SHRINKAGE OF LATEX-MODIFIED AND MICROSILICA CONCRETE OVERLAY MIXTURES

By

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(ABSTRACT)

Highway bridge decks are often overlaid to extend service life by reducing the rate of chloride ion ingress and the rate of corrosion of reinforcing steel in the sound chloride-contaminated concrete that is left in-place. Bridge deck overlays in Virginia are usually either latex-modified concrete or microsilica concrete, and both types of overlay are considered equivalent in terms of performance. However, the latex-modified concrete overlays are more expensive to construct than the microsilica concrete overlays. Thus, it is important to determine if these overlays do perform equivalently to ensure that short-term savings do not lead to higher long-term costs.

Shrinkage is one of the overlay performance parameters. Shrinkage is a three-dimensional deformation of concrete that results in an overall reduction in volume. Total shrinkage may be measured under either restrained or unrestrained conditions.

This research examines the shrinkage performances of Virginia Department of Transportation-approved latex-modified and microsilica concrete overlay mixtures and was conducted on both field-sampled and laboratory-fabricated restrained and unrestrained specimens. Based on crack and delamination surveys of sampled bridge decks and laboratory test results, a shrinkage performance-based specification for the Virginia Department of Transportation was developed.

There was no significant difference between the unrestrained shrinkage values of latex-modified and microsilica concrete overlay mixtures for the specified time periods. Restrained microsilica concrete specimens generally cracked earlier and more frequently than restrained latex-modified concrete specimens. However, the bridge deck crack and delamination surveys show that construction conditions and quality and traffic type and frequency may have a greater effect on cracking than the overlay material.

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INTRODUCTION

Highway bridges are often overlaid to reduce the rate of chloride ion diffusion to the reinforcing steel and extend the service life of the bridge. In Virginia, these overlays are generally either a latex-modified concrete (LMC) or a microsilica concrete (MSC). Both types of overlay mixture are considered to perform equivalently despite a lack of research into their comparative performances. However, they are not equivalent in cost. A LMC overlay mixture has to be mixed on-site in a mobile mixer, which is more expensive than a MSC overlay mixture that can be mixed at any concrete plant and trucked to the site. Thus, most new overlays in Virginia are MSC. It is therefore important to determine if both LMC and MSC overlays do, in fact, perform equivalently to ensure that short-term savings do not lead to higher long-term costs.

One performance assessment parameter of concrete overlays is its shrinkage. Shrinkage is a three-dimensional deformation of concrete that results in an overall reduction in volume. Typically, the shrinkage of a concrete specimen is expressed as a linear strain since one of the dimensions is significantly larger than the other two and "the effects of shrinkage are greatest in the largest dimension" (Aïtcin, et al, 1997). As these internal strains increase, so does the potential for cracking (Shah, et al, 1998). Cracks may ease the ingress of moisture, oxygen, and chloride ions to the depth of the reinforcing steel. This, in turn, may lead to an increase in the rate of corrosion of the steel and a reduction in service life.

There are four types of shrinkage: plastic, autogenous, drying, and carbonation. Plastic shrinkage is caused by water loss from the surface of concrete within a few hours of placement while the concrete is still plastic and before it gains any significant strength (Soroushian and Ravanbakhsh, 1998). Autogenous shrinkage takes place as a result of cement hydration and develops isotropically within the concrete mass (Aïtcin, et al, 1997). Drying shrinkage occurs in the hardened concrete as free water evaporates from the capillary pores (Tazawa and Yonekura, 1987). Carbonation shrinkage is poorly understood but is the result of carbonation of the hydrated cement products (Soroka, 1979). Total shrinkage can be measured under either restrained or unrestrained conditions.

This research examines the shrinkage performances of Virginia Department of Transportation-approved LMC and MSC overlay mixtures. The research was conducted on both field-sampled and laboratory-fabricated specimens. The results of this research were used to develop a suggested shrinkage performance specification.

PURPOSE AND SCOPE

There are three objectives of this research. The first is to assess the shrinkage strains and shrinkage cracking of both latex-modified and microsilica concrete bridge deck overlay mixtures. The second is to determine whether or not microsilica concrete overlays are equivalent to latex-modified concrete overlays from a shrinkage standpoint. The final objective is to develop a shrinkage performance specification for LMC and MSC overlays in order to minimize cracking.

To accomplish these objectives, field samples were collected from six bridge overlay projects in Virginia. Three sets of samples were from LMC overlays and three were from MSC overlays. Laboratory specimens based on the mixture designs of the field overlays were made and subjected to different curing regimes. Both restrained and unrestrained shrinkage specimens were tested. Approximately half of each mixture's unrestrained specimens were stored in a controlled temperature and relative humidity environment while others were stored in ambient air in the laboratory. In addition to shrinkage testing, specimens were cast for compressive strength and modulus of elasticity; rapid permeability tests were also conducted to aid in the development of the shrinkage performance specification.

METHODS AND MATERIALS

The restrained drying shrinkage of the concrete specimens was tested per AASHTO PP34-99, Practice for Estimating the Crack Tendency of Concrete (AASHTO Provisional, 2000). This test method requires casting a 76 mm wide by 152 mm high concrete ring around a 305 mm diameter steel ring, as shown in Figure 1. Strain gages are attached to the interior of the steel ring at quarter points to monitor the strain caused by the shrinkage of the concrete. As the concrete shrinks, the steel ring is placed in compression; the resulting compressive strain should decrease as the concrete cracks. These cracks were visually monitored approximately biweekly for changes in length and width. Crack widths were measured using a crack comparator and crack lengths were measured with a standard ruler.

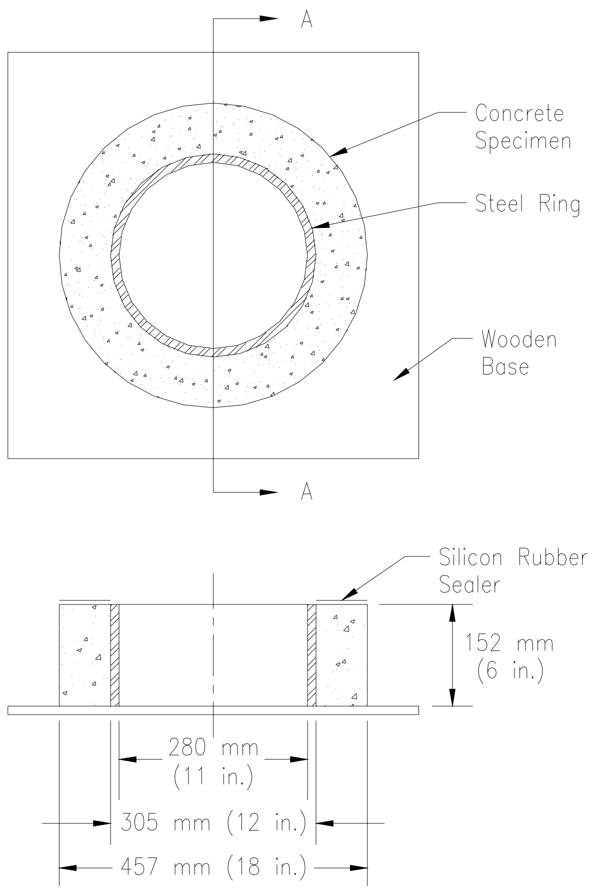

Figure 1: AASHTO PP34-99 Specimen Construction

The unrestrained shrinkage testing was conducted on prisms measuring 75 mm by 75 mm by 286 mm per ASTM C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (ASTM, 2001). For this test method, the length change of each prism is measured. The measurements were made with a comparator every day for the first seven days and then once every seven days thereafter for a minimum of ninety days. These length changes were then converted to percent shrinkage.

The compressive strength was tested according to ASTM C 39, Compressive Strength of Cylindrical Concrete Specimens, using steel end caps and neoprene pads (ASTM, 2001). The 102 mm by 203 mm cylinders were tested at 7, 28, 56, and 90 days of age.

The modulus of elasticity was measured per ASTM C 469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ration of Concrete in Compression (ASTM, 2001). One 152 mm by 305 mm cylinder was cast from each truck sampled for field samples and one for each laboratory mixture. Each cylinder was tested at 7, 28, 56, and 90 days.

The Virginia Transportation Research Council performed the rapid permeability tests according to AASHTO T277, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO, 2000). The test was modified for the LMC specimens to allow formation of the polymer film. The 102 mm by 203 mm cylinders were tested at 7, 28, and 90 days.

Field Overlay Sampling

The Virginia Department of Transportation (VDOT)-approved mixture proportions for the field samples are summarized in Table 1 and are for one cubic meter of concrete based on SSD conditions.

Table 1: Field Sample Mixture Designs

	MSC Overlays		LMC Overlays	
	Rt. 56	Rt. 150	Rt. 1	Wilson Creek Bridge
		(Falling Creek and Rt. 10)	(NBL and SBL)	(7 bag mixture)
Cement: Type I/II (kg)	377	363	390	390
Silica Fume (kg)	30	27	0	0
Sand (kg)	899	844	921	892
Stone (kg)	831	864	704	742
Water (kg)	163	156	87	86
AEA (mL)	39 - 310	as req.	0	0
Water Reducer (mL)	1587 - 3713	0	0	0
HRWR (mL)	0 - 5300	1393 - 3125	0	0
Latex (kg)	0	0	121	121
w/cm	0.40	0.40	0.39	0.38

The field samples were tested according to the sampling plan outlined in Table 2.

Table 2: LMC and MSC Field Sampling Plan

	LMC Overlays				MSC Overlays		
	Number of	Specimens/Sample			Number of	Specimens/Sample	
Structure	Samples	Prisms	Rings	Structure	Samples	Prisms	Rings
Rt. 1 NBL	3	2	2	Rt. 56	3	2	2
Rt. 1 SBL	3	4	2	Rt. 150/10	3	4	2
Wilson Creek	3	6	2	Rt. 150/FC	3	6	2

Both sets of samples from Rt. 1 near Doswell, Virginia, were from the same bridge but were taken from different placements, one from the northbound lane overlay placement and one from the southbound lane overlay placement. This bridge is located near a quarry; the southbound lanes carry loaded quarry trucks that return over the northbound lane empty. In contrast, the Wilson Creek Bridge in Blacksburg, Virginia, experiences little traffic since it is part of a test roadway. The Wilson Creek Bridge was the only newly constructed bridge sampled as part of this research. The 7 bag overlay mixture sampled from this bridge was a replacement for the original 7.5 bag overlay mixture that had been placed previously. The original overlay experienced a large amount of cracking soon after placement, so it was removed and the overlay mixture was redesigned.

The Rt.56 bridge is located in rural Nelson County, Virginia, and experiences little traffic volume although it does experience some heavy truck traffic due to loaded log trucks. In contrast, the sampled bridges from Rt. 150 outside Richmond, Virginia, experience heavy traffic volumes but this traffic consists mainly of cars and light trucks.

The field samples were used to compare the effects of the contractor as well as to determine whether there is a significant difference in the overall performances of LMC and MSC overlays. Both overlays from Route 150 were performed by the same contractor, as were both overlays sampled from Route 1. With the exception of the specimens from the Wilson Creek Bridge, half of the prisms were stored at a controlled temperature of 23°C ± 2°C and relative humidity of 50% ± 4%, while the remaining specimens were stored in uncontrolled laboratory air. Temperature and relative humidity variations in the laboratory were measured and recorded. For the Wilson Creek Bridge prism specimens, two specimens from each sampling site were stored in the controlled environment with the remaining four stored in the uncontrolled environment.

Field samples were collected for restrained and unrestrained shrinkage, compressive strength, modulus of elasticity, and permeability testing. All MSC permeability specimens were moist cured for three days, then were stored in 38°C water except while the specimens were being tested. All LMC permeability specimens were moist cured for two days, then were stored in 38°C air except while the specimens were being tested to allow the polymer film to form.

After nine to twelve months, the bridge decks from which field samples were taken were examined for cracking and delaminations. The purpose of this inspection was to compare field performance with laboratory results.

Laboratory Overlay Sampling

The mixture designs for laboratory specimens are summarized in Table 3 and are for a one cubic meter batch. The mixtures designated as SF-L3, SF-L7, and LMC-L2 are proportioned to represent the field overlay mixtures. The final number in these designations refers to the number of days the specimens from that mixture are subjected to moist curing. All of the LMC-WCL mixtures are based on the mixture proportions used on the Wilson Creek Bridge. The final number in these designations refers to the number of bags of cement used in the mixture for one cubic yard of concrete. The LMC-WCL mixtures were subjected to two days of moist curing.

Table 3: Laboratory Mixture Proportions, SSD Conditions

	SF-L3, L7	LMC-L2	LMC-WCL-7.5	LMC-WCL-7	LMC-WCL-6.5	LMC-WCL-6.5A	LMC-WCL-6.5B
Cement: Type I/II (kg)	377	388	418	390	362	362	362
Silica Fume (kg)	30	0	0	0	0	0	0
Sand (kg)	899	876	882	892	934	934	823
Stone (kg)	831	804	694	742	775	775	854
Water (kg)	163	87	86	86	86	98	73
AEA (mL)	193	0	0	0	0	0	0
Water Reducer (mL)	0	0	0	0	0	0	0
HRWR (mL)	2650	0	0	0	0	0	0
Latex (kg)	0	120	130	121	104	81	114
w/cm	0.40	0.38	0.36	0.38	0.38	0.38	0.36

The LMC laboratory specimens were assembled according to the test matrix outlined in Table 4. Half of all the prism specimens were stored in the controlled environment; the remaining specimens were stored in the uncontrolled environment.

Table 4: LMC Overlay Laboratory Test Matrix

	Number of	Specimens/Batch	
Cement Content	Batches	Prisms	Rings
7.5 Bag Mixture	2	6	2
7 Bag Mixture	2	6	2
6.5 Bag Mixture	2	6	2
Latex Content			
9.5 L/bag	2	6	2
13.2 L/bag	2	6	2
Water/Cement Ratio			
0.36	2	6	2
0.38	2	6	2

The MSC laboratory specimens were assembled according to the test matrix shown in Table 5. Half of all the prism specimens were stored in the controlled environment and the remaining specimens were stored in the uncontrolled environment.

Table 5: MSC Overlay Laboratory Test Matrix

	Number of	Specimens/Batch	
Curing Regime	Batches	Prisms	Rings
3 Days	2	6	2
7 Days	2	6	2

Curing regimes for the permeability specimens also varied; these are outlined in Table 6.

Table 6: Curing Regimes for Permeability Testing

	Cylinders/Batch	Moist Cure (days)	Lab Air (days)	38ºC Air (days)	38ºC Water (days)
MSC Overlay Laboratory Mixtures	1	3	4	0	83
	1	2	5	0	83
	1	3	4	0	21
	1	2	26	0	0
	1	3	25	0	0
LMC Overlay Laboratory Mixtures	1	2	5	83	0
	1	3	4	83	0
	1	2	5	0	21
	1	2	26	0	0
	1	3	25	0	0

A test matrix showing the specimens collected or cast from each field and laboratory mixture for each test conducted is given in Appendix H.

RESULTS

Statistical analyses including modified t-tests and contrast tests performed using SAS on the data showed no significant differences at the 95% confidence level (CL) between results obtained from specimens stored in the controlled environment and specimens stored in the ambient laboratory air, nor were there significant differences between batches. Thus, the data were combined to provide a larger sample size for comparisons. The results discussed in this section are from the combined data and include 95% confidence intervals.

Crack widths for each set of samples were combined for simplification; the same was done for crack lengths for each set of samples. These were then compared to determine which mixtures experienced more severe cracking.

The results of compressive strength and modulus of elasticity testing are given in Appendix D. Results of rapid permeability testing are given in Appendix E.

Field Overlays

LMC Overlays

The samples taken from the northbound lane of Route 1 north of Richmond, Virginia, were designated LMC-1.1. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.041% ± 0.019%. None of the restrained specimens cracked.

The samples taken from the southbound lane of Route 1 north of Richmond, Virginia, were designated LMC-1.2. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.047% ± 0.009%. None of the restrained specimens cracked.

The samples taken from the Wilson Creek Bridge in Blacksburg, Virginia, were designated LMC-WC. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.089% ± 0.018%. The first crack in the restrained specimens was visually observed at an age of 33 days. At approximately 180 days, the combined crack widths on all restrained specimens reached 2.39 mm and the combined crack lengths was 1050 mm. All six specimens had at least one crack, with one specimen cracked in two places.

The unrestrained shrinkage as a function of time for the field LMC overlay samples is summarized in Figure 2 and numerically at ages 28 and 90 days in Table 7. Table 8 presents a summary of the ring crack results at 28, 90, and 180 days. Figure 3 presents a summary of the combined crack width and length results for the LMC-WC restrained ring specimens.

MSC Overlays

The samples taken from the westbound lane of Route 56 in Nelson County, Virginia, were designated SF-56. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.083% ± 0.013%. The first crack in the restrained specimens was visually observed at an age of 64 days. At approximately 180 days, the total number of cracks was 20 and all restrained specimens had cracked. The combined crack widths totaled 2.34 mm and the combined crack lengths reached 1524 mm.

The samples taken from the Route 150 bridge over Route 10 south of Richmond, Virginia, were designated SF-150/10. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.057% ± 0.013%. The first crack in the restrained specimens was visually observed at an age of 58 days. At approximately 180 days, the total number of cracks was 14 and all restrained specimens had cracked. The combined crack widths totaled 2.40 mm and the combined crack lengths totaled 1388 mm.

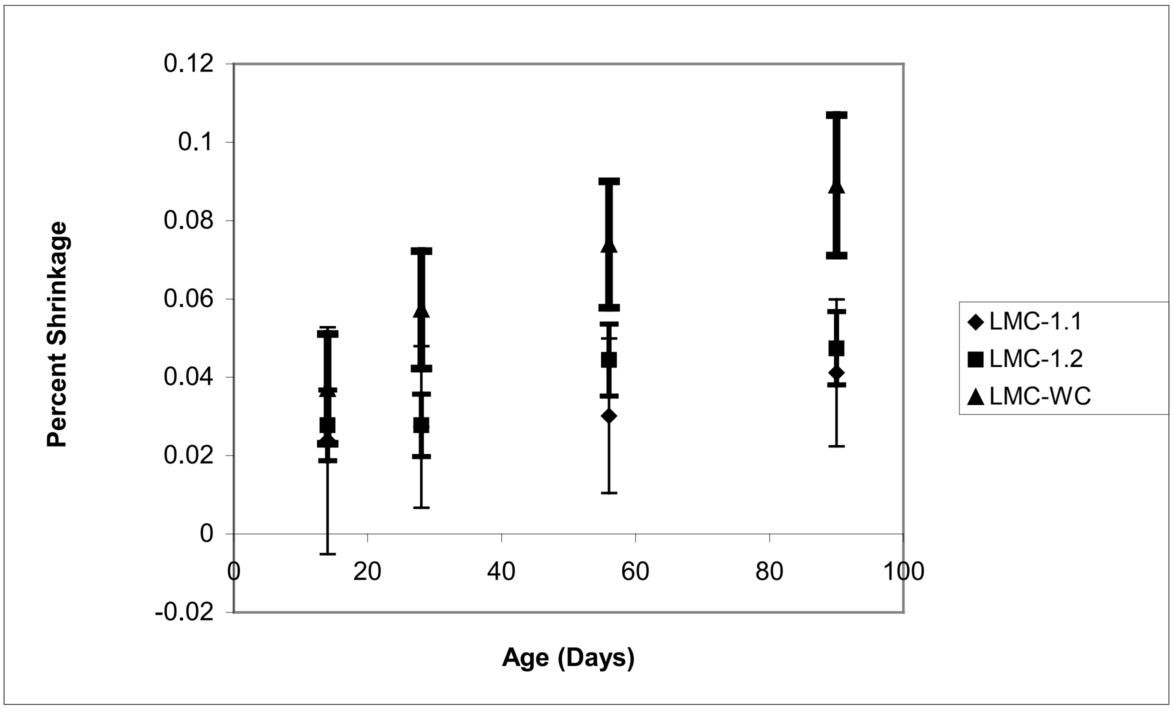

Figure 2: Field LMC Overlay Unrestrained Shrinkage, Average and 95% CL

The samples taken from the Route 150 bridge over Falling Creek south of Richmond, Virginia, were designated SF-150/FC. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.086% ± 0.014%. The first crack in the restrained specimens was visually observed at an age of 30 days. At approximately 180 days, the total number of cracks was 9 and all restrained specimens had cracked. The combined crack widths totaled 1.96 mm and the combined crack lengths totaled 1295 mm.

The unrestrained shrinkage as a function of time for the field MSC overlay samples is summarized in Figure 4 and numerically at ages 28 and 90 days in Table 7. Numerical results for ages 28, 90, and 180 days are presented in Table 8. Figures 5, 6, and 7 present the combined crack width and length results for the restrained ring specimens for SF-56, SF-150/10, and SF-150/FC, respectively.

Table 7: Unrestrained Shrinkage Values

Age (days)	Average Unrestrained Shrinkage Values at 95% CL (%)					
	LMC-1.1	LMC-1.2	LMC-WC	SF-56	SF-150/10	SF-150/FC
28	0.03 ± 0.02	0.03 ± 0.01	0.06 ± 0.01	0.07 ± 0.02	0.04 ± 0.01	0.07 ± 0.01
90	0.04 ± 0.02	0.05 ± 0.01	0.09 ± 0.02	0.08 ± 0.01	0.06 ± 0.01	0.09 ± 0.01

Table 8: Crack Data Summary

Mixture	Total Number of Rings	Number of Cracked Rings			Combined Crack Width (mm)			Combined Crack Length (mm)		
		28 days	90 days	180 days	28 days	90 days	180 days	28 days	90 days	180 days
LMC-1.1	6	0	0	0	0	0	0	0	0	0
LMC-1.2	6	0	0	0	0	0	0	0	0	0
LMC-WC	6	0	4	6	0	1.01	2.39	0	690	1050
SF-56	6	0	5	6	0	1.66	2.34	0	1229	1524
SF-150/10	6	0	6	6	0	1.85	2.40	0	1300	1388
SF-150/FC	6	0	6	6	0	1.79	1.96	0	1306	1295

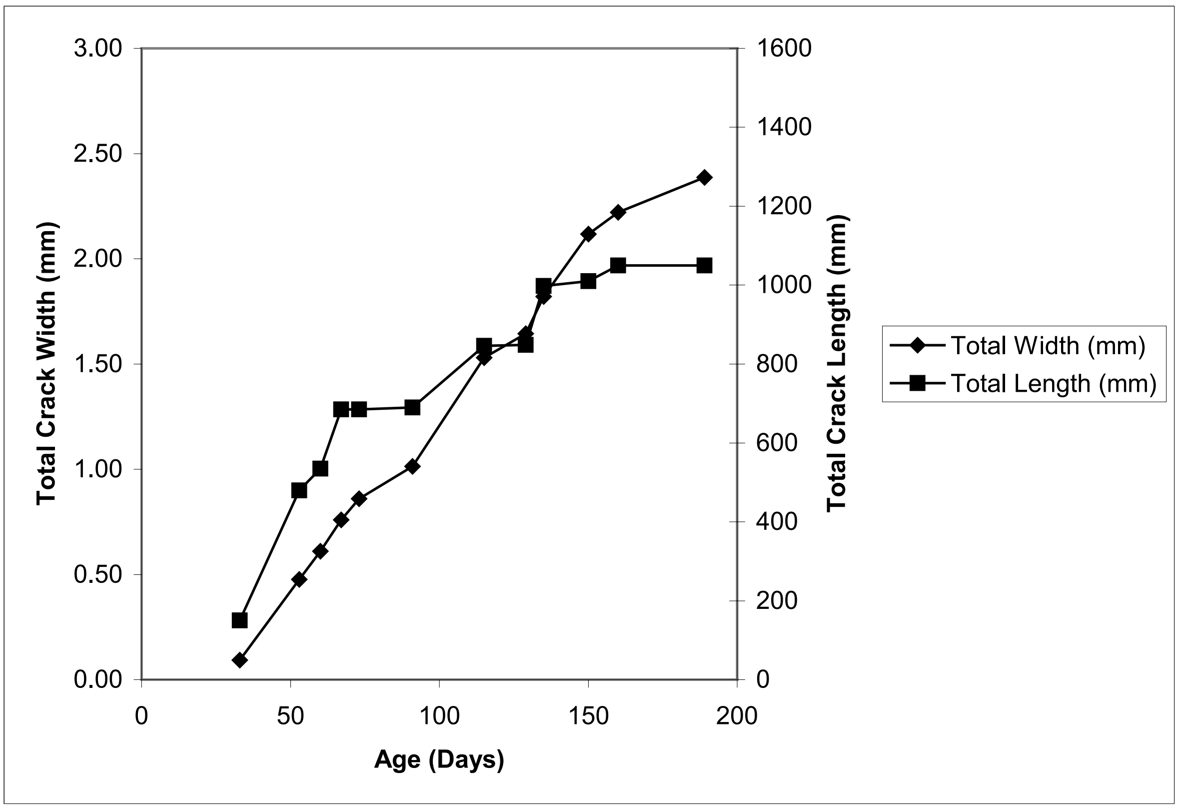

Figure 3: LMC-WC Combined Ring Crack Width and Length

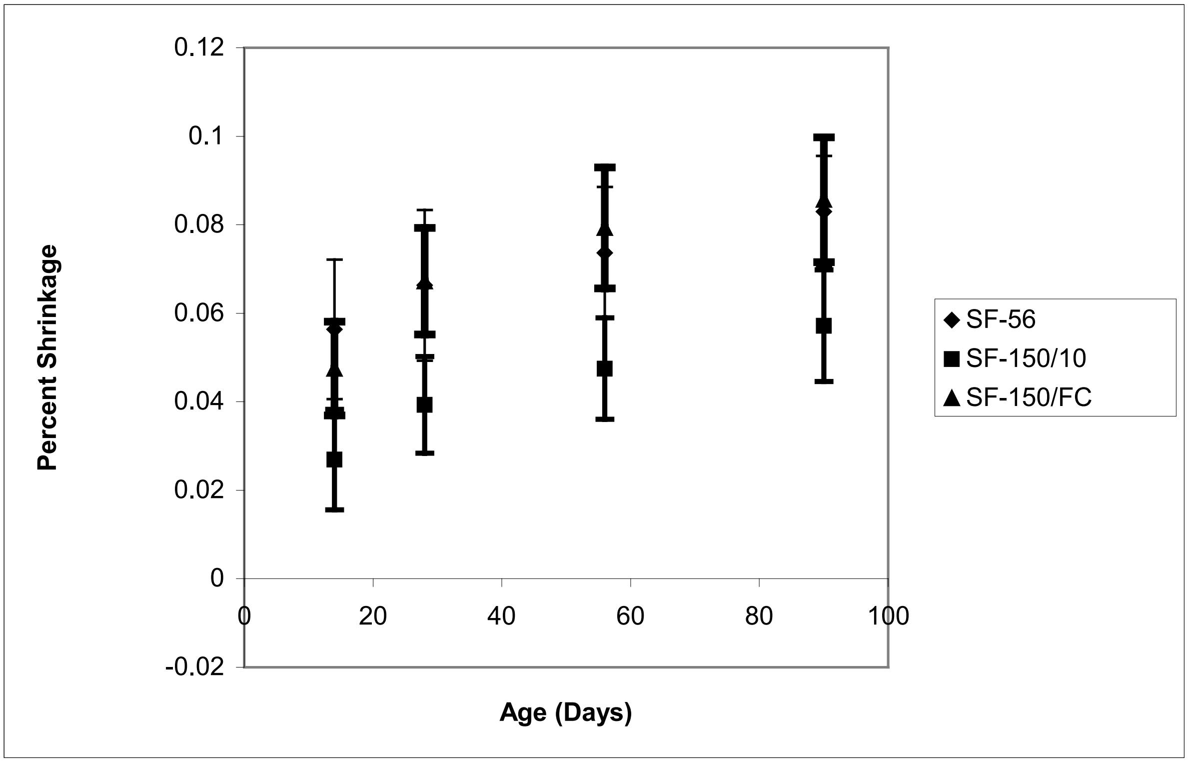

Figure 4: Field MSC Overlay Unrestrained Shrinkage, Average and 95% CL

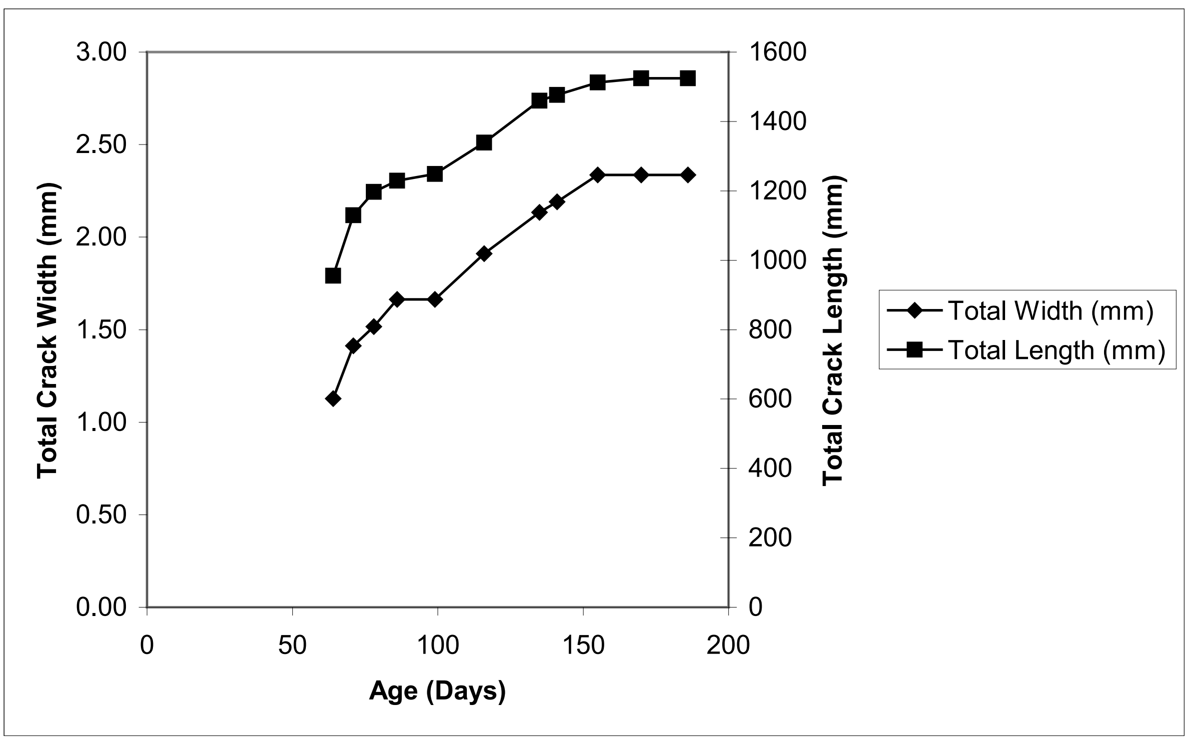

Figure 5: SF-56 Combined Ring Crack Width and Length

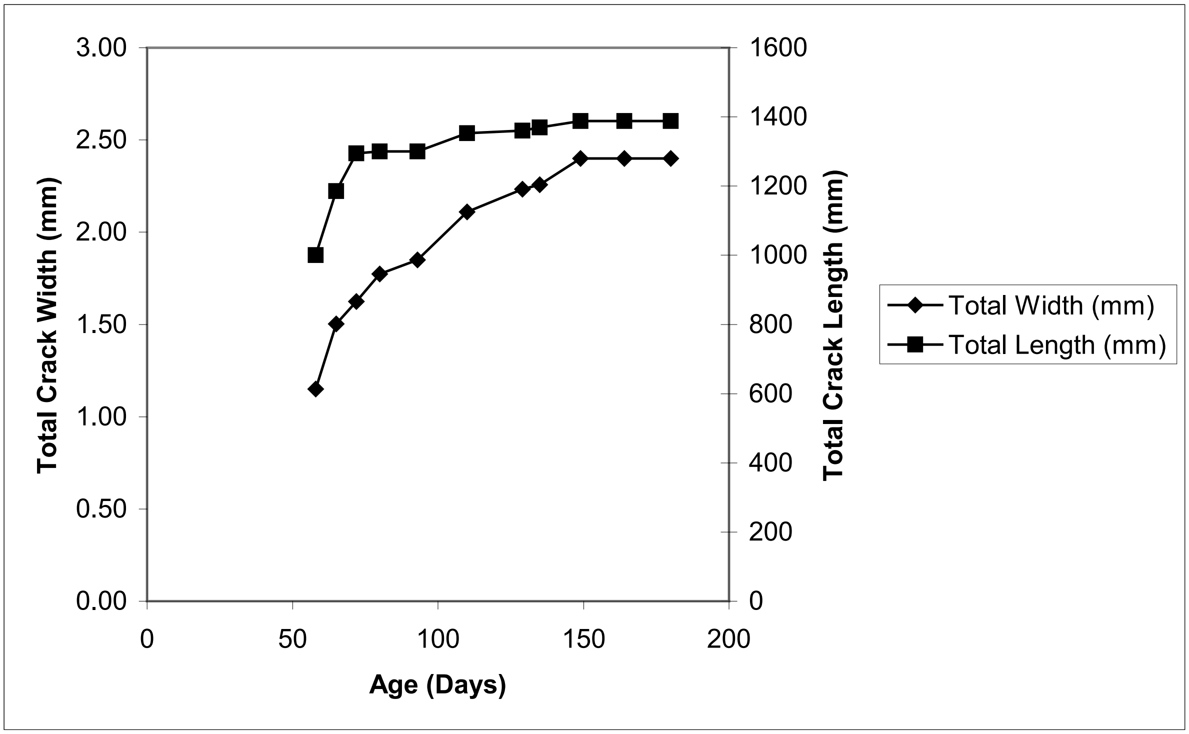

Figure 6: SF-150/10 Combined Ring Crack Width and Length

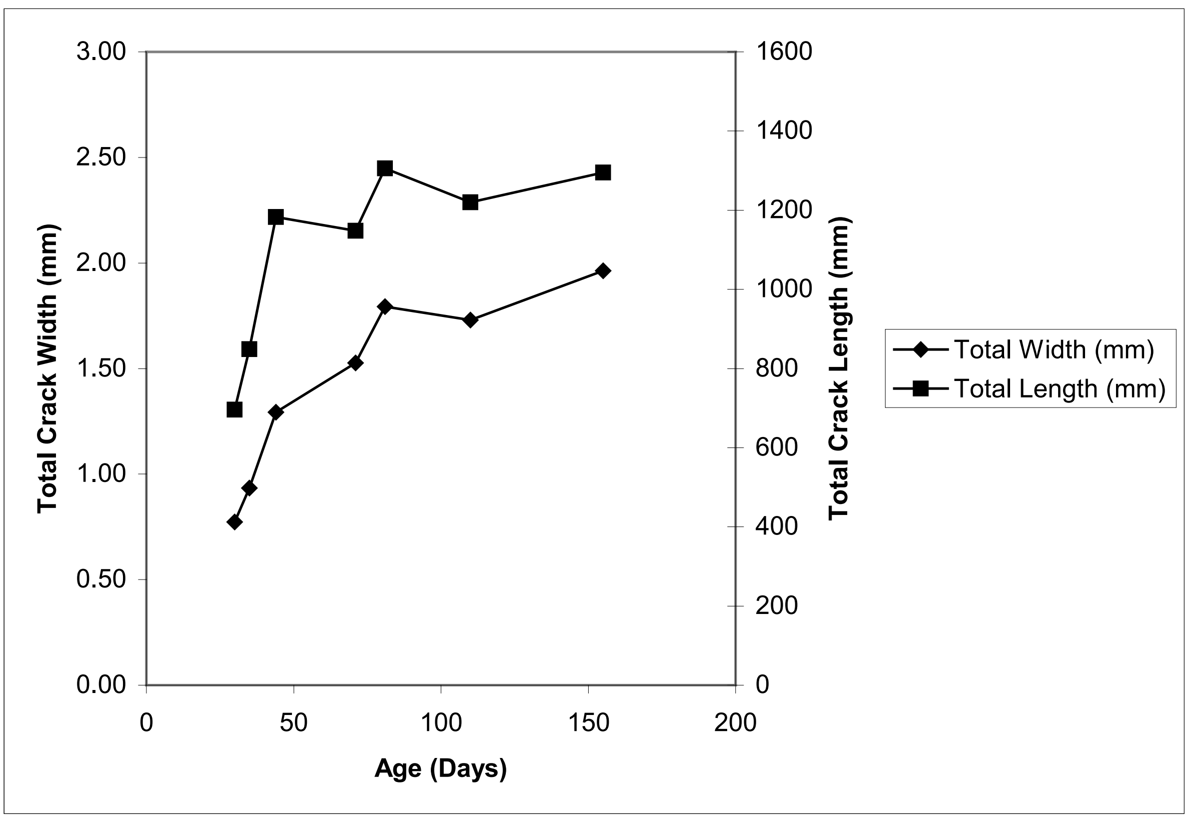

Figure 7: SF-150/FC Combined Ring Crack Width and Length Bridge Deck Surveys

The bridge deck crack and delamination survey results are presented in Table 9. Details are presented in Appendix F. The different types of crack were identified per the definitions provided in ACI 116R-90 (ACI Committee 116, 1990).

Table 9: Bridge Deck Crack and Delamination Survey

			Total Crack Frequency		
Bridge	LMC/MSC	Age of Overlay (days)	Transverse, Longitudinal, Diagonal (m/m2)	Pattern (m^2/m^2)	Delaminations (m^2)
Rt. 1 NBL	LMC	293	0.16	0	0
Rt. 1 SBL	LMC	224	0.30	0	0
Wilson Creek	LMC	289	3.14	0.27	0.55
Rt. 56 WBL	MSC	286	0.07	0	0.34
Rt. 150/10	MSC	278	0.37	0.46	0
Rt. 150/FC	MSC	235	0.01	0	0

Laboratory Mixtures

LMC Mixtures

The laboratory LMC overlay mixture based on the 7.5 bag Wilson Creek Bridge mixture design was designated LMC-WCL-7.5. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.100% ± 0.012%. The first crack in the restrained specimens was visually observed at an age of 26 days. At approximately 180 days, the total number of cracks was 4 and all of the restrained specimens had cracked. The combined crack widths totaled 2.43 mm and the combined crack lengths totaled 600 mm.

The laboratory LMC overlay mixture based on the 7 bag Wilson Creek Bridge mixture design was designated LMC-WCL-7. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.092% ± 0.013%. The first crack in the restrained specimens was visually observed at an age of 39 days. At approximately 180 days, the total number of cracks was 5 and all of the restrained specimens had cracked. The combined crack widths totaled 1.96 mm and the combined crack lengths totaled 680 mm.

The laboratory LMC overlay mixture based on the VDOT specifications was designated LMC-L2. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.055% ± 0.006%. The first crack in the restrained specimens was visually observed at an age of 144 days. At approximately 180 days, the total number of cracks was 2 and 2 of the 4 restrained specimens had cracked. The combined crack widths totaled 0.16 mm and the combined crack lengths totaled 300 mm.

The 6.5 bag laboratory LMC overlay mixture using 13.2 L of latex per bag of cement and having a water-cement ratio (w/c) of 0.38 was designated LMC-WCL-6.5. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.082% ± 0.016%. The first crack in the restrained specimens was visually observed at an age of 39 days. At approximately 180 days, the total number of cracks was 9 and all the restrained specimens had cracked. The combined crack widths totaled 1.72 mm and the combined crack lengths totaled 1320 mm.

The 6.5 bag laboratory LMC overlay mixture using 9.5 L of latex per bag of cement and having a w/c of 0.38 was designated LMC-WCL-6.5A. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.074% ± 0.009%. No restrained specimens were cast for this mixture.

The 6.5 bag laboratory LMC overlay mixture using 13.2 L of latex per bag of cement and having a w/c of 0.36 was designated LMC-WCL-6.5B. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.047% ± 0.009%. No restrained specimens were cast for this mixture.

Figure 8 presents the unrestrained shrinkage as a function of time for LMC-WCL-7.5, LMC-WCL-7, and LMC-WCL-6.5B. Figure 9 presents the unrestrained shrinkage as a function of time for LMC-L2, LMC-WCL-6.5, and LMC-6.5A. Figures 10, 11, 12, and 13 show summaries of the crack data from the restrained ring specimens for LMC-WCL-7.5, LMC-WCL-7, LMC-L2, and LMC-WCL-6.5, respectively.

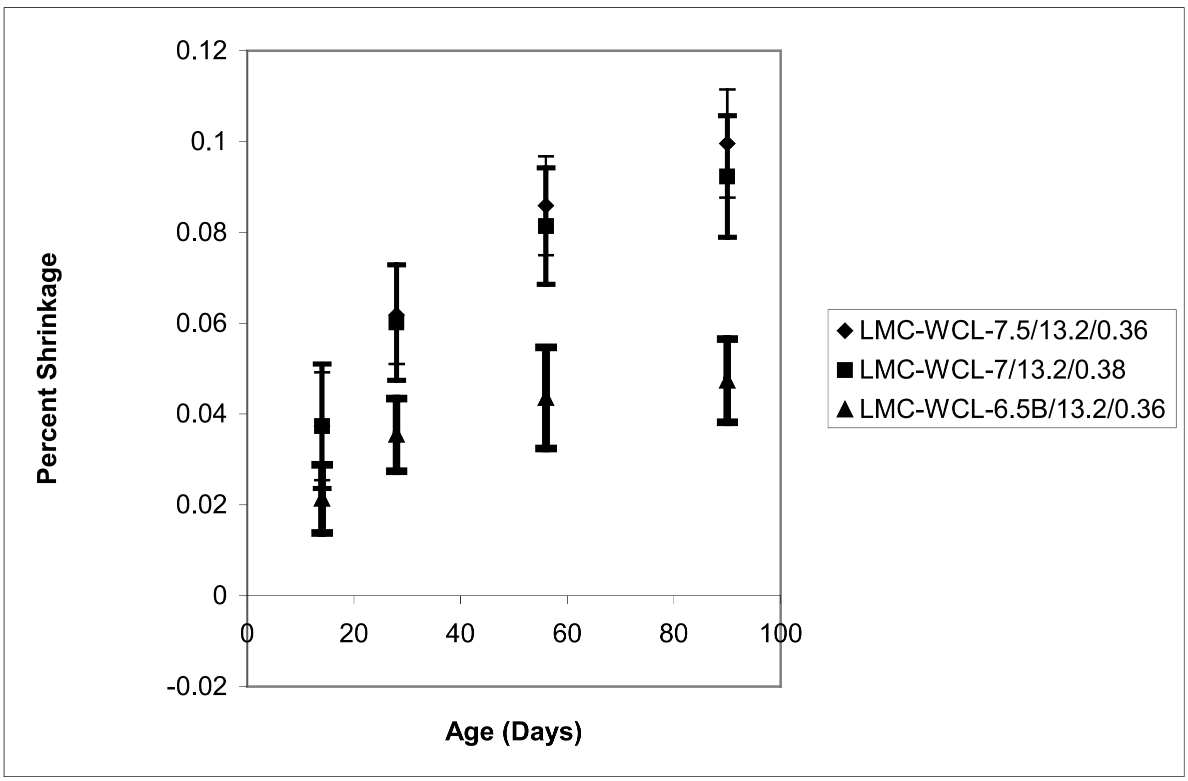

Figure 8: LMC-WCL-7.5, LMC-WCL-7, and LMC-WCL-6.5B Mixtures Unrestrained Shrinkage, Average and 95% CL

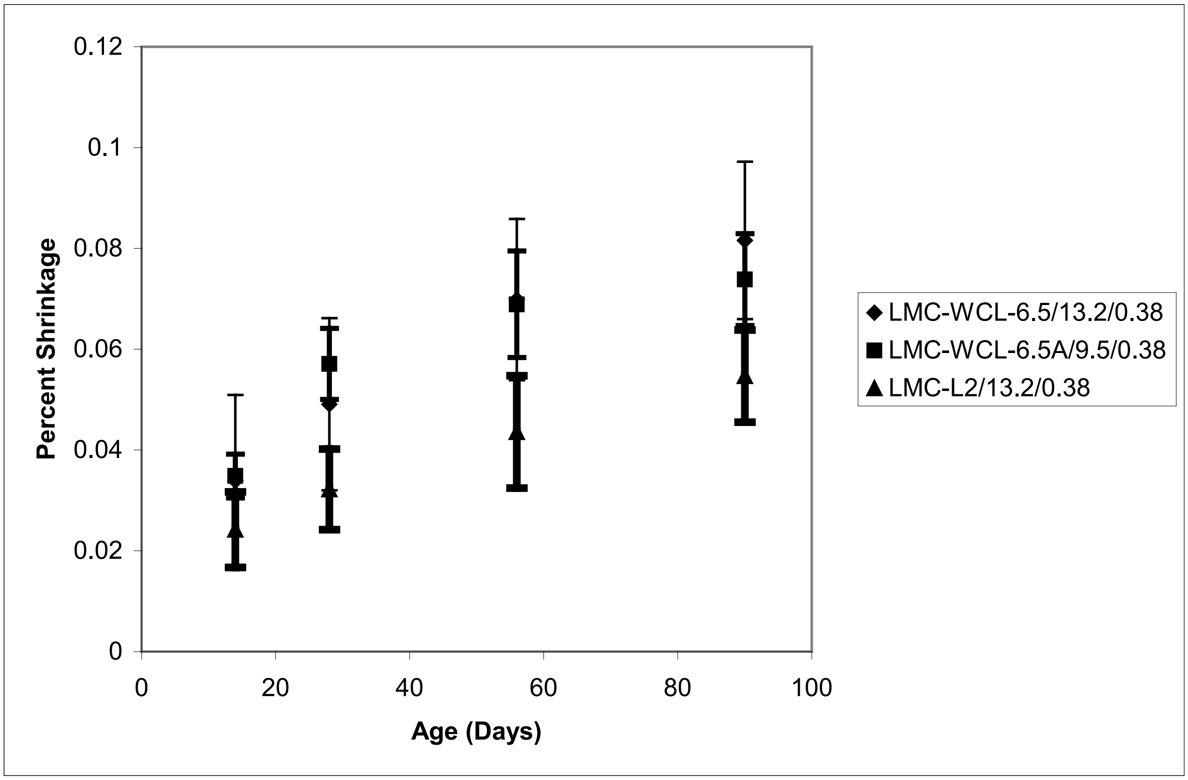

Figure 9: LMC-WCL-6.5, LMC-WCL-6.5A, and LMC-L2 Mixtures Unrestrained Shrinkage, Average and 95% CL

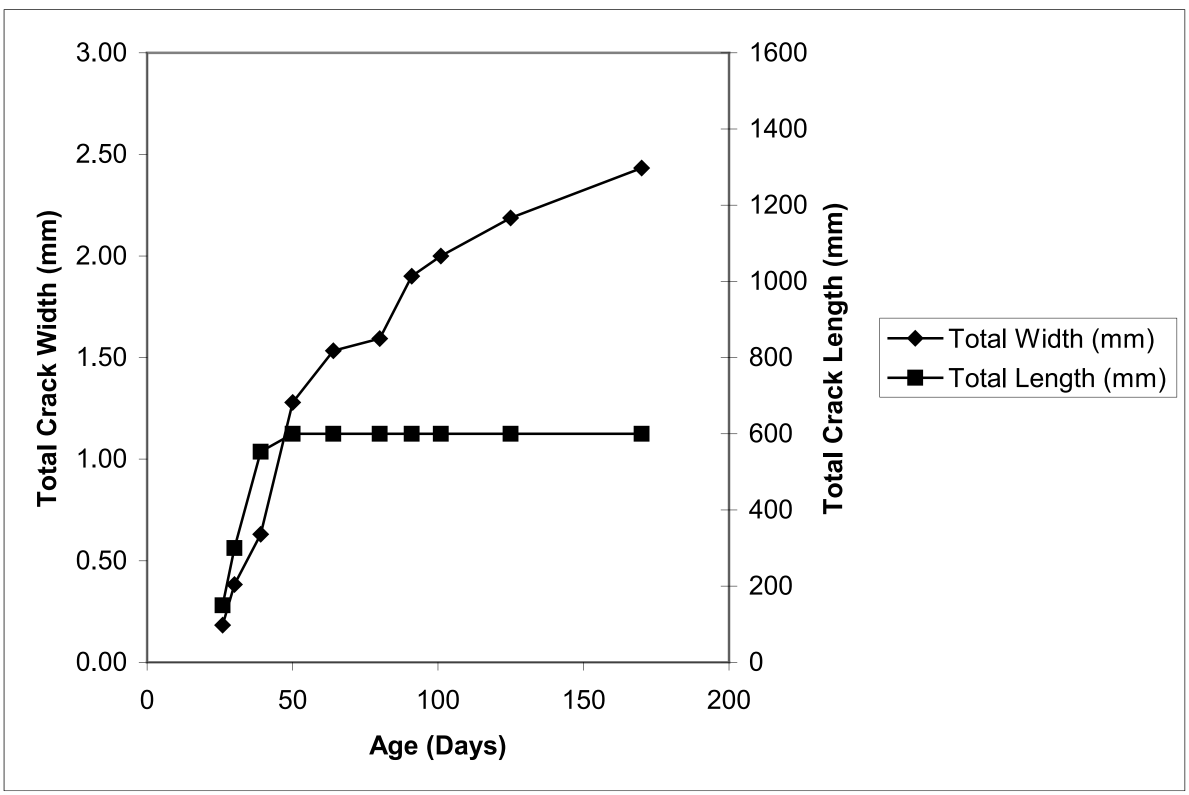

Figure 10: LMC-WCL-7.5 Combined Ring Crack Width and Length

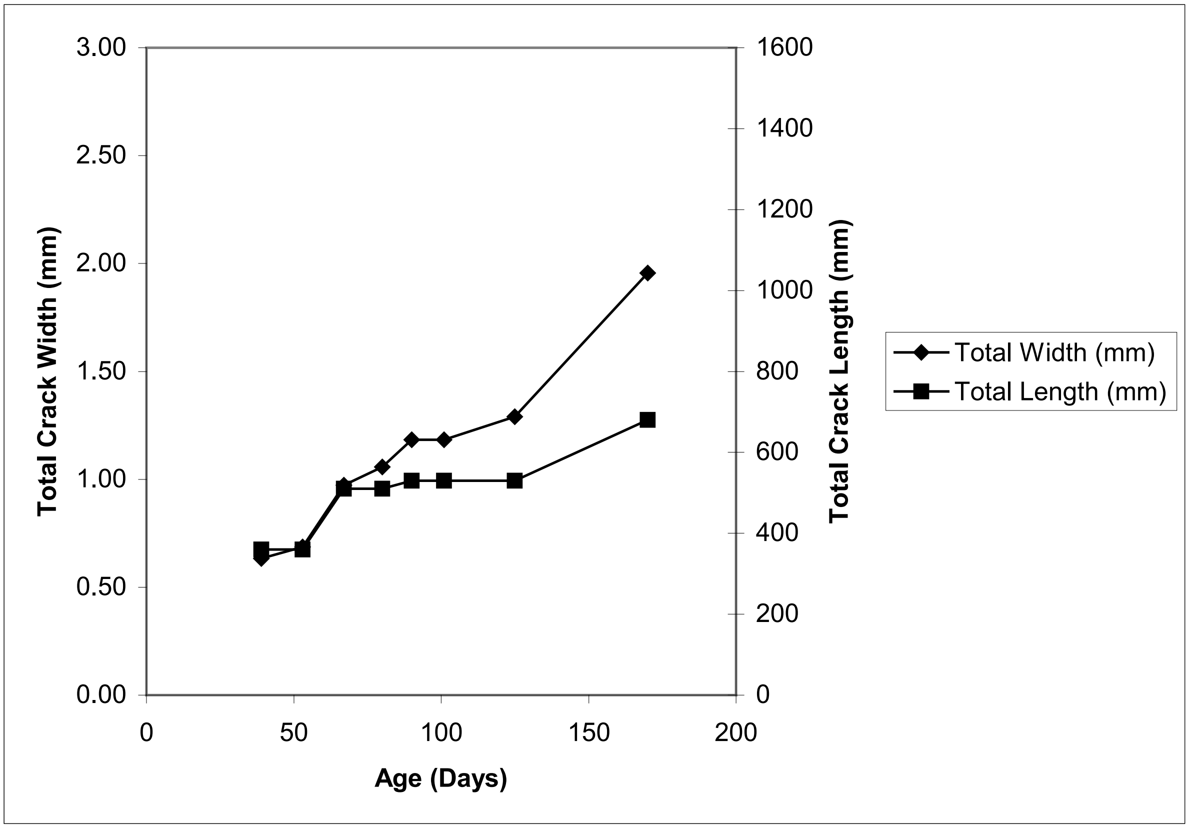

Figure 11: LMC-WCL-7 Combined Ring Crack Width and Length

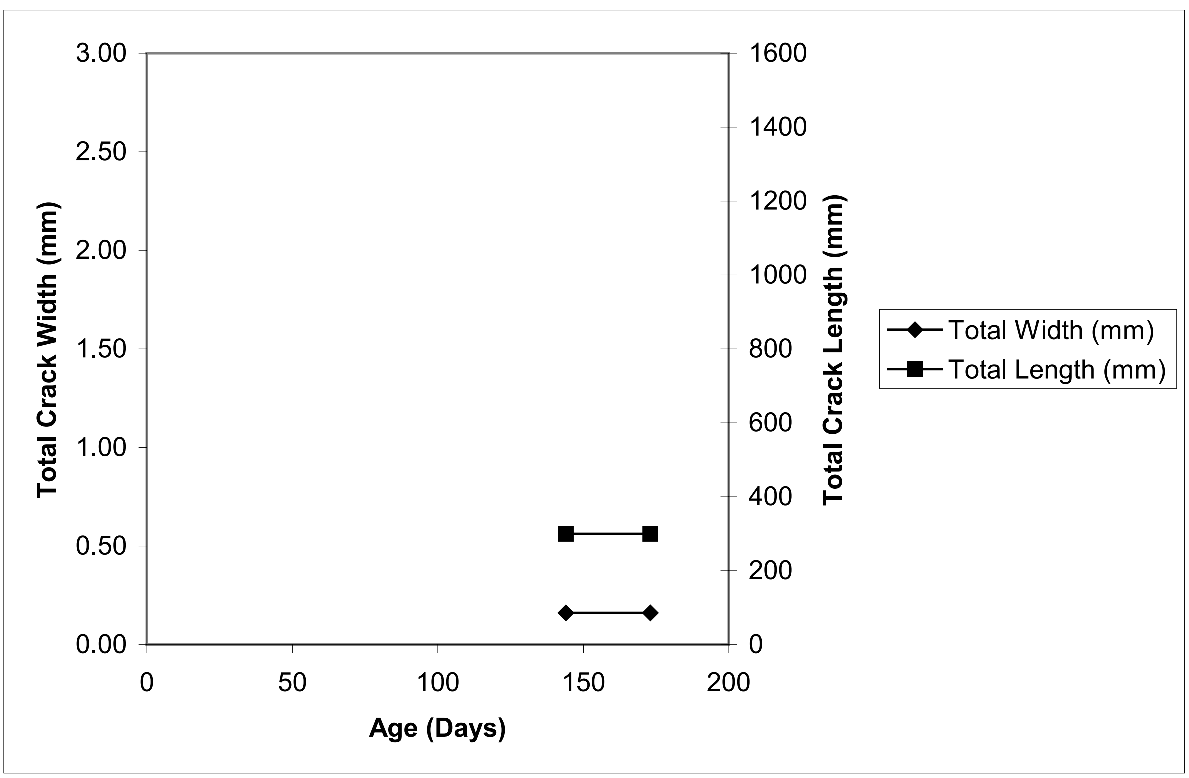

Figure 12: LMC-L2 VDOT Specification Mixture Combined Ring Crack Width and Length

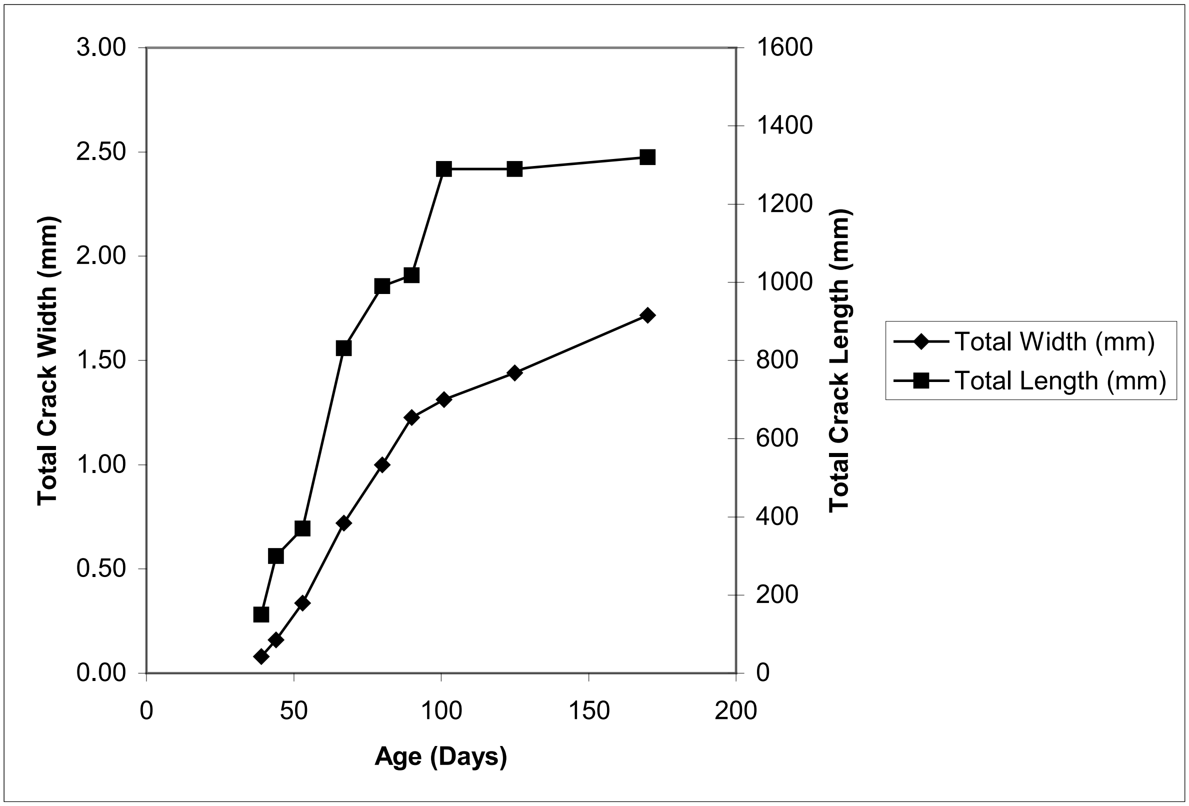

Figure 13: LMC-WCL-6.5 (w/c = 0.38) Combined Ring Crack Width and Length

MSC Mixtures

The laboratory MSC overlay mixture that was moist cured for 3 days was designated SF-L3. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.061% ± 0.007%. The first crack in the restrained specimens was visually observed at an age of 144 days. At 180 days, only one specimen was cracked in one location. The crack was 0.080 mm wide and 110 mm in length.

The laboratory MSC overlay mixture that was moist cured for 7 days was designated SF-L7. At a shrinkage age of 90 days, the unrestrained shrinkage of the specimens averaged 0.056% ± 0.008%. At 180 days, none of the restrained specimens had cracked.

The unrestrained shrinkage as a function of time for the laboratory MSC overlay samples is summarized in Figure 14. Figure 15 presents the combined crack width and length for the restrained ring specimens for SF-L3.

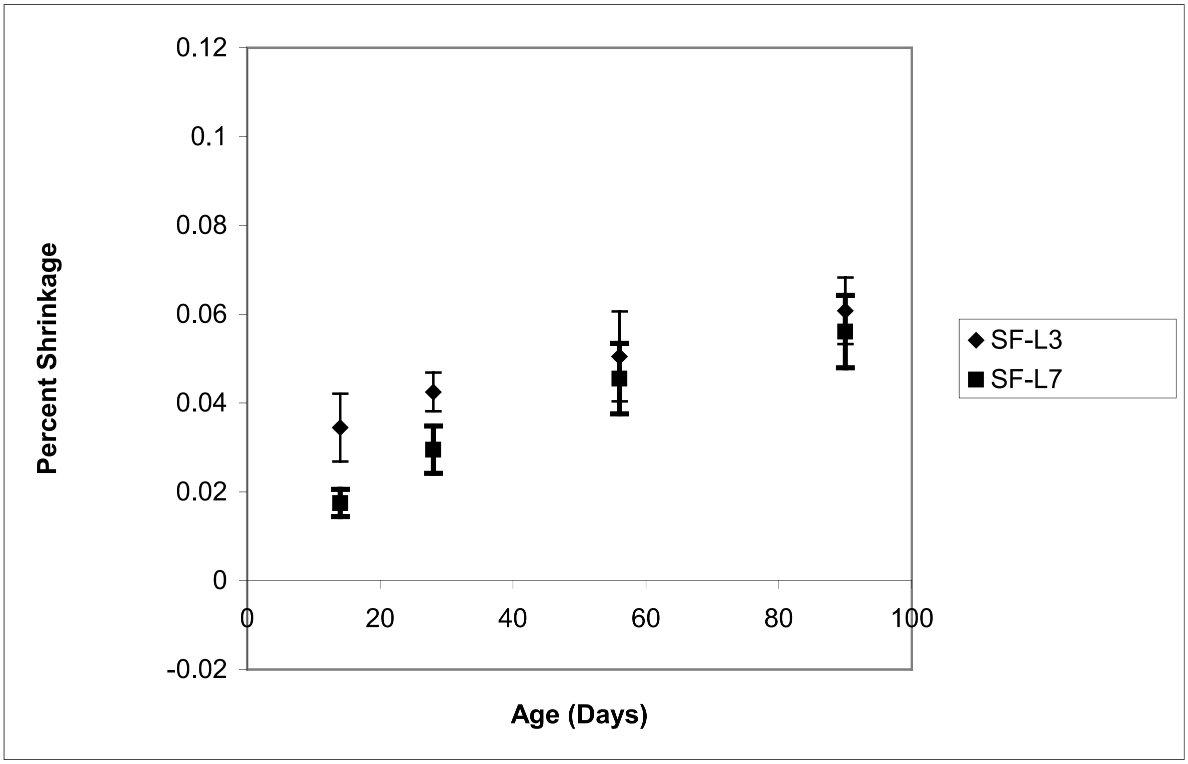

Figure 14: Laboratory MSC Mixtures Unrestrained Shrinkage, Average and 95% CL

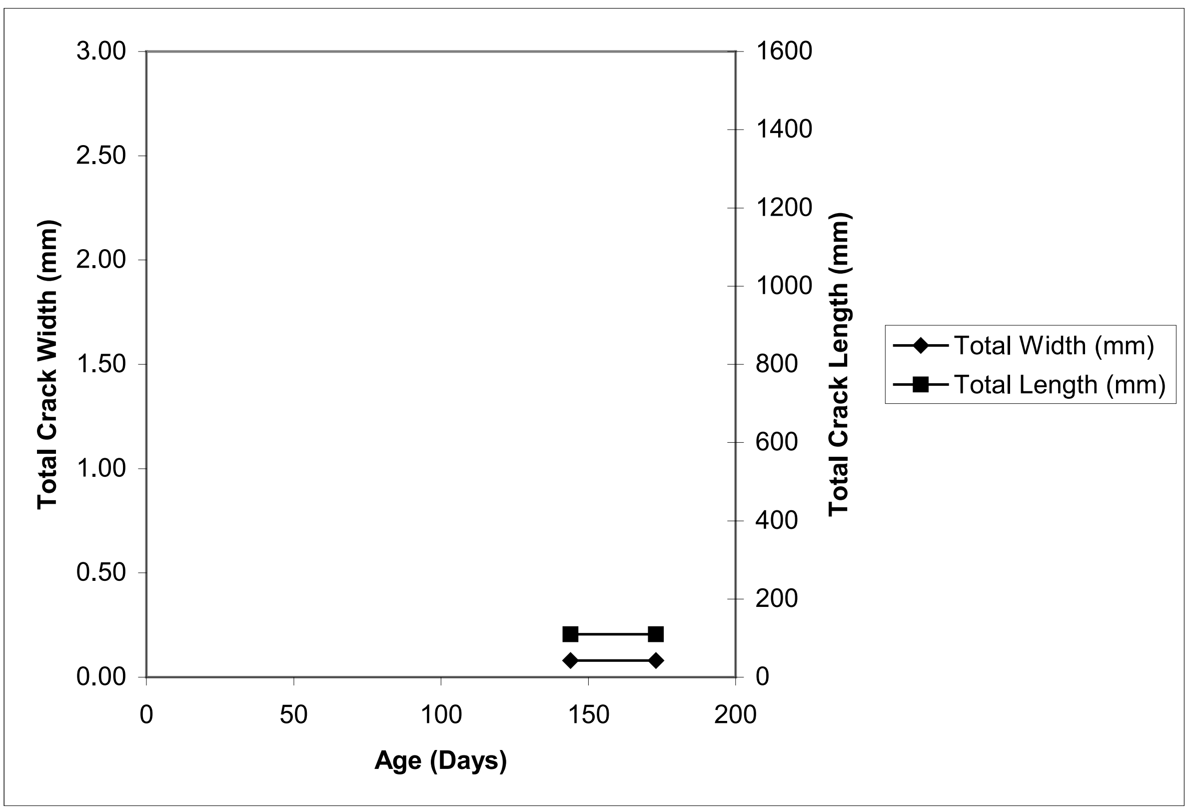

Figure 15: SF-L3 Combined Ring Crack Width and Length

DISCUSSION

Field Overlays

As shown in Figure 2, the LMC overlay specimens from the Wilson Creek Bridge experienced greater unrestrained shrinkage than either overlay from Route 1. In addition, the restrained specimens from Wilson Creek developed large cracks at an early age, while the Route 1 restrained specimens never cracked. The Wilson Creek Bridge deck also exhibited a significantly larger amount of linear and pattern cracking than the Route 1 LMC overlays. In comparison, there is little difference between crack frequencies of the Route 1 overlays, as shown in Table 9.

The significant difference between shrinkage and cracking performance of the Route 1 and Wilson Creek LMC overlays are related to a combination of construction quality (contractor workmanship) and traffic conditions. The Wilson Creek Bridge is part of a test roadway and has experienced relatively little traffic in the time period between overlay placement and field inspections. The deck was too wet at the beginning of placement and the measured concrete slumps ranged from 108mm when the inspector was on-site to 229 mm after the inspector left. There is little doubt that the amount of shrinkage and cracking of this LMC overlay is the result of poor workmanship.

However, the difference in linear cracking in the Route 1 northbound and southbound lanes is the result of traffic conditions. Loaded stone quarry trucks travel over the southbound lanes and return over the northbound lanes empty. Since the shrinkage test results were the same for these two overlay placements, the difference in linear cracking appears to be related to the heavier loading of the Route 1 SB lanes.

There is less variation between the MSC overlay specimens. The unrestrained shrinkage values for SF-150/10 are less than those for the other MSC overlays sampled, but not significantly less. All of the MSC restrained shrinkage specimens had begun cracking by 90 days, and by 180 days, the SF-56 restrained specimens had experienced the most cracking. The combined crack widths for SF-56 and SF-150/10 were very similar. The Route 56 and Route 150 over Falling Creek bridge decks experienced similar amounts of cracking; the Route 150 over Route 10 bridge overlay experienced significantly more cracking than the other two MSC overlays, as shown in Table 9.

Again, the difference in cracking in the MSC overlays appears to be more of the result of quality of construction than shrinkage of the sampled mixtures. Traffic conditions for the Route 150 bridges over Route 10 and Falling Creek are approximately the same, with very heavy traffic count but very little truck traffic. The bridge over Route 10 carries northbound traffic while the Falling Creek Bridge carries southbound traffic; the two bridges are less than three kilometers apart. Placement and curing of Route 150 over Route 10 overlay was done in the early to late morning hours under less than ideal conditions. The Route 150 over Falling Creek overlay was placed during the night and early morning hours, as was the Route 56 overlay. Unlike Route 150, Route 56 is a rural route with a low traffic count with some heavy truck traffic (loaded log trucks).

A comparison of the unrestrained shrinkage versus time for the overall average values of shrinkage for LMC and MSC is shown in Figure 16. The variations are large, so to eliminate the effect of differing contractors, the unrestrained shrinkage over time for the average values of shrinkage for LMC overlays by the same contractor and MSC overlays by the same contractor is shown in Figure 17. As shown, there does not appear to be a significant difference between the unrestrained shrinkage values of LMC and MSC overlays. This was verified by statistical analysis at the 95% confidence level. However, there is a significant difference between the LMC and MSC restrained specimens. While all of the MSC specimens cracked by 180 days, the only LMC specimens to crack by that age were those taken from the Wilson Creek Bridge, once again demonstrating the influence of workmanship. Although the MSC overlay specimens exhibited more linear shrinkage and restrained cracking, this does not translate into more deck cracking.

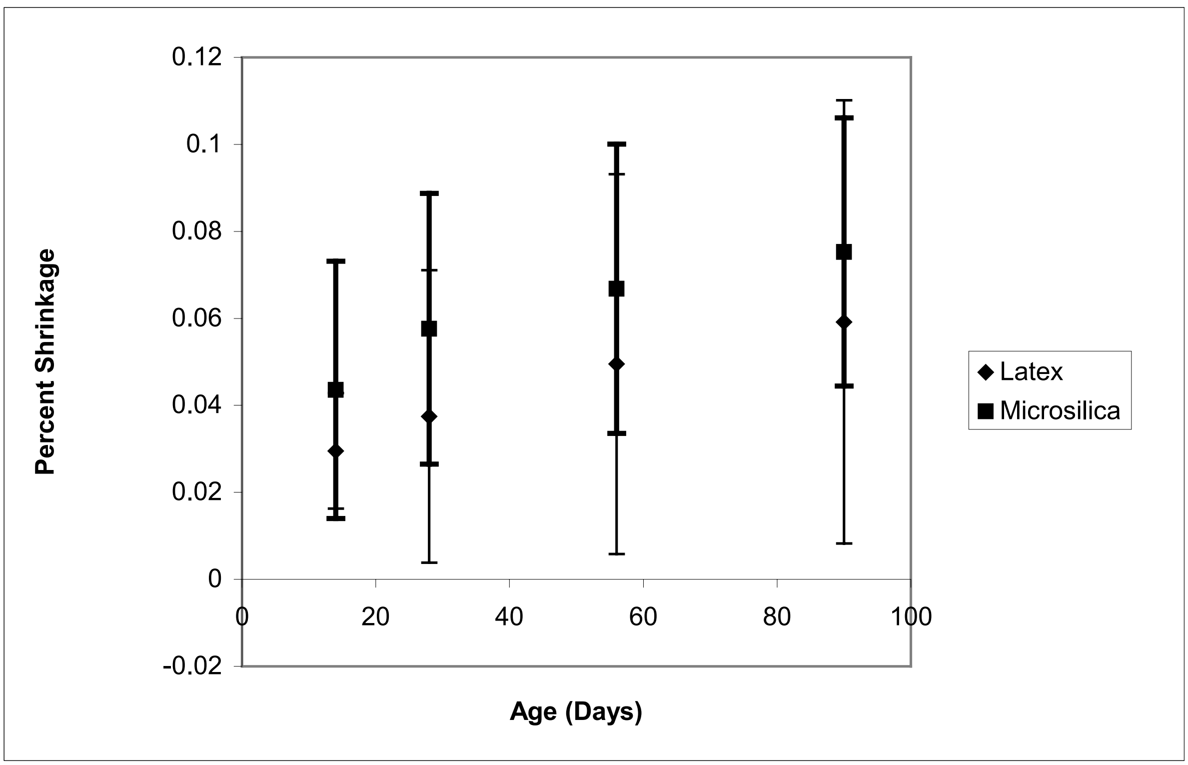

Figure 16: LMC and MSC Average Field Overlay Unrestrained Shrinkage

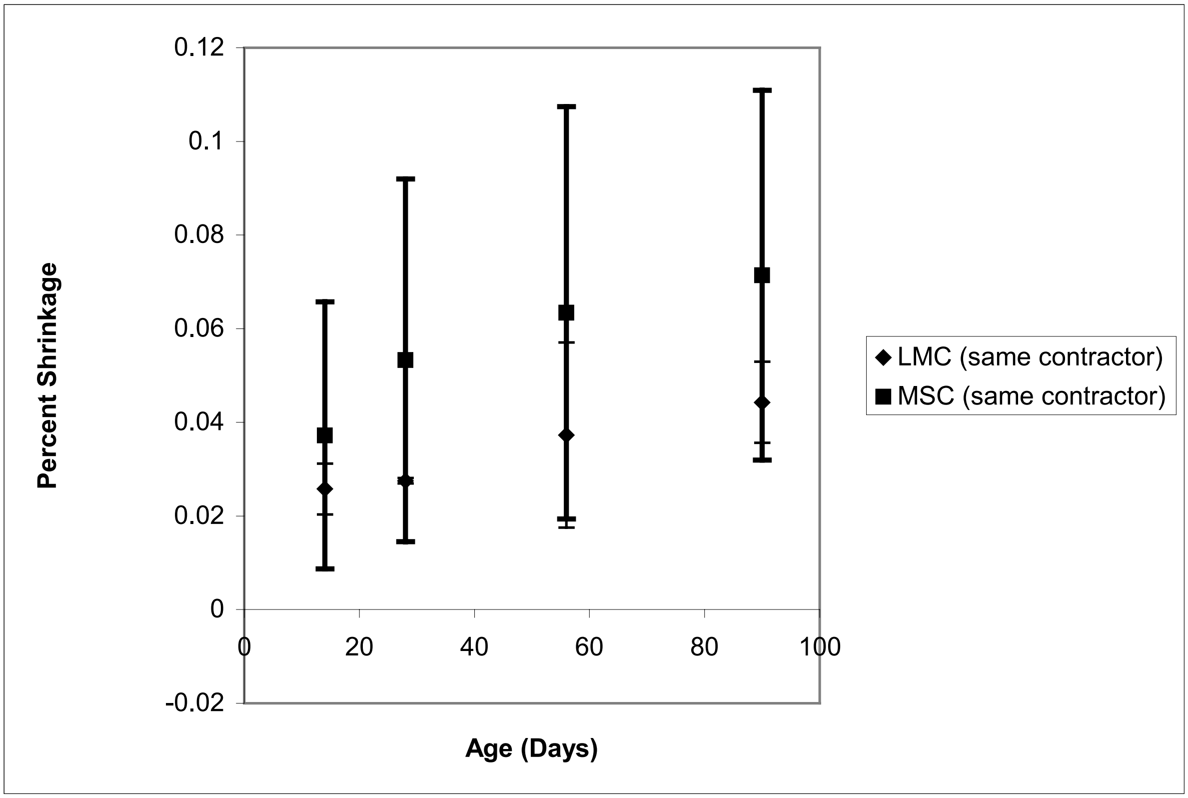

Figure 17: Average LMC and MSC Same Contractors Field Overlay Unrestrained Shrinkage

Laboratory Overlay Mixtures

Influence of Cement Content

Figure 8 presents the unrestrained shrinkage values for LMC-WCL-7.5, LMC-WCL-7, and LMC-WCL-6.5B. These mixtures have the same latex content of 13.2 L/bag of cement. The w/c for each are similar. The 7.5 bag and 7 bag Wilson Creek mixtures have significantly larger values of unrestrained shrinkage than those of the LMC-WCL-6.5B mixture. The unrestrained shrinkage values for the 7.5 bag and 7 bag mixtures are not significantly different at any age. Results from the restrained shrinkage testing are similar to those of the unrestrained shrinkage. All of the restrained specimens for both the 7.5 bag and 7 bag mixtures had cracked by 180 days, although the LMC-WCL-7.5 specimens began cracking at an earlier age than the LMC-WCL-7 specimens. No restrained specimens were cast from the LMC-WCL-6.5B mixture.

Influence of Different 7 Bag Mixture Designs

A comparison of the unrestrained shrinkage values for LMC-L2 and LMC-WCL-7 is given in Figure 18. Both mixtures have the same cement and latex contents as well as the same w/c. However, the LMC-WCL-7 mixture experienced significantly greater shrinkage than the LMC-L2 mixture. This is also shown in a comparison of the restrained shrinkage results. The LMC-WCL-7 ring specimens began cracking at an age of 39 days and all had cracked by 180 days. The LMC-L2 ring specimens began cracking at 144 days and only half of the specimens had cracked by 180 days. These mixtures are very similar; the primary difference between them is the type of latex used. The 7.5 bag and 7 bag Wilson Creek mixtures both used a BASF latex, while the LMC-WCL-6.5, LMC-WCL-6.5A, LMC-WCL-6.5B, and LMC-L2 mixtures used a Dow latex.

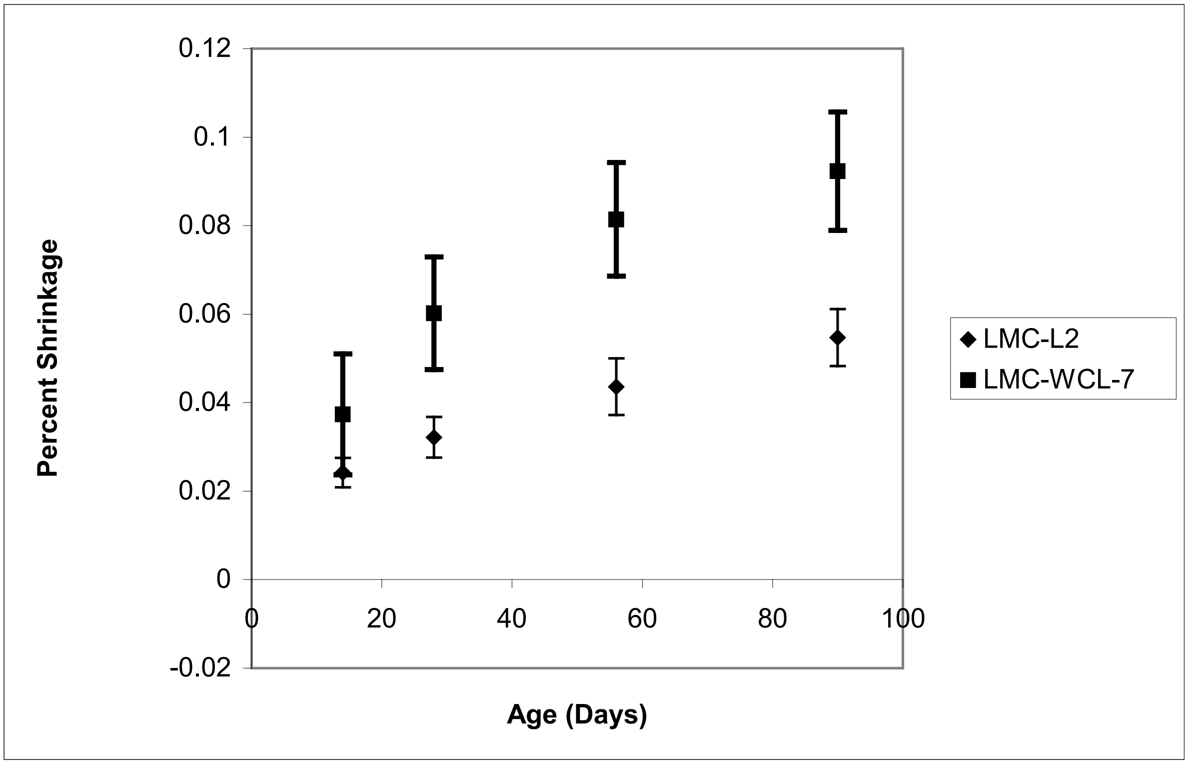

Figure 18: Comparison of 7 Bag Mixtures, Unrestrained Shrinkage

Influence of Latex Content

Figure 19 examines the unrestrained shrinkage of LMC-WCL-6.5A, which has 9.5 L of latex/bag of cement, and LMC-WCL-6.5, which has 13.2 L of latex/bag of cement. Both mixtures have the same w/c of 0.38 and the same cement content. There is no significant difference between the shrinkage values of LMC-WCL-6.5A and LMC-WCL-6.5.

Influence of w/c

The effect of w/c on unrestrained shrinkage is shown in Figure 20. Both LMC-WCL-6.5 and LMC-WCL-6.5B have the same cement and latex contents. The LMC-WCL-6.5 specimens, with a w/c of 0.38, exhibited significantly greater shrinkage than the LMC-WCL-6.5B specimens, with a w/c of 0.36.

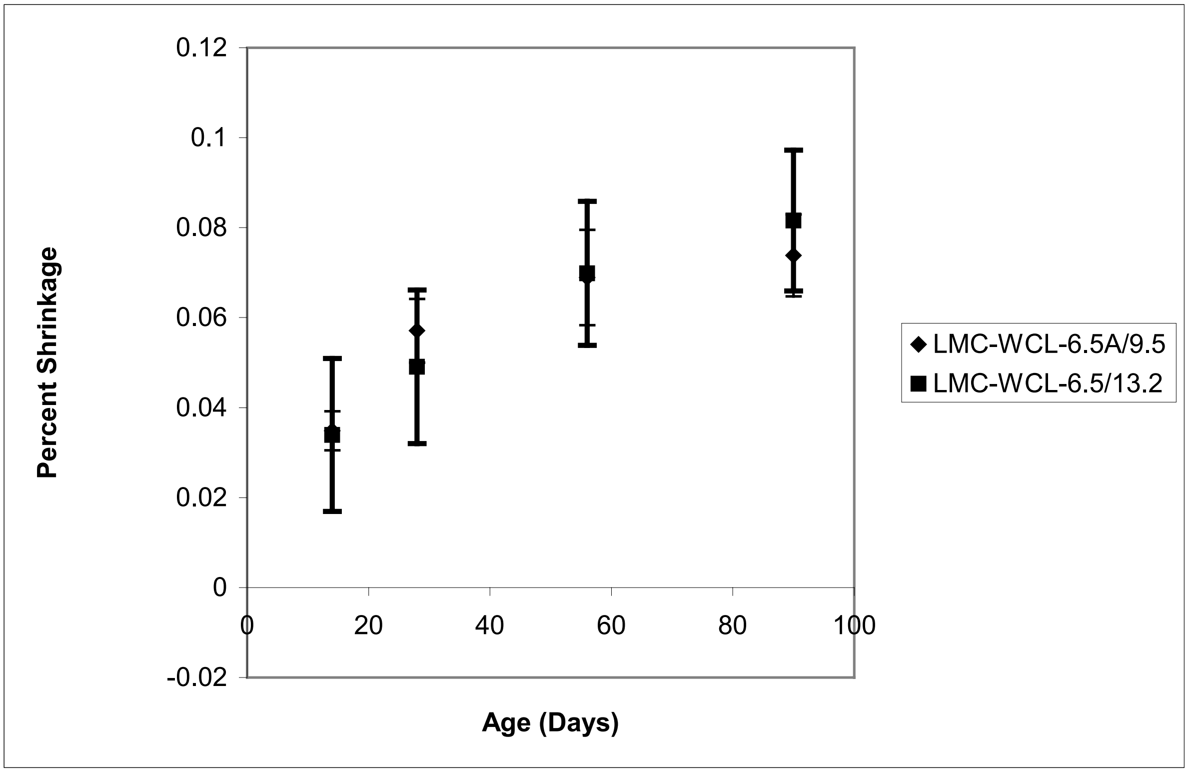

Figure 19: Comparison of Latex Content, Unrestrained Shrinkage

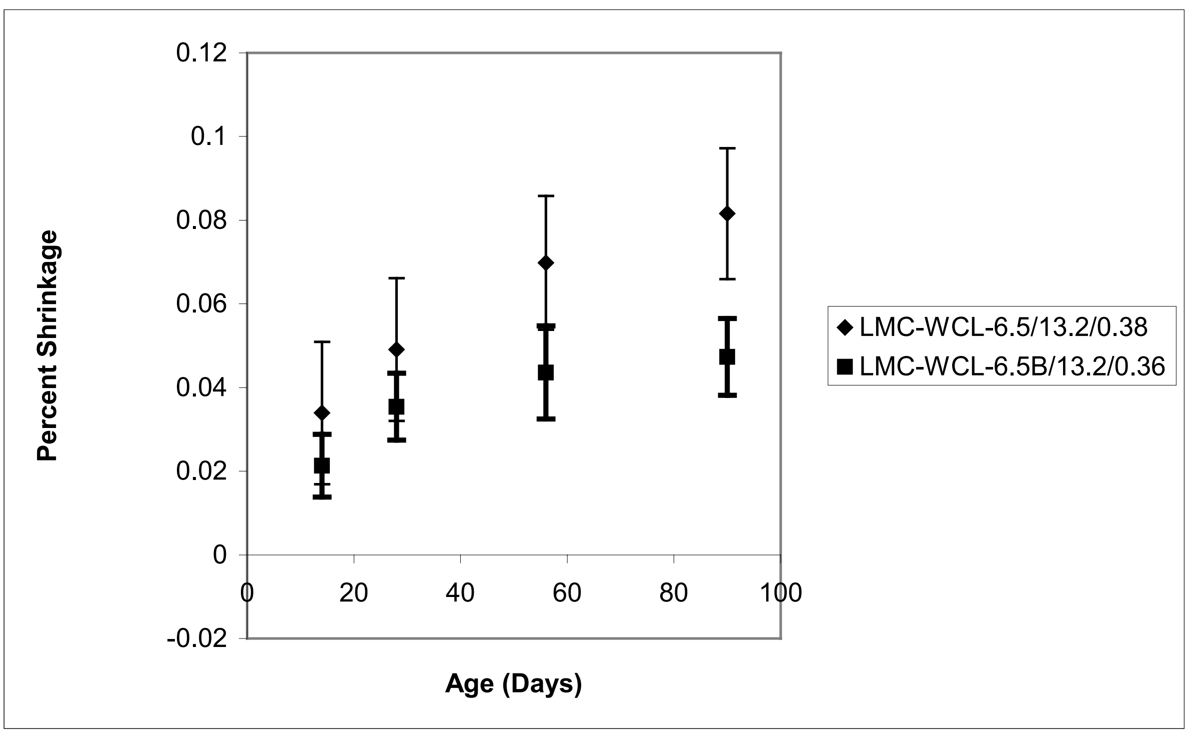

Figure 20: Comparison of w/c, Unrestrained Shrinkage

Influence of Curing Time

The effect of curing regime on the unrestrained shrinkage of the laboratory MSC overlay mixture is shown in Figure 14. Both mixtures had the same cement and microsilica contents as well as the same w/c. At 7 and 28 days, there are significant differences between the shrinkage values; however, by 56 days, there is no significant difference between the unrestrained shrinkage values. These results are similar to the restrained shrinkage testing results. Only one of the SF-L3 restrained specimens cracked by 180 days, while none of the SF-L7 specimens cracked.

Comparison of Laboratory LMC and MSC Mixtures

A comparison of LMC-L2 and SF-L7 is shown in Figure 21 to contrast the unrestrained shrinkage values of laboratory LMC and MSC mixtures. There is no significant difference in the unrestrained shrinkage values of these mixtures although some differences do exist in the restrained shrinkage results. By 180 days, half of the LMC-L2 ring specimens were cracked while none of the SF-L7 specimens were cracked. This illustrates the influence of construction conditions on the shrinkage and cracking of MSC and LMC mixtures. The field-sampled MSC mixtures exhibited a significantly larger amount of shrinkage and cracking than the laboratory-cast mixtures, which is probably a result of tighter mixture, and mixing controls in the laboratory.

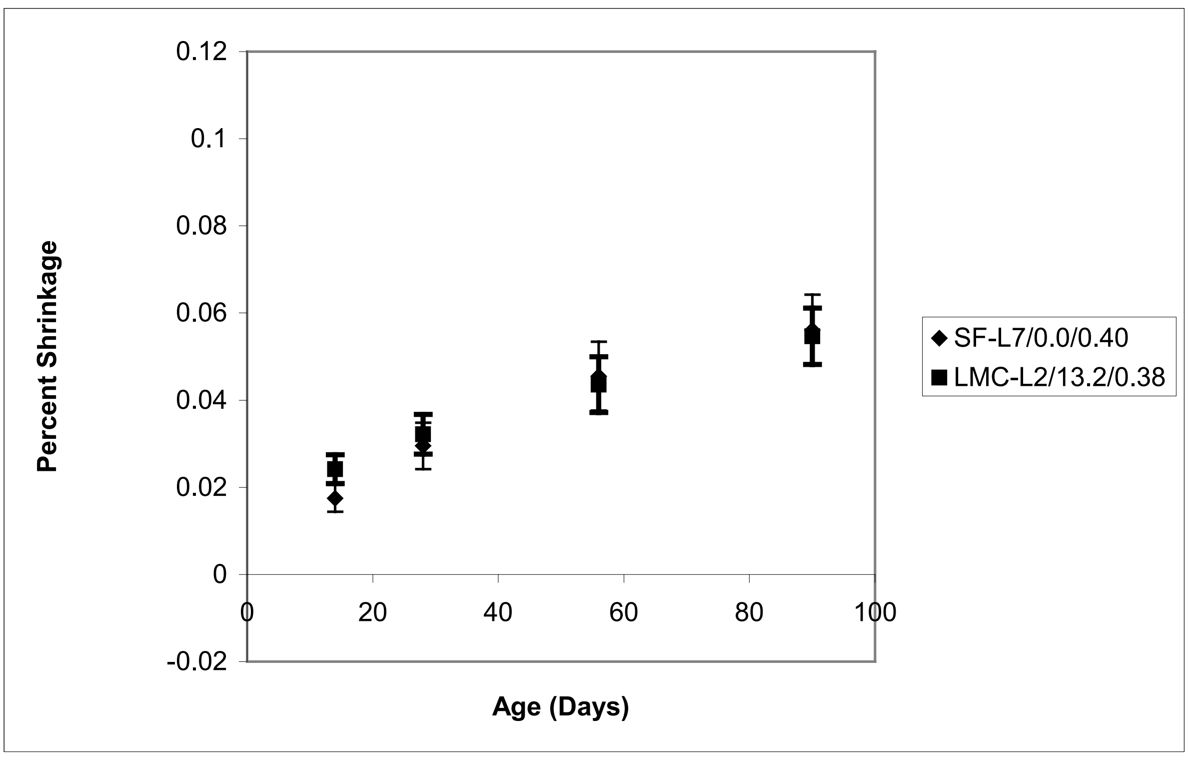

Figure 21: LMC and MSC Laboratory Overlay Mixtures, Average Unrestrained Shrinkage

CONCLUSIONS

Increasing the cement content increases the amount of shrinkage. However, the differences between shrinkage values for the 7.5 bag and 7 bag LMC overlay mixtures from the Wilson Creek Bridge are not significant.

Decreasing the latex content of a LMC overlay mixture does not have a significant effect on the amount of shrinkage.

Increasing the w/c of a LMC overlay mixture significantly increases the amount of shrinkage.

Increasing the moist curing time from 3 to 7 days for a MSC overlays mixture has no significant effect on long-term shrinkage although the effect on shrinkage values prior to 56 days is significant. The difference in curing regimes has little effect on shrinkage cracking.

Mixtures with unrestrained shrinkage values of 0.05% with a 95% upper confidence limit (UCL) of 0.06% at an age of 90 days and 0.04% with a 95%UCL of 0.05% at an age of 28 days experience less cracking as determined by AASHTO PP34-99.

Both field and laboratory specimens show no significant difference between LMC and MSC overlay mixtures' shrinkage values. However, shrinkage cracking is more prevalent and severe in the field MSC overlay specimens. The bridge deck crack and delamination surveys show that cracking results more from construction conditions and quality and traffic type and frequency than from the overlay material.

RECOMMENDATIONS

Further research should be conducted on different MSC overlay mixtures exposed to different curing regimes to determine whether the significant short-term differences in shrinkage values have a significant effect on cracking.

The rapid permeability test procedure (AASHTO T277) should be modified for LMC mixtures. After 1 day of moist curing, LMC specimens should be stored in 38ºC air for 27 days to allow the polymer film to form. MSC specimens should be moist cured for 7 days and then stored in 38ºC water for 21 days.

A performance specification should be implemented to minimize the number and severity of shrinkage cracks. This specification should include the following points:

- LMC is to be moist cured for a minimum of 2 days to allow the polymer film to form while MSC is to be moist cured for a minimum of 7 days to reduce short-term shrinkage.
- Based on the permeability results for cracked and uncracked specimens presented in Appendix E, the average permeability for both LMC and MSC overlays tested at 28 days as outlined above should be less than or equal to 800 coulombs with a 95% UCL of less than or equal to 1200 coulombs to minimize shrinkage cracking.
- Unrestrained average shrinkage (ASTM C157) of LMC and MSC at 28 days of drying is to be less than or equal to 0.04% with a 95% UCL of less than or equal to 0.05%.

Recommended Practice Based on Other Research

The performance specification should also include the following:

- The air content for LMC should be 5% ± 2% and for MSC should be 6% ± 2%.
- The compressive strength of both LMC and MSC overlays should be at least 34.5 MPa at 28 days.
- Bond strength for both LMC and MSC overlays should be at least 1.03 MPa (150 psi) at 28 days.
- Any delaminations found using the chain drag method at 28 days should be removed and replaced.
- Any areas exhibiting pattern cracking at 28 days should be removed and replaced.
- Any areas exhibiting greater linear crack frequency than 0.39 m/m^2 at 1 year should be removed and replaced.

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APPENDIX A: LITERATURE REVIEW

LATEX-MODIFIED AND MICROSILICA CONCRETE SHRINKAGE LITERATURE REVIEW

Introduction

Shrinkage is a three-dimensional deformation of concrete that results in an overall reduction in volume. Typically, the shrinkage of a concrete specimen is expressed as a linear strain since one of the dimensions is generally significantly larger than the other two and "the effects of shrinkage are greatest in the largest dimension" (Aïtcin, et al, 1997). As these internal strains increase, so does the potential for cracking (Shah, et al, 1998). Cracks may ease the ingress of chloride ions to the reinforcing steel. This, in turn, may lead to an increase in the rate of corrosion of the steel and a further reduction in strength.

There are four types of shrinkage: plastic shrinkage, autogenous shrinkage, drying shrinkage, and carbonation shrinkage (Aïtcin, et al, 1997). The total shrinkage can be measured under either restrained or unrestrained conditions. This review of the literature will examine the different types of shrinkage, specifically with respect to latex-modified concrete (LMC) and silica fume (microsilica) concrete (SFC), and is restricted to the past twenty-five years.

Plastic Shrinkage

Introduction

Plastic shrinkage is caused by water loss from the surface of concrete within a few hours of placement while the concrete is still plastic and before it gains any significant strength (Soroushian and Ravanbakhsh, 1998). This loss is generally due to evaporation to the atmosphere, which depends upon temperature, relative humidity, wind velocity, and the rigidity of the fresh concrete (Aïtcin, et al, 1997). Plastic shrinkage will occur if conditions exist which permit "a faster rate of evaporation of water from the surface of fresh concrete than the water replaced by bleeding from the concrete underneath" (Malhotra, et al, 1987). Therefore, any admixture that reduces bleeding increases the risk of plastic shrinkage occurring. The effects of surface evaporation are amplified by the "[s]uction of water from concrete by the sub-base or formwork materials or due to the internal consumption of water during hydration" (Soroushian and Ravanbakhsh, 1998).

Latex-Modified Concrete

Styrene-butadiene latexes are often used in bridge deck overlays to increase resistance to chloride intrusion. Latexes used in latex-modified concrete (LMC) overlays contain surfactants to prevent coagulation; these surfactants also function as water reducers in the concrete (Kuhlmann, 1990). Since this results in a lower water-cement ratio (w/c), less water is available for bleeding, increasing the probability of plastic shrinkage occurring.

In Virginia, a study conducted by Michael Sprinkel (1984) of the Virginia Highway Transportation Research Council of twelve bridges with LMC overlays showed that plastic shrinkage in LMC is more likely than in A4 concrete. The overlays studied ranged in age from new to thirteen years. Since LMC has a lower w/c than A4 concrete, less water is readily available to forestall plastic shrinkage. Of the bridges studied, only two had significant amounts of shrinkage cracking, from which Sprinkel surmised that if the proper care is taken at the time of placement, plastic shrinkage cracking in LMC overlays is preventable (Sprinkel, 1984).

In an examination of LMC overlaid bridges in Washington state, Khossrow Babaei and Neil Hawkins (1990) performed "[d]etailed field and laboratory studies…on twelve selected concrete overlaid bridge decks (six LMC and six LSDC [low-slump dense concrete]) in Washington to determine performance and where unforeseen problems had occurred in the overlays' performance to recommend modifications to design and construction procedures". The LMC overlays they studied during the summer of 1986 had a nominal thickness of 38 mm (1.5 in.), an average age of 5 years, and experienced an average daily traffic (ADT) volume of approximately 7000 vehicles. Field investigations determined that "[t]he maximum amount of cracking the in LMC overlays was 40% of the deck area," but cited nationwide inspections that indicate that LMC overlays "have the potential to develop 100% surface cracking". They believed plastic shrinkage to be the main cause of the majority of the cracks. In cores taken from newly placed LMC overlays cracks only extend 10 mm ($3/8$ in.) to 19 mm ($3/4$ in.) deep, while in the test overlays cracks reached at least as far as the bonded surface. They felt this shows that the cracks formed during the plastic state and increased in size over time due to repeated live and environmental loading (Babaei and Hawkins, 1990).

Silica Fume Concrete

As with latex, silica fume (SF) "induces a tendency for plastic shrinkage," although in the case of SF this is due to the fineness of the material (Ozyildirim, 1987). The fineness increases the water demand, leaving less free water to evaporate and thus is more susceptible to plastic shrinkage than conventional Portland cement concretes (PCCs). In fact, SFC overlays generally do not bleed, which increases the likelihood of plastic shrinkage (Luther, 1993). Research conducted to date indicates that SFC is most vulnerable to plastic shrinkage just prior to initial set (Malhotra, et al, 1987; Luther, 1993; Khayat and Aïtcin, 1993).

Prevention/Reduction

Proper curing techniques are essential to the prevention of plastic shrinkage cracking. Both LMC and SFC overlays need to be covered with wet burlap and plastic promptly after placement (Kuhlmann, 1990; Babaei and Hawkins, 1990; Sprinkel, 1984; Luther, 1993; Kuhlmann, 1991; Sprinkel, 1988).

According to Babaei and Hawkins (1990), plastic shrinkage cracks in LMC overlays can be kept to a minimum "by allowing a maximum evaporation rate of 0.73 $kg/m^2/h$ (0.15 $lb/ft^2/h$) while placing the overlay" and using measures to reduce the rate of evaporation, including those listed below.

- Erecting wind barriers
- Shading the aggregate to keep it cool
- Using cold mix water, possibly by including ice
- Using fog nozzles to maintain a sheen of moisture on the concrete surface before curing (Babaei and Hawkins, 1990)

Kuhlmann (1991) agrees with Babaei and Hawkins on the maximum evaporation rate and includes the recommendation that the damp burlap and polyethylene film be placed closely behind the finishing operation. The film should be white to "minimize the solar heat gain" and resulting quick increase in the temperature of the fresh concrete, and it should be weighted to prevent being blown off the concrete. He further urges tight control of the amount of water in the mix, decreasing the maximum allowable evaporation rate to 0.10 $lb/ft^2/h$, and revising the normal practice of damp curing for only one day to damp curing for two days instead, especially when the temperature and wind conditions are conducive to plastic shrinkage. Increasing the damp curing time will cause a slight expansion of the LMC overlay, putting the concrete into compression and decreasing the tendency towards plastic shrinkage cracking while having a negligible effect on compressive strength (Kuhlmann, 1991). On average, the typical LMC overlay is ready for traffic after four to seven days of total curing (Malhotra, 1987).

Luther (1993) recommends gently placing "dripping wet burlap" on each section of the SFC overlay immediately after texturing. If plastic is used, it is then placed on top of the burlap. Soaker hoses may then be strung under the plastic or, if no plastic is used, after every few strips of burlap. SFC needs to be wet cured for a minimum of two to seven days, although longer wet cure times are encouraged. Curing compounds and evaporation retarders can be useful, but are not a substitute for wet curing. Like Kuhlmann, Luther also recommends not allowing the evaporation rate to exceed 0.10 $lb/ft^2/h$ (1993).

Autogenous Shrinkage

Introduction

Autogenous shrinkage, also known as self-desiccation or chemical shrinkage, takes place as a result of cement hydration and develops isotropically within the concrete mass (Aïtcin, et al, 1997). Jensen and Hansen (1996) define self-desiccation as the "lowering of internal relative humidity in a closed isothermal cement paste system" resulting from the "internal volume reduction associated with the hydration of portland cement." The hydration process is a chemical reaction between Portland cement (PC) and water and the products of this reaction have less volume than the reactants. Autogenous shrinkage results from this self-desiccation in the following manner: water is removed from progressively smaller pores to allow hydration to proceed and this leads to self-desiccation, a reduction in the relative humidity of the pores in the hydrating concrete. As the pore size decreases, water tension increases, and these tensile stresses lead to shrinkage of the cement paste (Jensen and Hansen, 1996; Persson, 1997). Autogenous shrinkage can occur even in unloaded specimens (Persson, 1997) in the absence of water evaporation (Paillère, et al, 1989).

Latex-Modified Concrete

The literature search did not identify any articles published within the last twenty-five years that address the autogenous shrinkage of LMC.

Silica Fume Concrete

Paillère, et al (1989) examined the effect of steel fiber addition on the autogenous shrinkage of concrete. The w/c, amount of superplasticizer, amount of fibers, and SF content of the test mixtures were varied. To prevent evaporation, every exposed surface of each specimen was covered with a product based on a synthetic resin. They found that concrete with a low w/c experienced high amounts of autogenous shrinkage, autogenous shrinkage caused rapid cracking in restrained SFC specimens, and steel fibers can increase time to cracking and help provide confinement after cracking. The researchers believed the large values of autogenous shrinkage experienced by high strength concretes were caused by "an intense self-desiccation of the cement paste component in these concretes, resulting from an extremely low w/c" (Paillère, et al, 1989).

De Larrard and le Roy (1993) studied the influence of mixture composition on the mechanical properties of high-performance concrete (HPC) containing SF. The reference concrete contained no admixtures or SF while all other mixtures included varying amounts of SF and superplasticizer. The w/c of the test mixtures ranged from 0.33 to 0.50. All specimens were sealed with two sheets of self-adhesive aluminum after demolding to prevent any moisture exchange with the environment. The specimens were stored in a controlled temperature room of 20±1°C and measurements began at an age of 48 hours. By the age of 5000 hours, the reference concrete mixtures had autogenous shrinkage values of less than 50 microstrain compared to values ranging from 64 to 111 microstrain for all mixtures containing SF (de Larrard and le Roy, 1993).

Jensen and Hansen (1996) conducted research into autogenous deformation and change of the relative humidity in silica fume-modified cement paste. They varied the type of cement used as well as the amount of SF and the w/c. The researchers found that while all of the variations in mixture composition affected autogenous shrinkage, SF dosage had a "dominating influence." A 10 percent addition of SF increased the autogenous deformation by 1000 microstrain after 2 weeks; however, an decrease in the w/c from 0.40 to 0.25 only increased the autogenous deformation by 200 microstrain in the same amount of time (Jensen and Hansen, 1996).

Persson (1997) examined self desiccation of HPCs with w/c varying between 0.25 and 0.38. He measured specimens for autogenous shrinkage from one day to two years of age. He found that decreasing the w/c and increasing the SF content had the greatest effect on autogenous shrinkage (Persson, 1997).

In a later study by Persson (1998), he conducted further research on the shrinkage of HPC. All mixture proportions were varied and w/c ranged from 0.25 to 0.38. Specimens were insulated by 2 millimeters of butyl rubber clothing and stored in a controlled environment of 20°C and 55% relative humidity. Beginning at an age of one hour and continuing until an age of three to four years, autogenous shrinkage measurements were taken by mechanical devices. Concretes with the lowest w/c and highest SF replacement experienced the greatest amounts of autogenous deformation over time (Persson, 1998).

Prevention/Reduction

Autogenous shrinkage can be reduced by limiting the amount of SF replacement, increasing the w/c, and by ensuring proper curing of the concrete. According to Aïtcin, et al (1997), "[t]he development of autogenous…shrinkage can be delayed by wet curing, and prolonged curing can help avoid the development of cracking." Wet curing should commence as soon as hydration begins, especially with rapid-hardening cements, and should continue until the concrete has developed the necessary tensile strength to resist cracking (Aïtcin, et al, 1997).

Drying Shrinkage

Introduction

Drying shrinkage occurs in the hardened concrete as free water evaporates from the capillary pores. Capillary tension theory explains that "drying shrinkage is caused by the capillary tension occuring [sic] in the moisture existing in the pores in the cement gel" (Tazawa and Yonekura, 1987). The smaller the pore, the greater the tension is in the pore water. As this tension increases, it is harder for the water to evaporate. Thus, free water evaporates from larger pores first and "the loss of water is progressive and proceeds at a decreasing rate" (Aïtcin, et al, 1997). The rate of progression of drying shrinkage depends on the ratio of volume to exposed surface area of the concrete specimen. Drying shrinkage decreases as this ratio increases (Ohama, 1995).

Latex-Modified Concrete

In Sprinkel's (1984) examination of LMC overlays in Virginia, he found that "the 28-day shrinkage for LMC is about twice the 0.025% typically exhibited by A4 concrete." Of the four sets of samples prepared in 1983, measurements indicated that drying shrinkage resulted in length changes varying from 0.042 percent to 0.056 percent, showing that LMC overlay concrete is subject to more drying shrinkage than is conventional concrete (Sprinkel, 1984).

Another investigation conducted by Sprinkel (1988) compared the physical and mechanical properties of a high early strength latex modified concrete (LMC-HE) overlay with those of a standard LMC overlay. The LMC-HE mixture contained more cement with a lower w/c than the LMC mixture. Specimens for shrinkage testing were moist cured for two weeks and then were dried in air in the laboratory. Tests were conducted on 6 to 8 prism specimens measuring 76 mm by 76 mm by 286 mm. At 28-days, the drying shrinkage values of the LMC-HE averaged 0.042 percent, which is lower than that of LMC but still significantly higher than the drying shrinkage of A4 concrete (Sprinkel, 1988).

Although Babaei and Hawkins (1990) determined that the majority of the cracks found in their study of Washington state bridge deck overlays were caused by plastic shrinkage, their research showed that drying shrinkage could be significant. They found that "in spite of the small amount of water in its mix, the long-term shrinkage of LMC is high, especially in the first two weeks after construction." This shrinkage would have little effect on newly constructed bridge decks since the shrinkages of deck and overlay are compatible; however, placing a new overlay on an existing bridge deck that has already shrunk may cause cracking in the shrinking LMC overlay (Babaei and Hawkins, 1990).

According to Kuhlmann (1991), the drying shrinkage of LMC is controlled by the w/c of the mixture. He stressed the importance of ensuring excess water is not added to ensure that an LMC mixture will have the same shrinkage characteristics as a conventional concrete mixture with the same w/c (Kuhlmann, 1991).

Ohama (1995) examined latex-modified mortar specimens that varied in size, polymer type, and polymer-cement ratios. Of the styrene butadiene latex emulsions studied, he found that increasing the polymer-cement ratio of a concrete tends to decrease the measured drying shrinkage at 28 days. The reduction in drying shrinkage may be attributable to the effects of surfactants and antifoamers in the emulsion (Ohama, 1995).

Folic and Radonjanin (1998) conducted experimental research on polymer modified concrete using a latex dispersion based on butadiene styrene rubber. The total fluid to cement ratio of the mixtures was held to a constant 0.43 with varying latex contents. Specimens were damp cured for one day, demolded, and further cured according to one of the four following regimes: air cure for 27 days, water cure for 2 days followed by 25 days of curing in air, water cure for 6 days followed by 21 days of air cure, or 27 days of water cure. They found that drying shrinkage decreased as the polymer-cement ratio increased. Also, specimens subjected to a combination of wet and dry cure evidenced less drying shrinkage (Folic and Radonjanin, 1998).

Silica Fume Concrete

Carette and Malhotra (1983) examined the mechanical properties, durability, and drying shrinkage of PCC incorporating SF. The research was conducted in three series. Series A examined mixtures of constant slump with an initial w/c of 0.64 and up to 30 percent replacement of cement by SF. Series B investigated mixtures with a constant water to cementitious materials ratio (w/c+s) of 0.40 and up to 30 percent replacement of cement by SF using a superplasticizer. Series C looked exclusively at the compressive strength development of Series B mixtures. Drying shrinkage specimens were cured under wet burlap for 24 hours, demolded, further cured in a water tank until an age of 28 days, and then were stored in air at 23±1°C and 50±4% relative humidity. Changes in length and weight were recorded for 84 days. The researchers concluded that "[t]he drying shrinkage of concrete incorporating silica fume is generally comparable to that of control concrete regardless of the w/c+s" (Carette and Malhotra, 1983).

Ozyildirim (1986; 1987) studied concrete containing SF for use in bridge deck overlays. Specimens had a w/c of either 0.35 or 0.40 and were moist cured for one month before storage in ambient laboratory air. Compared to control concrete mixtures not containing SF, the experimental mixtures had similar but lower drying shrinkage values at an age of 32 weeks (Ozyildirim, 1986; Ozyildirim, 1987).

Tazawa and Yonekura (1987) studied drying shrinkage and creep of concrete containing condensed silica fume (CSF). Specimens were subjected to one of two curing regimes, specifically, standard and autoclave curing. Measurements were generally taken in air at 20°C and 50% relative humidity, although some were taken in water at 20°C. The w/c varied from 0.25 to 0.65 in order to cause variations in pore size to evaluate the effects of pore structure on drying shrinkage. Changes in length and weight were measured for 800 days. They found that conventional concrete specimens with w/c between 0.40 and 0.65 showed an increase in drying shrinkage strains with an increase of unit cement paste volume, but specimens with w/c of 0.25 and 0.30 demonstrated a decrease in drying shrinkage strains despite the large unit cement paste volume. Comparatively, all specimens containing CSF except those with a w/c of 0.65 had lower values for drying shrinkage strain, leading the researchers to believe that the "drying shrinkage of concrete is closely related not only to unit cement paste volume, but also to w/c and the existence of condensed silica fume" (Tazawa and Yonekura, 1987).

Kohno and Komatsu (1987) tested mixtures containing ground bottom ash and SF for drying shrinkage. Specimens were cured either conventionally, steam cured, or cured in an autoclave and subsequently stored at 20±1°C and 65±10% relative humidity. Measurements were taken using a microscope-type comparator. Their results showed that the drying shrinkage of concretes containing SF were about ten percent higher than that of conventional concrete, leading them to conclude that concretes containing SF tend to have greater drying shrinkage because water content has to be increased to obtain the same slump as a standard concrete mixture (Kohno and Komatsu, 1987).

Wolsiefer, et al (1995) examined the performance of concretes incorporating various forms of SF. Eleven different product forms of SF were used and the water to cementitious materials ratio (w/c+sf) varied between 0.22 and 0.40. All mixtures utilized a superplasticizer and an ordinary water reducer-retarder and, except for the concretes with a w/c+sf of 0.22, all mixtures were air entrained. Specimens were moist cured for either 7 or 28 days and drying shrinkage was measured at 448 days. The researchers found that the product form of the SF used did not have a significant impact on mechanical properties or durability. They found that regardless of product form, concretes containing SF had low drying shrinkage values of approximately $500x10^{-6}$ (Wolsiefer, et al, 1995).

Haque (1996) performed an experiment to study the strength development and drying shrinkage of high-strength concretes. His high-strength mixtures contained condensed silica fume (CSF) or a combination of CSF and either ground granulated blast furnace slag (GGBFS) or fly ash (FA) and were compared to conventional concrete specimens. Specimens were subjected to one of three different curing regimes: continuously cured in a fog room until testing, cured in a fog room for two days then moved to a control room until 24 hours before testing, or cured in a fog room for six days then moved to a control room until 24 hours before testing. The control room maintained a constant temperature of 23±2°C and 40±5% relative humidity. Twenty-four hours prior to testing, specimens were returned to the fog room "to negate skin effects and to bring all specimens to a standard level of moisture condition." He found that the drying shrinkage of all mixtures tested varied between 480 and 640 microstrain at an age of 91 days. The addition of CSF tended to reduce drying shrinkage values; however, the further addition of either FA or GGBFS tended to increase drying shrinkage. The reduction of shrinkage in specimens containing only CSF was believed to be due to "the densification of the hydrated cement paste and the resultant slowing down of the water evaporation" (Haque, 1996).

Whiting, et al (2000) studied the cracking tendency and drying shrinkage of SFC for bridge deck applications, including both full-depth and overlay placements. The water to cementitious materials ratio (w/cm) varied between 0.35 and 0.45 for full-depth bridge deck mixtures and between 0.30 and 0.40 for overlay mixtures. Restrained and unrestrained shrinkage tests were performed. All specimens were moist cured for 18 to 24 hours and demolded. Restrained (ring) specimens then had polyethylene sheets affixed to the top surface with a silicone sealant while unrestrained (prism) specimens were cured in limewater. Overlay specimens spent three days in the limewater; full-depth specimens were cured for seven days in limewater. All specimens were stored in a controlled environment of 23±1.7°C and 50±4% relative humidity. The results showed that the overlay mixtures, despite having a lower w/cm, experienced more shrinkage than corresponding full-depth concrete mixtures, especially at later ages. The researchers attributed this to: "1) the higher paste content of these mixtures; and 2) their shorter moist curing time (3 versus 7 days)." Comparisons of time to first crack show that overlay mixtures are more likely to crack and tend to crack at earlier ages than full-depth mixtures. All the overlay specimens had cracked by an age of 28 days; less than half of the full-depth specimens cracked. Control specimens not containing SF cracked at an average age of 42 days. From these results, the researchers concluded that drying shrinkage values in concretes containing SF are very sensitive to changes in w/cm (Whiting, et al, 2000).

Prevention/Reduction

To reduce drying shrinkage, Aïtcin, et al (1997) state that it is important to prevent evaporation of water from the concrete surface; thus, "an application of an impervious film is sufficient." Both LMC and SFC benefit from additional curing time. Kuhlmann (1990; 1991) averred that LMC should be cured for two days, instead of one, to decrease the tendency to form shrinkage cracks. Folic and Radonjanin (1998) found that LMC needed to be subjected to a combination of wet and dry curing to produce optimum results and recommended a six-day period of curing in a high humidity environment followed by curing in dry conditions. This regime provides the requisite humidity for cement hydration and still allows the polymer membranes to form and harden (Folic and Radonjanin, 1998). Whiting, et al (2000) believed that because of the sensitivity of SFC mixtures to changes in the w/cm, extra care should be taken during construction that excess water not be added to such mixtures. In addition, they recommended limiting the amount of SF in a mixture to no more than eight percent by mass of cementitious materials and curing the mixture for seven days to reduce cracking resulting from drying shrinkage (Whiting, et al, 2000). Kohno and Komatsu (1987) also recommend the use of a water-reducing admixture or high range water-reducing admixture to lower the amount of drying shrinkage experienced by SFC.

Carbonation Shrinkage

Introduction

Carbonation is a well-understood expansive chemical reaction that occurs in the presence of moisture between the hydrated cement paste and the carbon dioxide in the air (Aïtcin, et al, 1997). The American Concrete Institute (ACI) defines carbonation as the "reaction between carbon dioxide and calcium compounds, especially in cement paste, mortar, or concrete, to produce calcium carbonate" (ACI Committee 116, 1990). Researchers have found that, in addition to calcium hydroxide ($Ca(OH)_2$), carbonation reactions occur with calcium silicate hydrate (CSH), tricalcium silicate (C_3S), and dicalcium silicate (C_2S) (Claisse, et al, 1999). The presence of alkali ions causes a loss of cohesiveness in the concrete as a result of the carbonation reaction (George, 1983). The volume of the cement paste decreases as carbonation progresses (Soroka, 1979). This carbonation shrinkage is not well understood. One theory assumes "the precipitated calcium hydroxide crystals restrain the shrinkage of the cement gel." Once these crystals dissolve and react with the carbon dioxide, the restrained shrinkage is released (Jensen and Hansen, 1996). Carbonation also affects drying shrinkage, and this effect "reaches a maximum at approximately 50% relative humidity" (Soroka, 1979).

Latex-Modified Concrete

Kuhlmann (1990) published the results of an experiment in which LMC specimens were soaked in a sodium carbonate solution for a period of six months. The results showed that depth of carbonation of LMC increases with exposure time and decreases with an increase in the latex-cement ratio (Kuhlmann, 1990).

Silica Fume Concrete

Wolsiefer, et al (1995) measured the depth of carbonation after 448 days in their examination of the performance of concretes containing various forms of SF. They found that the form of SF had no effect on the carbonation depth. The specimens with w/c+sf of 0.30, 0.35, and 0.40 experienced a depth of carbonation of 5 millimeters or less, while specimens with a w/c+sf of 0.22 did not exhibit carbonation. The researchers felt that five millimeters of carbonation was not significant (Wolsiefer, et al, 1995).

Persson (1998) examined carbonation as part of his experimental studies of HPC. His results showed that weight loss due to drying shrinkage ceased because of carbonation at an age dependent on the w/c and that the internal relative humidity remains constant after initiation of carbonation. Additionally, none of the specimens with a w/c less than or equal to 0.25 exhibited carbonation. His findings showed that carbonation is dependent on the w/c and the SF content. An HPC with a low w/c and high SF content had little or no carbonation, and consequently no carbonation shrinkage. He stated that although it was appreciably smaller than drying or autogenous shrinkage, carbonation shrinkage could still have a significant effect on durability (Persson, 1998).

Prevention/Reduction

Maintaining a low w/c can reduce carbonation, and thus carbonation shrinkage (Kuhlmann, 1990; Wolsiefer, et al, 1995; Persson, 1998). For LMC, increasing the polymer-cement ratio also has a beneficial effect on carbonation (Kuhlmann, 1990). For SFC, carbonation may be reduced by increasing the amount of cement replacement by SF (Persson, 1998).

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APPENDIX B: FIELD CONDITIONS DURING SAMPLING

LMC OVERLAYS

US Route 1, NBL, 08/10/00

District: Richmond
County: Hanover
Structure: 09359 (042-10D1)

Table B1: LMC-1.1 Conditions

Location	Time	Air		Concrete		
		Temp (ºF)	RH (%)	Temp (ºF)	Slump (mm)	Air (%)
1	2:20 AM	--	--	80	--	4.5
	2:40 AM	--	--	85	159	--
2	3:30 AM	70	78	87	25	4.0
3	4:00 AM	69	80	84	114	4.2

No measurable wind

US Route 1, SBL, 10/18/00

District: Richmond
County: Hanover
Structure: 09359 (042-10D1)

Table B2: LMC-1.2 Conditions

Location	Time	Air		Concrete		
		Temp (ºF)	RH (%)	Temp (ºF)	Slump (mm)	Air (%)
1	7:48 AM	64	67	68	152	6-1/2
2	8:15 AM	62	77	68	152	6-1/2
3	8:49 AM	61	83	69	152	5-3/4

Weather cloudy, no measurable wind, slight mist at times

Wilson Creek Bridge, 05/23/01

District: Salem
County: Montgomery
Structure:

Table B3: LMC-WC Conditions

Location	Time	Air		Wind Speed	Concrete		
		Temp (ºF)	RH (%)	(KPH)	Temp (ºF)	Slump (mm)	Air (%)
	6:30 PM	71	44	3 - 6	--	--	--
	8:20 PM	61	74	0	--	--	--
1370'	12:25 AM	55	83	0 - 1	70.3	108	5.2
1340'	1:25 AM	52	98	0	66.9	229	3.9
1330'	2:45 AM	53	89	0 - 3	69.5	216	3.7

Periodic wind gusts

MSC OVERLAYS

Route 56, WBL, 08/22/00

District: Lynchburg
County: Nelson
Structure: 1019

Table B4: SF-56 Conditions

Location	Time	Air		Concrete		
		Temp (ºF)	RH (%)	Temp (ºF)	Slump (mm)	Air (%)
1	5:28 AM	53	91	78	191	8.5
	6:15 AM	52	98	--	--	--
2	7:00 AM	53	98	76	95	4.5
	7:44 AM	52	86	--	--	--
3	10:07 AM	69	85	75	83	4.5
	11:00 AM	76	75	--	--	--

No measurable wind, misty until about 8:00 AM

Route 150, Over Route 10, 08/28/00

District: Richmond
County: Chesterfield
Structure: B644

Table B5: SF-150/10 Conditions

		Air		Concrete		
Location	Time	Temp (ºF)	RH (%)	Temp (ºF)	Slump (mm)	Air (%)
1	7:15 AM	68	75	78	121	4.9
	7:35 AM	68	94	--	--	--
	8:00 AM	69	95	--	--	--
2	8:30 AM	69	94	79	165	5.5
3	8:46 AM	--	--	79	133	6.3
	9:10 AM	75	87	--	--	--
	10:00 AM	79	83	--	--	--

Weather cloudy, no measurable wind

Route 150, Over Falling Creek, 08/15/01

District: Richmond
County:
Structure:

Table B6: SF-150/FC Conditions

		Air		Wind Speed	Concrete		
Location	Time	Temp (ºF)	RH (%)	(KPH)	Temp (ºF)	Slump (mm)	Air (%)
Span 3	3:00 AM	70	94	0-1	76	140	5.3
Span 3	3:45 AM	69	95	0-1	78	127	5.1
Span 2	4:35 AM	69	94	0	78	114	6
Span 2	5:20 AM	69	95	0	78	152	5.7
Span 1	6:00 AM	69	94	0	80	152	5.5
Span 1	6:45 AM	70	90	--	81	159	6.4

No measurable wind, misty from approximately 2:00 AM to 8:00 AM

APPENDIX C: AMBIENT LABORATORY AIR TEMPERATURE AND RELATIVE HUMIDITY

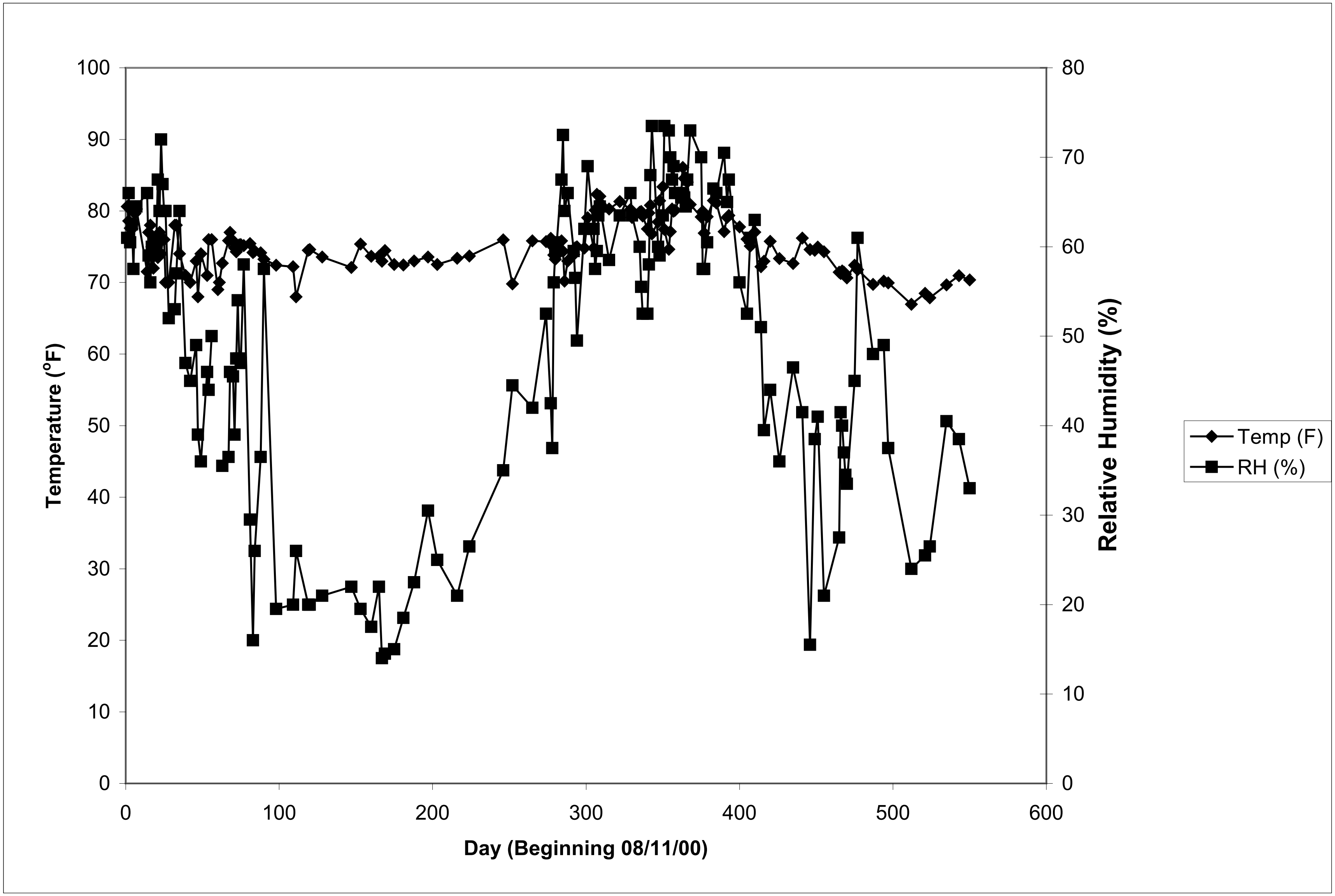

Figure C1: Ambient Laboratory Air Temperature and Relative Humidity as a Function of Time

APPENDIX D: COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY

FIELD MIXTURES

Field-cast compressive strength specimens were stored in the uncontrolled laboratory environment after the initial moist cure and adjacent to the shrinkage specimens. In addition, some of the field-cast specimens were stored in a moist room at 100% RH and 22ºC. The compressive strength results from cylinders stored in the uncontrolled environment are designated "Dry Strength," while the compressive strength results from cylinders stored in the moist room are designated "Wet Strength." All the specimens used in modulus of elasticity testing were stored in the uncontrolled laboratory air.

LMC Mixtures

Table D1: LMC-1.1 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 8	38.7	--	--
Day 28	47.4	--	27.6
Day 56	47.3	--	27.4
Day 90	49.9	--	27.4

Table D2: LMC-1.2 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	37.2	--	--
Day 28	48.1	45.9	25.8
Day 56	53.0	46.6	27.0
Day 90	49.1	--	28.5

Table D3: LMC-WC Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	43.4	--	19.6
Day 28	46.5	--	22.4
Day 56	52.5	--	24.5
Day 90	54.7	--	26.8

MSC Mixtures

Table D4: SF-56 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	50.6	--	--
Day 28	53.9	58.5	24.0
Day 56	--	64.5	24.9
Day 90	56.4	64.5	23.5

Table D5: SF-150/10 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	32.0	--	--
Day 28	42.8	43.0	25.2
Day 56	--	46.9	25.4
Day 90	37.0	46.9	25.0

Table D6: SF-150/FC Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	--	31.4	28.3
Day 28	--	48.3	27.9
Day 56	--	52.3	28.3
Day 90	--	52.6	26.8

LABORATORY MIXTURES

The cylinders cast for compressive strength testing from each of the laboratory mixtures were not stored in separate environments. The cylinders cast from LMC mixtures were all stored in ambient laboratory air after moist curing to allow formation of the polymer film. The cylinders cast from MSC mixtures were all stored in a controlled humidity environment with a RH of approximately 100% and temperature of 22ºC.

LMC Mixtures

Table D7: LMC-L2 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	29.9	21.5
Day 28	35.0	24.6
Day 56	36.2	27.8
Day 90	40.7	25.1

Table D8: LMC-WCL-7.5 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	33.3	15.4
Day 28	42.9	22.1
Day 56	48.7	21.8
Day 90	51.4	21.6

Table D9: LMC-WCL-7 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	32.5	17.0
Day 28	42.7	18.9
Day 56	47.8	21.1
Day 90	56.3	20.8

Table D10: LMC-WCL-6.5 Compressive Strength and Modulus of Elasticity

Age	Avg Dry Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	30.1	21.0
Day 28	36.5	22.9
Day 56	41.2	23.2
Day 90	44.6	23.6

No specimens were cast for modulus of elasticity testing from either the LMC-WCL-6.5A or LMC-WCL-6.5B mixtures.

Table D11: LMC-WCL-6.5A Compressive Strength

Age	Avg Dry Strength (MPa)
Day 7	35.2
Day 28	42.6
Day 56	47.0
Day 90	47.2

Table D12: LMC-WCL-6.5B Compressive Strength

Age	Avg Dry Strength (MPa)
Day 7	35.6
Day 28	42.7
Day 56	46.4
Day 90	46.1

MSC Mixtures

Table D13: SF-L3 Compressive Strength and Modulus of Elasticity

Age	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	45.3	29.4
Day 28	53.1	31.7
Day 56	52.2	33.8
Day 90	53.8	33.7

Table D14: SF-L7 Compressive Strength and Modulus of Elasticity

Age	Avg Wet Strength (MPa)	Avg E (x 10^3 MPa)
Day 7	45.4	28.6
Day 28	53.5	34.3
Day 56	--	--
Day 90	60.5	32.1

APPENDIX E: RAPID PERMEABILITY RESULTS

FIELD SAMPLED LMC OVERLAYS

Table E1: Rapid Chloride Permeability of Latex Modified Concrete Overlay Samples

	Curing Condition/Coulombs			
Structure	7 days 1-wet burlap @ jobsite 6 – air dry lab	90 days 1 – wet burlap @ jobsite 89 – air dry lab	28 days 1 – wet burlap @ jobsite 6 – air dry lab 21 – 37.8°C	90 days 1 – wet burlap @ jobsite 6 – air dry lab 83 – 37.8°C
Rt. 1/NB	2126 2027	630 850	657 700	243 258
Rt. 1/SB	1428 1544 1500	404 398 379	468 510 502	279 312 288
WC	1707 2887 2081	386 48 --	374 616 377	550 73 --
N	8	7	8	7
$\overline{X}$	1912	442	525	286
σ_{n-1}	481	247	122	140
C.V.	25%	56%	23%	49%

Note: Test specimens remained in the plastic molds during laboratory air dry curing period.

FIELD SAMPLED MSC OVERLAYS

Table E2: Rapid Chloride Permeability of Micro-silica Modified Concrete Overlay Samples

	Curing Condition/Coulombs			
Structure	7 days 1-wet burlap @ jobsite 6 – moist lab	90 days 1 – wet burlap @ jobsite 89 – moist lab	28 days 1 – wet burlap @ jobsite 6 – moist lab 21 – 37.8°C Water	90 days 1 – wet burlap @ jobsite 6 – moist lab 83 – 37.8°C Water
Rt. 56	4790 3480 5143	966 666 1150	930 666 1056	870 621 1082
Rt. 150/10	4202 4677 4555	899 937 898	645 753 716	708 797 768
Rt. 150/FC	6245 5946 5544 5913 6231 5559	-- -- -- -- -- --	853 808 973 1080 821 874	804 763 924 1030 825 862
N	12	6	12	12
$\overline{X}$	5190	919	848	838
σ_{n-1}	868	155	142	128
C.V.	17	17	17	15

Note: Test specimens remained in the plastic molds during laboratory moist curing period.

LABORATORY LMC MIXTURES

Table E3: Influence of Cement Content and Curing Conditions on Rapid Chloride Permeability in Coulombs

Mixture	WCL-7.5	WCL-7	WCL-6.5B
	(7.5 bags)	(7.0 bags)	(6.5 bags)
Age/Conditions	(w/c = 0.36)	(w/c = 0.38)	(w/c = 0.36)
7 days 2 - wet burlap 5 - lab air	2550 2473	2551 2328	3287 2695
7 days 3 - wet burlap 4 - lab air	2521 2770	2916 2393	3261 2739
28 days 2 - wet burlap 26 - lab air	1241 1832	1520 1704	1463 1191
28 days 3 - wet burlap 25 - lab air	1302 1852	1048 1732	1370 1125
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC air	530 876	537 715	854 740
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC air	510 926	984 724	930 722
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC water	1187 1536	964 1361	970 851
90 days 2 - wet burlap 5 - lab air 83 - 37.8ºC air	94 154	165 129	-- --
90 days 3 - wet burlap 4 - lab air 83 - 37.8ºC air	46 82	657 107	-- --

Note: Latex addition was 13.2 L per bag of cement, and specimens were cured 7 days in the plastic molds.

Table E4: Comparison of Two 7 Bag LMC Mixtures and Curing Conditions on Rapid Chloride Permeability in Coulombs

Mixture	L2	WCL-7
	(7.0 bags)	(7.0 bags)
Age/Conditions		
7 days 2 - wet burlap 5 - lab air	3025 3393	2551 2328
7 days 3 - wet burlap 4 - lab air	3574 3146	2916 2393
28 days 2 - wet burlap 26 - lab air	2069 2751	1520 1704
28 days 3 - wet burlap 25 - lab air	2511 2762	1048 1732
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC air	1712 1567	537 715
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC air	1580 1500	984 724
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC water	2023 1906	964 1361
90 days 2 - wet burlap 5 - lab air 83 - 37.8ºC air	168 393	165 129
90 days 3 - wet burlap 4 - lab air 83 - 37.8ºC air	348 347	657 107

Note: w/c = 0.38, latex addition was 13.2 L per bag of cement, and specimens were cured 7 days in the plastic molds.

Table E5: Influence of Latex Content and Curing Conditions on Rapid Chloride Permeability in Coulombs

Mixture	WCL-6.5A	WCL-6.5
	(9.5 L/bag)	(13.2 L/bag)
Age/Conditions		
7 days 2 - wet burlap 5 - lab air	3698 4105	4748 4387
7 days 3 - wet burlap 4 - lab air	3856 3765	4495 3916
28 days 2 - wet burlap 26 - lab air	1361 1604	3539 3579
28 days 3 - wet burlap 25 - lab air	1332 1414	3387 3475
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC air	749 941	2042 2557
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC air	830 809	2174 2308
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC water	71 927	2408 2287
90 days 2 - wet burlap 5 - lab air 83 - 37.8ºC air	463 643	961 3470
90 days 3 - wet burlap 4 - lab air 83 - 37.8ºC air	500 625	1094 2831

Note: w/c = 0.38 and specimens were cured 7 days in the plastic molds.

Table E6: Influence of Water-to-Cement Ratio and Curing Conditions on Rapid Chloride Permeability in Coulombs

Mixture	WCL-6.5B	WCL-6.5
	(w/c = 0.36)	(w/c = 0.38)
Age/Conditions		
7 days 2 - wet burlap 5 - lab air	3287 2695	4748 4387
7 days 3 - wet burlap 4 - lab air	3261 2739	4495 3916
28 days 2 - wet burlap 26 - lab air	1463 1191	3539 3579
28 days 3 - wet burlap 25 - lab air	1370 1125	3387 3475
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC air	854 740	2042 2557
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC air	930 722	2174 2308
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC water	970 851	2408 2287
90 days 2 - wet burlap 5 - lab air 83 - 37.8ºC air	-- --	961 3470
90 days 3 - wet burlap 4 - lab air 83 - 37.8ºC air	-- --	1094 2831

Note: Cement content 362 kg per cubic meter (6.5 bags per cubic yard), latex addition was 13.2 L per bag, and specimens were cured 7 days in the plastic molds.

LABORATORY MSC MIXTURES

Table E7: Influence of Moist Curing Period on Rapid Chloride Permeability in Coulombs

Mixture	SF-L3		SF-L7
	(3 day cure)		(7 day cure)
Age/Conditions		Age/Conditions	
7 days 2 - wet burlap 5 - lab air	 1852 3292	 7 days 7 - wet burlap	3218 3336 3150 2907
7 days 3 - wet burlap 4 - lab air	 2849 2946		
28 days 2 - wet burlap 26 - lab air	 796 1212		
28 days 3 - wet burlap 25 - lab air	 457 990		
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC water	 365 2039	28 days 7 - wet burlap 21 - 37.8 C water	 745 670
28 days 2 - wet burlap 5 - lab air 21 - 37.8ºC water	 307 752		
28 days 3 - wet burlap 4 - lab air 21 - 37.8ºC water	 390 756	28 days 7 - wet burlap 21 - 37.8ºC air	1172 1201 818 1140
90 days 2 - wet burlap 5 - lab air 83 - 37.8ºC water	 342 726	90 days 7 - wet burlap 83 - 37.8ºC water	 689 668
90 days 3 - wet burlap 4 - lab air 83 - 37.8ºC water	 405 726	90 days 7 - wet burlap 83 - 37.8ºC air	 1718 1285

Note: w/c = 0.40 and specimens were cured in the plastic molds for 7 days.

APPENDIX F: BRIDGE DECK CRACK AND DELAMINATION SURVEY RESULTS

CRACK AND DELAMINATION SURVEY OF LMC OVERLAY AT 293 DAYS AFTER PLACEMENT, ROUTE 1 NBL

Table F1a: Span 1, Length 10.4 m, Width 6.1 m, Skew 30°

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	--	None
Longitudinal	0.10 – 0.19	0.63
Diagonal	0.10 – 0.19	5.08
Subtotal		5.71
Pattern	--	None
Delaminations	--	None

Table F1b: Span 2, Length 14.4 m, Width 6.1 m, Skew 30°

Transverse	--	None
Longitudinal	0.10 – 0.19	6.15
Diagonal	0.10 – 0.19	0.88
Subtotal		7.03
Pattern	--	None
Delaminations	--	None

Table F1c: Span 3, Length 10.4 m, Width 6.1 m, Skew 30°

Transverse	--	None
Longitudinal	0.10 – 0.19	17.13
Diagonal	0.10 – 0.19	5.08
Subtotal		22.21
Pattern	--	None
Delaminations	--	None

Northbound Total Frequencies

Trans, Long, Diagonal	0.16 m/m^2
Pattern	None
Delaminations	None
Area	215 sq. m

CRACK AND DELAMINATION SURVEY OF LMC OVERLAY AT 224 DAYS AFTER PLACEMENT, ROUTE 1 SBL

Table F2a: Span 1, Length 10.4 m, Width 6.1 m, Skew 30°

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	0.10 – 0.19	9.52
Longitudinal	0.10 – 0.19	9.52
Diagonal	0.10 – 0.19	4.44
Subtotal		23.48
Pattern	--	None
Delaminations	--	None

Table F2b: Span 2, Length 14.4 m, Width 6.1 m, Skew 30°

Transverse	--	None
Longitudinal	0.10 – 0.19	6.15
Diagonal	0.10 – 0.19	0.88
Subtotal		7.03
Pattern	--	None
Delaminations	--	None

Table F2c: Span 3, Length 10.4 m, Width 6.1 m, Skew 30°

Transverse	--	None
Longitudinal	0.20 – 0.29	20.94
Diagonal	0.10 – 0.19 0.20 – 0.29	7.61 5.08
Subtotal		33.63
Pattern	--	None
Delaminations	--	None

Southbound Total Frequencies

Trans, Long, Diagonal	0.30 m/m^2
Pattern	None
Delaminations	None
Area	215 sq. m

CRACK AND DELAMINATION SURVEY OF LMC OVERLAY AT 289 DAYS AFTER PLACEMENT, WILSON CREEK BRIDGE

From West end, 424 m and proceeding East for the entire width, Width 11 m, Skew 0º

Table F3a: Sample area 1, 50.17 m^2

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	0.10 – 0.19	54.9
Longitudinal	0.10 – 0.19	137.1
Diagonal	--	None
Subtotal		192.0
Pattern	--	None
Delaminations	--	0.32 sq. m

Table F3b: Sample area 2, 50.17 m^2

Transverse	--	None
Longitudinal	0.10 – 0.19	102.8
Diagonal	--	None
Subtotal		102.8
Pattern	--	None
Delaminations	--	0.23 sq. m

Table F3c: Sample area 3, 38.41 m^2

Transverse	0.20 – 0.29	146.4
Longitudinal	0.20 – 0.29	146.4
Diagonal	--	None
Subtotal		292.8
Pattern	--	None
Delaminations	--	None

Table F3d: Sample area 4, 50.17 m^2

Transverse	--	None
Longitudinal	--	None
Diagonal	--	None
Subtotal		None
Pattern	0.10 – 0.19	50.17 sq. m
Delaminations	--	None

Note: Representative sample areas were chosen because of the extensive cracking in the deck survey area.

Total Frequencies

Trans, Long, Diagonal	3.14 m/m^2
Pattern	0.27 m^2/m^2
Delaminations	0.55 sq. m
Area	189 sq. m

CRACK AND DELAMINATION SURVEY OF MICROSILICA OVERLAY AT 282 DAYS AFTER PLACEMENT, ROUTE 56 WBL

Table F4a: Span 1, Length 9.14 m, Width 3.35 m, Skew 58°

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	0.10 – 0.19	2.14
Longitudinal	--	None
Diagonal	0.10 – 0.19	1.53
Subtotal		3.67
Pattern	--	None
Delaminations	--	0.25 sq. m

Table F4b: Span 2, Length 14.6 m, Width 3.35 m, Skew 54°

Transverse	0.08 – 0.09	3.91
Longitudinal	--	None
Diagonal	0.10 – 0.19	0.98
Subtotal		4.89
Pattern	--	None
Delaminations	--	0.07 sq. m

Table F4c: Span 3, Length 14.6 m, Width 3.35 m, Skew 49°

Transverse	0.08 – 0.09	2.45
Longitudinal	--	None
Diagonal	0.20 – 0.30	1.96
Subtotal		4.41
Pattern	--	None
Delaminations	--	None

Table F4d: Span 4, Length 14.6 m, Width 3.35 m, Skew 44°

Transverse	0.08 – 0.09	0.49
Longitudinal	0.08 – 0.09	0.98
Diagonal	0.08 – 0.09	0.98
Subtotal		2.45
Pattern	--	None
Delaminations	--	0.02 sq. m

Table F4e: Span 5, Length 10.0 m, Width 3.35 m, Skew 40°

Transverse	--	None
Longitudinal	--	None
Diagonal	0.08 – 0.09	0.34
Subtotal		0.34
Pattern	--	None
Delaminations	--	None

Westbound Total Frequencies

Trans, Long, Diagonal	0.07 m/m^2
Pattern	None
Delaminations	0.34 sq. m
Area	211 sq. m

CRACK AND DELAMINATION SURVEY OF MICROSILICA OVERLAY AT 278 DAYS AFTER PLACEMENT, ROUTE 150 NBL OVER ROUTE 10

Two Spans, Length 62 m, Width 7.3 m, Skew 20°.

Table F5a: 0 to 18.3 m, Width 7.3 m, Skew 20°

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	--	None
Longitudinal	0.10 – 0.20	54.8
Diagonal	--	None
Subtotal		54.8
Pattern	--	None
Delaminations	--	None

Table F5b: 18.3 m to 39.6 m, Width 7.3 m, Skew 20º

Transverse	--	None
Longitudinal	0.10 – 0.20	46.6
Diagonal	--	None
Subtotal		46.6
Pattern	0.10 – 0.15	124.3 sq. m
Delaminations	--	None

Table F5c: 39.6 m to 62 m, Width 7.3 m, Skew 20°

Transverse	--	None
Longitudinal	0.10 – 0.20	63.8
Diagonal	--	None
Subtotal		63.8
Pattern	0.10 – 0.20	81.8 sq. m
Delaminations	--	None

Total Frequencies

Trans, Long, Diagonal	0.37 m/m^2
Pattern	0.46 sq. m/sq. m
Delaminations	None
Area	453 sq. m

CRACK AND DELAMINATION SURVEY OF MICROSILICA OVERLAY AT 235 DAYS AFTER PLACEMENT, ROUTE 150 SBL OVER FALLING CREEK

Table F6a: Span 1, Length 16.2 m, Width 6.1 m, Skew 35°

Cracks/Delaminations	Crack Width (mm)	Crack Length (m)
Transverse	0.10 – 0.19	0.30
Longitudinal	0.10 – 0.19	0.30
Diagonal	--	None
Subtotal		0.60
Pattern	--	None
Delaminations	--	None

Table F6b: Span 2, Length 22.2 m, Width 6.1 m, Skew 35°

Transverse	--	None
Longitudinal	0.20 – 0.29	1.49
Diagonal	--	None
Subtotal		1.49
Pattern	--	None
Delaminations	--	None

Table F6c: Span 3, Length 16.2 m, Width 6.1 m, Skew 35°

Transverse	--	None
Longitudinal	0.10 – 0.19	1.98
Diagonal	--	None
Subtotal		1.98
Pattern	--	None
Delaminations	--	None

Total Frequencies

Trans, Long, Diagonal	0.01 m/m^2
Pattern	None
Delaminations	None
Area	333 sq. m

APPENDIX G: RESULTS OF STATISTICAL ANALYSES

Table G1: Results from Statistical Analyses Performed Using SAS

	Day 14			Day 28			Day 56			Day 90		
	F Values	Σ Squares	Pr > F	F Values	Σ Squares	Pr > F	F Values	Σ Squares	Pr > F	F Values	Σ Squares	Pr > F
Lab Mixtures												
LMC-WCL-7 vs LMC-WCL-7.5	0.00	5.17E-12	0.9824	0.14	9.91E-10	0.7173	1.54	1.06E-08	0.2496	4.18	2.89E-08	0.0753
LMC-WCL-6.5 vs LMC-WCL-6.5A	0.05	5.04E-10	0.8362	5.46	3.84E-08	0.0477	0.07	5.04E-10	0.7931	5.20	3.60E-08	0.0520
LMC-WCL-6.5 vs LMC-WCL-6.5B	8.60	9.50E-08	0.0189	15.92	1.12E-07	0.0040	60.30	4.13E-07	< 0.0001	101.56	7.04E-07	< 0.0001
LMC-WCL-6.5A vs LMC-WCL-6.5B	9.89	1.09E-07	0.0137	40.01	2.82E-07	0.0002	56.16	3.85E-07	< 0.0001	60.80	4.21E-07	< 0.0001
LMC-L2 vs LMC-WCL-7 & 7.5	12.25	1.35E-07	0.0081	91.81	6.46E-07	< 0.0001	183.46	1.26E-06	< 0.0001	192.96	1.34E-06	< 0.0001
SF-L3 vs SF-L7	15.69	1.73E-07	0.0042	14.41	1.01E-07	0.0053	2.19	1.50E-08	0.1774	1.89	1.31E-08	0.2070
Latex vs Microsilica	4.85	5.36E-08	0.0587	44.59	3.14E-07	0.0002	80.14	5.49E-07	< 0.0001	69.99	4.85E-07	< 0.0001
Field Mixtures												
LMC-1.1 vs LMC-1.2	1.11	6.14E-09	0.2969	5.87	2.83E-08	0.0183	15.45	8.12E-08	0.0002	2.79	1.56E-08	0.1001
LMC-1.1 & LMC-1.2 vs LMC-WC	19.57	1.08E-07	< 0.0001	113.64	5.49E-07	< 0.0001	212.60	1.12E-06	< 0.0001	298.05	1.67E-06	< 0.0001
SF-150.1 vs SF-150.2	25.81	1.43E-07	< 0.0001	65.07	3.14E-07	< 0.0001	79.83	4.20E-07	< 0.0001	55.49	3.11E-07	< 0.0001
SF-150.1 & SF-150.2 vs SF-56	39.60	2.20E-07	< 0.0001	23.36	1.13E-07	< 0.0001	14.91	7.84E-08	0.0003	18.27	1.02E-07	< 0.0001
Latex vs Microsilica	39.75	2.20E-07	< 0.0001	75.43	3.64E-07	< 0.0001	66.49	3.49E-07	< 0.0001	50.33	2.82E-07	< 0.0001
Overall												
LMC-WC vs LMC-WCL-7	0.01	3.56E-11	0.9228	2.10	7.22E-09	0.1498	10.81	4.39E-08	0.0013	2.32	9.39E-09	0.1296
LMC-WC vs LMC-WCL-7.5	0.05	1.88E-10	0.8236	4.43	1.53E-08	0.0370	25.44	1.03E-07	< 0.0001	20.12	8.13E-08	< 0.0001
LMC-WCL-7 vs LMC-WCL-7.5	0.01	5.27E-11	0.9061	0.41	1.40E-09	0.5251	2.85	1.16E-08	0.0933	7.57	3.06E-08	0.0067
LMC-WC vs LMC-WCL-7 & 7.5	0.04	1.41E-10	0.8471	4.56	1.57E-08	0.0343	25.11	1.02E-07	< 0.0001	13.17	5.32E-08	0.0004
SF-56 vs SF-L3	50.48	1.91E-07	< 0.0001	65.95	2.27E-07	< 0.0001	52.88	2.15E-07	< 0.0001	48.99	1.98E-07	< 0.0001
SF-56 vs SF-L7	159.70	6.03E-07	< 0.0001	157.52	5.43E-07	< 0.0001	78.17	3.17E-07	< 0.0001	71.70	2.90E-07	< 0.0001
SF-56 vs SF-L3 & SF-L7	116.92	4.42E-07	< 0.0001	128.19	4.42E-07	< 0.0001	77.89	3.16E-07	< 0.0001	71.77	2.90E-07	< 0.0001
Latex vs Microsilica	20.01	7.56E-08	< 0.0001	3.40	1.17E-08	0.0673	2.87	1.17E-08	0.0923	4.40	1.78E-08	0.0377
Lab vs Field	30.06	1.14E-07	< 0.0001	4.59	1.58E-08	0.0338	13.13	5.33E-08	0.0004	18.49	7.47E-08	< 0.0001

Note: Pr > F values of 0.0500 or greater indicate that the mixtures compared are not significantly different. Pr > F values of less than 0.0500 indicate that the mixtures compared are significantly different.

APPENDIX H: ALL-INCLUSIVE TEST MATRIX

Table H1: All-Inclusive Test Matrix

	Restrained		Unrestrained		Cylinders		
	(Rings)		3" x 3" x 11-1/4" (Prisms)		4" x 8"		6" x 12"
	Controlled	Uncontrolled	Controlled	Uncontrolled	Strength	Permeability	Modulus
SFC Overlays							
Rt. 56	0	6	3	3	12	6	2
Rt. 150 (Tye River)	0	6	6	6	12	6	2
Rt. 150 (Falling Creek)	0	6	9	9	21	9	3
LMC Overlays							
Rt. 1 (NBL)	0	6	0	6	8	4	2
Rt. 1 (SBL)	2	6	6	6	10	8	2
Wilson Creek	0	6	6	12	12	6	3
SFC Lab Mixtures							
SF-L3	0	4	6	6	10	10	2
SF-L7	0	4	6	6	14	6	2
LMC Lab Mixtures							
LMC-L2	0	4	6	6	10	10	2
LMC-WCL-7.5	0	4	6	6	10	10	2
LMC-WCL-7	0	4	6	6	10	10	2
LMC-WCL-6.5	0	4	6	6	10	10	2
LMC-WCL-6.5A	0	0	6	6	10	10	0
LMC-WCL-6.5B	0	0	6	6	10	10	0

Note: Laboratory mixtures were cast in two batches; the values above are the overall total of specimens cast.

PATRICIA MICHELLE BUCHANAN

Patricia was born in Portsmouth, Virginia, on September 7, 1978, to Ronald and Darlene Buchanan. She grew up in Frederick County, Virginia, and attended James Wood High School and Sherando High School. Tricia graduated from Sherando in 1996 first in her class. After high school, she attended Virginia Tech and graduated in 2000 with a Bachelor of Science degree in Civil Engineering. She then pursued a Master of Science in Civil Engineering at Virginia Tech. Upon completion of her graduate degree, Tricia will be working as a forensic engineer for Whitlock, Dalrymple, Poston, and Associates in Manassas, Virginia.