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BRIDGE DECK CONCRETE VOLUME CHANGE

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Abstract:

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The project evaluated the early, first 24 hours, and long-term, 180 days, shrinkage of Virginia Department of Transportation overlay and A4 general bridge deck concrete mixtures. A modified ASTM C157 prism was developed to measure the early-age shrinkage, as was a unique hygral cylinder test. Long-term shrinkage was measured using the ASTM C157 prism test. In addition, scaled bridge deck overlay specimens were cast to assess cracking potential. Overlay mixtures tested were latex modified mixtures using portland cement, Type K cement, an expansive mixture and portland cement, fly ash and microsilica blend. Deck concrete mixtures evaluated were fly ash, slag, Type K cement and an expansive mixture.

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ABSTRACT

Concrete structures such as bridge decks, with large surface area relative to volume, shrink and crack, thus reducing service life performance and increasing operation costs.

The project evaluated the early, first 24 hours, and long-term, 180 days, shrinkage of Virginia Department of Transportation overlay and A4 general bridge deck concrete mixtures. A modified ASTM C157 prism was developed to measure the early-age shrinkage, as was a unique hygral cylinder test. Long-term shrinkage was measured using the ASTM C157 prism test. In addition, scaled bridge deck overlay specimens were cast to assess cracking potential. Overlay mixtures tested were latex modified mixtures using portland cement, Type K cement, an expansive mixture and portland cement, fly ash and microsilica blend. Deck concrete mixtures evaluated were fly ash, slag, Type K cement and an expansive mixture.

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INTRODUCTION

All concrete deterioration mechanisms, internal and external, involve water. Such internal mechanisms such as alkali silica reaction and ettringite need water to be replenished to maintain the reactions. In external mechanisms such as carbonation and chloride induced corrosion of the reinforcing steel, water is required to maintain the rate of corrosion. Water may penetrate concrete through the capillary void system. Thus, the rate of water ingress is governed by characteristics of the pore system or permeability. However, cracks short-circuit the normal slow rate of water penetration and increase the rate of deterioration of concrete structures. By minimizing concrete cracking, the time-to-repair and rehabilitate concrete structures can be increased for both new and rehabilitated structures.

Concrete bridge decks are particularly susceptible to chloride induced corrosion of the reinforcing steel through the application of deicing salts. Decks also have a higher propensity of shrinkage cracking because of the large surface to volume ratios. Shrinkage cracking is the result of volume changes that take place during the hydration of hydraulic cements.

Volume changes associated with the hydration of hydraulic cements occurs immediately upon the introduction of water into the cement. Volume changes occurring during hydration are:

- Chemical shrinkage: volume of hydration products is smaller than the reactants,
- Autogenous shrinkage: volume reduction caused by the reduction of water in the small capillary voids as a result of hydration,
- Drying shrinkage: loss of water from the small capillary voids to the external environment,

- Thermal strain: expansion from heat of hydration and the environment and subsequent cooling.

For hydraulic cement concrete, aggregate particles provide resistance to reductions in volume shrinkage. The concrete system is extremely dynamic. Shrinkage is counteracted by thermal expansion. Expansion and shrinkage stresses are relieved by creep. Initial creep is rapid as the hydrating cement begins to gain strength. The creep rate or stress relaxation rate decreases as the hydrating cement increases in strength. Simultaneously, shrinkage stresses increase from the combination of chemical, autogenous, drying and thermal volume changes (Lee et al., 2006). Cracking occurs within the system when the restrained shrinkage minus the creep plus the thermal stress exceeds the developing tensile strength throughout the hydration process (Mehta and Monterro, 2006).

Newly constructed concrete bridge deck shrinkage is restrained by shear studs, reinforcing steel and stay-in-place forms. Overlay bridge deck concrete shrinkage is restrained by the developing chemical bond and friction between the base and overlay concrete. Limiting concrete shrinkage limits cracking and the subsequent associated accelerated deterioration. Shrinkage cracking may be limited by implementing a quality control field test limit using an associated field test method.

PURPOSE AND SCOPE

The overall purpose of the project was to develop methods to measure the early volume change of concrete mixtures and to evaluate the early and long-term volume change characteristics of typical concrete mixtures used for bridge deck and bridge deck overlay construction. The objective of the project was to be accomplished by the development of a field quality control shrinkage test method and its associated limits.

The scope of the overlay phase of the project was limited to latex modified concrete (LMC); shrinkage compensating cement latex modified concrete (LMK), Type G admixture latex modified concrete (LMG); rapid set cement latex modified concrete (RSL); ternary cementing materials (fly ash, microsilica, portland cement) concrete (TRN); and a microsilica concrete (MSC) used as a control for its shrinkage cracking potential. Overlay shrinkage test methods consisted of two early age (24 hours) shrinkage, two long term (180 days) shrinkage, two long term (180 days) shrinkage cracking potential, and a scaled bridge deck overlay test method.

The scope of new bridge deck concrete construction was limited to Virginia Department of Transportation (VDOT) A-4 bridge deck concrete mixtures. Mixtures used were fly ash A4 (A4-FA), slag A4 (A4-S) and two shrinkage compensating concretes, Type K cement (A4-K) and Type G admixture (A4-G). Shrinkage test methods included two early age (24 hours) shrinkage, long term (168 days) shrinkage, and a shrinkage cracking potential test method.

METHODS AND MATERIALS

Laboratory testing consisted of plastic and hardened concrete properties, early age and long term shrinkage, shrinkage cracking potential and scaled bridge deck overlay specimens.

Methods

Plastic Properties

Slump, air content, relative yield and temperature were determined in accordance with ASTM C143, C231, C138, and C1064, respectively.

Curing

All overlay mixtures were moist-cured for 24 hours, then stored in a controlled environment of approximately 68°F and 50% R.H., except for the TRN mixtures. The TRN mixture specimens were moist-cured for three days followed by storage in the controlled environment.

The A4 mixtures proportioned with Type K cement and Type G admixtures were moist-cured for 24 hours followed by storage in moist room for 6 days. The A4 mixtures proportioned with fly ash and slag were moist-cured for 3 and 7 days. Following the cure regimen, all specimens were stored in the laboratory.

Hardened Properties

Compressive strength and splitting tensile strength tests were conducted in accordance with ASTM C39 and C496, respectively.

Early Age Shrinkage Measurements

The early age, first 24 hours, shrinkage measurements were conducted using a modified ASTM C157 prism test and a newly developed hygral cylinder test.

Modified C157

The C157 prism molds are modified such that the prisms are left in the molds during the course of the shrinkage measurements and drying occurs from only one face of the prism. To prevent adherence to the mold wall, Teflon tape was used on the prism molds. The surfaces of the prism molds were also coated with lithium grease. The prism length is also changed slightly from 11 to 12 inches due to the removal of the gage stud holders. The C157 gage length is preserved by using a 2 inch long, ¼ inch x 20 stainless steel screws in place of gage studs. Vacuum grease was used to seal the orifice in the mold where the gage stud passes through. Dimensional changes were recorded using two Linear Variable Displacement Transducers

(LVDTs) connected to a data acquisition system at a rate of 0.1 Hz. The LVDTs were affixed to the prism mold using two aluminum frames. The concrete was free to shrink, but expansion was restrained by the fixed end plates. A typical modified ASTM C157 prism mold is presented in Figure 1.

Figure 1. Modified ASTM C157 Prism Mold

Hygral Cylinders

The hygral cylinder allows for shrinkage measurements with minimal moisture loss due to evaporation. The cylinder is machined from Nylon 10, 8.5 inches long and 4 inches in diameter. Two 2 inch long, ¼ inch x 20 stainless steel screws are used in place of gage studs. Embedding the studs ¾ inches into the concrete cylinder provides for a 7 inch gage length. The bottom gage stud is fixed, while the top one is free to move. Measurements are obtained using an LVDT mounted to the frame supporting the hygral cylinder. Similar to the modified C157 tests, the hygral cylinder apparatus employed a digital data acquisition system with a collection rate of 0.1 Hz. The frame dimension and materials holding the specimen and the mounted LVDT complied with ASTM C671 Critical Dilation of Concrete Specimens Subjected to Freezing. The apparatus is presented in Figure 2.

Figure 2. Hygral Cylinder Apparatus

The difficulty in interpreting the length change measurement of the hygral cylinder is separating the settlement from the chemical-autogenous shrinkage. Powers (1968) showed that concrete gains sufficient strength to support a column of concrete at the end of the dormant period. The end of the dormant period was estimated by placing a thermocouple in the center of the hygral cylinder and noting the time at which the temperature began to rise. Thus, shrinkage measurement zero point was selected to be 4 hours after casting. The exception was the rapid cement set specimens. Strength gain of these specimens began within minutes after casting. A rapid temperature rise was recorded to begin at one hour and peaked at two hours after casting. Thus, shrinkage measurement zero point was selected as one hour after casting. Figure 3 presents the average hydration temperature for LMC mixtures, RSL mixtures and ambient curing temperatures. The LMC mixture behavior was typical for all mixtures containing Type I/II or shrinkage compensating cements.

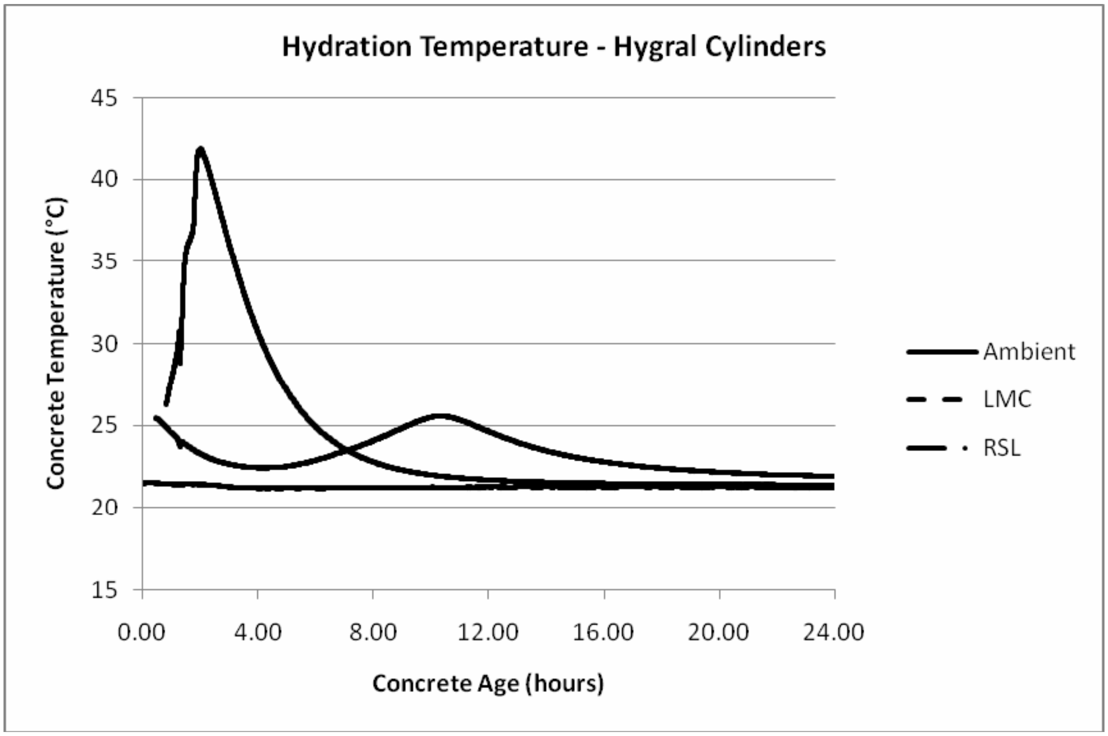

Figure 3. Typical Overlay Hygral Cylinder Hydration Temperature Response

Long Term Shrinkage

Two long term shrinkage tests were used to track the shrinkage after a 24-hour moist-cure in the molds. ASTM C157 was used for both the shrinkage compensating and non-shrinkage compensating concrete mixtures.

ASTM C157

Two specimens were cast from each batch mixed. Measurements were performed every day for seven days starting at 24 hours after casting followed by measurements at 14, 28, 56, 90 and 120 days after casting. During the course of the experiment, the prisms were stored in an environmentally controlled room at ~68°F and ~50% R.H. from the time they were cast. The curing regimen during the initial 24 hours consisted of wet burlap covered by a polyethylene sheet.

ASTM C878

The dimensions of the ASTM C878 are similar to the ASTM C157 prism. This test however, differs from C157 in that it restrains the test specimen using a threaded low-carbon ¼ inch diameter rod and two end plates. This test was used with the expansive Type K cement and Type G admixture. The test was discontinued however after Phase II of the three phase project due to the inconsistent results related to the end characteristics of the threaded rod. Thus, results of the ASTM C878 test are not presented in this report.

Shrinkage Cracking Potential

Three specimen types were used to assess the potential shrinkage cracking of the bridge deck overlay mixtures: a modified ring specimen, a V-notch specimen and scaled bridge deck overlays.

Mini-rings

The mini-ring specimens were six inches inside diameter, eight inches outside diameter and three inches in height. The concrete rings were cast around a six inch outside diameter, 0.5 inch thick steel ring. During casting the ring form was fixed to a Teflon base. The concrete rings were moist cured for 24 hours by covering the top of the ring with wet burlap and a plastic sheet. After curing the outer form, the 8 inch inside diameter Sonotube form was removed and a plastic sheet was adhered to the top of the concrete ring. Thus, drying was limited to the circumference of the three inch high wall. The ring specimen is a restrained shrinkage test during hydration of the cementing materials starting at the completion of casting and drying after 24 hours of moist-curing.

V-notches

V-notch specimens were of two different sizes. The specimens were 48 in long, and the sides of the V were 3 in and 6 in. The V-notch specimens were cast by placing the concrete into inverted three and six inch steel equal angle molds. The angle thickness was 0.25 inches and four feet in length with the ends of the angle closed by welding a 0.25 inch thick steel plate on each end. The V-notch specimens were also moist-cured for 24 hours with wet burlap covered by a plastic sheet. Like the mini-rings, the V-notch specimens are restrained shrinkage specimens with drying limited to the top surface of the specimen. The restrained condition is induced by the bond between the concrete and the mold walls.

Scaled Bridge Deck Overlays

Base slabs of the scaled bridge deck overlay specimens were cast on August 27, 2007 and September 17, 2007. The first set of 12 base slabs were 84 inches long, 17 inches wide, and 8 inches deep. The second set of 12 base slabs were 72 inches long, 18 inches wide, and 8 inches deep. The second set of base slabs were cast because of the low measured air content of the first set of base slabs. Both sets were cast on steel stay-in-place (SIP) forms and were reinforced with two mats of uncoated #4 reinforcing bars to control shrinkage cracking. The form sides were wood 2 x 8s.

Following consolidation and screeding, a surface retarder was sprayed on the base slab surfaces and moist-cured for 24 hours with wet burlap covered with a plastic sheet. The surface mortar was removed with a high pressure water hose at the end of the 24-hour initial curing period. The resulting roughened surface is similar to a milled concrete deck. The slabs were then moist cured for an additional six days using wet burlap and a plastic covered sheet. The 24 base slabs remained outdoors at the Civil Engineering Structures and Materials Laboratory in Blacksburg, VA until they were overlaid the summer of 2008. The forms were left in place during storage and the overlay test period with the base slabs elevated about 8 inches above the concrete slab of the outdoor exposure area.

Prior to overlaying, the base slabs were grid-blasted to remove surface laitance and further increase the surface roughness. Sand patch tests were performed in accordance with ASTM E965 Standard Test Method for Measuring Pavement Macro-texture Depth Using a Volumetric Technique.

Test Program

A total of six specimens, two specimens for each of the three batches, were cast for the overlay and new construction laboratory mixtures.

Overlay Tests

Overlay laboratory tests included fresh and hardened properties, early and long term shrinkage, cracking potential and scaled bridge deck overlays. Measured fresh concrete properties were slump, temperature, air content, and unit weight. Hardened properties included compressive and tensile strength and rapid chloride permeability. Shrinkage performance testing consisted of hygral cylinders, modified ASTM C157, C157, V-notch and mini-rings. For the scaled bridge deck tests, four specimens, two specimens for each of the two batches, received a two inch overlay.

New Construction Tests

New construction laboratory tests included fresh and hardened concrete properties. Fresh properties included slump, temperature, air content and unit weight. Hardened concrete properties consisted of compressive, tensile, elastic modulus, and rapid chloride permeability. Shrinkage performance testing included modified ASTM C157, C157, hygral cylinders and mini-rings.

Materials

Concrete ingredients were hydraulic cements, tap water, aggregate, mineral admixtures, and chemical admixtures.

Aggregate

The fine aggregate was silica sand mined at Sand Mountain, Wytheville, VA. The coarse aggregate was dolomite limestone mined at Elliot Valley, VA.

The bulk dry specific gravity and absorption of the fine aggregate were 2.55 and 1.02%, respectively. The overlay mixtures used a Number 8 stone, top size 3/8 inch, whereas the new construction mixtures used a Number 57 stone, top size 1 inch. The bulk dry specific gravity and absorptions for the No. 8 and 57 stone were 2.75 and 1.07% and 2.65 and 0.80%, respectively.

Chemical Admixtures

All the new construction mixtures used an air entraining agent. One overlay mixture, the ternary mixture also used an air entraining agent and a super plasticizer. Except for the ternary mixture, all the overlay mixtures contain a latex admixture.

Mineral Admixtures

Two of the new construction mixtures were fly ash mixtures and two were ground granulated blast furnace slag (slag) mixtures. One new construction mixture contained a Type G expansive admixture. For the overlay mixtures, one contained microsilica. The ternary mixture contained a microsilica and fly ash. Two mixtures contained a Type G expansive admixture of both older and newer formulations. The concrete proportioned with the older Type G admixture was designated LMG while the concrete proportioned with the new Type G admixture was labeled LMNG. Overlays proportioned with both new and old Type G admixture were analyzed. Only the new Type G formulation was used in the new construction mixtures. The particle size distribution analysis was performed by laser diffraction. The oxide analysis was performed by X-ray fluorescence spectrometry. The samples were fused with $Li_2B_4O_7$ at 1000°C.

Fly ash

Fly ash was of Class F. The chemical oxide composition and particle size distribution are presented in Table 1. As shown in Table 1, about 20% of the particles are greater than 45 μm, and thus would have a slow reactivity. The $SiO_2 + Al_2O_3 + Fe_2O_3$ reactive oxide combination is 90% by volume which illustrates a high Class F fly ash.

Table 1. Chemical Analysis and Particle Size Distribution of Type F Fly ash

Oxide	Weight %	Particle Size, μm	Volume % Equivalent Spheres
SiO_2	62.6	<45	80.2
Al_2O_3	20.2	<30	69.8
Fe_2O_3	7.3	<10	37.6
CaO	2.0	<7	27.2
MgO	1.4	<1	3.1
SO_3	0.4		
Na_2O	0.4	15.1	At 50
K_2O	.7		
T_1O_2	1.0	Specific Surface	1.08 m^2/g
Remaining	3.0		
$SiO_2 + Al_2O_3 + Fe_2O_3$	90.1		
L.O.I. 750°C	2.2		

Microsilica

The chemical oxide analysis and particle size distribution is presented in Table 2. As shown, the microsilica contains about 30% more silicon dioxide than the fly ash. The particle size of the microsilica is significantly smaller. Where the fly ash size at 50% by volume is about 15 μm, the microsilica is about 0.3 μm at 50% by volume. The specific surface of the microsilica is significantly greater than the fly ash, 19.9 and 1.08 m^2/g, respectively. Thus, the microsilica water demand will be greater but the reactivity in portland cement will be greater.

Table 2. Chemical Analysis and Particle Size Distribution of Microsilica

Oxide	Weight %	Particle Size, µm	Volume % Equivalent Spheres
SiO_2	95.7	<45	97.9
Al_2O_3	0.2	<30	95.7
Fe_2O_3	0.0	<10	91.5
CaO	0.4	<7	90.4
MgO	0.1	<1	87.3
SO_3	0.0		
Na_2O	0.1	0.30	At 50%
K_2O	0.6		
T_1O_2	0.0	Specific Surface	19.9 m^2/g
Remaining	2.9		
L.O.I. 750°C	2.3		

Cements

Three types of cements were used: a Type I/II portland cement meeting ASTM C150 specifications, a Type K cement meeting ASTM C845 specifications and CTS Rapid Set® cement (RSC). Additionally, two blends were also used which incorporated a Type G expanding admixture; an older formulation and a newer formulation. The Type I/II+G blend was comprised of 90% portland cement and 10% Type G admixture by weight of cement. The Type G admixture was mixed into the final product during the batching process.

Table 3 shows particle size distribution. The particle size distribution of the Type I/II, the Type K and the Type I/II+G blend were similar. The Type K cement has a slightly higher surface area than the Type I/II and the Type I/II+G blend with 0.46 and 0.44 m^2/g, respectively. This difference cannot account for the drastic difference in the initial and final set times. In contrast with the previous cement types which have a particle size between 13.2 and 14.4 at 50% volume, the RSC particle size at 50% volume is 6.9 µm. This significant increase in surface area coupled with the chemical changes presented in Table 4 result in a highly accelerated hydration process.

Table 3. Particle Size Distribution of Type I/II, K, RSC Cements and Type G Admixture

Particle Size, µm	Volume% Equivalent Spheres				
	Type I/II	Type K	RSC	Old Type G + PC I/II	New Type G + PC I/II
<45	93.0	88.6	96.7	87.9	95.9
<30	79.5	76.6	90.3	74.5	83.6
<10	38.8	42.1	61.0	40.2	41.3
<7	30.0	33.4	50.4	32.0	32.2
<1	4.9	5.2	8.7	4.6	4.5
At 50% Volume, µm	14.3	13.2	6.9	14.4	13.2
Specific Surface, m^2/g	0.44	0.46	--	0.44	0.44

Table 4 presents the chemical oxide analyses of the three cement types. As shown in Table 4, in comparison to the Type I/II portland cement, the Type K cement has greater quantities of Al_2O_3 and SO_3. These compounds react with calcium to produce ettringite, an expansive material. Thus, Type K cement has lower shrinkage characteristics than portland cements. The RSC cement has lower SiO_2, higher Al_2O_3, lower CaO, and higher SO_3 than the Type I/II portland cement. The result of these chemical changes is a very rapid strength gain. Set times are also significantly less for the Type K and RSC, compared to the Type I/II portland cement. The initial set times were reduced from 185 minutes for the portland cement to 25 and 7 minutes for Type K and RSC, respectively. Final set times were also significantly reduced, 90 minutes and 12 minutes, for the Type K and RSC cement, respectively. The set times were determined in accordance with ASTM C191, Time of Setting of Hydraulic Cement by Vicat Needle.

Table 4. Chemical Analysis and Set Times for Type I/II, K, RSC Cements and Type G Admixture

Oxide	Weight %				
	Type I/II	**Type K**	**RSC**	**Old Type G + PC I/II**	**New Type G + PC I/II**
SiO_2	20.3	19.4	14.5	19.9	19.8
Al_2O_3	4.8	7.6	14.9	5.8	4.7
Fe_2O_3	3.1	2.6	1.0	3.6	3.1
CaO	62.9	57.2	49.7	61.9	62.4
MgO	3.1	1.8	1.7	1.6	3.1
SO_3	3.0	7.6	15.1	2.7	2.8
Na_2O	0.2	0.2	0.2	0.4	0.2
K_2O	0.9	0.5	0.6	0.3	0.9
TiO_2	0.2	0.3	0.5	0.4	0.2
Remaining	1.5	2.8	1.8	0.4	0.5
L.O.I. 950°C	1.2	2.9	1.3	2.9	1.9
Alkalis as NaO_2	0.79	0.56	0.61	0.55	0.80
Vicat Set Times, minutes					
Initial	185	25	7	130	155
Final	250	90	12	195	270

Concrete Mixtures

Seven overlay concrete mixtures were tested. A microsilica (MSC), a latex modified (LMC), a Type K latex modified (LMK), a RSC latex modified (RSL), two Type G admixtures latex modified (LMG and LMNG) and a ternary mixture of portland cement, fly ash and microsilica (TRN).

Six new construction mixtures were tested. A three and seven day cure fly ash (A4-FA3 and A4-FA7), a three and 7 day cure slag (A4-S3 and A4-S7), a seven day cure Type G admixture (A4-G), and a seven day cure Type K cement (A4-K).

Overlay Mixtures

Table 5 presents the concrete mixture proportions for the seven overlay mixtures. With the exception of the MSC mixture which was used as a control cracking mixture, the overlay mixture water/cement ratios (w/c) were all 0.38. The w/c of the MSC mixture was 0.50.

Table 5. Overlay Concrete Mixture Proportions, SSD Weights, lbs/cy

Ingredient	MSC	LMC	LMK	RSL	LMG/LMNG	TRN
Cement	626	658	658	658	592	495
Water	337	144	144	144	144	235
Latex*	--	203	203	203	203	--
Fly ash	--	--	--	--	--	106
Microsilica	79	--	--	--	--	18
Coarse Agg	1251	1251	1251	1251	1251	1251
Fine Agg	1690	1503	1503	1503	1503	1503
Total aggregate	2941	2754	2754	2754	2754	2754
AEA, oz	2.2	--	--	--	--	5.4
HRWR, oz	24.6	--	--	--	--	52.6
Expansive Admixture	--	--	--	--	66	--
Total	3983	3759	3759	3759	3759	3610
w/cm	0.48	0.38	0.38	0.38	0.38	0.38

* water from latex is 52% = 106 lbs for a total water of 279 lbs.

New Construction Mixtures

Table 6 presents the new construction concrete mixture proportions. All mixtures were proportioned with a w/c of 0.45.

Table 6. New Construction Concrete Mixture Proportions, SSD Weights, lbs/cy

Ingredient	A4-FA3/A4-FA7	A4-S3/A4-S7	A4-K	A4-G
Cement	508	382	635	572
Fly ash	127	--	--	--
Slag	--	253	--	--
Water	286	286	286	286
Coarse Agg	1742	1742	1742	1742
Fine Agg	1084	1084	1084	1084
Expansive Admixture	--	--	--	63
Total	3747	3747	3747	3747
w/cm	0.45	0.45	0.45	0.45

Total aggregate = 2826 lbs

RESULTS

Fresh Properties

The measured concrete fresh properties for the overlay and new construction mixtures were slump air content, concrete temperature, and unit weight.

Overlay Mixtures

Table 7 presents the average and range of the fresh concrete properties for the overlay mixtures. All batches were proportioned and mixed using the same materials, equipment and procedures. As shown in Table 7, the slump for the RSL mixture was generally low as a result of the rapid rate of hydration for this mixture. The temperature of all the mixtures was within an acceptable range of greater than 50°F and less than 91°F. The air content of all the latex modified mixtures was relatively low. The air content of the TRN and MSC was too high, greater than 9% on occasion as the air content of these mixtures was somewhat difficult to control. The unit weights are a reflection of the air contents; higher for lower air contents and lower for higher air contents.

Table 7. Measured Fresh Concrete Properties, Overlay Mixtures

Mixture	**Slump in.**	**Air Content %**	**Concrete Temperature °F**	**Unit Weight lbs/cf**
LMC, Average	5.8	2.8	77	142.5
Range	4.5-7	2.5-3.0	69-82	140.5-143.7
RSL, Average	2.7	3.7	81	140.2
Range	0.5-6.0	2.0-5.0	78-88	138.6-142.1
LMK, Average	5.1	3.4	80	140.8
Range	1.00-8.3	2.4-4.1	78-86	139.7-142.1
LMCG, Average	7.6	3.3	73	142.3
Range	6.0-8.5	3.0-3.6	69-75	141.1-143.5
LMCNG, Average	5.1	3.7	83	140.8
Range	3.0-8.5	3.0-4.5	82-90	138.9-142.9
TRN, Average	7.0	8.7	78	135.2
Range	3.0-9.0	6.0-15.0	72-85	124.8-142.1
MSC, Average	4.3	9.3	71	134.6
Range	3.0-5.0	7.0-12.0	70-72	131.5-137.7

New Construction Mixture

Table 8 presents the average and range of the fresh concrete properties of the new construction, A4 concrete mixtures. As shown, there is good control of the fresh properties of slump, air content, concrete temperature, and unit weights.

Table 8. Measured Fresh Concrete Properties, New Construction A4 Concrete Mixtures

Mixture	**Slump in.**	**Air Content %**	**Concrete Temperature °F**	**Unit Weight lbs/cf**
A4-FA3, Average	4.20	5.7	78	142.0
Range	3.75-4.50	5.5-6.10	77-79	140.8-142.8
A4-FA7, Average	4.20	5.4	77	142.0
Range	2.75-5.50	4.5-6.3	76-79	141.6-142.4
A4-S3, Average	3.60	4.5	75	145.0
Range	2.75-4.00	3.0-5.4	74-78	143.6-147.6
A4-S7, Average	3.40	4.8	77	144.0
Range	2.50-4.25	3.6-5.8	76.79	142.4-146.4
A4-G, Average	3.80	5.4	78	142.3
Range	3.00-4.25	4.6-6.8	74-81	138.4-145.6
A4-K, Average	2.60	5.3	78	142.9
Range	1.75-3.25	4.7-6.2	77-80	142.4-143.6

Hardened Properties

Compressive and tensile strength and rapid chloride permeability tests were conducted for the overlay mixtures. For the A4 mixtures, compressive strength, tensile splitting, modulus of elasticity, and rapid chloride permeability test were performed.

Overlay Mixtures

Table 9 presents the average rapid chloride permeabilities. The RSL and LMK have a very low permeability (< 1000 coulombs); the MSC a low permeability (1000 to < 2000 coulombs); whereas, the LMC and TRN have moderate permeability (2000 to < 3000 coulombs), and the, LMG has a high permeability (3000 to 4000 coulombs). The RSL and LMK mixtures are very low because of the rapid cement hydration rate and because of the addition of microsilica in the MSC mixtures.

Table 10 presents the average compressive strengths at 7 and 28 days and the average splitting tensile strengths at 1, 3, 7 and 28 days. As shown, the RSL mixture has a high strength at 3 hrs; however, the other mixture with the same w/c of 0.38 has near equivalent compression and splitting tensile strength at later ages. The lower strength of the MSC mixture is the result of the higher w/c of 0.48 and air content.

Table 9. Rapid Chloride Permeability of Overlay Mixtures

Mixture	28 Day Coulomb
LMC	2830
RSL	415
LMK	539
LMG	3135
TRN	2480
MSC	1260

Table 10. Compressive and Splitting Strengths for Overlay Mixtures

Test Age,	Compressive			Splitting Tensile				
Days, Mixture	3 hrs	7 day	28 day	3 hrs	1 day	3 day	7 day	28 day
LMC Average		5950	7750		490	480	550	690
RSL Average	5070	6650	8520	360	530	540	620	670
LMK Average		6440	8320		460	480	570	740
LMG Average		6530	7700		460	550	610	710
LMNG Average		5020	8070		420	430	460	570
TRN Average		5410	7140		440	480	550	640
MSC Average		4070	6110		300	320	370	520

New Construction Mixtures

Table 11 presents the average compressive strength, tensile splitting strength and modulus of elasticity of the A4 new construction mixtures. All mixture exceeded A4 General Bridge Deck compressive strength of 4000 psi at 28 days, splitting tensile strength and modulus of elasticity are in general agreement with the compressive strength. The difference in three and seven day curing appears to have effect on the compressive strength results as shown in Table 11.

Table 12 presents the average rapid chloride permeability results at 28 days. As shown, the fly ash mixtures and slag S3 mixture permeabilities are in the low range, whereas, the two expansive mixtures, A4-K and A4-G are significantly higher in the moderate and high ranges respectively.

Table 11. Compressive Strength and Modulus of Elasticity and Splitting Tensile Strength of A4 Mixtures

Test Age, Days	Compressive (psi)			Modulus Elasticity (10^6 psi)			Splitting Tensile
Mixture	7 day	28 day	90 day	7 day	28 day	90 day	28 day
A4-FA3	4100	5430	5710	3.77	4.28	4.30	540
A4-FA7	3910	5550	6350	3.86	4.22	4.30	710
A4-S3	4770	6670	7530	3.90	4.12	4.56	710
A4-S7	3900	6670	6870	3.52	4.29	4.26	605
A4-G	4170	5820	7250	3.58	4.21	4.21	670
A4-K	4760	6770	7960	3.81	4.39	4.70	770

Table 12. Rapid Chloride Permeability of A4 Mixtures

Mixture	28 Day Coulomb
A4-FA3	1133
A4-FA7	1122
A4-S3	1367
A4-S7	973
A4-G	3351
A4-K	2902

Early Age Shrinkage

Two methods were used to measure the early age shrinkage, first 24 days after consolidation, the hygral cylinder (HC) and a modified C157 (MC157). The MC157 prisms were cast and measured in the horizontal direction; whereas, the HC were cast in the vertical position. Thus, the initial 4 hours measurements are the result of settlement. The values presented for the HC represent the measured shrinkage with the zero point being 4 hours after casting, while the initial point for the MC157 values is immediate after casting.

Overlay Mixtures

Table 13 presents the HC and MC157 measured shrinkage for a 24-hour period after casting for the LMC and RSL mixtures. The LMC mixture HC and MC157 results differ significantly in the first 4 hours. However, at 20 hours after casting the two measurements are about equal at approximately 200 $\mu\varepsilon$. The RSL mixture measurements are significantly

Table 13. Average Early Age Shrinkage, HC and MC157, for LMC and RSL

Shrinkage Time , hrs	LMC, -με		RSL, -με	
	HC	MC157	HC	MC157
1	76	11	12	237
2	128	14	38	161
4	194	45	73	99
8	206	112	103	84
12	204	180	109	84
16	206	189	111	87
20	210	194	112	165
24	--	198	113	164

different. The HC measurements show a continuing shrinkage to 113με at 20 hours. However, the RSL shrinkage values indicate an early contraction, followed by expansion from 1 to 8 hours, stable to 16 hours after casting and then a rapid shrinkage between 16 and 20 hours. These changes in measured shrinkage strains may be related to thermal expansion after one hour then contraction after 16 hours as shown in Figure 3. The difference in behavior of the RSL mixture HC and MC157 may be related to the difference in forms and curing method. The HC is from a polymeric material which would retain the heat of hydration better than the metal MC157 form. In addition, the MC157 specimens were moist-cured but the HC were not, as the concrete remains encased in the capped cylinder throughout the case.

Table 14 presents the first 24-hour micro-strain measurements for the LMK, LMG, and LMNG. The results of these three expansive mixtures are remarkably different between materials and test methods. The LMG mixture results for the HC and MC157 show continuing shrinkage after casting. However, the HC method shows a rapid shrinkage over the first four hours, whereas the MC157 shows little shrinkage over this same time period. But, at 20 hours, the results of both test method are similar at 249 and 201 με for the HC and MC157 methods, respectively.

The LMNG mixture expanded throughout the 24-hour time period as measured by both test methods, HC and MC157. But, the results are at least an order of magnitude different; at 20 hours the HC expansion was 26 με and the expansion was 347 με for the MC157 method. The difference between the LMG and LMNG may be related to the difference in chemistry of the two materials as shown in Table 3. The differences between the HC and MC157 LMNG results may

Table 14. Average Early Age Shrinkage, HC and MC157 for LMK, LMG, and LMNG

Shrinkage Time, hrs	LMK, -με		LMG, -με		LMNG, -με	
	HC	MC157	HC	MC157	HC	MC157
1	52	-34	69	9	-10	-74
2	81	-52	133	0	-3	-179
4	128	-67	199	66	8	-336
8	168	-49	232	146	-11	-368
12	165	-17	239	185	-26	-357
16	149	-13	244	199	-27	-351
20	134	-16	249	201	-26	-347
24	--	-18	--	198	--	-347

Note, negative sign indicate expansion.

be related to curing conditions and degree of confinement during the test period. Differences in confinement may arise from different coefficients of friction between the concrete and the molds and different surface area in contact with the mold.

Table 15 presents the results for the TRN mixture and MSC mixture. It needs to be noted the MSC mixture was not included in the original test plan but added later because none of the other overlay mixtures had cracked to any significant degree. It was hoped that the MSC mixture's greater shrinkage potential would crack and thus provide a cracking performance basis of comparison for the other overlay mixtures.

Both the HC and MC157 methods showed continuing shrinkage for the TRN mixture throughout the 20 hr test period, but at different rates, the HC method had a faster shrinkage rate than the MC157. Again, this may be related to the difference in curing methods, moist-curing for the MC157 method and at the cast moisture content for the HC method.

The MSC mixture MC157 results indicate an early expansion for the first four hours, followed by shrinkage for the remaining 20 hours. The TRN mixture showed greater shrinkage than the MSC mixture in the MC 157 test method, 89 and 31 με at 24 hours.

Table 15. Average Early Age Shrinkage, HC and MC157, for TRN and MSC

Shrinkage	**TRN, - με**		**MSC**
Time, hrs	**HC**	**MC157**	**MC157**
1	8	30	0
2	18	29	-5
4	49	39	-10
8	85	62	-6
12	104	72	12
16	109	84	20
20	110	88	26
24	--	89	31

Note, negative sign indicates expansion.

A4 New Construction Mixtures

Table 16 presents the fly ash mixture. Table 17 presents the slag mixture and Table 18 presents the shrinkage compensating mixtures, Type G admixture and Type K cement results. Both the fly ash and slag mixture included a 3- and 7-day cure period. The cure periods are relevant to hardened property measurements. For the early age shrinkage results, the measurements start immediately after cast. For the later reported long term shrinkage results, C157, measurements begin 24 hours after casting. Thus, the results presented as A4-FA3, A4-FA7, A4-S3 and A4-S7 are mere repeat tests of the same mixtures from different batches for both the early age and long term shrinkage tests.

Table 16 presents the HC and MC157 A4-FA3 and A4-FA7 με measurement results. The measurements between the HC and MC157 results are significantly different. The HC method shows a general expansion trend while the MC157 shows a general trend towards shrinkage. Other than these general trends, the measurements are quite variable over the test period.

Table 16. Average Early Age Shrinkage, HC and MC157, A4-FA3 and A4-FA7

Shrinkage Time, hrs	A4-FA3, - με		A4-FA7, - με	
	HC	MC157	HC	MC157
1	-4	18	-14	10
2	11	22	-5	7
4	-8	16	-4	13
8	-5	23	0	7
12	4	42	-7	13
16	3	42	-7	8
20	-14	32	5	12
24	--	24	23	15

Note, negative sign indicates expansion.

Table 17 presents the HC and MC157 A4-S3 and A4-S7 με measurement results. The results are similar to the A4-FA results but more variable with inconsistent trends within the test period.

Table 18 presents the Type G and Type K mixture με measurement for the HC and MC157 test methods. The HC results are highly variable and small in magnitude. The small HC values are consistent throughout the A4 mixtures. The apparent inconsistence may be related to inaccuracies in making these very small measurements. The MC157 results for the Type K and Type G mixtures, in general, indicates that the mixtures are shrinking, Type K more so than Type G. These results are significantly different from the overlay Type K and Type G mixtures where the MC157 test shows Type K to be expanding and Type G shrinking, see Table 14.

Table 17. Average Early Age Shrinkage, HC and MC157, A4-S3 and A4-S7

Shrinkage Time, hrs	A4-S3, - με		A4-S7, - με	
	HC	MC157	HC	MC157
1	3	12	1	-6
2	-16	18	8	15
4	-18	23	-11	30
8	-10	22	-1	32
12	11	-1	-7	43
16	8	7	8	19
20	-2	7	5	41
24	--	12	--	24

Note, negative sign indicates expansion.

Table 18. Average Early Age Shrinkage, HC and MC157, A4-K and A4-G

Shrinkage Time, hrs	A4-K, - με		A4-G, - με	
	HC	MC157	HC	MC157
1	14	11	8	14
2	-11	11	3	13
4	8	37	4	23
8	3	49	3	42
12	3	56	8	43
16	14	46	7	25
20	1	62	13	28
24	--	64	--	--

Note, negative sign indicates expansion.

Long Term Shrinkage

The overlay and new construction mixtures were both assessed using the ASTM C157 unrestrained shrinkage test method. Specimens are moist-cured for 24 hours then placed in a controlled environment of about 50% relative humidity and 68°F. The specimens were not submerged in lime-saturated water prior to performing the measurements because the specimens were stored in a temperature/moisture controlled environment. Tables 19 and 20 present the measured results for the overlay and A4 new construction mixtures respectively.

Table 19. Average Drying Shrinkage, C157, for LMC, RSL, LMK, LMG, LMNG, TRN, and MSC Overlay Mixtures

Shrinkage	Mixtures, - με												
Time, days	LMC	%	RSL	%	LMK	%	LMG	%	LMNG	%	TRN	%	MSC
1	80		91		-59		9		54		117		63
3	220		148		87		26		124		275		215
7	443	42	278	50	261	42	390	40	439	45	599	68	503
14	558		298		309		548		552		708		585
28	705	68	318	57	373	60	683	71	658	68	739	84	690
56	833	80	404	73	438	72	784	82	761	79	777	89	870
90	931	89	503	90	537	87	881	92	814	84	826	94	--
180	1042	100	554	100	615	100	958	100	968	100	880	100	--

Note, negative sign indicates expansion.

Table 20. Average Drying Shrinkage, C157, for A4 Mixtures for New Construction

Shrinkage	Mixtures, - με											
Time, days	FA3	%	FA7	%	S3	%	S7	%	G	%	K	%
7	225	36	187	29	350	48	385	55	250	42	273	40
21	353		293		445		473		283		390	
28	413	66	327	50	537	73	517	74	362	61	385	56
56	508	82	388	60	562	76	575	83	430	73	442	65
84	543	87	522	80	655	89	638	92	538	91	548	80
112	568		530		685		648		525		610	
140	615		630		715		685		573		665	
168	623		650		735		695		590		678	
168 combined	636				715				590		678	

Note, negative sign indicates expansion

As shown in Table 19, all overlay mixtures showed consistent shrinkage throughout the 180-day test period. The rank order, from smallest to largest shrinkage at 180 days, is RSL, LMK, TRN, LMG, LMNG, TRN, and LMC. The mixture shrinkage may be placed in two groups: the first group, RSL and LMK, at 554 and 615 με. The second group is TRN, LMG, LMNG and LMC with shrinkage of 880, 958, 968, and 1042 με. But there is no difference between the LMG and LMNG mixtures. Also, there is significant difference between the shrinkage compensating mixtures Type K and Type G with Type K having a significantly less shrinkage than the Type G mixture, 615 and 963με, respectively. Also of interest is the rate of shrinkage as shown by the percent shrinkage at 7, 28, and 90 days. In general, all mixtures shrink at same rate except for the TRN mixture which exhibited 68% of its 180-day shrinkage in 7 days; whereas, the other overlays ranged from 40 to 50% at 7 days. The results are the same at 28 days, 84% compared to 60 to 68%. The percent shrinkage at 90 days is more uniform, 94% for TRN and 84 to 92% for the other mixtures. The percent shrinkage of the MSC specimens was not calculated since the shrinkage rate is reported as a percentage of specimen shrinkage at 180 days. Additionally, the early age shrinkage data are not included in drying shrinkage values presented in Tables 19 and 20. The early-age shrinkage results and long-term shrinkage data are independent because of test differences.

Table 20 presents the C157 test results for the A4 new construction mixtures. As shown in Table 20, the fly ash and slag mixture results are the same and thus may be combined. At 168 days, rank order from smallest to largest, is as follows Type G, FA, Type K, and S with 590, 636, 678 and 715 με, respectively. Results are not significantly different at 168 days. The slag mixture also had the highest rate of shrinkage at 7 and 28 days at 55 and 74% respectively.

Cracking Propensity

Cracking assessment of the overlay mixtures included mini-rings, v-notches, and scaled bridge deck overlays; whereas only mini-rings were used in the A4 mixture evaluations.

Mini-Rings

None of the A4 mini-ring specimens cracked. However, four LMC specimens, batch one and two, cracked and two LMK specimens, batch one, cracked. Table 21 presents the batch crack length and frequency based on the sum of the two specimens and the average crack width. The crack frequency is the total crack length divided by the surface area of the specimen.

The LMC mixture exhibited the greatest C157 drying shrinkage at 56, 90, and 180 days, see Table 19. Whereas, the LMK mixture had significantly less drying shrinkage than the LMC at all test ages, see Table 19.

Table 21. Overlay Mixtures Mini-ring Cracking

Mixture-Batch	Length in.	Cracking Width in.	Frequency in/in^2
LMC-1	6.75	0.005	0.045
LMC-2	11.5	0.013	0.076
LMK-1	6.62	0.018	0.044

V-Notch

Two of the shrinkage compensating V-notch LMG and LMK specimens cracked, one of the two batch one specimens for each mixture. Table 22, presents the crack length and frequency based on the sum of the two small V-notch specimens of batch one and the average crack width.

Table 22. Overlay V-notch Overlay Mixtures Cracking

Mixture-Batch	Length in.	Cracking Width in.	Frequency in/in^2
LMG-1	43.5	0.058	0.107
LMK-1	31.6	0.028	0.078

Although batch one of these two shrinkage compensating mixtures cracked, batch two and three did not. While LMG did exhibit drying shrinkage values comparable to LMC, LMK showed approximately 30% less shrinkage, see Table 19.

Scaled Bridge Overlays

Four overlay specimens, two from each of the two batches were cast. Two overlays were cast on the low air content and normal air content scaled bridge deck slabs. Overlays were cast using six mixtures, LMC, RSL, LMK, LMG, LMNG, and TRN. The overlays were placed about one year after the bridge deck base slabs were cast and within 7 days after they were grit blasted. Four overlays were cast, two from each of the two batches of the same mixture on the same day. Overlays were cast between 7:00 and 8:00 am and between August 5, 2008 and September 1, 2008. The overlays were moist-cured for three days using wet burlap covered by a plastic sheet.

The overlays were periodically wetted and visually examined for cracks for about one year, through one fall, winter, spring and summer exposure in Blacksburg, Virginia. None of the overlays had cracked.

As cracking is highly influenced by restrained conditions, the overlays were sounded for delaminations and subsequently bond pull-off tests were conducted. Both RSL overlays on the low air content base slabs were delaminated, one had 45% delaminations and the other had 65%. Thus, bond strength tests were conducted on the normal air slabs for the RSL overlay mixture. Whereas, the other overlay bond tests were conducted on the low air content base slabs.

As previously stated, sand patch tests, ASTM E965, were conducted on 8 of the 24 slabs to determine average depth of surface macro-texture. Table 23 presents those results. The texture for an overlay for bonded purposes is to be 0.06 in. (ASTM E965). The average texture of 0.0642 exceeded the 0.06 value. Five of the individual results were less than 0.06, see Table 23. However, four of the five were 0.0598 and one was 0.0587. Thus, the measured textures should have been sufficient for the overlays to bond to the base bridge deck slabs.

Table 24 presents the results of the bond tests for the six overlay mixture, the results are an average of three bond tests for each mixture. As shown, only the RSL failure was at the interface between the base slab and the overlay, an adhesive failure. The other mixtures failed

Table 23. Mean Texture Depth for Eight Bridge Deck Base Slabs

Slab	Mean Texture Depth in^3/in^2
1	0.0598
2	0.0626
3	0.0587
4	0.0598
5	0.0814
6	0.0781
7	0.0598
8	0.0598
Average	0.0642

Table 24. Overlay Bond Strength and Failure Mode

Mixture	Bond Strength psi	Failure Mode		
		Within Overlay, %	Within Deck Slab, %	Adhesive, %
LMC	410	100	--	--
RSL	70	--	--	100
LMK	450	100	--	--
LMG	410	67	33	--
LMNG	390	100	--	--
TRN	450	--	100	--

with the overlay or the base concrete, indicating the bond strength was greater than either concrete. The bond strength of the RSL mixture was significantly less than the other mixtures, 70 psi and 390 to 450 for the RSL mixture and the other overlays, respectively.

The low adhesive strength of the RSL overlay may be related to the time required to transport the RSL concrete from the laboratory mixing room to the slabs at the outdoor exposure area and subsequent casing of the overlays. The time interval from completion of mixing to finishing of the overlay was about 20 to 30 minutes. This length of time delay is not experienced in the field when the RSL is mixed and placed with a mobile mixer directly on to the deck, and screeding, consolidation and finishing begins almost immediately. Also, the RSL mixture is the only overlay mixture that does not have a bonding grout spread over the saturated surface dry deck surface just ahead of the placing of the overlay concrete.

DISCUSSION

Concrete shrinkage is influenced by cement type and quantity, water content, and aggregate type and quantity. Table 25 presents a summary of the mixture quantities to illustrate the difference and similarities between the overlay and A4 mixtures. Both mixture types used the same fine and coarse aggregate produced by the same quarries. The difference is that the overlay mixtures used a maximum size aggregate of 3/8 inch and the A4 mixtures used a maximum size aggregate of ¾ inch.

As shown in Table 25, the total aggregate content of the overlay and A4 mixtures were within 71 lbs, 0.43 cf of a greater volume for the A4 mixtures. The difference in cementing materials' volume between overlay mixtures and A4 mixtures is negligible. The major difference between the overlay and the A4 mixtures was the water content, 51 lbs (0.82 cf)

Table 25. Summarized Mixture Proportions for Select Overlay and A4 Mixtures

Ingredient	SSD Mixture, lbs/cy				
	TRN	A4-FA	LMC	LMK	A4-K
Cementing Materials	619	635	658	658	635
Water	235	286	250	250	286
Total Aggregate	2755	2826	2755	2755	2826
Latex Solid	--	--	97	97	--
Total	3666	3747	3760	3760	3747
w/c	0.38	0.45	0.38	0.38	0.45

between TRN and the A4-FA, and 36 lbs (0.58 cf) between the LMK and A4-Kmixtures. Difference in water content results in w/c of 0.38 and 0.45 for the overlay and A4 mixtures, respectively.

Thus, the expectation is that the A4 concrete would shrink more than the overlay concretes, unless the differences in aggregate volume and latex influence the shrinkage. The following presents a discussion of the long term shrinkage, cracking propensity, and early age shrinkage.

Long Term Shrinkage

Table 26 presents a comparison between the TRN, A4-FA, LMC and A4-K mixtures at ages 7, 28, and 56 days. Except for the shrinkage compensating mixtures (using Type K cement), the overlay mixtures shrink the most when comparing the TRN and A4-FA and the LMC and A4-S mixtures. The difference may be related to the rate of hydration of the cementing materials. Although it would be expected the rate of hydration for the TRN and A4-FA would be similar. However, at 7 and 28 days the TRN and A4-FA3 compressive strength was 5410 and 7140 and 4100 and 5430, respectively. Thus it appears that the TRN mixture hydrated faster, producing more hydration products at a given time and thus shrinking more. Conditions are similar for the LMC and A4-S mixtures. LMC has a greater compressive strength than A4-S3 at 7 and 28 days. At 7 days, the LMC and A4-S3 compressive strengths were 5950 and 4370 psi while at 28 days, 7750 and 6670 psi, respectively.

Within the overlay mixture group, the LMC had the greatest shrinkage followed by the LMGs, TRN, LMK, and with RSL the least shrinkage. As expected, the RSL would have the least shrinkage because of its rapid hydration rate. Also, the LMK mixture shrinks less because of its expansive hydration products. The TRN and MSC shrinkage was about the same, most likely related to their slower rates of hydration and higher water content, respectively. The anomaly is the LMGs mixtures. The shrinkage of these specimens was relatively high, greater than the TRN mixture and less than the LMC mixture.

Although the LMC shrinkage appears to be large, the values presented in this study are in agreement with a previous study that used similar mixture properties, and cement, aggregate, latex and water from the same sources (Buchanan, 2002). Also, the A-F4 shrinkage values presented in this study are in agreement with a previous study (Mokarem, 2002). Whereas, the A4-S shrinkage values presented in this study are about 30% greater than the previous study. However, the previous study w/c+p ratio was 0.43, where 0.45 was used in this study.

Table 26. Long Term Shrinkage Comparisons for Overlay and A4 mixtures

Mixtures	ASTM C157, -με		
	Age, 7 days	**Age, 28 days**	**Age, 56 days**
TRN	599	739	777
A4-FA	206	370	448
LMC	443	705	833
A4-S	350	537	562
LMK	261	373	438
A4-K	273	385	442

With respect to the A4 mixtures, the unrestrained shrinkage and rate of shrinkage are similar. The A4-G shrinks the least and the A4-S shrinks the most. However, the difference between these two mixtures is relatively small, 126με (20%), at 168 days. The other differences are less, A4-K is 15% greater and A4-FA is 8% greater than the A4-G mixture at 168 days.

Propensity for Cracking

The standard ring dimensions are: steel ring inside and outside radius 5 ½ and 6 inches; concrete inside and outside radius 6 and 9 inches with a height of 6 inches. In comparison, the mini-ring uses the same size steel ring, the concrete wall thickness is 1 inch rather than 3 inches and the height is 3 inches rather than 6 inches. It has been shown that as the concrete specimen gets larger (increases ratio of the outside concrete radius to the inside radius of the concrete, R_o/R_i, the potential for cracking is reduced (Weiss et al., 2000). The R_o/R_i ratio of the standard and mini-ring are 1.5 and about 1.2. Thus, the mini-ring would have a greater propensity for cracking than the standard ring.

Four of the six LMC mini-rings and two of the six LMK mini-rings cracked. None of the RSL, LMG, LMNG and TRN mini-rings cracked. Also, none of the A4 mini-rings cracked. The LMC mixture had the greatest shrinkage, 1042 με at 180 days. However, the LMK shrinkage was significantly less, 615 με at 180 days. It is also important to note that while the LMCNG mini-ring and V-notch specimens did not crack, all specimens, including the hardened properties cylinders, exhibited pop-outs as deep as 3/8 inch and as large as 1 inch diameter. These pop-outs were unique to the Type G admixture specimens, Figure 4.

It is noteworthy that standard rings used in the previous study using similar materials and mixtures proportions (mixture LMC-W) also cracked (Buchanan, 2002). The other two LMC mixtures (LMC 1.1 and 1.2) tested in the previous study did not crack, their shrinkage was significantly less than the LMC-WC mixture that cracked, about 450 με and 850 με at 90 days,

Figure 4. Evidence of Pop-outs in LMCNG Mixtures

respectively. Also, the bridge deck overlay represented by the LMC-WC specimen had significantly more cracking than the other two bridge decks, 0.94 ft/ft^2 and 0.05 and 0.09 ft/ft^2 respectively.

Also, in a previous study using standard rings and an A4 fly ash and slag mixture, the standard rings did not crack in 180 days (Mokarem, 2002). The 180-day C157 unrestrained shrinkage was 550 and 500 με for the fly ash and slag mixtures, respectively.

The only V-notch specimens to crack were batch one specimens for the LMG and LMK mixtures. The unrestrained shrinkage for the LMG and LMK batch one specimens was 790 and 800 με at 180 days, respectively. Other LMG and LMK batches had greater unstrained shrinkage, but their V-notch specimens did not crack.

None of the scaled bridge overlay specimens cracked. The length to width ratio was 5 to 1. This is equivalent to a deck overlay of 125 feet long and 25 feet wide, or the placing of an overlay on the shoulder and right traffic lane on a 125 ft. long span.

Table 27 presents the 3-, 7-, and 28-day unrestrained C157 shrinkage for the scaled bridge deck specimens. As shown, the shrinkage of the LMG mixtures is similar to the LMC mixture at 7 and 28 days. Thus, it appears that neither the LMG nor the LMNG influence unrestrained shrinkage; whereas the RSL and LMK mixtures also have significantly lower shrinkage, also shown in Table 27.

The TRN has a greater shrinkage at 28 days than the LMC. However, fly ash mixtures also are more resistance to cracking because they will creep more and thus reduce the restrained strain (Mokarem, 2002).

Table 27. Scaled Bridge Deck C157 Unrestrained Shrinkage

	Shrinkage, -με		
Mixtures	**3 days**	**7 days**	**28 days**
LMC	310	395	580
RSL	125	215	295
LMK	125	280	350
LMG	155	370	540
LMNG	215	410	530
TRN	380	670	750

Early Age Shrinkage

The early shrinkage of the HC and MC157 test methods is presented in Tables 13, 14, and 15 for the overlay mixtures. Reasonable agreement between the two methods occurred for the LMC, LMG, and TRN mixtures. These three mixtures also had the largest unrestrained shrinkage. For the LMC, LMG, and TRN mixtures the early age HC shrinkage was 20%, 26%, and 12% of the long term C157 test results, respectively. In addition, the RSL and LMK demonstrated continuous shrinkage for the 20-hour test period; the percent early age HC shrinkage was 20% and 22% of the long term C157 tests, respectively. Thus, the HC early age shrinkage for the latex overlay mixtures, excluding the LMNG mixture, ranged from 20 to 26% with an average of 22% of the long term C157 test results.

The importance of the early age shrinkage relative to cracking is the magnitude of the restrained strain. The restrain strain is the difference between the shrinkage strain minus creep, and the developing tensile strength. If the tensile stress developed by the restrained strain exceeds the tensile strength, cracking occurs, either internally or externally. In mixtures such as the LMC and TRN overlays, the early age creep may be sufficiently large to keep the shrinkage stresses less than the material tensile strength. For the RSL mixture types, the strength develops so rapidly, that the strength is always greater than the shrinkage stress, regardless of the reduced creep capacity.

For the remaining overlay early shrinkage test results, MC157 LMK mixture appeared to expand, LMNG HC and MC157 indicated an early expansion followed by a small shrinkage. All of these results are possible, but are certainly questionable experimental results.

Of the A4 mixtures, only the A4-G mixtures showed continuously shrinkage throughout the test period and the recorded values are small. For the other A4 mixtures, there are no agreeable or observable trends, other than the measured values for shrinkage and expansion are small.

The ASTM C157 test method should be used to evaluate shrinkage in overlay and A4 mixtures. Shrinkage limits for various mixtures are presented in Table 28. As the scaled bridge deck specimens best mimic field conditions, the values presented in Table 28 were taken from the results shown in Table 27.

Table 28. ASTM C157 Shrinkage Control Limits for Overlay and A4 Bridge Deck Mixtures

Upper Strain Limit, -με	**Overlay Mixtures**			
	LMC	**RSL**	**LMK**	**TRN**
3 Days	300	150	150	400
7 Days	400	250	300	700
28 Days	600	350	400	800
Upper Strain Limit, -με	**A4 Mixtures**			
	A4-FA	**A4-S**	**A4-K**	
7 Days	250	350	300	
28 Days	500	500	400	

CONCLUSIONS

- The overlay laboratory mixtures showed little propensity for cracking, regardless of the test method. Cracking does occur in the mini-ring test when the measured C157 shrinkage is relatively large as for the LMC mixture.

- The ASTM C157 test gave the most consistent results. The MC157 early shrinkage results were variable and inconsistent for the most part in its present configuration. The HC test demonstrated more consistent results and showed that the early age shrinkage is about 20% of the long term C157 test results.

- The LMC, A4-FA and A4-S long term shrinkage results for this study are in general agreement with previous work. The long term ASTM C157 unrestrained shrinkage for the LMK and RSL shrinkage are significantly less than the LMC mixture, at 41 and 47% less, respectively. Both the LMG and LMNG long term C157 test results are about the same as the LMC results, only about 7% less, even though these mixtures are shrinkage compensation mixtures as the LMK mixture.

- In addition, the LMC values are consistent with a previous field study results where field C157 shrinkage specimens were evaluated and the deck overlay cracking was measured (Buchanan, 2002).

- Although the LMCNG did not crack in the traditional sense, all the specimens cast using the new Type G admixture exhibited severe surface deterioration in the form of pop-outs at admixture particle locations. This surface deterioration will compromise the performance ability of the overlay in all aspects.

- The A4 mixtures did not crack in the mini-ring test. In general the A4 mixtures demonstrated less shrinkage than the overly mixtures in the ASTM C157 test.

RECOMMENDATIONS

1. *VDOT's Materials Division should implement the use of the ASTM C157 test method to control the shrinkage of field overlay and A4 concrete mixtures.* Shrinkage limits for various mixtures are presented in Table 27.

2. *The Virginia Transportation Research Council should consider the further development of the HC cylinder as a standard early age shrinkage test method.*

COSTS AND BENEFITS ASSESSMENT

For an average bridge deck, 200 ft long and 42 ft wide, the testing cost for three samples and three specimens per batch would be about $1000.00. For an overlay, where stage construction is necessary, the testing cost is about $2000.00. These costs are based on conducting the shrinkage testing only. They would be somewhat lower since a technician will to be on the job doing other testing such as slump, air content, temperature and unit weight.

The benefit would be

- reduced cracking and thus less maintenance costs
- lower impact on driver delay
- driver and worker safety resulting from longer lasting decks and overlays.

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