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Effect of Wet Curing Duration on Durability Parameters of Hydraulic Cement Concretes

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D. STEPHEN LANE
Associate Principal Research Scientist

Virginia Transportation Research Council, 530 Edgemont Road,
Charlottesville, VA 22903-2454, www.vtrc.net, (434) 293-1900

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16. Abstract:

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The success rate of the humidity measurements within the slabs was low because of water condensation. However, water condensation qualitatively indicates that the slabs did not dry out to an extent that would adversely impact concrete property development. Neither the strength, electrical conductivity, nor sorptivity results were impacted appreciably by the duration of moist curing. At most, 1 to 3 days wet curing was sufficient.

Reducing w/cm had a positive impact on reducing permeability parameters, and previous work by others has shown the duration of curing needed to achieve discontinuity in the capillary pore system decreases with decreasing w/cm. No added benefit was observed by application of liquid membrane-forming curing following the wet curing. The prevailing weather conditions in the months during and following placement were humid, which would obviate any benefit from post wet-curing applications of liquid membrane-forming curing compound to slow drying. Prevailing weather conditions and the w/cm of the concrete mixture are important factors in determining adequate curing procedures and duration and should be considered by the project management team at the time of construction to establish appropriate procedures.

A direct cost savings could be realized by removing the requirement for wet curing and using LMFC only in situations where it is likely to benefit the curing process. Alternatively, there may be long-term benefits that could be realized by applying these cost savings to the application of penetrating sealers, particularly for concretes that will be subjected early in their life to aggressive anti-icing and deicing programs.

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FINAL REPORT

EFFECT OF WET CURING DURATION ON DURABILITY PARAMETERS OF HYDRAULIC CEMENT CONCRETES

D. Stephen Lane
Associate Principal Research Scientist

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ABSTRACT

Hydraulic cement concrete slabs were cast and stored outdoors in Charlottesville, Virginia, to study the impact of wet curing duration on durability parameters. Concrete mixtures were produced using portland cement, portland cement with slag cement, and portland cement with Class F fly ash concretes with water–cementitious materials ratios (w/cm) of 0.45 and 0.35. These concretes were subjected to immediate liquid membrane-forming curing or 1, 3, 7, or 14 days wet curing. Two slabs were cast for each of the wet curing durations. Following the curing period, one slab was allowed to dry naturally, and liquid membrane-forming curing compound was applied to the other. Three additional concretes containing saturated lightweight fine aggregate were produced to study the potential impact of internal curing on the durability parameters. These concretes contained portland cement with fly ash, silica fume, and both, at 0.35 w/cm. Three slabs were cast from each mixture and subjected to liquid membrane-forming curing, 1 or 3 days wet curing. The slabs were instrumented with humidity probes at two depths below the surface. Specimens were removed from two depths and tested for tensile strength, electrical conductivity, and sorptivity at 3 and 12 months of age.

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FINAL REPORT

EFFECT OF WET CURING DURATION ON DURABILITY PARAMETERS OF HYDRAULIC CEMENT CONCRETES

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INTRODUCTION

Hydraulic cements and cement-pozzolan systems react with water to produce the cementitious paste that serves as the matrix of concrete. If the concrete dries too rapidly, the durability of the paste may be compromised by (1) stresses that develop causing cracking; and (2) insufficient hydration of the cementitious materials leaving a more continuous capillary pore system. Both serve to increase the ability of solutions to move through the concrete, facilitating deterioration mechanisms. Proper curing to restrict moisture loss is one of the basic steps in concrete construction. Current Virginia Department of Transportation (VDOT) specifications permit the following materials to be used in curing concrete: waterproof paper, polyethylene (PE) film, a combination of burlap and PE film, liquid membrane-forming compound (LMFC), and water. LMFC is by far the most commonly used material for curing pavements. For bridge decks, moist curing is required for a minimum of 7 days and until 70% of design compressive strength (f'c) is achieved. For normal bridge deck construction, this can be accomplished using PE film with or without wet burlap, with the stipulation that the concrete surface under the PE film must remain moist for the duration of the moist-curing period. Wet burlap with PE film is required for concrete subject to the low-permeability specification and for hydraulic cement concrete bridge deck overlays. Immediately following the moist curing period, LMFC is applied. At a minimum age of 14 days and following the moist-curing period, closely spaced grooves are sawed transversely across the bridge deck surface to maintain good skid resistance.

With the increased use of slag cement and pozzolans, both of which hydrate at a slower rate than portland cement, and a reduced water–cementitious materials ratio (w/cm), some have emphasized the need for wet curing of critical elements, in particular, bridge decks, and some departments of transportation (DOTs) have instituted requirements for wet curing of up to 14 days for high performance concretes (HPC). Other concrete technologists have suggested that although the prompt application of moist curing to prevent water loss is critical, the benefits of moist curing diminish fairly rapidly so that beyond a few days, little actual benefit is realized with low w/cm concretes; a few have suggested that it may in fact be detrimental by contributing to increased cracking. The use of saturated, absorptive lightweight fine aggregate (LWFA) has been proposed as a method of providing water for internal curing of low w/cm concretes and thus achieving better curing of such concretes.

Although VDOT has adopted requirements for wet curing of bridge decks, the construction industry has raised concerns about practicality and actual benefits. This study examines these issues and provides information that will be useful in better defining appropriate curing practices for concrete construction.

PURPOSE AND SCOPE

The purpose of this study was to determine the effects of wet curing duration on the strength and transport properties of hydraulic cement concretes.

This was a laboratory/field study. Test slabs were constructed from nine batches of ready-mixed concrete at an outdoor site in central Virginia and subjected to curing regimes including immediate application of wet curing up to 14 days duration and immediate application of a LMFC. Subsequently, the slabs were cored, and the cores tested for concrete properties. In addition, test cylinders were cast at the time the slabs were fabricated and subjected to a range of laboratory curing regimes prior to testing.

METHODOLOGY

Six hydraulic cement concretes with normal weight aggregates were produced at two w/cm: 0.35 and 0.45. Three additional sets of concretes with 0.35 w/cm containing fly ash and/or silica fume were produced with absorptive LWFA to investigate this means of providing internal curing. The proportions for the concrete mixtures are shown in Table 1. All concretes were batched at ready-mixed concrete plants and delivered to the laboratory/field site in concrete mixing trucks. Test specimens for strength and transport properties were cast from fresh concrete and subjected to four curing regimes: (1) standard laboratory moist curing, (2) VDOT accelerated curing for permeability testing, (3) an extended 56-day moist curing, and (4) an accelerated 7-day curing.

The slabs were cast in water-resistant forms that remained in place for the duration of the experiment to prevent drying from the sides or bottoms. Following strike-off, the top surface of the slabs was finished with a burlap drag. Subsequently, a bead of silicone caulk was placed at the junction of the slab surface and the form. For the normal-weight aggregate concretes, two slabs each were subjected to 1, 3, 7, and 14 days moist curing using wet burlap and PE film. Following cessation of wet curing, one slab was allowed to dry naturally; the other slab immediately received an application of LMFC. The ninth slab in each mixture received no moist curing, but LMFC was applied to the surface as soon as possible after finishing. A reduced set of three slabs each was fabricated from the three concrete mixtures with LWFA for internal curing. The proportion of the LWFA portion of these mixtures followed the practice described by Bentz et al. (2005). An outline of the slab-curing conditions is given in Table 2.

Table 1. Ingredient Proportions for Concrete Mixtures (Mass per Cubic Yard)

Ingredient	Batch								
	A	B	C	D	E	F	G	H	I
Portland Cement, lb	635	400	540	635	407	540	540	628	540
7% Silica Fume, lb	-	-	-		-	-		47	34
40% Slag Cement, lb	-	266	-	-	255	-	-	-	-
20% Class F Fly Ash, lb	-	-	135	-	-	135	135	-	101
Coarse Aggregate, lb[a]	1804	1743	1781	1781	1731	1781	1781	1781	1781
Fine Aggregate (normal weight), lb	1148	1153	1158	1286	1163	1285	514	399	448
Fine Aggregate (lightweight), lb	-	-	-	-	-	-	259	311	291
Water, lb	285	240	302	232	291	235	236	236	236
W/cm	0.45	0.36	0.45	0.36	0.44	0.35	0.35	0.35	0.35
Air, %	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5

[a] The coarse aggregate in Batches B and E was crushed carbonate rock; in the remaining batches it was crushed granitic gneiss.

Table 2. Outline of Curing Conditions for Slabs

Batches and Slabs	Curing Condition
Batches A, B, C, D E, and F slabs	
1	Liquid membrane-forming compound (LMFC) after finishing
2	1 day wet burlap, allowed to dry
3	1 day wet burlap, LMFC following wet curing
4	3 days wet burlap, allowed to dry
5	3 days wet burlap, LMFC following wet curing
6	7 days wet burlap, allowed to dry
7	7 days wet burlap, LMFC following wet curing
8	14 days wet burlap, allowed to dry
9	14 days wet burlap, LMFC following wet curing
Batches G, H, and I	
1	LMFC after finishing
2	1 day wet burlap, allowed to dry,
3	3 days wet burlap, allowed to dry

The slabs were instrumented with two humidity/temperature probes each at different depths (¾ in and 3 in) from the surface (Figures 1 and 2). To provide space and access to the probes, two lengths of 1-in outer diameter PVC pipe with screen covering the end were cast into the slabs at the desired depths. The probes were inserted the day of casting, within 2 to 3 hours after finishing was completed. At ages of 3 months and 1 year, 4-in-diameter cores were drilled and specimens taken from two depths (0 to 2 in and 3 to 5 in) for transport property testing. The transport property testing includes three methods: (1) bulk chloride diffusion (ASTM C 1556), which directly measures chloride ingress into concrete; (2) sorptivity (ASTM C 1585), which directly measures the rate of water absorption into the pore system of concrete at a given internal humidity condition; and (3) electrical conductivity, which indirectly assesses the connectivity of the pore system. Also at 3 months and 1 year, a 2-in-diameter core bit was drilled to selected depths and the core plug subjected to pull-off testing to measure the tensile strength. For 3-month testing, each slab was drilled to two depths for tensile pull-off testing: 5/8 in and 4 in; for 1-year testing, cores were drilled only to the 4-in depth.

Figure 1. Cast Slab With Probe Assemblies Ready for Positioning

Figure 2. Humidity/Temperature Probe and Assembly. The rubber stopper is compressed by turning the thumbscrew to seal the probe near the base of the pipe. The pipe has an inside diameter of 1 in.

RESULTS AND DISCUSSION

The slabs were fabricated in August and September 2006. Data from the placement conditions and the results of tests on fresh concrete are presented in Table 3. Concrete temperatures for Batches A, B, and D exceeded the 85 ^{o}F maximum specified by VDOT for bridge deck placement; B was 1 degree above, and A and D exceeded the limit by 7 and 14 degrees, respectively. Batches A and D were the two straight portland cement mixtures, so heat of hydration likely played a role. Jobsite additions of admixtures were made to Batches A through F to make adjustments in either slump or air content or both. The temperature of the air during placement of the concrete in the forms was 80 ^{o}F or above for Batches A through E and 70 ^{o}F or below for Batches F through I. With the exception of Batch D, during which the RH of the air was less that 50%, it remained above 60% for Batches A through F and above 80% for Batches G through I. Slump ranged from 5 to 7 in for Batches A through F and from 2¾ to 4½ for Batches G through I. Air content ranged from 5.3% to 8.5%, and unit weight from 140 to 144 lb/ft^3. Test specimens for strength and transport property measurement were fabricated and taken to the laboratory for curing under the stated conditions.

The compressive and splitting tensile strengths of the fabricated specimens cured under the four regimes are shown in Figures 3 and 4. Error bars represent the repeatability ranges given in ASTM C 39 for compressive strength (9.1%) and ASTM C 496 for splitting tensile strength (14%). Generally speaking, compressive strengths were higher for Batches B, D, E, G, H, and I than for Batches A, C, and F. All except Batch E were 0.35 w/cm batches. The two slag cement mixtures, Batches B and E, gave roughly equivalent strengths despite batching information indicating a w/cm of 0.35 and 0.45, respectively. A similar trend occurred with the fly ash mixtures in that the strength levels of both Batches C and F, 0.45 and 0.35 w/cm, respectively, were at a level expected of the higher w/cm. The 28-day accelerated curing had a profound impact on the strength of the mixtures containing fly ash, with the compressive strength exceeding the 56-day standard cured by at least 500 psi for Batches C, F, and G and slightly less than 500 psi for Batch I. For the slag cement and straight portland cement mixtures, the highest compressive strengths were observed with the 56-day standard cured specimens.

For splitting tensile strength, the 28-day accelerated curing values were roughly similar to the 56-day standard curing except for Batches B, D, and I, for which the 56-day strengths were approximately 10% higher. Similarly, 7-day accelerated curing values were in rough agreement or slightly lower than the 28-day tensile strengths with the exception of Batches G and I.

Figure 5 presents the electrical conductivity of specimens cast during the placement operations and cured under the four regimes. The error bars represent the repeatability range of 14% based on a pooled coefficient of variation of 5% for conductivity tests (Lane, 2005). Electrical conductivity is the property that governs the response in the rapid chloride permeability test (RCPT) (ASSHTO T 277, ASTM C 1202) that is used by VDOT to assess compliance with the low-permeability specification. In its assessment protocol, VDOT uses the 28-day accelerated curing procedure as an indicator of the value expected at later ages for concretes. From the relationship between electrical conductivity and RCPT results developed by Lane (2005), Batches B, C, E, G, H, and I would be expected to yield RCPT values of approximately 1500 coulombs, Batch F approximately 2500 coulombs, Batch D approximately

Table 3. Placement Conditions and Results of Tests on Plastic Concrete

Batch	A	B	C	D	E	F	G	H	I
Date	8/1/06	8/7/06	8/15/06	8/21/06	8/28/06	9/6/06	9/13/06	9/13/06	9/13/06
Time	9:00	8:15	8:55	9:15	8:15	8:50	9:30	12:00	1:10
T, air, °F	83	73	76	74	75	72	60	63	64
RH, air, %	70	79	77	53	72	70	83	83	83
Initial slump, in	3.0	3.75	---	--	--	3.0	---	---	---
In. air, %	---	---	4.7	3.8	4.7	4.0	---	---	---
Additions at jobsite	HRWR	32 oz HRWR	AEA	1A: 120 oz HRWR/ 5 oz AEA 2A: 10 oz AEA	4 oz AEA	1A: 5 oz AEA 2A: 32 oz HRWR, 6 oz AEA	---	---	---
T, con, °F	92	86	84	99	83	80	77	77	63
Slump, in	7.0	7.0	5.0	5.25	7.0	7.0	2.75	4.25	4.5
Air, %	7.0	5.9	5.6	7.6	5.3	8.5	6.5	6.0	6.8
Unit weight, lb/ft^3	140.8	141.6	143.6	142.8	144.4	140.0	144.0	142.0	142.0
Placement	9:50	9:00	9:20	10:00	8:45	9:45	9:45	12:15	1:25
T, air, °F	86	80	85	80	82	70	60	63	64
RH, air, %	70	68	65	47	60	70	83	83	83
Curing	10:50	10:15	10:45	10:55	1040	10:55	10:30	12:40	2:00
T, air, °F	92	82	85	---	82	75	61	64	64
RH, air, %	62	74	65	----	60	63	83	83	83

T = temperature; RH = relative humidity; In. = Initial; HRWR = ASTM C494 Type A/F admixture; AEA = ASTM C 260 air-entraining admixture; con = concrete; 1A = 1st addition; 2A = 2nd addition.

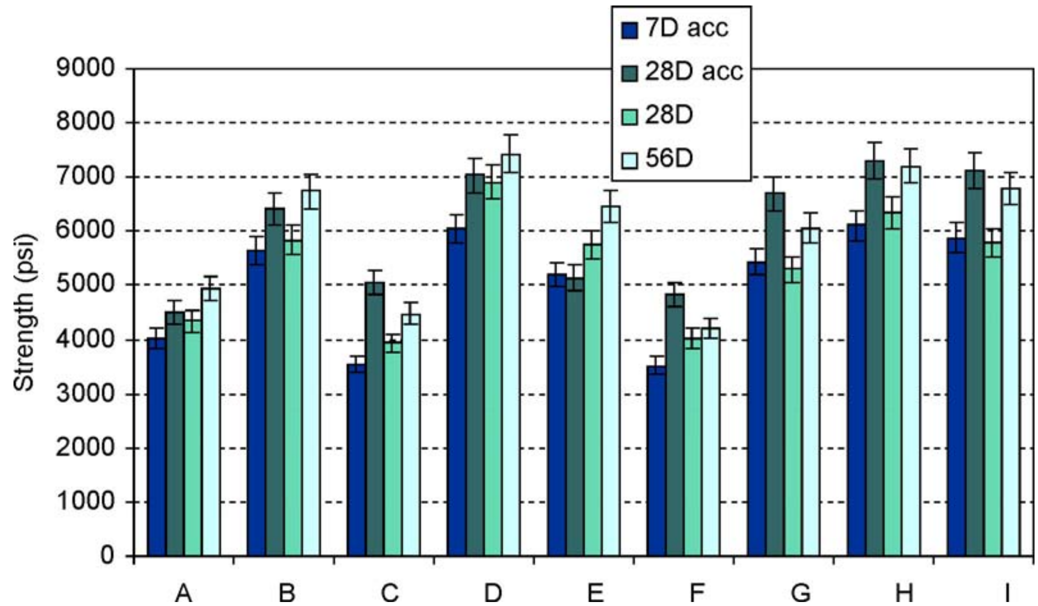


Figure 3. Compressive Strength of Cylinders Fabricated During Placement Operations and Subjected to Various Curing Conditions. The repeatability range is 9.1%.

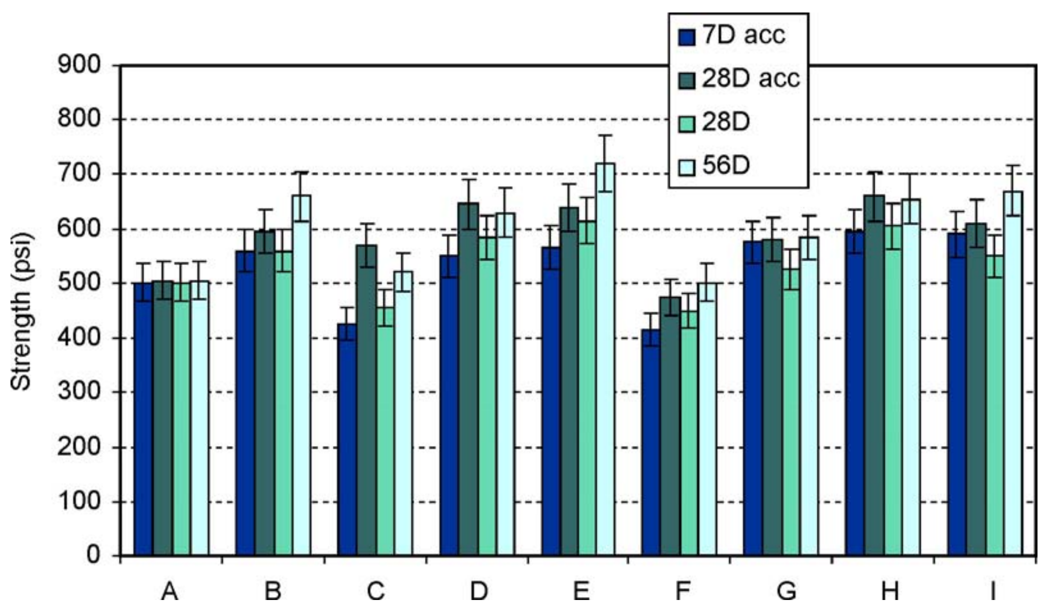


Figure 4. Splitting Tensile Strength of Cylinders Fabricated During Placement Operations. The repeatability range is 14%.

3600 coulombs, and Batch A approximately 6000 coulombs. For the portland cement and slag cement mixtures, Batches A, D, B, and E, the 28-day accelerated values provide a good indicator of the value obtained for 56-day standard curing; for fly ash mixtures such as Batch F, the 28-day accelerated curing value is typically expected to relate to a much later age, for instance, 1 year (Ozyildirim, 1998). The effect of pozzolanic materials and slag cement on electrical conductivity can be observed by comparing the results for Batch D with those for Batches B, G, H, and I.

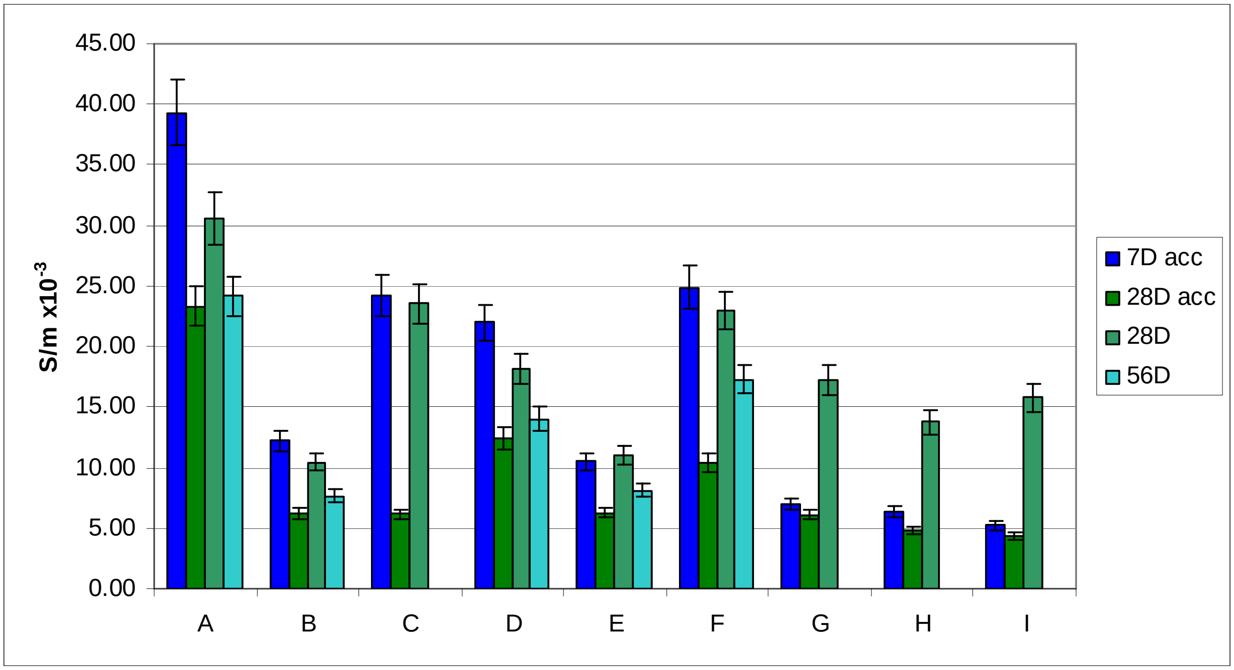


Figure 5. Electrical Conductivity of Cylinders Fabricated During Placement Operations. The repeatability range is 14%.

Figures 6 and 7 present the initial and secondary rates of absorption data, respectively. The error bars represent expected repeatability ranges of 26% and 19% for the initial and secondary absorption values (Lane, 2006b). For the rate of absorption tests, Batches D, G, H, and I had similar low results for the 56-day standard cured specimens. These were all 0.35 w/cm

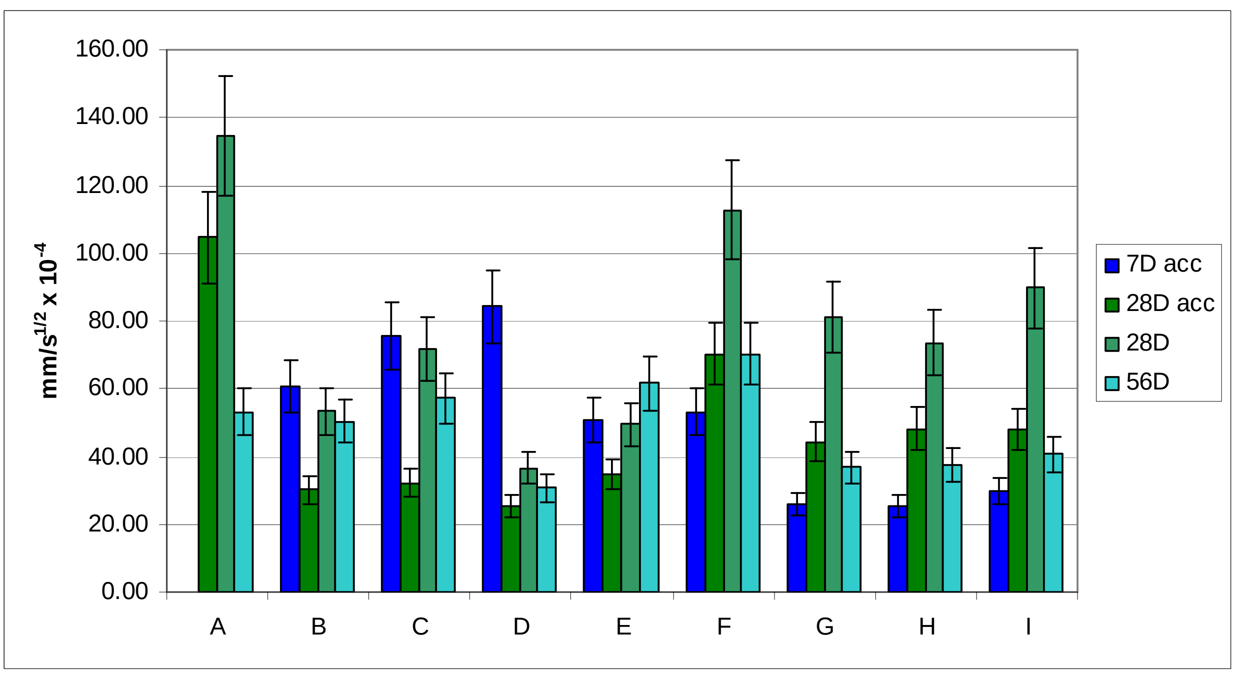


Figure 6. Initial Rate of Absorption (x 10^{-4}) of Cylinders Fabricated During Placement Operations. The repeatability range is 26%.

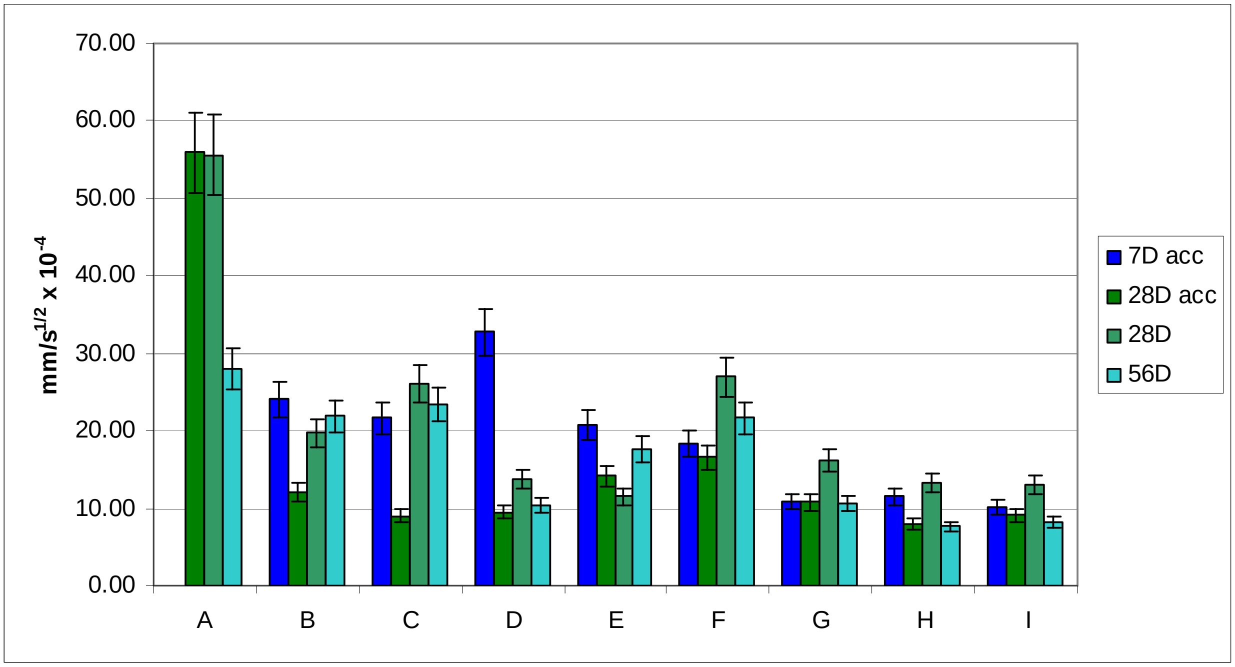


Figure 7. Secondary Rate of Absorption of Cylinders Fabricated During Placement Operations. The repeatability range is 19%.

mixtures. Batches A, portland cement at 0.45 w/cm; B and E, slag cement mixtures; and C and F, the fly ash mixtures, had higher values. Whereas in the electrical conductivity test, pozzolans or slag cement is necessary to provide low test values, the rate of absorption seems more responsive to w/cm as a controlling factor, as demonstrated by the results for Batch D, the 0.35 w/cm portland cement mixture. An explanation for the contrasting results of the electrical conductivity and rate of absorption tests is that the rate of absorption test responds primarily to the microstructure while the electrical conductivity is subject to both microstructure and the ionic conductivity of the pore solution, with pozzolanic reactions reducing the conductivity of the pore solution in concretes containing pozzolans or slag cement.

Chloride diffusion coefficients for select specimens are presented in Table 4. The values, on the order of 10 to 12 m^2/s, are typical of those often reported for concretes (Rosenberg et al., 1989). They are 1 to 1.5 orders of magnitude higher than values reported for existing bridge decks (Williamson et al., 2009) and HPC bridge deck overlays (Sprinkel, 2009).

The higher diffusion coefficients for the standard specimens in this study are related to two factors: maturity; 56-day standard curing or 28-day accelerated curing versus 10 to 20 years field exposure; and chloride exposure conditions. The standard specimens were saturated and exposed to a high-concentration (16.5%) salt solution so that diffusion driven by a high concentration is the primary mechanism for chloride penetration, whereas the field concretes were subjected to variable conditions of wetting and drying and either environmental (sub-aerial marine) or deicing salt applications in a range of climate zones such that multiple factors of varying degree enter into the driving force for the chloride penetration.

Table 4. Chloride Diffusion Coefficients for Specimens Fabricated During Placement Operations (m^2/s)

Batch	7-Day Accelerated Cure	28-Day Accelerated Cure	28-Day Standard Cure	56-Day Standard Cure
A	20.3E-12		10.1E-12	15.8E-12
	16.4E-12		13.6E-12	
B	5.1E-12			1.4E-12
	4.0E-12			1.5E-12
C		5.4E-12		9.8E-12
D	6.7E-12	7.8E-12		7.1E-12
	9.6E-12	6.2E-12		
F	10.4E-12	11.5E-12		9.5E-12
	12.6E-12			
G		6.7E-12		6.8E-12
H	6.0E-12			3.5E-12

Field-Cured Slabs

Temperature and humidity data were downloaded from the probes periodically. Figure 8 shows outdoor temperature and RH from the time of placement in early August through mid-December. Humid conditions prevailed throughout the period, with the average daily RH not dropping much below 60% even during the relatively low humidity periods. Examples of the data from the probes placed in the slabs are shown in Figures 9 through 12. Although the temperature function continued to work on the probes, the humidity record in most cases gave readings that indicated that water was condensing in the chamber containing the probe, rendering the readings obtained unreliable. Qualitatively though, this does serve to indicate that the slabs were not drying to a substantial degree.

In Figures 8 through 11, the initial temperature peak occurs 8 to 9 hours after casting began and reflects the thermal rise of the concrete attributable to cement hydration, in addition to solar heating. The shallow probes (D1-High and F1-High) exhibited a greater range of values because of the greater influence of solar heating. Strong drops in humidity shortly after peak temperature and persisting for 2 to 3 days were observed with the near-surface probes for Slabs D1 and F1, both of which were cured with LMFC only. After this initial period, the humidity rose to a high and more stable level, with repeated diurnal fluctuations reflecting temperature rise and fall. A similar drop in humidity, but of lesser degree and shorter duration, was noted with the deep probe in Slab D7, which received wet curing for 7 days, whereas the deep probe in Slab F1 showed a gradual increase in humidity over the initial 18 hours and then transitioned into diurnal fluctuation. Unfortunately, the success rate with these measurements was not sufficient to discern clearly the influence of the different curing regimes on early humidity conditions at the two levels in the slabs, but the early drop in humidity in Slabs D1 and F1 suggest there is some benefit to immediate application of wet curing.

Slabs were cored for testing at 3 months and 1 year; 4-in-diameter cores were removed for electrical conductivity, sorptivity, and chloride diffusion testing, and 2-in-diameter cores were drilled for the pull-off tensile tests. Although the electrical conductivity and sorptivity testing was completed, the chloride diffusion testing was suspended following exposure to the chloride solution because the facilities to complete chloride analyses were out of commission. If resources become available, this testing could be completed.

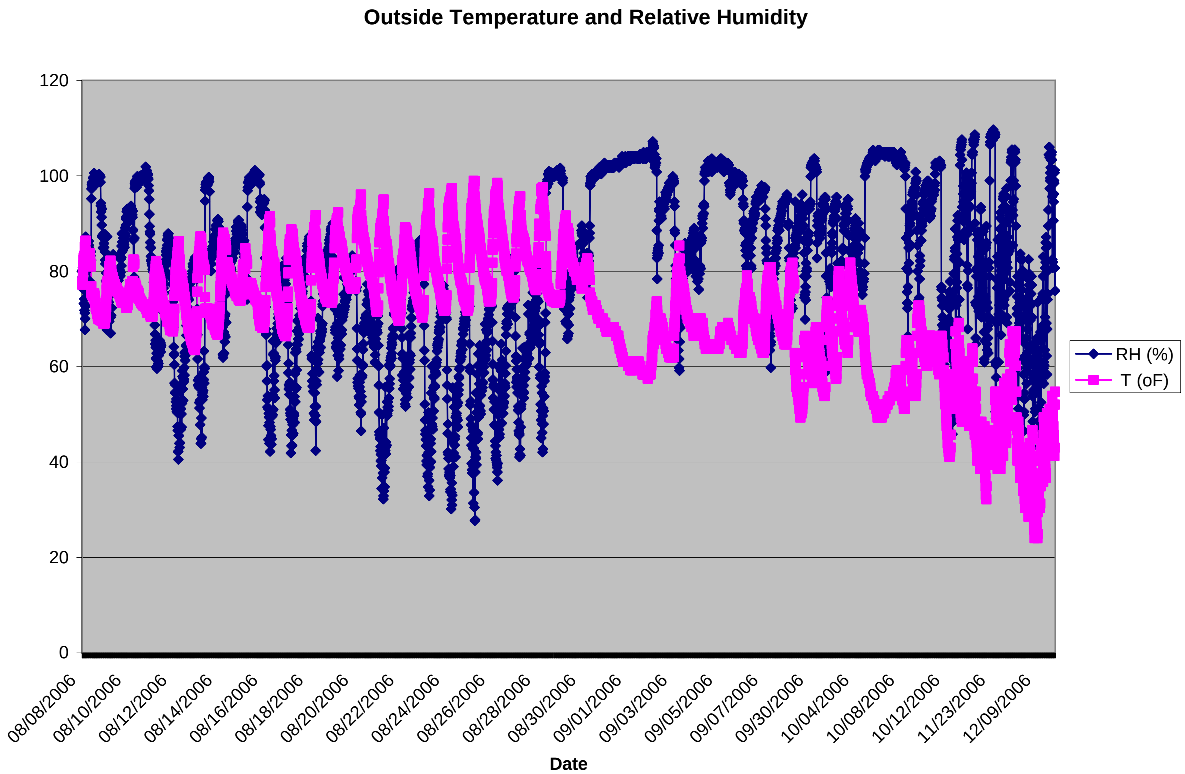


Figure 8. Outside Temperature and Relative Humidity During Initial 4 Months After Placements

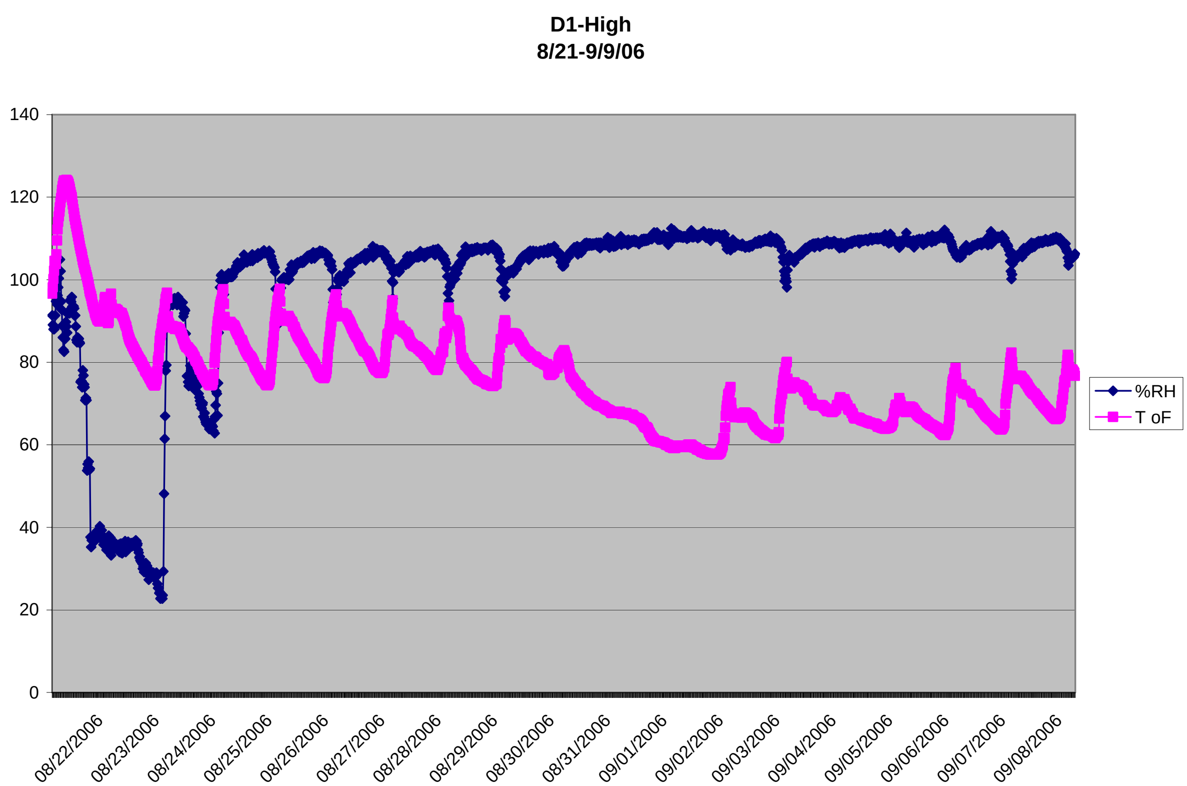


Figure 9. Temperature and Relative Humidity Data for Block D1, ¾ in Below Surface

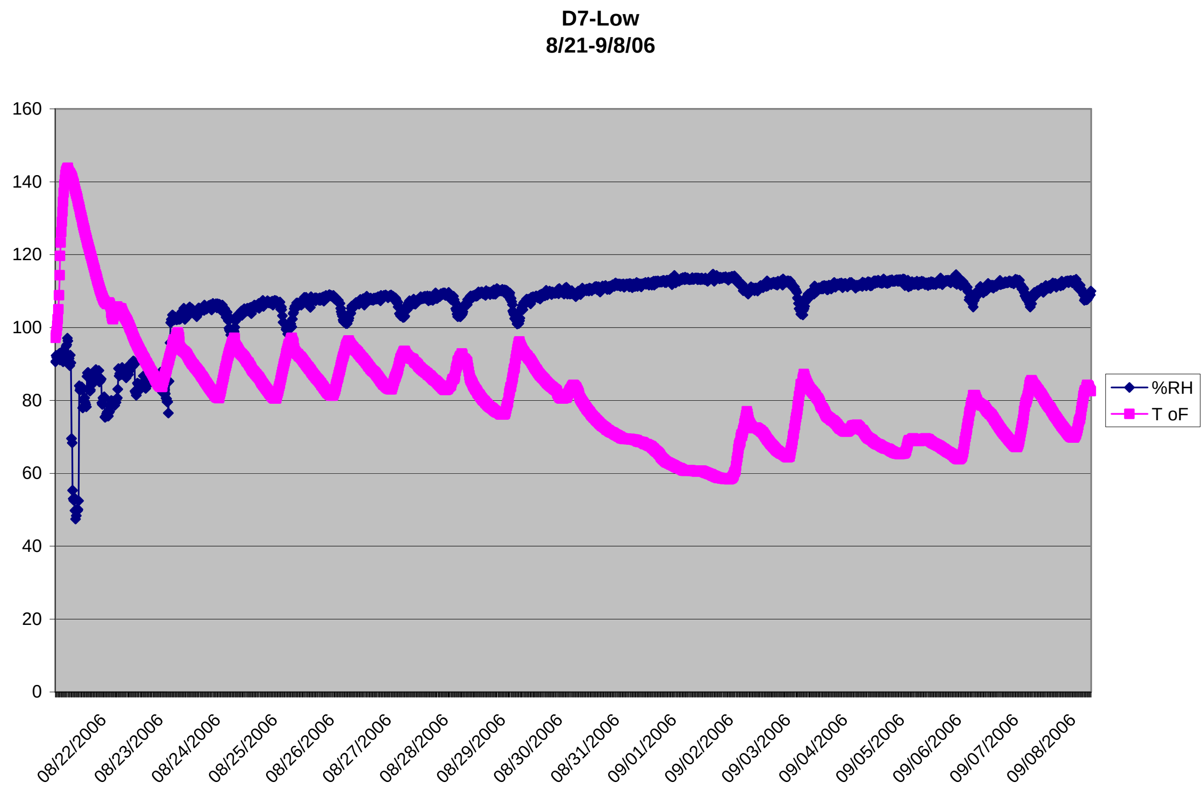


Figure 10. Temperature and Relative Humidity Data for Block D7, 3 in Below Surface

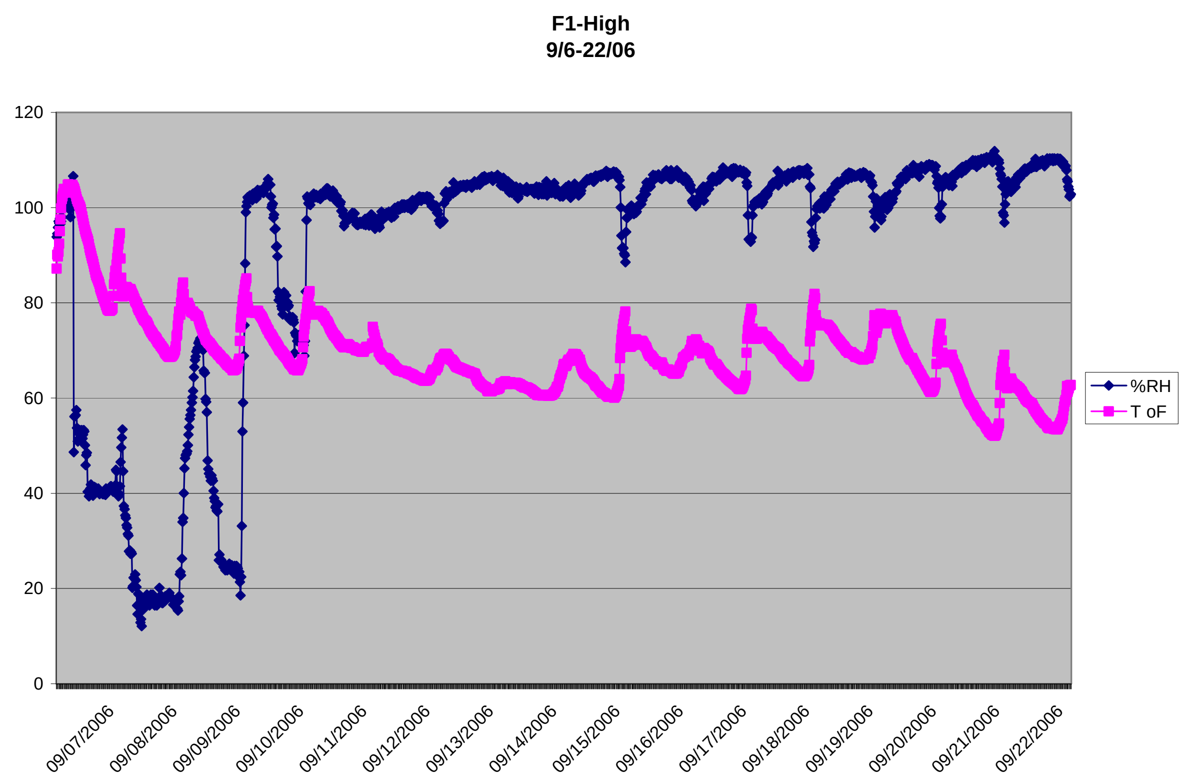


Figure 11. Temperature and Relative Humidity Data for Block F1, ¾ in Below Surface

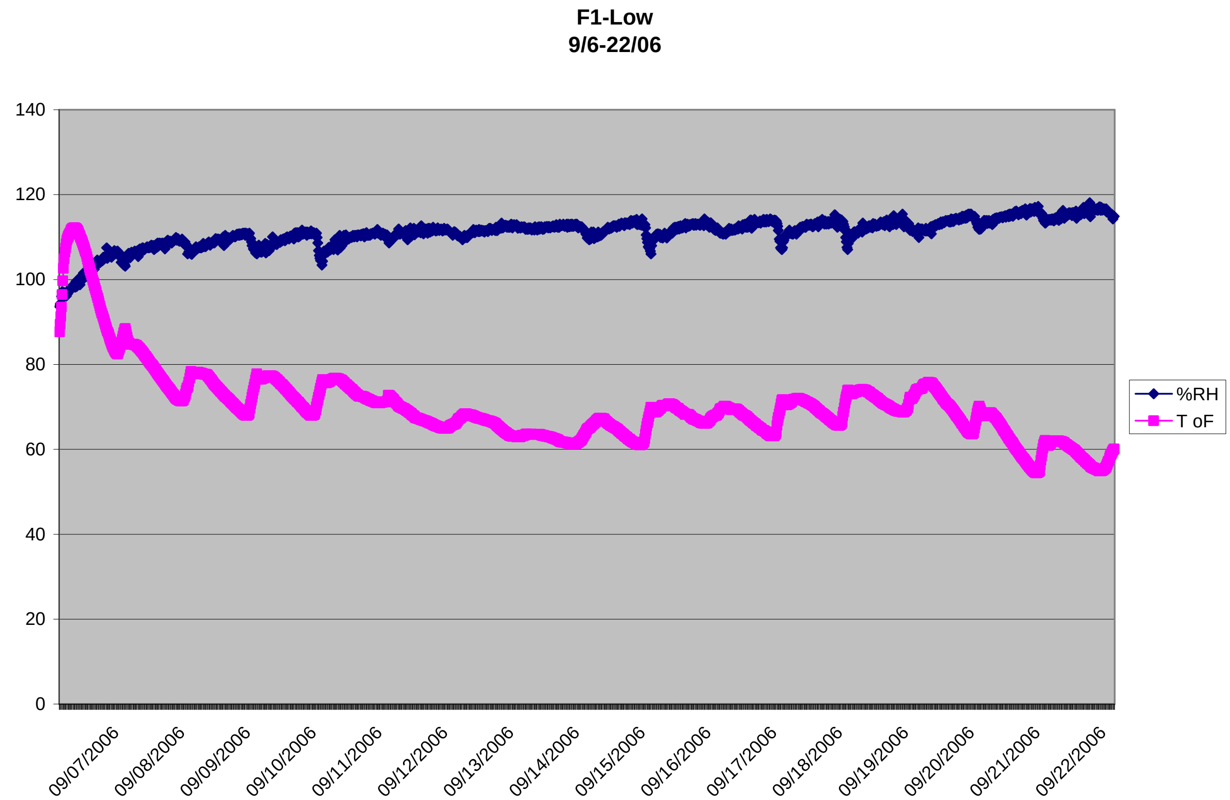


Figure 12. Temperature and Relative Humidity Data for Block F1, 3 in Below Surface

Coring for tests at an age of 3 months was limited to two or three slabs. For Batches A through F, three slabs were cored: Slab 1 (LMFC), Slab 6 (7-day wet), and Slab 7 (7-day wet-LMFC). For Batches G through I, two slabs were cored: Slab 1 (LMFC) and Slab 3 (3-day wet). Two-inch-diameter core bits were drilled into these slabs at two depths for pull-off testing to determine the tensile strength of the concrete. The results are shown in Figures 13 and 14 for 5/8-in and 3-in depths, respectively. The error bars represent the repeatability range (29%) based on the pooled coefficient of variation (10.2%) for the pull-off tests in this study. At the 5/8-in depth (Figure 13), the 0.45 w/cm mixtures tended to show higher tensile strength with wet curing in contrast to the 0.35 w/cm mixtures. With Batches D and E, the 7-day wet-LMFC was considerably lower than the other curing conditions for these batches, but these may simply be outliers. Overall strengths were generally lower for the 3-in depths. The LMFC condition for the 0.45 w/cm Batch A at 5/8-in depth was significantly lower than the corresponding wet cured conditions, in contrast to its corresponding 0.35 w/cm Batch D.

One-year tensile strengths at 3-in depth were obtained for selected blocks of all batches and are presented in Figures 15 through 23. No clear trend emerges with respect to the impact curing condition on tensile strength from these results. Although certain values stand out, in particular, the Slab 7 7-day LMFC for Batch B, the high value for this curing condition was not borne out in other batches such as Batch D (same w/cm) or E (also slag cement), so the value appears to represent an aberrant value. Likely, the 3-in depth is beyond the influence of surface curing.

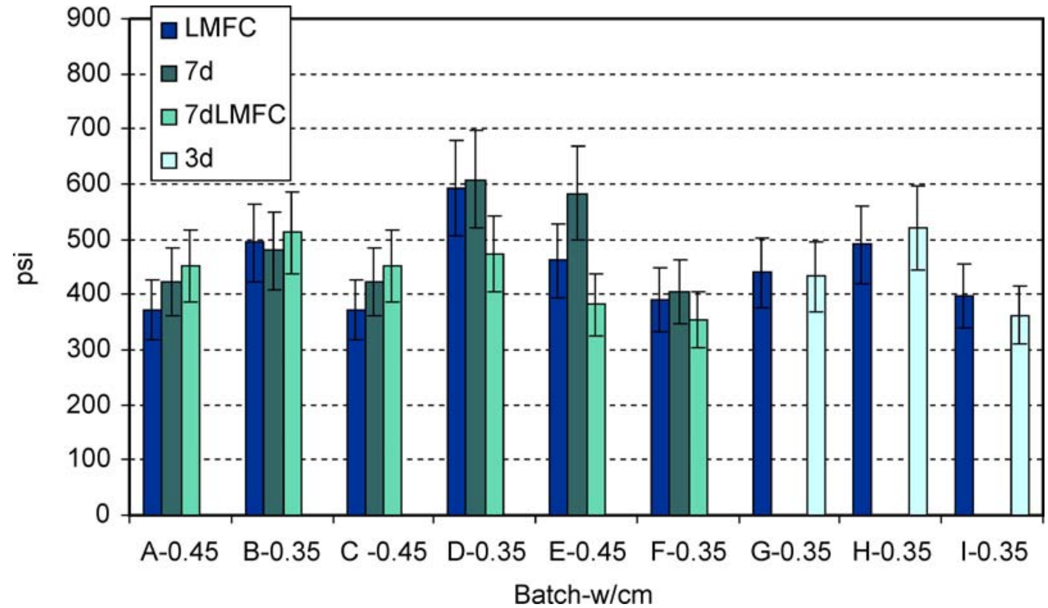


Figure 13. Three-Month Pull-Off Tensile Strength at 5/8-in Depth for Batches A Through I. The repeatability range is 29%.

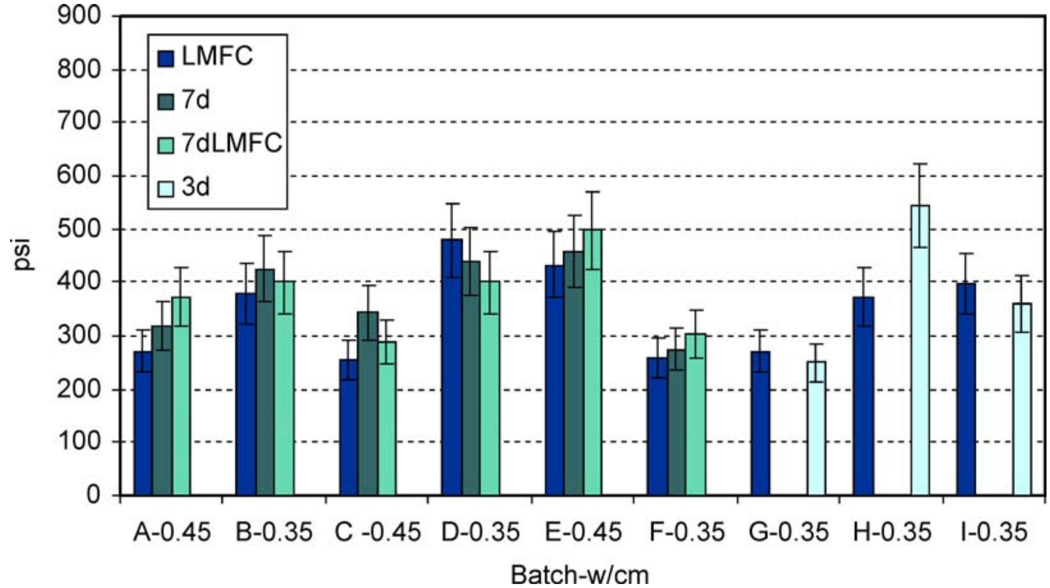


Figure 14. Three-Month Pull-Off Tensile Strength at 3-in Depth for Batches A-I. The repeatability range is 29%.

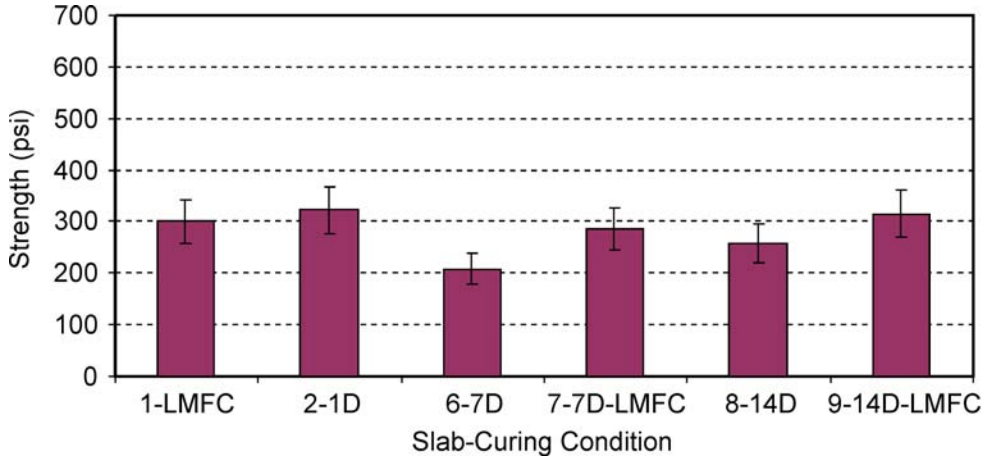


Figure 15. Tensile Strength at 3-in Depth for Selected Slabs, Batch A. The repeatability range is 29%.

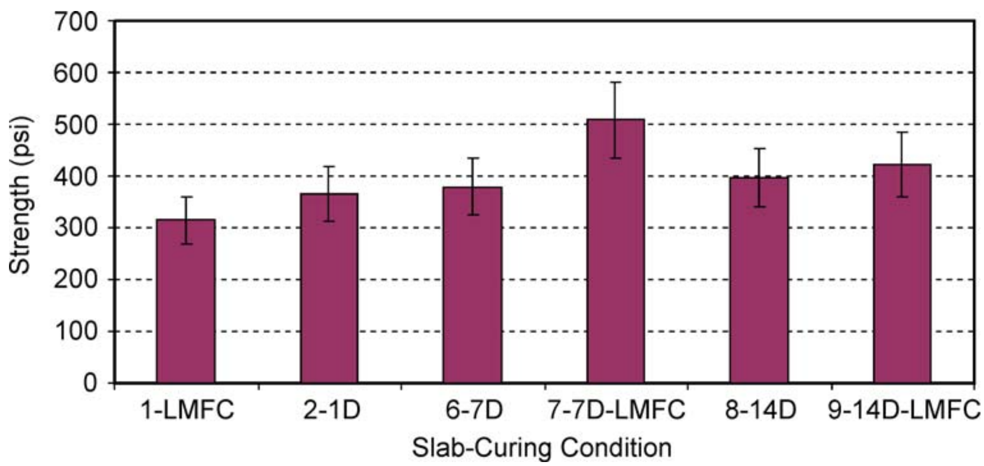


Figure 16. Tensile Strength at 3-in Depth for Selected Slabs, Batch B. The repeatability range is 29%.

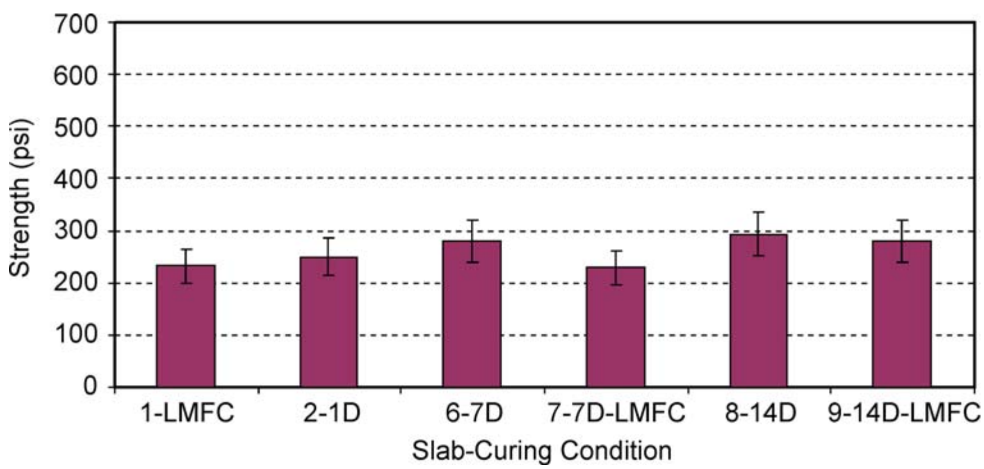


Figure 17. Tensile Strength at 3-in Depth for Selected Slabs, Batch C. The repeatability range is 29%.

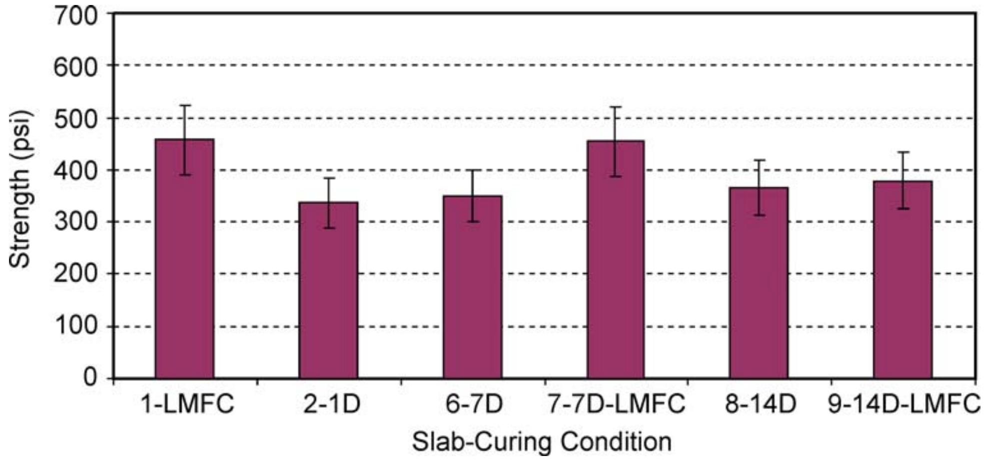


Figure 18. Tensile Strength at 3-in Depth for Selected Slabs, Batch D. The repeatability range is 29%.

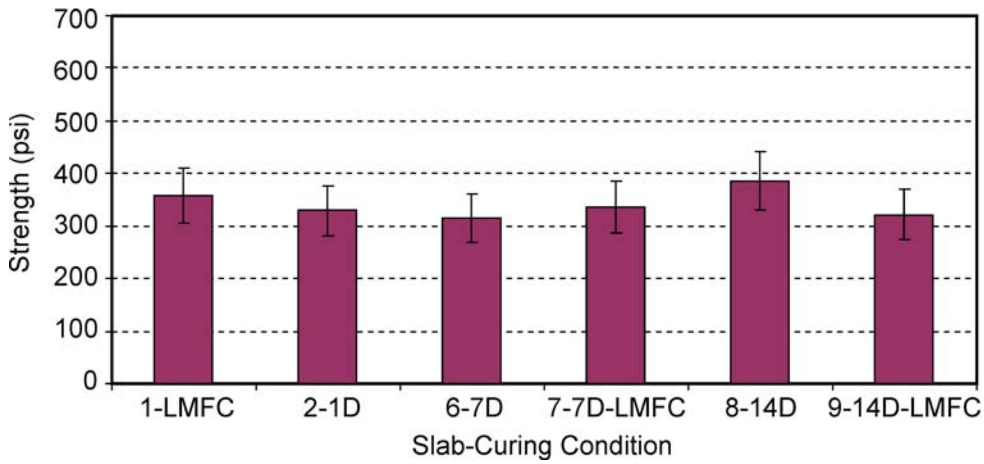


Figure 19. Tensile Strength at 3-in Depth for Selected Slabs, Batch E. The repeatability range is 29%.

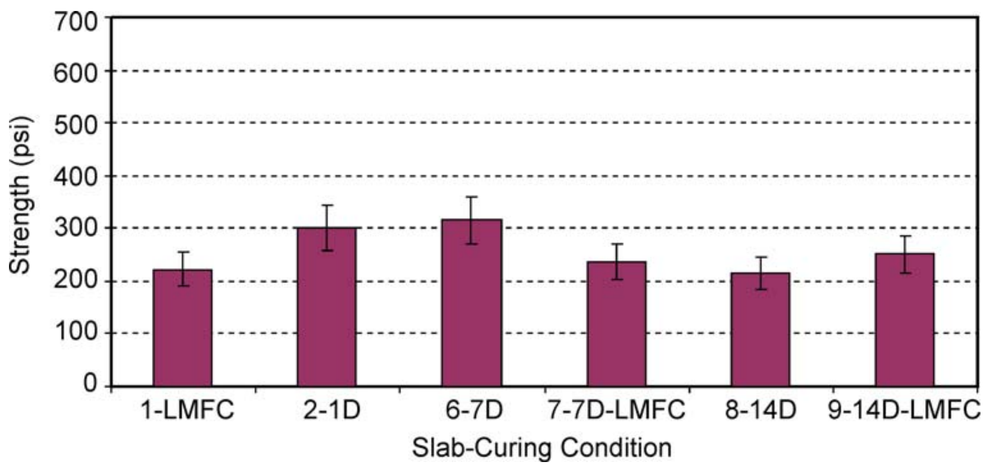


Figure 20. Tensile Strength at 3-in Depth for Selected Slabs, Batch F. The repeatability range is 29%.

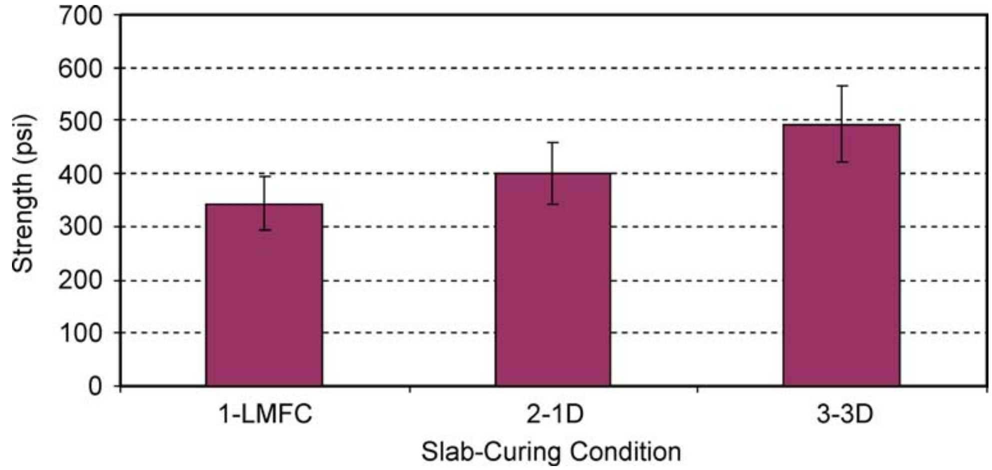


Figure 21. Tensile Strength at 3-in Depth for Selected Slabs, Batch G. The repeatability range is 29%.

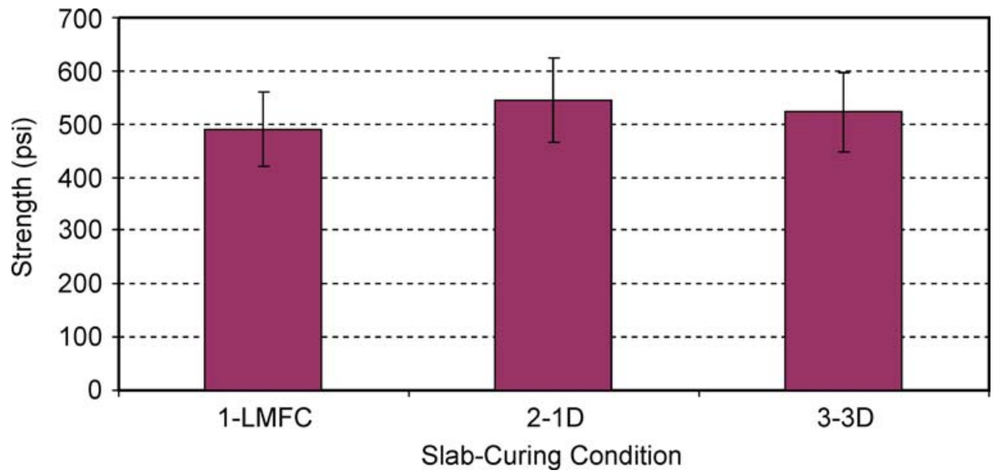


Figure 22. Tensile Strength at 3-in Depth for Selected Slabs, Batch H. The repeatability range is 29%.

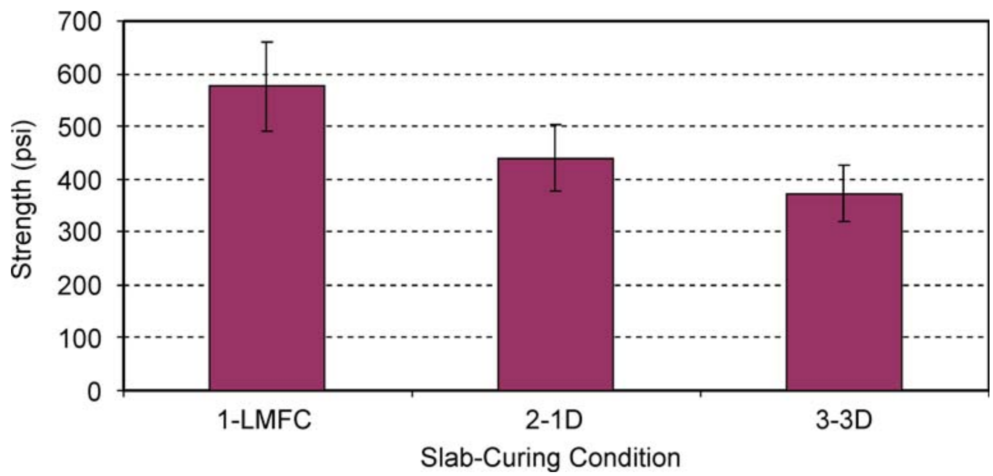


Figure 23. Tensile Strength at 3-in Depth for Selected Slabs, Batch I. The repeatability range is 29%.

The lack of a dramatic impact of length of moist curing on strength in these tests may seem surprising. Conventional wisdom holds that the longer the moist curing, the better—particularly for HPCs with pozzolans or slag cement and/or with low w/cm. However, certain aspects of the findings with regard to strength are similar to those reported by Carino and Meeks (2001) who found 1 day of moist curing likely sufficient for HPC. Their study examined mortars at 0.30 and 0.45 w/cm, moist cured for 1, 3, or 7 days followed by drying from one surface at 50% or 70% RH and compared to continuous moist curing. Tensile testing was performed at 28 days. They noted a potential confounding influence on strength measurement that drying may have because of physical aspects that result in increased strength. However, they indicated that the drying front did not progress much beyond ½ in with deeper penetrations associated with lower RH and higher w/cm. Likewise, they found a large decrease in moisture loss after 5 days of drying for 0.45 w/cm specimens that had been moist cured for 3 days as opposed to 1 day but only a subtle effect from extending moist curing to 7 days. For the 0.30 w/cm mortars, the moist curing duration effect on moisture loss was only subtle. Carino and Meeks (2001) drew from this and much earlier work (Powers et al., 1959) that the benefit to durability of longer duration moist curing increases with increasing w/cm.

Comparisons used to support extended moist curing are often referenced between continuous moist curing and indoor drying conditions at constant low humidity. This study contrasts a range of moist curing conditions that are being applied to bridge decks (up to 14 days) followed by outdoor environmental exposure over an extended period. As such, the results of this study are likely more relevant to actual field practices in similar climatic regions.

The 1-year electrical conductivity results for cores removed from selected slabs are shown in Figures 24 through 32. Conductivities were measured on specimens retrieved from two depths below the surface of the slab: 0 through 2 in and 3 through 5 in. The conductivity values for Batch A (PC, 0.45 w/cm) were considerably higher than for the other batches, as is typical for straight portland cement concrete at this w/cm. For Batch D (PC 0.35 w/cm), the conductivities were considerably lower and nearly on par with the conductivities of mixtures containing pozzolans or slag cement. Batch D conductivities were lowest for the LMFC and 1-day wet curing conditions, both near-surface and at-depth. For Batch F, the near surface conductivities tended to increase with increasing wet curing duration, but the conductivities at depth were constant across curing conditions. For the remaining batches, conductivities both near-surface and at-depth were low and did not show a consistent trend with increasing wet curing duration. Batches B and C near-surface conductivities were reduced by the 1-day wet curing over the LMFC conditions, but beyond that, differences in curing exhibited little impact.

The initial and secondary sorptivities for cores removed from selected slabs at 1 year are shown in Figures 33 through 41. The initial sorptivity is a function of the rate of absorption over the initial 6-hour period. The secondary sorptivity is the longer-term rate of absorption extending from 6 hours over several days (Lane, 2006b). Typically in concretes with good transport characteristics, the initial sorptivity will be higher than the secondary sorptivity, indicating a closing-off of the capillary pore system (Martys and Ferraris, 1997), suggesting that the secondary rate may be of more significance with respect to long-term durability than the initial rate. As points of reference, Lane (2006a) reported values of 20×10^{-4} and 10×10^{-4}

mm/s$^{1/2}$, respectively, for initial and secondary sorptivity as desirable upper limits based on a survey of mature bridge decks.

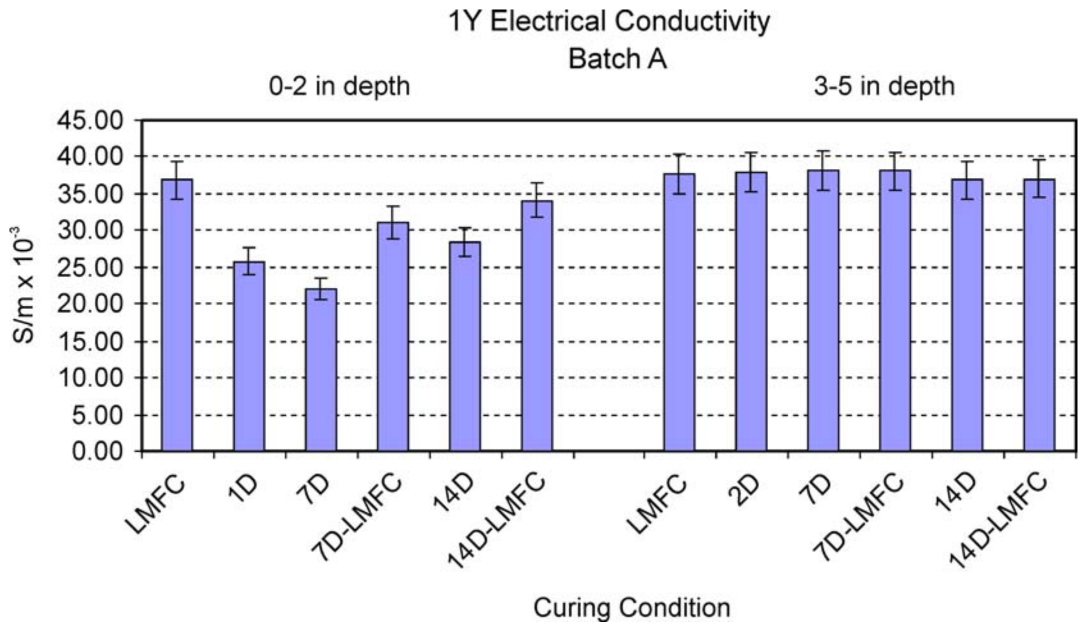


Figure 24. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch A. The repeatability range is 14%.

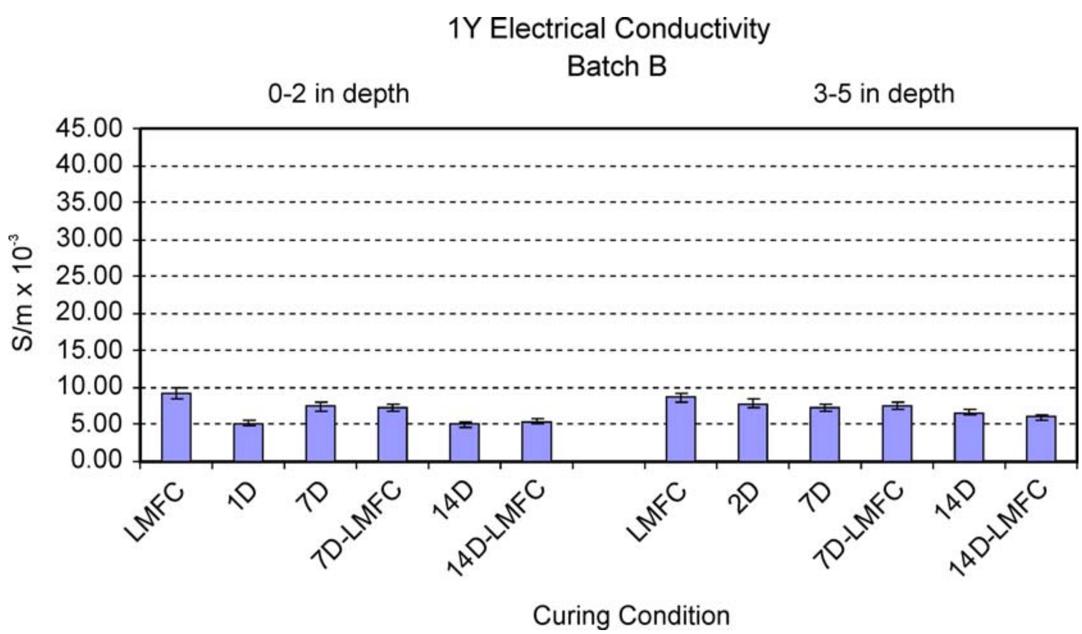


Figure 25. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch B. The repeatability range is 14%.

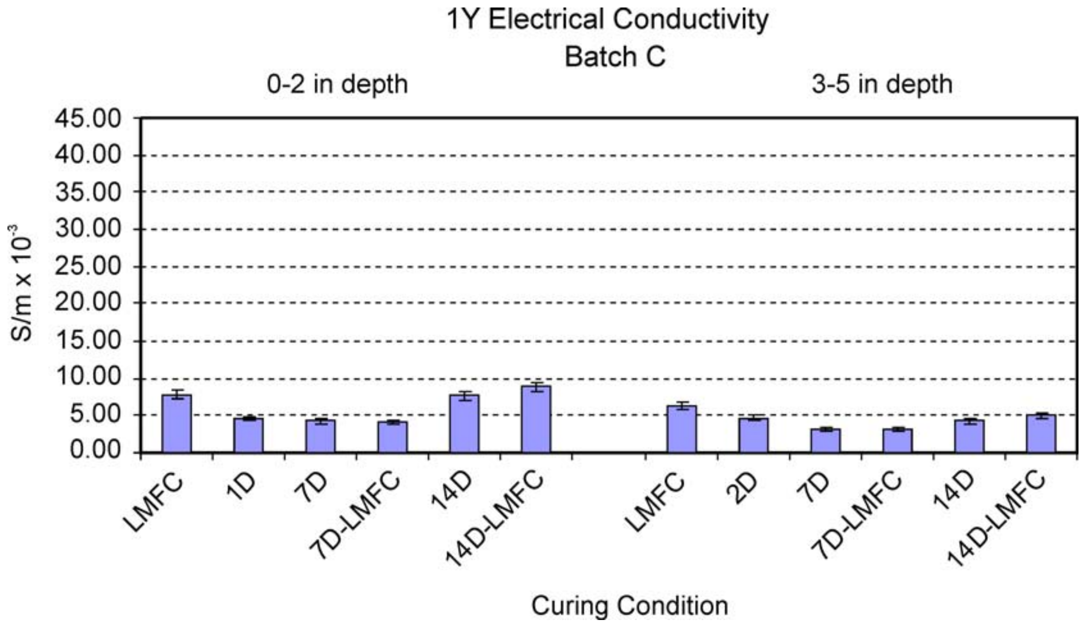


Figure 26. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch C. The repeatability range is 14%.

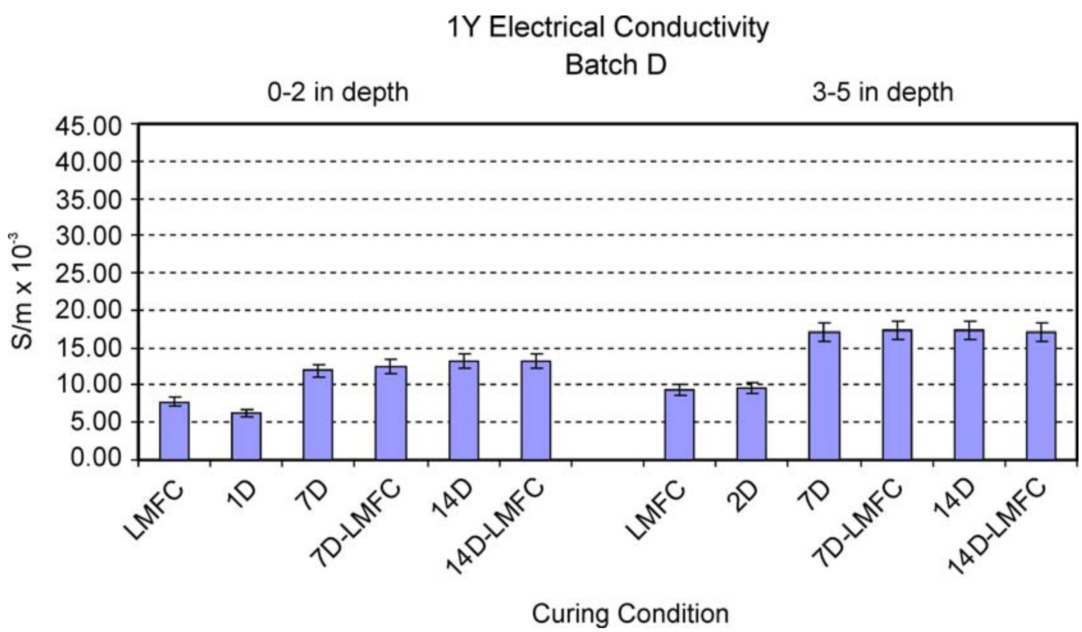


Figure 27. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch D. The repeatability range is 14%.

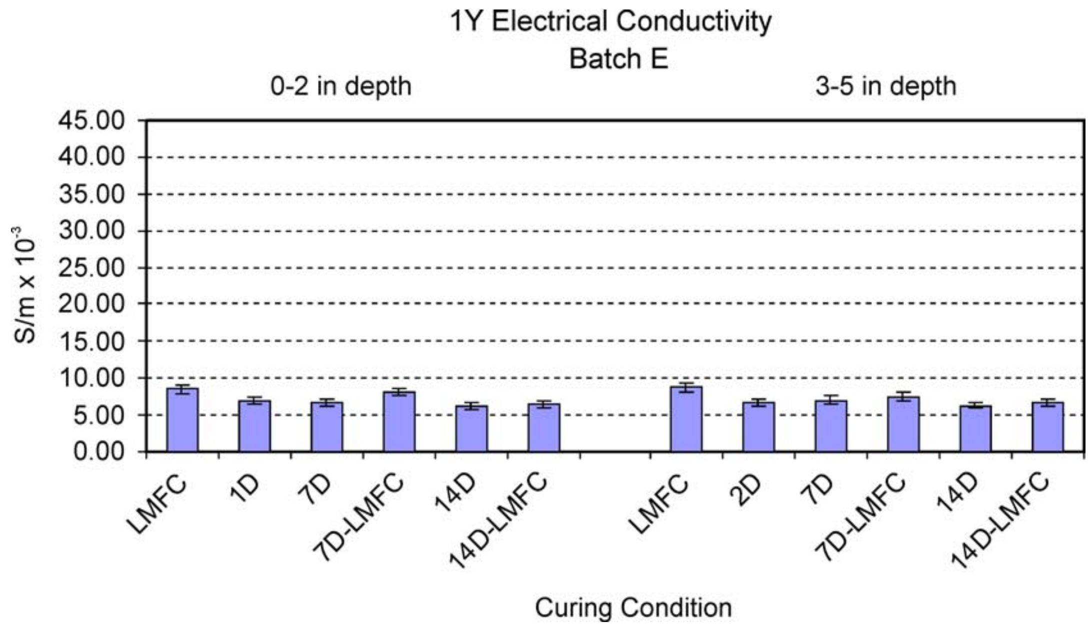


Figure 28. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch E. The repeatability range is 14%.

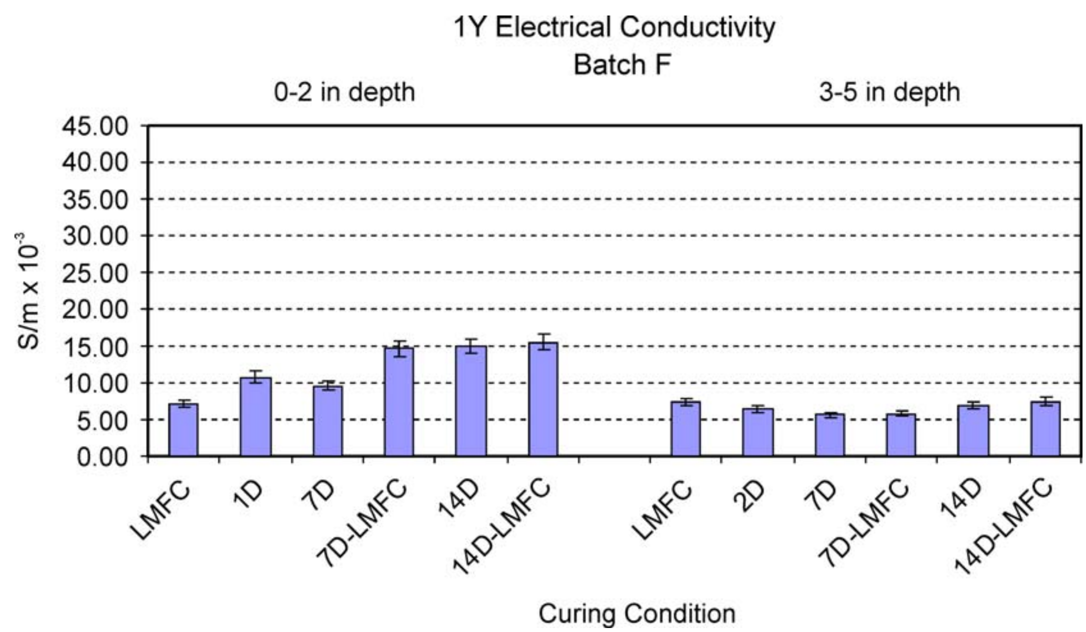


Figure 29. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch F. The repeatability range is 14%.

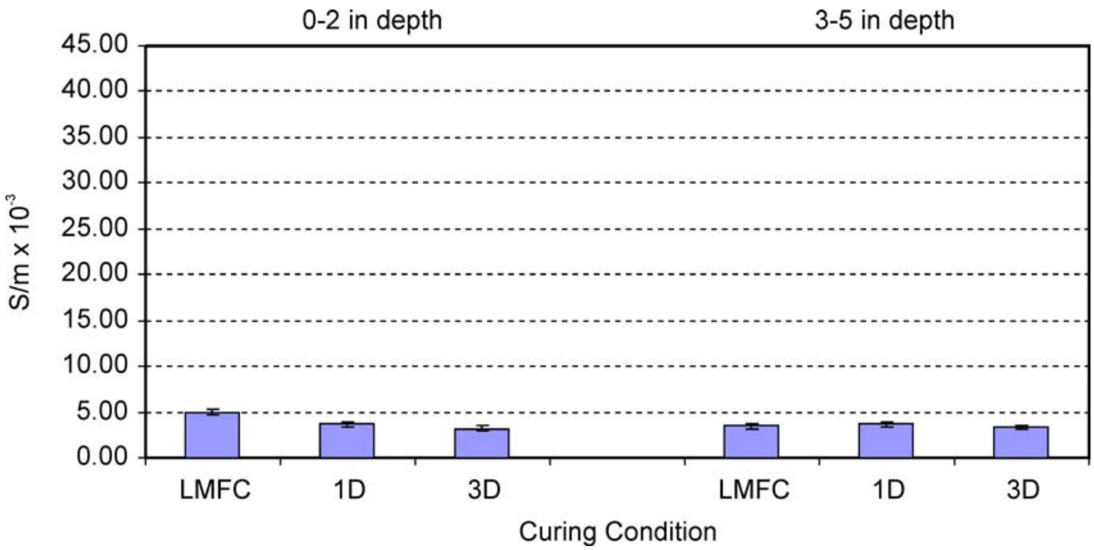


Figure 30. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch G. The repeatability range is 14%.

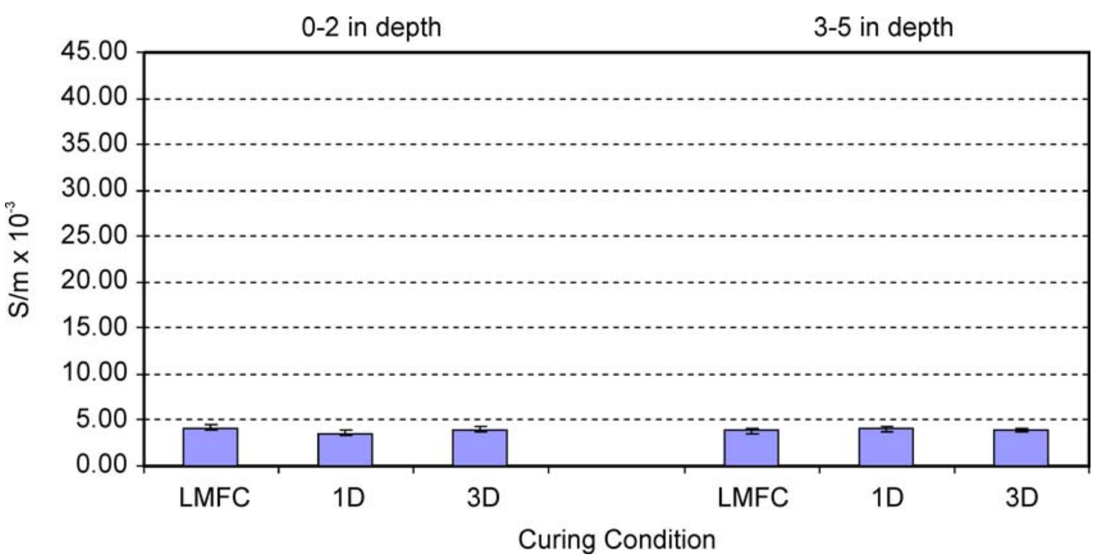


Figure 31. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch H. The repeatability range is 14%.

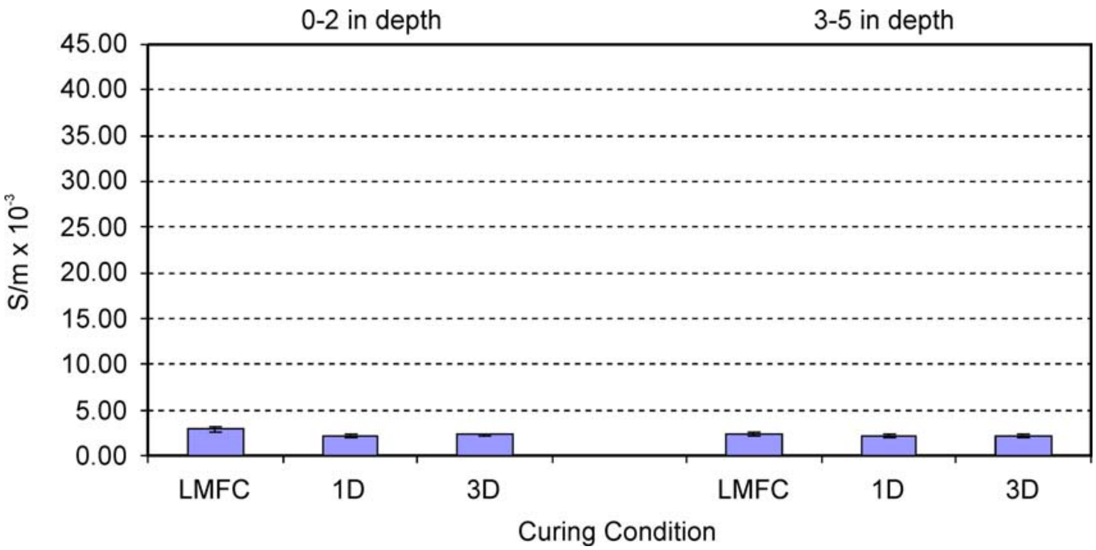
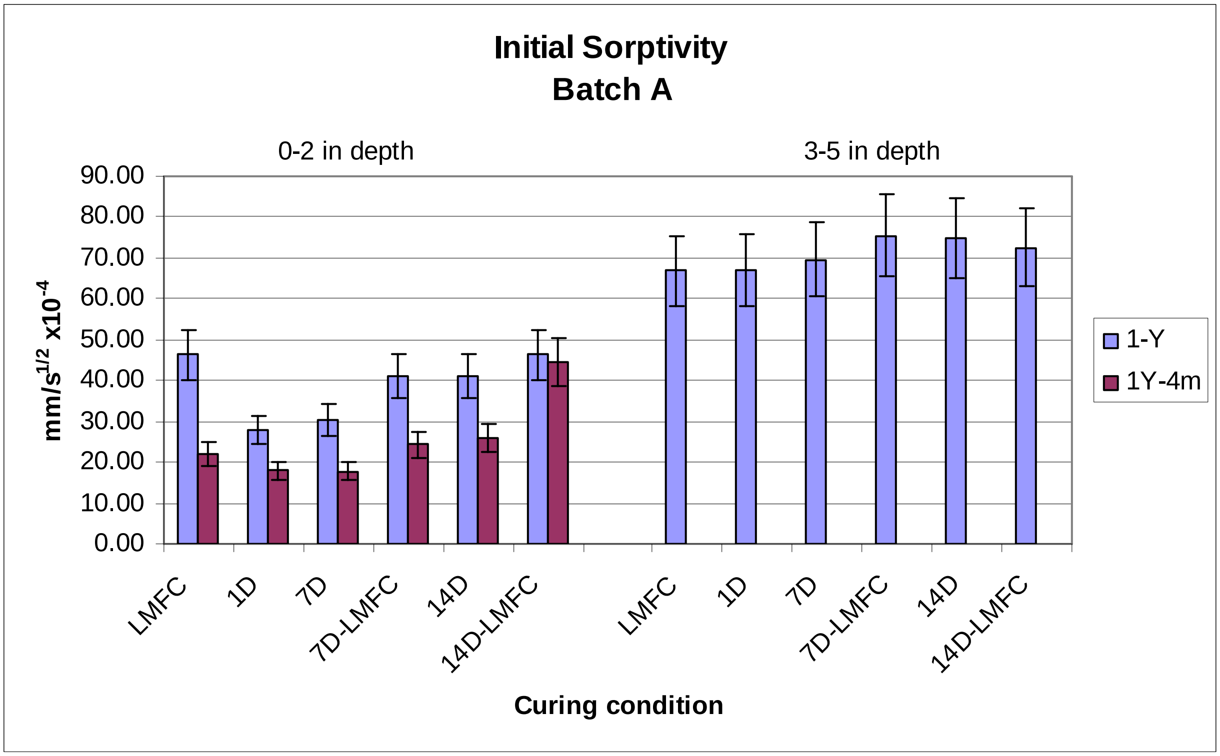


Figure 32. 1-Year Electrical Conductivity at Depths of 0-2 in and 3-5 in Below Surface for Selected Curing Conditions, Batch I . The repeatability range is 14%.

Sorptivities were originally measured at 1 year following standard conditioning at 80% RH. The initial sorptivity values for Batch C (Figure 35) showed a precipitous drop between the 14-day and 14-day-LMFC conditions that raised concern that a systematic error had occurred. A likely cause for the disparate results was that specimens were not brought to similar internal RH conditions; e.g., a nearly saturated specimen will yield much lower sorptivity values that one in which the capillary pore systems have dried to a substantial extent. Consequently, the specimens were allowed to equilibrate in the laboratory atmosphere for 4 months and then retested. Following the retesting of all Batch C specimens, the near-surface specimens for the other batches were retested. Because of the differences in conditioning, direct comparisons between the 1-year and 1-year-4M values should not be made. Following the retesting of the Batch C specimens, the large disparity in results apparently related to curing did not occur.

Although the initial sorptivity results do not present a dramatic impact of wet curing duration on this property, there does seem to be at least a subtle positive influence of at least 1-day through 3-day wet curing over simple LMFC in Batches A (Figure 33), B (Figure 34), E (Figure 37), G (Figure 39), and H (Figure 40), but there seemed to be little or no impact provided by the use of LMFC following moist curing. These effects are not apparent in the secondary sorptivity results. The biggest influence on sorptivity in these concretes was w/cm, where both initial and secondary sorptivities were much lower for the concretes with 0.35 w/cm (Batches D, F, G, H, and I) than for those with 0.45 w/cm (Batches A and C). The notable exceptions to this trend were Batches B (0.35 w/cm) and E (0.45 w/cm), the two slag cement concretes. Comparing the results for these two batches, the initial sorptivities were fairly similar, and both showed minimal values for 1-day wet curing. Powers et al. (1959) noted the strong influence of w/c on the continuity of the pore system and estimated necessary moist curing durations of 7 days for 0.45 w/c and 3 days for 0.40 w/c pastes to achieve a discontinuous capillary system.



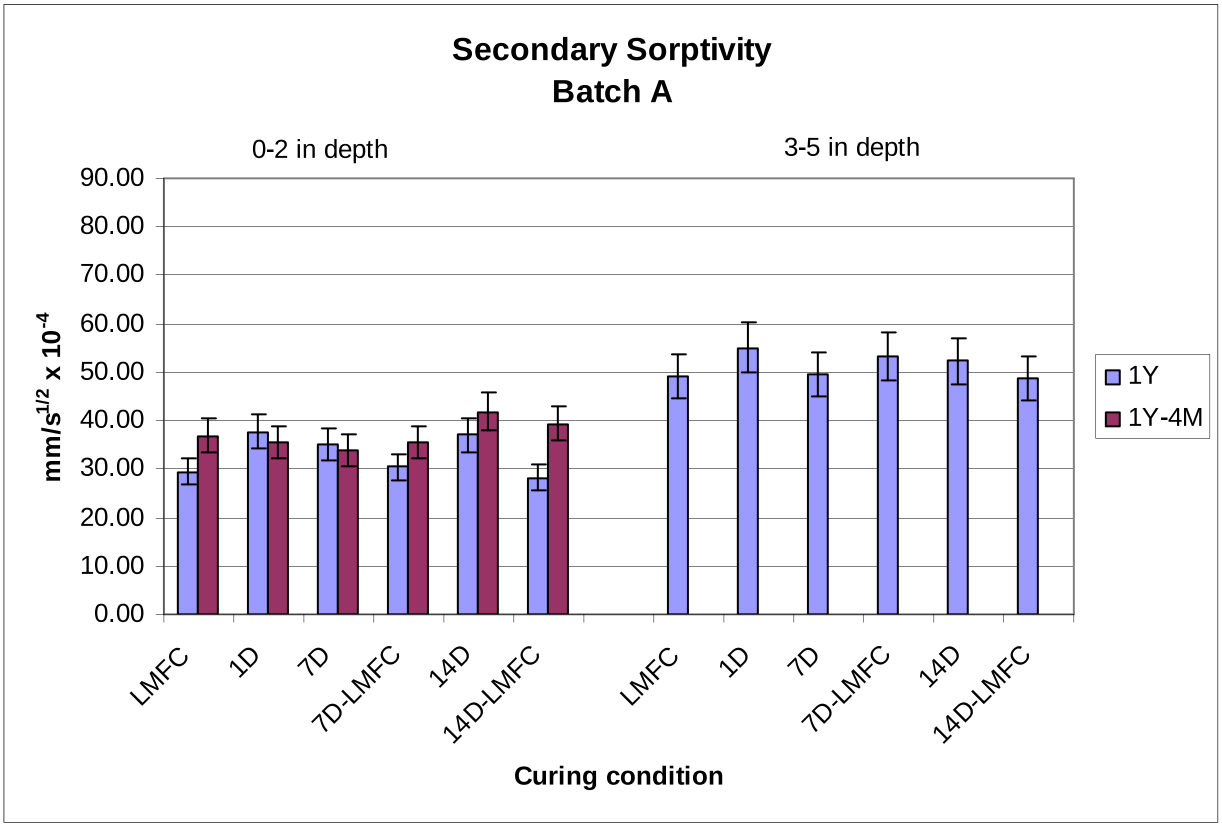
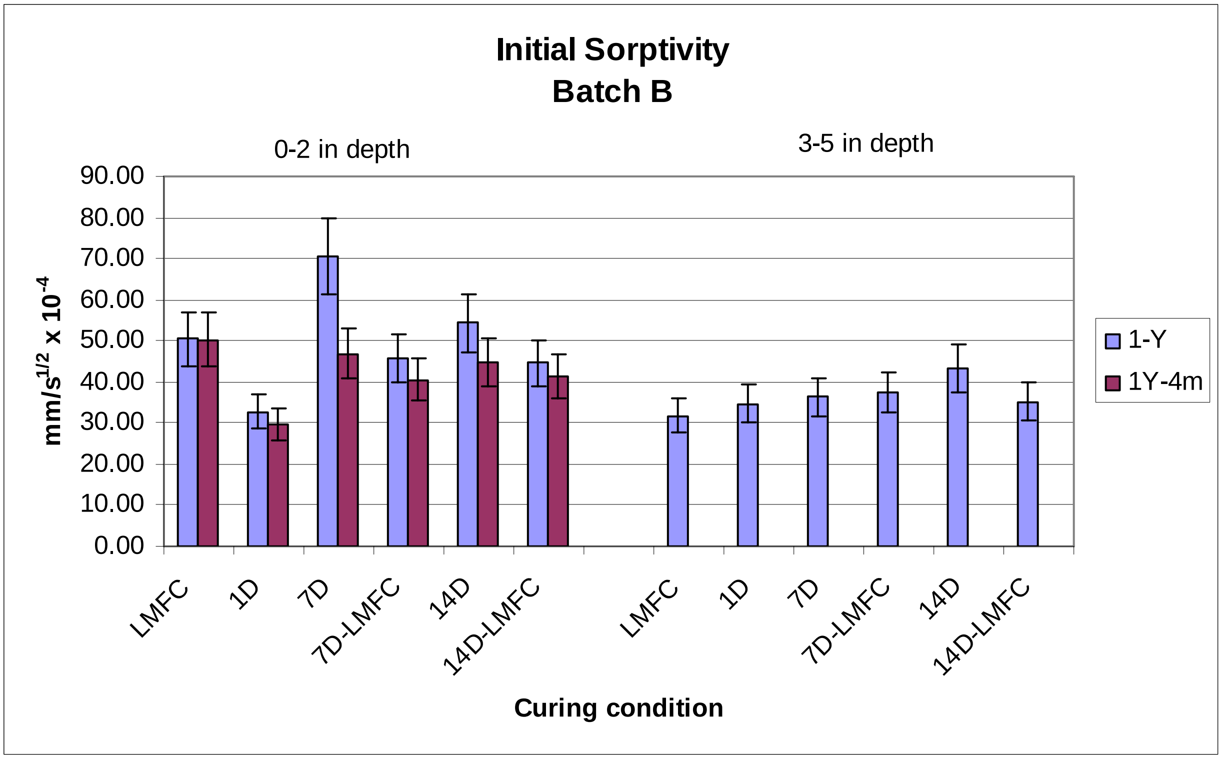


Figure 33. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch A. The repeatability range is 26%.



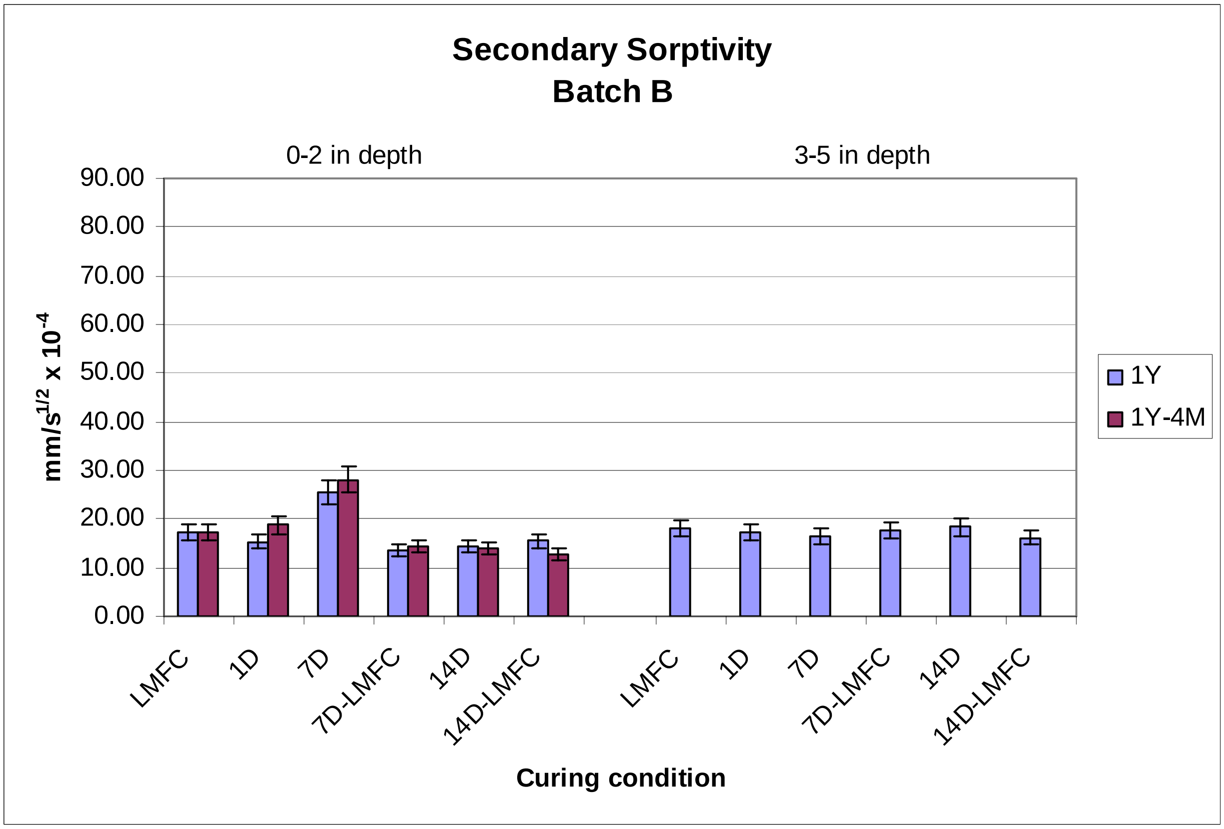
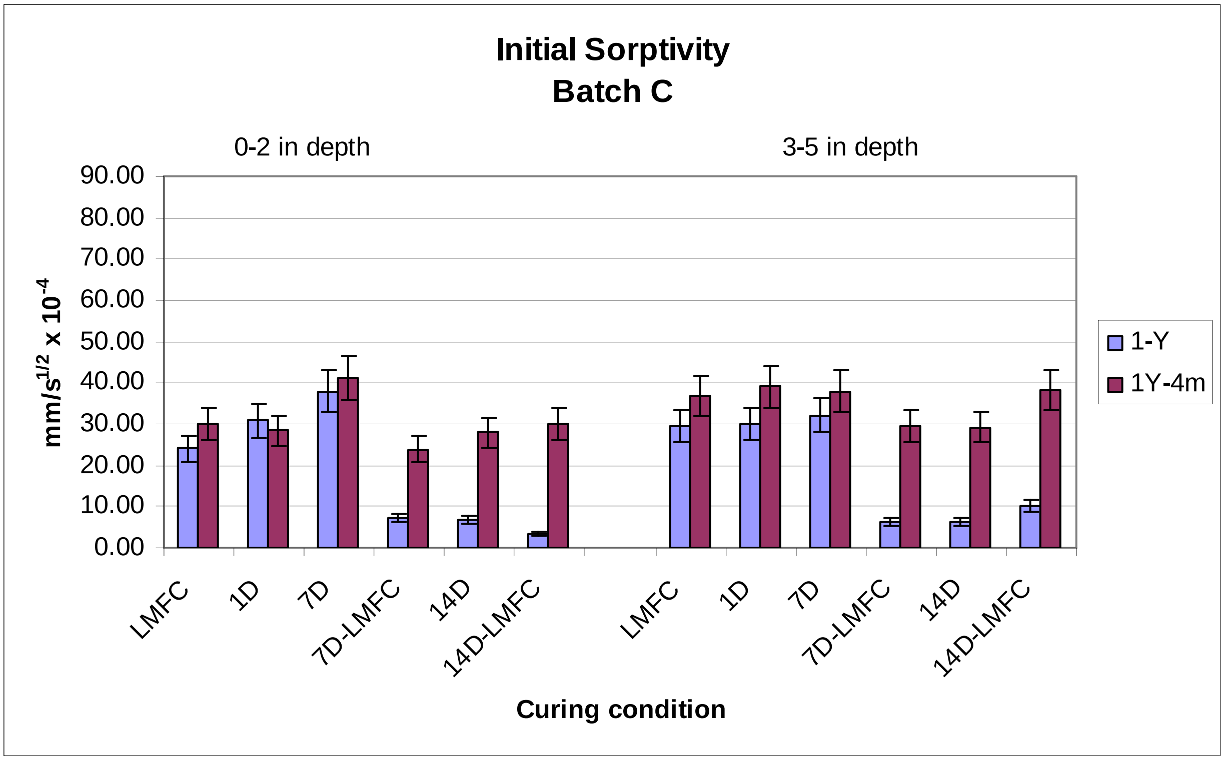


Figure 34. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch B. The repeatability range is 26%.



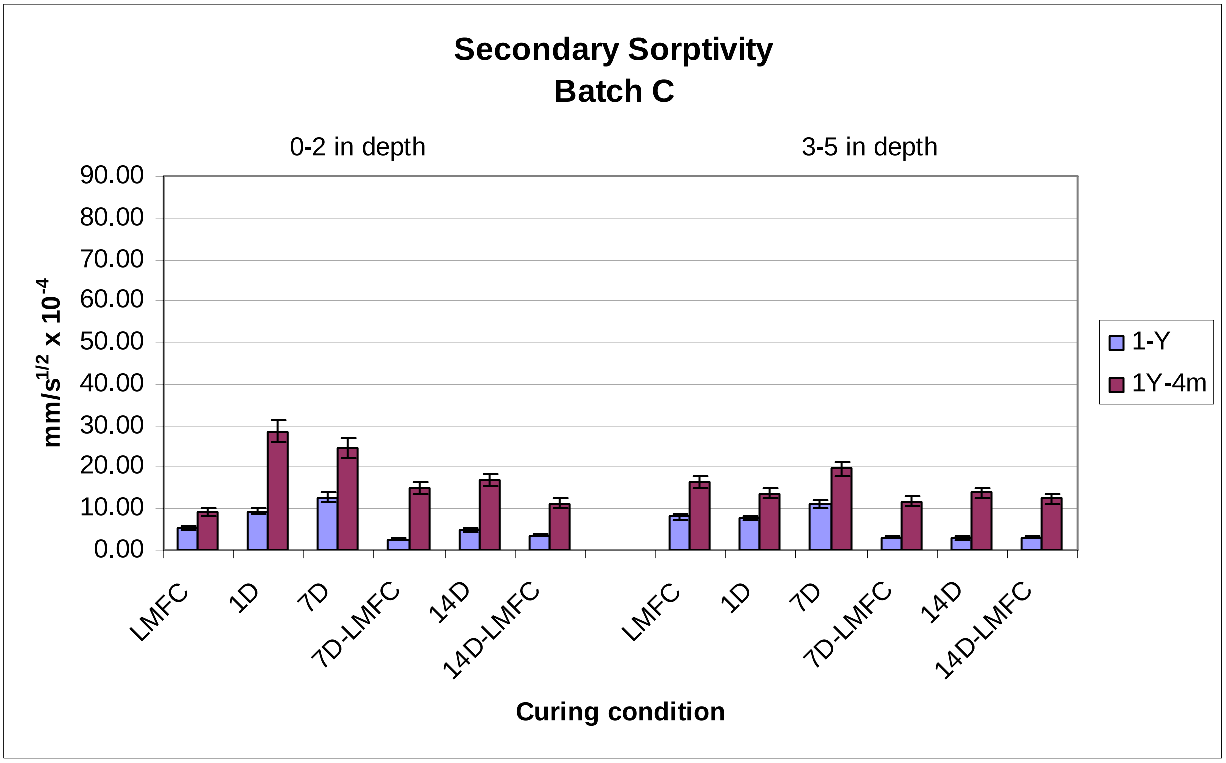
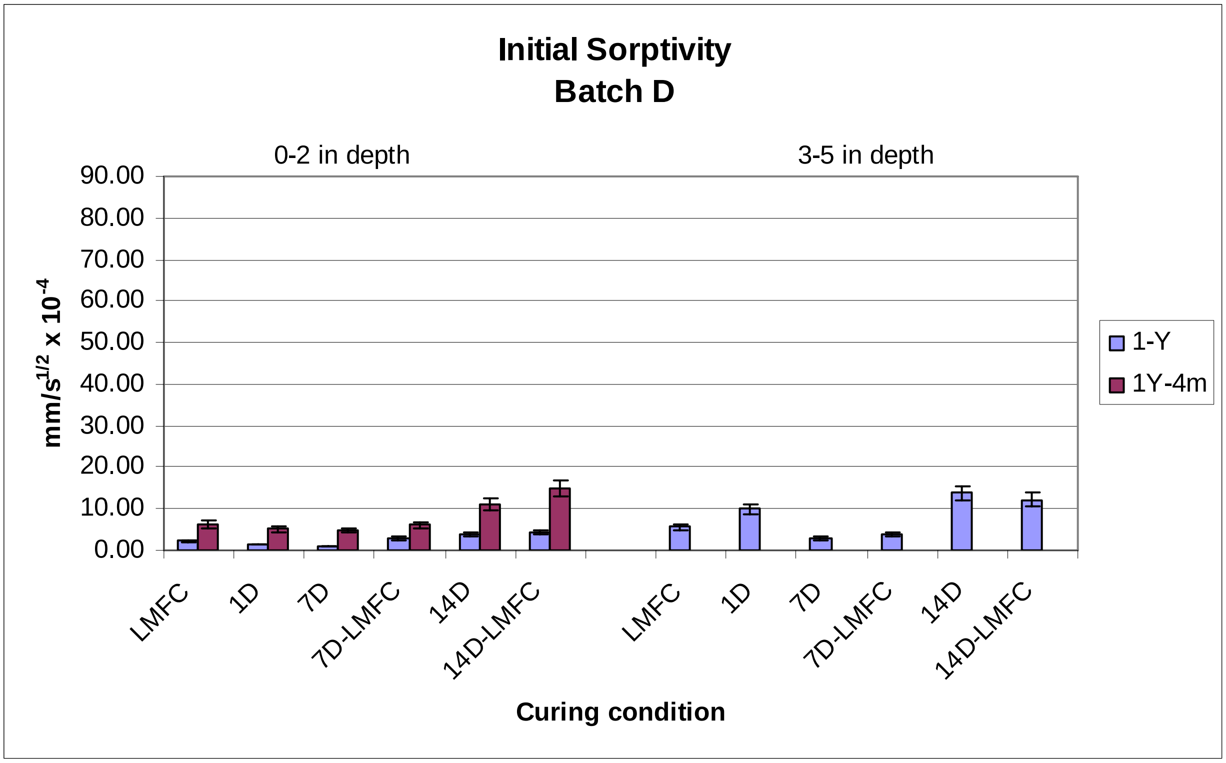


Figure 35. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch C. The repeatability range is 26%.



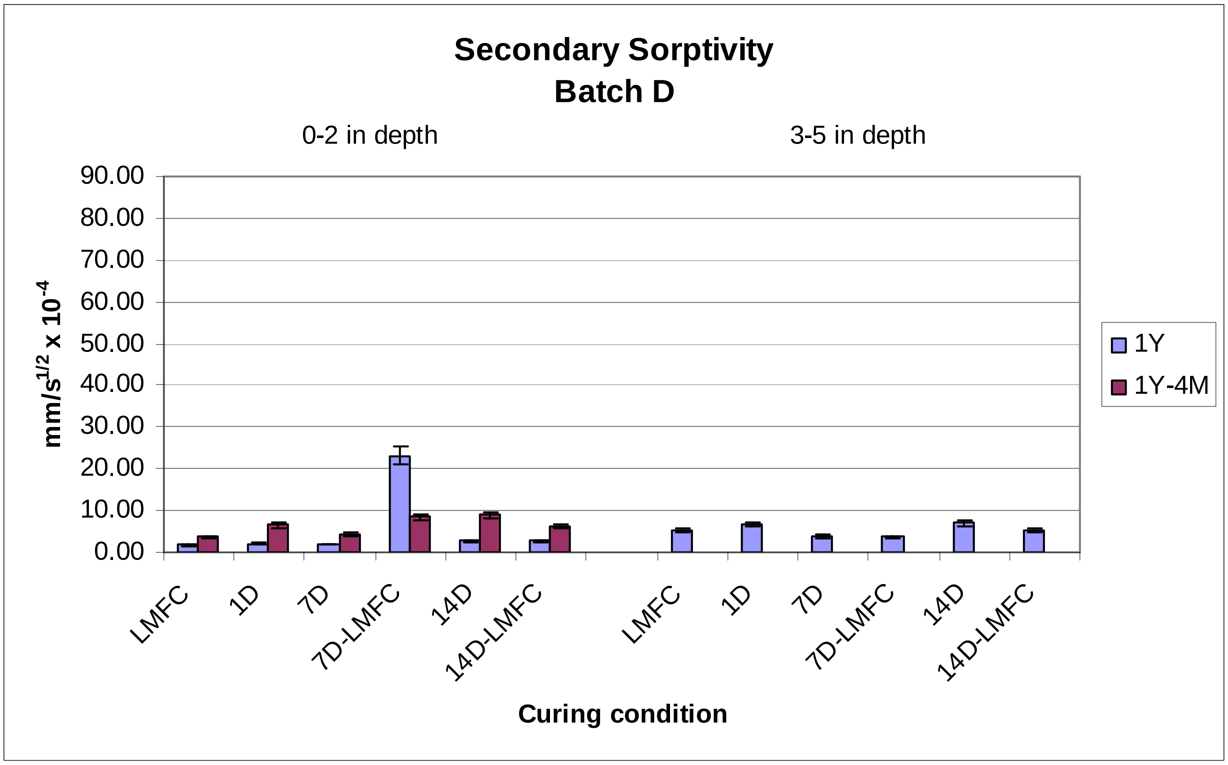
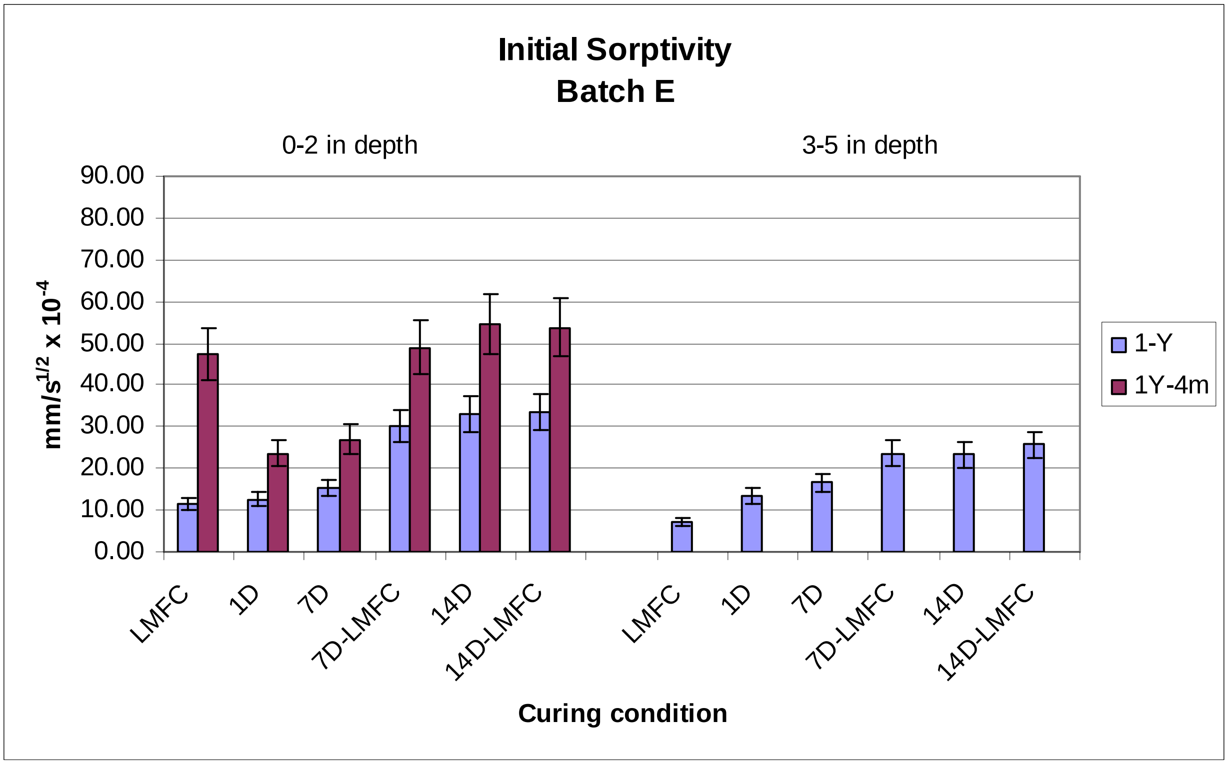


Figure 36. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch D. The repeatability range is 26%.



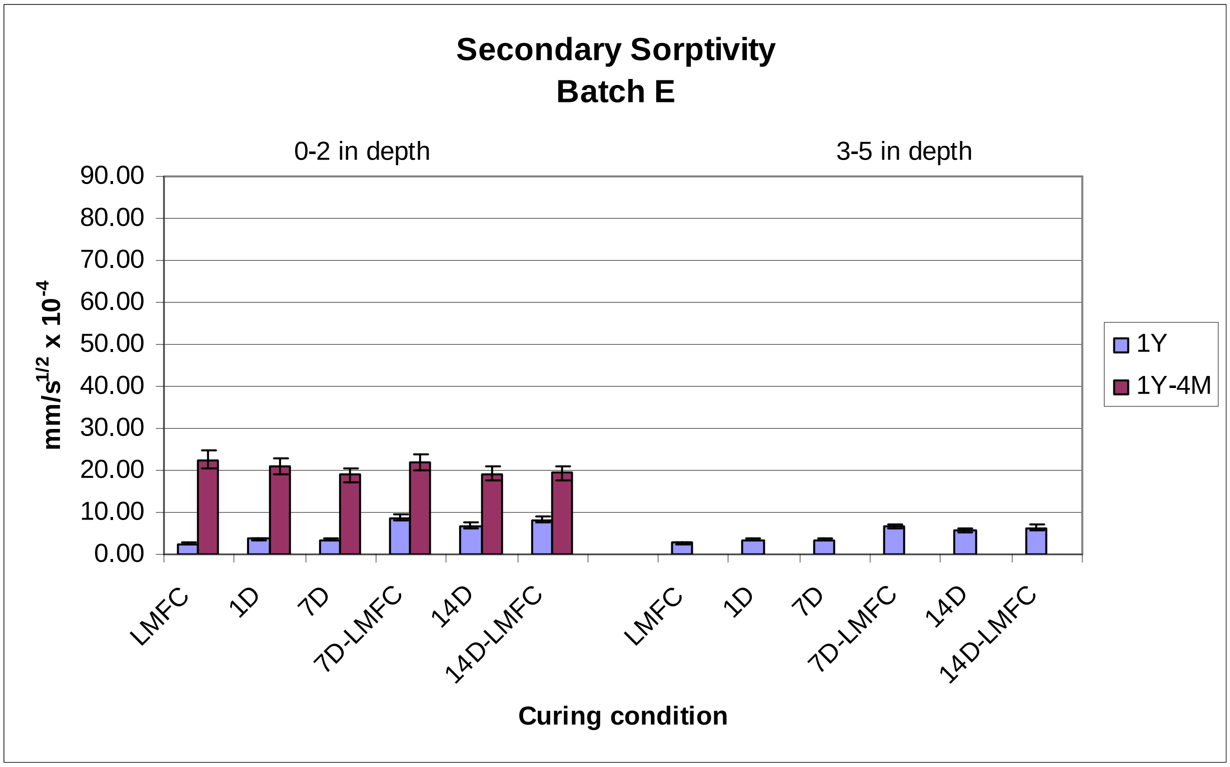
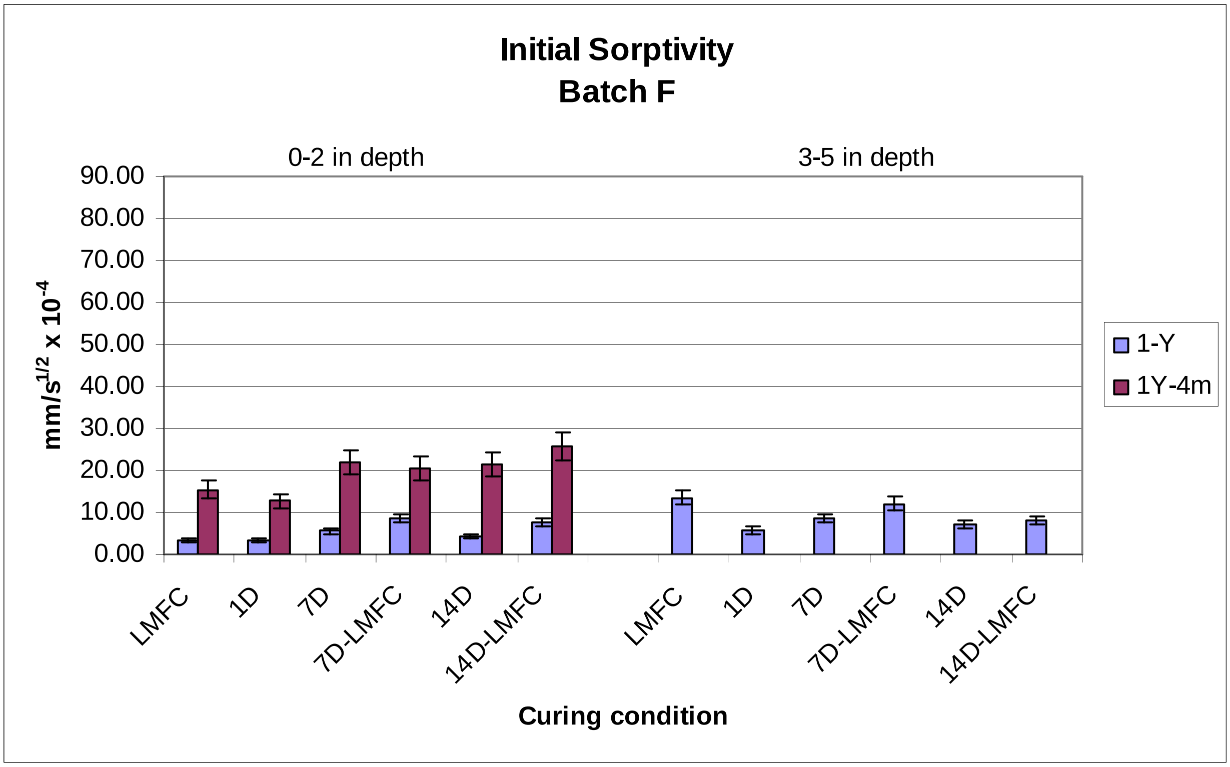


Figure 37. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch E. The repeatability range is 26%.



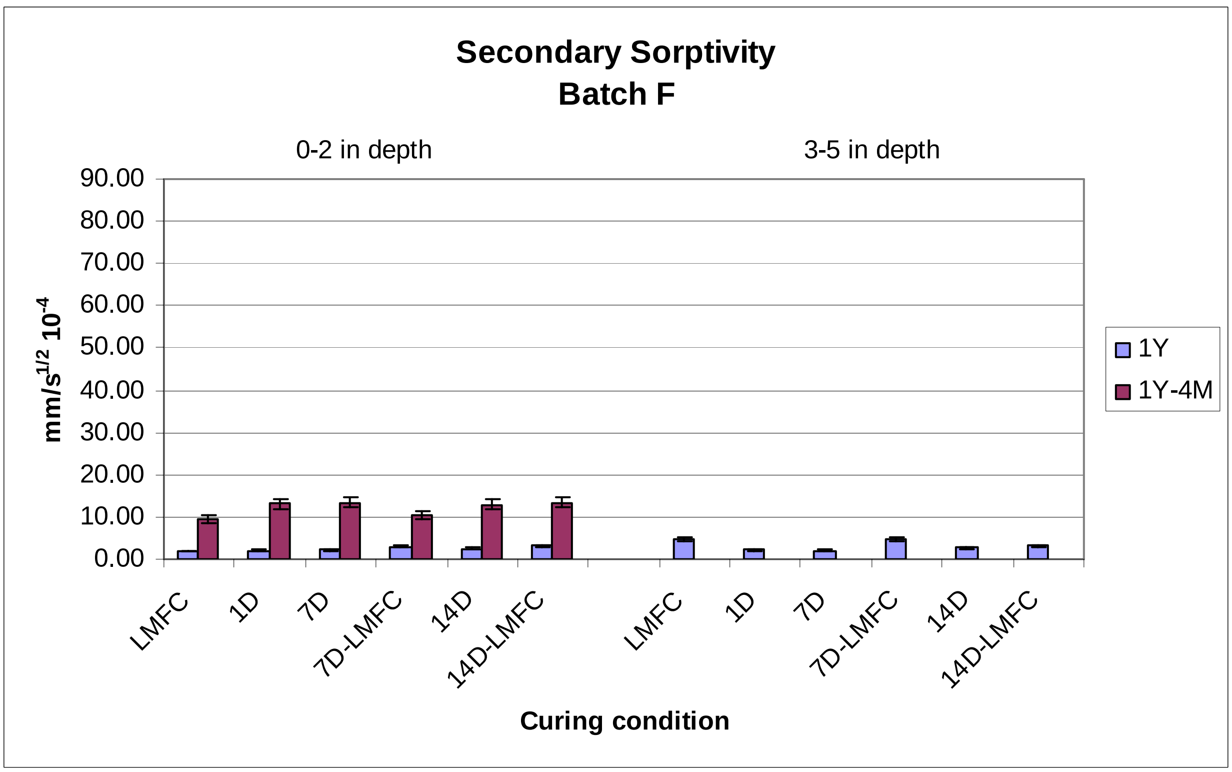
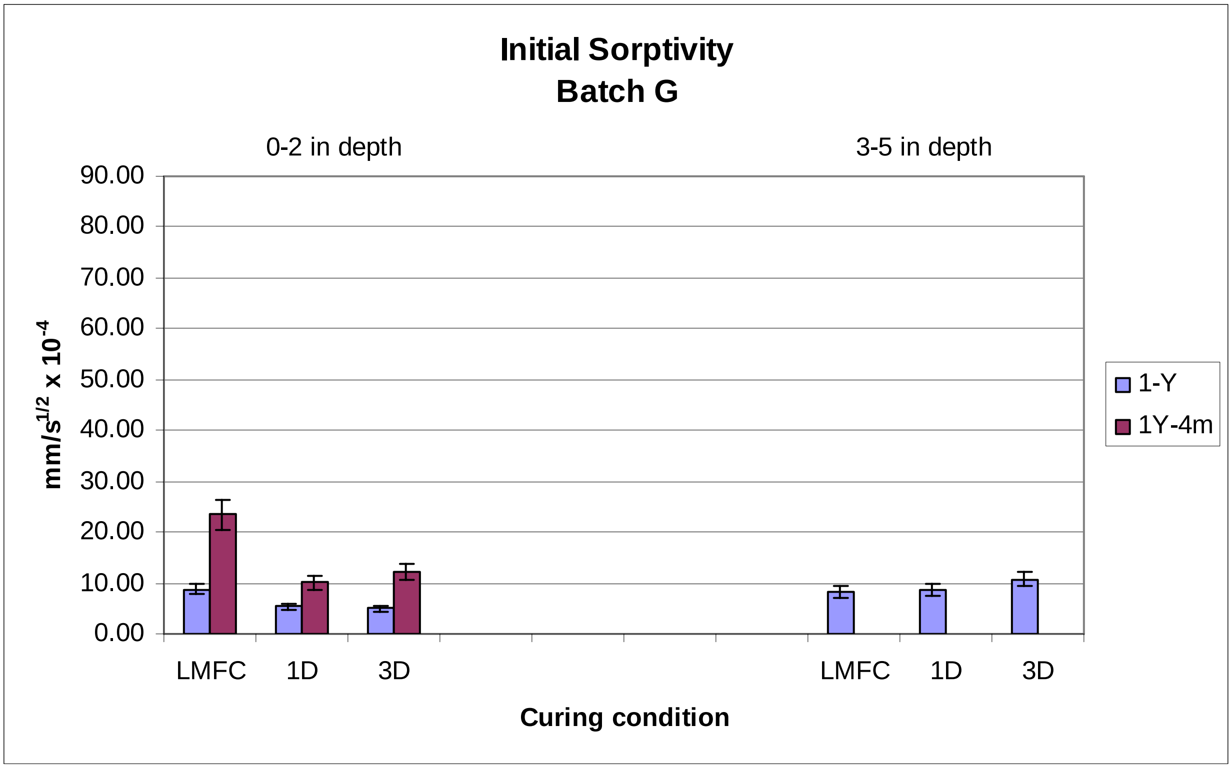


Figure 38. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch F. The repeatability range is 26%.



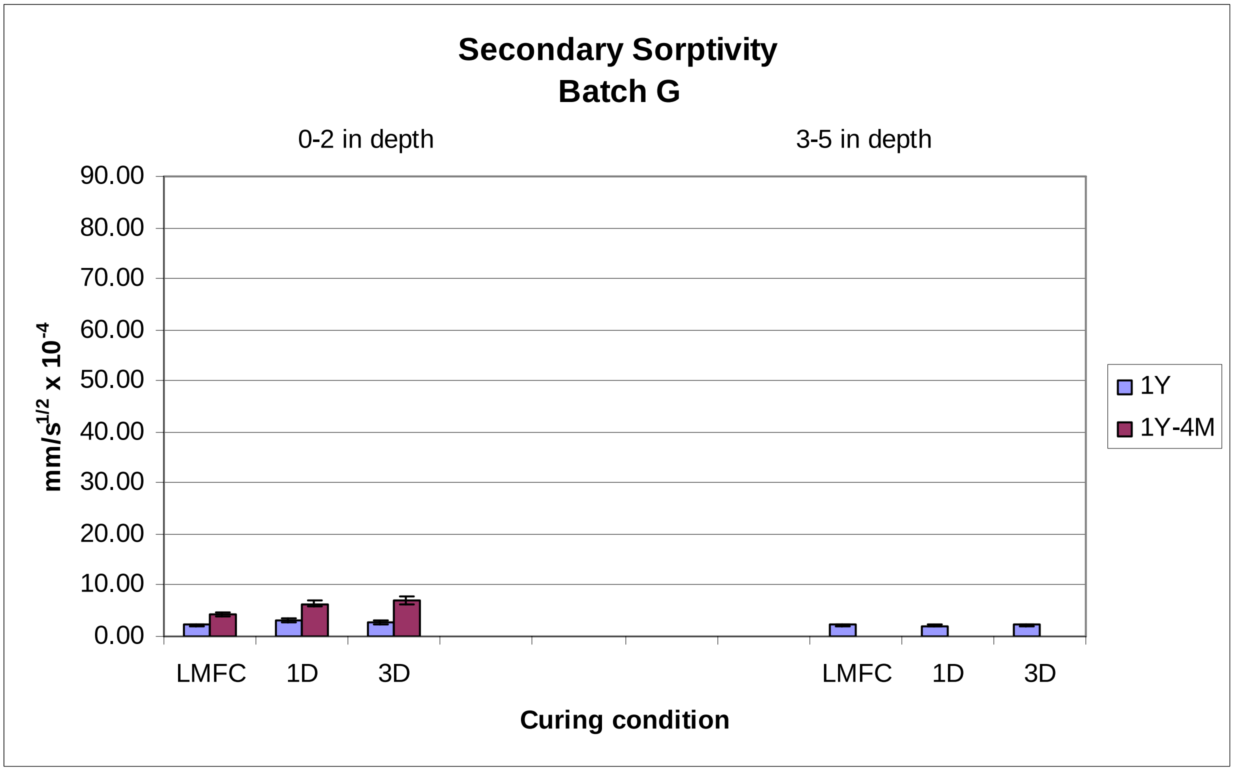
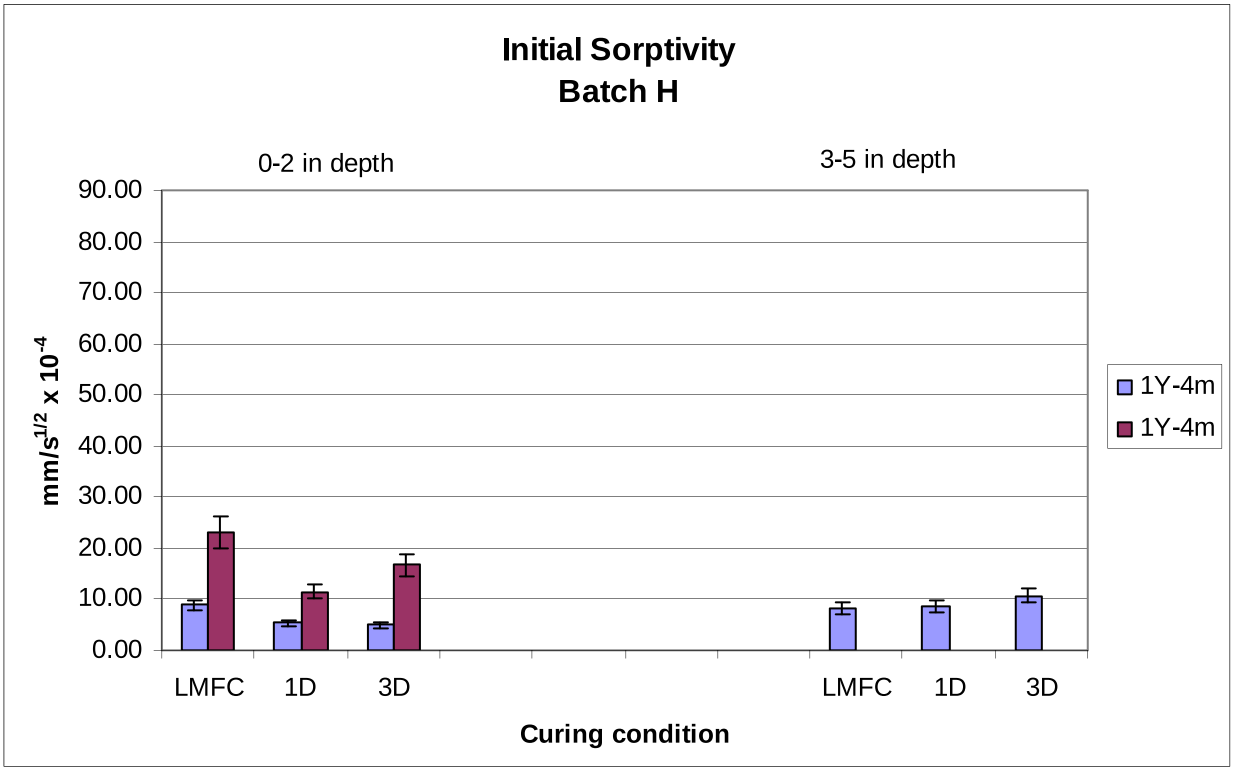


Figure 39. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch G. The repeatability range is 26%.



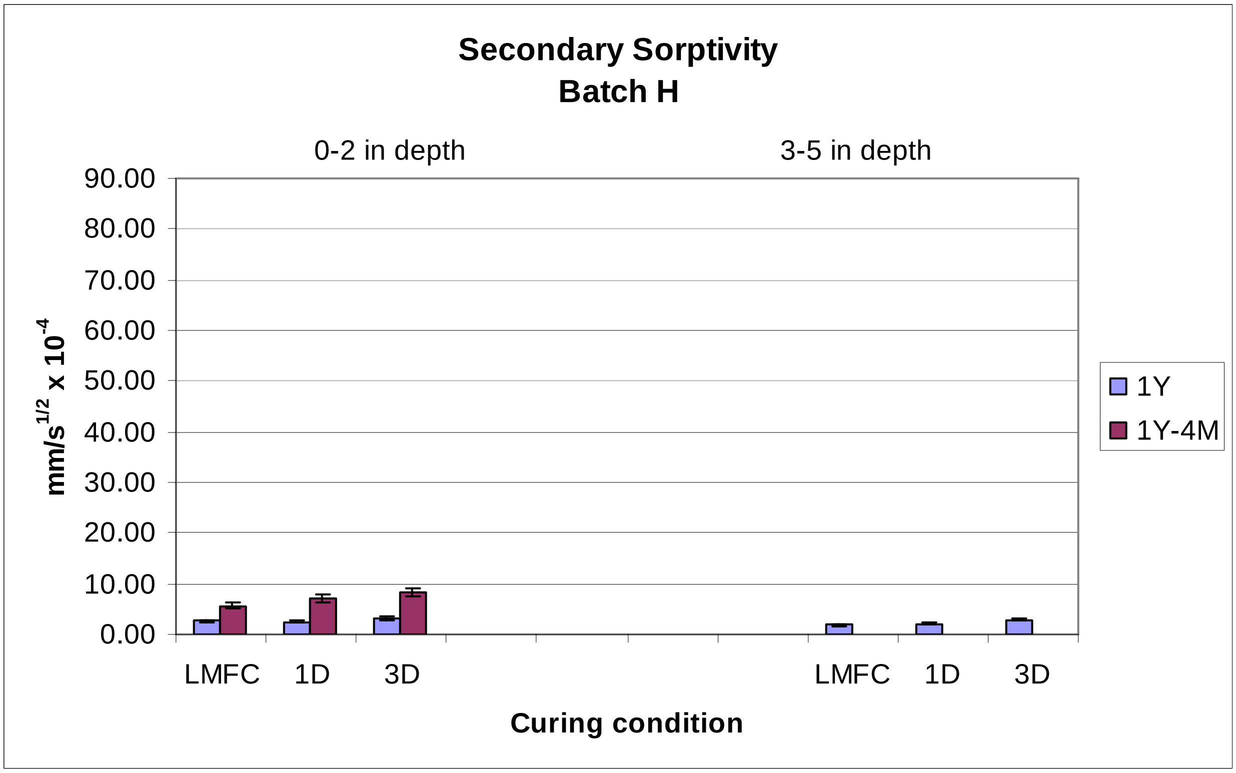


Figure 40. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch H. The repeatability range is 26%.

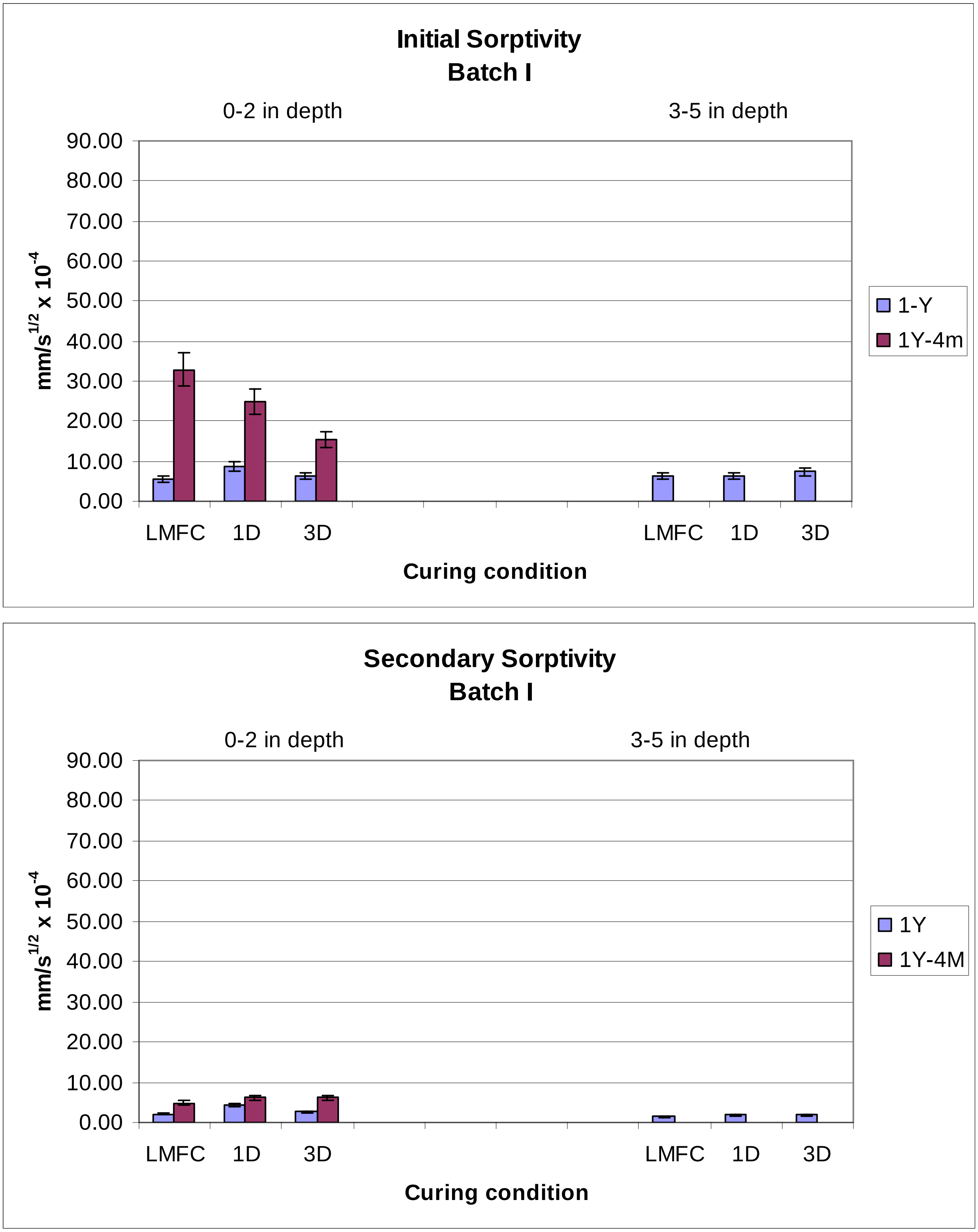


Figure 41. 1-Year + Initial and Secondary Sorptivity at Selected Curing Conditions, Batch I. The repeatability range is 26%.

Examination of thin sections revealed a fair amount of cracking in the slag cement concretes (Figures 42 through 45), which likely explains the relatively high initial sorptivities for these concretes. The slag concretes did, however, also contain residual unhydrated slag cement particles (Figure 45) that can continue to hydrate provided sufficient moisture is present. The prospect for this appears good based on the apparent high moisture content of the slabs and from examinations of mature bridge deck concretes containing slag cement where sorptivities generally were low (Lane, 2006a), but continued monitoring of these slabs or actual bridge decks containing slag cement should be carried out to confirm their ability to provide low transport properties in the long term.

The observation of unhydrated remnants of grains of cementitious materials is to be expected in concretes of this general quality. Figures 46 and 47 show unhydrated fly ash and silica fume agglomerate, respectively. Ideally the silica fume agglomerate would have been broken into the much finer individual particulates, dispersed, and hydrated. Often, a lack of unhydrated particles of portland cement, fly ash, or slag cement is a sign of high w/cm. For instance, Powers et al. (1959) reported that 100% hydration of cement was necessary to achieve discontinuity in the capillary system of a paste at 0.7 w/c; only 70% hydration was needed at 0.5 w/c. Although severe early drying could result in an excessive amount of unhydrated cementitious material, the general properties of these concretes and the observations regarding RH do not support a conclusion that that occurred.

The relatively high sorptivities for the slag cement concretes (Batches B and E) stand in contrast to their low electrical conductivity (Figures 25 and 28). This feeds a recurring question of the meaningfulness of the electrical measures of concrete transport properties, particularly for mature concretes. Lane (2006a) reported low electrical conductivity for many bridge deck concretes that stood in contrast to their high initial and secondary sorptivities. Similarly, Ozyildirim and Halstead (1992) reported data for bridge deck concretes showing little correspondence between electrical charge passed in coulombs (AASHTO T 277, ASTM C 1202) and chloride penetration.

Similar to the findings of the pull-off strength tests, the results of the electrical conductivity and sorptivity tests do not show a systematic improvement of transport properties of the concrete tied to increasing duration of wet curing. At best, a case might be made for 1-day through 3-day wet curing as being slightly preferable to simple LMFC. This should not be taken to imply that curing is not important for durability properties, but rather that all of the curing regimes evaluated appear more or less adequate for the weather conditions (warm, humid) during and after placement. It should also be kept in mind that regardless of what curing practice is followed, it is important to prevent drying of the concrete surface between finishing and the curing application.

Further, there appears to be no impact related to following wet curing with an application of LMFC. The rationale for this practice has been that it will slow drying and thus result in slower stress development as the surface dries, thus lessening the potential for cracking. The weather conditions following cessation of wet curing may determine whether an application of LMFC is necessary to slow drying. If the prevailing air mass for the days following the curing period will be dry, conceptually there may be some benefit to the LMFC application. On the other hand, if humid conditions will prevail, as was the case in this study, then little benefit would likely be observed. As it seems that atmospheric conditions during and after placement and curing periods may impact what practices are necessary, construction personnel and engineers should pay close attention to these conditions and plan and execute curing practices accordingly.

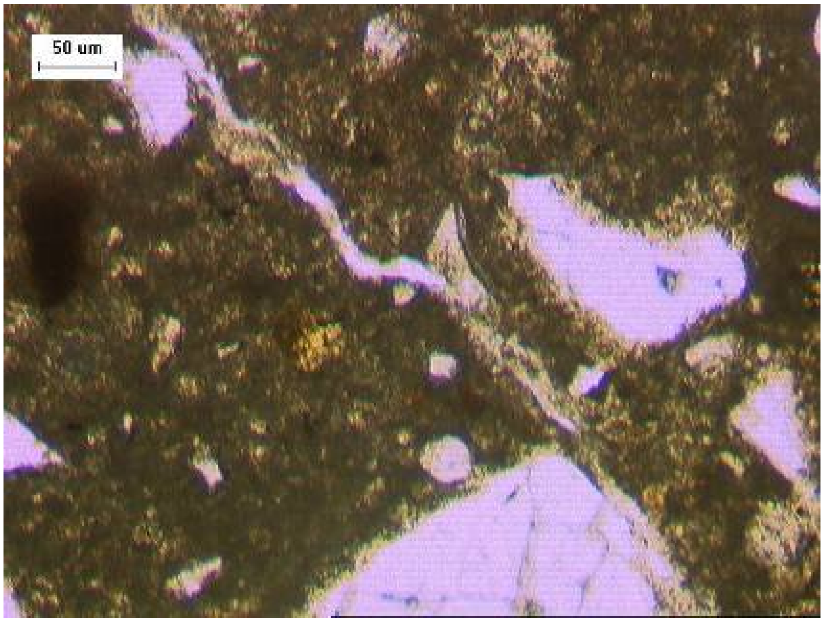


Figure 42. Thin Section of Batch B (slag cement, 0.35 w/cm), Slab 2 (1-day wet) Near Surface Showing Crack Through Paste

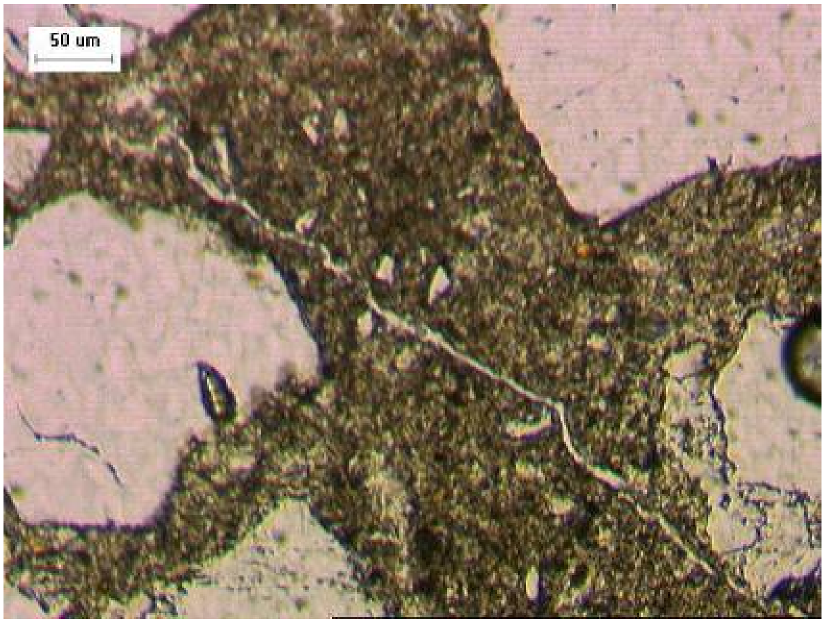


Figure 43. Thin Section of Batch B (slag cement, 0.35 w/cm), Slab 7 (7-day wet-LMFC) Near Surface Showing Crack Through Paste

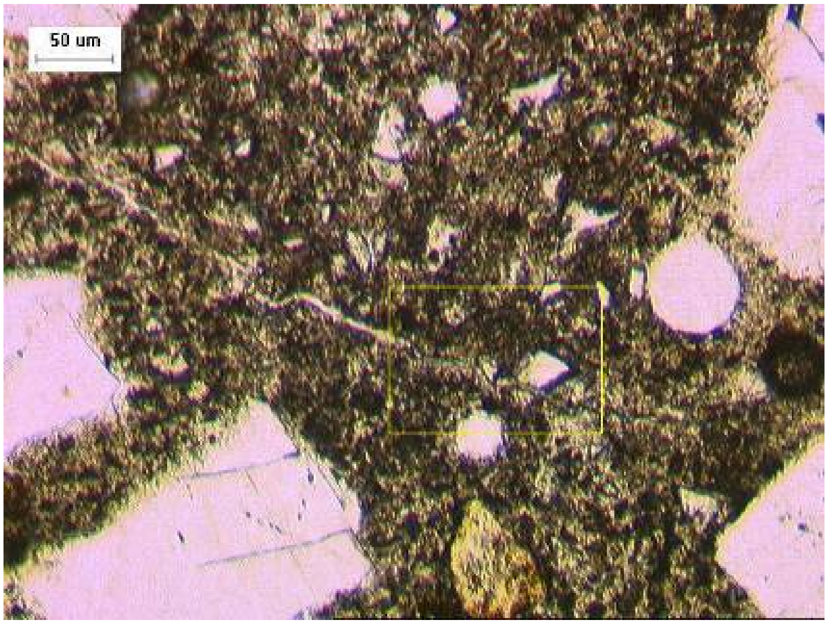


Figure 44. Thin Section of Batch E (slag cement, 0.45 w/cm), Slab 1 (LMFC) Near Surface Showing Crack Through Paste. Box outlines field of view in Figure 44.

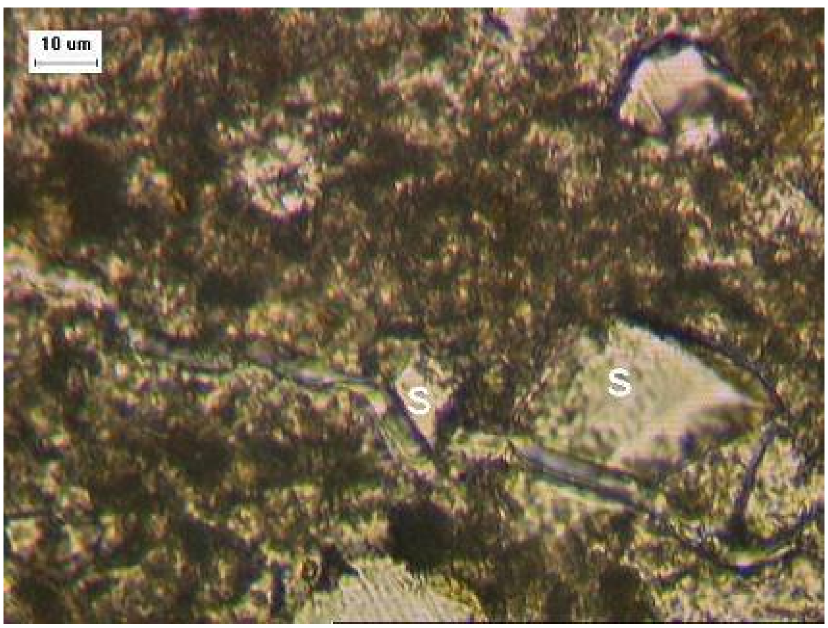


Figure 45. Thin Section of Batch E (slag cement, 0.45 w/cm), Slab 1 (LMFC) Near Surface Showing Crack Through Paste. *S* indicates unhydrated portions of slag cement particles.

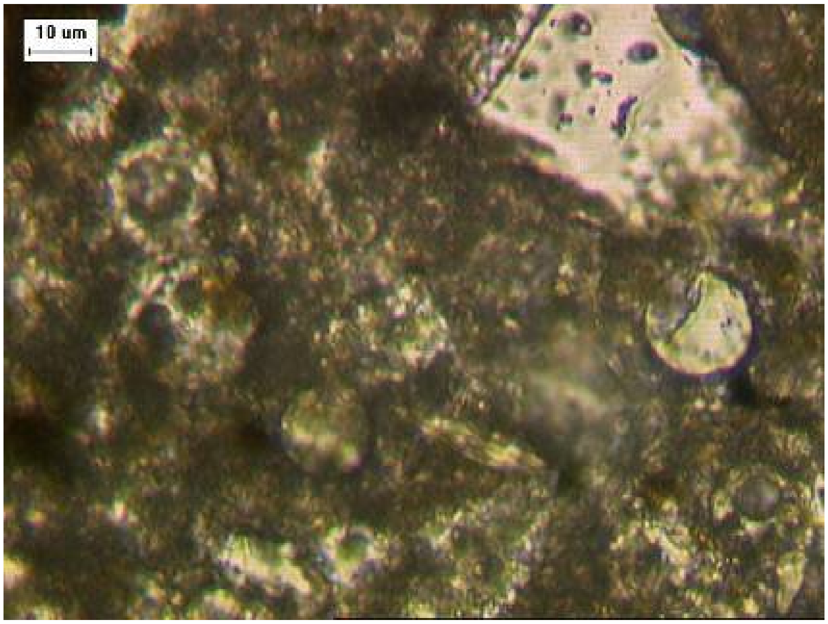


Figure 46. Thin Section of Batch G (fly ash, 0.35 w/cm, LWFA), Slab 3 (3-day wet) Near Surface Showing Largely Unhydrated Fly Ash Particle *(middle right)*. Several cement grains with unhydrated cores are present.

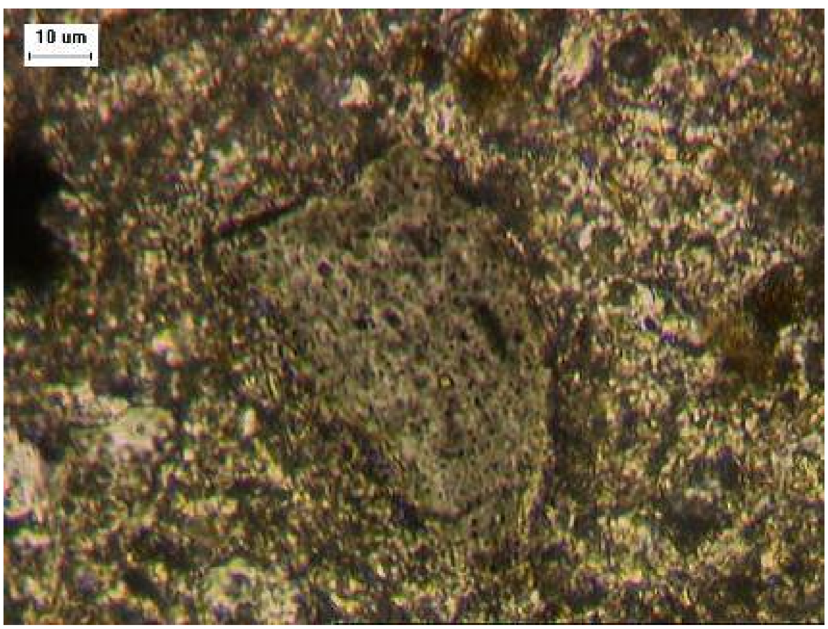


Figure 47. Thin Section of Batch H (silica fume, 0.35 w/cm, LWFA), Slab 3 (3-day wet) Near Surface Showing Largely Unhydrated Silica Fume Agglomerate *(middle)*.

Current practice for bridge deck curing requires the application of LMFC following the minimum 7-day curing period. This is followed at a minimum age of 14 days (or delayed up to 6 months with the engineer's approval) with saw cutting grooves into the deck surface. Since this practice effectively breaks the curing membrane and creates additional surface area from which drying can occur, the LMFC would seem to provide little or no benefit unless the saw cutting were to be delayed for an extended period and low humidity conditions were expected.

Although it appears that the benefits of LMFC application following wet curing are limited, there are alternative strategies that could benefit concrete durability. The full development of low transport properties in concrete is time-dependent and can take 1 to several years to approach the desired level. Consequently, there is a window of opportunity for deicing or anti-icing chemical penetration into the concrete, particularly for structures placed late in the construction season that open to traffic prior or during the winter season. Concretes placed late in the year are also at a greater risk of frost damage because of their relative immaturity and high degree of saturation of their capillary pore system. Sutter et al. (2008), reporting on potential deleterious effects of various deicing and anti-icing chemicals, recommended the use of tri-siloxane penetrating sealer as an effective means of inhibiting the penetration of such chemicals, and early application of these sealers may be beneficial to both short- and long-term durability.

Sutter et al. (2008) reported a significant deleterious effect of magnesium chloride (MgCl2) on cementitious materials based on their laboratory experiments. Their study noted that concretes containing slag cement or fly ash, which have been used in most VDOT concretes for nearly the last 20 years, were less susceptible to damage than straight portland cement concretes. Their findings stand in contrast to a study by VDOT's Materials Division (Mack, 1995) that reported a very benign effect for MgCl2. The difference may be because of different methodologies employed by the studies, with Sutter et al. using extended soaking of specimens in concentrated solutions at various temperatures and the VDOT study using only a standard deicer scaling method (ASTM C 672) with ponding of a 3% MgCl solution on slab specimens. In fact, Sutter et al. reported a similar benign effect of MgCl2 for their salt scaling tests. Although the laboratory results of Sutter et al. indicate a strong potential for chemical attack of MgCl2 on concrete, their examination of field concretes exposed to MgCl2 solutions for winter maintenance did not clearly demonstrate that the use was having a deleterious impact.

VDOT's use of MgCl2 as an anti-icing agent may nonetheless warrant a structured program to track and assess concrete condition in structures where this material is being used. It may also justify the use of penetrating sealers (silane/siloxane) both to aid in promoting the early drying of concrete to reduce the potential for frost damage and to inhibit the early penetration of deicing and anti-icing chemicals during the early life of the concrete. This strategy would need to take into consideration both the age of the concrete and its moisture condition at the time of application. Most manufacturers recommend a minimum age of 28 days for the concrete and a minimum drying period prior to application (Attanayake et al., 2006). It is not clear whether the stated 28-day minimum has a functional reason or is simply a nod to concrete's conventional "age of majority." The length of the drying period for adequate penetration is a function of several factors including RH and concrete quality. Attanayake et al. (2006) described procedures for selecting sealant materials and application procedures that may provide guidance in the development of a plan to assess procedures, techniques, and timing of application to achieve the maximum benefit. With regard to current practice, the sealer application should follow the saw cutting of grooves in bridge decks.

The performance of Batches G, H, and I, which contained LWFA for internal curing, was certainly on par with that of the other concretes for near-surface properties and perhaps showed slight improvement in the properties at depth, beyond the influence of surface curing. The use of LWFA for internal curing in low w/cm concrete has also been shown to lessen the potential for autogenous shrinkage (Duran-Herrera et al., 2007), an issue not covered in this study but that is of concern in reducing micro-cracking that can adversely impact transport properties. The use of LWFA for internal curing conceptually has more bearing on bulk concrete properties in low w/cm concretes than single surface curing practices and should be considered for inclusion in the specifications.

CONCLUSIONS

- *No clear benefit in strength or transport property development related to the duration of wet curing was found.* There was a subtle positive benefit to immediate application of wet curing over application of LMFC. However, this benefit did not extend beyond a few days of wet curing; at most, 1 to 3 days moist curing should provide adequate property development.

- *No benefit from the application of LMFC following wet curing was found.* Any benefit from this measure is likely to be realized only if low humidity conditions will prevail immediately following the wet curing period and the membrane will remain intact for an extended period (i.e., at least 1 month). Prevailing atmospheric humidity conditions should be taken into consideration.

- *The reduction of w/cm has a greater impact on transport property reduction than the duration of wet curing.* The curing duration needed to achieve a discontinuous capillary pore system increases with w/cm.

- *Saturated, absorbent LWFA can provide water for curing in the interior mass of concretes with low w/cm.* Although in this study the LWFA was confined to mixtures containing fly ash or silica fume or both, similar benefits should be expected with other cementitious materials. This method of internally providing curing water may help reduce the potential for self-desiccation and attendant shrinkage cracking.

- *The results of this study should draw attention to the importance of prevailing atmospheric conditions, particularly humidity, during the placement, curing, and post-curing periods and reinforce in construction personnel the importance of these factors in the planning and execution of the concrete placement.*

RECOMMENDATIONS

1. *VDOT's Materials Division should reduce the minimum duration of wet curing for bridge deck concretes from 7 days to 1 to 3 days.* This change will expedite the construction of bridge decks.

2. *VDOT's Materials Division should revise its concrete specifications to permit the use of saturated LWFA as a portion of the fine aggregate in concrete mixtures where high durability and low transport properties are important.*

3. *VDOT's Materials Division should revise the requirements for post wet-curing application of LMFC so that such application is made only when it is likely to be beneficial.*

SUGGESTED FUTURE RESEARCH

- A study on bridge deck construction projects should be conducted to verify the findings of this study and determine actual costs related to varied curing practices.

- The potential benefits of early application of penetrating sealants, particularly for concretes placed late in the year that will be subjected to early application of anti-icing or deicing chemicals should be examined. The examination should include a determination of the timing and procedures needed to gain the most benefit from the application.

- A study should be initiated to track the condition of concretes subjected to frequent and aggressive anti-icing and deicing practices to establish the concrete's response under actual field conditions.

BENEFITS AND IMPLEMENTATION PROSPECTS

This study shows that longer duration of wet curing does not necessarily result in improved concrete properties related to durability. It follows that the established minimum period for wet curing duration in the specifications is often unnecessary for its intended purpose of ensuring achievement of the desired concrete properties. The requirements for proper curing are a function of the concrete mixture and, most important, the prevailing weather conditions during and after concrete placement. As such, decisions regarding the appropriate curing method and duration are project specific and should be determined by the project management team at the time of construction to ensure that the measures taken are appropriate for the situation and unnecessary measures are avoided.

The specified practice of requiring LMFC application immediately on cessation of moist curing does not necessarily benefit the development of concrete properties. Further, it is a pointless practice except perhaps under the most severe evaporative conditions when the membrane is breached within a week or two by the saw cutting of grooves in the deck surface.

The specification of this requirement should be rescinded and the need for the practice determined by the project management team at the appropriate time. A direct cost savings could be realized by removing this requirement and using LMFC only in situations where it is likely to benefit the curing process. Alternatively, there may be long-term benefits that could be realized by applying these cost savings to the application of penetrating sealers, particularly for concretes that will be subjected early in life to aggressive anti-icing and deicing programs. Conceptually, greater benefit to the bulk concrete properties can be achieved using saturated LWFA as a portion of the fine aggregate component to provide an internal source of water for curing than by external wet curing methods. This method of curing is feasible and can be permitted by revising the specifications.

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