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research report

Measurement of Early Age Shrinkage of Virginia Concrete Mixtures

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16. Abstract

Concrete volume changes throughout its service life. The total in-service volume change is the resultant of applied loads and shrinkage. When loaded, concrete undergoes an instantaneous elastic deformation and a slow inelastic deformation called creep. Deformation of concrete in the absence of applied loads that result in a volume decrease is often called shrinkage and is related to moisture loss and temperature change.

Drying shrinkage has been studied extensively; ASTM C 157 measures the shrinkage of concrete prisms over time. The specimens are cured and tested in a variety of ways; however, they are not tested for length change during the first 24 hr after they are cast. Therefore, the magnitude of the early age (first 24 hr) volume change is not measured using this standard. With the use of high performance concrete and rapid setting cements, there is a potential for a significant early age volume change because of the increased cement content and heat of hydration within the first 24 hr after the concrete is cast. Therefore, there is a need to measure this early age volume change in order to determine its magnitude and its effect on the durability of the concrete structure.

The first objective of this investigation was to develop a simple, accurate technique to measure the early age volume change of concrete. The second objective was to investigate the early age volume change of a variety of concrete mixtures used by the Virginia Department of Transportation using the developed technique to aid in determining if the mixtures tested had significant early age shrinkage, which could lead to a higher probability of concrete cracking.

Measurements on a variety of concretes using the testing procedure developed showed that mixtures with lower early age shrinkage tended to have greater shrinkage at later ages relative to mixtures with greater early age shrinkage. By using this procedure, VDOT will be able to determine the total magnitude of shrinkage in various concrete mixtures, which will lead to a better understanding of the material being used. The result will be project specifications that will lead to a more durable, longer lasting, and safer concrete structure.

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FINAL REPORT

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ABSTRACT

Concrete volume changes throughout its service life. The total in-service volume change is the resultant of applied loads and shrinkage. When loaded, concrete undergoes an instantaneous elastic deformation and a slow inelastic deformation called creep. Deformation of concrete in the absence of applied loads that result in a volume decrease is often called shrinkage and is related to moisture loss and temperature change.

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INTRODUCTION

Concrete volume changes throughout its service life. The total in-service volume change is the resultant of applied loads and shrinkage. When loaded, concrete undergoes an instantaneous elastic deformation and a slow inelastic deformation called creep. Deformation of concrete in the absence of applied loads that result in a volume decrease is often called shrinkage and is related to moisture loss and temperature change.

Five main types of shrinkage are associated with concrete: plastic, carbonation, drying, autogenous, and chemical.[1] Plastic shrinkage is due to moisture loss from the concrete before it sets. Carbonation shrinkage is caused by the chemical reaction of various cement hydration products with carbon dioxide present in the air. This type of shrinkage is usually limited to the surface of the concrete. Drying shrinkage is associated with the loss of moisture from the hardened concrete during drying. Initially the concrete loses free water from the larger voids in the concrete structure, there is a large amount of moisture loss, however; there is little to no shrinkage. The ensuing moisture loss is from the bound water in the smaller capillary voids. Although the amount of moisture loss is small relative to the free water loss, the volume change is greater due to the introduction of tensile stresses produced from the moisture loss. Autogenous shrinkage is associated with the loss of water from the capillary voids due to the hydration of cement. This is sometimes referred to as “self-desiccation” of the concrete. This type of shrinkage occurs with the continuing hydration of the cementing materials. Chemical shrinkage is the result of reactions between the cement particles and water that cause a reduction in the absolute volume of the cement paste.

Drying shrinkage has been studied extensively. Two of the test methods used to investigate the shrinkage over time involves unrestrained and restrained specimens. For the unrestrained specimens, ASTM C 157[2] measures the shrinkage over time of concrete prisms. The specimens are cured and tested in a variety of ways; however, the specimens are not tested for length change during the first 24 hr after they are cast. Therefore, the magnitude of the early age volume change is not measured using this standard. (For the purposes of this study, *early age volume change* refers to the volume change during the first 24 hr after the concrete is cast.) For the restrained specimens, a concrete ring is cast around a steel ring, with the steel ring providing the restraint to the concrete. As the concrete hydrates and dries, stresses are created in the concrete, and eventually, cracks may form in the concrete. This gives an indication of the cracking potential for concretes; however, the early age volume change is not directly measured using this technique.

Sant et al.[3] discussed the importance of the magnitude of autogenous shrinkage with respect to the cracking potential of concrete. Their testing showed that the magnitude of the autogenous shrinkage measured is great in the first 24 hr after the concrete is cast. Their study employed four measurement techniques for autogenous shrinkage: the membrane method, the corrugated tube method, the rigid form method, and ASTM C157 on sealed specimens. These tests were performed on cement paste specimens.

It is clear that early age volume change may have an effect on the performance of concrete throughout its service life. Autogenous shrinkage is difficult to measure; however, the significance of this type of shrinkage needs to be investigated to determine its effect on the overall performance of the concrete, especially in widely used conventional concretes with a water–cementitious material ratio (w/cm) exceeding 0.40 and less used concretes with a w/cm less than 0.40.

PURPOSE AND SCOPE

The purpose of this investigation was twofold: (1) to develop a simple, accurate technique to measure the early age volume change of concrete, and (2) to investigate the early age volume change of a variety of concrete mixtures used by the Virginia Department of Transportation (VDOT) using the developed technique. The developed technique could aid in determining if the mixtures tested had significant early age shrinkage, which could lead to a higher probability of cracking of the concrete.

METHODS

Concrete Mixtures Used

The following mixtures were included in the investigation:

- VDOT Class A4—General Bridge Deck Concrete using portland cement only

- VDOT Class A4—General Bridge Deck Concrete with a portion of the portland cement being replaced with slag cement, fly ash, or silica fume

- VDOT Class A4—General Bridge Deck Concrete—Ternary using portland cement and two of the following: slag cement, fly ash, or silica fume

- overlay mixture with slag cement

- latex overlay mixture using Rapid Set Cement, a proprietary material manufactured by CTS Cement Manufacturing Corporation

- latex-modified concrete overlay using Ultimax Cement, a proprietary material manufactured by Ultimax Corporation

- latex-modified concrete overlay using Low P500 Cement, a proprietary material manufactured by CTS Cement Manufacturing Corporation

- lightweight self-consolidating concrete with silica fume.

Table 1 lists the 12 concrete mixtures fabricated for this investigation. A granite-gneiss crushed stone coarse aggregate and its associated natural fine aggregate were used. The A4 concrete mixture using portland cement only was used as the control for the investigation.

One batch was fabricated for each mixture except for the latex overlay mixtures using Rapid Set and Ultimax cements. For each of these mixtures, three batches were fabricated. For the A4 mixtures, concrete was used to fabricate specimens from ready-mix trucks that were delivering concrete for another project being conducted at the Virginia Transportation Research Council (VTRC). The mixture test series was separated into three subgroups: A4, overlay, and self-consolidating concretes.

Table 2 provides the mixture proportions for the A4 mixtures investigated, and Table 3 presents the mixture proportions for the overlay mixtures investigated.

Table 1. Mixture Test Series

A4 straight portland cement (A4)
A4 portland cement and slag cement (A4 SC)
A4 portland cement and fly ash (A4 FA)
A4 portland cement and silica fume (A4 SF)
A4 ternary 1 (with slag cement and silica fume) (A4 SC/SF)
A4 ternary 2 (with fly ash and silica fume) (A4 FA/SF)
A4 ternary 3 (with slag cement and fly ash) (A4 SC/FA)
Overlay mixture with slag cement (OL S)
Latex overlay mixture with Rapid Set Cement (RSOL)
Latex overlay mixture with Ultimax Cement (ULT)
Overlay mixture with Low P500 Cement (LP500)
Lightweight self-consolidating concrete with silica fume (SCC)

Table 2. Mixture Proportions for A4 Concrete Mixtures (lb/yd^3)

Constituent	A4	A4 SC	A4 FA	A4 SF	A4 SC/SF	A4 FA/SF	A4 SC/FA
Portland cement	635	381	540	590	460	524	318
Slag cement (SC)	---	254	---	---	159	---	159
Fly ash (FA)	---	---	95	---	---	95	158
Silica fume (SF)	---	---	---	44	16	16	---
Coarse aggregate	1881	1881	1881	1881	1881	1881	1881
Fine aggregate	1097	1097	1097	1097	1097	1097	1097
Water	286	286	286	286	286	286	286
w/cm	0.45	0.45	0.45	0.45	0.45	0.45	0.45

The maximum size of the coarse aggregate was 1 in.

Table 3. Mixture Proportions for Overlay Mixtures (lb/yd^3)

Constituent	OL S	RSOL	ULT	LP500
Portland cement	395	---	---	---
Slag cement	263	---	---	---
Rapid Set cement	---	658	---	---
Ultimax cement	---	---	658	---
Low P500 cement	---	---	---	658
Latex	---	206	206	---
Coarse aggregate	1453	1277	1288	1455
Fine aggregate	1739	1493	1482	1688
Water	296	148	154	263
w/cm	0.45	0.39	0.40	0.39

OL S = overlay mixture with slag cement; RSOL = Rapid Set cement overlay; ULT = Ultimax cement overlay; LP500 = Low P500 cement overlay. The maximum coarse aggregate size was ½ in.

Table 4 presents the mixture proportions for the lightweight self-consolidating concrete mixture investigated. This mixture was fabricated to determine if a compressive strength of 12,000 psi could be attained using the lightweight aggregate.

Table 4. Mixture Proportions for the Lightweight Self-Consolidating Concrete Mixture (lb/yd^3)

Constituent	Mixture Proportion
Portland cement	893
Silica fume	150
Coarse aggregate	1000
Fine aggregate	1169
Water	260
w/cm	0.25

Development of Early Age Shrinkage Measurement Technique

The first phase of the investigation focused on developing a technique to measure the early age shrinkage of the concrete. The technique needed to measure early age shrinkage accurately and be user-friendly. Different measurement techniques were conducted with varying degrees of success. The first technique employed used the traditional prism molds used to measure length change in accordance with ASTM C 157. The molds use end inserts to secure metal studs on the ends of the concrete prism during casting of the specimen. After the specimen has cured for 24 hr, the specimens are demolded and the end inserts are removed to expose an end stud that can be used for subsequent length change measurement. However, to measure early age shrinkage, length change measurements needed to be conducted while the specimen was still in the mold. The thought process was that as the concrete began to shrink, the length change could be measured using a linear variable differential transformer (LVDT) inserted in the ends of the prism mold. In order for this technique to yield useful results, the end inserts had to be free to move without resistance from the sides of the mold. In addition, the concrete had to be free to move without resistance from the sides of the mold. As expected, the sides of the molds did provide resistance and thus did not allow the end inserts to move. Specimens were also tested in this manner after Teflon tape was placed on the inside of the molds. This allowed the concrete to move freely without resistance from the sides of the mold, but the end inserts were again restricted from movement because of resistance on the sides of the mold.

The second technique employed was casting concrete specimens in a plastic mold 4 in in diameter and 8 in high and measuring the length change from an opening in the top of the mold using an LVDT. A plastic plate was placed on the top of the specimen, and the LVDT was in contact with the plate. This technique did measure some movement but it was also thought that the sides of the mold were providing some resistance and that the results might not be accurate. There was also concern that some of the movement being measured was the result of the concrete settling in the mold as it cured.

The third technique involved modifying the prism molds used for ASTM C 157. The end inserts were removed from the molds. In their place, a bolt was placed through the holes on the end plate and a washer was secured at the top of the bolt. A washer was also placed on the bottom of the bolt to be in direct contact with the LVDT. Figure 1 shows the bolt/washer assembly placed on both ends of the prism mold. Figure 2 shows the test setup with LVDTs

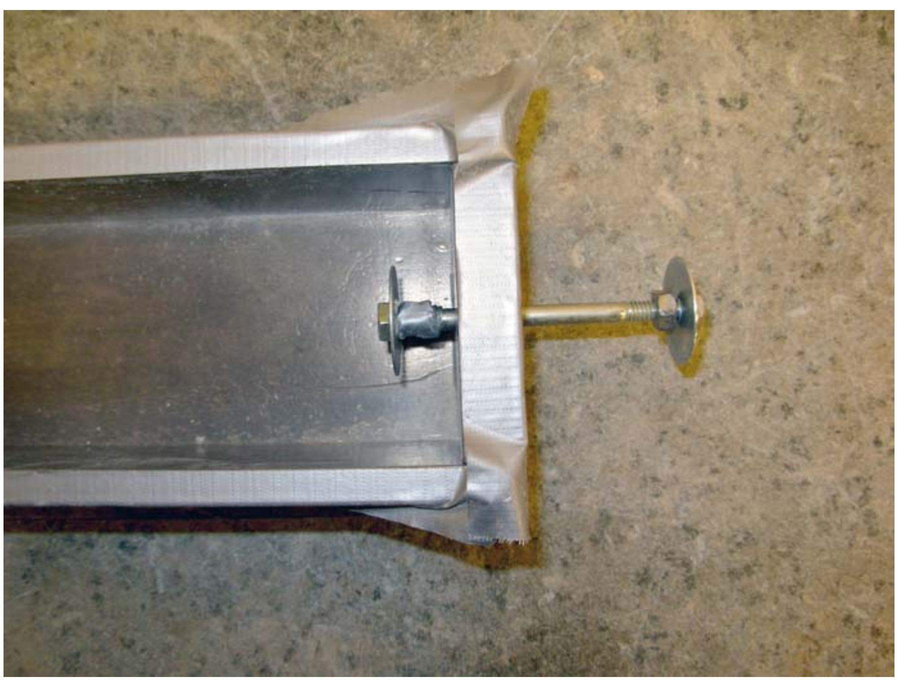

Figure 1. Bolt/Washer Assembly

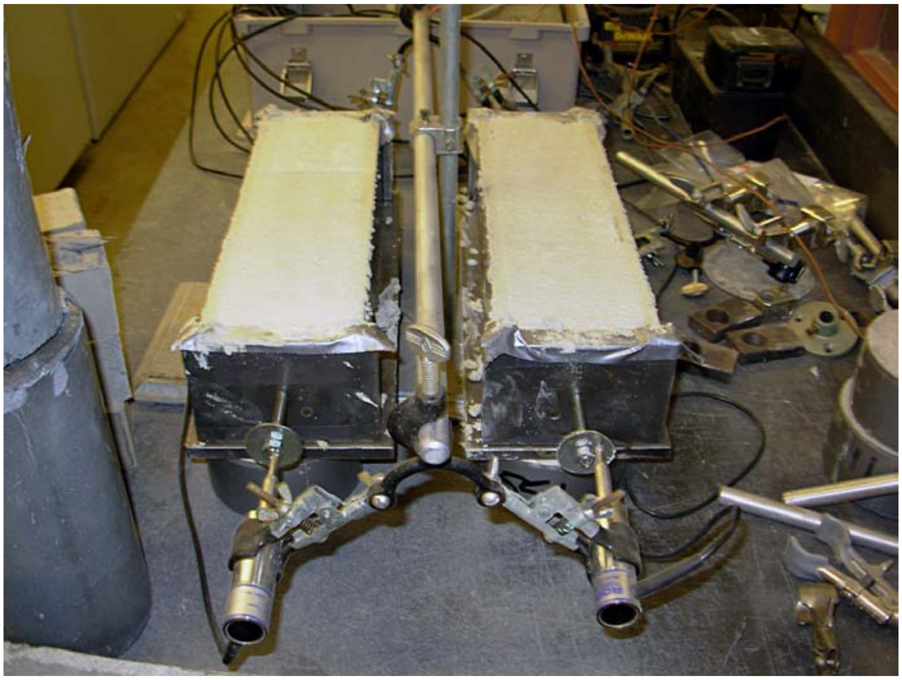

Figure 2. Test Setup Using Bolt/Washer Assembly

measuring the length change. The inside of the prism molds was lined with Teflon tape so that the specimen could move freely without resistance from the sides of the mold. This technique yielded measurable length change results. A variety of mixtures were initially tested to determine if measured length change was different among the mixtures. The mixtures that were expected to exhibit greater shrinkage did indeed produce greater length change during testing.

Based on the successful measurements made using the bolt/washer assembly, this technique was used to measure the early age length change of the concrete mixtures used in this investigation. The modifications were simple, and the results appeared to be precise.
used in this investigation. The modifications were simple, and the results appeared to be precise.

Unrestrained Shrinkage Testing

For the unrestrained shrinkage testing, the modified ASTM C 157 specimens were tested for early age length change. Traditional type specimens were also fabricated and tested in accordance with ASTM C 157. The early age specimens were tested for the first 24 hr after casting in the modified molds. They were covered with wet burlap and plastic during the duration of testing. The length change measurements were performed using LVDTs, and the data were acquired by a data acquisition machine. After testing, the data were downloaded and compiled.

For the traditional ASTM C 157 testing, specimens were cast and cured for 24 hr while covered with wet burlap and plastic. After 24 hr, the specimens were demolded and an initial length measurement was performed using a comparator. The specimens were then placed in a moist room for 28 days and allowed to cure. After 28 days of curing, the specimens were removed from the moist room and a length measurement was performed. The specimens were then placed in a controlled environment (50% relative humidity, 72 °F) and tested in accordance with ASTM C 157.

For all of the mixtures investigated, two specimens were cast for the early age length change measurements. For the traditional ASTM C 157 length change measurements, in most cases, three specimens were cast for testing of each mixture. In some cases, because of an insufficient amount of material, only two specimens were cast.

Restrained Shrinkage Testing

One restrained shrinkage specimen was cast for the A4, A4–Supplemental Cementitious Material (A4-SCM), and A4-Ternary (A4-T) mixtures. The test involved the casting of a concrete ring around a steel ring. The steel ring was 12 in in diameter and ½ in thick. The concrete was 3 in thick and 6 in high. As the concrete shrinks, stresses build up in the concrete and it is restrained by the steel ring. When the concrete stresses are greater than the tensile strength of the concrete, the concrete should crack to relieve these stresses. This test method gives an indication of the probability of cracking of a particular mixture and the time to cracking of that mixture.

Compressive Strength Testing

Compressive strength specimens were fabricated for each mixture and tested in accordance with ASTM C 39.[4] For all mixtures investigated, two or three specimens were tested at 7 and 28 days after casting. For the mixtures using rapid hardening cements (Rapid Set, Ultimax, and Low P500 cements), specimens were also tested at 3 hr and 1 day after casting. For these mixtures, the testing was performed to monitor the early age strength gain of the material, as this material is used as an early strength gain material.

Modulus of Elasticity

The compressive strength specimens were subjected to modulus of elasticity testing before failure in accordance with ASTM C 469.[5] Three specimens were tested at 7 and 28 days after casting.

Splitting Tensile Strength

Splitting tensile strength specimens were fabricated and tested in accordance with ASTM C 496.[6] Two specimens were tested at 7 and 28 days after casting. Splitting tensile strength testing was conducted on specimens of the A4 concrete with and without slag cement, fly ash, or silica fume and on the ternary mixtures because of availability of material.

RESULTS AND DISCUSSION

Unrestrained Shrinkage Testing

Modified Unrestrained Shrinkage Testing

As described in the Methods section, testing was performed on specimens fabricated for each mixture to determine the amount of shrinkage in the first 24 hr after the specimens were cast. The testing technique involved the usage of the bolt/washer assembly to measure the early age length change of the specimens. Two specimens were tested for each batch.

A4 Concrete Mixtures

Figure 3 presents the early age length change results for the A4 concrete mixtures. The values are the average of measurements taken on two specimens. Figure 3 shows that the A4 SF mixture exhibited about twice as much early age shrinkage as the other A4 mixtures containing just portland cement or portland cement with slag cement or fly ash. This could be attributed to silica fume being about 100 times finer than portland cement. This in turn creates a finer pore system creating greater shrinkage stresses in the concrete.[7] The average compressive strength values for the A4 SF mixture were lower than for the other A4 mixtures at both 7 and 28 days. This could be an indication that the real water content of the mixture was higher than for the other A4 mixtures, which in turn would produce higher shrinkage values. The other three A4 concrete mixtures exhibited similar early age length change.

Figure 4 presents the early age length change results for the A4 ternary concrete mixtures. The values are the average of measurements taken on two specimens. Figure 4 shows that the mixture containing slag cement and silica fume exhibited the greatest amount of early

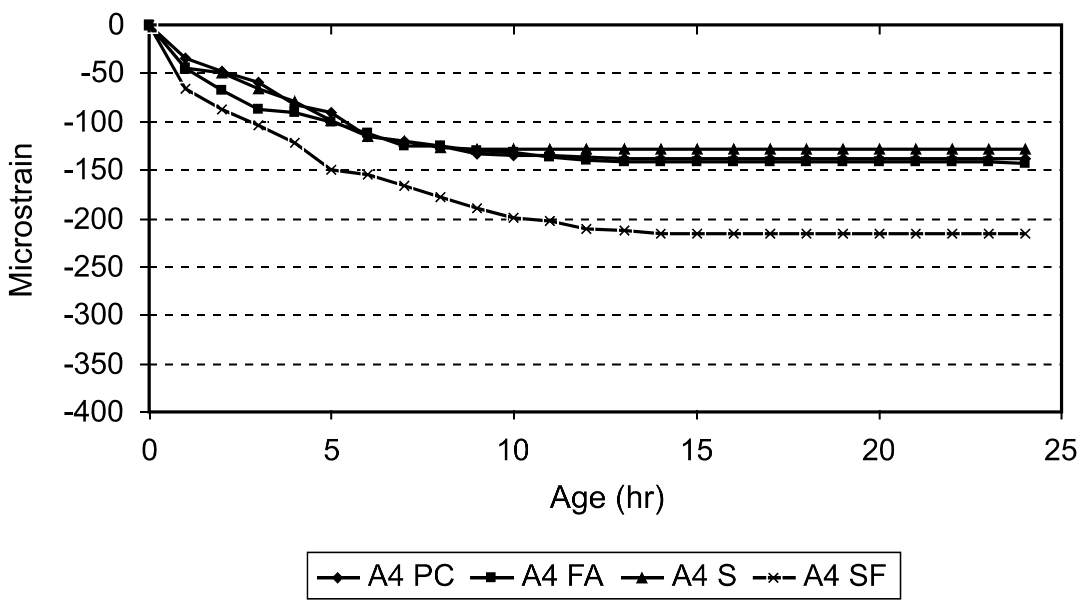

Figure 3. Average Early Age Length Change for A4 Concrete Mixtures. PC = portland cement, FA = fly ash, S = slag cement, SF = silica fume

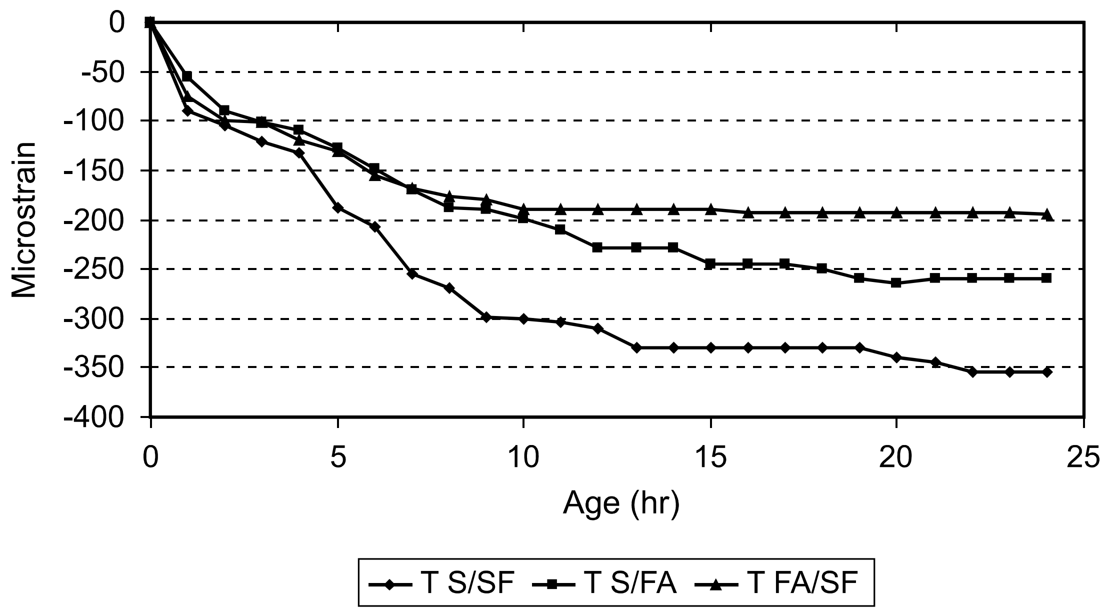

Figure 4. Average Early Age Length Change for A4 Ternary (T) Concrete Mixtures. S/SF = slag cement/silica fume, S/FA = slag cement/fly ash, FA/SF = fly ash/silica fume.

age shrinkage, followed by the mixture containing slag cement and fly ash. The mixture containing fly ash and silica fume exhibited less early age shrinkage than did the other two ternary mixtures. All of the ternary mixtures exhibited greater early age shrinkage than the other A4 mixtures, except for the A4 SF mixture which had an early age shrinkage similar to the T FA/SF mixture. For the mixture containing the slag cement and silica fume that exhibited the greatest amount of early age shrinkage, the temperature of the concrete during placement was 96 °F. This elevated placement temperature probably contributed to the greater amount in early age shrinkage exhibited by the mixture.

Overlay Concrete Mixtures

As described in the Methods section, a total of eight batches were tested using overlay concrete. Figures 5 through 8 present the early age length change results for these mixtures. The values are the average of measurements taken on two specimens.

The Low P500 Cement mixture exhibited the greatest amount of early age shrinkage, followed by Rapid Set cement, the Ultimax cement, and the slag cement, respectively. On average, the overlay mixtures with Rapid Set cement exhibited greater shrinkage than did the A4 concrete and slag overlay concrete mixtures. This is likely due to the fact that the Rapid Set cement used produced more heat of hydration and thus created greater shrinkage stresses at early ages in the mixtures. Other factors included more cement and less coarse aggregate in the overlay mixtures than in the A4 mixtures.

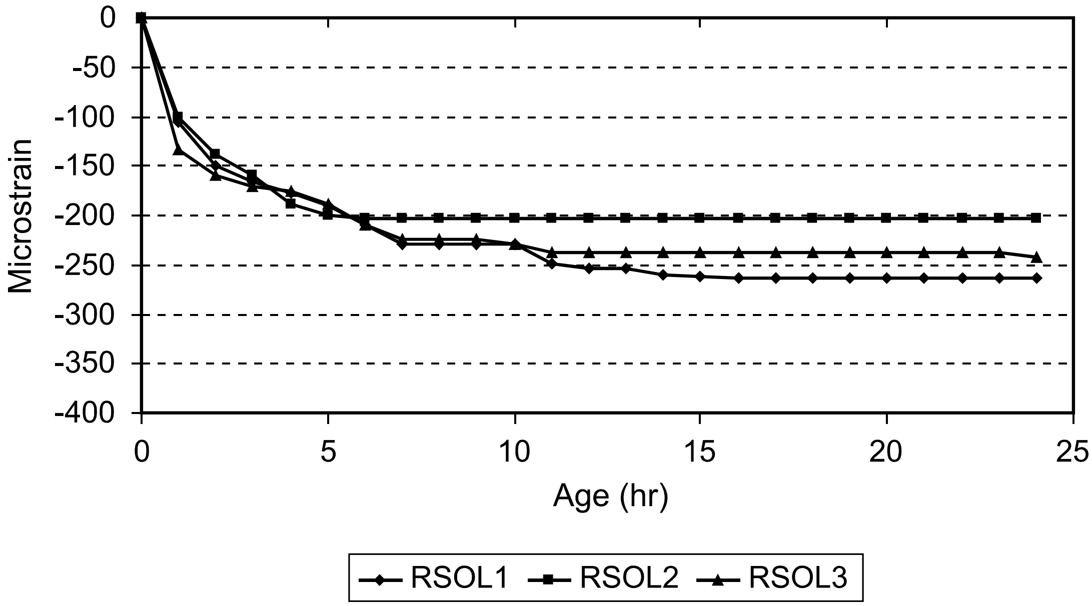

Figure 5. Average Early Age Length Change for Rapid Set Cement Overlay Mixtures

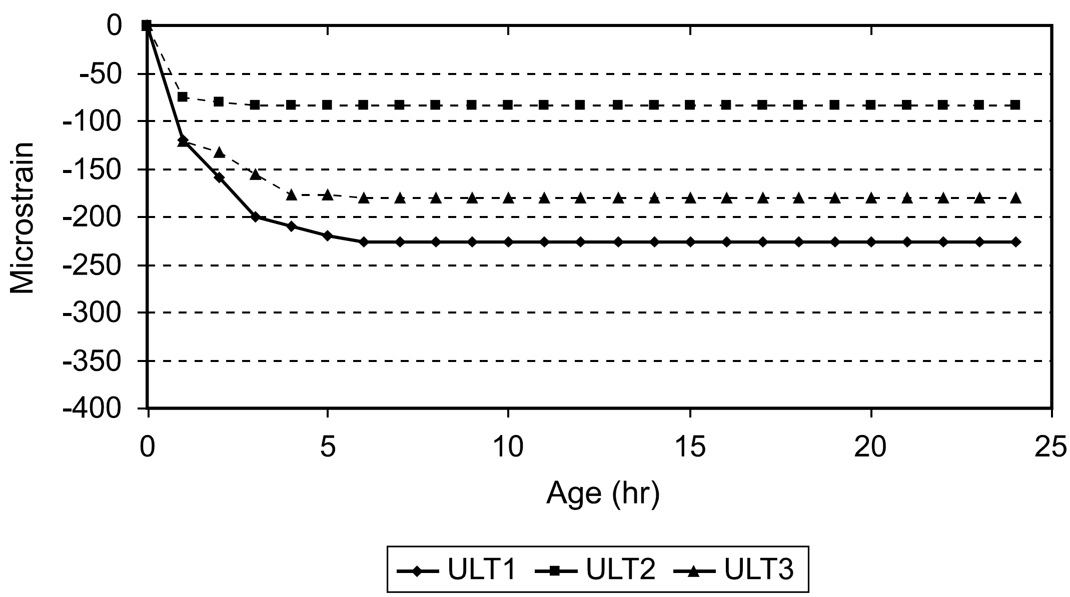

Figure 6. Average Early Age Length Change for Ultimax Cement Overlay Mixtures

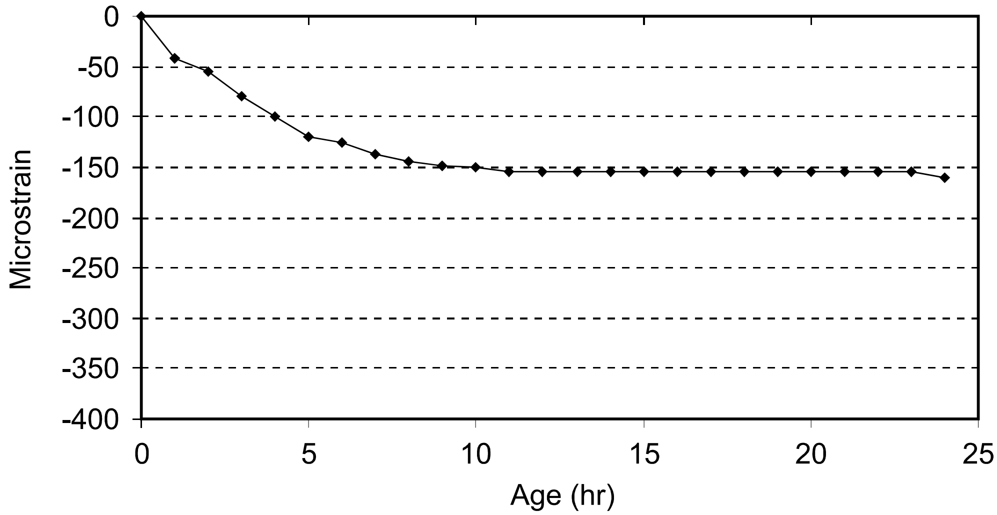

Figure 7. Average Early Age Length Change for Slag Cement Overlay Mixture

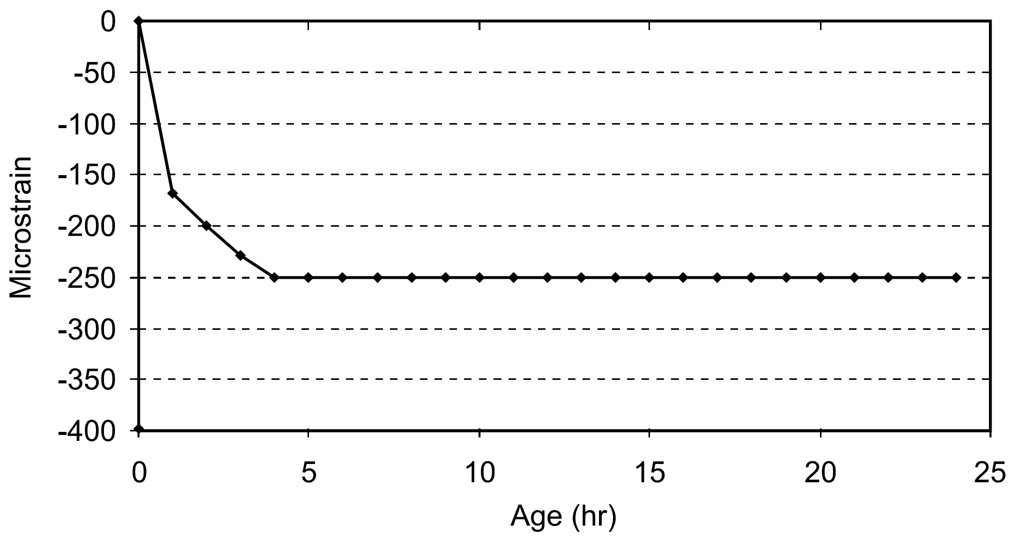

Figure 8. Average Early Age Length Change for the Low P500 Cement Overlay Mixture

Lightweight Self-Consolidating Concrete Mixture

Figure 9 presents the early age length change results for the SCC mixture. The values are the average of measurements taken on two specimens. The mixture exhibited early age shrinkage similar to that of the overlay mixtures with Rapid Set cement and greater than that of the regular A4 mixtures. As noted previously, this mixture was fabricated to determine if a compressive strength of 12,000 psi could be attained using lightweight aggregate. The w/cm was very low. A large amount of chemical admixtures was used to produce workable concrete, which could have contributed to the early age shrinkage.

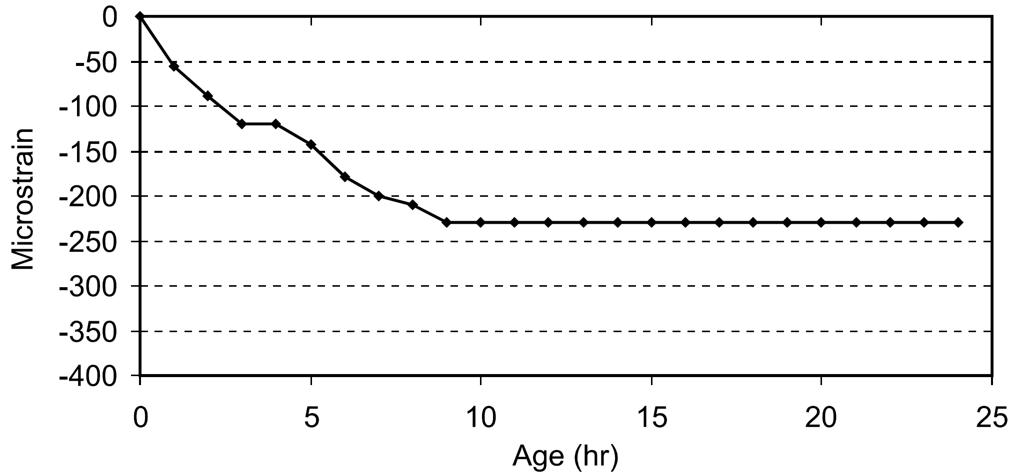

Figure 9. Average Early Age Length Change for Lightweight Self-Consolidating Concrete Mixture

Traditional Unrestrained Shrinkage Testing

As discussed in the Methods section, testing was performed on specimens fabricated for each mixture to determine the amount of shrinkage in accordance with ASTM C 157. The specimens were demolded after 24 hr, measured for initial length and then placed in a moist room for 28 days. After 28 days, the specimens were removed from the room, measured for length change, and placed in a controlled environment. Subsequent length change measurements were conducted at 7, 28, 56, and 90 days. To date, the specimens are in the controlled environment and continue to be measured for length change on a monthly basis. In most cases, three specimens were fabricated for each batch investigated. Because of material availability, only two specimens were fabricated for some batches.

A4 Concrete Mixtures

Table 5 presents the length change data for the A4 mixtures with and without slag cement, fly ash, or silica fume. The data show that the A4 control mixture exhibited the greatest shrinkage over time followed by the A4 with silica fume and the A4 with fly ash. The A4 concrete mixture with the slag cement consistently exhibited the least amount of shrinkage. As expected, the A4 control mixture with portland cement only ultimately exhibited the greatest amount of drying shrinkage.

Table 5. Length Change for A4 Concrete Mixtures (microstrain)

Age (Days)	A4	A4 SC	A4 FA	A4 SF
28	-290	-200	-233	-265
35	-373	-300	-310	-335
56	-447	-373	-420	-440
84	-510	-433	-450	-490
118	-593	-483	-503	-540

The age noted is the age after casting. The length change value for each day is the average of measurements on three prisms.
SC = slag cement, FA = fly ash; SF = silica fume.

Table 6 presents the length change data for the A4 ternary concrete mixtures. The data show that the A4 ternary mixture with slag cement and fly ash consistently exhibits greater shrinkage. The A4 ternary mixture with slag cement and silica fume had the least amount of shrinkage over time.

Table 7 presents the length change data for the overlay mixtures and the lightweight self-consolidating concrete. The data show that shrinkage for the overlay mixtures, with the exception of the mixture using slag cement, was low. The overlay mixture using the slag cement exhibited shrinkage similar to that of the A4 mixtures. The Rapid Set, Ultimax, and Low P500 cements used are rapid hardening cements that are used for early strength gain. It appears from these data that shrinkage is minimal after these cements cure and harden. The standard ASTM C157 test started at 24 hr underestimates the shrinkage of these mixtures by not capturing the shrinkage exhibited in the first 24 hr after casting of the specimens.

Table 6. Length Change for A4 Ternary Mixtures (microstrain)

Age (Days)	A4 Ternary SC/SF	A4 Ternary FA/SF	A4 Ternary SC/FA
28	-183	-273	-367
35	-280	-400	-510
56	-373	-463	-550
84	-423	-573	-613
118	-477	-610	-703

The age noted is the age after casting. The length change value for each day is the average of measurements on three prisms.
SC = slag cement, SF = silica fume; FA = fly ash.

Table 7. Length Change for Overlay and Lightweight Self-Consolidating Concrete Mixtures (microstrain)

Age (Days)	RSOL 1	RSOL 2	RSOL 3	ULT 1	ULT 2	ULT 3	S OL	SCC	LP 500
7	-50	-70	-70	-85	-95	-25	-170	-15	-10
14	-70	-85	-80	-110	-135	-25	-290	-10	-10
28	-70	-115	-75	-105	-155	-65	-405	-15	-10
90	-80	-85	-110	---	---	---	-505	---	---

RSOL Rapid Set cement overlay; ULT = Ultimax cement overlay; S OL = slag cement overlay; SCC = self-consolidating concrete; LP 500 = Low P500 cement overlay.

Summary of Unrestrained Shrinkage Testing

One of the interesting trends observed in this investigation was the total shrinkage exhibited by the mixtures, the total shrinkage being the early age shrinkage (first 24 hr) and the later age shrinkage. The data showed that mixtures exhibiting relatively large early age shrinkage exhibited very little shrinkage at later ages; the converse was also true. Table 8 presents the total shrinkage for the mixtures that exhibited less early age shrinkage.

Table 9 presents the total shrinkage for the mixtures that exhibited higher early age shrinkage. In comparison, the mixtures using Rapid Set, Ultimax, and Low P500 cements showed less total shrinkage than did the A4 concrete mixtures that used portland cement, slag cement, fly ash, and silica fume. Although the early age shrinkage was higher, the total shrinkage at later ages was significantly less than with the A4 concrete mixtures.

Table 8. Total Shrinkage for Mixtures with Lower Early Age Shrinkage (microstrain)

Age (Days)	A4	A4 SC	A4 FA	A4 SF	A4 Ternary SC/SF	A4 Ternary FA/SF	A4 Ternary SC/FA	Slag Overlay
1	-139	-129	-144	-215	-354	-194	-259	-160
28	-429	-329	-377	-480	-537	-467	-626	-565
56	-586	-502	-564	-655	-727	-657	-809	-612
84	-649	-562	-594	-705	-777	-767	-872	-665
118	-732	-612	-647	-755	-831	-804	-962	---

SC = slag cement; FA = fly ash; SF = silica fume.

Table 9. for Mixtures with Higher Early Age Shrinkage (microstrain)

Age (Days)	RSOL 1	RSOL 2	RSOL 3	ULT 1	ULT 2	ULT 3	SCC	LP 500
1	-264	-204	-242	-226	-83	-181	-230	-251
7	-314	-274	-312	-311	-178	-206	-245	-261
14	-334	-289	-322	-336	-218	-206	-240	-261
28	-334	-319	-317	-331	-238	-246	-245	-261
90	-344	-289	-352	---	---	---	---	---

RSOL Rapid Set cement overlay; ULT = Ultimax cement overlay; S OL = slag cement overlay; SCC = self-consolidating concrete; LP 500 = Low P500 cement overlay.

Another note of interest regarding the unrestrained shrinkage testing results from this investigation is that the A4 mixture results correspond well to those of previous research conducted on similar mixtures by Mokarem et al,[8] who investigated the shrinkage of a variety of mixtures used by VDOT, including A4 mixtures with and without slag cement and pozzolans.

Restrained Shrinkage Testing

Only one of the rings for the restrained shrinkage specimens has cracked to date, that being the specimen from the A4 slag cement mixture. The ring cracked 39 days after it was cast, with the crack extending the full height of the specimen. All of the other rings were in good condition and showing no visible signs of cracking 150 days after casting.

Compressive Strength Testing

Table 10 presents the compressive strength data for the mixtures. The results indicate varying strength levels ranging from 2120 psi at 7 days to 11360 psi at 28 days. The lowest strength was with some of the ternary mixtures; however, with age the mixtures are expected to yield high strengths.

Table 10. Average Compressive Strengths (psi)

Age	A4	A4 SC	A4 FA	A4 SF	A4 Ternary SC/SF	A4 Ternary FA/SF	A4 Ternary SC/FA	Slag Overlay
7 days	3380	3480	3600	2490	4130	2290	2120	3330
28 days	4340	5270	4830	3920	5760	3480	3910	4500
Age	**RSOL 1**	**RSOL 2**	**RSOL 3**	**ULT 1**	**ULT 2**	**ULT 3**	**SCC**	**LP 500**
3 hr	3430	3610	3700	2220	1630	2010	---	6350
1 day	5120	5690	5440	3600	2770	3170	---	8390
7 days	6210	6350	6590	4430	3610	3740	9900	---
28 days	6640	7130	6820	5110	4300	4200	11360	10880

The value is the average of two compressive strength tests.
SC = slag cement; FA = fly ash; SF = silica fume, RSOL Rapid Set cement overlay; ULT = Ultimax cement overlay; S OL = slag cement overlay; SCC = self-consolidating concrete; LP 500 = Low P500 cement overlay.

Modulus of Elasticity Testing

Table 11 presents the modulus of elasticity data for the mixtures. The results indicate some variability but not as much as with the compressive strengths. The lower modulus values corresponded with the lower compressive strength values as expected.

Table 11. Average Modulus of Elasticity (million psi)

Age (Days)	A4	A4 SC	A4 FA	A4 SF	A4 Ternary SC/SF	A4 Ternary FA/SF	A4 Ternary SC/FA	Slag Overlay
7	2.83	2.82	2.57	2.26	2.92	1.97	2.45	---
28	3.25	3.16	3.31	3.04	3.78	2.53	3.02	5420
Age (Days)	**RSOL 1**	**RSOL 2**	**RSOL 3**	**ULT 1**	**LT 2**	**ULT 3**	**SCC**	**LP 500**
7	2.95	3.32	2.99	---	---	---	---	---
28	3.14	3.24	3.05	---	---	---	3.92	---

SC = slag cement; FA = fly ash; SF = silica fume, RSOL Rapid Set cement overlay; ULT = Ultimax cement overlay; S OL = slag cement overlay; SCC = self-consolidating concrete; LP 500 = Low P500 cement overlay.

Splitting Tensile Strength Testing

Table 12 presents the splitting tensile strength data for the mixtures. Splitting tensile strengths correlated well with the compressive strength values. The mixtures with the lower splitting tensile strength values had lower compressive strength values.

Table 12. Average Splitting Tensile Strength (psi)

Age (days)	A4	A4 SC	A4 FA	A4 SF	A4 Ternary SC/SF	A4 Ternary FA/SF	A4 Ternary SC/FA
7	400	490	450	320	465	340	320
28	585	585	530	470	555	425	485

SC = slag cement; FA = fly ash; SF = silica fume

CONCLUSIONS

- The testing procedure developed can measure the length change of concrete specimens during the first 24 hr after casting of the specimens.

- Early age shrinkage of A4 concrete mixtures with and without slag cement, fly ash, or silica fume is less than the early age shrinkage of A4 ternary concrete, rapid hardening cement overlays, and lightweight self-consolidating concrete mixtures.

- Total shrinkage of A4 ternary concrete mixtures is more than that of A4, overlay, and lightweight self-consolidating concrete mixtures.

- Early age shrinkage of mixtures with rapid hardening cements is greater that that of mixtures using portland cement, slag cement, fly ash, or silica fume; however; shrinkage at later ages and total shrinkage are less

- Mixtures with lower early age shrinkage tended to have greater shrinkage at later ages and greater total shrinkage than mixtures with higher early age shrinkage.

- For cracking potential, in addition to shrinkage, other properties such as tensile strength, elastic modulus, and creep are important.

RECOMMENDATIONS

1. *VTRC concrete research staff, when possible, should use the test procedure developed in this study (i.e., the bolt/washer assembly) to measure early age shrinkage.* This can be done for concrete mixtures that are fabricated at VTRC as part of the overall concrete research program. The fabrication and testing of these specimens is easy and requires little material. This will aid in further developing the procedure and will provide an indication of excessive early age shrinkage of various concrete mixtures.

2. *After further testing and development of this procedure by VTRC, VDOT's Materials Division should adopt the early age length change test procedure.*

FUTURE RESEARCH

A study at VTRC, in conjunction with researchers at Virginia Tech, is currently being conducted regarding early age and later age volume change of various concrete mixtures currently used by VDOT. The study will also investigate the cracking associated with these volume changes. The results from the current investigation should be considered in the final analysis of the VTRC/Virginia Tech study to determine similarities/correlations between the results.

COSTS AND BENEFITS ASSESSMENT

One of the durability issues associated with concrete is the propensity of a mixture to crack because of volume change. By limiting the rate of volume change over time, the probability of cracking is reduced. This can lead to a more durable, longer lasting concrete structure. A more durable concrete structure will also require less maintenance during its service life, which will reduces the costs associated with maintenance.

The results of this investigation have yielded a new tool to measure the early age volume change of concrete. This procedure was developed for ease of use and accuracy. By using this procedure, VDOT will have the ability to determine the total magnitude of shrinkage in various concrete mixtures, which in turn will lead to a better understanding of the material being used in construction. Translating this better understanding of the material into project specifications will lead to a more durable, longer lasting, and safer concrete structure.

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