Internal Curing of Concrete Pavements and Overlays

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Abstract
Internal curing is an innovative technology to improve the mechanical properties and performance of concrete. The internal water was supplied by fine saturated lightweight aggregate particles (LWA) in this study. The LWA was used to replace a portion of the conventional fine aggregate in the mixture. An internal curing effect has also been observed when comparing concrete made with low and moderate absorption coarse aggregate. Because concrete pavements have large surface to volume ratios and are exposed to the environment, it is particularly difficult to achieve proper curing. However, proper curing of pavements is important because it reduces early age cracking tendencies and shrinkage and improves concrete fatigue strength. Cracking risk also influences the joint saw cutting window. These considerations are also valid, and probably more important, for thin overlays, whether bonded concrete or ultra-thin/ thin whitetopping overlays. Internal curing is a tool that can increase strength and reduce cracking tendency of concrete, under some circumstances. Splitting tensile and flexural strength are increased, without a corresponding increase in modulus of elasticity.

Introduction

The importance of curing concrete is well known. "Concrete must be properly cured if its optimum properties are to be developed. An adequate supply of moisture is necessary to ensure that hydration is sufficient to reduce the porosity to a level such that the desired strength and durability can be attained and to minimize volume changes in the concrete due to shrinkage. Concrete structures rarely fail because the specified design strength is not attained… loss of potential durability in the long term due to inadequate curing is a more widespread and insidious problem since the maintenance-free service life is reduced." (Mindess et al., 2003, p. 287).

Poole (2005, p. 1) defines curing as "the process of deliberate control of moisture and temperature conditions within prescribed limits. The process allows concrete properties to develop and prevents damage as a result of drying and/or thermal gradients during the early history of the structure."

Cracking occurs when the tensile stress exceeds the tensile strength of the concrete. This is a time-dependent phenomenon, since both the stress and strength change at early ages. Moisture loss increases stress (with increasing shrinkage) and impairs strength gain.

This problem is of particular significance with high performance and high strength concretes with a low water/cementitious materials ratio (w/cm). "At the low w/cm ratios used for high-strength concrete, complete hydration cannot take place." (Mindess et al., 2003, p. 535). Concrete with w/cm below 0.42 will self-dessicate unless water is added during the curing period. This leads to bulk, or autogenous shrinkage, with potential for internal microcracking (Mindess et al., 2003, p. 85).

Curing is particularly important for pavements because of their high surface to volume ratios. Poor curing can result in significant damage to concrete pavements. Damage occurs due to plastic shrinkage cracking, thermal stress, or drying shrinkage cracking. Poorly cured concrete pavements may also have poor abrasion resistance and may not resist de-icing salts and other deterioration mechanisms as well. Typically, concrete pavements are cured by spraying white pigmented or clear curing compounds.

Shrinkage occurs entirely in the paste fraction of the concrete. "The drying shrinkage of concrete will be less than that of pure paste because of the restraining influence of the aggregate. With rare exceptions, aggregates are dimensionally stable under changing moisture conditions. The amount of restraint provided by the aggregate depends on the amount of aggregate in the concrete, its stiffness, and the maximum size of the coarse aggregate" (Mindess et al., 2003, p. 427). Therefore, the risk of cracking may be reduced through the use of larger sizes of coarse aggregate, and through the use of dense gradations to minimize paste volume.

Research Significance

Internal curing represents a potentially very important tool for addressing early age cracking of pavements and overlays. Early age cracking of concrete is an important issue with many elements of infrastructure.

Background

This paper focuses on the use of internal curing in concrete pavements and thin overlays. Results from internal curing for high performance and conventional concrete have been reported elsewhere (Mack, 2006, Cleary, 2007, Delatte, Mack, and Crowl, 2007, Delatte, Mack, and Cleary, 2007). These references also provide considerable background on internal curing, along with Delatte and Cleary (2007).

Internal curing is a tool to improve the strength gain and reduce early age shrinkage of high performance and high strength concrete. This can be provided by an absorptive coarse aggregate, an absorptive lightweight fine aggregate (LWA), or some other material such as superabsorbent polymer particles (SAP). Internal curing is "the process by which hydration of cement occurs because of the availability of additional internal water that is not part of the mixing water" (Roberts, 2004). Bentz et al. (2005) note the following benefits of internal curing:

- Concrete properties that are improved by internal curing include early age and ultimate compressive, flexural, and tensile strength, as well as durability. Autogenous cracking and permeability are both reduced.
- Cement particle hydration at lower w/cm ratios is improved by providing water through a source such as lightweight sand produced from structural grade expanded shale

An internal curing effect has also been observed when comparing high performance concrete bridge decks made with low and moderate absorption coarse aggregate (Crowl and Sutak, 2002).

In Dallas, Texas, concrete with internal curing has been used for residential paving. Intermediate sized lightweight aggregate with 9.5 to 2.36 mm particle size (3/8 inch to number 4) was used as a substitution for about 120 kg/m^3 (200 lb/yd^3) of fine aggregate and 180 kg/m^3 (300 lb/yd^3) of coarse aggregate. Intermediate sized particles provide internal curing and improve the overall aggregate gradation. Over two years, about 420,000 m^3 (550,000 yd^3) of this concrete has been placed, nearly half on a single large project. Strength was improved, and the projects have exhibited very little cracking. A typical increase in compressive strength is about 7 MPa (1,000 psi) (Villareal and Crocker, 2007).

In earlier phases of this research, internal curing with LWA substitution proved effective at reducing the cracking tendency of high performance concrete made with small size (# 8) coarse aggregate (Mack, 2006, Delatte, Mack, and Cleary, 2007). This subsequent testing with pavement and overlay mixtures was carried out to see if similar benefits would be observed in these classes of concrete.

Laboratory and Field Testing

This paper focuses on ODOT mixtures for repairs, pavements, and overlays, Classes S, C, and Overlay, respectively. Results from high performance (Class HP) mixtures are reported elsewhere (Delatte, Mack, and Cleary, 2007). The testing program encompassed fresh concrete properties, strength, shrinkage, and cracking tendency. The fresh concrete testing verified that all mixtures met ODOT specifications for air and slump.

Mixture Proportions and Constituents. Mixture proportions are provided in table 1. One key variable of the study was the absorption level of the coarse aggregates, and the inclusion of lightweight aggregates. Aggregate properties including the LWA (Hydrocure 500) are described in Table 2 2. Aggregate absorption was important because it was used to evaluate the internal curing effect of the different absorption levels.

Table 1: Mixture Quantities for 1 yd^3 (m^3)

Mixture	#57 CA lb (kg)	#8 CA lb (kg)	FA lb (kg)	LWA lb (kg)	Cement lb (kg)	SCM lb (kg)	w/cm
Class C	1610(995)	–	1270(753)	–	600(356)	–	0.50
Class C LWA	1610(995)	–	973 (577)	206(122)	600(356)	–	0.50
Class C Option 1	1595(946)	–	1260(748)	–	510(303)	90 (53)[1]	0.50
Class C Opt. 1 LWA	1595(946)	–	961 (570)	206(122)	510(303)	90 (53)[1]	0.50
Class S	1510(896)	–	1240(736)	–	715(424)	–	0.44
Overlay	–	1450(860)	1410(836)	–	600(356)	50 (30)[2]	0.40
Overlay LWA	–	1450(860)	1062(630)	224(133)	600(356)	50 (30)[2]	0.40

1 Includes 90 lbs (53 kg) of Class F fly ash
2 Includes 50 lbs (30 kg) of silica fume

Following the procedure suggested by Bentz et al. (2005), some of the mixtures investigated in this research replaced approximately 83 kg/m^3 (138 lb/yd^3) of natural sand fine aggregate with 120 kg/m^3 (200 lb/yd^3) on an absolute volume basis. The amount used is directly proportional to the quantity of cementitious materials and inversely proportional to the absorption of the LWA. The LWA was slightly coarser than the natural sand, so one additional benefit was an improvement in the combined gradation of the aggregate. Generally, at these replacement levels there are no difficulties with batching, mixing, placing, or finishing the concrete. The LWA must be kept saturated. The mixtures containing LWA are listed in table 1. LWA was generally used only with low absorption coarse aggregate.

Table 2: Aggregate Absorption; Bulk, SSD Specific Gravity

Aggregate	Size/Type	Absorption (%)	Bulk Specific Gravity	SSD Specific Gravity
Cedarville	#8 / LS	0.7	2.732	2.752
Cedarville	#57 / LS	0.35	2.795	2.805
Rogers City	#8 / LS	1.74	2.515	2.559
Rogers City	#57 / LS	1.38	2.529	2.565
Marblehead	#8 / LS	3.77	2.471	2.565
Marblehead	#57 / LS	3.03	2.493	2.569
Fairborn	#8 / GR	1.73	2.625	2.671
Fairborn	#57 / GR	1.51	2.645	2.686
Shalersville	Natural Sand	1.12	2.576	2.605
Hydrocure 500 (LWA)	Fine Lightweight	21.2	–	1.800

Strength Test Results. The complete testing program is shown in table 3. Compressive, splitting tensile, and flexural strength were tested at 7 and 28 days, with some tests also carried out at 56 and 90 days.

Table 3: Test Program

Test	Protocols and methods	Number of tests
Fresh Concrete Properties		
Workability	ASTM C 143	1
Air content	ASTM C 231	1
Unit weight	ASTM C 138	1
Hardened Concrete Properties		
Compressive strength	ASTM C 39, 4 x 8 in cylinders*	2 each age, total 4
Flexural strength	ASTM C 78, 6 x 6 x 20 in beams**	1 each age, total 2
Splitting tensile strength	ASTM C 496, 4 x 8 in cylinders*	2 each age, total 4
Modulus of elasticity	ASTM C 496, 4 x 8 in cylinders*	2 each age, total 4
Shrinkage and Cracking Tendency		
Unrestrained, unsealed shrinkage	ASTM C 157	2
Unrestrained, sealed shrinkage	ASTM C 1090	2
Restrained shrinkage ring tests	AASHTO PP34-99	2

* 100 x 200 mm cylinders
** 150 x 150 x 500 mm beams

After completing this program, fatigue and freeze thaw testing were also carried out. These tests provided additional strength data. The fatigue and freeze thaw testing results did not show a specific benefit for internal curing for the mixtures investigated.

Compressive and splitting tensile strength data for mixtures with limestone aggregate are provided in tables 4 and 5, respectively. A few observations may be made. The mixtures that incorporated LWA generally had higher strength than the similar mixtures without (with low absorption aggregate). Also, the splitting tensile strength for concrete made with the high absorption aggregate was often lower than that made with the medium or low absorption aggregate. This suggests that the high absorption aggregate may have been inherently weaker than the other types.

Table 4: Compressive Strength Data

Mix Identification	7 Day		28 Day		56 Day		90 Day	
	psi	MPa	psi	MPa	psi	MPa	psi	MPa
Class S High	4550	31	5930	41	6540	45	6710	46
Class S Medium	5340	37	6530	45	7200	50	7220	50
Class S Low	3840	26	4820	33	5080	35	5120	35
Class C Option 1 High	3860	27	4630	32	4790	33	5270	36
Class C Option 1 Medium	3980	27	5080	35	5540	38	5960	41
Class C Option 1 Low	2810	19	3590	25	4190	29	-	-
Class C Option 1 Low w/LWA	3180	22	4180	29	4790	33	5430	37
Microsilica Overlay High	5190	36	6510	45	7090	49	7430	51
Micro Overlay High with Fibers	4810	33	6480	45	7360	51	7470	52
Microsilica Overlay High w/LWA	7330	51	9860	68	10380	72	9810	68

Table 5: Splitting Tensile Strength

Mix Identification	7 Day		28 Day		56 Day		90 Day	
	psi	Mpa	psi	Mpa	psi	Mpa	psi	Mpa
Class S High	515	3.55	425	2.93	660	4.55	670	4.62
Class S Medium	435	3.00	780	5.38	570	3.93	560	3.86
Class S Low	370	2.55	490	3.38	530	3.65	680	4.69
Class C Option 1 High	380	2.62	660	4.55	455	3.14	660	4.55
Class C Option 1 Medium	465	3.21	420	2.90	590	4.07	715	4.93
Class C Option 1 Low	320	2.21	285	1.97	490	3.38	425	2.93
Class C Option 1 Low w/LWA	520	3.59	445	3.07	570	3.93	–	–
Microsilica Overlay High	395	2.72	480	3.31	565	3.90	545	3.76
Overlay High with Fibers	460	3.17	495	3.41	510	3.52	–	–
Microsilica Overlay High w/LWA	595	4.10	615	4.24	590	4.07	585	4.03

The compressive and splitting tensile 28 day strength results for Class C concrete with gravel are shown in table 6. Average splitting tensile strength was 9 % higher for concrete with LWA, although average compressive strength was 4 % lower. Splitting tensile strength, of course, is much more relevant for pavements than compressive strenght. Higher splitting tensile strength should also relate to higher resistance to cracking, all other factors being equal.

Table 6: Compressive and Splitting Tensile Strengths for Class C Gravels

Mixture	Splitting Tensile				Compressive Strength	
	psi		Average (psi)	Average (MPa)	psi	MPa
Class C Gravels (w/cm = 0.4)	555	567	561	3.9	6920	47.7
Class C Gravels (w/cm = 0.4)	556	539	547	3.8	6500	44.8
Class C Gravels (w/cm = 0.4)	546	464	505	3.5	7404	51.0
Class C Gravels (w/cm = 0.4)	450	529	489	3.4	6775	46.7
Average Class C Gravels (w/cm = 0.4)			526	3.6	6890	47.5
Class C Gravels w/LWA (w/cm=0.4)	662	631	647	4.5	6712	46.3
Class C Gravels w/LWA (w/cm=0.4)	546	713	630	4.3	6720	46.3
Class C Gravels w/LWA (w/cm=0.4)	647	536	591	4.1	6785	46.8
Class C Gravels w/LWA (w/cm=0.4)	650	474	562	3.9	6235	43.0
Class C Gravels w/LWA (w/cm=0.4)	679	481	580	4.0	6519	44.9
Class C Gravels w/LWA (w/cm=0.4)	532	383	458	3.2	6268	43.2
Class C Gravels w/LWA (w/cm=0.4)	529	555	542	3.7	6984	48.2
Average Class C Gravels w/LWA (w/cm=0.4)			573	4.0	6603	45.5

Test results for the overlay mixtures, which were all made with limestone aggregate, are shown in table 7. Average splitting tensile strength was 33 % higher, and average compressive strength was 41 % higher. This suggests that internal curing may be more effective at improving strength with lower w/cm (0.40) overlay type mixtures than with higher w/cm (0.50) conventional paving mixtures.

Table 7: Compressive and Splitting Tensile Strengths for Overlay Mixtures

Mixture	Splitting Tensile				Compressive Strength	
	psi		Average (psi)	Average (MPa)	psi	MPa
Overlay Medium	458	453	456	3.1	6230	43.0
Overlay Medium	406	388	397	2.7	7634	52.6
Overlay Medium	464	542	503	3.5	9758	67.3
Overlay Medium	410	453	431	3.0	8081	55.7
Average Overlay Medium	669	581	447	3.1	7930	54.7
Overlay Medium w/LWA	608	566	587	4.0	10457	72.1
Overlay Medium w/LWA	630	668	649	4.5	10868	74.9
Overlay Medium w/LWA	675	656	666	4.6	10871	75.0
Overlay Medium w/LWA	491	480	485	3.3	11869	81.8
Overlay Medium w/LWA	601	491	546	3.8	11683	80.5
Overlay Medium w/LWA	669	581	625	4.3	11472	79.1
Average Overlay Medium w/LWA			593	4.1	11200	77.2

Modulus of rupture results are shown in table 8 for the first round of testing. The mixtures incorporating LWA tended to have higher strength. Additional MOR testing at 28 days was carried out for the fatigue testing program, and results are shown in table 9. Again, MOR seems to be higher for mixtures with LWA.

Table 8: Modulus of Rupture for Pavements and Overlay Mixtures

Mix Identification	1 Day		3 Day		7 Day		28 Day		56 Day	
	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa
Class S High	590	4.1	735	5.1	780	5.4	735	5.1	750	5.2
Class S Medium	735	5.1	750	5.2	880	6.1	800	5.5	880	6.1
Class S Low	650	4.5	640	4.4	795	5.5	950	6.6	1075	7.4
Class C Option 1 High	555	3.8	645	4.4	630	4.3	950	6.6	775	5.3
Class C Option 1 Medium	515	3.6	755	5.2	605	4.2	665	4.6	875	6.0
Class C Option 1 Low	400	2.8	535	3.7	615	4.2	790	5.4	-	-
Class C Option 1 Low w/LWA	450	3.1	465	3.2	565	3.9	540	3.7	825	5.7
Microsilica Overlay High	565	3.9	765	5.3	785	5.4	1095	7.5	890	6.1
Microsilica Overlay High Fibers	585	4.0	800	5.5	815	5.6	905	6.2	835	5.8
Microsilica Overlay High w/LWA	685	4.7	900	6.2	875	6.0	1020	7.0	-	-

Table 9: Modulus of Rupture from Fatigue Testing Program

Mixture	psi	MPa
Class C Option 1 Low	496	3.4
Class C Option 1 Low	541	3.7
Class C Option 1 Low w/LWA	525	3.6
Class C Option 1 Low w/LWA	563	3.9
Class C Medium	561	3.9
Class C Medium	603	4.2
Class C Medium w/LWA	592	4.1
Class C Medium w/LWA	610	4.2
Class C Medium (w/cm = 0.4)	679	4.7
Class C Medium (w/cm = 0.4)	719	5.0
Class C Medium w/LWA (w/cm=0.4)	635	4.4
Class C Medium w/LWA (w/cm=0.4)	616	4.2
Class C Gravels (w/cm = 0.4)	678	4.7
Class C Gravels (w/cm = 0.4)	674	4.6
Class C Gravels w/LWA (w/cm=0.4)	691	4.8
Class C Gravels w/LWA (w/cm=0.4)	709	4.9
Overlay Medium	831	5.7
Overlay Medium	795	5.5
Overlay Medium w/LWA	931	6.4
Overlay Medium w/LWA	955	6.6

Modulus of Elasticity. Modulus of elasticity results are shown in table 10. The low quantity of LWA used was not expected to significantly affect the modulus of elasticity, except for enhancing strength.

Table 10: Modulus of Elasticity

Mix Identification	7 Day		28 Day		56 Day		90 Day	
	10^6 psi	MPa	10^6 psi	MPa	10^6 psi	MPa	10^6 psi	MPa
Class S High	3.70	25511	4.20	28958	3.70	25511	4.35	29992
Class S Medium	4.65	32061	4.45	30682	4.40	30337	4.90	33784
Class S Low	3.60	24821	4.90	33784	4.50	31026	5.40	37232
Class C Option 1 High	3.20	22063	-	-	3.70	25511	4.35	29992
Class C Option 1 Medium	3.90	26890	4.00	27579	4.50	31026	4.95	34129
Class C Option 1 Low	3.35	23097	3.45	23787	3.35	23097	-	-
Class C Option 1 Low w/LWA	3.75	25855	4.20	28958	4.75	32750	3.90	26890
Microsilica Overlay High	2.95	20340	3.40	23442	3.65	25166	4.10	28269
Microsilica Overlay High with Fibers	3.15	21718	4.20	28958	4.05	27924	4.25	29303
Microsilica Overlay High w/LWA	2.95	20340	3.50	24132	4.00	27579	4.35	29992

Unrestrained Shrinkage. The unrestrained shrinkage specimens were 4 x 4 x 12 in (100 x 100 x 300 mm) prisms, with steel studs embedded in the ends. After demolding at one day, half of the specimens were left unsealed and half were sealed with paraffin. Then, half of each type of specimen was put in a lime bath, and half were put in a moist curing room. Results from sealed and unsealed specimens stored in the lime bath are provided in tables 11 and 12, respectively. Results from sealed and unsealed specimens stored in the moist cure room are provided in tables 13 and 14, respectively.

Table 11: Percent Shrinkage of Sealed Specimens in Lime Bath

Mix Identification	Percent Length Change			
	7 Day	28 Day	56 Day	90 Day
Class C Option 1 High	0.014%	0.005%	0.012%	0.015%
Class C Option 1 Medium	0.011%	0.005%	-	0.003%
Class C Option 1 Low	0.002%	0.014%	0.004%	0.003%
Class C Option 1 Low w/LWA	0.005%	0.000%	0.009%	0.010%
Class S High	0.001%	0.004%	0.008%	0.008%
Class S Medium	0.002%	0.000%	0.003%	0.003%
Class S Low	0.005%	0.001%	0.001%	0.001%
Microsilica Overlay High w/Fibers	0.001%	0.001%	0.004%	0.007%
Microsilica Overlay High	0.040%	0.003%	0.007%	0.005%
Microsilica Overlay High w/LWA	0.005%	0.010%	-	0.001%

Table 12: Percent Shrinkage of Unsealed Specimens in Lime Bath

Mix Identification	Percent Length Change			
	7 Day	28 Day	56 Day	90 Day
Class C Option 1 High	0.016%	0.014%	–	–
Class C Option 1 Medium	0.004%	0.015%	–	0.014%
Class C Option 1 Low	0.009%	0.006%	0.007%	0.013%
Class C Option 1 Low w/LWA	0.003%	0.003%	0.006%	0.006%
Class S High	0.001%	0.006%	0.009%	0.012%
Class S Medium	0.003%	0.006%	0.008%	0.002%
Class S Low	0.001%	0.002%	0.004%	0.005%
Microsilica Overlay High w/Fibers	0.005%	0.007%	0.103%	0.006%
Microsilica Overlay High	0.040%	0.032%	0.090%	0.002%
Microsilica Overlay High w/LWA	0.002%	0.007%	–	0.006%

Table 13: Percent Shrinkage of Sealed Specimens in Moist Cure Room

Mix Identification	Percent Length Change			
	7 Day	28 Day	56 Day	90 Day
Class C Option 1 High	0.002%	0.015%	0.020%	0.026%
Class C Option 1 Medium	0.015%	0.017%	–	0.029%
Class C Option 1 Low	0.001%	0.040%	0.046%	0.047%
Class C Option 1 Low w/LWA	0.011%	0.025%	0.022%	0.029%
Class S High	0.010%	0.014%	0.022%	0.027%
Class S Medium	0.015%	0.025%	0.037%	0.044%
Class S Low	0.024%	0.033%	0.041%	0.048%
Overlay High w/Fibers	0.011%	0.025%	0.024%	0.025%
Microsilica Overlay High	0.028%	0.087%	0.028%	0.022%
Overlay High w/LWA	0.004%	0.020%	–	0.016%

Table 14: Percent Shrinkage of Unsealed Specimens in Moist Cure Room

Mix Identification	Percent Length Change			
	7 Day	28 Day	56 Day	90 Day
Class C Option 1 High	0.011%	0.033%	0.035%	0.061%
Class C Option 1 Medium	0.019%	0.032%	–	0.037%
Class C Option 1 Low	0.000%	0.056%	0.055%	0.045%
Class C Option 1 Low w/LWA	0.035%	0.055%	0.052%	0.059%
Class S High	0.024%	0.022%	0.043%	0.068%
Class S Medium	0.025%	0.039%	0.051%	0.059%
Class S Low	0.032%	0.044%	0.058%	0.063%
Microsilica Overlay High w/Fibers	0.032%	0.045%	0.039%	0.057%
Microsilica Overlay High	0.028%	0.051%	0.074%	0.062%
Microsilica Overlay High w/LWA	0.030%	0.059%	–	0.059%

The specimens stored in the lime bath showed very little shrinkage, whether or not LWA was used. For the specimens stored in the moist curing room, there may be some shrinkage reduction with the use of LWA, but it is not dramatic. The sealed specimens were only subject to autogenous shrinkage, whereas the unsealed specimens had both autogenous and drying shrinkage. Therefore, the difference in shrinkage between unsealed and sealed specimens represents drying shrinkage.

Cracking Tendency. The cracking tendency of the mixtures was investigated using restrained shrinkage rings, with testing carried out until the specimen cracked or until 90 days had elapsed. Results are provided in table 15.

Table 15: Restrained Shrinkage Ring for Class S, Class C Option 1, and Overlay

Mixture	Concrete Ring Thickness	Time To Cracking	Crack Width	Strain at Cracking	Stress Rate at Cracking	Maximum Tensile Stress
	in (mm)	days*	in (mm)	micro-strain	psi/day (KPa/day)	psi (MPa)
Class S High	2.5 (64)	69 (45)	0.02 (0.51)	46	3 (21)	670 (4.6)
Class S High	2.5 (64)	90 (59)	No Crack	98	4 (28)	620 (4.3)
Class S Medium	2.5 (64)	60 (39)	0.016(0.41)	81	4 (28)	510 (3.5)
Class S Medium	2.5 (64)	36 (24)	0.025(0.64)	77	7 (48)	490 (3.4)
Class S Low	2.5 (64)	90 (59)	No Crack	85	2 (14)	540 (3.7)
Class S Low	2.5 (64)	57 (37)	0.013(0.33)	64	3 (21)	400 (2.8)
Class C Option 1 High	2.5 (64)	90 (59)	No Crack	85	3 (21)	530 (3.7)
Class C Option 1 High	2.5 (64)	90 (59)	No Crack	85	3 (21)	540 (3.7)
Class C Option 1 Medium	2.5 (64)	88 (58)	No Crack	–	–	–
Class C Option 1 Medium	2.5 (64)	88 (58)	No Crack	16	1 (7)	100 (0.7)
Class C Option 1 Low	2.5 (64)	90 (59)	No Crack	144	7 (48)	910 (6.3)
Class C Option 1 Low	2.5 (64)	90 (59)	No Crack	101	3 (21)	630 (4.3)
Class C Option 1 Low w/ LWA	2.5 (64)	90 (59)	No Crack	3	–	20 (0.1)
Class C Option 1 Low w/ LWA	2.5 (64)	90 (59)	No Crack	–	–	–
Microsilica Overlay High w/ Fibers	1.5 (38)	29	0.02 (0.51)	139	23 (159)	1460 (10.1)
Overlay High w/ Fibers	1.5 (38)	90	No Crack	74	3 (21)	770 (5.3)
Overlay High	1.5 (38)	51	0.02 (0.51)	83	8 (55)	860 (5.9)
Overlay High	1.5 (38)	40	0.02 (0.51)	46	10 (69)	480 (3.3)
Overlay High w/ LWA	1.5 (38)	18	0.07 (1.78)	60	23 (159)	630 (4.3)
Overlay High w/ LWA	1.5 (38)	19	0.07 (1.78)	36	12 (83)	380 (2.6)

For the 2.5-inch (54 mm) ring thickness the time to crack was divided by 1.53 to obtain the equivalent 1.5 inch (38 mm) ring time in parenthesis. Cracking potential is evaluated in terms of time to cracking and average stress rate, as shown in table 16. The cracking potentials of the different mixtures are shown in table 17.

Table 16: Potential for Cracking (ASTM C 1581)

Net Time-to-Cracking, t_{cr} (days)	Average Stress Rate S (psi/day)	Potential for Cracking
$0 < t_{cr} \leq 7$	$S \geq 50$	High
$7 < t_{cr} \leq 14$	$25 \leq S < 50$	Moderate-High
$14 < t_{cr} \leq 28$	$15 \leq S < 25$	Moderate-Low
$t_{cr} > 28$	$S < 15$	Low

Table 17: Summary of Cracking Potential

Mixture	ASTM Classification
Class S High*	Low
Class S Medium*	Low
Class S Low*	Low
Class C Option 1 High*	Low
Class C Option 1 Medium*	Low
Class C Option 1 Low*	Low
Class C Option 1 Low w/ LWA*	Low
Microsilica Overlay High w/ Fibers	Low
Microsilica Overlay High	Low
Microsilica Overlay High w/ LWA	Moderate – Low

Fatigue and Freeze-Thaw Testing. It was hypothesized that internal curing would improve fatigue and freeze-thaw performance. However, test results did not show any significant difference in fatigue for concrete with and without LWA. Internal curing improved the fatigue performance of RCC in another study, but RCC is a more brittle material than conventional concrete (Amer, 2007). Similarly, freeze-thaw testing showed that all mixtures evaluated were durable, with or without LWA. Results might be different with different mixtures. Complete results of the fatigue and freeze-thaw tests are reported by Cleary (2007).

Discussion, Summary, and Conclusions

In a relatively benign laboratory environment, internal curing with partial LWA replacement did not demonstrate the same cracking reduction benefits with paving and overlay mixtures as had been observed with high-performance bridge deck mixtures. In the field, however, the protection against cracking provided by LWA internal curing might be more beneficial. The strength gain results suggest that internal curing may prolong the life of concrete pavements and overlays, because the flexural strength is increased and thus the stress ratio will be reduced. With the limited test results from this study, no reduction in overall shrinkage was observed.

Internal curing is a tool that can increase strength and reduce cracking tendency of concrete, under some circumstances. Splitting tensile and flexural strength are increased, without a corresponding increase in modulus of elasticity. It is most beneficial with low w/cm ratio concretes, such as high performance concrete for overlays and repairs. Overall, the test results suggest that internal curing may be more effective at improving strength with lower w/cm (0.40) overlay type mixtures than with higher w/cm (0.50) conventional paving mixtures.

Recommendations for Future Research

Internal curing has a number of potential benefits for pavements and bonded overlays. Some of the potential benefits depend on whether a significant reduction in overall shrinkage or drying shrinkage can be achieved. Further laboratory and field research is necessary to determine whether these potential benefits exist and can be quantified.

Saw cutting. It is possible that internal curing can delay early age cracking enough to lengthen the window for saw cutting.

Warping. Moisture warping of pavements is due to moisture differentials through the thickness of the slab. Early drying of the top of the slab can cause a locked in warping phenomenon, with the slab permanently cupped upward. If internal curing reduces overall drying shrinkage, warping could also be reduced.

Joint opening and faulting. Joint openings between adjacent slabs depend on shrinkage as well as thermal movements. Tighter joints due to reduced shrinkage could potentially reduce the progression of faulting over time.

Early opening to traffic. Some of the internal curing results suggest significantly higher earlier strength. This is important for early opening of pavements and overlays to traffic. In addition, traffic can damage curing membranes, thus making internal curing more beneficial.

Field tests of thin overlays – UTW. Debonding stresses in bonded concrete overlays depend on contraction of the overlay. Internal curing may reduce this contraction, as well as promoting bond strength development at the interface with the existing pavement.

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