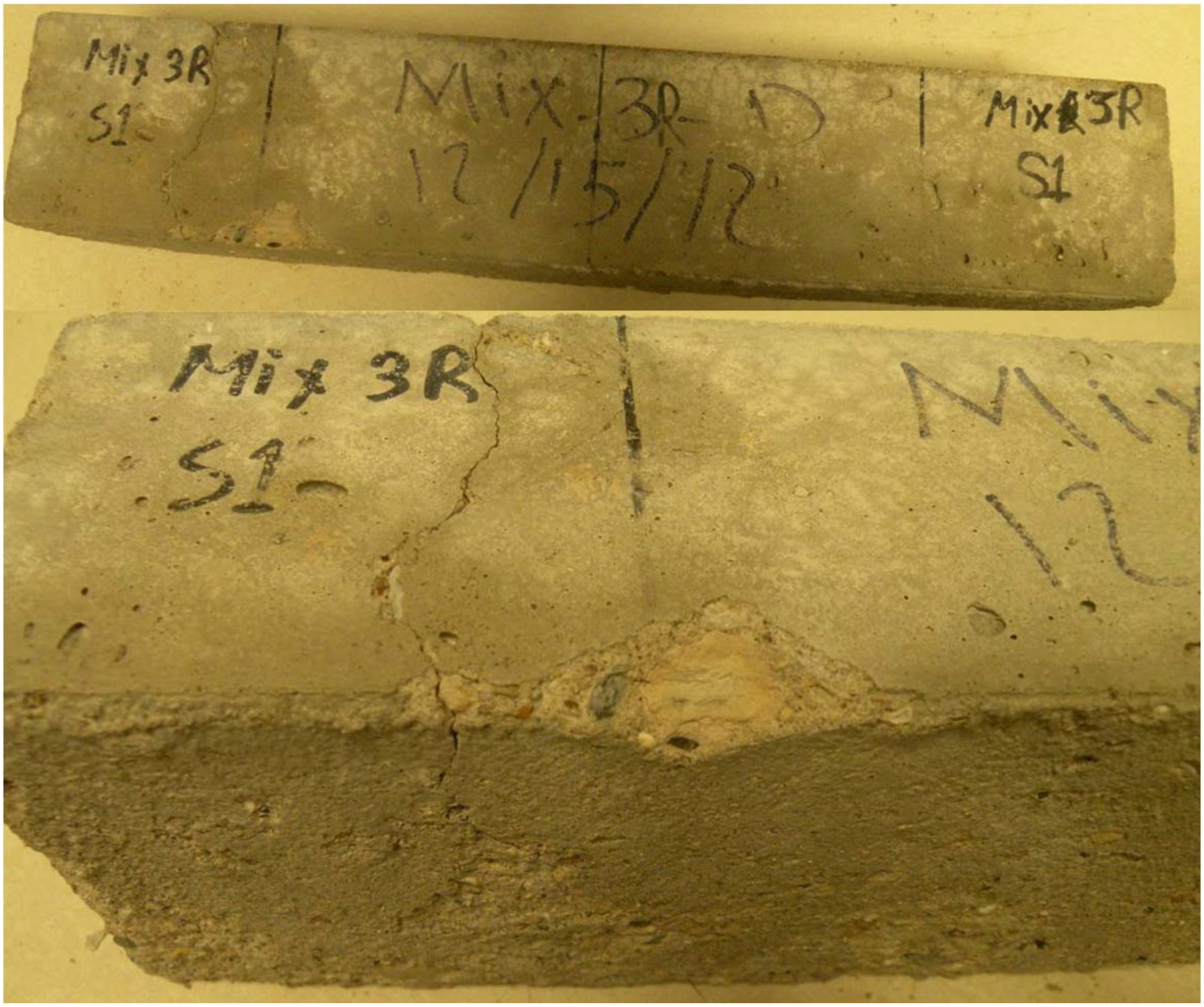

Figure O-11 Mix 3R–Specimen #1
(DF = N/A, Fresh Air = 7.5%, Hardened Entrained Air = 7.47%)

Figure O-12 Mix 3R–Specimen #4
(DF = 85.21, Fresh Air = 7.5%, Hardened Entrained Air = 7.47%)

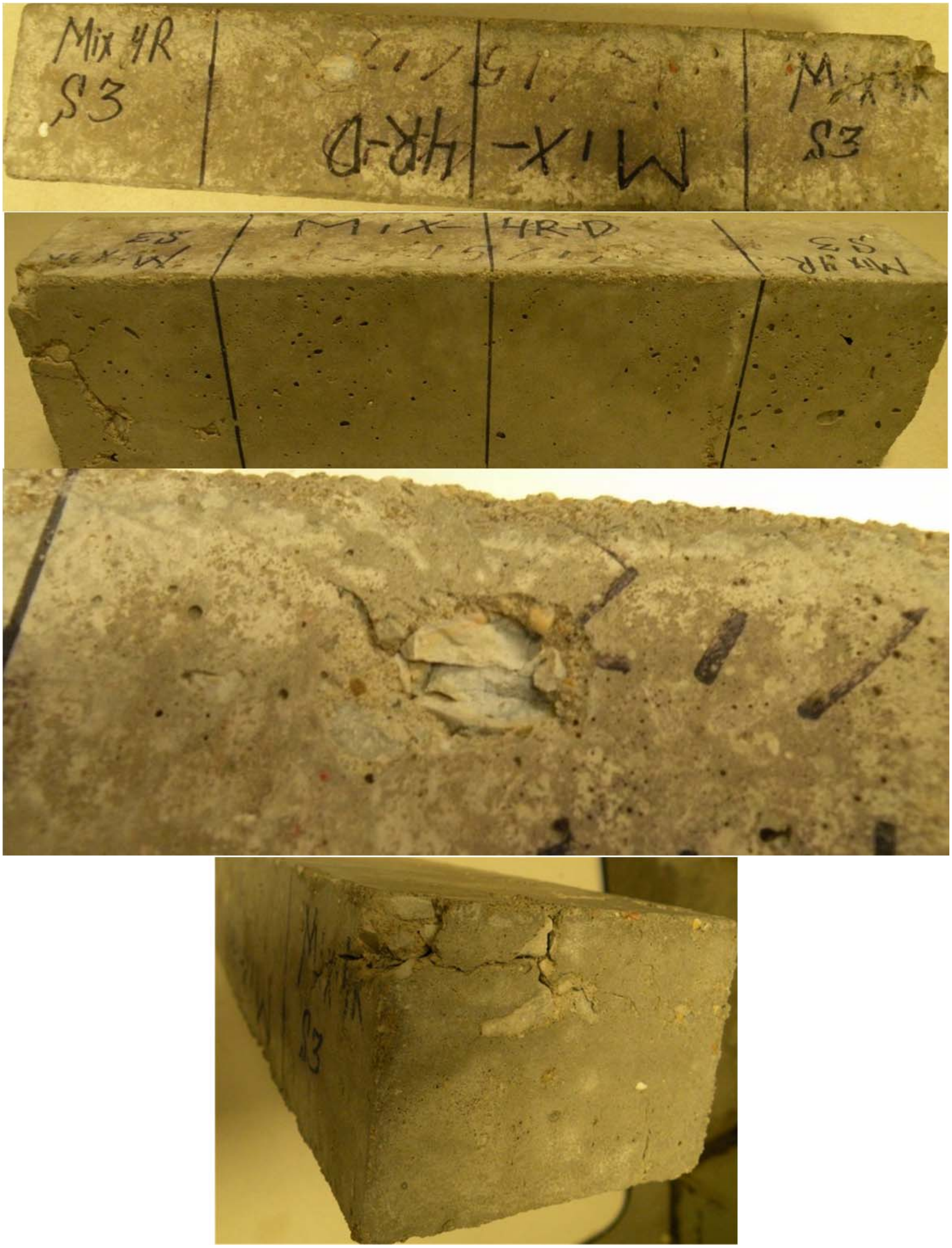

Figure O-13 Mix 4R–Specimen #3
(DF = 68.06, Fresh Air = 7.3%, Hardened Entrained Air = 7.92%)

Figure O-14 Mix 5–Specimen #2
(DF = 94.85, Fresh Air = 7.9%, Hardened Entrained Air = 6.09%)

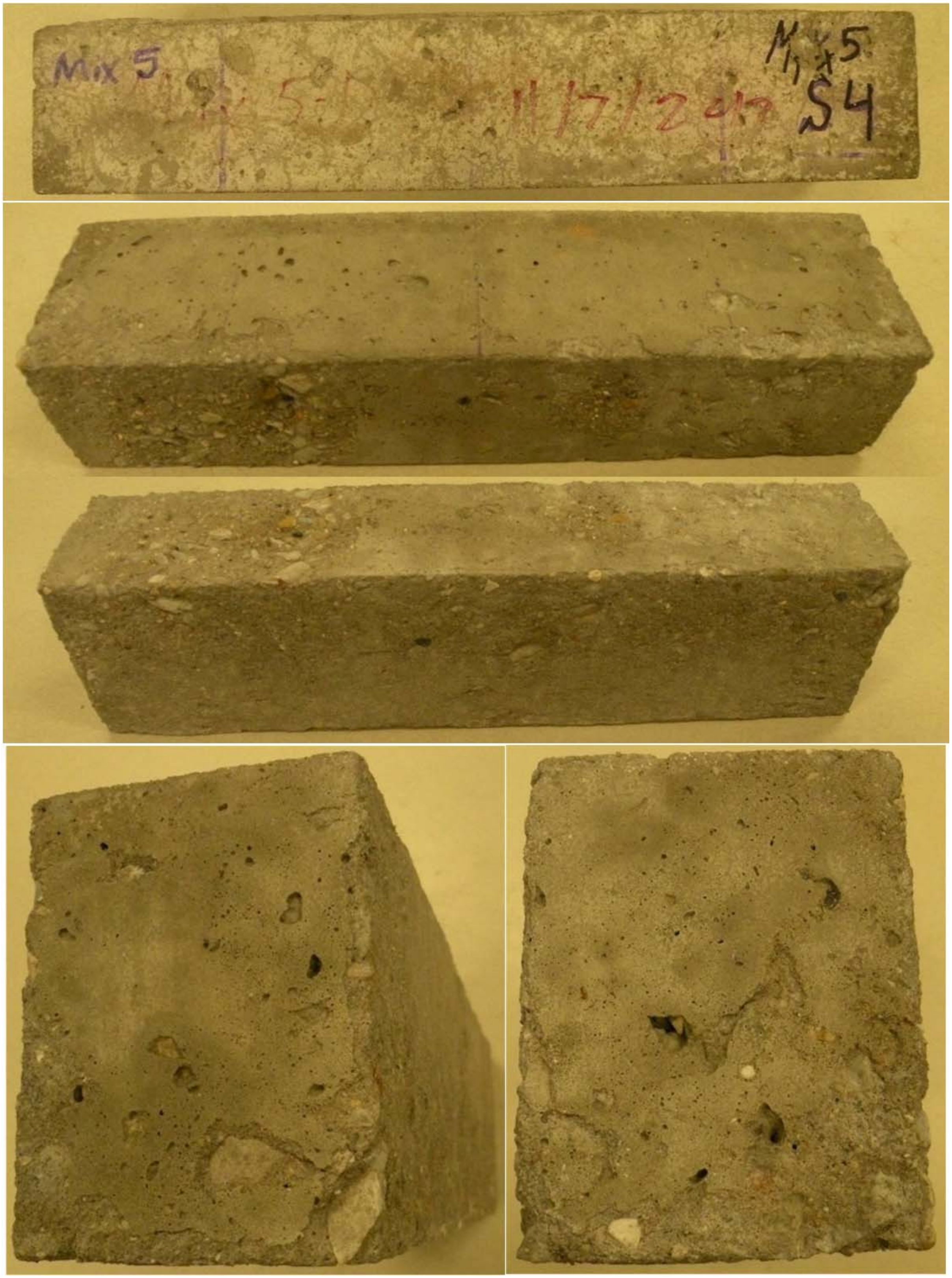

Figure O-15 Mix 5–Specimen #4
(DF= 94.76, Fresh Air = 7.9%, Hardened Entrained Air = 6.09%)

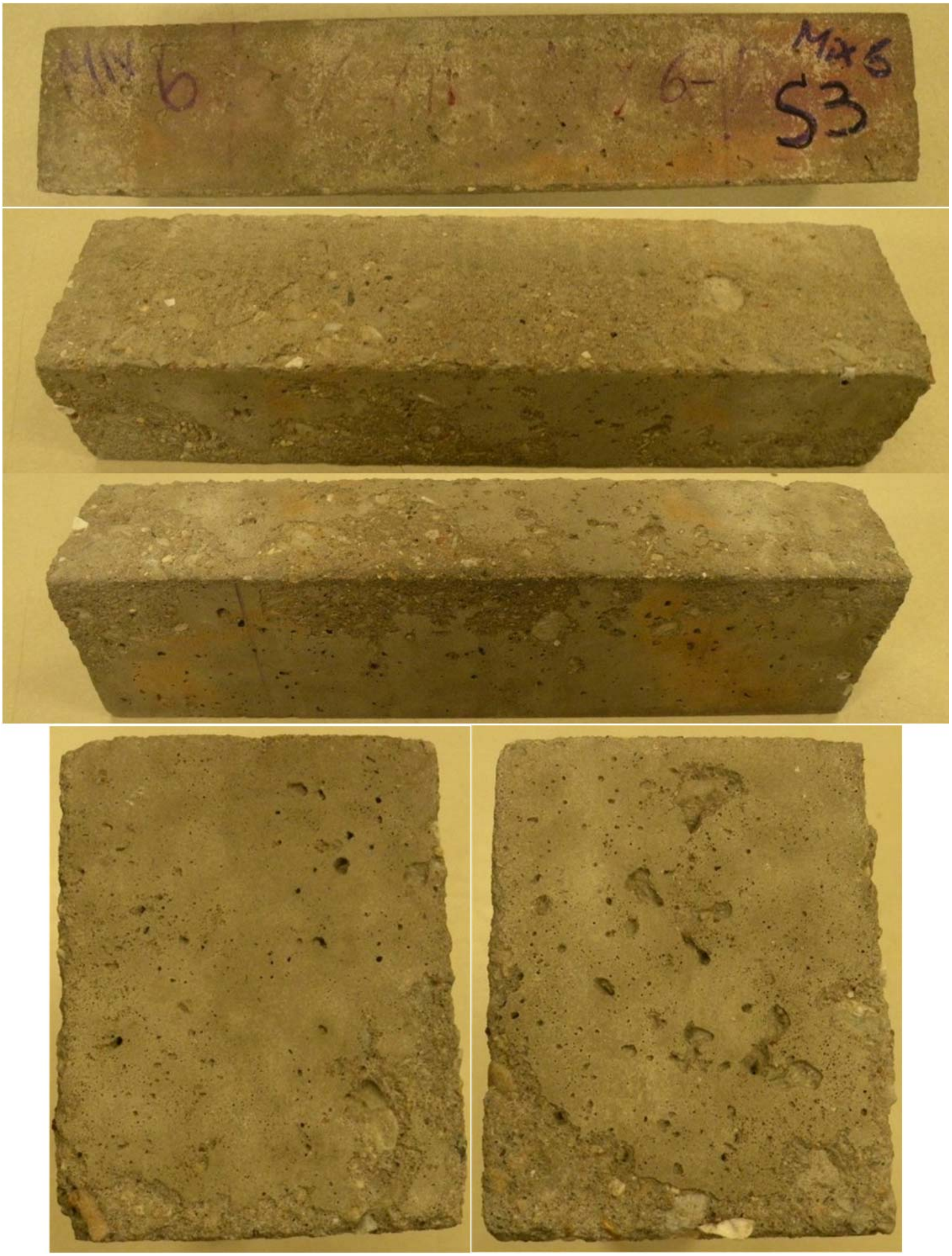

Figure O-16 Mix 6–Specimen #3
(DF = 96.49, Fresh Air = 8.1%, Hardened Entrained Air = 6.91%)

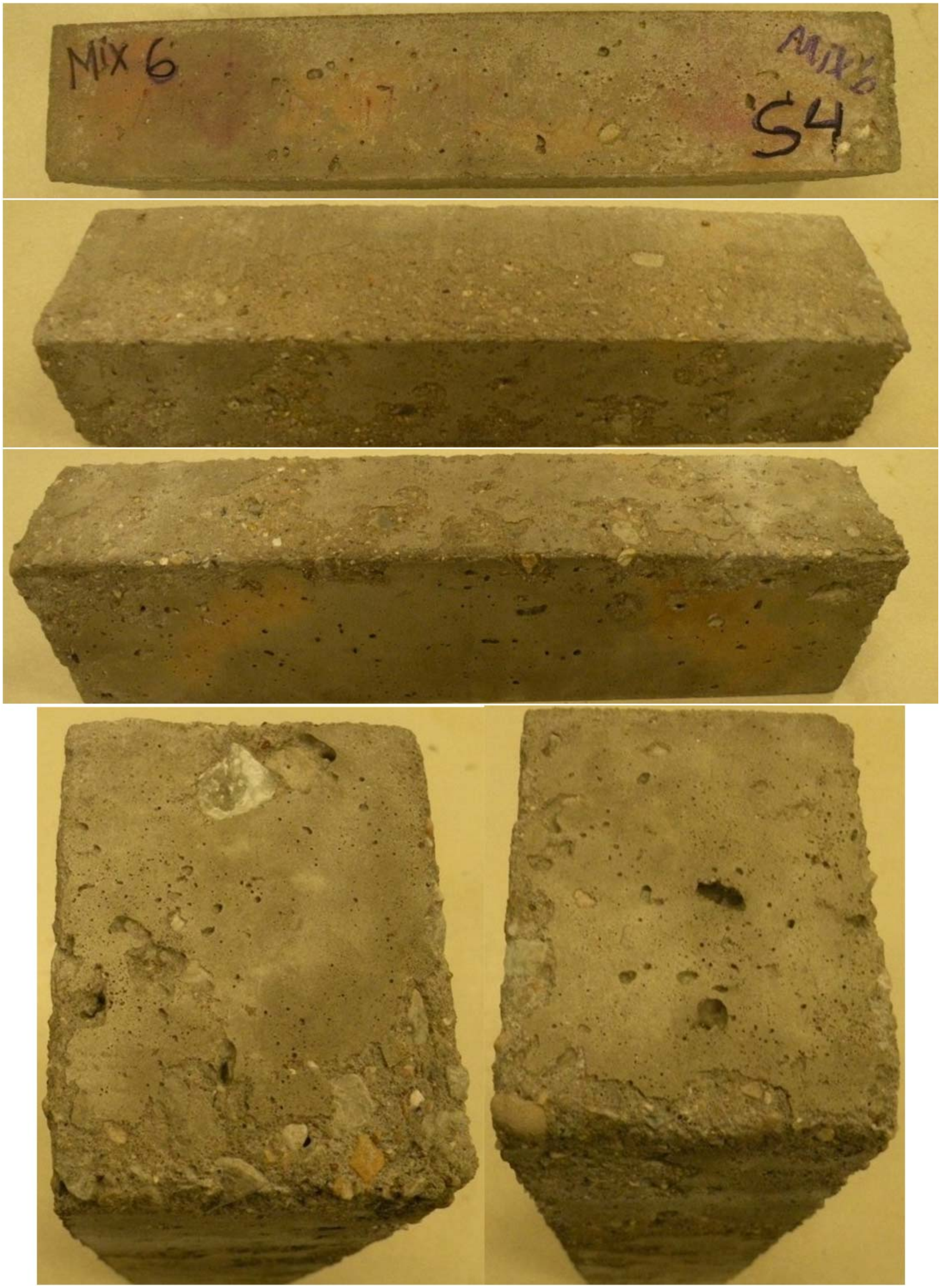

Figure O-17 Mix 6–Specimen #4
(DF= 96.49, Fresh Air = 8.1%, Hardened Entrained Air = 6.91%)

Figure O-18 Mix 7–Specimen #1
(DF= 91.49, Fresh Air = 8.0%, Hardened Entrained Air = 7.13%)

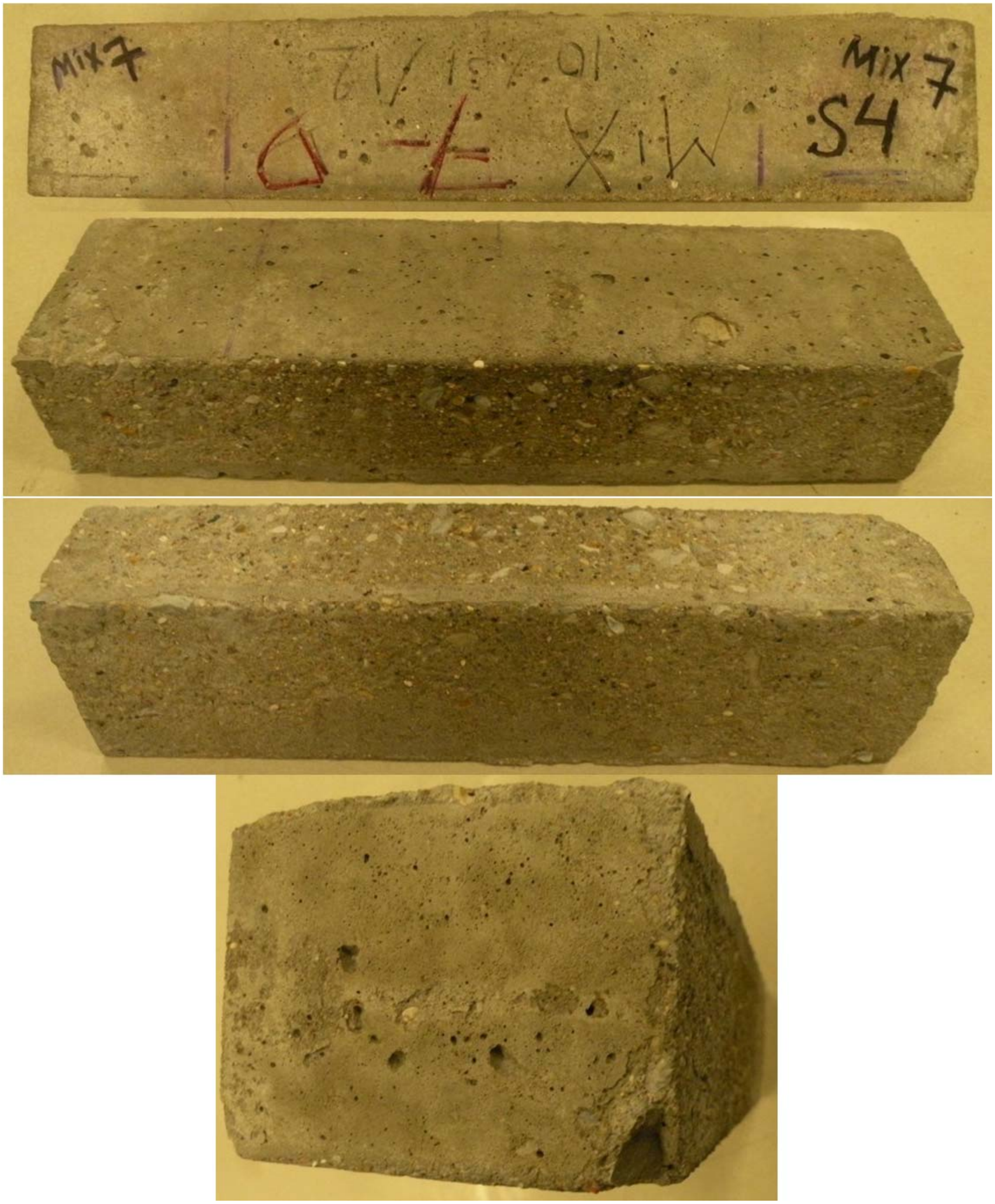

Figure O-19 Mix 7–Specimen #4
(DF = 93.16, Fresh Air = 8.0%, Hardened Entrained Air = 7.13%)

Figure O-20 Mix 8–Specimen #1
(DF = 88.2, Fresh Air = 8.0%, Hardened Entrained Air = 5.9%)

Figure O-21 Mix 9–Specimen #1
(DF = 59.31, Fresh Air = 6.6%, Hardened Entrained Air = 3.76%)

Figure O-22 Mix 9–Specimen #2
(DF = 66.09, Fresh Air = 6.6%, Hardened Entrained Air = 3.76%)

Figure O-23 Mix10–Specimen #2
(DF = 33.20, Fresh Air = 6.5%, Hardened Entrained Air = 3.92%)

Figure O-24 Mix 10–Specimen #3
(DF = 50.62, Fresh Air = 6.5%, Hardened Entrained Air = 3.92%)

Figure O-25 Mix 11–Specimen #4
(DF = 87.04, Fresh Air = 6.6%, Hardened Entrained Air = 3.90%)

Figure O-26 Mix12–Specimen #3
(DF = 39.33, Fresh Air = 6.3%, Hardened Entrained Air = 3.72%)

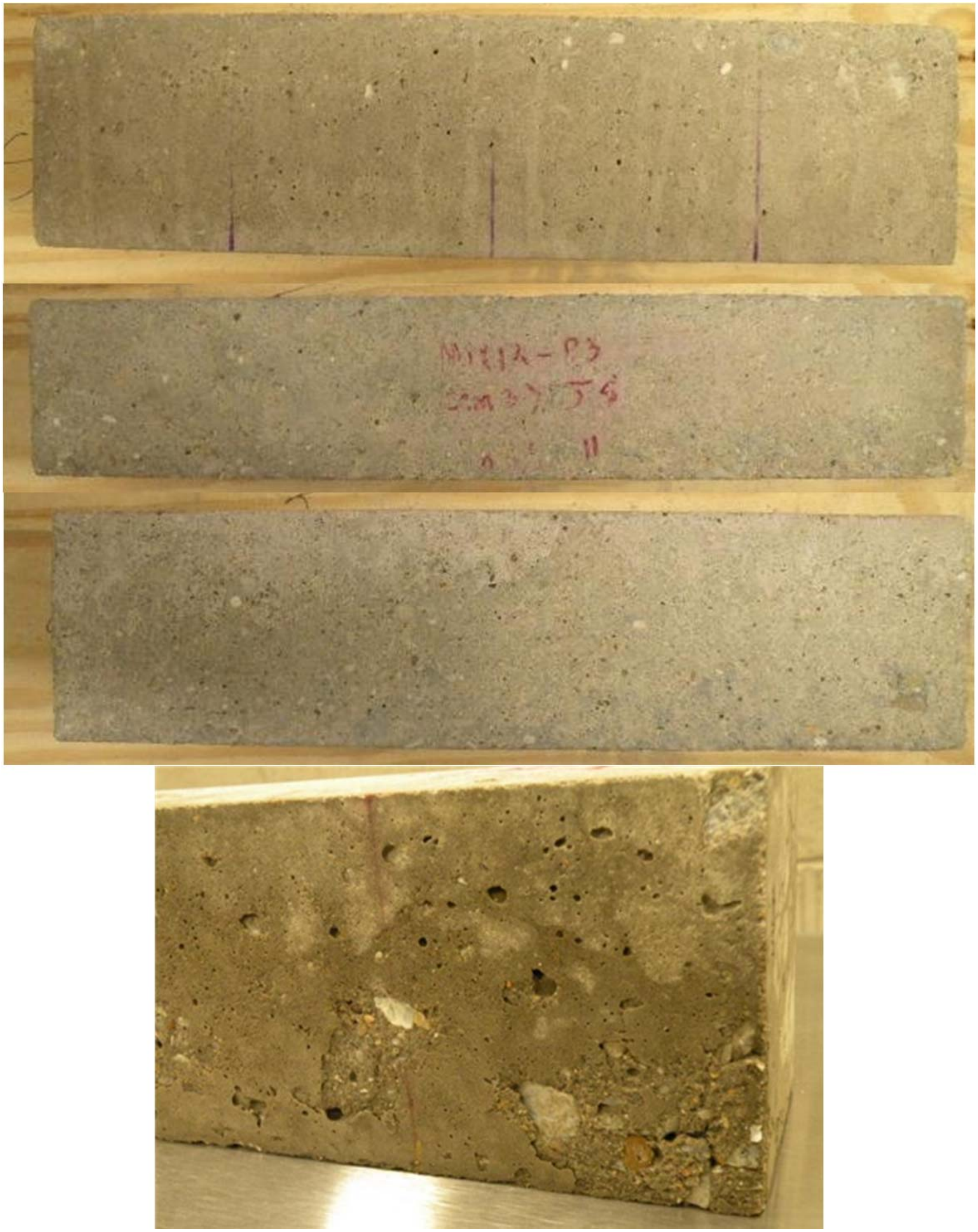

Figure O-27 Mix 12–Specimen #4
(DF = 84.31, Fresh Air = 6.3%, Hardened Entrained Air = 3.72%)

Figure O-28 Mix 9R–Specimen #2
(DF = 43.69, Fresh Air = 8%, Hardened Entrained Air = 5.29%)

Figure O-29 Mix 9R–Specimen #4
(DF = 48.29, Fresh Air = 8%, Hardened Entrained Air = 5.29%)

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Figure O-29 (continued) Mix 9R–Specimen #4
(DF = 48.29, Fresh Air = 8%, Hardened Entrained Air = 5.29%)

Figure O-30 Mix 10R–Specimen #1
(DF = 90.56, Fresh Air = 7.5%, Hardened Entrained Air = 4.5%)

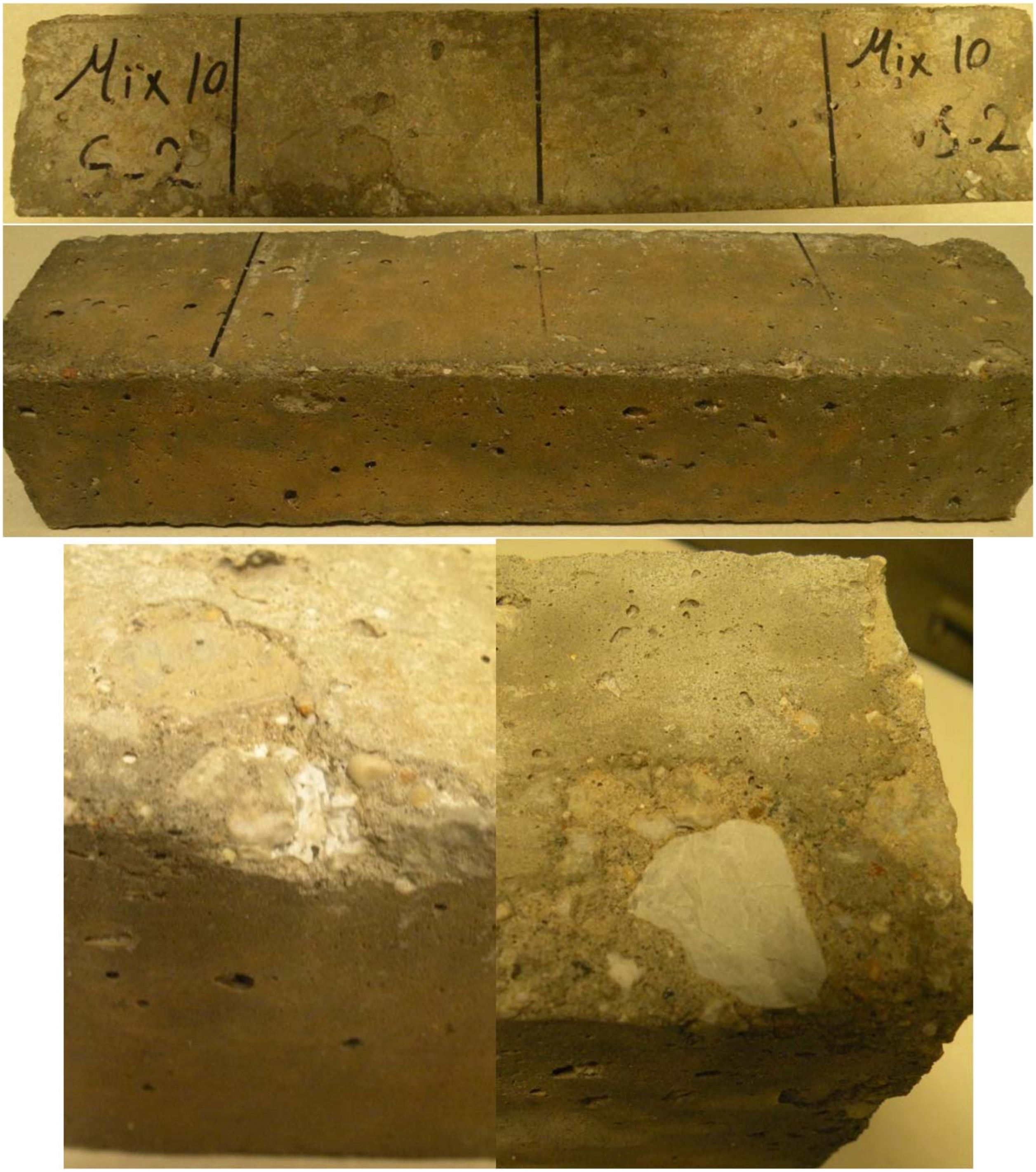

Figure O-31 Mix 10R–Specimen #2
(DF = 85.56, Fresh Air = 7.5%, Hardened Entrained Air = 4.5%)

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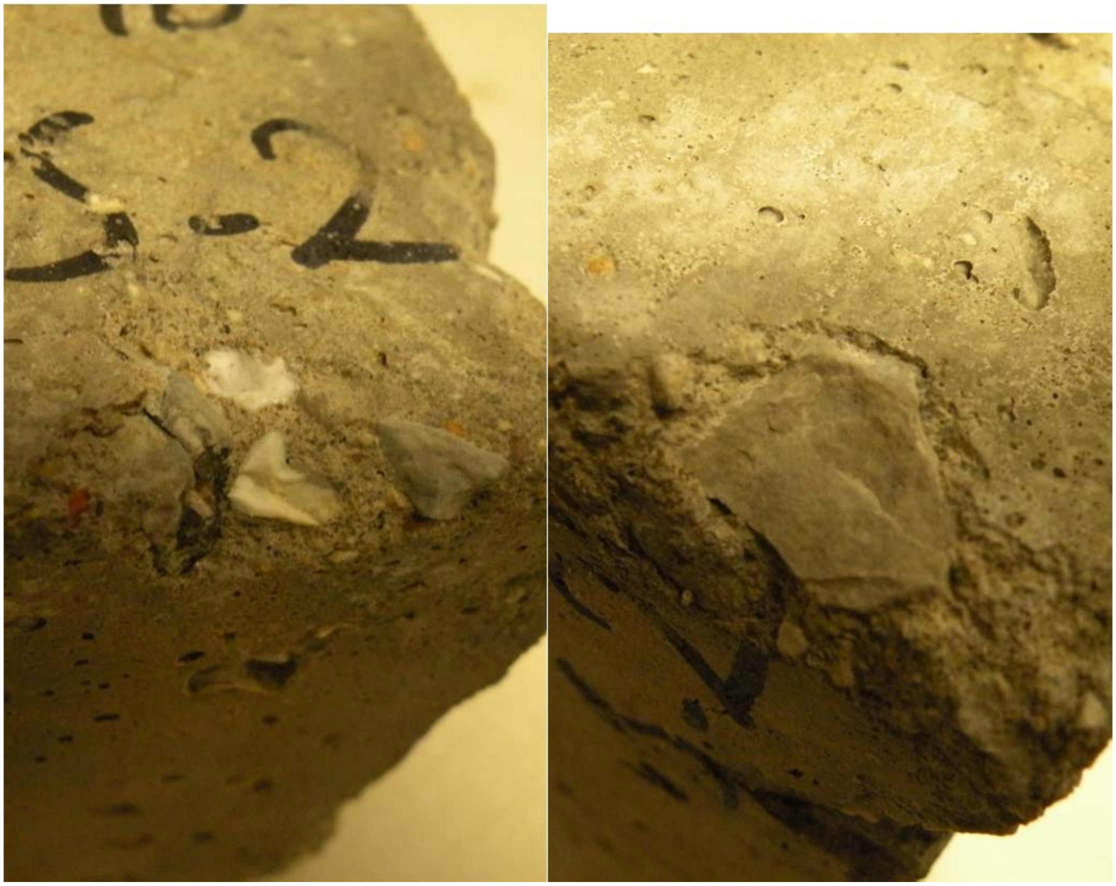

Figure O-31 (continued) Mix 10R–Specimen #2
(DF = 85.56, Fresh Air = 7.5%, Hardened Entrained Air = 4.5%)

Figure O-32 Mix 11R–Specimen #2
(DF = 62.12, Fresh Air = 8.1%, Hardened Entrained Air = 7.17%)

(figure continues, next page)

Figure O-32 (continued) Mix 11R–Specimen #2
(DF = 62.12, Fresh Air = 8.1%, Hardened Entrained Air = 7.17%)

Figure O-33 Mix 12R–Specimen #3
(DF = 74.07, Fresh Air = 8%, Hardened Entrained Air = 5.75%)

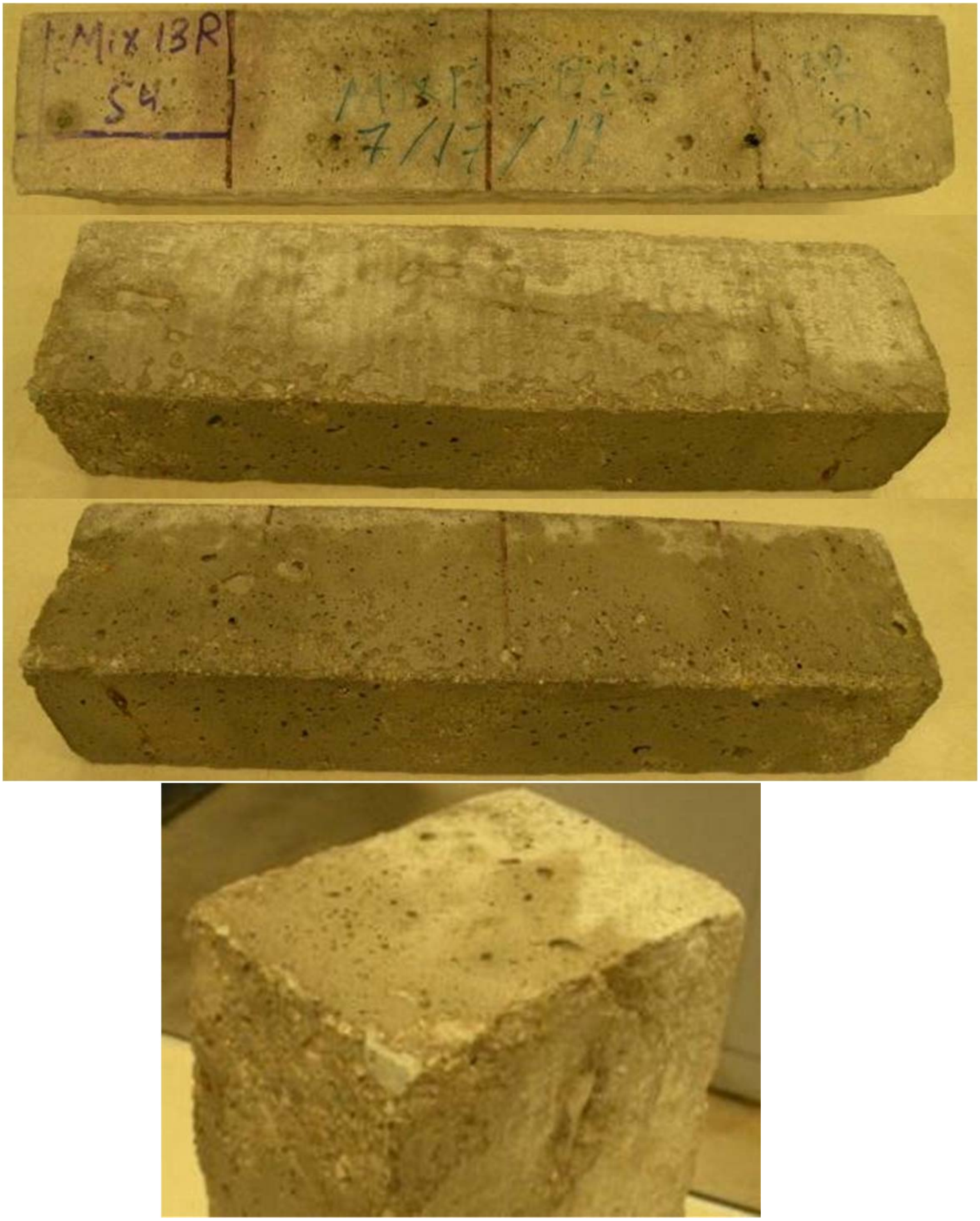

Figure O-34 Mix 13R–Specimen #4
(DF = 89.28, Fresh Air = 8%, Hardened Entrained Air = 9.08%)

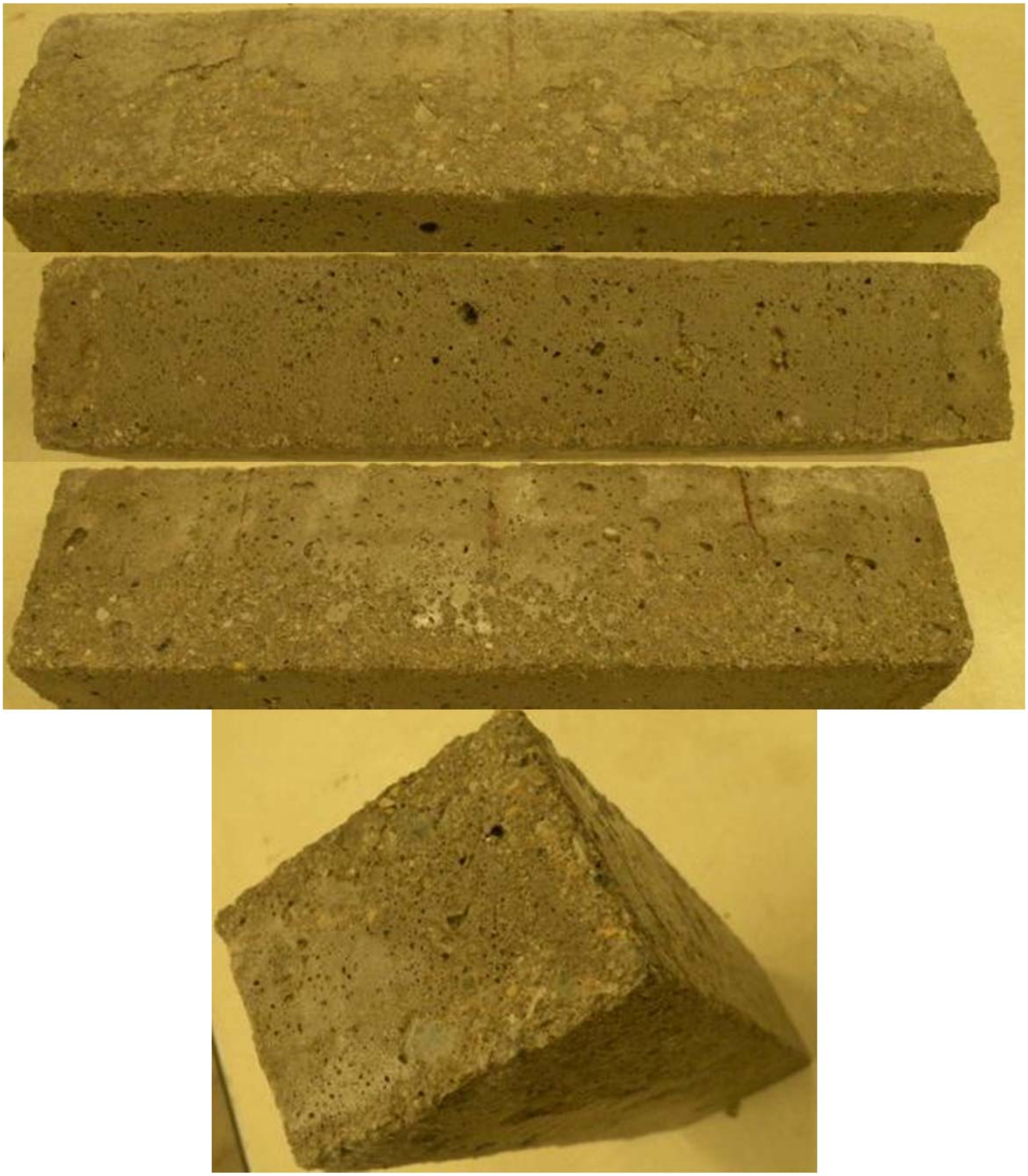

Figure O-35 Mix 14–Specimen #4
(DF = 90.74, Fresh Air = 7.4%, Hardened Entrained Air = 5.99%)

Figure O-36 Mix 15–Specimen #1
(DF = 45.59, Fresh Air = 8.1%, Hardened Entrained Air = 4.34%)

Figure O-37 Mix 16–Specimen #1
(DF = 77.47, Fresh Air = 6.9%, Hardened Entrained Air = 4.99%)

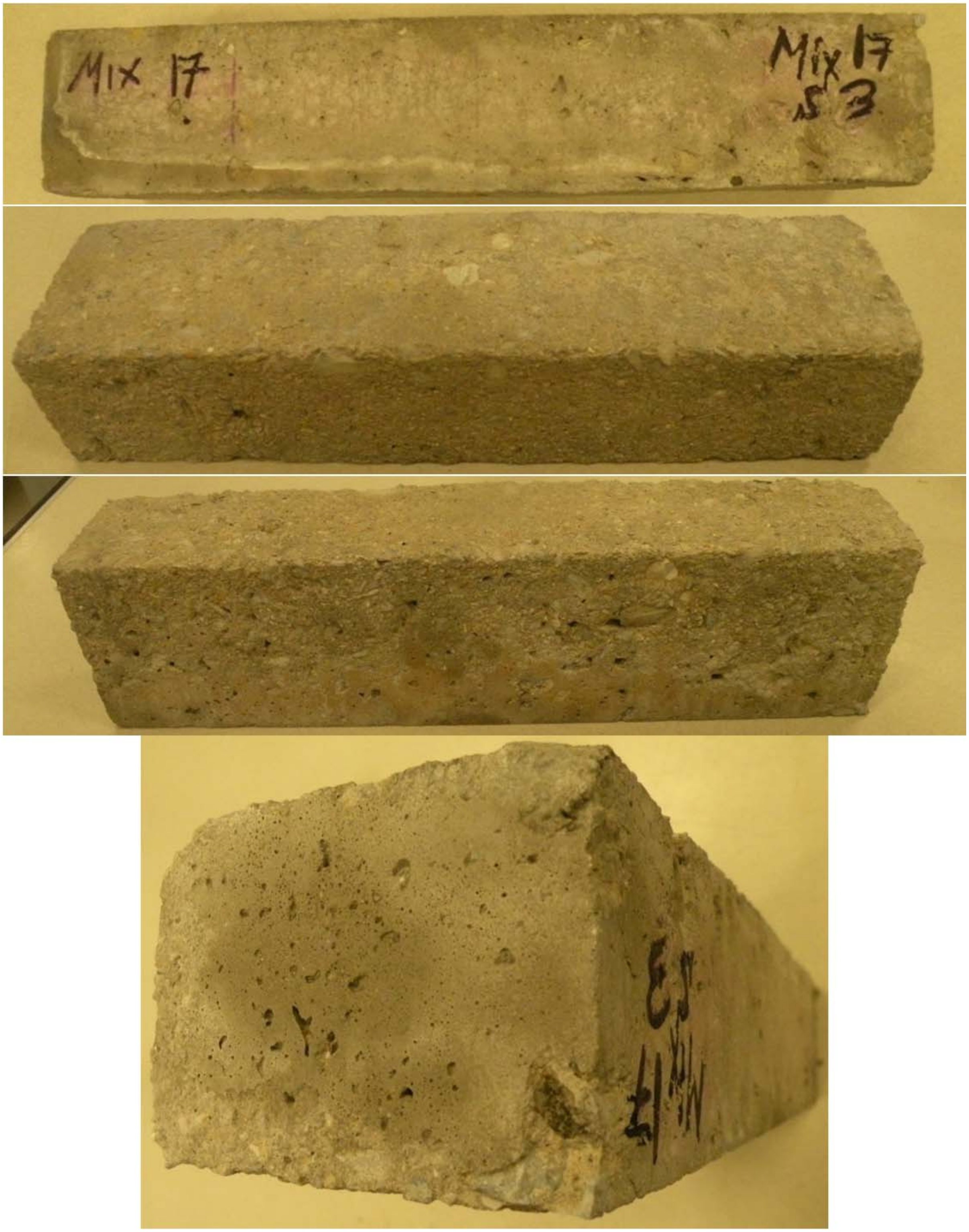

Figure O-38 Mix 17–Specimen #3
(DF = 92.92, Fresh Air = 7.9%, Hardened Entrained Air = 5.95%)

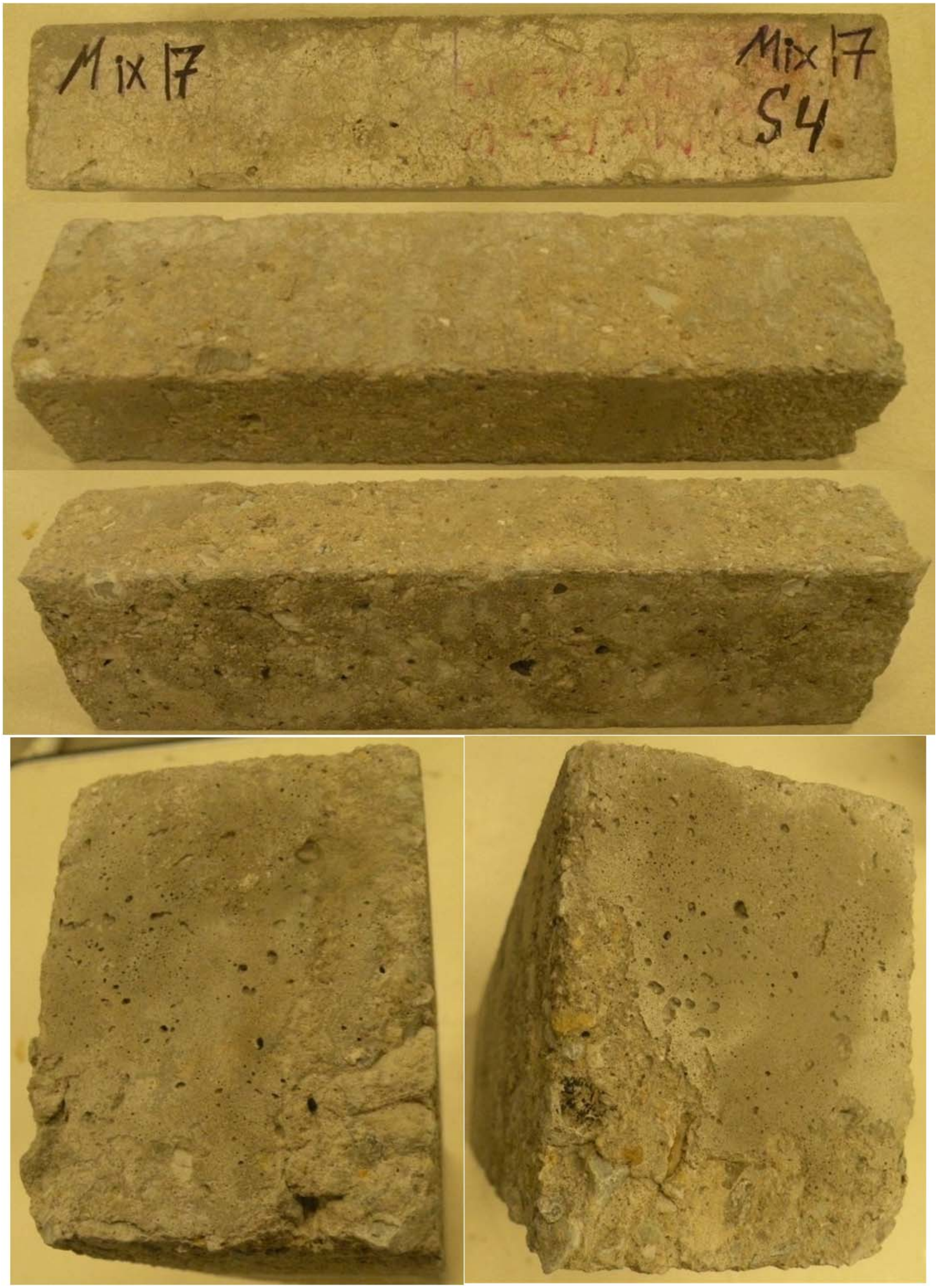

Figure O-39 Mix 17–Specimen #4
(DF= 92.86, Fresh Air = 7.9%, Hardened Entrained Air = 5.95%)

Figure O-40 Mix 18–Specimen #1
(DF = 94.67, Fresh Air = 8.0%, Hardened Entrained Air = 5.8%)

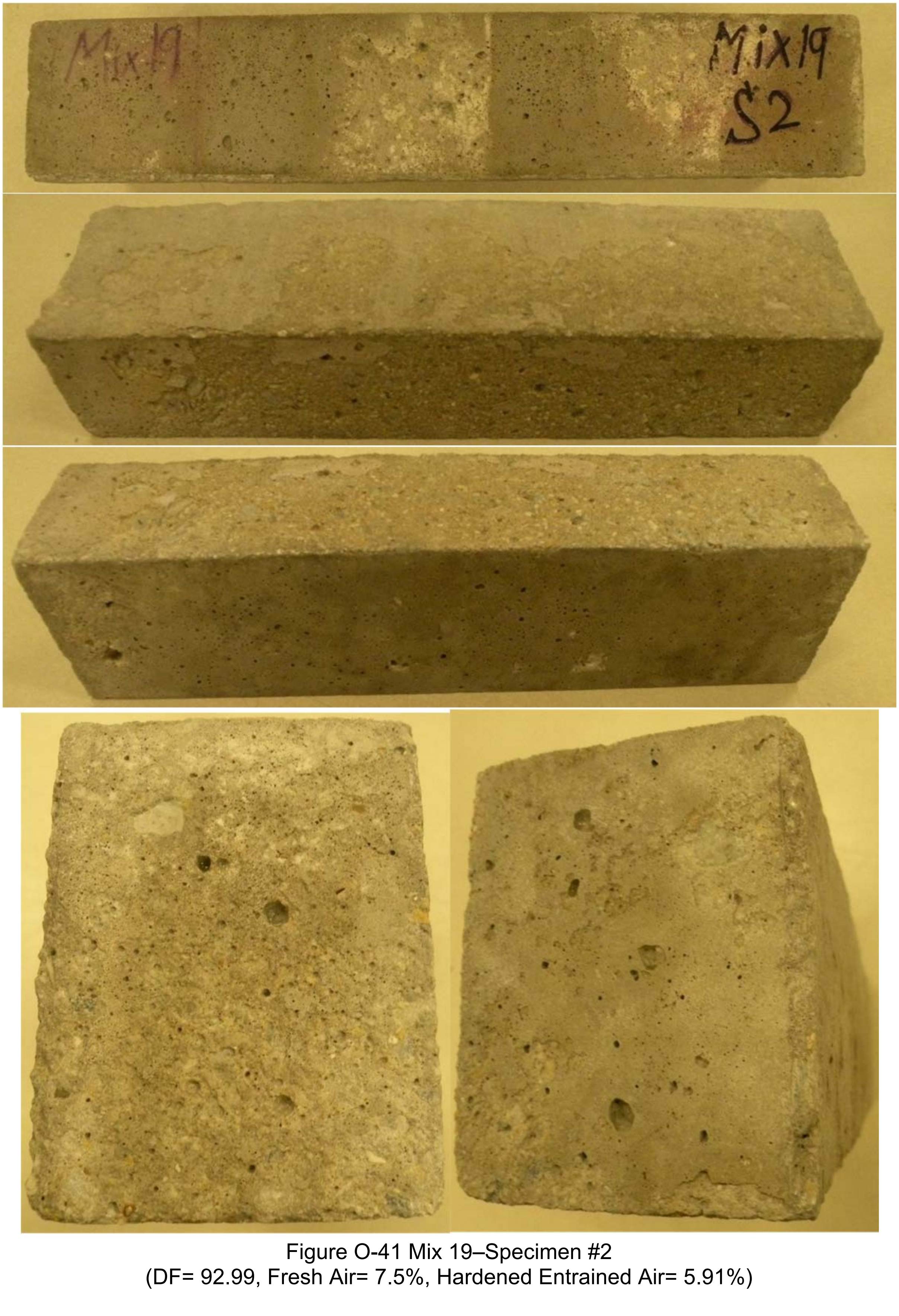

Figure O-41 Mix 19–Specimen #2
(DF= 92.99, Fresh Air= 7.5%, Hardened Entrained Air= 5.91%)

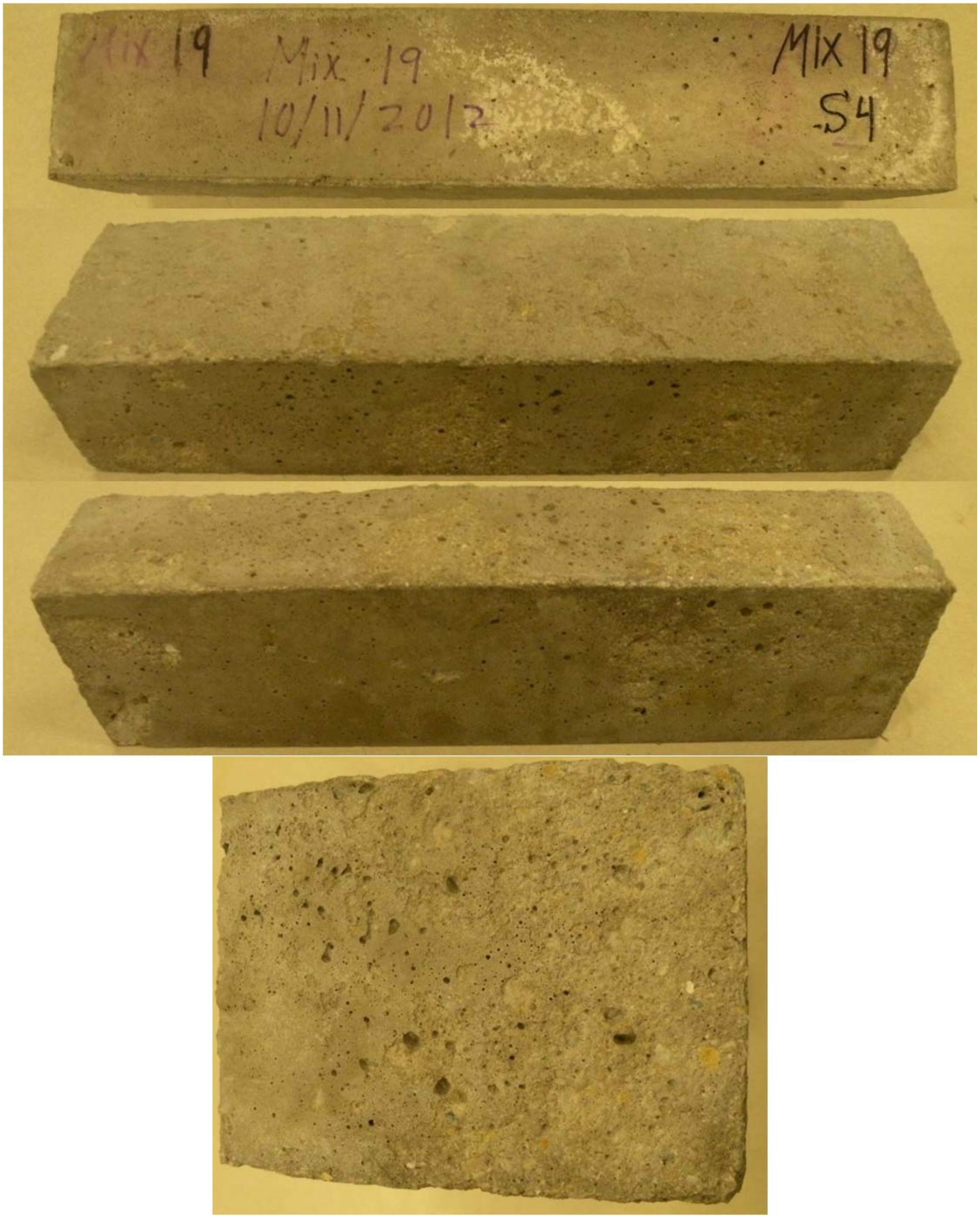

Figure O-42 Mix 19–Specimen #4
(DF = 94.71, Fresh Air = 7.5%, Hardened Entrained Air = 5.91%)

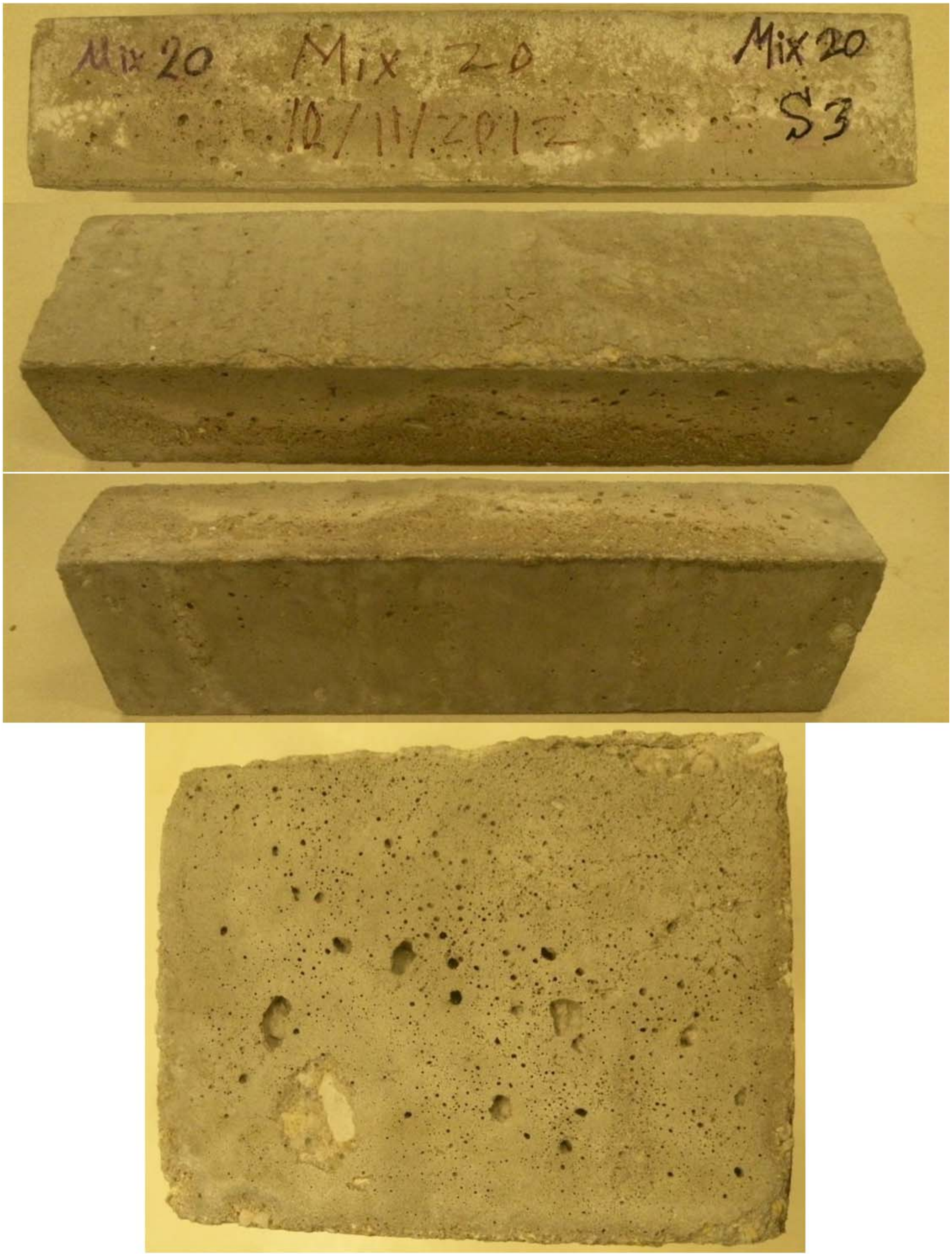

Figure O-43 Mix20–Specimen #3
(DF= 94.71, Fresh Air = 7.8%, Hardened Entrained Air = 6.05%)

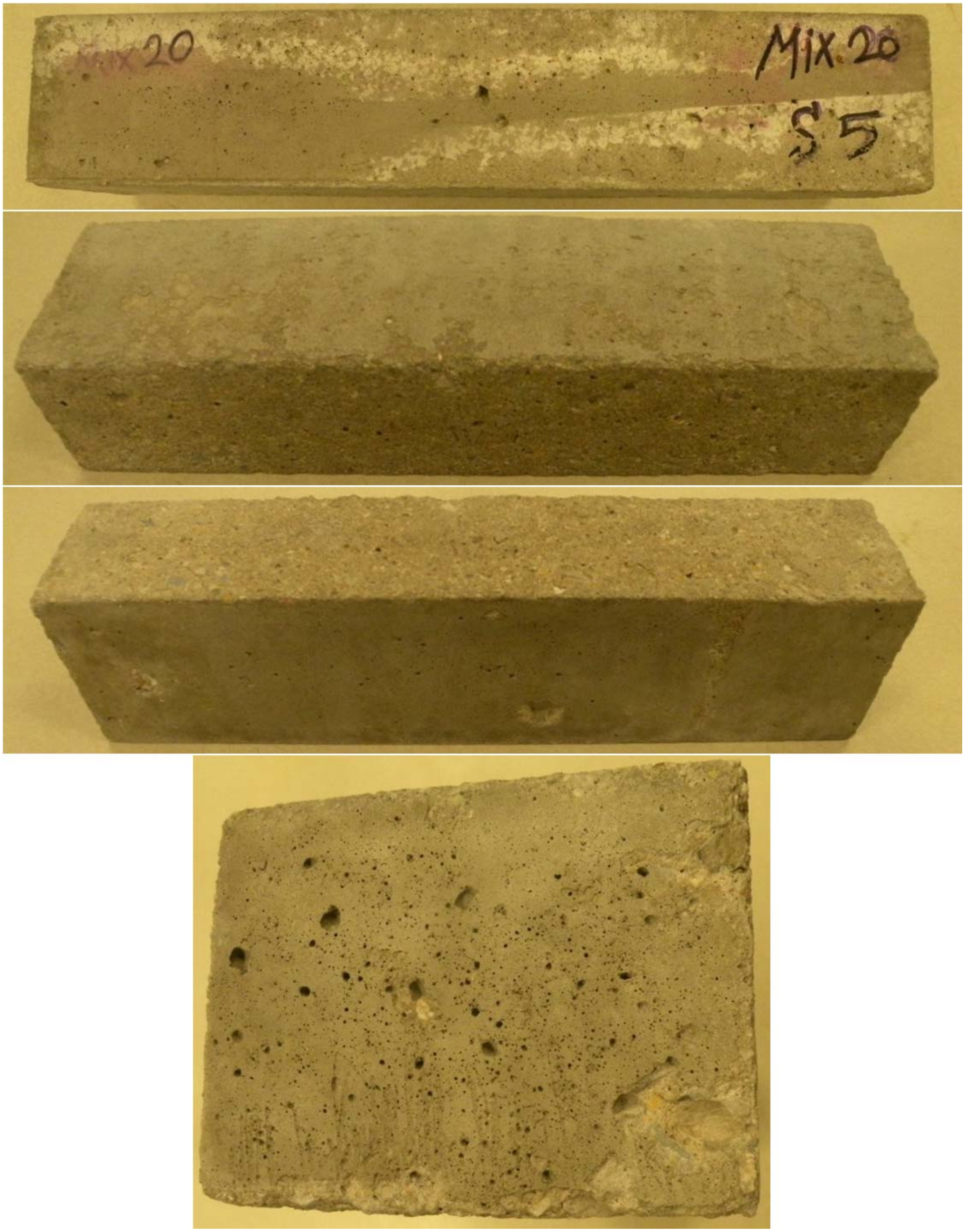

Figure O-44 Mix 20–Specimen #5
(DF = 94.71, Fresh Air = 7.8%, Hardened Entrained Air = 6.05%)

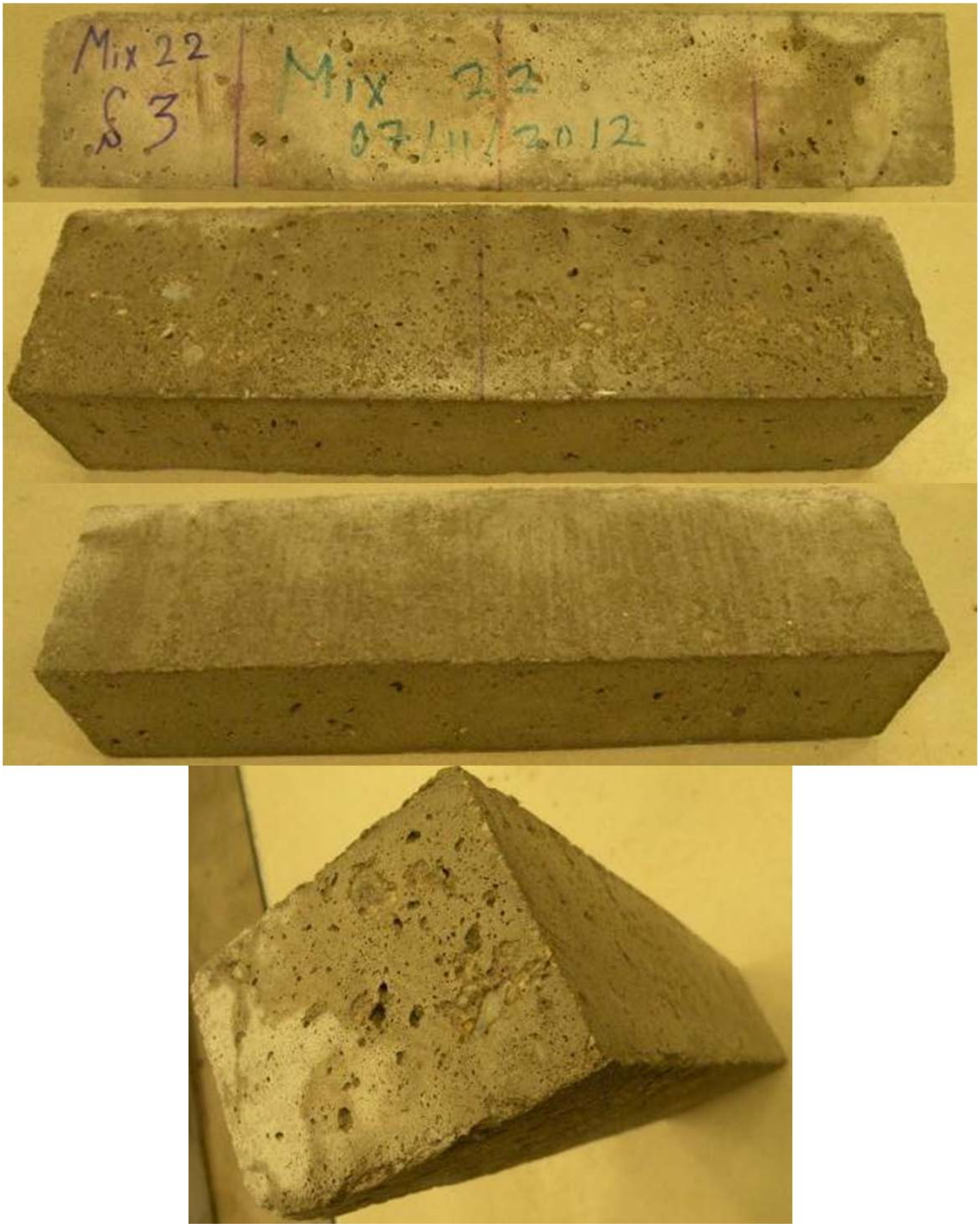

Figure O-45 Mix 22–Specimen #3
(DF = 89.66, Fresh Air = 7.2%, Hardened Entrained Air = 6.46%)

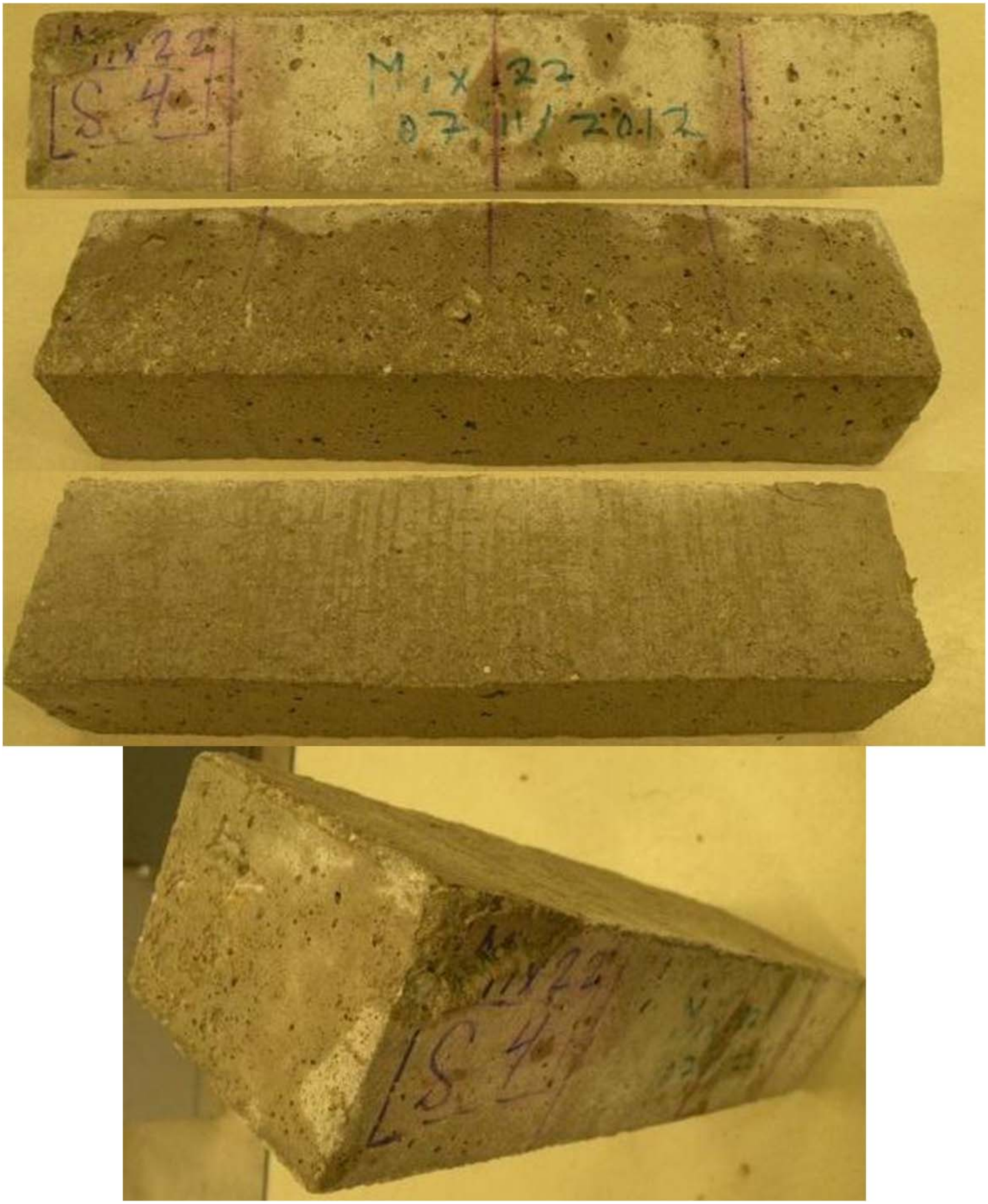

Figure O-46 Mix 22–Specimen #4
(DF= 89.39%, Fresh Air= 7.2% Hardened Entrained Air= 6.46%)

Figure O-47 Mix 23–Specimen #1
(DF = 78.45, Fresh Air = 7.8%, Hardened Entrained Air = 6.21%)

Figure O-48 Mix 23–Specimen #3
(DF = 24.06, Fresh Air = 7.8%, Hardened Entrained Air = 6.21%)

Figure O-49 Mix 24–Specimen #1
(DF = 91.35, Fresh Air = 7.3%, Hardened Entrained Air = 5.92%)

Figure O-50 Mix 24–Specimen #5
(DF = 76.37, Fresh Air = 7.3%, Hardened Entrained Air = 5.92%)

APPENDIX P EFFECT OF CHEMICAL ADMIXTURES ON AIR CONTENT STABILITY OF CONCRETE

Table A-38 Air Content, Slump, and Strength Results for Concrete Mixes with Combined Sand and Fly Ash (Cem1 < 5%)

Mix Type	w/cm Ratio	Water Reducer WRDA 82	Water Reducer ADVA Cast 575	Air Entr. Daravair 1400	Slump, in 0 min	Slump, in 12 min	Initial Time (min)	Initial %	Final Time (min)	Final %	Rate of Air Loss %/min	3 Day	7 Day	14 Day
		Amount (fl. oz/cwt)					Percentage of Air					Strength, psi		
Mix-CF-44-1	0.44	2.98	2.55	1.28	3.75	2.5*	0	10.5	45	7.2	0.073	2575	na	na
Mix-CF-44-2	0.44	3.5	1.7	1.7	na	na	12	14	45	13	0.030	1013.5	1491	1888
Mix-CF-42-3	0.42	3.5	0	1.28	2.25	na	0	9	45	7	0.044	2130	3160	3380
Mix-CF-42-4	0.42	3.5	1.7	1.44	4	3	5	11	45	8.5	0.063	1686.5	2610	2990
Mix-CF-42-5	0.42	3.5	1.7	1.28	2.75	na	12	10.5	45	8.5	0.061	1581	2430	3020
Mix-CF-42-6	0.42	3.5	1.7	1.02	2.75	na	12	10.75	45	9	0.053	1374	1751	2580
Mix-CF-42-8	0.42	3	1.27	1.02	3.75	na	12	9.5	45	8.25	0.038	1777.5	2680	3330
Mix-CF-42-9	0.42	2.13	2.13	1.28	3.5	2.75	12	7.6	45	5.1	0.076	2780	4130	4680
Mix-CF-42-11	0.42	2.55	1.28	1.28	3.6	na	12	10	45	8.5	0.045	1560	2390	2840
Mix-CF-42-12	0.42	2.38	1.7	1.28	3.6	2.25	12	9.5	45	7.6	0.058	2060	2820	3340
Mix-CF-42-13	0.42	2.13	1.7	1.28	3.6	2.65	12	9.6	45	7.5	0.064	2050	2930	3410
Mix-CF-42-14	0.42	1.87	1.96	1.28	3.6	2.5	12	9.25	45	6.9	0.071	2085	3050	3660
Mix-CF-42-15	0.42	1.87	1.96	1.28	2.75	na	12	7.6	45	5.9	0.052	2520	3920**	4470
Mix-CF-42-16	0.42	2.99	4.69	3.41	3	1.85	12	5.4	30	4.6	0.044	3710	5400	6810
Mix-CF-42-17	0.42	2.99	3.41	6.82	4.25	2.5	12	12.75	45	7.2	0.168	2480	3280	4510
Mix-CF-42-18	0.42	2.99	3.41	6.82	5	2.75	12	14	45	7.8	0.188	1686	2740	3740
Mix-CF-42-19	0.42	5.12	2.56	3.41	4.15	3.25	12	14.5	45	7.5	0.212	2020	2830	3240
Mix-CF-42-20	0.42	4.69	2.13	3.41	3.5	2.75	12	15.3	45	8.8	0.197	1463	2030	2500
Mix-CF-42-21	0.42	4.26	2.56	2.99	3	2	12	11.4	45	6	0.164	2480	na	na
Mix-CF-42-22	0.42	5.12	2.56	2.56	3	1.75	12	9.4	30	6.8	0.144	3030	4330	5270
Mix-CF-42-24	0.42	5.54	2.56	2.99	3.6	3	12	13.4	45	7.35	0.183	2210	3290	3760
N.G.	OK	*22 min	** 8 Day											

Table A-39 Air Content, Slump, and Strength Results for Concrete Mixes with Combined Sand and Slag (Cem1 < 5%)

Mix Type	w/cm Ratio	Water Reducer		Air Entr.	Slump, in		Percentage of Air				Rate of Air Loss %/min	Strength, psi		
		WRDA 82	ADVA Cast 575	Daravair 1400			Initial		Final					
		Amount (fl. oz/cwt)			0 min	12 min	Time (min)	%	Time (min)	%		3 Day	7 Day	14 Day
Mix-CS-44-1	0.44	2.98	0.85	1.96	2.25	na	10	9	60	8	0.020	1499	na	na
Mix-CS-44-2	0.44	2.98	1.27	2.13	2.75	na	12	11.5	65	9	0.047	1305.5	na	na
Mix-CS-44-3	0.44	2.98	1.7	1.87	4	na	0	13	50	10	0.060	1301.5	na	na
Mix-CS-44-4	0.44	2.98	1.7	1.62	2	na	45	9.75	70	8.75	0.040	1980.5	na	na
Mix-CS-44-5	0.44	2.98	1.96	1.28	2.75	na	15	9.5	45	8.75	0.025	2050	na	na
Mix-CS-44-7	0.44	3.5	2.55	1.02	3	na	0	5	12	4.45	0.046	2990	4420	5530
Mix-CS-44-8	0.44	3	3.41	1.27	3.75	na	0	4.5	12	4	0.042	2905	4550	5330
Mix-CS-44-10	0.44	3.5	3.41	1.7	2	na	0	5.5	12	5	0.042	2640	4100	5320
Mix-CS-44-11	0.44	2.98	4.26	1.7	4.25	na	0	4.5	20	3.95	0.028	3225	4610	6050
Mix-CS-44-12	0.44	3.5	3.41	1.7	3.41	na	6	5.5	32	5	0.019	2615	4100	5330
Mix-CS-44-13	0.44	3.5	3.41	2.55	na	3.35	5	8.6	50	7	0.036	2045	3140	4220
Mix-CS-44-14	0.44	3.5	3.41	2.98	4.75	3.5	5	10	45	7.5	0.063	2215	3050	4070
Mix-CS-44-15	0.44	3	2.55	1.7	3.25	2.5	5	8	45	5.75	0.056	2355	3470	4810
Mix-CS-44-16	0.44	3	2.55	2.13	3.25	3	5	9.5	45	7	0.063	1973	3110	4380
Mix-CS-44-17	0.44	3	2.55	2.13	3.15	2.25	5	7.5	45	6	0.038	2690	3930*	4980
Mix-CS-44-19	0.46	2.99	2.56	2.99	2	1.5	12	6.3	30	5.3	0.053	3170	4310	5560
Mix-CS-44-20	0.46	3.41	2.99	2.99	2.75	2	12	6.8	30	5.8	0.053	2980	4240	5340
Mix-CS-44-21	0.48	2.13	2.13	2.99	4	3.5	12	12.0	45	8.3	0.112	1749	2590	3260
Mix-CS-44-22	0.48	1.71	2.13	2.81	3.25	3	12	10.5	45	7.8	0.083	1943	2890	4000
Mix-CS-44-23	0.46	4.26	3.41	2.99	2.25	2	12	5.5	30	4.5	0.056	3270	4840	6220
Mix-CS-44-24	0.46	5.03	4.26	2.99	3	2.5	12	4.2	30	3.9	0.017	3470	5150	6770
Mix-CS-44-25	0.46	2.99	5.97	12.79	OS	OS	12	13.0	85	7.9	0.070	2890	4260	5400
Mix-CS-44-26	0.46	2.99	4.26	10.66	OS	OS	12	17.8	70	8.9	0.153	2240	3400	4450
Mix-CS-44-27	0.44	2.99	5.12	6.82	3.5	2.75	12	7.0	45	5.4	0.048	3410	4880	6610
Mix-CS-44-28	0.44	2.99	4.52	7.68	4.25	3.4	12	10.1	45	7.0	0.094	2870	4050	5260
Mix-CS-44-29	0.44	2.99	3.84	7.68	3	2.4	12	8.6	45	6.1	0.076	2740	4160	5320
Mix-CS-44-30	0.44	2.99	3.84	8.10	2.75	2.15	12	9.5	45	7.0	0.076	2950	4380	5180
Mix-CS-44-32	0.44	2.99	5.12	9.38	4.5	3.25	12	7.8	45	6.1	0.052	3440	5130	6450
Mix-CS-44-33	0.44	2.99	4.26	10.23	4	2.85	12	10.9	45	7.3	0.111	2600	4060	5320
Mix-CS-44-34	0.44	2.99	4.26	10.23	4	2.7	12	11.3	45	7.0	0.129	2840	4050	5260
Mix-CS-44-36	0.44	4.26	4.26	10.23	4.25	2.85	12	10.5	45	7.0	0.106	2900	na	na
Mix-CS-44-37	0.44	4.26	3.41	11.09	4.75	3.25	12	18.8	60	8.6	0.211	1215	na	na
Mix-CS-44-38	0.44	4.26	3.84	10.23	5	3.75	12	14.8	60	8.0	0.141	2060	na	na
Mix-CS-44-39	0.44	3.84	3.84	10.23	3.75	2.25	12	13.0	45	7.6	0.164	2650	na	na
Mix-CS-44-40	0.44	2.99	3.84	10.23	3.25	2.75	12	13.0	45	7.8	0.158	2670	na	na
Mix-CS-44-41	0.44	3.41	3.84	10.23	3.25	2.25	12	11.8	45	7.3	0.136	2790	na	na
N.G.	OK		* 8 Day											

Table A-40 Air Content, Slump, and Strength Results for Concrete Mixes with Natural Sand and Fly Ash (Cem1 < 5%)

Mix Type	w/cm Ratio	Water Reducer WRDA 82	Water Reducer ADVA Cast 575	Air Entr. Daravair 1400	Slump, in 0 min	Slump, in 12 min	Percentage of Air Initial Time (min)	Percentage of Air Initial %	Percentage of Air Final Time (min)	Percentage of Air Final %	Rate of Air Loss %/min	Strength, psi 3 Day	Strength, psi 7 Day	Strength, psi 14 Day
		Amount (fl. oz/cwt)												
Mix-NF-42-1	0.42	1.36	na	1.02	na	3.5	5	7.75	45	6.75	0.025	2180	3400	na
Mix-NF-42-2	0.42	1.36	na	1.28	5	3.5	5	9.25	45	7.9	0.034	1621	2600	3350
Mix-NF-42-3	0.42	0.42	na	1.27	4.25	3.25	5	7	45	5.9	0.028	2560	3820	4470
Mix-NF-42-4	0.42	na	na	1.7	4.25	3.25	5	7.75	45	6.5	0.031	2440	3630	4230
Mix-NF-42-5	0.42	na	na	2.13	4.25	3.75	5	8	45	7	0.025	2195	3130	3610
Mix-NF-40-6	0.40	0.25	0.25	2.13	3.5	2.6	5	9	45	7.9	0.028	2145	3100	3900
Mix-NF-40-7	0.40	0.25	0.25	1.7	3.25	2.25	5	8.2	45	6.6	0.040	2385	3630	4320
Mix-NF-40-8	0.40	0.85	0.43	2.13	3	2.75	12	9	45	7.1	0.058	na	3120	3550
Mix-NF-40-9	0.40	0.85	0.43	2.13	4	3.25	12	10	45	8.5	0.045	na	2630	3180
Mix-NF-40-10	0.40	0.85	0.43	2.13	3.5	2.75	12	9.5	45	7.9	0.048	na	2840	3310
Mix-NF-40-11	0.40	0.85	0.43	2.13	3.75	3.25	12	11	45	8.25	0.083	na	2800	3350
Mix-NF-40-12	0.40	1.28	0.85	1.71	3.5	2.5	12	9.5	45	7.6	0.058	2480	3260	3790
Mix-NF-40-14	0.40	0.9	1.3	2.1	3.5	3	12	11.75	45	8.25	0.106	2210	2960	3270
Mix-NF-40-15	0.40	1.3	1.1	1.7	3.5	2.5	12	10.1	45	7.2	0.088	2380	3560	4300
Mix-NF-40-14	0.40	0.9	1.3	2.1	3.5	3	12	11.75	45	8.25	0.106	2210	2960	3270
N.G.	OK													

Table A-41 Air Content, Slump, and Strength Results for Concrete Mixes with Natural Sand and Slag (Cem1 < 5%)

Mix Type	w/cm Ratio	Water Reducer WRDA 82	Water Reducer ADVA Cast 575	Air Entr. Daravair 1400	Slump, in 0 min	Slump, in 12 min	Percentage of Air Initial Time (min)	Percentage of Air Initial %	Percentage of Air Final Time (min)	Percentage of Air Final %	Rate of Air Loss %/min	Strength, psi 3 Day	Strength, psi 7 Day	Strength, psi 14 Day
		Amount (/cwt)												
Mix-NS-42-1	0.42	3.5	1.06	1.7	na	3.6	12	12.5	45	11	0.045	1414.5	2010	2880
Mix-NS-42-3	0.42	3.41		0.85	4.5	4	12	9	45	8.75	0.008	1591	2520	3650
Mix-NS-42-5	0.42	3.5	0.42	1.28	3.75	3.25	12	11	45	9.25	0.053	1770	2210	3080
Mix-NS-42-6	0.42	2.55	1.02	1.28	4.25	na	12	9.75	45	9	0.023	1653.5	2420	3120
Mix-NS-42-7	0.42	1.7	1.27	1.28	3.5	3.25	12	9	45	8	0.030	2400	3390	4340
Mix-NS-42-8	0.42	1.7	1.27	1.28	4.25	3.75	12	9	45	7.7	0.039	2110	3280*	4100
Mix-NS-42-9	0.42	0.9	0.9	1.3	3	2.25	12	7.5	45	6.1	0.042	na	3100	4440
Mix-NS-42-11	0.42	1.7	1.3	2.1	3.4	2.75	12	10	45	7.5	0.076	2410	3460	4440
N.G.	OK		* 8 Day											

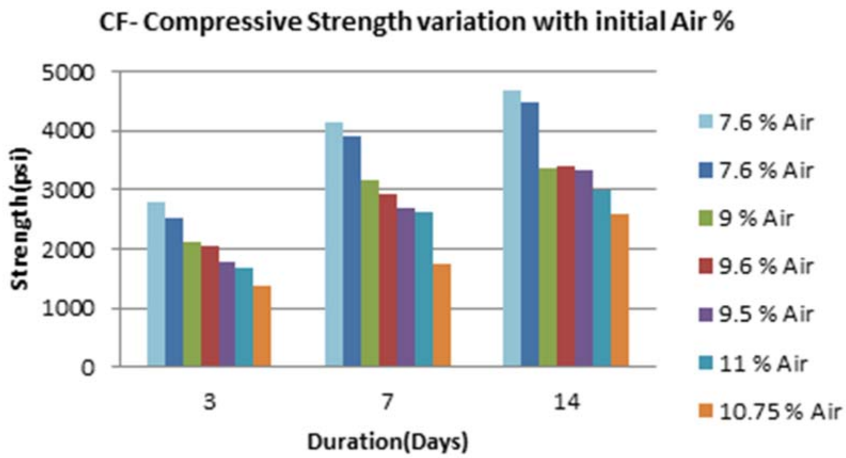

Figure A-31 Percentage of initial air vs. compressive strength of combined sand and fly ash concrete mix.

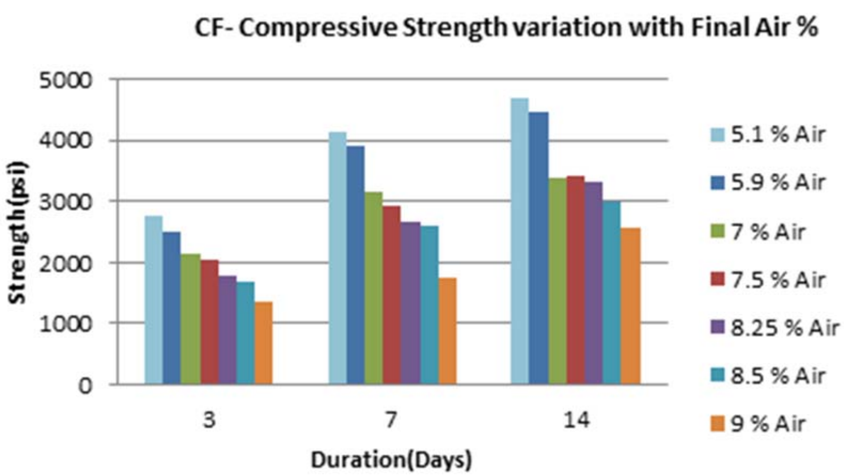

Figure A-32 Percentage of final air vs. compressive strength of combined sand and fly ash concrete mix.

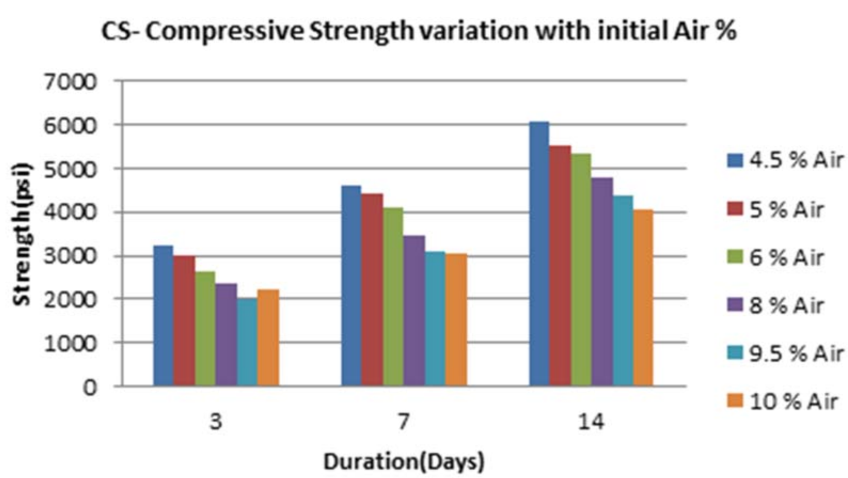

Figure A-33 Percentage of initial air vs. compressive strength of combined sand and slag concrete mix.

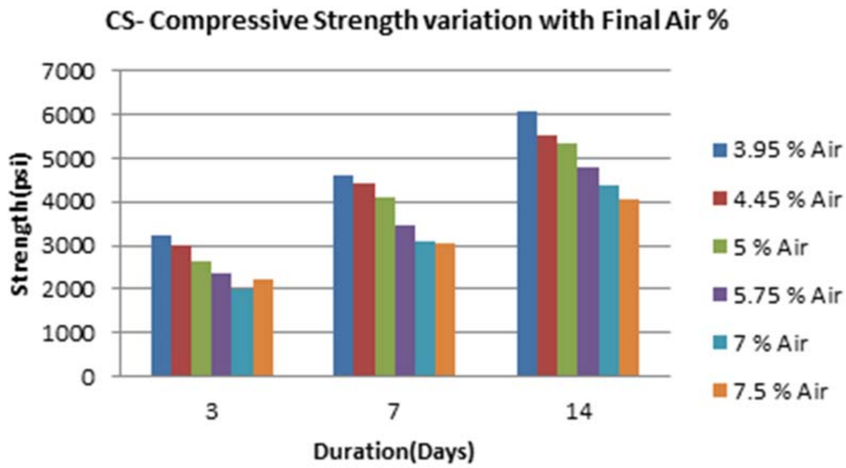

Figure A-34 Percentage of final air vs. compressive strength of combined sand and slag concrete mix.

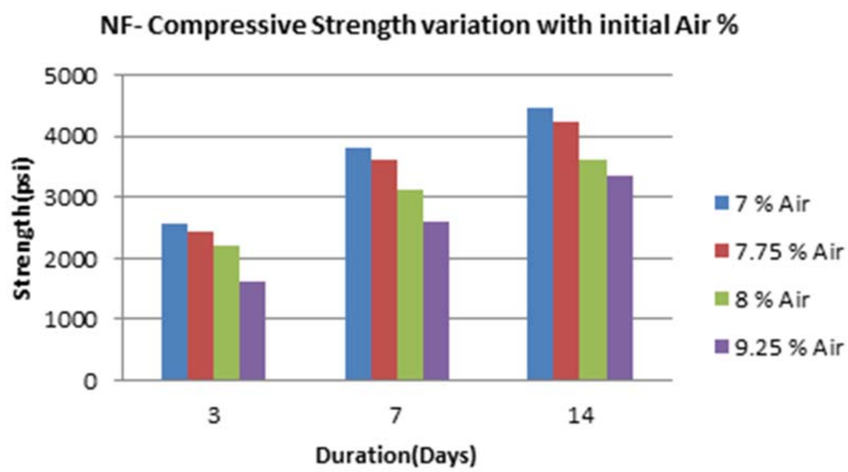

Figure A-35 Percentage of initial air vs. compressive strength of natural sand and fly ash concrete mix.

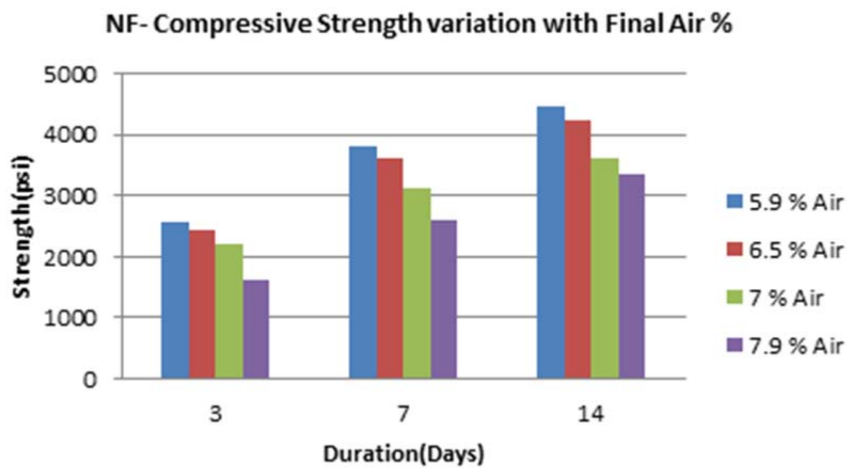

Figure A-36 Percentage of final air vs. compressive strength of natural sand and fly ash concrete mix.

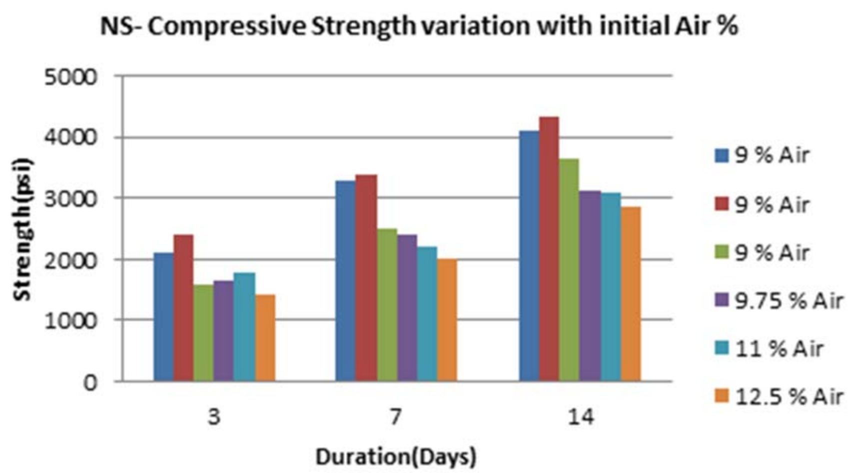

Figure A-37 Percentage of initial air vs. compressive strength of natural sand and slag concrete mix.

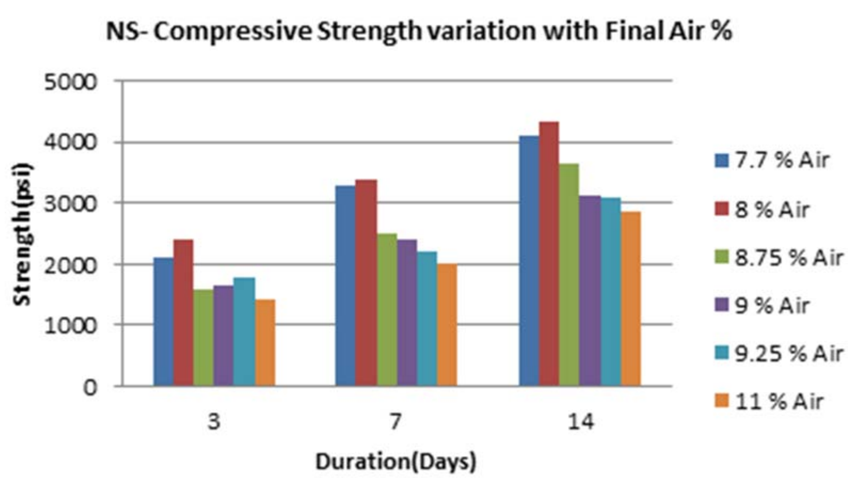

Figure A-38 Percentage of final air vs. compressive strength of natural sand and slag concrete mix.