OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

DIMENSIONAL STABILITY OF CONCRETE SLABS ON GRADE

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16. ABSTRACT

Drying shrinkage is one of the major causes of cracking in concrete slabs on grade. The moisture difference between the top and bottom surface of the slabs causes a dimensional or “shrinkage” gradient to develop through the depth of the slabs. This can cause cracks and warping which result in serviceability and performance problems for concrete slabs on grade. There have been numerous analytical and experimental investigations to characterize drying shrinkage as a material property. However, there have not been significant improvements in terms of validation and calibration to provide engineers with a reliable evaluation of the strains and stresses within a concrete element subjected to moisture gradients and restrained shrinkage.

This test program characterizes the dimensional properties of selected concrete materials, evaluating their performance as real slabs-on-grade in that they are exposed to ground moisture on the bottom surface and drying conditions on the top surface. The concrete mix designs examined included low and high strength concrete (PCC and HPC), typical Portland concrete using two common types of shrinkage reducing admixtures (PCC+SRA), and type K, shrinkage compensated concrete which uses Calcium sulfoaluminate cement (CSA). The data includes standard concrete material characterization tests, joint opening measurements, internal relative humidity and temperature in ½ in. increments through the depth of the slab, prism tests and compression test results. It was found that type K, shrinkage compensated concrete is very stable, with no long term shrinkage, cracking or warping while typical PCC and HPC continue to show crack growth at over 600 days of age. Shrinkage Reducing Admixtures have a minor impact at early age but do not impact long term sectional stability. The SRA concrete exhibited shrinkage, cracking and warping nearly similar to typical PCC but slightly better than HPC.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in²	square inches	645.2	square millimeters	mm
ft²	square feet	0.0929	square meters	m²
yd²	square yards	0.8361	square meters	m²
ac	acres	0.4047	hectares	ha
mi²	square miles	2.590	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.0283	cubic meters	m³
yd³	cubic yards	0.7645	cubic meters	m³
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in²	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm²	square millimeters	0.00155	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.196	square yards	yd²
ha	hectares	2.471	acres	ac
km²	square kilometers	0.3861	square miles	mi²
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m³	cubic meters	35.315	cubic feet	ft³
m³	cubic meters	1.308	cubic yards	yd³
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in²

ACKNOWLEDGEMENTS

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DIMENSIONAL STABILITY OF CONCRETE SLABS ON GRADE

FINAL REPORT

October 10, 2012

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Executive Summary

Cracking caused by drying shrinkage is probably the major problem that occurs in concrete slabs that impacts serviceability, longevity and durability. If the crack is not controlled, it can lead to serious performance and serviceability problems from excessive deflection, and durability problems caused by freeze-thaw and corrosion at the cracks. Unfortunately, even though many studies have been done and some computer models are available now, significant improvements in terms of validation and calibration do not exist to provide engineers with a reliable evaluation of strains and stresses within a concrete element subjected to restrained shrinkage. Especially, warping due to the moisture gradient of the slab is one of the most important aspects of shrinkage and is rarely considered in design because there is very little data available concerning this phenomenon.

This research project has a unique potential to improve our understanding of warping and our ability to predict its effect. This experimental program is designed to characterize the warping of a slab as a function of various parameters and to establish correlations with basic properties. In addition, this research has the potential to improve the stability behavior of a slab on grade while lowering the need for the maintenance of the concrete. This research increases the reliability of shrinkage data by measuring shrinkage from the point of initial set with the "shrinkage from the time zero" test. The focus of this research is to develop an innovative, economical and practical pavement system based on using Calcium SulphoAluminate (CSA) and Portland cement concrete. Thereby, it is research on drying shrinkage, warping and joint opening performance of slab-on-grade pavement systems. This research is conducted in a unique testing facility built to provide the required specific condition for the experimental test program of the research project.

This research has five phases. Phase I, included preparing the lab structure--the construction process of the test facility for concrete research lab. Phase II included initial study, trailed batch data, and testing the specimens. The purpose of this phase was to select concrete mix design to use in the slab specimens for the next phase. Phase III the accumulation of data is still in process. This phase is the main phase of this study. It included casting seven slab specimens following Bissonnette et al.'s (2007) test procedure. The specimen mix designs were selected based on mix designs results from the Phase II study. The slabs are sized 3"x36"x240". The slabs were cast over 4 in. moist compacted sand on ground. This phase focuses on comparison using Calcium

SulphoAlominate (CSA) and Portland cement at slab on grade. During the evaluation, slab monitoring consisted of: visual observation of cracking, surface strain and joint opening measurement using Demec strain gages, internal slab temperature and relative humidity, ambient temperature and relative humidity, warping of the slab measured by Standard Testing Company. Additionally, laboratory testing program consisted of the compression strength of the cylinder specimens ASTM C39, and the length changes of the prism specimens based on ASTM C157and ASTM C878 (free shrinkage and expansion).

Phase IV included conducting additional test specimens is still in process. The purpose of these tests was to provide data regarding shrinkage of prism specimens using shrinkage compensating cement (Note: ASTM C878 is only used for expansion of shrinkage compensating cement specimen).

Phase V, also in process, included reducing relative humidity of the lab from 60% to 20%. All monitoring, measurements, and tests will be continued in order to characterize shrinkage and warping in low ambient relative humidity at the top surface of the slab while exposing the bottom of the slab to the ground relative humidity.

As a preliminary conclusion, the shrinkage compensating concrete Komp I and Rapid Set are very stable and only small amount of shrinkage, cracking and warping are obtained in the early age and at 12 months while growth of cracking is obtained for typical PCC and HPC in the long term. In the case of using shrinkage reducing admixture, only a minor impact at the early age has been noticed, and no impact in the long term is obtained. Additionally, shrinkage, cracking and warping are very close to typical PCC and slightly better than HPC.

1. **Introduction**

There is a wealth of information on drying shrinkage in the literature (Hart, 1928; Washa, 1955; Powers, 1959; Tremper and Spellman, 1963; Meininger, 1966; Baron and Satery, 1982; Weiss et al. 1998; Suprnant, 2002) and how drying shrinkage has an impact on warping of panel on ground (Carlson, 1938; Ytterberg ,1987; Rollings 1993; Dobson 1995; Walker and Holland 1999; Gilbert 2001; Tarr et al., 2006). However, most of the previous research has been in the realm developing an understanding of shrinkage at the micro level without consideration of design implications (Perenchio, 1997). There is also a wealth of information on shrinkage reduction. However, most of the previous research has been in the laboratory focused on the materials science aspect (Shah et al., 1992; Balogh, 1996; Nmai et al. 1998; Newberry, 2001; Weiss and Berke, 2003; Zhibin et al., 2008). With the exception of Bissonnette et al. (2007) very little substantive work has been done regarding shrinkage reduction with actual slabs. Finally, no work has been done regarding shrinkage reduction with actual slabs on ground exposed to constant moisture beneath the slabs. Thus, the gap in the body of knowledge is the lack of engineering data concerning the shrinkage behavior of true slabs on ground.

One of the major problems encountered with slab-on-ground is cracking caused by drying shrinkage, warping, and curling on the slab. Shrinkage continues in slab-on-ground for years, but most of the shrinkage occurs in the first years. Drying shrinkage is very difficult to predict because many parameters affect this phenomenon. The parameters can be water content, cement content, type of aggregate and aggregate gradation and environment, etc. Although many studies have been done in this category, there is still not enough data to provide a reliable evaluation of strains and stresses of restrained concrete elements. Furthermore, there is not enough data for engineers to consider drying shrinkage and warping in their design (Perenchio, 1997). Additionally, there is not an acceptable method to evaluate drying shrinkage and warping tendency of a concrete slab. Generally, unrestrained length change method (ASTM C157) is the only available data used to discuss concrete shrinkage problems.

This experimental program is designed to characterize the shrinkage of a slab as a function of various parameters and to establish correlations with basic properties. This study provides data for shrinkage of slabs on ground using different types of concrete mix in a controlled environment with a constant source of moisture below the slab. The focus of this project is developing an innovative, economical and practical pavement system that will have superior serviceability and durability. For the purposes of this research, fifteen slabs were cast on 4 in. of sand sub-base placed on a soil base (i.e. on ground). The slabs are 3”x36”x240” and the mixes include: Type K Shrinkage Compensated Concrete, Calcium SulphoAluminate based Rapid set concrete, Portland cement based normal concrete, high performance concrete and normal concrete two types of shrinkage reducing admixture.

2. Objectives

The objectives of this study is to provide reliable shrinkage data, to develop a better understanding of some of the tests being used to evaluate the properties of cementitious materials, to develop rules relating to joint spacing, and to characterize reliable performance criteria for the selection of materials used in slabs-on-ground where shrinkage occurs, especially warping, are a concern. Finally this study will contrast the various methods of shrinkage control as they relate to both laboratory and the behavior of slabs on ground exposed to a realistic environment.

3. Materials

The concrete mixture used in this research is provided in Table 3.1.This table shows the concrete mix used in fifteen slab specimens. Type K based Shrinkage compensating concrete, Calcium SulphoAluminate based Rapid Set concrete are in the right hand columns. Dolese Company provided concrete for most of the other slabs. Shrinkage reducing admixtures, Eclipse and Tetragaurd, were added to the Portland cement concrete at the time of casting.

Table 3.1. Concrete Mix Design

Materials	SRA#1	SRA#2	PCC	HPC	CTS Shrinkage Compensating	Rapid Set
Komp I	-	-	-	-	120	-
P C	356.3	355	355	547	370	-
Flyash	87.5	87.5	87.5	182	-	-
Rapid Set Cement	-	-	-	-	-	658
itric Acid	-	-	-	-	-	5
Course Aggregate	1850	1850	1850	1850	1750	1772
Sand	1525	1530	1505	1188	1315	1307
Water	209.5	197.8	207.3	218.8	271.5	290
MR (Polyheed (oz))	13	14	14	29	17.47	1555 (mL)
Eqlipse (oz)	35.93	-	-	-	-	-
Tetraguard (oz)	-	36.06	-	-	-	-
W/C	0.50	0.43	0.47	0.3	0.55	0.44

4. Method of Investigation

This research project was broken into four phases. Phase I included preparing the lab structure, a construction process of the test facility for concrete research lab. The research lab is a 1,800 ft^2 building sponsored by CTS Cement Manufacturing Corp. This building was built by CEES students in Fears Lab under the mentorship of Dr. Ramseyer. The students constructed everything from digging the foundation to installing the steel paneling on the walls and ceiling. The only sub-contracted work was casting the interior slab and the electrical work. The lab is a unique project named the Advanced Concrete Research Laboratory. This lab provides a controlled environment and includes seven reinforced test beds for studying the long-term behavior of concrete slabs on ground. The test beds allow the researchers to test 3-foot-by-20-foot slabs. The slabs top surface is exposed to a controlled environment, which helps to eliminate the impact of curling while the bottom surface is exposed to soil temperature and moisture.

Phase II included initial tests to select mix designs for the slab specimens. A variety of concrete mixes (over 30 mixes) was batched and tested to select concrete mix designs. Various tests such as flow table (ASTM C230), compression strength of concrete (ASTM C39), length change of hardened hydraulic cement mortar and concrete (ASTM C157), and restrained expansion of shrinkage-compensating concrete (ASTM C878) were done as part of pre-research work.

Phase III included casting slab specimens located on the ground in the controlled environment lab and testing and monitoring them. The results provided in the report are an average of these tests. This program followed Bissonnette et al. (2007) test procedure with two exception; the slabs are exposed to a constant source of soil moisture. The slab specimens were located on the ground in the controlled environment of the Advanced Concrete Research Laboratory.

Phase IV included providing additional test specimens to provide data for shrinkage of prism specimens using shrinkage compensating cement. The results from the shrinkage of the prism tests are used to compare with the slab specimens' results and Bissonnette et al.'s (2007) test results. (Note: According to ASTM, C878 standard test method is only used for measuring expansion of prism tests specimens using shrinkage compensating concrete; therefore, additional tests are provided using Demec target strain gages for the same mixes of slab specimens using type K shrinkage compensating and Rapid Set concrete. The Demec surface strain gage measurements method is used instead of ASTM C878 standard test method to provide data for both expansion and shrinkage of prism specimens.)

4.1. Summary of Bissonnette et al.'s Method

Bissonnette et al. (2007) studied drying shrinkage, curling, and joint opening of slab-on-ground. The purpose of their investigation was characterizing curling and joint opening of Portland cement based concrete slabs in a controlled environment. The variables of Bissonnette et al.'s experimental slab tests were concrete mix and the amount of steel reinforcement. Two concrete mixtures were used in their research, normal-strength concrete with a water-cement ratio of 0.53, and a high-strength concrete with a water-cement ratio of 0.36. A water-reducing admixture and a high-range water-reducing admixture were used in both mixtures. The 3 in. x 40 in. x 240 in. slabs were cast over a concrete warehouse floor on a vapor barrier and 4 in. of moist (14%) compacted sand and conditioned in a controlled environment at a 30% RH and 73.4ºF temperature. Slabs were restrained in longitudinal direction with three stiff channels (CSA C 200x28 channels). To transfer the load from the concrete slab, the channels were tied with welded transverse reinforcing bars. The amounts of steel reinforcement investigated were ρ_s=0, 0.08, and 0.23%. Welded wire fabric reinforcements were installed at the mid height of the slab. Slab monitoring, which began after 7-day moist curing, consisted of the curvature of the slab, axial strains, joint movements, surface cracking, and concrete RH. It was found that curling and joint opening develop early and they are related to drying shrinkage. In other words, the rate of developing curling is proportional to that of drying shrinkage, and curling has a direct influence on joint opening. In addition, it was found that with increasing reinforcement ratio, cracking was observed at mid-span between joints and high stiffness combined with drying shrinkage; therefore it was concluded that the crack can be caused with reinforcement. Bissonnette et al. noted that the 4 inch sand beds they cast on dried out during the year long test and that the slabs became dimensionally stable at about six months.

4.2. Research Method

This research follows Bissonnette et al.'s (2007) test procedure with some exceptions. This research located the slab on ground to ensure that moisture is maintained at the bottom of the slab. This ensured that the slabs on ground behave similar to a true application and do not dry out as they did with Bissonnette et al.'s research. Also the relative humidity was measured at 1/2 in. increments through the depth of the slab. This measurement provided data concerning the movement of moisture through the slab. Additionally, the temperature was measured at 1/2 in. increments through the depth of the slab to verify that there was no temperature gradient present which could cause curling (Note- curling is not addressed by this research).

For the purposes of this research, fifteen 3" x 36" x 240" slabs were cast on 4 in. of sand sub-base placed on a soil base (i.e. on ground). This duplicates a true slab on ground exposed to a realistic environment. The slabs are exposed to constant ground moisture, similar to any slab on ground. This ground moisture provided a constant source of moisture to the slab and potentially acts as the source of the moisture gradient in the slab (ACI 302.2R-06). The slabs were cast over 4 inches of moist compacted sand on ground. The moisture transfers from ground to the sand and from sand to the bottom of the slab. The lab relative humidity and temperature was controlled and it was generally 30% or 60% RH and 70º F. The bottom of the slab was exposed to the ground moisture (100% RH) and the top of the slab was exposed to the controlled environment (30% or 60% RH) creating a moisture gradient through the slab depth. The minimum required longitudinal reinforced steel for shrinkage (ρ_s =0.0015, ACI 360 R) was used for all of the slabs. The slabs were fully restrained longitudinally by casting the test slabs around a transverse steel truss that is attached to the edges of the existing highly reinforced slab. This means the test slabs were restrained against any length change due to shrinkage and/or expansion. The steel trusses transfer all the loads to the two #8 rebar rebar embedded in the lab floor along each edge of the test area. Contraction joints were saw cut 1 inch deep with a diamond blade, 5 feet from each end to provide a 10 ft long central test section. The longitudinal reinforcement is continuous through the joints. Slab specimens were cured with wet burlap and a plastic sheet for 7 days. Extended curing only delays warping and curling; it does not reduce the warping and curling (Child and Kapernick, 1958). But it helps develop concrete strength and prevents early edge shrinkage.

The slabs using type K and shrinkage compensating cement were mixed at Fears Lab and delivered to the Advanced Concrete Research Laboratory in a Georgia Buggy. DOLESE Company provided concrete for rest of the slabs. During the evaluation, slab monitoring consisted of: visual observation of cracking, surface strain and joint expansion measurements using Demec surface strain gages, internal slab temperature and relative humidity, ambient temperature and RH, warping of the slab measured by Standard Testing Company. Additionally, fresh and hardened properties of the material were tested

4.3. Scope of the Work before Casting the Slabs:

1) Steel trusses were installed at both ends of the test area.
   - #7 reinforcing bar were welded into trusses for both ends of the test area. (Fig.4.1)
   - Drilled two holes at both sides of ends of the slab horizontally into the existing slab
   - 1”x3”x12” plates with two 13/16” holes at their mid height (Fig. 4.2)
   - Epoxy 3/4” A490 Bolts to fasten the end plate to the existing slab (Fig. 4.2)
   - Poured grout into the gap between the plate and the existing slab to provide total attachment of plate to the existing slab (Fig. 4.3)
   - Weld the truss at mid- height of the plates (Fig. 4.4)
2) Removed a small amount of existing soil from the base of the experimental slab to place 4 in. moist compacted sand (Fig. 4.5)
   - Removed existing Soil
   - Poured 4 in. sand in layers
   - Watered the sand to make it moist and compacted it.

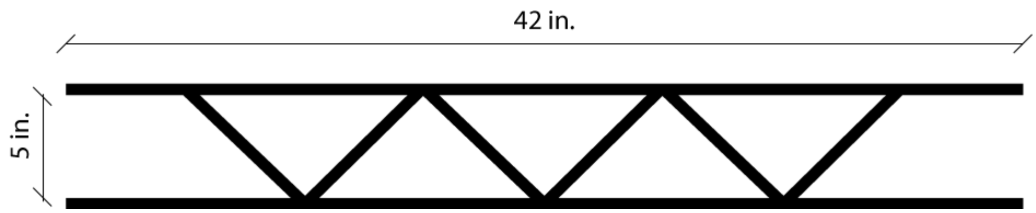

Figure 4.1: End Slab Truss Shape

Figure 4.2: End of Slab before Welding Truss to the End Plate

Figure 4.3: Using Grout between Plate and Existing Slab

Figure 4.4: Welded Truss at Mid- Height of the Plates

Figure 4.5: Watering Sand to help compact the sub-base

3) Installed 1in. thick foam around the slab, except at the ends of the slab. The foam was used as a form for the slab specimens and had a nominal 4” height (Fig. 4.6). Then the surface of the sand bed was leveled (Fig. 4.7).

4) The sand was sloped to make a 9 in. thickened section at the end of the slab to accommodate restraining the slab specimen without creating a stress riser at the steel trusses (Fig. 4.8).

5) To provide the form for the end of the slab, 1 in. thick foam was cut, placed at the end, and taped over the holes around the truss (Fig. 4.8 and 4.9).

Figure 4.6: Four inches Moist Compacted Sand

Figure 4.7: Compacting Sand

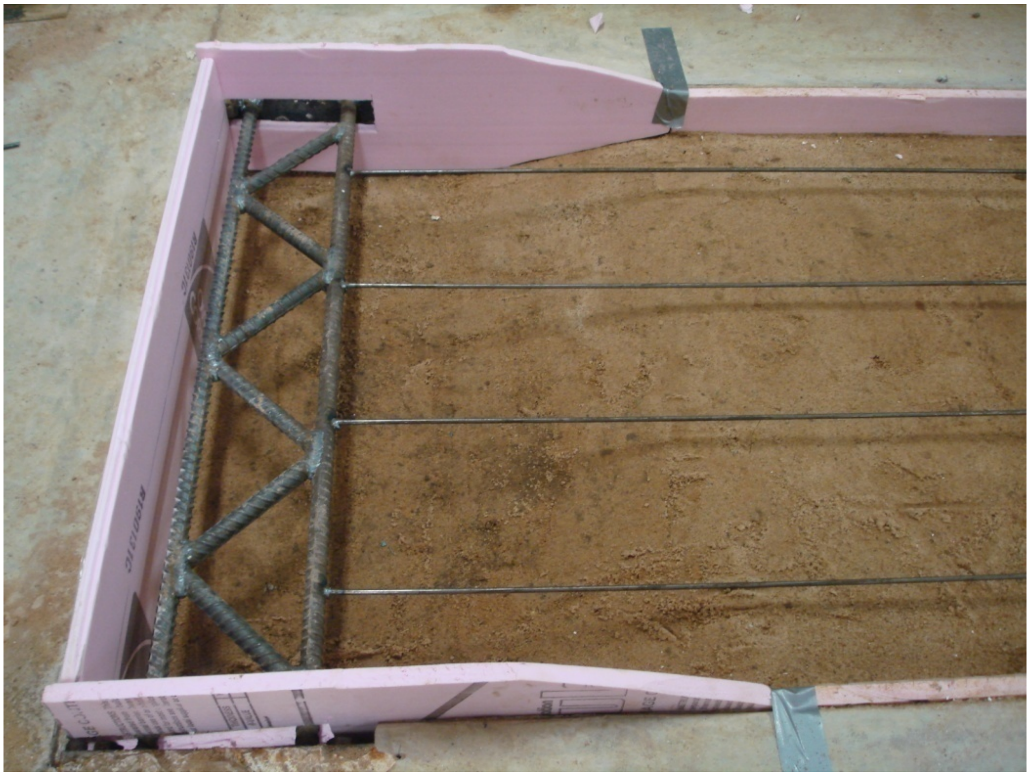

Figure 4.8: Nine inches End Foam

Figure 4.9: Finished End Truss

6) Welded (4) 1/4” diameter @ 9 in. o.c. longitudinal rebar to the ends’ trusses. The bars are located at the mid-height of the 3 inches slab (Fig. 4.10). (Note: The bars continue across the expansion joint locations.)
7) Placed chairs below the rebar to keep reinforcements at the required elevation (Fig. 4.10). The chairs were placed on aluminum sheet metal to hold the chairs at the required elevation and to prevent the chairs from sinking into the sand.
8) Wood forms were placed at the ends of the slabs to provide support to the foam sheeting above the surface of the walk way (Fig. 4.11).
9) At this point the slab were ready to be cast (Fig. 4.11).

Figure 4.10: Longitudinal Reinforcement

Figure 4.11: Slab is ready to be cast

4.4. Scope of the Work: Casting and After Casting the Slab:

A 24 cu foot mixer located at Fears Lab was used for batching the type K and CSA mixes. Concrete was delivered to the testing site with a Georgia Buggy (Fig. 4.12). Portland cement based concrete mixes were delivered by DOLESE Company (Fig. 4.13). After the concrete was cast (Fig. 4.14), a commercial crew finished the concrete surface (Fig. 4.15, 4.16 and 4.17). Test cylinders and prisms were cast for each batch following ASTM standard test methods. Following the casting process the scope of the work consisted of:

1. Curing the slab with wet burlap and a plastic sheet for 7 days (Fig. 4.18 and 4.19)

Figure 4.12: Mixer and Georgia Buggy

Figure 4.13: Delivering Portland cement based Concrete by the DOLESE Company

Figure 4.14: Casting Slab

Figure 4.15: Finishing Concrete Surface (End of the Slab)

Figure 4.16: Finishing Concrete

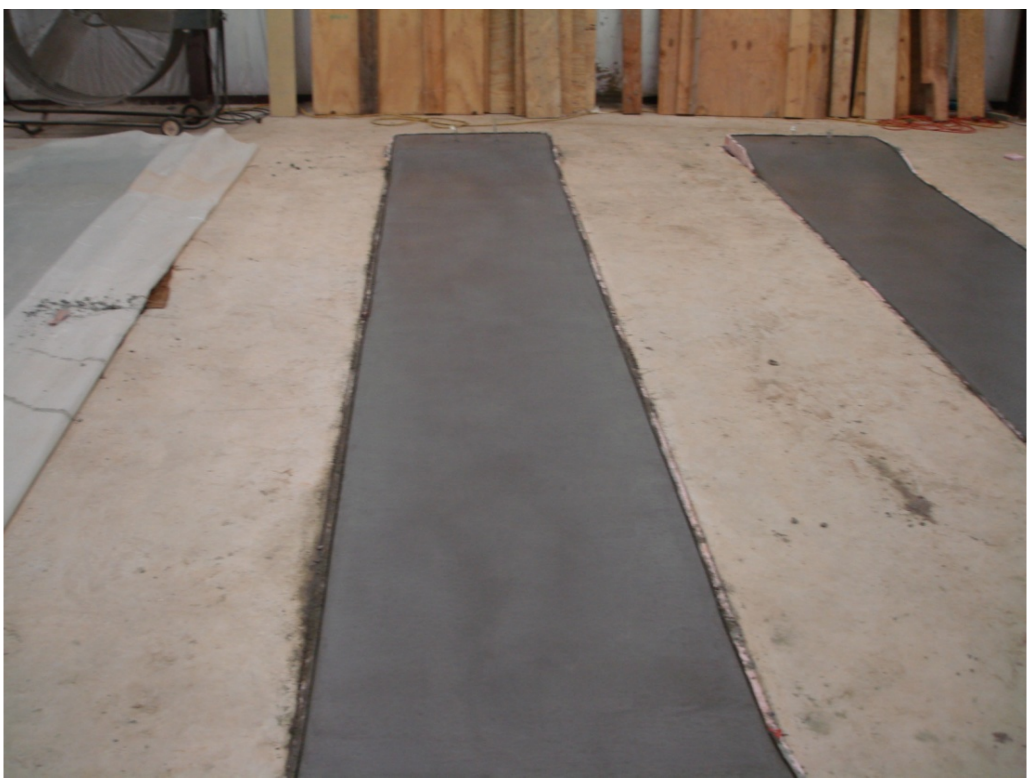

Figure 4.17: Concrete Slab Cast and Ready for Curing

Figure 4.18: Moist Curing of Slabs

Figure 4.19: Curing Concrete with Wet Burlap Covered by Plastic Sheet

2. Provided contraction joints by diamond saw cut method (Fig. 4.20).
   - Joint depths are 1 in.
   - Joints were located at 5 ft from each end, the west and east sides, to provide a 10 ft long central test section between the joints (Fig. 4.21).
3. Attached Demec targets above the rebar locations at joints and mid span using epoxy. Figures 4.22 through 4.24 show the device used for strain measurements while Fig.4.25 through 4.29 show the steps required to epoxy the Demec targets, fix the location of the targets with the comparator, and monitoring Demec surface strain gage.
4. Weekly slab monitoring began after 7 of days curing. The one exception was for CSA cement Rapid Set slabs. Monitoring started on the second day for the slabs using Rapid Set since this material cures in only 4-5 hours. The following procedures were followed:
   - Regular visual inspections searching for surface cracking
   - Surface strain and joint opening measurements using Demec target strain gauges with a 7 in. gauge length (Fig. 4.28 and 4.29).

Figure 4.20: One inch Depth Joint Using Saw Cut

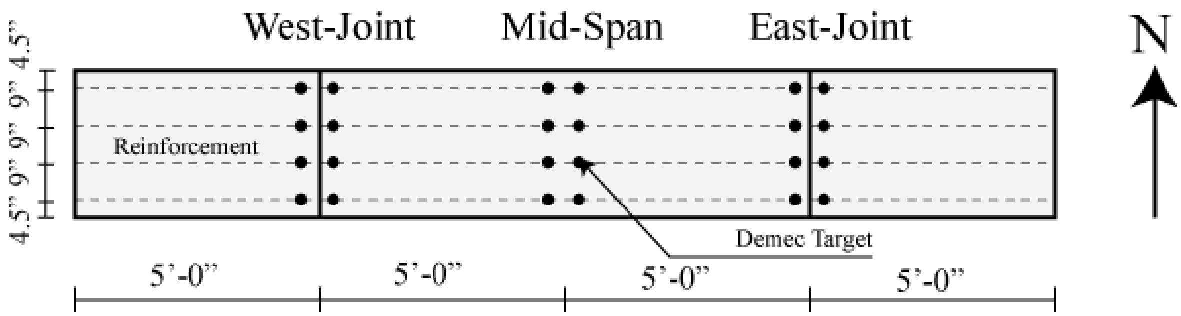

Figure 4.21: Demec Target Placed at Top of Reinforcements' Locations (Top View)

Figure 4.22: Demec Comparator

Figure 4.23: Demec Strain Gage

Figure 4.24: Device Using for Crack Measurements

Figure 4.25: Demec Target Located at Saw Cut Contraction Joint

Figure 4.26: Fixing Demec Targets at Required Location

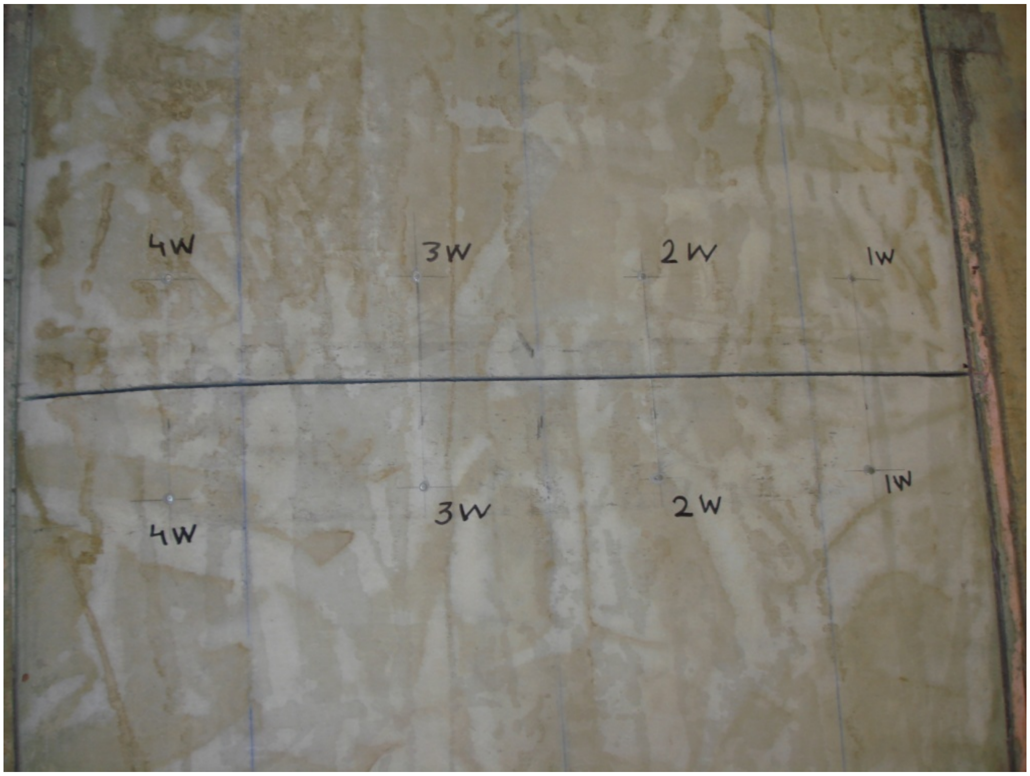

Figure 4.27: Demec Target at Joint Opening

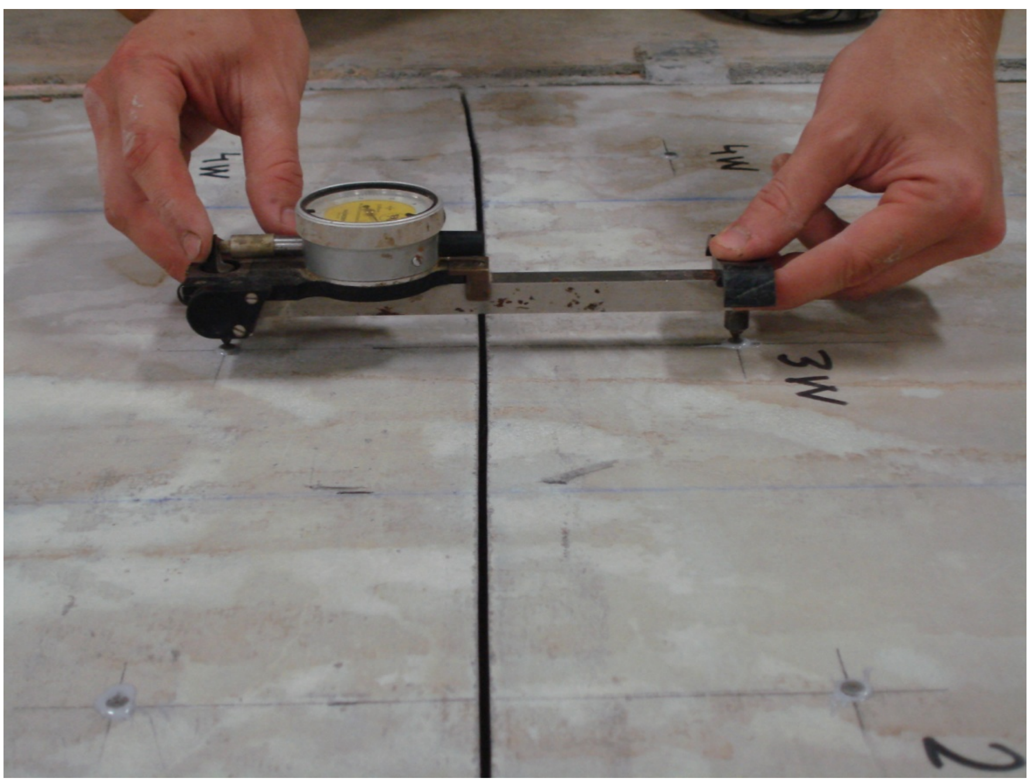

Figure 4.28: Monitoring Slab Shrinkage or Expansion with Demec Strain Gage

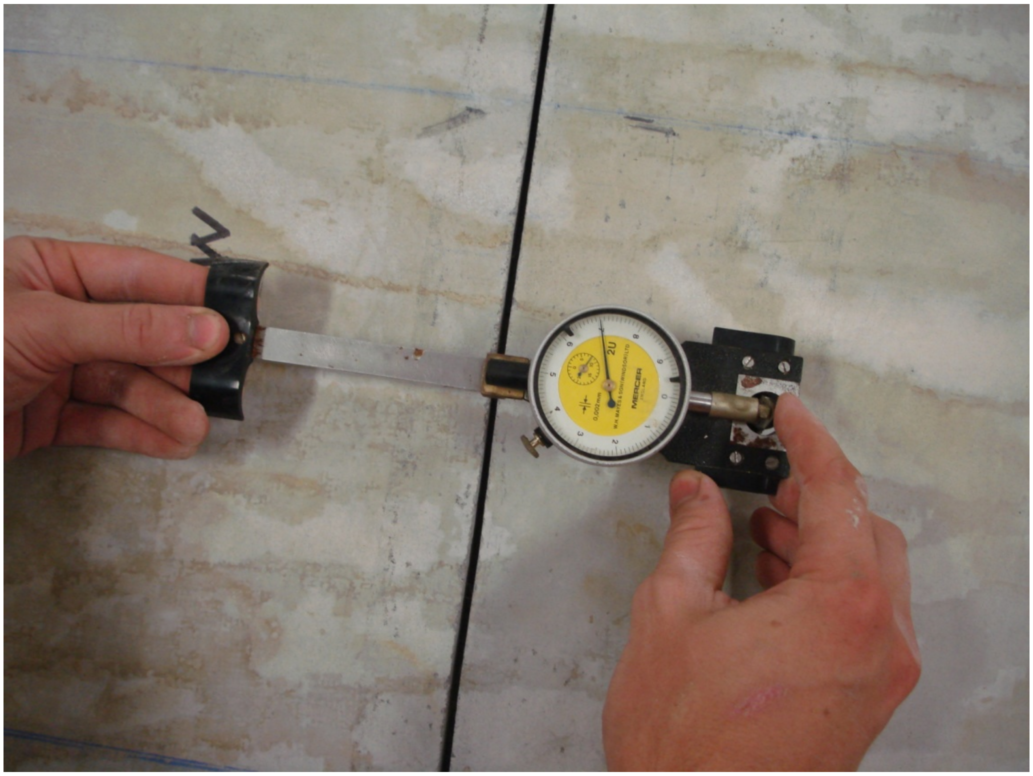

Figure 4.29: Demec Strain Gage

- Determination of the warping profiles was measured by the Standard Testing Company. Vertical elevation changes between two points 12 inches apart were measured (Fig. 4.30 and 4.31). Fig. 32 shows the use of a manual dipstick device used as an additional resource for measuring warping of the slab.
- 4 in. x 8 in. cylinders were tested for compressive strength per ASTM C39 (Fig. 4.33 and 4.34).
- Length change tests measurements (3”x3”x10”) (ASTM C157) Fig 4.35 - 4.37.
- Restrained expansion tests measurements (ASTM C878) Fig. 4.35 through 4.37.
- Internal relative humidity (ASTM F 2170) at 1/2 in. increments through the depth of the slab.
- Internal temperature at 1/2 in. increments through depth of the slab.
- Ambient relative humidity.
- Ambient temperature.

Figure 4.30: Standard Testing Dipstick Machine

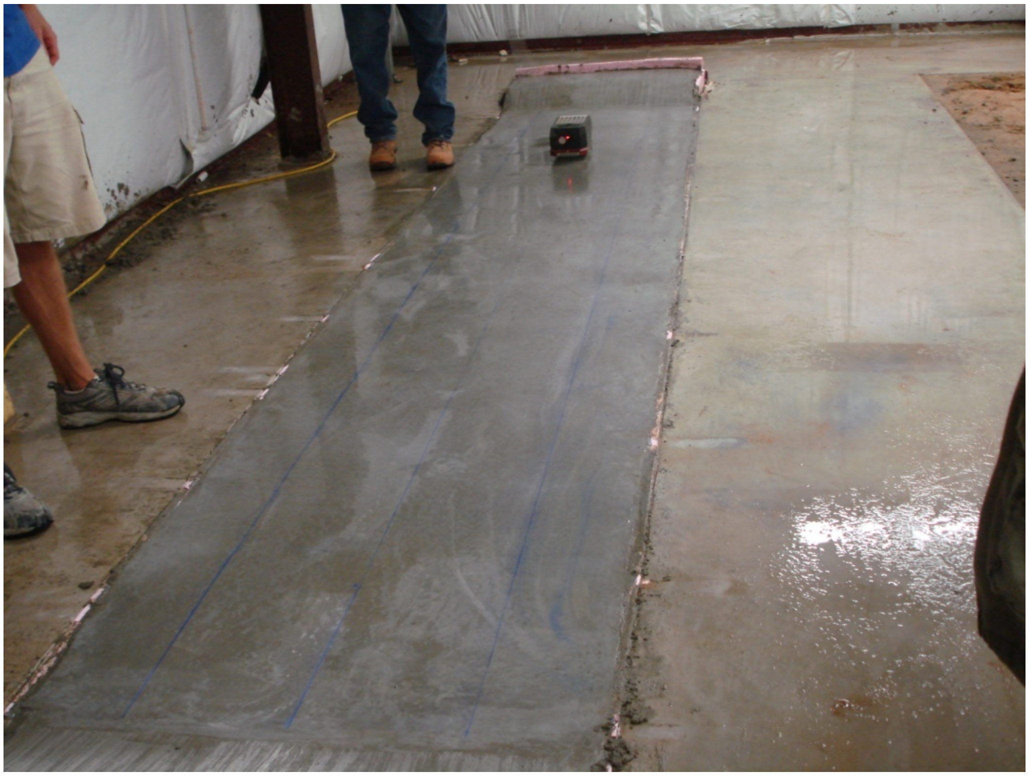

Figure 4.31: Running Dipstick Machine

Figure 4.32: Manual Dipstick Device, Measuring Vertical Elevation

Figure 4.33: Forney Machine Used for Compression Strength Test

Figure 4.34: Cylinder Specimen Located in Forney Machine Ready for Test

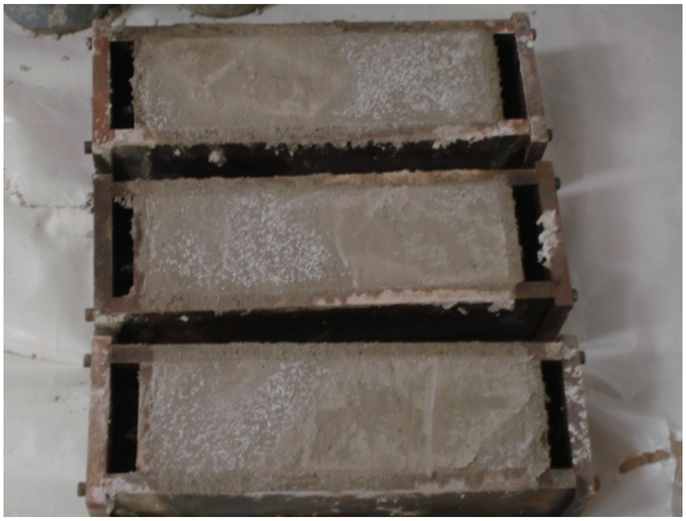

Figure 4.35: Prism Test Specimens

Figure 4.36: Apparatus Used for Measurement of Length Changes

Figure 4.37: Measuring Prism Length Change

5. The one inch foam used as forms for the concrete slab were removed after one week. Then, two layers of 1 in. flexible Backer Rod was placed in the gap left by the foam around the slab specimens. The backer rod was used to eliminate the moisture difference between top and bottom of the slab and to prevent transferring moisture between the to and bottom surface of the slabs along the edge of the slab (Fig.4.38 through 4.40).
6. Five holes were drilled, close to Mid-Span, to install the Relative Humidity (RH) meter device. These meters measure interior temperature and relative humidity at 1/2 in. increments through the depth of the slab (Fig. 4.41). Holes were drilled at a depth of 2.5", 2", 1.5", 1", and 0.5" inches measured from the top of the slab.

Figures 4.42 through 4.43 show the device used for measuring temperature and moisture of the interior slab. Figure 4.44 shows thermometer for monitoring ambient temperature and relative humidity.

Figure 4.45 shows the de-humidifier used to reduce the ambient relative humidity. Figure 4.46 and 4.47 shows interior views of the controlled environment of the Advanced Concrete Research Laboratory. These figures show the seven slab specimens located on ground. Figure 4.48 shows the cylinder and prism test specimens located in the lab. Figure 4.49 is a larger view of the prism specimens, and Figure 4.50 shows a larger view of the cylinder specimens in the lab. Figure 4.51 shows a cross section profile of slab deformation due to warping. It identifies the end restrain region, showing it to be three times thicker at 3 inches than the primary slab and shows the saw cuts five feet from each end creating a ten foot long center span. The slab is resting on a four inch sand base and Oklahoma red clay base.

Figure 4.38: Backer Rod Placed at Two Elevations in the Gap at the Edge of the Slab

Figure 4.39: Placing Backer Rod in the Gap at the Slab Edge

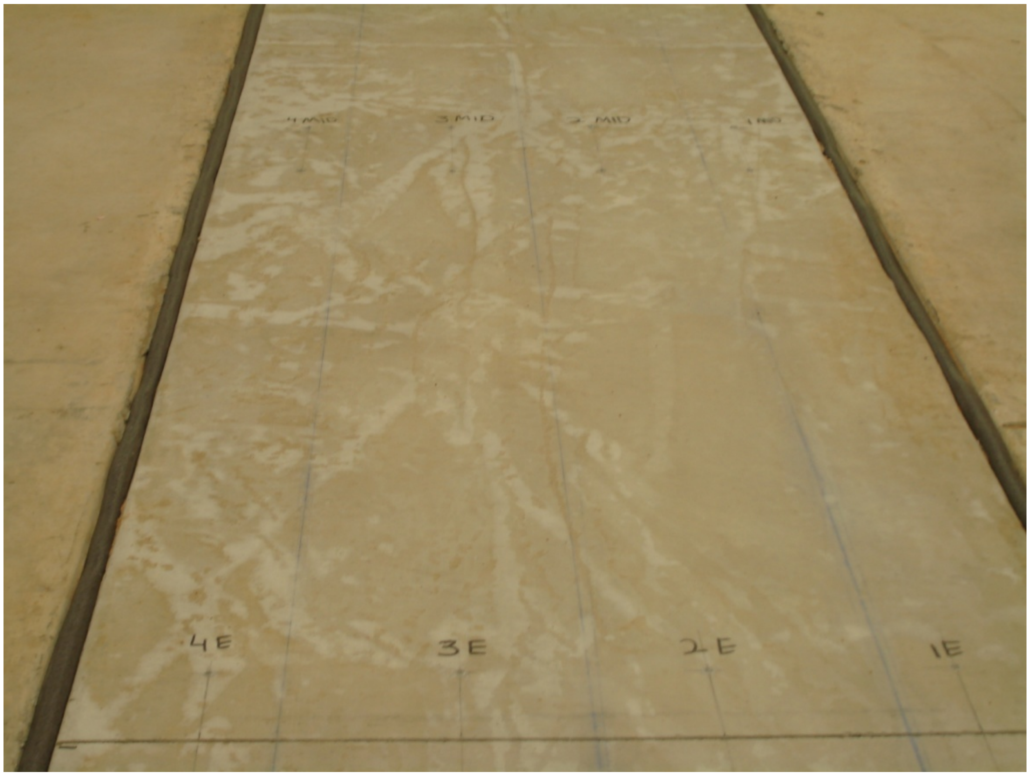

Figure 4.40: One Inch Backer Rod Placed at Two Elevations

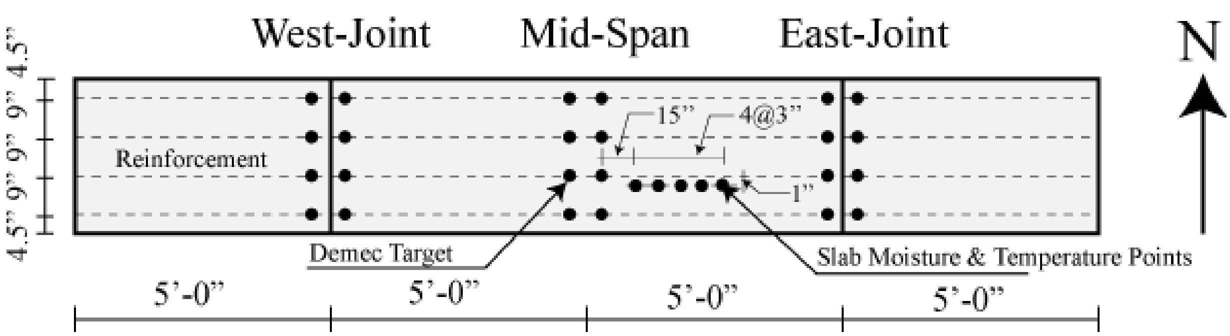

Figure 4.41: Holes at 1/2 in. Increments through the Depth of the Slab Located Close to the Mid-Span of the Slab

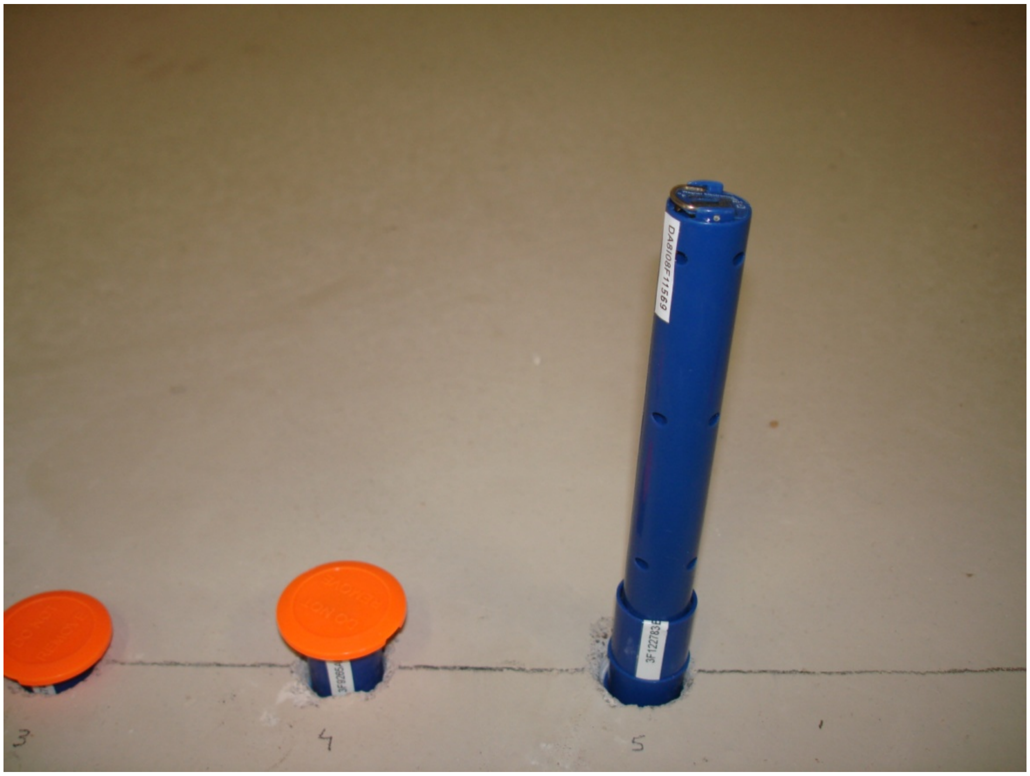

Figure 4.42: RH meter for Measuring Temperature and Moisture of the Slab

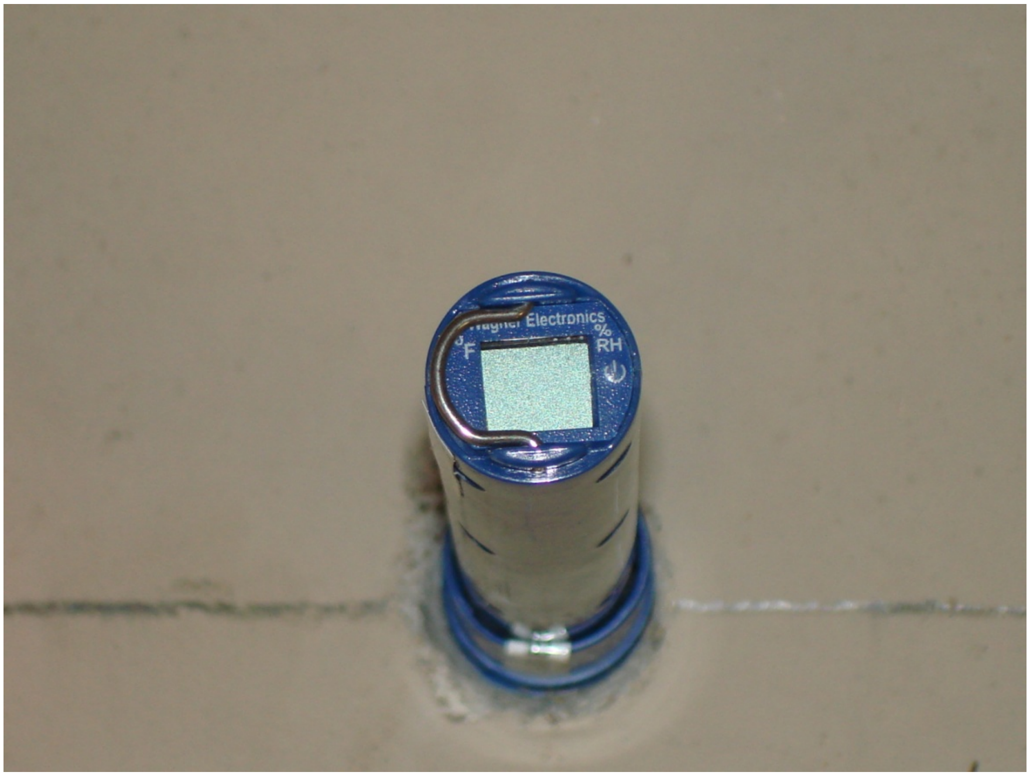

Figure 4.43: Meter for Measuring Interior Slab Temperature and Relative Humidity

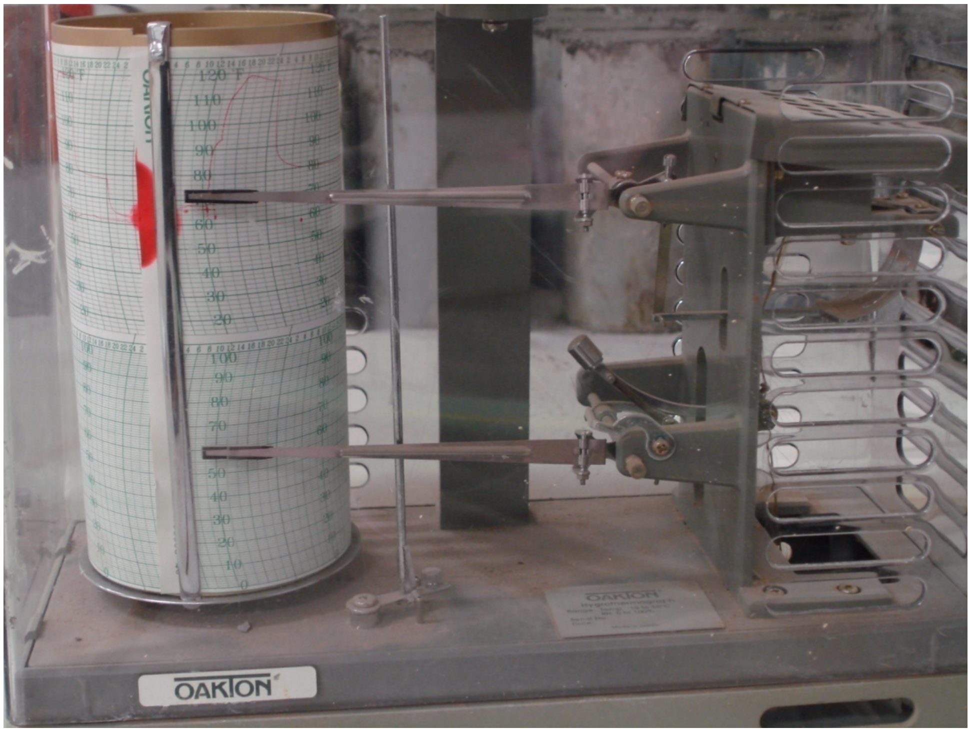

Figure 4.44: Monitoring Ambient Temperature and Relative Humidity

Figure 4.45: De-Humidifier

Figure 4.46: Seven Slab Specimens Located on Ground in Testing Facility (South View)

Figure 4.47: Interior North View of the Lab Facility

Figure 4.48: Test Specimens in Controlled Environment Lab

Figure 4.49: Prism Test Specimens

Figure 4.50: Cylinder Test Specimens

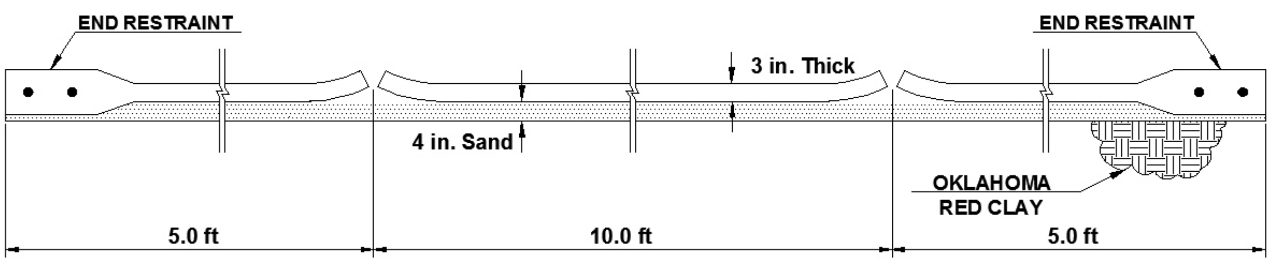

Figure 4.51: Profile of Slab Deformation Due to Warping

5. Presentation of the Results

The experimental program includes measurements of the linear shrinkage of prism specimens made with Portland cement based on ASTM C157, measuring linear expansion of prism specimens made with shrinkage compensating cement (CSA) and Rapid Set cement (RSCC) based on ASTM C878, and concrete compression strengths of cylinder specimens based on ASTM C39 standard test methods. Additionally the fresh properties of the concrete were measured.

Testing of the slabs on grade included monitoring the slab specimens which consisted of: visual observation of cracking, surface strain and joint opening measurement using Demec surface strain gages, internal slab temperature and relative humidity, ambient temperature and relative humidity, and determination of warping profiles as measured by the Standard Testing Company.

Table 5.1 presents concrete the mixes used for the large scale slabs-on-grade tests. Table 5.2 and Figure 5.1 illustrate the one year average compressive strength test results for the slab specimens. As expected, the compression test results show that Rapid Set concrete gains its strength in the first hours. Rapid Set concrete reached 3,500 psi in 7 hours, and 5,550 psi in one day.

Table 5.1: Concrete Mix

Materials	SRA#1	SRA#2	PCC	HPC	CTS Shrinkage Compensating	Rapid Set
Komp I	-	-	-	-	120	-
P C	356.3	355	355	547	370	-
Flyash	87.5	87.5	87.5	182	-	-
Rapid Set Cement	-	-	-	-	-	658
itric Acid	-	-	-	-	-	5
Course Aggregate	1850	1850	1850	1850	1750	1772
Sand	1525	1530	1505	1188	1315	1307
Water	209.5	197.8	207.3	218.8	271.5	290
MR (Polyheed (oz))	13	14	14	29	17.47	1555 (mL)
Eqlipse (oz)	35.93	-	-	-	-	-
Tetraguard (oz)	-	36.06	-	-	-	-
W/C	0.50	0.43	0.47	0.3	0.55	0.44

Table 5.2: Compression Strength (psi)

Time (Days)	SRA #1	SRA #2	PCC	HPC	Shrinkage Comp. (CSA)	Rapid set
6 Hours	-	-	-	-	-	2750
7 Hours	-	-	-	-	-	3400
1	650	650	750	1650	1900	5550
3	1800	1900	1900	3850	3125	6600
7	2700	2750	2800	5100	4425	7500
14	-	-	-	-	5650	8850
28	3800	3450	3150	5250	5800	10000
60	-	-	-	-	-	10350
90	3550	3750	3400	5750	6650	10750
365	3450	3800	3000	4900	6800	10700

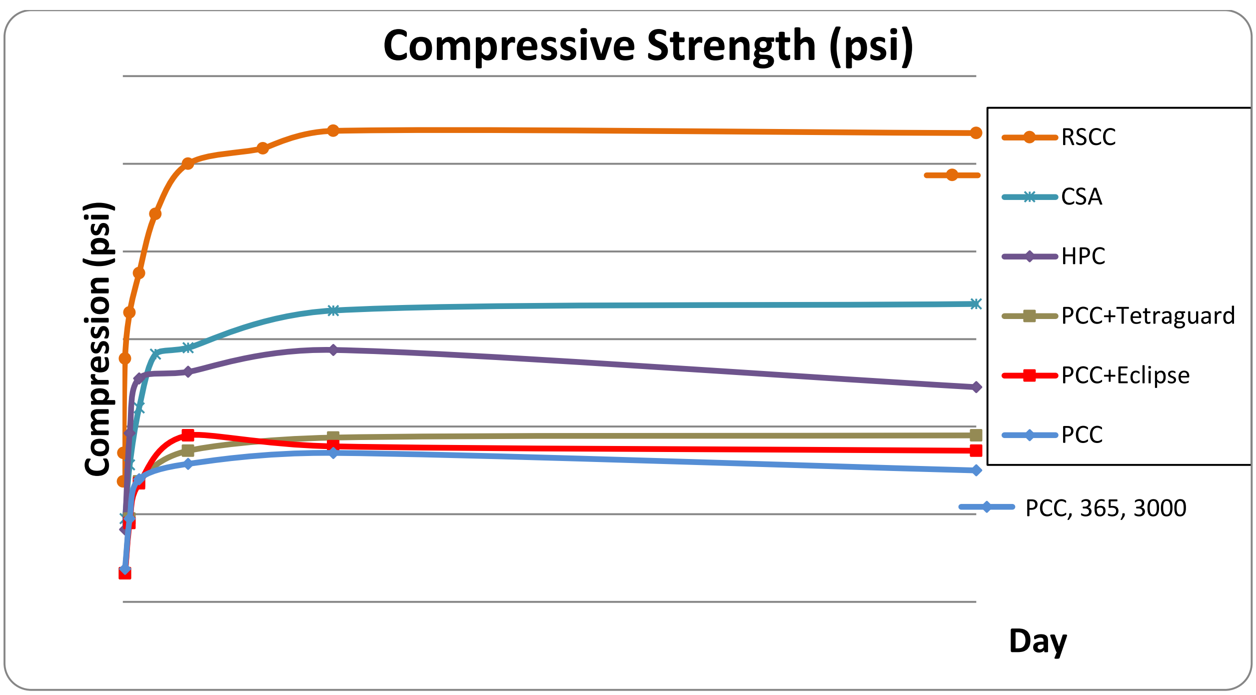

Figure 5.1: Average Compression Strength vs. Time for all of the Slabs

5.1 Length Changes of Prism Test Specimens

These tests are based on ASTM C 157 and C 878 test methods. The prism specimens sizes were 3 x 3 x 12 in. ASTM C 157 is a standard test method for unrestrained length change of hardened hydraulic-cement mortar and concrete and ASTM C 878 is a standard test method for restrained expansion of shrinkage compensating concrete. Upon wet curing the specimens for 7 days, the initial measurement was taken.

Figure 5.2 shows general strain test results (ASTM C 157) for the slab using Portland cement concrete. Figure 5.3 presents general strain test results (ASTM C 878) for the slab using shrinkage compensating cement concrete. Expansion is represented as positive number and shrinkage is as negative number in these graphs.

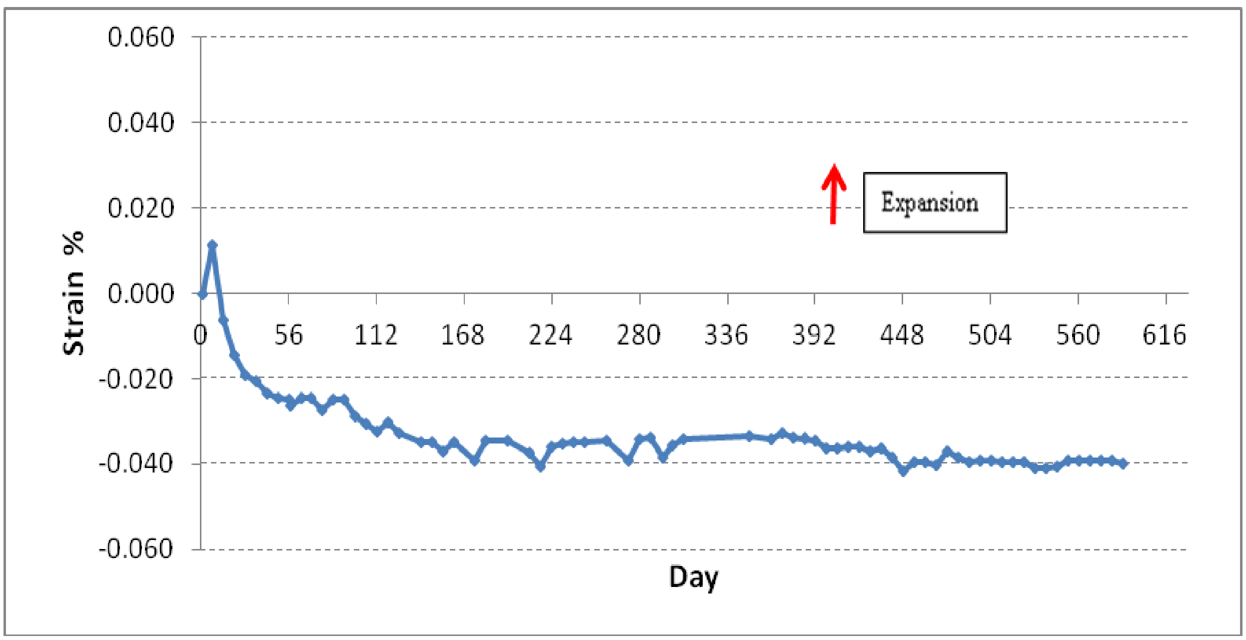

Figure 5.2: Unrestrained Expansions (ASTM C 157) vs. Time for PCC

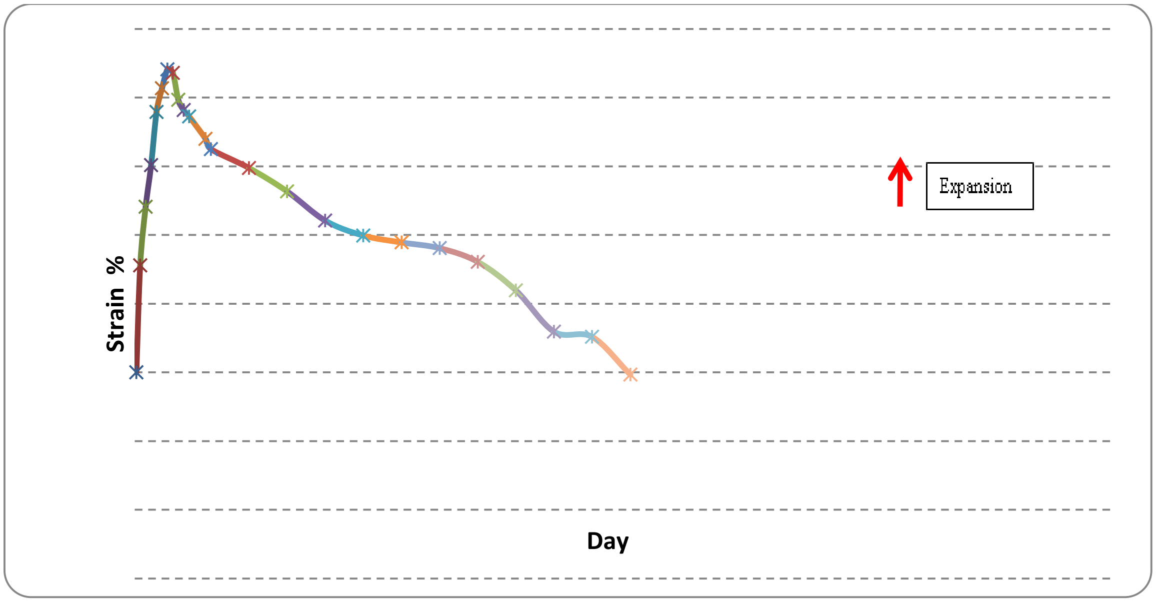

Figure 5.3: Restrained Expansions (ASTM C 878) vs. Time for type K shrinkage compensating concrete

Figure 5.4 shows C 157 test results for PCC verses PCC with Eclipse (SRA). It can be seen that the shrinkage reducing admixture (SRA) has minimal impact on shrinkage at short term, and almost No impact at long term. The early expansion is due to the wet curing. We can concluded that using shrinkage reducing admixture does not have a noticeable improvement on reducing shrinkage.

Figure 5.5 shows C 157 test results for PCC verses HPC. It shows that HPC shrinkage is greater than PCC.

Figure 5.6 shows ASTM C 157 and C 878 for all the slab mixes. It appears that HPC has the greatest shrinkage at both short and long terms, and type K shrinkage compensating cement concrete (CSA) has the largest expansion (about four times larger than the other mixes expansion) during the first few days of curing. It can be expected that the large expansion of CSA is able to offset the restrained shrinkage caused by drying shrinkage of concrete at the long term. [Note: ASTM C 878 method provides data only for expansion of CSA. Therefore, additional tests are provided later in this report that include both expansion and shrinkage by using the shrinkage from time zero test].

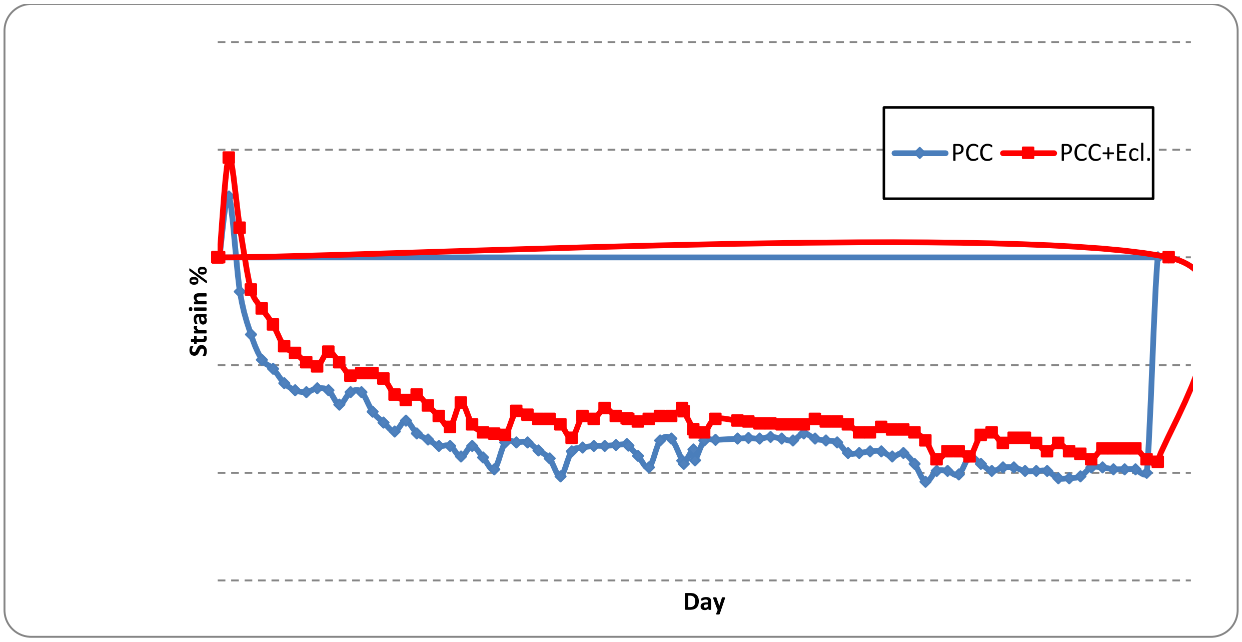

Figure 5.4: Unrestrained Expansions (ASTM C 157) vs. Time for PCC and PCC + Eclipse (SRA)

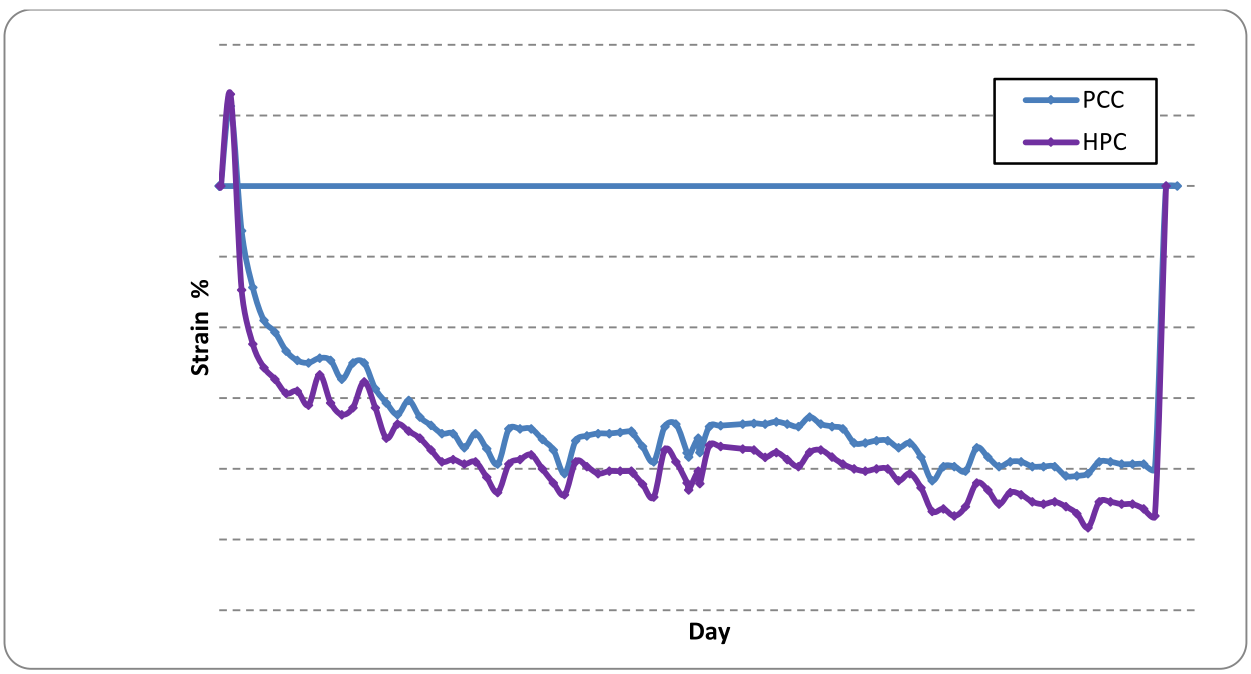

Figure 5.5: Unrestrained Expansions (ASTM C 157) vs. Time for PCC and HPC

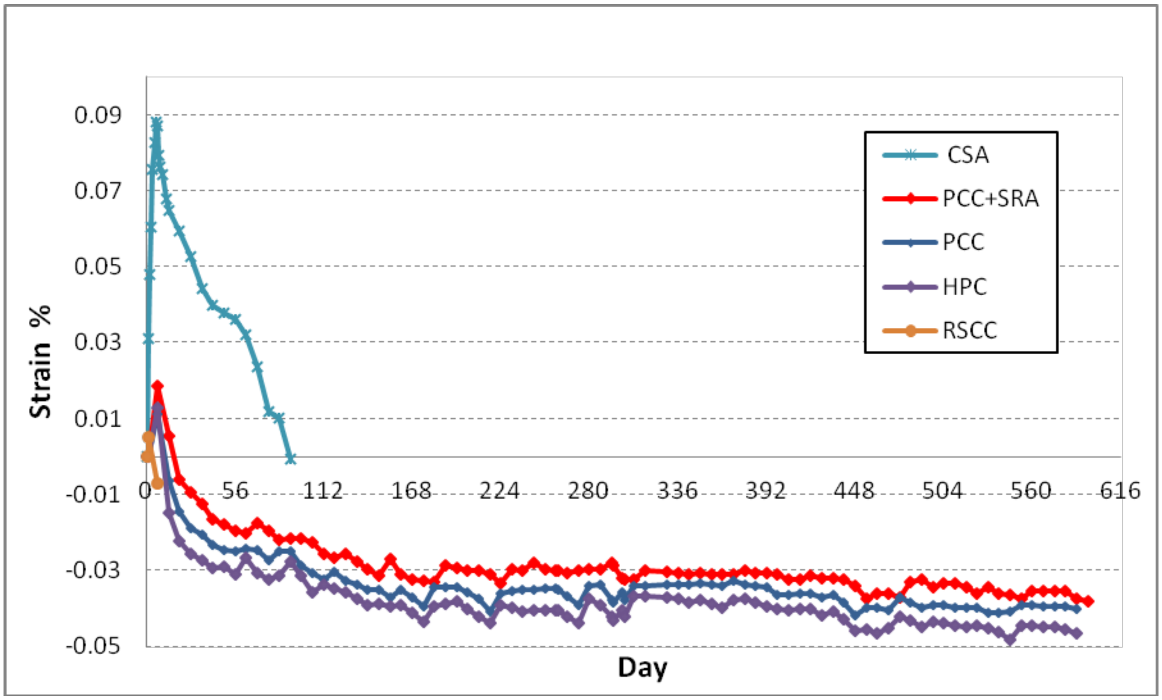

Figure 5.6: Restrained (ASTM C 878) and Unrestrained (ASTM C 157) Expansions vs. Time for all slab test specimens

5.2 Joint Openings and Surface Strain Measurements

As previously mentioned (in chapter 3), demec targets were installed on the slab across each joint to monitor their movement in the longitudinal direction. Each slab has two control joints located 5 ft. from the ends to provide a 10 ft. central length test. Four pairs of targets spaced as previously shown in Figure 3.39 to measure surface strain across the joint or crack at longitudinal direction. Demec target were also installed with the same configuration at mid-length of the slabs to monitor surface strains with no crack at longitudinal direction. This way width of joint opening or crack can be calculated by subtracting the behavior of the material at mid-span from the behavior at the joints.

The averages of four targets located at the control joints and at mid-span are calculated respectively. Each division of the demec gage is multiplied by 0.81×10^{-5} to obtain strain (based on the demec gage directions). The surface strains were measured from the point of initial set and continued for 600 days at the request of the matching sponsor, CTS. Figures 5.7 and 5.8 illustrates the expansion at a joint opening. Figures 5.9 and 5.10 present the strain of the control joints and mid-span of the slabs using PCC and using CSA respectively.

Note: Expansions are shown as positive numbers and shrinkages as negative numbers. Comparing the expansion of the control joints and shrinkage at mid-span from Figures 5.9 and 5.10, it can be seen that joint opening expansion and slab shrinkage at mid span made with PCC are much greater than the slab specimens made with CSA.

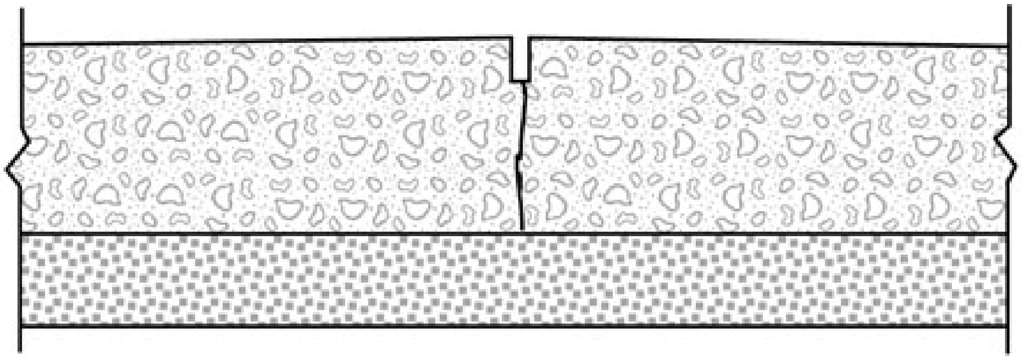

Figure 5.7: Schematic side view at joint opening

Figure 5.8: Top View of joint expansion or crack at large scale slab specimen

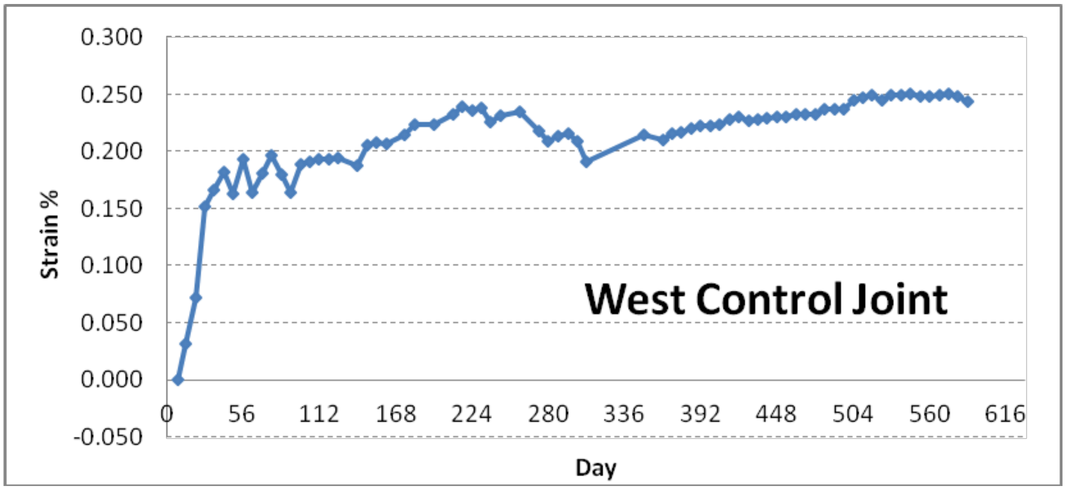

Figure 5.9a: Demec Expansion vs. Time for slabs using PCC – West Control Joint

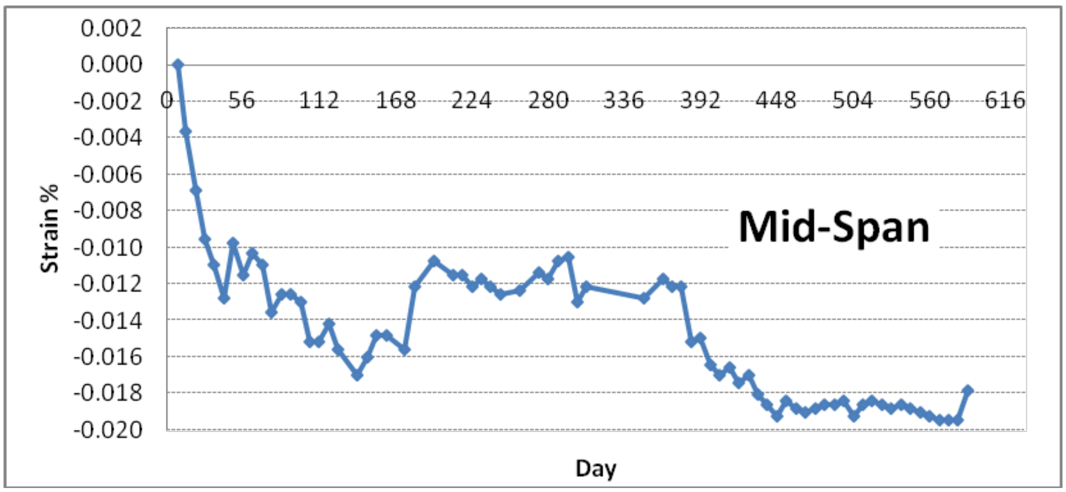

Figure 5.9b: Demec Expansion vs. Time for slabs using PCC – Mid-Span Control Joint

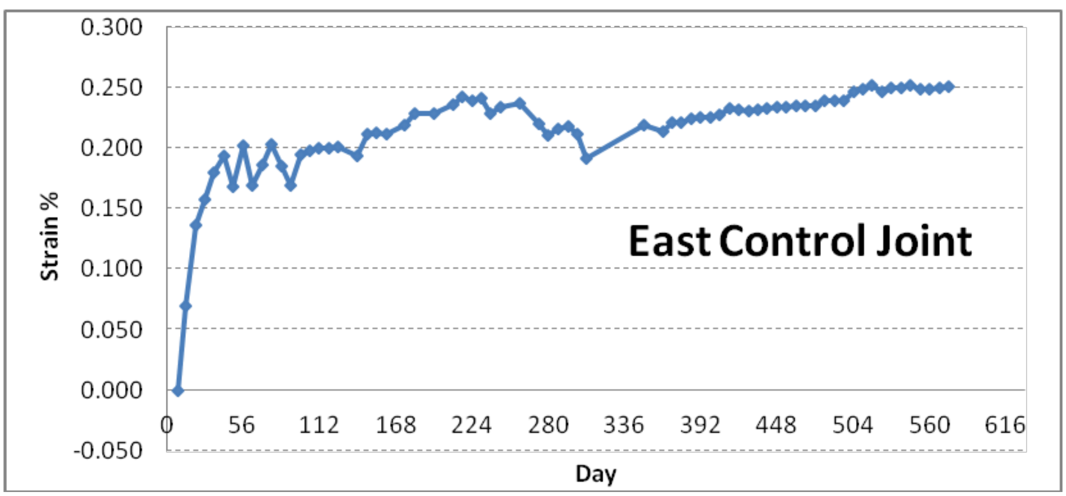

Figure 5.9c: Demec Expansion vs. Time for slabs using PCC – East Control Joint

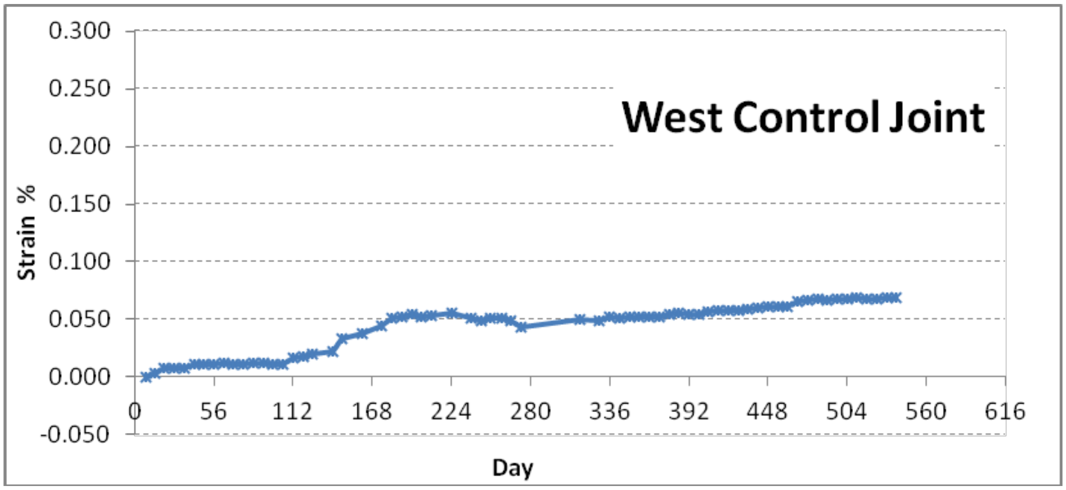

Figure 5.10a: Demec Expansion vs. Time at West Control Joint for slabs using type K concrete

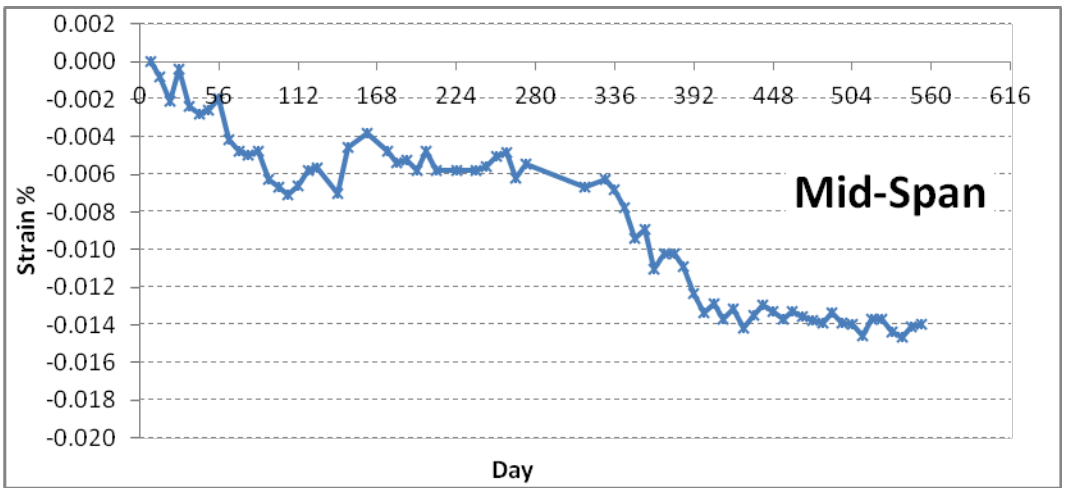

Figure 5.10b: Demec Expansion vs. Time at Mid-Span for slabs using type K concrete

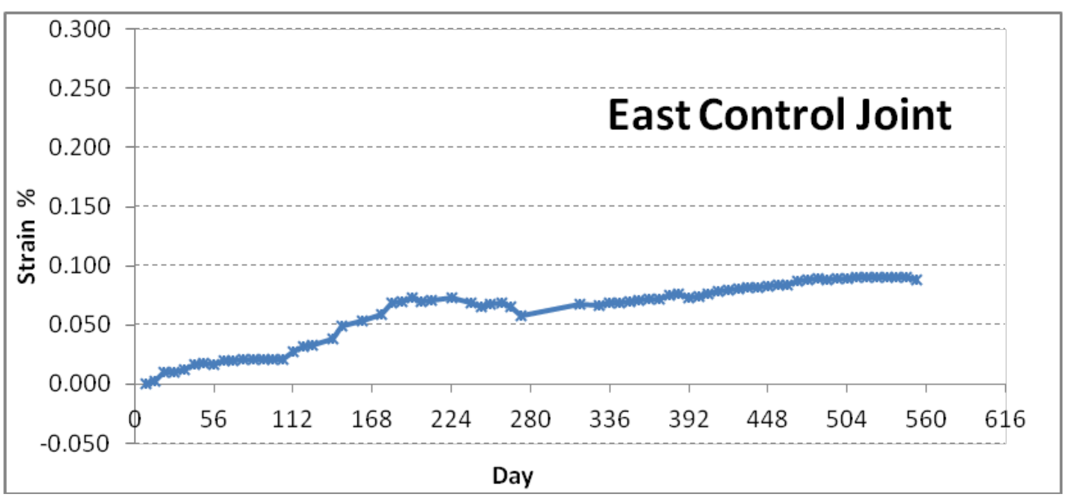

Figure 5.10c: Demec Expansion vs. Time at East Control Joint for slabs using type K concrete

5.3 Width of Joint Opening at Control Joint

Calculation of Width of Joint Openings

Expansion of joint opening (Δε) is calculated based on strain at joint (A) and strain at mid-span or center line (C) during the time (Figure 5.11).

$\Delta\varepsilon = A - C$

Joint Opening (Crack) = A − C

$A = \varepsilon_{sh-crack} = \frac{\Delta L_1}{L} + Crack$

Strain of shrinkage with no crack + crack (Strain at control joint)

$C = \varepsilon_{sh-no,crack} = \frac{\Delta L_1}{L}$

Strain of shrinkage with no crack * at center line (Strain at mid-span)

$\Delta\varepsilon = A - C = \frac{\Delta L_1}{L} + Crack - \frac{\Delta L_1}{L} = Crack$

This results from substituting A & C into the first equation

* These measurements are not equal to ASTM C 157 and C 878 because the bottom of slab is exposed to the moisture in the soil and the top of slab is exposed to the low relative humidity of controlled environment while for ASTM C 157 and C 878 all sides of the specimens are exposed to the environment relative humidity.

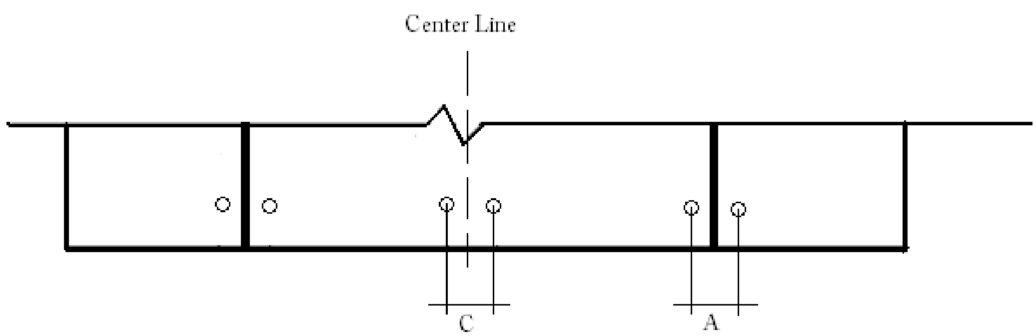

Figure 5.11: Joint opening and mid-span

Figures 5.12 and 5.13 present a general strain/expansion at both control joints (West and East sides) for PCC. As expected, both control joints of each slab show nearly the same expansion width. Comparing joint opening for different concrete mixes is discussed in the next chapter. [Note: The average of west and east joint opening strains are averaged in the test results].

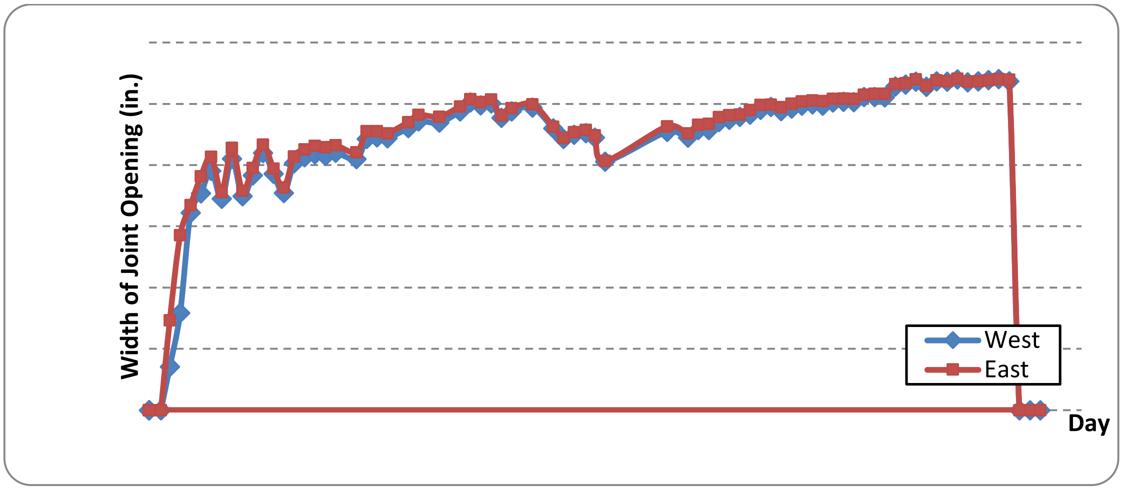

Figure 5.12: Width of Joint Opening vs. Time for slabs using PCC

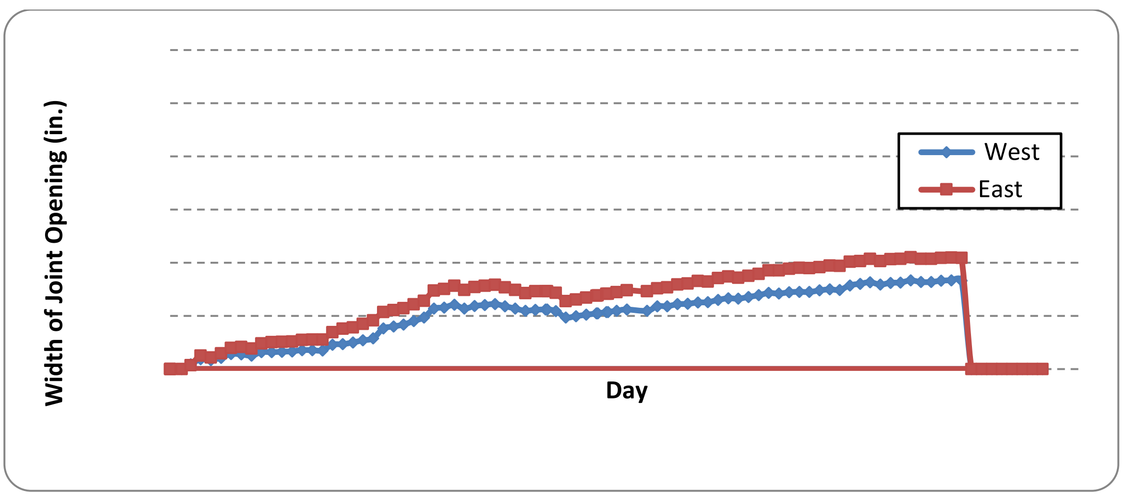

Figure 5.13: Width of Joint Opening vs. Time for type K, Shrinkage Compensating concrete

Figures 5.14 represents the average strain at the control joints for the normal concrete (PCC) versus PCC+SRA, while Figure 5.15 show the expansion or width of joint opening for (PCC) verses normal concrete using shrinkage reducing admixture (PCC+SRA). It can be seen that using SRA only reduces shrinkage in the first week. The slope of the rest of the curve are the same for normal concrete and concrete using SRA. The curves are only shifted (both curves are parallel with an offset approximately equal to the initial reduction of shrinkage provided by the SRA). Figure 5.16 represents the behavior of the material in the slab with no crack at mid-span. It can be seen that there is a minor impact on reducing shrinkage with a SRA at short term and almost no impact at long term when compared to PCC. So while the SRA delays the shrinkage for the first few days, shrinkage occurs and the concrete cracks as shown in Figures 5.14, 5.15, and 5.16. Essentially using a SRA will help prevent cracks for the first few days but after that the only difference with PCC is the width of the crack. It should also be noted that at 600 days these slabs are still shrinking. The data trend still has a positive slope.

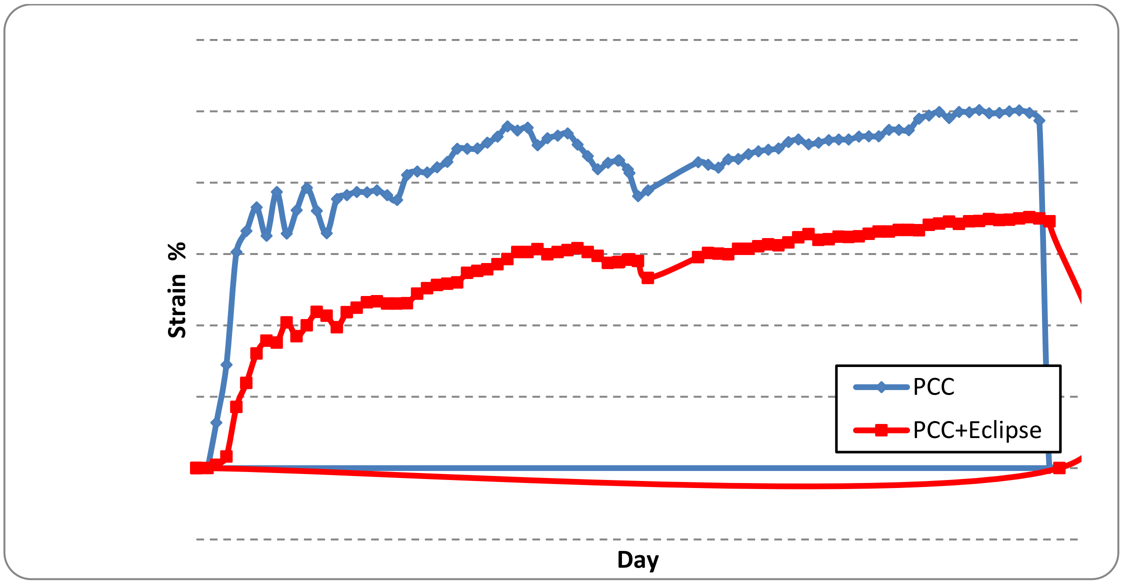

Figure 5.14: Strain at Joint Opening vs. Time for PCC and PCC+ Eclipse

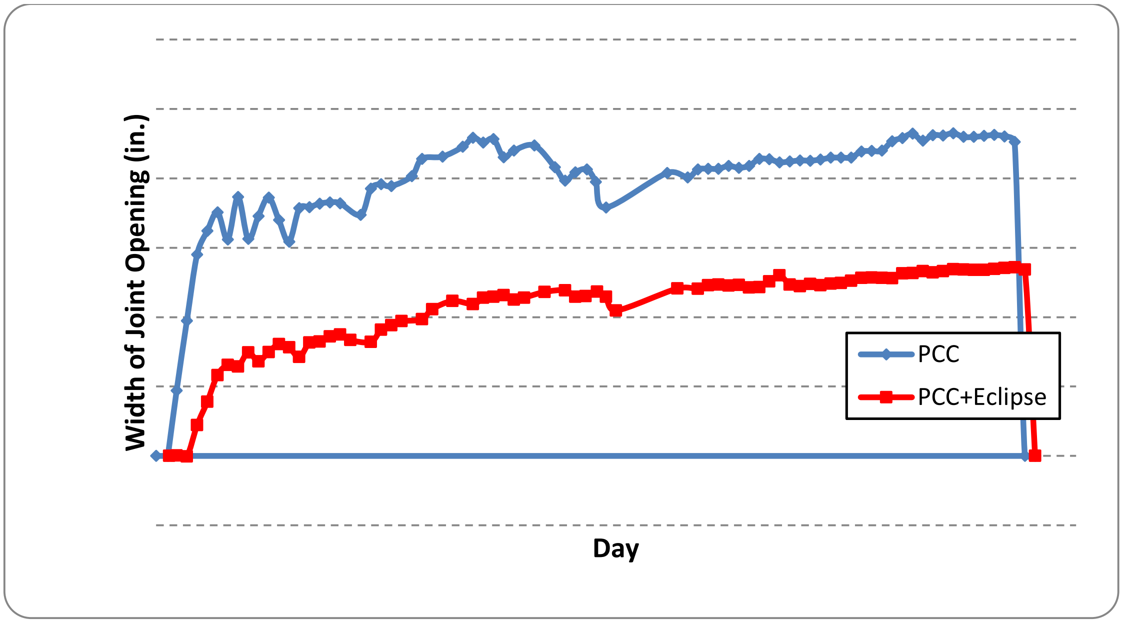

Figure 5.15: Width of Joint Opening vs. Time for PCC and PCC+ Eclipse

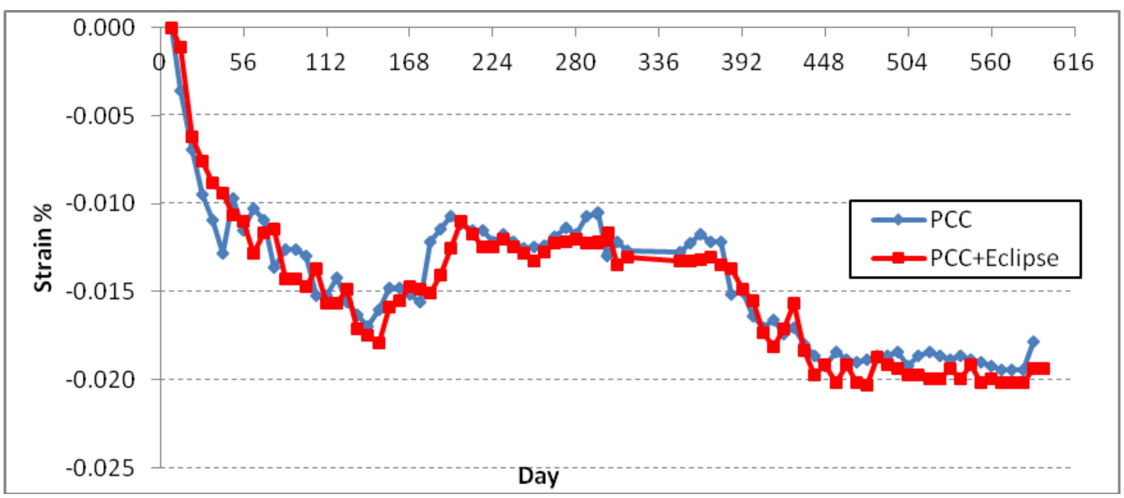

Figure 5.16: Strain at Mid-Span vs. Time for slabs using PCC and slabs using PCC+ Eclipse

Figure 5.17 presents expansion of the joints (calculated by taking the average of west and east joint openings) for all of the slabs. The results show that the slab with HPC has the largest expansion or crack at the joints and the slab with CSA (type K shrinkage compensating concrete) has the smallest expansion or crack at the joints. Also, it can be seen that joint opening expansion continues for long term (600 days) with slab constructed using Portland cement based concrete. Comparing HPC and PCC shows that HPC cracks are wider than PCC.

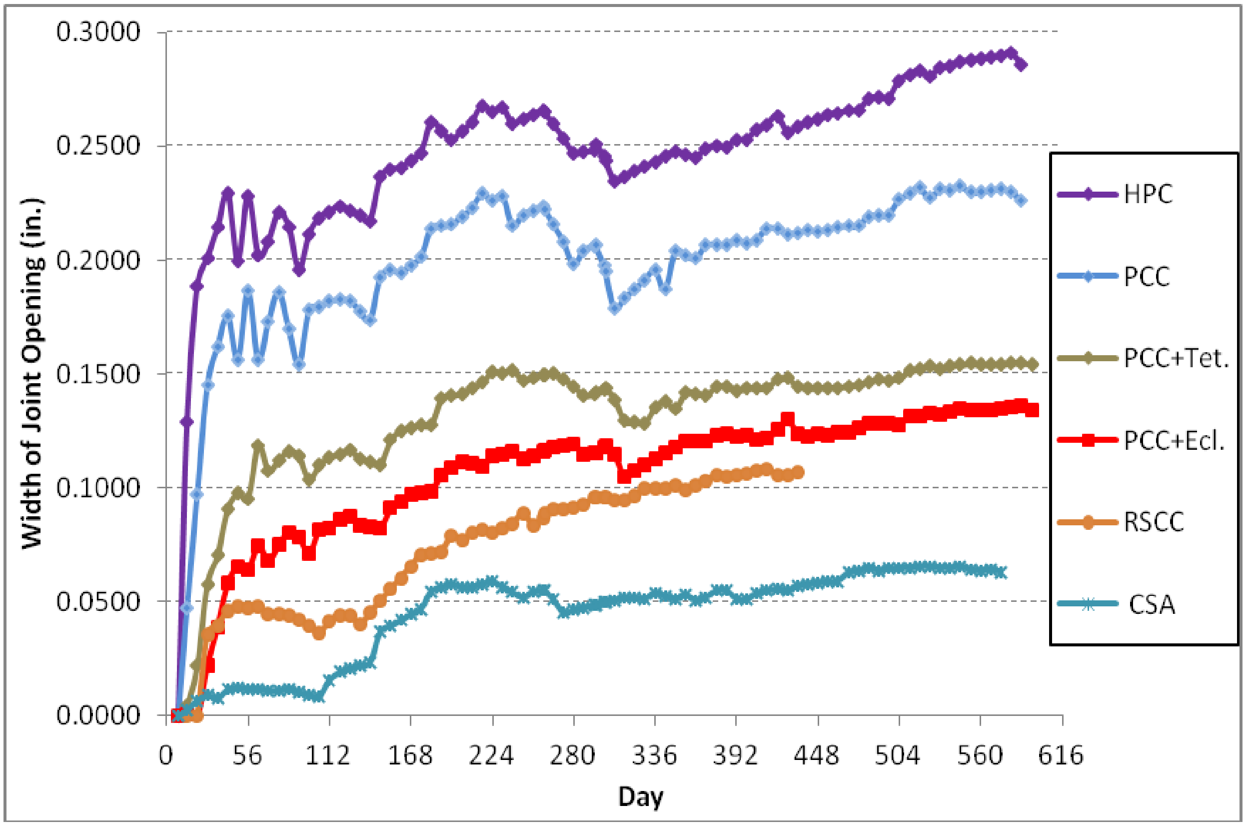

Figure 5.17: Width of Joint Opening vs. Time for all slabs

Figure 5.18 illustrates the strain across the control joints for normal concrete (PCC) verses high performance concrete (HPC). It shows that HPC shrinks quicker than normal concrete. And shrinkage of HPC occurs at a faster rate during the first few weeks after curing when compared with the normal PCC concrete. Additionally, HPC and PCC shrinkage continues to grow at 600 days.

Figure 5.19 illustrates the strain of control joints for shrinkage compensating cement concrete (CSA) verses PCC+ Eclipse (SRA). It can be seen that shrinkage compensating concrete has a positive impact on reducing shrinkage of concrete at both short and long terms when compared to the SRA.

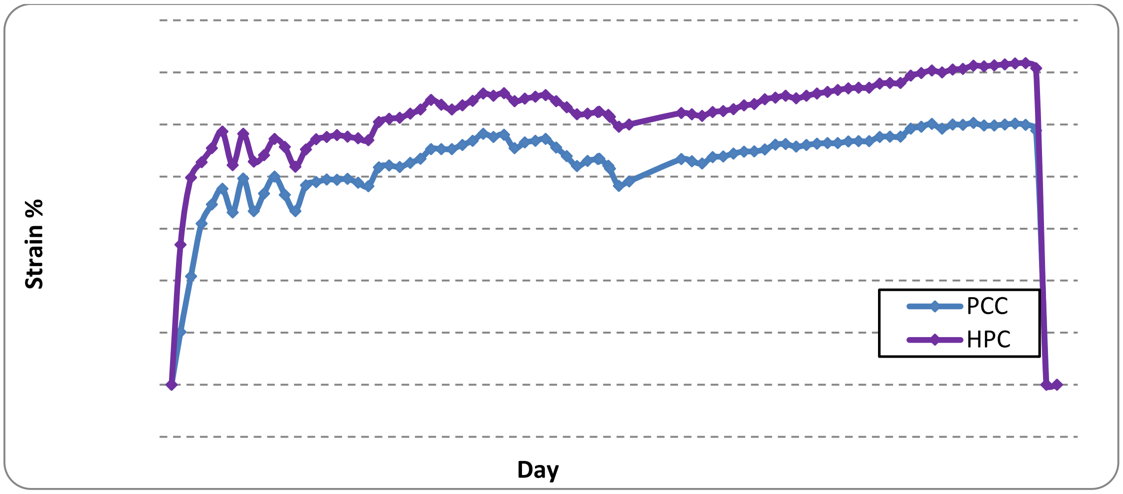

Figure 5.18: Average strain at control joints vs. Time for PCC slabs and HPC slabs

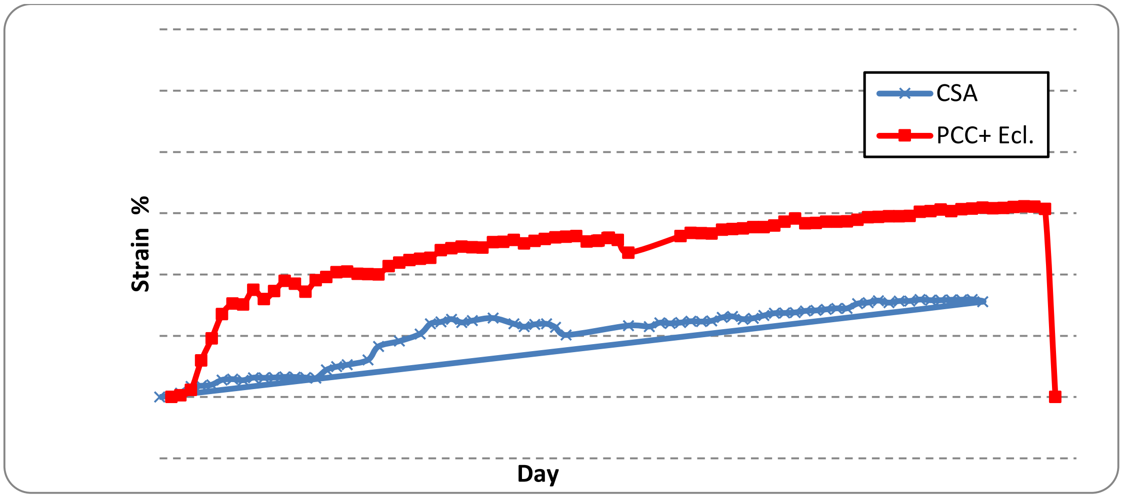

Figure 5.19: Average strain at control joints vs. Time for CSA slabs and PCC+ Eclipse slabs

5.4 Comparing Slab Test Results with ASTM C 157

Figure 5.20, 5.21, and 5.22 compare slab behavior at mid-span (no crack) with ASTM C 157 method using PCC+ Eclipse, PCC, and HPC respectively. It can be seen that there are significant differences in the results between slab on ground behavior and ASTM C- 157 results. Thus, it can be concluded that ASTM C 157 does not provide an accurate method for predicting slab behavior.

Note: It is not possible to compare slab shrinkage behavior with ASTM C 878 method because ASTM C 878 is only used for expansion and is not acceptable for shrinkage.

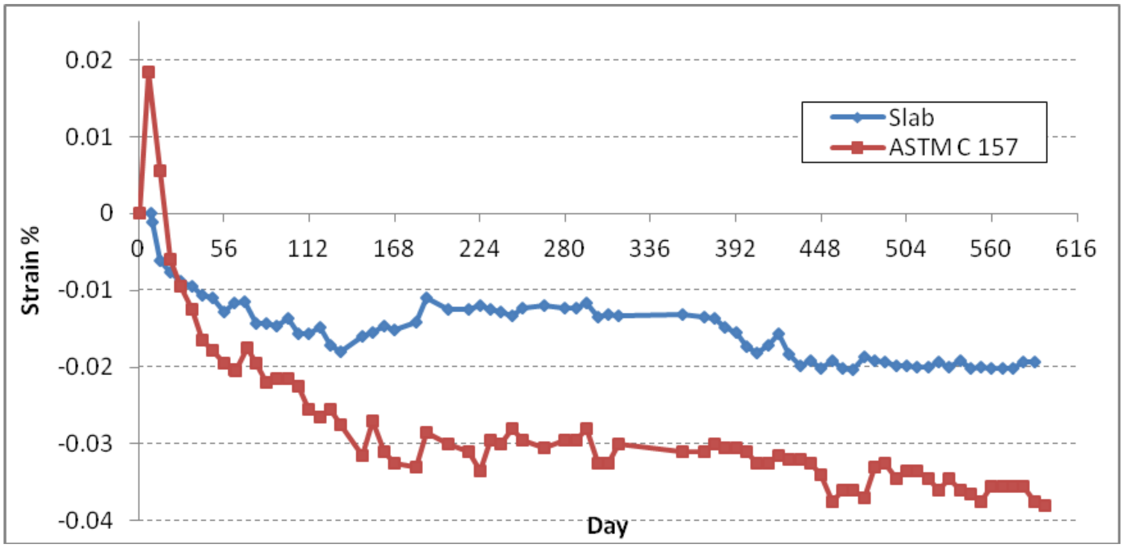

Figure 5.20: Strain at mid-span vs. ASTM C 157 using PCC+Eclipse

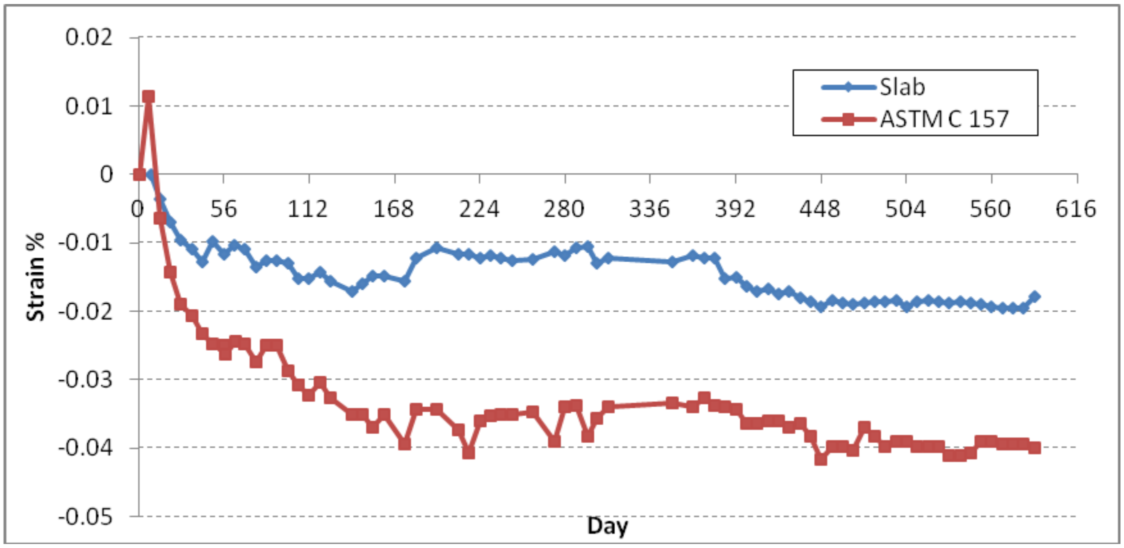

Figure 5.21: Strain at mid-span vs. ASTM C 157 using PCC

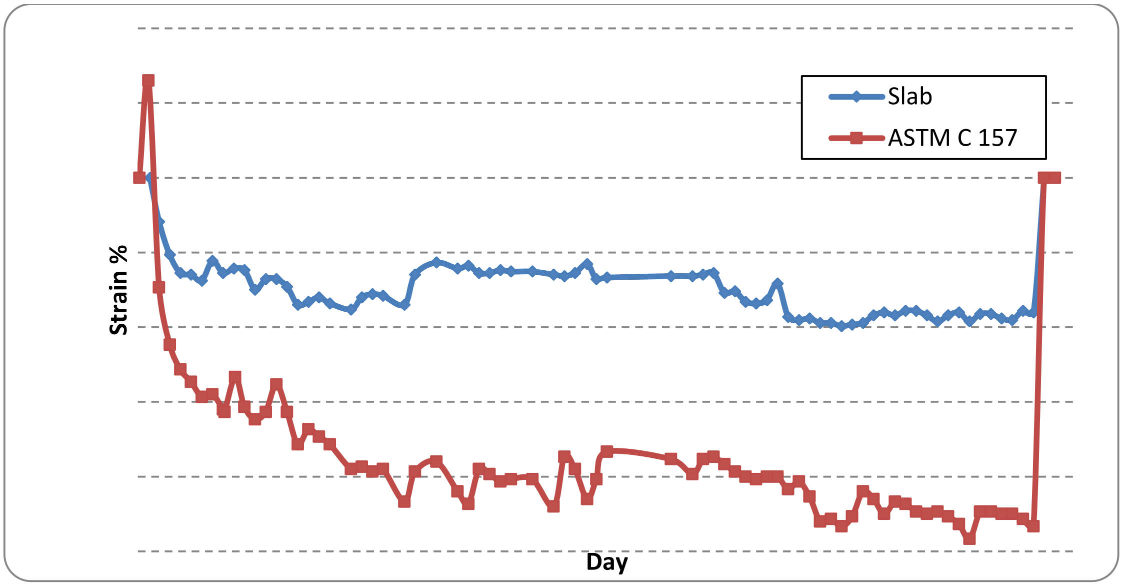

Figure 5.22: Strain at mid-span vs. ASTM C 157 using HPC

5.5 Slab Temperature and Relative Humidity

Temperature and relative humidity were monitored at each concrete slab by using calibrated probes installed at ½ in. increments through the depth of the slabs. The calibrated probes were located at mid-span as previously shown in Figure 3.34 and 3.37. A general result for temperature and relative humidity of slabs on day 7/13/2010 are presented in Tables 5.3 and 5.4 and also Figures 5.23 and 5.24. Table 5.3 and Figure 5.23 show that there minimal temperature changes through the depth of the slabs which means that curling is not an issue. Table 5.4 and Figure 5.24 illustrates how relative humidity varies through the depth of the slabs. All of the slabs are at equilibrium with the environment at the top (60% RH) and bottom (100% RH) surfaces. It can be seen that the slab with HPC has the greatest drying through the slab depth while type K, shrinkage reducing concrete (CSA) maintains a more constant moisture profile through the slab depth. The other mixes are between HPC and CSA. In addition, there are almost no changes in the moisture content past 2.5 in. depth in the slab. Also, moisture content changes only within 1.5-2.0 inches from top surface of the slab.

Table 5.3: Slabs interior temperature (°F), 7/13/2010

Depth (in.)	PCC+ Eclipse	PCC+ Tetraguard	PCC	HPC	CSA	Rapid Set
0						
-0.5	71	71	71	71	71	72
-1	71	71	71	71	71	71
-1.5	71	71	71	71	71	71
-2	71	71	71	71	72	72
-2.5	71	71	71	71	72	72
-3						

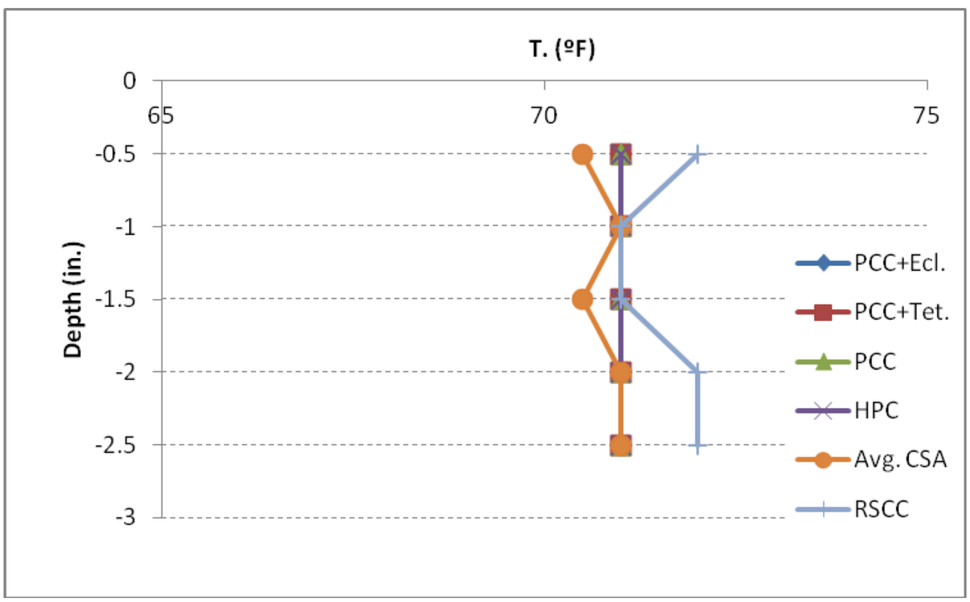

Figure 5.23: Interior slabs temperature in depth vs. Time (7/13/2010)

Table 5.4: Slabs interior relative humidity (7/13/2010)

7/13/2010	Slab Relative Humidity (%)					
Depth (in.)	PCC+ Eclipse	PCC+ Tetraguard	PCC	HPC	Average CSA	RSCC
0						
-0.5	68	70	73	63	81	61
-1	75	71	76	68	92	82
-1.5	87	82	84	76	97	91
-2	94	91	90	80	100	96
-2.5	100	97	96	100	100	100
-3						

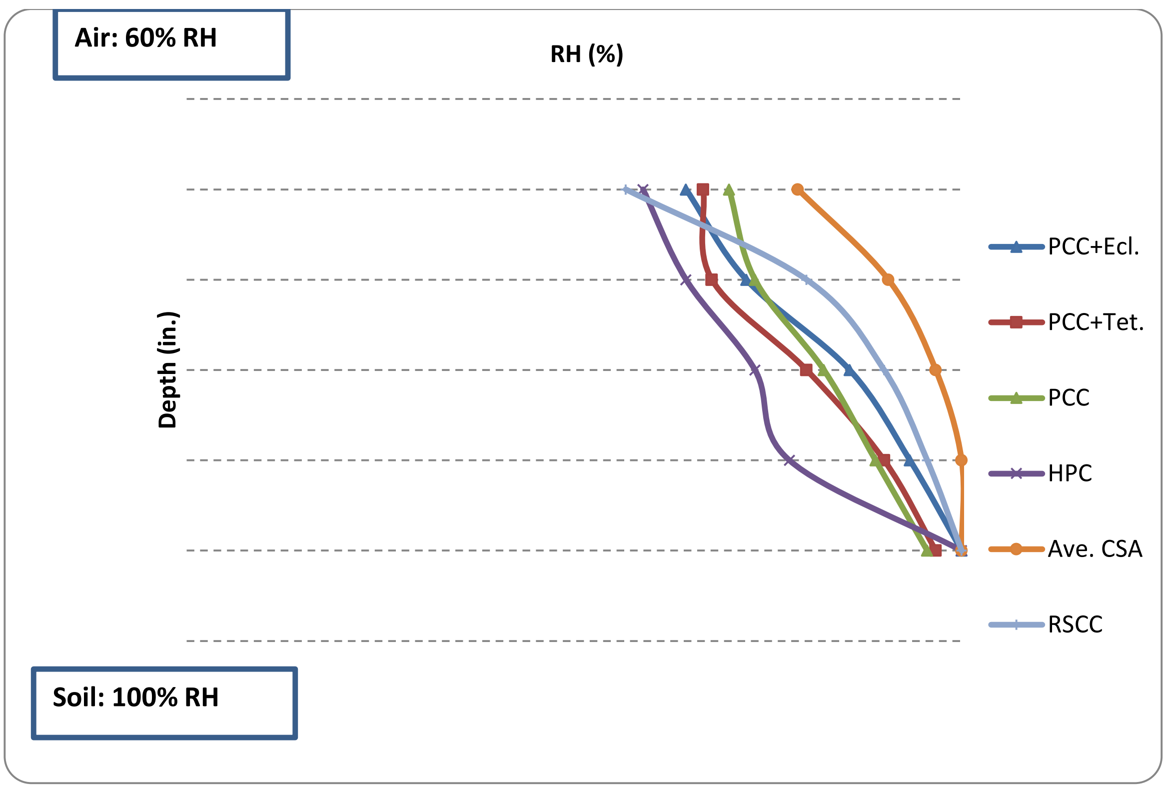

Figure: 5.24 Interior slabs relative humidity in depth vs. Time (7/13/2010)

Figure 5.25 shows interior slabs RH vs. depth on day 3/15/2011. The ambient relative humidity was reduced to 30% for a few months by then. The same relationship exists as in Figure 5.24; the slab with HPC has the greatest drying through the slab depth while type K, shrinkage reducing concrete (CSA) maintains a more constant moisture profile through the slab depth. The other mixes are between HPC and CSA.

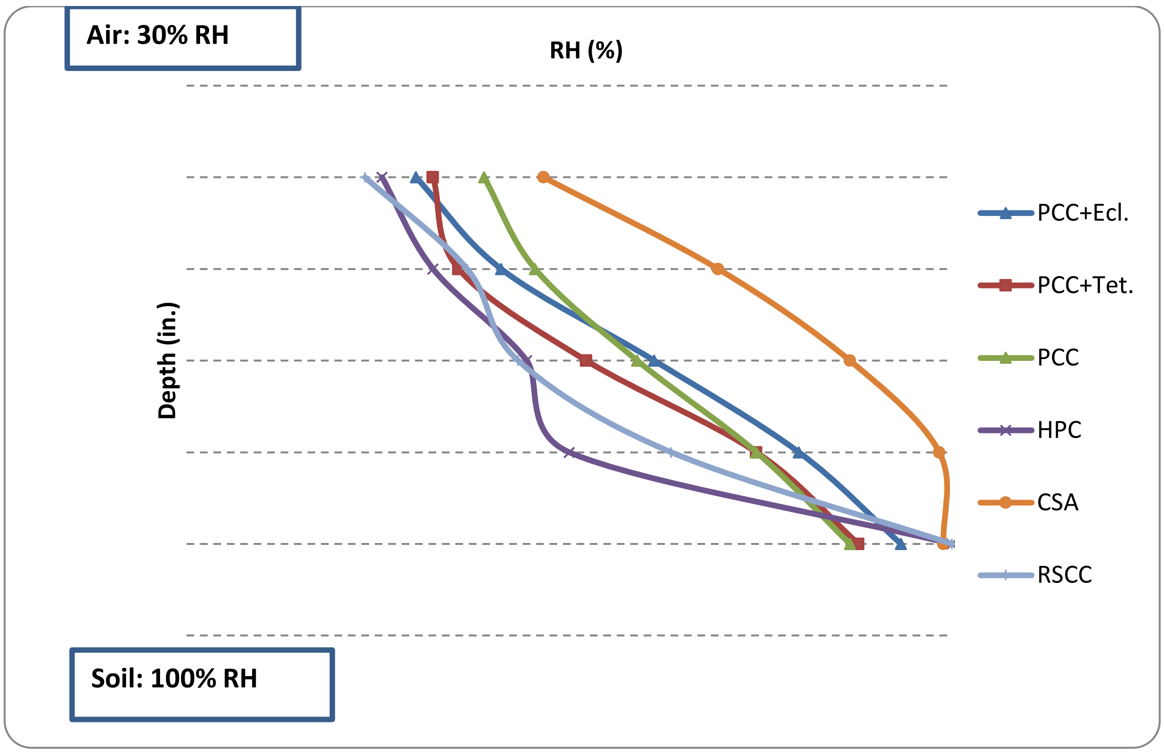

Figure 5.25: Interior slabs relative humidity in depth vs. Time (3/15/2010)

5.6 Shrinkage from Time Zero Tests

This research used the special test frame proposed by Ramseyer (1998) with a few modification; three rectangular (13 in length, 3 in x 3 in) steel forms were used for the “Shrinkage from Time Zero” tests. The frames were coated with grease and covered with a plastic sheet to avoid contact between the concrete and the steel walls of the forms. Once the concrete was placed in the steel frame, the dial indicator strain gages were set and after a prescribed curing time, the demec target strain gages were placed. The environmental chamber was set at 73.4 °F and 50% relative humidity respectively. The measurements were taken in accordance with the ASTM C 403. The grease-plastic lining allows the concrete to shrink without restraint. The dial indicator strain gage and demec target strain gages were used to measure the shrinkage.

The equipment used in this investigation was developed by Ramseyer for the measurement of shrinkage of concrete at an early age. Figures 5.26 shows the improved Ramseyer apparatus used in this investigation. Note this setup has one free end with a dial indicator and fixed end to restrain any movement in that end. The sides are removable so that the surface area to volume compares favorably with the ASTM C 157 prisms.

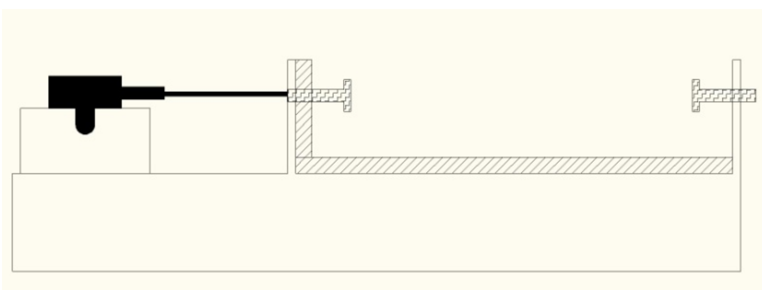

Figure 5.26a: Improved Ramseyer apparatus in elevation view

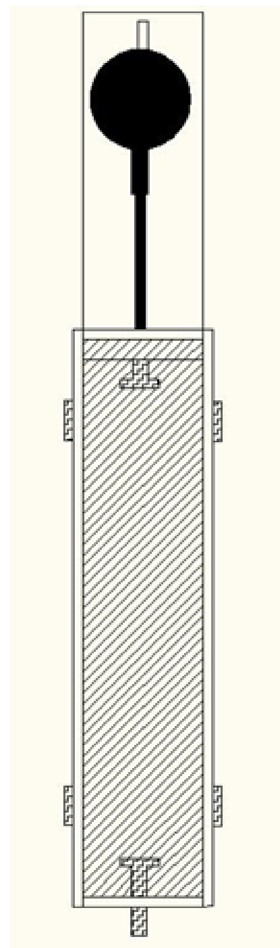

Figure 5.26b: Improved Ramseyer apparatus in plan view

Rectangular length change steel frames were used to hold the concrete as shown in Figure 5.27 and 5.28. The frames dimensions (concrete area) were 3 x 3 x 13 inches and 10 inches between the studs. The process of batching included coating the steel walls and the Teflon top located at the bottom with grease as shown Figures 5.29 and 5.30. Afterward, the thin layer of grease on the inside frame was covered with a plastic sheet to avoid contact between the concrete and grease as shown in Figure 5.31. The plastic sheet was required for easy removal of the steel walls after the curing period and as an additional friction barrier. Dial indicator strain gages as shown in Figure 5.32 were placed as soon as the concrete was poured into the steel frames inside of the

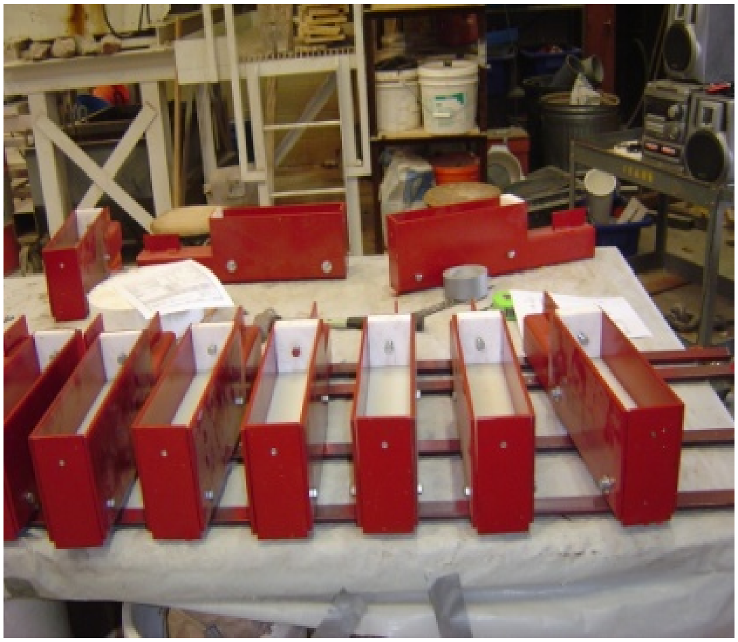

Figure 5.27: Rectangular steel frames

Figure 5.28: Placing the plastic sheet

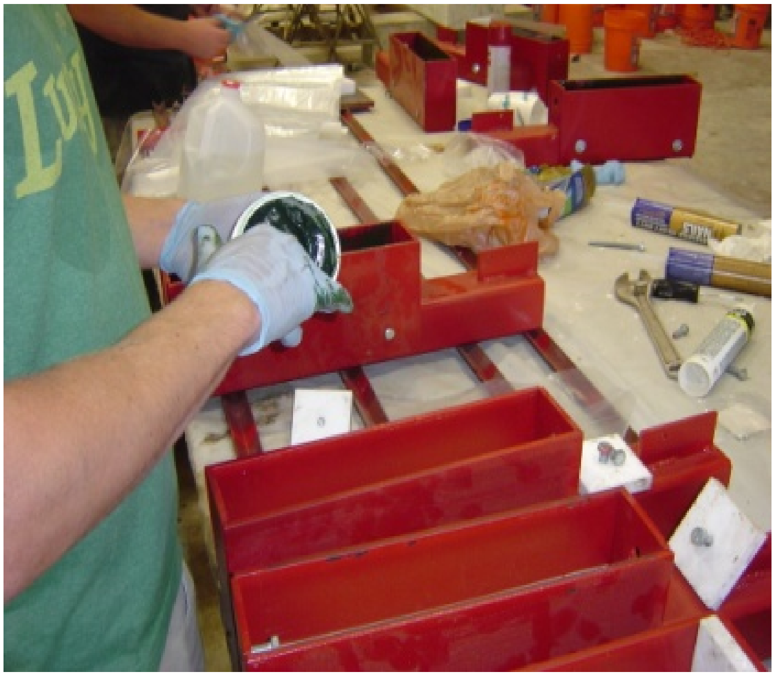

Figure 5.29: Applying the grease layer

Figure 5.30: Grease layer applied over the steel walls and the Teflon bottom

Figure 5.31: Covering the greased surfaces with a plastic sheet

Figure 5.32: Test Frame with Dial indicator strain gage

curing chamber to start recording the shrinkage. Once the concrete had hardened after initial curing, demec strain gages targets were glued on the surface of the concrete using epoxy to continue the recording process.

1. To assemble the time length change frames a layer of grease was applied on the Teflon and the steel walls (as shown in Figure 5.28), and after this, a plastic sheet covered the

Teflon and the walls to avoid the contact between the grease and the concrete and also for the ease of the free movement of the concrete (as shown in Figure 5.31). The time length change frames were put inside of boxes made of pink insulating foam (each mix design had a separate box).

2. As soon as the concrete was ready, the crew placed a small amount of concrete in a separate bucket and took it inside of the environmental chamber to be poured in the time length change frame. The dial indicator was placed in the frame to start recording the change in volume (as shown in Figure 5.32) due to the shrinkage of the concrete after it was cast and tamped (in this step the concrete inside of the rectangular frame was tamped 25 times per layer as shown in Figure 5.33). After placing the dial indicator and tamping the fresh concrete, water was poured over the fresh concrete during the first 24 hours of curing and until the surface of the fresh concrete was hard enough that it would not glue the surface to the sponge as shown in Figure 5.34 (foam carpet saturated with water used after the first 24 hour of curing). During the first 24 hours, water was poured every 3 hours. After the initial curing time for each of the design mixes, the side walls were removed as shown in Figure 5.35. The condition inside of the environmental chamber was set to 73.4° F and 50% relative humidity. Measurements were recorded every day for 28 days.

Figure 5.33: Tamping concrete in the steel frames

Figure 5.34: Sponge saturated with water

Figure 5.35: Side wall removed

Figure 5.36 represents 28 days "shrinkage from time zero" test results. This shows the behavior of the concrete from time zero. It can be seen that type K, shrinkage reducing concrete (CSA) expands during the first 7 days of curing and has the largest expansion, and HPC has the greatest early age shrinkage and the largest shrinkage in 28 days when compared with the other concrete mixes. The other mixes shrinkage is very close to each other and are between CSA and HPC. Note that PCC with SRAs still exhibit shrinkage using this test, but not as much.

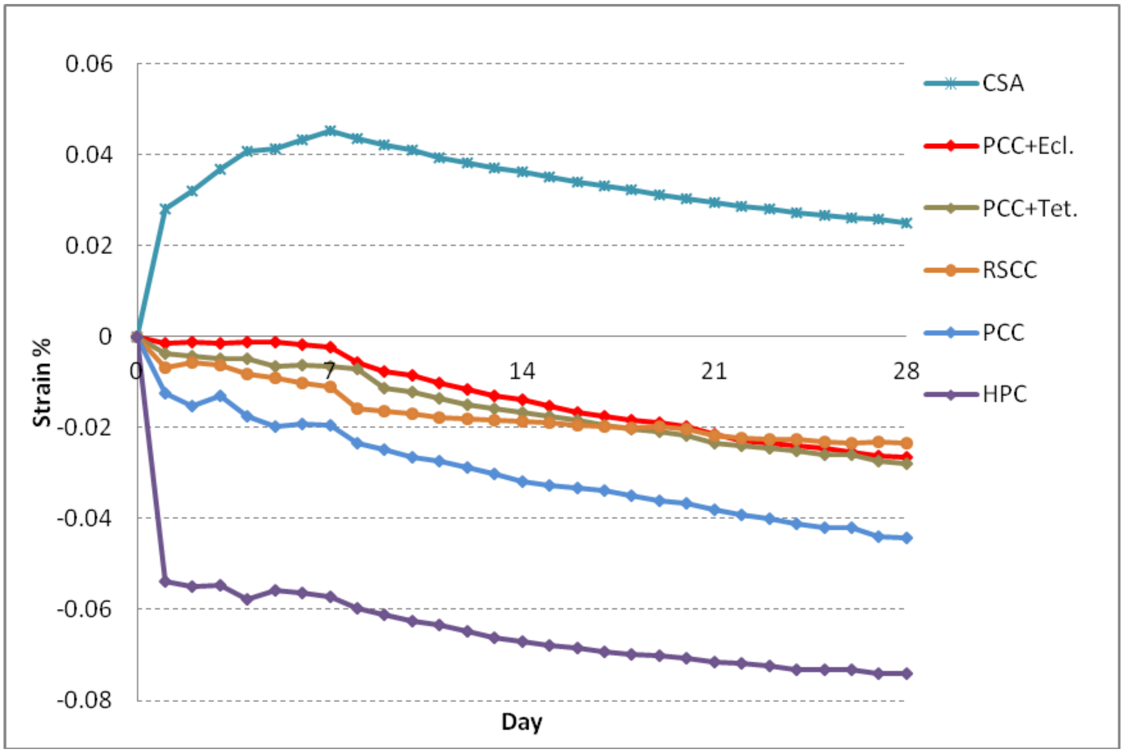

Figure 5.36: Shrinkage from time zero for all the specimens (Phase IV) for 28 days

Figure 5.37 illustrates the test results for shrinkage from time zero in comparison to the unrestrained expansion (ASTM C 157) with PCC+Eclipse. It can be seen that there is no expansion in concrete using the “shrinkage from time zero” method probably because these test

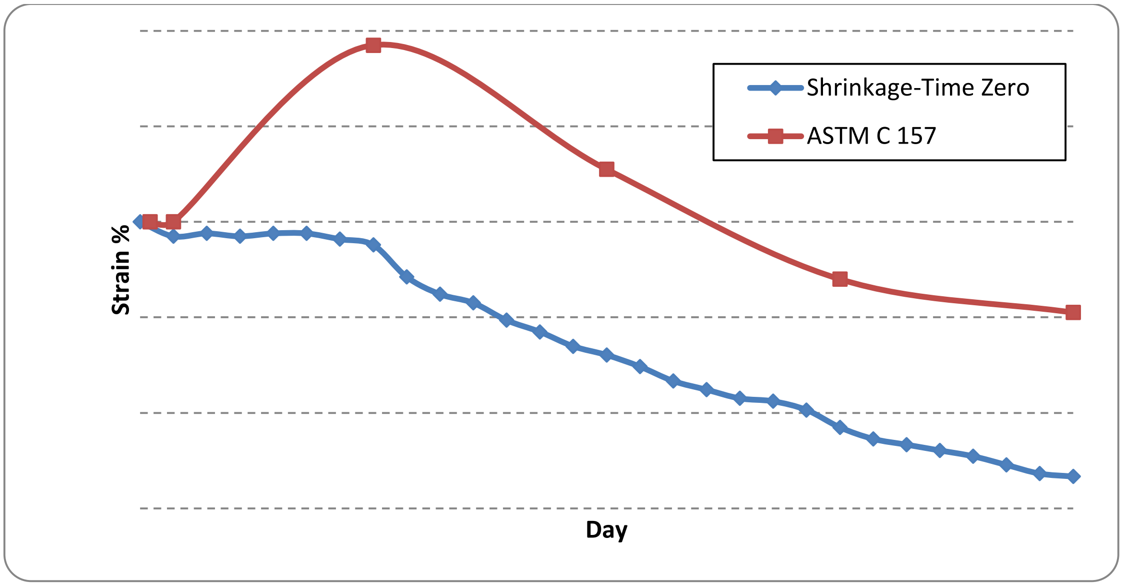

Figure 5.37: Shrinkage from time zero compared to ASTM C 157 for PCC+Eclipse

specimen are cured with damp towels on the surface of the concrete (the mechanical dial micrometers can not be submerged) while the ASTM C 157 and ASTM C 878 specimen are cured fully submerged in water. This may allow the C157 and C 878 specimen to swell due to water absorption while this would be very limited with the shrinkage from time zero specimen.

Figure 5.38 illustrates the 28 days test results for shrinkage from time-zero compared to the unrestrained expansion ASTM C 157 for PCC. Results from shrinkage from time zero method shows that PCC shrinks from the early age. Also the two testing methods result in a very similar trend (slope of the curves are similar) after the curing period ends at seven days.

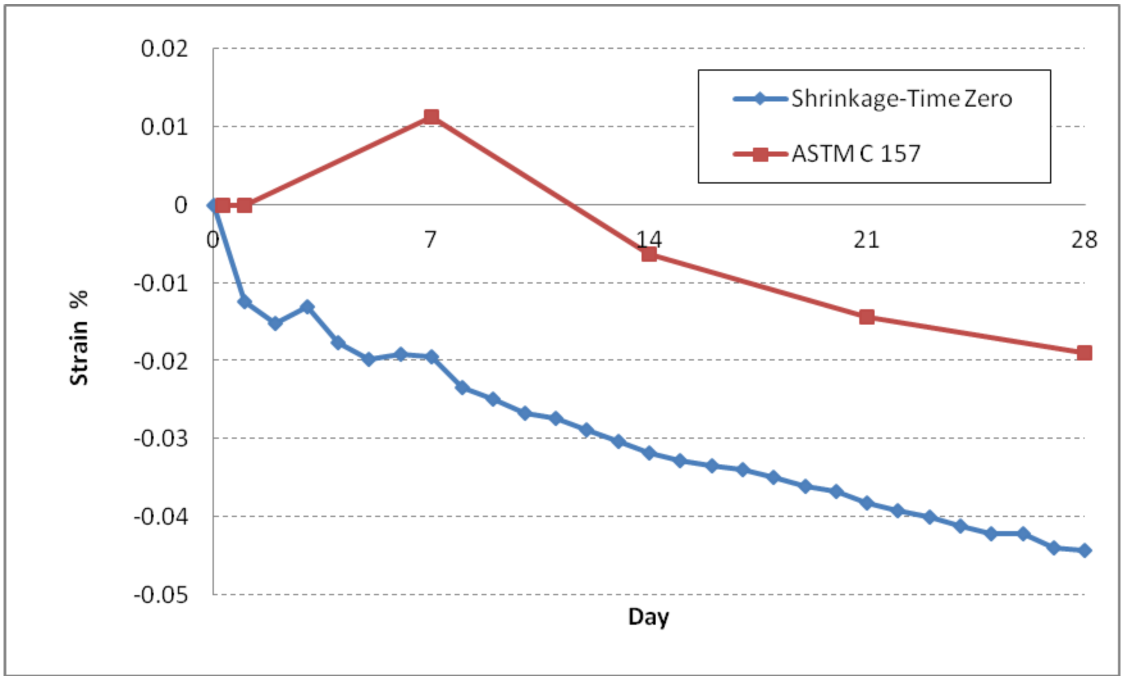

Figure 5.38: Shrinkage from time zero in compare to ASTM C 157 using PCC

Figure 5.39 compares ASTM C 878 with shrinkage from time zero with type K, shrinkage reducing concrete (CSA). This has comparison shows the same trend of increased expansion with saturated early curing (C 878). This variation is more complicated since the shrinkage from time zero is restrained from expansion (in the format used in this investigation) due to the steel frame while the C 878 is only restrained by a rather small diameter steel rod.

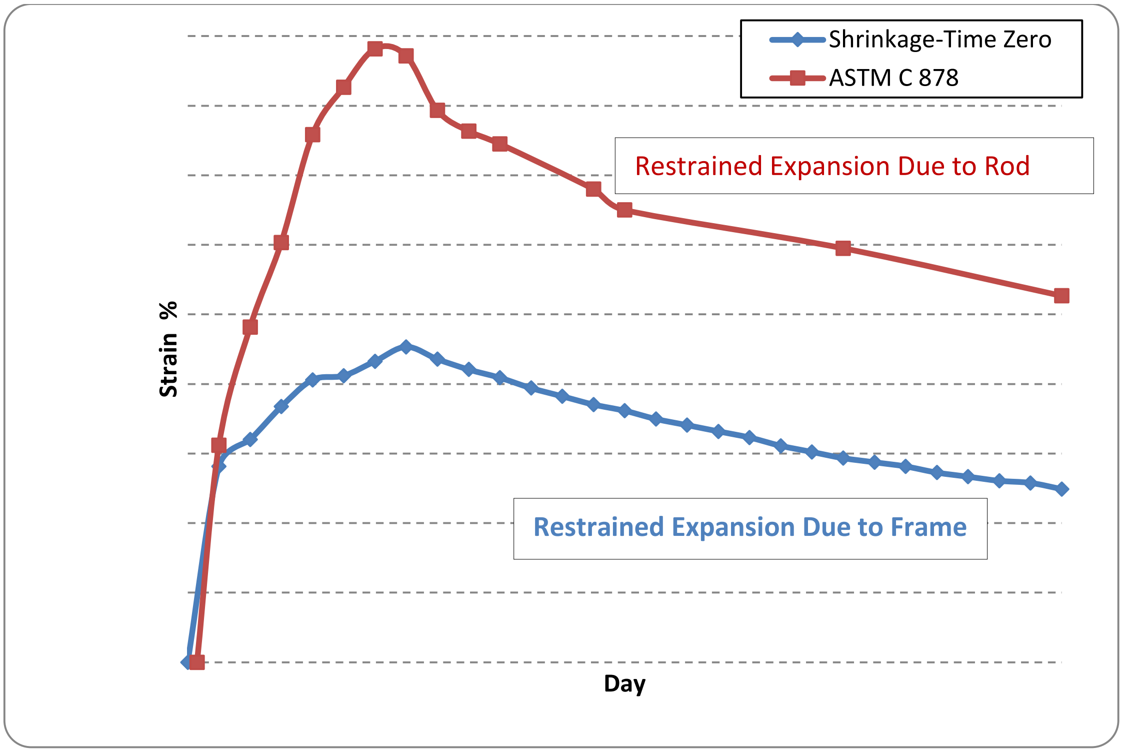

Figure 5.39: Shrinkage from time zero in compare to ASTM C 878 using CSA

Figure 5.40 presents a 110 day comparison for the shrinkage from time zero method with slab on grade behavior for the PCC mix design. Figure 5.41 shows a 110 day shrinkage from time zero with on grade slab behavior using the CSA shrinkage comp mix design. It can be seen that the results from the shrinkage from time zero test does not match the slab on grade test results. Therefore, it can be concluded that the constant moisture that is coming from underneath of the slab changes the behavior of the concrete slab. Thus, behavior of the concrete slab on grade is dependant on the moisture gradient through depth of the slab.

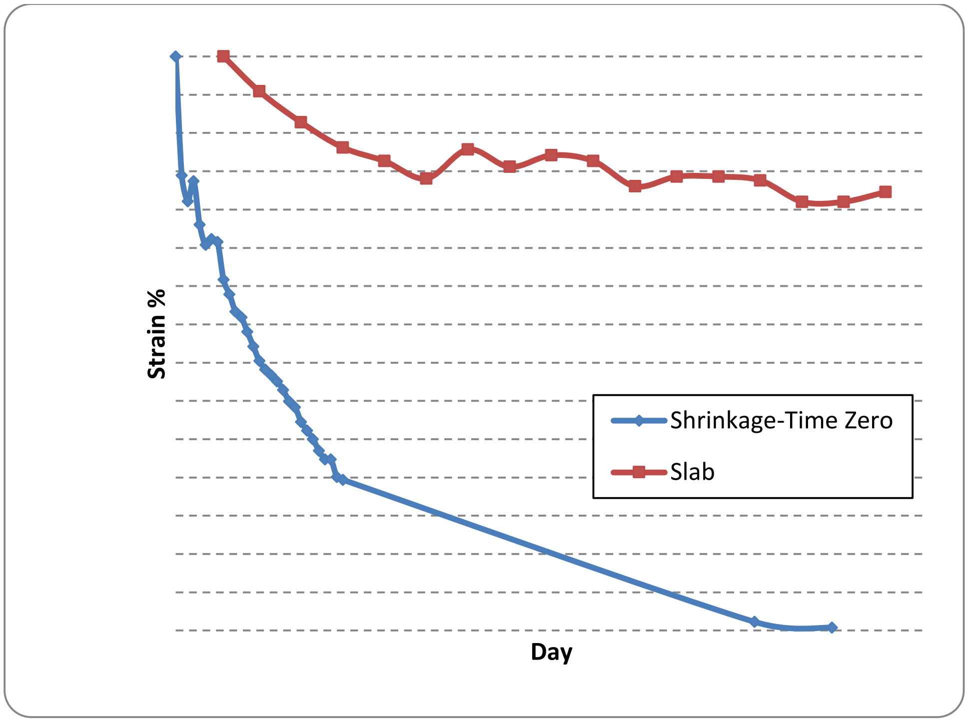

Figure 5.40: Shrinkage from time zero vs. Slab-on-Grade using PCC

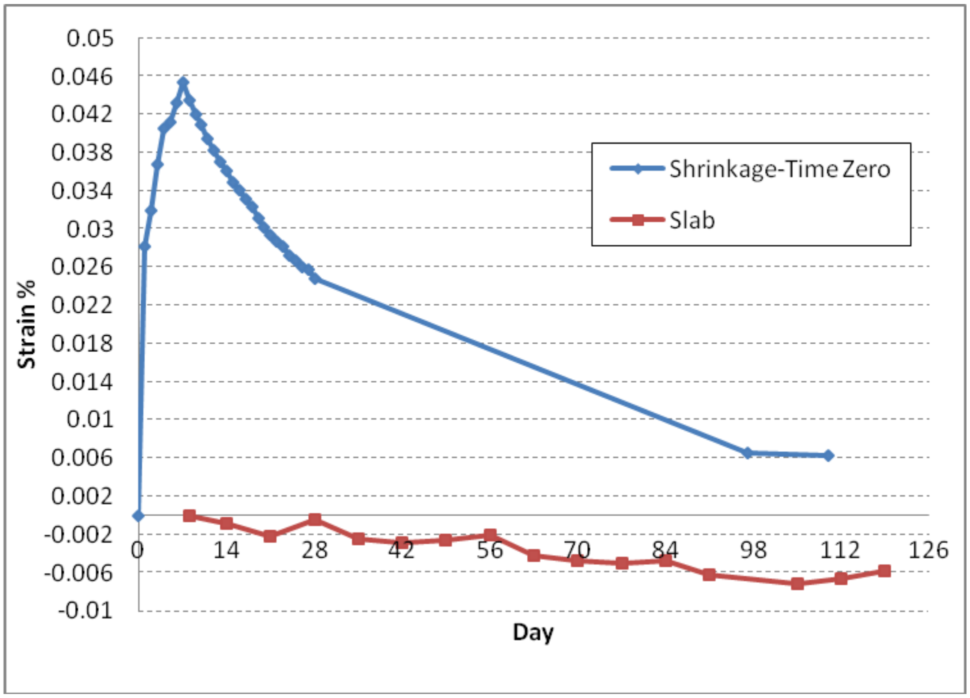

Figure 5.41: Shrinkage from time zero vs. Slab-on-Grade using CSA

6. Discussion of the Results

From the data collected at University of Oklahoma, the following results should be noted. Rapid Set gains its design compressive strength in the first few hours as is expected. It reaches 3,500 psi in 7 hours, reaches 5,550 psi in one day and can achieve 10,000 psi at 28 days.

According to Carrier et al. (1975) moisture loss occurs significantly in the top few inches of the slab. Our results from the relative humidity through the slab's depth agree with Carrier et al.'s conclusion. As we have shown in this investigation the moisture content changes only for the first 1.5-2.0 inches from the top surface of the slab, and there is almost no change in moisture past 2.5 in. of the depth of the slab. But this may be influenced by the availability of 100% RH (i.e. moisture) at the bottom surface of the slabs, located only 0.5 inches below this point. Further research may be required to determine if the RH through depth readings are sensitive to the depth of the slab. It is noted that the slab with HPC has the greatest drying through the slab depth while type K, shrinkage reducing concrete (CSA) maintains a more constant moisture profile through the slab depth. The other mixes are between HPC and CSA. As expected drying shrinkage is greatest in high performance concrete.

6.1 Tests Based on ASTM C 157 and ASTM C 878

Test results in this investigation demonstrate the expansive strain of concrete made with type K, shrinkage compensating concrete (CSA) is much greater at about 0.08%, when compared to concrete using shrinkage reducing admixture (SRA)with an expansion of at about 0.02% (Figure 6.1). The same results can be seen when comparing type K, shrinkage compensating concrete (CSA) to any of the other materials. This testing shows that the expansion of type K, shrinkage compensating concrete (CSA) offsets the drying shrinkage at the long term and that the possibility of warping and cracking caused by drying shrinkage is greatly reduced. It can be concluded that CSA reduces warping of concrete slab and expansion of joint openings which are caused by drying shrinkage.

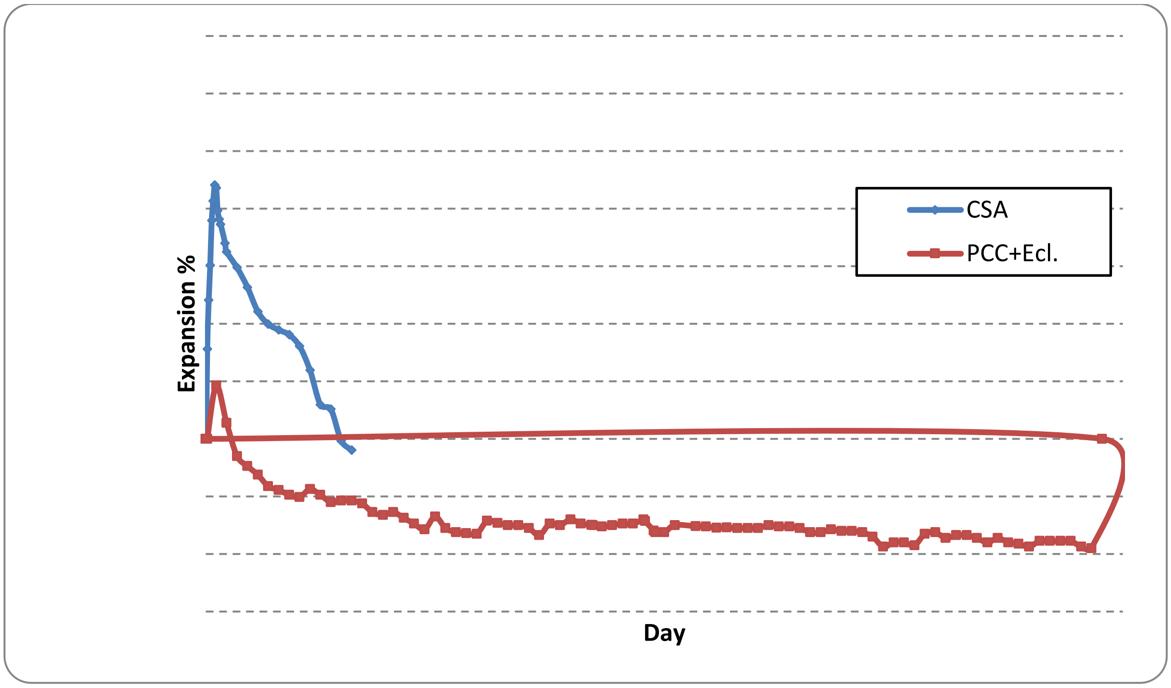

Figure 6.1: C878 and C157 tests using shrinkage compensating concrete vs. PCC with Eclipse

From a review of the ASTM C 157 test results it can be seen that the shrinkage reducing admixtures evaluated has minimal impact on shrinkage at early age and none at long term. HPC exhibits the greatest shrinkage at both short and long terms when compared to the other types of concrete mixtures investigated in this research. Comparing ASTM C 157 with the slab test results shows that ASTM C 157 and ASTM C 878 results do not match the behavior of slabs on ground. This points out the need for a better material evaluation test for determining acceptability for design and construction.

6.2 Joint Opening and Surface Strain

Comparing the joint opening of type K, shrinkage compensating concrete (CSA) with that of PCC, PCC + Eclipse, PCC + Tetraguard, and HPC (i.e. all Portland cement based concretes evaluated) shows that CSA has a major impact on the expansion, or opening (cracking) of joints at both short and long terms. CSA exhibited the smallest joint opening expansion and HPC shows the greatest joint opening expansion, which correlates with our understand of shinkage in that CSA exhibit the negligible shrinkage while HPC exhibit the largest shrinkage in both early age short and long term. It can be concluded that using CSA increases dimensional stability of the slab in comparison to the other types of concrete used in this research. Also, PCC and HPC showed continuing crack growth even at 600 days of age. This fact points us to the conclusion that Portland cement based concretes are not dimensionally stabile even at an extreme testing age.

6.3 Internal Relative Humidity and Temperature

From the internal relative humidity measurements, it was found that the HPC slab had the greatest drying through the slab depth while type K, shrinkage reducing concrete (CSA) maintains a more constant moisture profile through the slab depth. The other mixes are between HPC and CSA. This suggests two possible hypotheses. The first possible hypothesis is that the porosity of the CSA is the lowest since there seems to be less of an impact through the depth of the slab due to the dryer (30% - 60% RH) ambient conditions at the top surface. The second possible hypothesis is that the porosity of the HPC is the lowest since there seems to be less of an impact through the depth of the slab due to the 100% RH conditions at the bottom surface. These two hypotheses will require further research to resolve.

6.4 Shrinkage from Time Zero Discussion

The results from the shrinkage from time zero generally agreed with the results from the ASTM C 157 and C 878 tests. The shrinkage from time zero method agrees with the general trend for restrained expansion when compared to ASTM C 878 and also agrees with the general trend for unrestrained shrinkage when compared to ASTM C 157. In addition, shrinkage from time zero was found easier to perform than the ASTM C 157 and C 878 methods.

Comparing shrinkage from time zero with slab behavior shows a poor correlation. Thus, shrinkage from time zero does not replicate, or predict the behavior of concrete slab on ground, but neither can the ASTM C 157 and C 878 methods. The shrinkage from time zero should not be used as early method to determine the behavior of the slab on ground.

7. Conclusions

The main goal of this research was to perform controlled experiments to relate internal strain measurements of slab strips with ASTM C157 and C878 drying shrinkage measurements, with a realistic characterization of dimensional properties for the selected concrete mixtures based on both Calcium SulphoAluminate cement and Portland cement. And to evaluate their performance in slabs on ground exposed to drying conditions at the top surface and soil moisture conditions on the bottom surface. The main findings from this investigation can be summarized as follows:

- Typical PCC and HPC continue to exhibit expansion of at the joints (i.e. crack growth) in the long term i.e. at approximately 2 years.
- Type K, shrinkage compensating concrete is extremely stable, with little or no long term shrinkage, cracking or warping. This stability is noted at both early age and at approximately 2 years.
- Shrinkage Reducing Admixtures (SRA) have a minor impact at early age but do not impact long term sectional stability. Shrinkage, cracking and warping are nearly similar to typical PCC but slightly better than HPC.
- Shrinkage from time zero accurately measures shrinkage when compared to ASTM C 157.
- Shrinkage from time zero follows the general trend for restrained expansion when compared to ASTM C 878.
    - The difference noted in this research may due to the stiffness of the steel frame compared to the stiffness of the rod restraining the two systems.
- Shrinkage from time zero test method is easier to perform when compared to either ASTM C 157 or C 878.
    - The shrinkage from time zero can accurately perform both unrestrained shrinkage and restrained expansion.

- The shrinkage from time zero test does not provide accurate results for predicting slab on ground behavior.
    - Comparing slab on ground shrinkage at mid-span with shrinkage form time zero shows significant differences between the results.
    - This difference is probably due to the constant source of moisture on the bottom surface of a slab on ground
- ASTM C 157 does not provide accurate results for predicting slab on ground behavior.
    - Comparing slab on grade shrinkage at mid-span with ASTM C 157 shows significant differences between the results.
- Based on the measured internal relative humidity of the slabs on ground and our understanding of the mechanics of warping, type K, shrinkage compensating concrete than inherently less sensitive to warping than PCC or HPC.
    - Type K, shrinkage compensating concrete exhibits the most constant moisture gradient and lowest shrinkage.
        - Material behavior that results in increased dimensional stability and a decreased tendency to warp.
    - HPC showed the most extreme moisture gradient and largest shrinkage.
        - Material behavior that results in increased dimensional instability and an increased tendency to warp.

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