DEVELOPMENT OF A MODIFIED EXPERIMENTAL SETUP TO EVALUATE THE EFFECTS OF SHRINKAGE-REDUCING ADMIXTURE

Rajarajan Subramanian, Pennsylvania State University at Harrisburg; Mang Tia, University of Florida;
Michael J. Bergin, Florida Department of Transportation; Charles A. Ishee, Applied Research Associates, Inc.

Abstract

In this study, the authors developed a cutting-edge tool for evaluating the potential shrinkage-induced stresses in concrete and its potential for shrinkage cracking in service. The effects of a shrinkage-reducing admixture on the shrinkage-induced stresses of 30 different concrete mixes were evaluated by using a constrained long specimen (CLS) test. The existing apparatus was refined by the following modifications: 1) replacing the Whittemore gauge with a high-sensitivity linear variable differential transformer (LVDT); 2) replacing the proving ring with a load cell; 3) introducing an automation system to record strains and stresses through a data acquisition system; and, 4) replacing the existing single AC voltage function generator with eleven LVDT signal conditioners.

Using the CLS test method enabled the creep component to be properly considered, and a realistic determination of the expected induced shrinkage stresses in concrete in service. Also, the results of the CLS tests on 30 concrete mixes showed the possible benefits of using a shrinkage-reducing admixture and fly ash in reducing the potential shrinkage cracking of concrete in service. The results of the CLS tests on 30 concrete mixes showed the possible benefits of using a laboratory setup that measures the early shrinkage in concrete reasonably well.

Introduction

Shrinkage cracking of concrete bridge decks is a critical problem in Florida and in many other states throughout the U.S. Many concrete bridge decks have been observed to develop plastic shrinkage cracks soon after construction. These cracks could shorten the service life of the bridge decks and increase the costs for maintenance and repairs. In recent years, the use of high-performance concretes in bridge decks might have aggravated this problem further. Results of several research studies [1-3] have indicated that high-performance concretes, which are usually produced by using high cement content and additives such as silica fume, have higher free shrinkage and a higher tendency for shrinkage cracking.

One possible solution to this problem is to modify concrete mix designs such that concretes would be less susceptible to shrinkage cracking, while maintaining their other high-performance properties. Another possible solution would be to modify the mix design by adding a shrinkage-reducing admixture and/or fly ash to reduce the possible drying shrinkage of the concrete and, thus, reduce the potential shrinkage-induced stresses in the concrete. The tendency of a given concrete to shrinkage cracking is not just a simple function of its free shrinkage but is also affected by factors such as the constraints on the concrete, rate of strength gain, temperature, and the elastic modulus of the concrete. The creep of the concrete during its plastic stage can also relieve some of the induced stresses due to shrinkage. All of these pertinent factors need to be fully considered in evaluating a concrete mix for its resistance to shrinkage cracking.

An effective test procedure and analysis method for evaluating the potential shrinkage-induced stresses in concrete and its potential for shrinkage cracking in service was developed by Tia et al. [4] at the University of Florida in 1998. The developed procedure was known as the modified constrained long specimen (CLS) test. Some additional improvements in the instrumentation for this test procedure were made subsequently. This developed test procedure and method of analysis was used to evaluate the effects of a shrinkage-reducing admixture on the potential shrinkage-induced stresses of different concrete mixes and their potential for shrinkage cracking in service.

Literature Review

A literature review on methods for evaluating concrete for resistance to shrinkage cracking was conducted before the modified constrained long specimen (CLS) test apparatus was developed. Three existing test methods of particular interest are summarized here.

Constrained Ring Specimen Method

The first test method of interest was a restrained shrinkage cracking test using a constrained ring specimen [1], [5].

The adopted ring test provided a high and nearly constant restraint, enabling tests on cement paste, mortar, and concrete.

The test specimen was made by casting a layer of concrete 1.4” thick and 5.5” high around a steel ring, which had an outer diameter of 8”. A PVC tube was used as an outer mold for casting the concrete around the steel ring. To fabricate a specimen, the inner steel ring would be placed concentrically on a wooden base and the fresh concrete would be placed between the PVC mold and the steel ring. After the concrete had been cured for six hours at 20^{o}C and 100% relative humidity (RH), the PVC mold would be removed. The top surface of the concrete would be sealed off using a silicon rubber so that drying would be allowed only from the outer circumferential surface. The specimen would then be exposed to a specified drying environment, and the cracks that might develop would be observed and used as indicators of shrinkage cracking potential of the concrete. Crack widths were measured by means of a special microscope.

Constrained Plate Specimen Method

The second test method was another restrained shrinkage cracking test using rectangular plate specimens [6]. Specimens were made by casting concrete into forms to produce 24” x 36” rectangular panels with a thickness of 3/4”. The forms were made of Plexiglas to prevent absorption of moisture from the concrete mix. An expended metal lathe was attached to the inside perimeter to provide edge restraint to the concrete. This test condition was intended to simulate the casting of a slab over a plastic vapor barrier. Temperature, relative humidity, and wind speed were controlled to simulate hot weather concreting conditions. Fans were placed next to the specimens to provide a controlled wind velocity of 7-8 mph. The length and average width of the cracks that might develop during the test were recorded and expressed as total crack area square inches.

Constrained Long Specimen Method

The third test method studied was a restrained shrinkage test using a long specimen with flared ends [2]. The concrete specimen had a cross section of 1.6” x 1.6” and was 39” long. It increased gradually in width at the two ends, which fit into two end grips. One grip was fixed and the other was free to move and could be monitored by a dial gauge. To fabricate a test specimen, the fresh concrete would be cast directly into the apparatus. The two sides of the mold could be removed immediately after setting of the concrete. The concrete specimen could then be exposed to a specified drying condition and tested.

The apparatus could be used to measure the free shrinkage of the concrete as well as the load experienced by the specimen in a restrained condition. Free shrinkage could be measured by the dial gauge as the concrete was allowed to contract freely. To measure the load experienced by the specimen in a complete restrained condition, the movable grip could be returned to its original position by a screw assembly connected to the grip through a load cell, which could measure the load exerted on the concrete. Synthetic resin-coated rails were placed on both sides of the grip to reduce eccentricity and friction. To reduce friction, the mold was resin-coated and a gap of 0.08” was provided between the movable grip and the bar supporting the concrete specimen. Dial gauges could be mounted on both sides of the movable grip to monitor the extent of the eccentricity.

Development of the Modified Constrained Long Specimen Method

The apparatuses for the three existing methods for evaluating shrinkage cracking resistance, as presented in the previous sections, were constructed and evaluated with regards to their effectiveness in determining shrinkage cracking potential of concrete in service. It was determined that the long constrained specimen method was one of the most promising approaches with regards to the ability to measure a concrete’s potential shrinkage-induced stresses, which could be used to determine the concrete’s potential for shrinkage cracking in service.

However, operational problems were encountered with the original design. Changes in design and test procedures were made in order to obtain better reliability and precision of the method. A detailed description of this investigation can be found in the report by Tia et al. [4]. Additional improvements in the instrumentation for this test method have also been made since the completion of that report. It is interesting to note that similar test setups have also been developed independently by other researchers for the same purpose. These researchers include Pigeon et al. [7], who used a specimen size of 2” x 2” x 20”, and Altoubat and Lange [8], who used a specimen size of 3” x 3” x 36”.

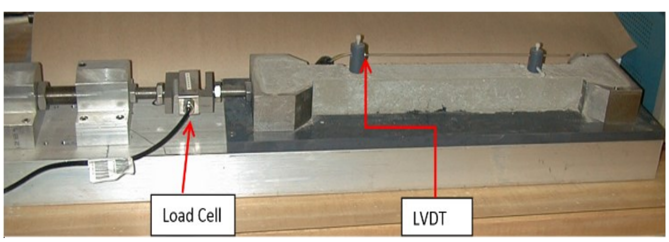
The Modified Constrained Long Specimen Test Method

Basic Test Setup

The existing apparatus was refined by the following modifications: 1) replacing the Whittemore gauge, which was used to measure the deformation of the specimen by a high-sensitivity LVDT; 2) replacing the proving ring, which was used to measure the induced force in the constrained long specimen by a load cell; 3) introducing automation system recording strains and stresses through a data acquisition system, an Agilent 34970A unit (by Agilent Technologies) with a HP 34901A (20-channel armature multiplexer) plug-in module; and, 4) replacing the existing single AC voltage function generator with eleven LVDT signal conditioners (Model LPC-2100 by Micro Sensors) to overcome a lack of needed excitation voltage of 3.0 Vrms at 2.4 kHz. The LVDTs (CD375-025 by Macro Sensors) provided the needed excitation voltage of 3.0 Vrms at 2.4 kHz to demodulate the AC output signal from the LVDT into a DC signal, and to amplify the DC signal before outputting it to the data acquisition system.

Another observed problem with the constrained long specimen apparatus was that the long concrete specimen appeared to be sticking to the steel plate below it. Wax paper was placed over the steel base plate in an effort to reduce the friction between the concrete specimen and the base plate. However, the wax paper got soaked by the wet concrete, which exacerbated the problem; thus, the idea was abandoned. Finally, Teflon sheets were introduced to take care of this sticking problem [9]. Figure 1 shows a picture of the test apparatus with a test specimen. Basically, this test involved casting the concrete to be tested in a test apparatus, which was constrained from movement, placing the test specimen under a specified exposure condition and measuring the induced force in the specimen during the test. Since the specimen could not be perfectly constrained from movement, due to the possible movement of the load cell and other components of the apparatus, the movement of the specimen was also monitored during the test.

Figure 1. Picture of a Constrained Long Specimen Apparatus



with a Test Specimen Showing the Load Cell and LVDT

The specimen was 21.25” long and 1.5” thick. The specimen was 1.5” in the middle and 3.25” wide at the two enlarged ends, which were held by two end grips. One of the end grips was fixed, while the other end grip was connected to a load cell, which measured the induced force in the specimen during the test.

LVDT for Measurement of Strain

Two gauge studs were installed in the mid-portion of the test specimen at a distance of 10” from each other. An AC LVDT was used to measure the relative movement between these two studs, which was used to determine the strain in the test specimen during the test. The LVDT was held by a holder that was attached to one of the two gauge studs. The end of the rod that was connected to the LVDT core was held by another holder, which was attached to the other gauge stud. The LVDT used was a CD375-025 by Macro Sensors. It had a stroke of ±0.125” and a weight of 2.8 grams (0.1 oz.). Each AC LVDT was connected to a separate LVDT signal conditioner (Model LPC-2100 by Micro Sensors). This LVDT signal conditioner provided the needed excitation voltage of 3.0 Vrms at 2.4 kHz. It also demodulated the AC output signal from the AC LVDT into a DC signal and amplified the DC signal before outputting it to the data acquisition system. Each LVDT signal conditioner was calibrated such that a full stroke of the LVDT of ± 0.125” produced an output of ±10.0 VDC from the signal conditioner. The displacement between the two gauge points could be computed from the voltage output as:

displacement (in inches) = output (in volts) x 0.0125

The strain was then computed from the displacement as strain = displacement / (gauge length), as given by Equation (1):

$$\begin{aligned} &= \text{displacement} / (10 \text{ inches}) \\ &= \text{output (in volts)} \times 0.00125 \qquad (1) \end{aligned}$$

Load Cell for Measurement of Stress

A load cell was used to measure the force experienced by the concrete specimen during a test. The load cell used was a LCCB-1K by Omega. Figure 2 shows a picture of the load cell. It was a tension and compression “S” type load cell with a maximum capacity of 1000 pounds. The rated output was 3mV/V for the full load of 1000 pounds. A DC voltage source was used to supply an excitation voltage of 10 V. With the 10 V excitation input, the load cell would deliver an output of 30 mV/1000 lbs., or 0.03 mV/lb. The axial force in the concrete sample was computed from the DC output voltage from the load cell, as given by Equation (2):

$$\text{force (in lb.)} = \text{output (in mV)} \times 33.33 \qquad (2)$$

The stress in the concrete sample was then calculated from Equations (2) and (3):

$$\begin{aligned} \text{stress} &= \text{force} / (\text{cross-sectional area of concrete}) \\ &= \text{force} / (2.25 \text{ in}^2) \qquad (3) \end{aligned}$$

Figure 2. Picture of the Load cell and LVDT with holder in the CLS test set-up

Data Acquisition System (DAS)

The outputs from the LVDT and the load cell were connected to an automatic DAS, which was an Agilent 34970A unit (by Agilent Technologies) with a HP 34901A (20-channel armature multiplexer) plug-in module. The data acquisition unit can be set up to take readings at specified time intervals and for a specified length of time. The HP 34901A multiplexer module can read up to 20 channels of AC or DC voltages with a maximum capacity of 300 V, and has a switching speed of up to 60 channels per second. It also has a built-in thermocouple reference junction for use in temperature measurement by means of thermocouples.

Thus, the Agilent 34970A data acquisition unit with one HP 34901A multiplexer module was adequate for the job of recording load and displacement readings from 10 testing apparatuses. The Agilent 34970A unit can take up to three plug-in modules. Thus, if needed, it can be expanded to take up to 60 channels of output, enough to accommodate 30 testing apparatuses. The stored data was downloaded to a personal computer via an RS232 cable connection. The data files were in CSV format and could be easily read by spreadsheet software such as Excel.

Preparation of the Constrained Long Specimen and Testing Procedure

The concrete mix to be evaluated was placed in the constrained long specimen apparatus for testing. Figure 3 shows a picture of the mold for the test specimen before a test concrete was placed. Before the fresh concrete was placed into the mold, a thin layer of motor oil was applied on the surface of the plate support and the two sides of the mold to reduce friction. The two gauge studs, which were held in position by two aluminum brackets, were installed at a distance of 10” from each other. The fresh concrete was then placed into the mold and finished with a small hand trowel. After the concrete had sufficiently set, the two side pieces of the mold were removed. The two aluminum brackets, which kept the gauge studs in place, were also removed. The LVDT was installed on one of the studs and the rod holding the core of the LVDT was connected to the other stud. The position of the rod was adjusted such that the core was placed at the center of the LVDT and the output from the LVDT was zeroed initially. The position of the end grip that was connected to the load cell was adjusted so that the output from the load cell was zero initially. The data acquisition system was then activated to record readings from the load cell and the LVDT from each CLS test apparatus at specified time intervals.

Figure 3. Picture of the CLS Mold before the Placement of the Concrete

Method of Analysis

The analysis consisted of several equations involving three different deformation components in the concrete specimen. The Constrained Long Specimen under tensile force induced by shrinkage of the concrete specimen, exhibiting the change of length of the specimen being measured by the proven ring (δ_{PR}). The first component was the shortening, due to shrinkage (δ_{sh}). The second component was the elastic lengthening, due to induced tensile stress (δ_E). The third one was the creep, due to the induced stresses (δ_{CR}). These three components were related to the total movement of the specimen, as defined by Equation (4):

$$\delta_{PR} = \delta_{CL} = \delta_{sh} - \delta_E - \delta_{CR} \quad (4)$$

In terms of strains (ε’s), the relationship can be written as shown in Equation (5):

$$\varepsilon_{CL} = \varepsilon_{sh} - \varepsilon_E - \varepsilon_{CR} \quad (5)$$

The three different components of strain in the concrete test specimen can be explained further. The first component was the free shrinkage strain, due to drying shrinkage (ε_{sh}). The second component was the elastic tensile strain, due to induced tensile stress (ε_E). The third component was the tensile creep strain, due to the induced tensile stress (ε_{CR}). These three components were related to the total movement of the specimen (ε_{CL}), as shown in Equation (5). The elastic strain (ε_E) was calculated from the induced stress (σ_{CL}) and the elastic modulus of the concrete (E), as shown in Equation (6):

$$\varepsilon_E = \sigma_{CL}/E \quad (6)$$

The elastic modulus of the concrete (E) was measured, in accordance with ASTM Standard Test Method C469, from specimens made of the same concrete and placed under the same conditions. The shrinkage strain (ε_{sh}) was assumed to be equal to the free shrinkage strain measured by the length comparator, in accordance with ASTM Standard Method C157. The creep strain (ε_{CR}) was calculated from the other strains, according to Equation (4), as shown in Equation (7):

$$\varepsilon_{CR} = \varepsilon_{sh} - \varepsilon_E - \varepsilon_{CL} \quad (7)$$

If a concrete member were fully constrained from movement, the induced stress due to drying shrinkage (σ_{FC}) could be expressed using Equation (8):

$$\sigma_{FC} = (\varepsilon_{sh} - \varepsilon_{CR})\ E \quad (8)$$

Substituting Equation (7) into Equation (8), σ_{FC} can be expressed as in Equation (9):

$$\sigma_{FC} = (\varepsilon_E + \varepsilon_{CL})\ E = \sigma_{CL} + \varepsilon_{CL}\ E \quad (9)$$

When the expected shrinkage-induced stress (σ_{FC}), as computed by Equation (9), exceeds the expected tensile strength of the concrete (σ_t) at any particular time, the concrete will be likely to crack at that time.

Concrete Mixtures Evaluated

Concrete mixtures were prepared in the laboratory and tested for their resistance to shrinkage cracking in order to evaluate: 1) the effectiveness of the shrinkage test apparatuses used; 2) the shrinkage characteristics of typical concretes used in bridge deck applications in Florida; and, 3) the effects of adding a shrinkage-reducing admixture. A typical mix design for a Florida Class IV concrete with a total cementitious materials content of 700 lbs. per cubic yard (lb./yd^3) of concrete was selected for use. Various percentages of fly ash and ground blast-furnace slag were incorporated into this basic mix design to form six different mix designs to be evaluated in the laboratory testing program. For each of the concrete mixtures evaluated, a pair of concrete mixes was prepared at the same time—one with the addition of a shrinkage-reducing admixture (SRA) and one without. Since various different test apparatuses were used during different stages of this study, several replicate batches of the same mixes were used, resulting in a total of 15 pairs of concrete mixes tested in this study.

Tables 1 through 15 show the mix proportions for the 15 pairs of concrete mixtures evaluated in this study. The concrete mixes were numbered according to the order by which they were prepared and tested. Mixes 1 and 13 had a cement content of 350 lb./yd^3 and a slag content of 350 lb./yd^3 of concrete. Mixes 2 and 3 had a cement content of 210 lb./ yd^3 and a slag content of 490 lb./yd^3. Mixes 4, 7, 8, and 11 had a cement content of 560 lb./yd^3 and a fly ash content of 140 lb./yd^3. Mixes 5, 9, 10, and 14 had a cement content of 455 lb./yd^3 and a fly ash content of 245 lb./yd^3. Mixes 6 and 12 had a cement content of 210 lb./yd^3, a fly ash content of 140 lb./yd^3, and a slag content of 350 lb./yd^3. Mix 15 had a cement content of 700 lb./yd^3 and no mineral admixture. The slump of the fresh concrete was targeted to be 8 ± 1.5".

Table 1. Mix Proportions for Mix 1

Mix – 1				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	350	350	350	350
Fly ash	-	-	-	-
Slag	350	350	350	350
Water	287	234	274	219
F.A.	1257	1252	1257	1252
C.A.	1513	1572	1513	1572
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.875	0.875	0.875	0.875
Admixture (Adva 120)	1.313	1.313	1.313	1.313
Admixture (Eclipse)	-	-	12	12
Slump (in inches)	6.25	6.25	7.25	7.25
Air (%)	3.75	3.75	3	3
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.33	0.41	0.33
Unit Weight (pcf)	139.1	139.2	139.1	139.1

Table 2. Mix Proportions for Mix 2

Mix – 2				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	210	210	210	210
Fly ash	-	-	-	-
Slag	490	490	490	490
Water	224	176	211	165
F.A.	1336	1331	1336	1331
C.A.	1583	1633	1583	1633
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.875	0.875	0.875	0.875
Admixture (Adva 120)	2.063	2.063	2.063	2.063
Admixture (Eclipse)			12	12
Slump (in inches)	8	8	9.25	9.25
Air (%)	2.75	2.75	1.75	1.75
Workability	Sticky	Sticky	Sticky	Sticky
W/C Ratio	0.32	0.25	0.32	0.25
Unit Weight (pcf)	142.3	142.2	142.3	142.3

Table 3. Mix Proportions for Mix 3

Mix – 3				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	210	210	210	210
Fly ash	-	-	-	-
Slag	490	490	490	490
Water	287	213	274	200
F.A.	1253	1248	1253	1253
C.A.	1507	1586	1507	1507
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.875	0.875	0.875	0.875
Admixture (Adva 120)	1.313	1.313	1.313	1.313
Admixture (Eclipse)			12	12
Slump (in inches)	9	9	8.5	8.5
Air (%)	3.5	3.5	2.5	2.5
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.30	0.39	0.29
Unit Weight (pcf)	138.8	138.8	138.3	135.5

Table 4. Mix Proportions for Mix 4

Mix – 4				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	56	560	560	560
Fly ash	140	140	140	140
Slag	-	-	-	-
Water	287	244	275	232
F.A.	1250	1246	1250	1246
C.A.	1486	1533	1486	1533
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	7.5	7.5	9	9
Air (%)	3.25	3.25	2.5	2.5
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.35	0.39	0.33
Unit Weight (pcf)	137.9	137.9	137.4	137.4

Table 5. Mix Proportions for Mix 5

Mix – 5				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	455	455	455	455
Fly ash	245	245	245	245
Slag	-	-	-	-
Water	287	228	275	216
F.A.	1217	1213	1217	1213
C.A.	1469	1533	1469	1533
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	9.25	9.25	8.75	8.75
Air (%)	3.25	3.25	3.25	3.25
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.33	0.41	0.33
Unit Weight (pcf)	136.0	136.1	136.0	136.1

Table 6. Mix Proportions for Mix 6

Mix – 6				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	210	210	210	210
Fly ash	140	140	140	140
Slag	350	350	350	350
Water	289	246	275	232
F.A.	1240	1236	1240	1236
C.A.	1475	1522	1475	1522
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	9.25	9.25	9	9
Air (%)	1.75	1.75	2.75	2.75
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.35	0.41	0.35
Unit Weight (pcf)	137.2	137.2	137.1	137.1

Table 7. Mix Proportions for Mix 7

Mix – 7				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	560	560	560	560
Fly ash	140	140	140	140
Slag	-	-	-	-
Water	254	235	242	223
F.A	1334	1330	1257	1330
C.A	1561	1554	1513	1554
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.31	1.31	0.88	0.88
Admixture (Adva 120)	1.31	1.31	1.31	1.31
Admixture (Eclipse)			12	12
Slump (in inches)	8	8	9	9
Air (%)	2.75	2.75	3.25	3.25
Workability	Good	Good	Good	Good
W/C Ratio	0.36	0.34	0.36	0.34
Unit Weight (pcf)	142.6	141.4	137.9	141.4

Table 8. Mix Proportions for Mix 8

Mix – 8				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	560	560	560	560
Fly ash	140	140	140	140
Slag	-	-	-	-
Water	224	264	212	252
F.A	1453	1449	1455	1451
C.A	1453	1417	1455	1419
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.88	0.88	0.88	0.88
Admixture (Adva 120)	2.06	2.06	2.06	2.06
Admixture (Eclipse)			12	12
Slump (in inches)	2.5	2.5	2.25	2.25
Air (%)	4.5	4.5	3.75	3.75
Workability	Stiff	Stiff	Stiff	Stiff
W/C Ratio	0.32	0.38	0.32	0.38
Unit Weight (pcf)	141.9	141.9	142.0	142.0

Table 9. Mix Proportions for Mix 9

Mix – 9				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	455	455	455	455
Fly ash	245	245	245	245
Slag	-	-	-	-
Water	287	324	275	312
F.A.	1351	1347	1351	1347
C.A.	1351	1318	1351	1318
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.88	0.88	0.88	0.88
Admixture (Adva 120)	1.31	1.31	1.31	1.31
Admixture (Eclipse)			12	12
Slump (in inches)	3.25	3.25	4.5	4.5
Air (%)	2.75	2.75	2.5	2.5
Workability	O.K	O.K	O.K	O.K
W/C Ratio	0.41	0.46	0.41	0.46
Unit Weight (pcf)	136.6	136.6	136.6	136.6

Table 10. Mix Proportions for Mix 10

Mix – 10				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	455	455	455	455
Fly ash	245	245	245	245
Slag	-	-	-	-
Water	252	289	240	278
F.A	1265	1261	1265	1261
C.A	1513	1480	1513	1480
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.88	0.88	0.88	0.88
Admixture (Adva 120)	1.31	1.31	1.31	1.31
Admixture (Eclipse)			12	12
Slump (in inches)	3.25	3.25	4.5	4.5
Air (%)	2.75	2.75	2.5	2.5
Workability	O.K	O.K	O.K	O.K
W/C Ratio	0.36	0.41	0.36	0.41
Unit Weight (pcf)	138.2	138.2	138.1	138.2

Table 11. Mix Proportions for Mix 11

Mix – 11				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	560	560	560	560
Fly ash	140	140	140	140
Slag				
Water	287	321	275	308
F.A.	1250	1246	1250	1246
C.A.	1486	1456	1486	1456
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	8.5	8.5	9	9
Air (%)	3	3	2.75	2.75
Workability	Good	Good	Good	Good
W/C Ratio	0.41	0.46	0.41	0.46
Unit Weight (pcf)	137.9	137.9	137.9	137.9

Table 12. Mix Proportions for Mix 12

Mix – 12				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	210	210	210	210
Fly ash	140	140	140	140
Slag	350	350	350	350
Water	224	194	212	183
F.A.	1516	1511	1516	1511
C.A.	1376	1410	1376	1410
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	3	3	6.5	6.5
Air (%)	3.25	3.25	3	3
Workability	Stiff	Stiff	Sticky	Sticky
W/C Ratio	0.32	0.28	0.32	0.28
Unit Weight (pcf)	141.3	141.3	141.3	141.3

Table 13. Mix Proportions for Mix 13

Mix – 13				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	350	350	350	350
Fly ash				
Slag	350	350	350	350
Water	224	285	212	273
F.A.	1547	1543	1547	1543
C.A.	1405	1348	1405	1348
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	1.75	1.75	7 (Sheared off)	7 (Sheared off)
Air (%)	3.75	3.75	3.25	3.25
Workability	Stiff	Stiff	Stiff	Stiff
W/C Ratio	0.32	0.41	0.32	0.41
Unit Weight (pcf)	143.6	143.5	143.6	143.6

Table 14. Mix Proportions for Mix 14

Mix – 14				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	455	455	455	455
Fly ash	245	245	245	245
Slag				
Water	224	209	212	197
F.A.	1502	1499	1502	1499
C.A.	1364	1383	1364	1383
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	1.75	1.75	1.75	1.75
Admixture (Adva 120)	2.188	2.188	2.188	2.188
Admixture (Eclipse)			12	12
Slump (in inches)	Sheared off	Sheared off	Sheared off	Sheared off
Air (%)	3.5	3.5	4.5	4.5
Workability	Stiff	Stiff	Stiff	Stiff
W/C Ratio	0.32	0.30	0.32	0.30
Unit Weight (pcf)	140.4	140.4	140.4	140.4

Table 15. Mix Proportions for Mix 15

Mix – 15				
Ingredients	Weight (lbs./yd^3)			
	Standard		Eclipse	
	Design Batch	Actual Batch	Design Batch	Actual Batch
Cement	700	700	700	700
Fly ash				
Slag				
Water	224	202	212	190
F.A.	1557	1553	1557	1553
C.A.	1415	1441	1415	1441
Air Entrainer	0.0625	0.0625	0.0625	0.0625
Admixture (WRDA 64)	0.875	0.875	0.875	0.875
Admixture (Adva 120)	1.313	1.313	1.313	1.313
Admixture (Eclipse)			12	12
Slump (in inches)	0.25	0.25	0.25	0.25
Air (%)	4.5	4.5	4	4
Workability	Stiff	Stiff	Stiff	Stiff
W/C Ratio	0.32	0.29	0.32	0.29
Unit Weight (pcf)	144.3	144.3	144.3	144.3

Evaluation of the Effects of a Shrinkage Reducing Admixture

The effects of a shrinkage-reducing admixture on the potential shrinkage-induced stresses in concrete and its potential for shrinkage cracking in service were evaluated using the modified CLS test method. Thirty concrete mixtures, which have been used in bridge decks in Florida and which have a water cement ratio varying from 0.25 to 0.46, were used in this evaluation. Each pair of concrete mixes consisted of a reference mix with no shrinkage-reducing admixture and one with the same mix design but with a shrinkage-reducing admixture added. The amount of shrinkage-reducing admixture added was 12 lbs. per cubic yard of concrete.

The following tests were performed on each of the concrete mixes evaluated:

1) Elastic modulus (ASTM C469) and compressive strength (ASTM C39) tests using 4” x 8” specimens at 3, 7, 14, and 28 days. (Two replicates per condition.)
2) Splitting tensile strength test (ASTM C496) using 4” x 8” specimens at 3, 7, and 14 days. (Two replicates.)
3) Free shrinkage measurement (ASTM C157) using 3” x 3” x 11¼” specimens. (Two replicates.)
4) CLS test, run at ambient lab conditions, monitored continuously for a minimum of 14 days. (Two replicates.)

Tables 16 through 19 display the following averaged quantities: 1) measured elastic modulus, E; 2) measured induced stress in the CLS test, σ_{CL}; 3) measured strain in the CLS test, ε_{CL}; 4) measured free shrinkage, ε_{sh}, from ASTM C157 test; and, 5) computed induced tensile stress under a fully constrained condition, σ_{FC}, for the first six pairs of concrete mixes at 3, 7, and 14 days, and for the rest at 3 and 7 days only. The expected induced stresses in the concrete, if it were fully constrained, σ_{FC}, were calculated from the measured induced stress in the CLS test, σ_{CL}, the measured strain in the CLS test, ε_{CL}, and the measured elastic modulus, E, according to Equation (9).

It can be seen that the free shrinkage, ε_{sh}, the measured induced stress in the CLS test, σ_{CL}, and the computed induced tensile stress under a fully constrained condition, σ_{FC}, were significantly reduced with the addition of the shrinkage reducing admixture for all of the concrete mixes tested.

Table 16. Shrinkage Properties of Concrete Mixes 1 to 4

Time (Days)	E (psi)	Specim. Stress, s_E (psi)	Elastic Strain, e_E	Free Shrinkage Strain, e_{sh}	Total Specimen Strain, e_{CL}	Creep Strain, e_{CR}	Computed Shrinkage Stress, s_{FC} (psi)	Splitting Tensile Strength (psi)
Mix - 1								
Standard								
3	4455155	103	0.000023	0.000222	0.000104	0.000094	569*	429
7	5150415	157	0.000030	0.000300	0.000194	0.000076	1151*	594
14	5535946	185	0.000033	0.000380	0.000204	0.000142	1314*	614
Eclipse								
3	4731254	106	0.000022	0.000082	0.000026	0.000033	234	456
7	5404991	164	0.000030	0.000183	0.000043	0.000110	394	603
14	5716239	175	0.000031	0.000262	0.000072	0.000159	588	718
Mix - 2								
Standard								
3	6427326	138	0.000022	0.000189	0.000084	0.000083	682*	492
7	7168223	194	0.000027	0.000320	0.000120	0.000172	1058*	632
14	7285077	192	0.000026	0.000397	0.000154	0.000217	1316*	700
Eclipse								
3	6538004	23	0.000003	0.000092	0.000012	0.000077	95	384
7	6981284	60	0.000009	0.000167	0.000112	0.000047	813*	512
14	7068646	88	0.000012	0.000237	0.000171	0.000054	1290*	600
Mix - 3								
Standard								
3	2905150	28	0.000010	0.000163	0.000115	0.000270	362	354
7	3427850	210	0.000061	0.000323	0.000204	0.000058	908*	661
14	4082624	236	0.000058	0.000395	0.000247	0.000090	1243*	699
Eclipse								
3	3650126	10	0.000003	0.000097	0.000076	0.000018	288	329
7	4185281	138	0.000033	0.000219	0.000153	0.000033	779*	540
14	4193226	168	0.000040	0.000303	0.000215	0.000048	1069*	640
Mix-4								
Standard								
3	3055865	51	0.000017	0.000142	0.000065	0.000060	249	376
7	3462333	108	0.000031	0.000250	0.000147	0.000072	618*	617
14	3901191	139	0.000036	0.000317	0.000195	0.000086	899*	695
Eclipse								
3	3008550	79	0.000026	0.000044	0.000004	0.000013	92	395
7	3343896	151	0.000045	0.000110	0.000034	0.000031	267	607
14	3856788	167	0.000043	0.000181	0.000090	0.000047	507	644

* Computed stress exceeded splitting tensile strength and the specimen cracked

Table 17. Shrinkage Properties of Concrete Mixes 5 to 8

Time (days)	E (psi)	Specim. Stress, s_E (psi)	Elastic Strain, e_E	Free Shrinkage Strain, e_{sh}	Total Specimen Strain, e_{CL}	Creep Strain, e_{CR}	Computed Shrinkage Stress, s_{FC} (psi)	Splitting Tensile Strength (psi)
Mix - 5								
Standard								
3	2861518	59	0.000021	0.000114	0.000045	0.000048	187	410
7	3441955	154	0.000045	0.000254	0.000123	0.000087	575	547
14	3619022	180	0.000050	0.000312	0.000167	0.000095	783*	526
Eclipse								
3	2869918	47	0.000016	0.000041	0.000010	0.000014	76	391
7	3336697	102	0.000030	0.000111	0.000057	0.000024	293	457
14	3568982	120	0.000034	0.000181	0.000128	0.000019	576	494
Mix - 6								
Standard								
3	4455155	48	0.000011	0.000045	0.000003	0.000031	1314*	366
7	5150415	70	0.000014	0.000240	0.000132	0.000094	753*	521
14	5535946	76	0.000014	0.000326	0.000188	0.000124	1121*	686
Eclipse								
3	5404263	57	0.000011	0.000013	0.000013	-0.000011	127	321
7	6250985	71	0.000011	0.000141	0.000140	-0.000011	947*	534
14	6457045	76	0.000012	0.000214	0.000225	-0.000023	1530*	615
Mix - 7								
Standard								
3	3606318	51	0.000014	0.000106	0.000069	0.000023	300	467
7	3992038	130	0.000033	0.000206	0.000141	0.000032	696*	561
Eclipse								
3	3388225	35	0.000010	0.000025	0.000008	0.000007	64	365
7	3785151	110	0.000029	0.000085	0.000042	0.000014	269	499
Mix - 8								
Standard								
3	3684585	99	0.000027	0.000103	0.000067	0.000009	346	504
7	4046461	149	0.000037	0.000194	0.000128	0.000029	667*	618
Eclipse								
3	4161028	48	0.000012	0.000032	0.000018	0.000003	122	465
7	4293893	89	0.000021	0.000086	0.000057	0.000008	334	596

* Computed stress exceeded splitting tensile strength and the specimen cracked

Table 18. Shrinkage Properties of Concrete Mixes 9 to 12

Time (Days)	E (psi)	Specim. Stress, s_E (psi)	Elastic Strain, e_E	Free Shrinkage Strain, e_{sh}	Total Speci- men Strain, e_{CL}	Creep Strain, e_{CR}	Computed Shrinkage Stress, s_{FC} (psi)	Splitting Tensile Strength (psi)
Mix - 9								
Standard								
3	2820558	51	0.000018	0.000068	0.000024	0.000026	118	314
7	3273363	130	0.000040	0.000204	0.000112	0.000052	497	412
Eclipse								
3	2963033	35	0.000012	0.000022	0.000006	0.000004	53	336
7	3300901	110	0.000033	0.000083	0.000029	0.000021	204	371
Mix - 10								
Standard								
3	3052549	89	0.000029	0.000080	0.000047	0.000004	233	351
7	3280739	154	0.000047	0.000184	0.000109	0.000028	512	468
Eclipse								
3	3114178	55	0.000018	0.000018	0.000005	-0.000005	71	373
7	3298157	101	0.000031	0.000058	0.000035	-0.000007	216	449
Mix – 11								
Standard								
3	3226966	149	0.000046	0.000102	0.000049	0.000007	306	330
7	3666718	158	0.000043	0.000247	0.000164	0.000040	758*	508
Eclipse								
3	3189941	125	0.000039	0.000038	0.000001	-0.000002	127	368
7	3507181	128	0.000037	0.000123	0.000082	0.000004	417	507
Mix – 12								
Standard								
3	3992077	134	0.000034	0.000193	0.000103	0.000055	549*	451
7	4239146	157	0.000037	0.000314	0.000199	0.000079	999*	546
Eclipse								
3	3880440	104	0.000027	0.000083	0.000037	0.000019	246	384
7	4417371	118	0.000027	0.000164	0.000102	0.000035	568	506

* Computed stress exceeded splitting tensile strength and the specimen cracked

Table 19. Shrinkage Properties of Concrete Mixes 13 to 15

Time (Days)	E (psi)	Specim. Stress, s_E (psi)	Elastic Strain, e_E	Free Shrinkage Strain, e_{sh}	Total Specimen Strain, e_{CL}	Creep Strain, e_{CR}	Computed Shrinkage Stress, s_{FC} (psi)	Splitting Tensile Strength (psi)
Mix - 13								
Standard								
3	3861868	119	0.000031	0.000212	0.000138	0.000043	654*	444
7	4539476	139	0.000031	0.000390	0.000281	0.000079	1413*	571
Eclipse								
3	4138054	107	0.000026	0.000086	0.000048	0.000013	304	404
7	4757098	132	0.000028	0.000183	0.000131	0.000025	754*	525
Mix - 14								
Standard								
3	3842707	100	0.000026	0.000094	0.000068	0.000000	361	346
7	3886822	134	0.000034	0.000162	0.000120	0.000008	599*	452
Eclipse								
3	3556466	93	0.000026	0.000037	0.000008	0.000002	122	324
7	4001058	119	0.000030	0.000084	0.000037	0.000017	269	429
Mix - 15								
Standard								
3	4167444	101	0.000024	0.000149	0.000108	0.000017	552*	647
7	4962452	144	0.000029	0.000228	0.000160	0.000039	936*	698
Eclipse								
3	4384647	111	0.000025	0.000075	0.000036	0.000014	266	528
7	4887643	155	0.000032	0.000124	0.000072	0.000020	508	707

* Computed stress exceeded splitting tensile strength and the specimen cracked

The compressive strength, splitting tensile strength, and the elastic modulus of the 15 pairs of concrete mixtures are shown in Tables 20 through 24.

Conclusions

From the test data and the analysis results obtained from the 30 concrete mixes tested, the developed CLS method demonstrated that it provided reasonable assessment of expected shrinkage-induced stresses in the concrete. Due to the creep of concrete at early age, the shrinkage-induced stress in the concrete was much lower than that estimated by multiplying the shrinkage strain by the elastic modulus of the concrete. Using the CLS test method enabled the creep component to be properly considered and a realistic determination of the expected induced shrinkage stresses in concrete in service. It is recommended that further tests may have to be conducted to see if it works with larger sizes of aggregate mixtures as well as for mixtures with fibers in them.

Table 20. Compressive Strength, Splitting Tensile Strength, and Elastic Modulus of the 15 Pairs of Concrete Mixtures

Mixes	Time (days)	E (psi)			Compressive Strength (psi)				Splitting Tensile Strength (psi)			
		1	2	Average	1	2	3	Average	1	2	3	Average
Mix - 1 (C-50, S-50), Std (w/c - 0.33)	3	4416855	4493455	4455155	4810	4470	5004	4761	461	396	428	429
	7	5308886	4991944	5150415	6950	7050	6790	6930	654	577	551	594
	14	5640288	5431603	5535946	7700	8160	7740	7867	614	551	676	614
Mix - 1 (C-50, S-50), Ecl (w/c - 0.33)	3	4584048	4878461	4731254	5030	4830	5020	4960	441	423	504	456
	7	5438242	5371741	5404991	7090	7120	7400	7203	640	613	557	603
	14	5642459	5790019	5716239	8220	8150	8410	8260	788	696	670	718
Mix - 2 (C-30, S-70), Std (w/c - 0.25)	3	6224478	6630175	6427326	6700	6440	6520	6553	493	486	495	492
	7	7063727	7272718	7168223	8710	8434	8430	8525	658	636	602	632
	14	7271631	7298524	7285077	9370	8760	8560	8897	694	726	680	700
Mix - 2 (C-30, S-70), Ecl (w/c - 0.25)	3	6445834	6169017	6307425	4710	4810	4960	4827	383	366	403	384
	7	6689849	6790581	6740215	6550	6650	6830	6677	506	516	513	512
	14	6838769	7231382	7035076	7360	7270	7070	7233	607	599	595	600
Mix - 3 (C-30, S-70), Std (w/c - 0.30)	3	2978144	2832156	2905150	4270	4310	4130	4237	314	384	365	354
	7	3386258	3469441	3427850	5695	5469	5442	5535	709	657	616	661
	14	4044965	4120283	4082624	7450	7570	7560	7527	773	656	667	699
Mix - 3 (C-30, S-70), Ecl (w/c - 0.29)	3	3618629	3681622	3650126	3590	3530	3570	3563	322	360	304	329
	7	4208640	4161921	4185281	5399	5620	5570	5530	565	555	499	540
	14	4181911	4204542	4193226	7170	6870	6870	6970	610	651	660	640

Table 21. Compressive Strength, Splitting Tensile Strength, and Elastic Modulus of the 15 Pairs of Concrete Mixtures

Mixes	Time (days)	E (Psi)			Compressive Strength				Splitting Tensile Strength (psi)			
		1	2	Average	1	2	3	Average	1	2	3	Average
Mix - 4 (C-80, F-20), Std (w/c-0.35)	3	3138865	2972865	3055865	2910	2830	2970	2903	360	403	366	376
	7	3511892	3412774	3462333	6680	6750	6520	6650	604	660	587	617
	14	3881511	3920872	3901191	7870	7910	8100	7960	766	632	688	695
Mix - 4 (C-80, F-20), Ecl (w/c-0.33)	3	3044235	2906975	2975605	2000	2040	2060	2033	391	400	395	395
	7	3275018	3464325	3369671	6400	6250	6370	6340	571	626	623	607
	14	3792704	3740321	3766512	7900	7940	7920	7920	646	656	630	644
Mix - 5 (C-65, F-35), Std (w/c-0.33)	3	3000886	2722150	2861518	3440	3460	3430	3443	376	415	439	410
	7	3390959	3492951	3441955	4500	4560	4530	4530	533	590	519	547
	14	3661683	3576361	3619022	5580	5540	5640	5587	566	471	542	526
Mix - 5 (C-65, F-35), Ecl (w/c-0.33)	3	2880273	2859563	2869918	3230	3300	3320	3283	406	436	331	391
	7	3382939	3290456	3336697	4710	4520	4510	4580	489	390	491	457
	14	3616783	3521181	3568982	5540	5540	5550	5543	529	487	464	494
Mix - 6 (C-30, S-50 & F-20), Std (w/c-0.35)	3	2618982	2622861	2620921	2450	2410	2380	2413	381	345	372	366
	7	3120751	3162391	3141571	4690	4790	4620	4700	574	496	492	521
	14	3514496	3510558	3512527	6669	6465	6903	6679	669	726	664	686
Mix - 6 (C-30, S-50 & F-20), Ecl (w/c-0.35)	3	2535208	2548807	2542007	2280	2210	2400	2297	376	303	284	321
	7	3349643	3362484	3356063	4720	4780	4690	4730	481	542	578	534
	14	3495439	3537646	3516542	6030	6450	6365	6282	649	588	607	615

Table 22. Compressive Strength, Splitting Tensile Strength, and Elastic Modulus of the 15 Pairs of Concrete Mixtures

Mixes	Time (days)	E (Psi)			Compressive Strength				Splitting Tensile Strength (psi)			
		1	2	Average	1	2	3	Average	1	2	3	Average
Mix - 7 (C-80, F-20), Std (w/c - 0.34)	3	3606318	3606318	3606318	4463	4439	4455	4452	465	467	467	467
	7	4076555	3900563	3988559	5855	6324	6006	6061	644	499	539	561
	14	4525851	4304663	4415257	7533	7509	7239	7427	581	478	606	555
	28	4537320	4525331	4531325	8002	8328	8265	8198	576	684	551	604
Mix - 7 (C-80, F-20), Ecl (w/c - 0.34)	3	3388225	3388225	3388225	3516	3548	3572	3545	376	366	354	365
	7	3729430	3840872	3785151	5194	5417	5314	5308	493	447	557	499
	14	3983873	3991834	3987853	6356	6197	6339	6297	552	514	523	530
	28	4138115	4332631	4235373	7636	7422	7517	7525	616	598	676	630
Mix - 8 (C-80, F-20), Std (w/c - 0.38)	3	3631600	3737570	3684585	4733	4781	4789	4767	483	512	516	504
	7	4056772	4036149	4046461	6539	6491	6658	6563	611	634	611	618
	14	4314802	4203692	4259247	7453	7557	7350	7453	718	718	704	713
	28	4497366	4609553	4553460	8178	8399	8341	8306	1970	2057	2100	2043
Mix - 8 (C-80, F-20), Ecl (w/c - 0.38)	3	4019694	4260053	4139874	4964	4805	4932	4900	413	520	463	465
	7	4281844	4305943	4293893	6722	6499	6451	6557	616	611	561	596
	14	4728351	4441247	4584799	7525	7636	7366	7509	628	734	595	652
	28	4724886	4831122	4778004	7881	8227	8402	8170	693	745	610	683
Mix - 9 (C-65, F-35), Std (w/c - 0.46)	3	2847699	2793418	2820558	2426	2490	2498	2471	326	290	326	314
	7	3230478	3316248	3273363	3651	3611	3611	3625	457	446	334	412
	14	3446445	3625646	3536046	4789	4653	4797	4746	479	557	563	533
	28	3599945	3822791	3711368	5878	5688	5823	5796	636	636	545	606
Mix - 9 (C-65, F-35), Ecl (w/c – 0.46)	3	2997575	2928491	2963033	2538	2649	2561	2583	358	318	332	336
	7	3223592	3378211	3300901	3802	3938	3985	3908	369	377	368	371
	14	3607691	3715169	3661430	4828	4868	4852	4850	561	519	416	498
	28	3864973	3711668	3788320	5727	5759	5664	5717	531	614	601	582

Table 23. Compressive Strength, Splitting Tensile Strength, and Elastic Modulus of the 15 Pairs of Concrete Mixtures

Mixes	Time (days)	E (psi)			Compressive Strength (psi)				Splitting Tensile Strength (psi)			
		1	2	Average	1	2	3	Average	1	2	3	Average
Mix - 10 (C-65, F-35), Std (w/c - 0.41)	3	2936739	3168360	3052549	2657	2792	2919	2789	360	364	328	351
	7	3295355	3266124	3280739	3651	3699	3906	3752	457	461	485	468
	14	3466569	3496266	3481417	4598	4765	4741	4701	523	523	463	503
	28	3702587	3719864	3711225	5759	5775	5743	5759	573	602	507	561
Mix - 10 (C-65, F-35), Ecl (w/c - 0.41)	3	3161160	3067196	3114178	2681	2705	2832	2739	360	382	378	373
	7	3240103	3356210	3298157	3866	3874	3930	3890	469	497	380	449
	14	3601638	3626390	3614014	5003	4860	4988	4950	507	459	581	516
	28	3712301	3959791	3836046	5839	5950	6157	5982	403	541	499	481
Mix-11 (C-80, F-20), Std (w/c - 0.46)	3	3258290	3195641	3226966	3691	3683	3747	3707	322	326	344	330
	7	3720572	3612864	3666718	5520	5409	5345	5425	464	612	447	508
	14	3862169	3827133	3844651	6064	6006	5979	6016	490	555	477	507
	28	4145363	4255670	4200516	7151	7199	7247	7199	542	441	537	506
Mix-11 (C-80, F-20), Ecl (w/c - 0.46)	3	3143982	3235900	3189941	3524	3516	3675	3572	346	439	320	368
	7	3498332	3516031	3507181	4956	5051	4972	4993	490	470	562	507
	14	3610294	3660458	3635376	5688	5823	5611	5707	549	542	604	565
	28	3834219	3949312	3891766	7151	7366	6889	7135	667	687	688	681
Mix-12 (C-30, S-50, F-20), Std (w/c -0.28)	3	3550043	4434111	3992077	4844	4645	5019	4836	414	414	527	451
	7	4203387	4274906	4239146	6618	6411	6634	6555	577	501	560	546
	14	4369976	4487084	4428530	7485	7533	7453	7491	594	543	652	596
	28	4591187	4564588	4577888	7803	8130	8225					
Mix-12 (C-30, S-50, F-20), Ecl (w/c-0.28)	3	4100167	3660713	3880440	3810	3922	3961	3898	362	430	360	384
	7	4442825	4391918	4417371	5727	5791	5759	5759	505	505	506	506
	14	4542769	4575835	4559302	6364	7016	6698	6692	593	577	614	595
	28	4794909	4926751	4860830	7247	7207	7151	7202	524	579	553	552

Table 24. Compressive Strength, Splitting Tensile Strength, and Elastic Modulus of the 15 Pairs of Concrete Mixtures

Mixes	Time (days)	E (Psi)			Compressive Strength				Splitting Tensile Strength			
		1	2	Average	1	2	3	Average	1	2	3	Average
Mix-13 (C-50, S-50), Std (w/c - 0.41)	3	3735773	3987963	3861868	6189	6491	6523	6401	414	507	412	444
	7	4570450	4508502	4539476	8114	8193	8201	8169	556	498	659	571
	14	4747266	5123076	4935171	9259	9378	9514	9384	755	671	729	718
	28	4781950	5146989	4964470	9657	9736	9553	9649	911	656	867	811
Mix-13 (C-50, S-50), Ecl (w/c - 0.41)	3	4111928	4164180	4138054	5497	5314	5417	5409	406	410	396	404
	7	4658387	4855809	4757098	7398	7278	7613	7430	483	515	576	525
	14	5001046	5001046	5001046	8543	8519	8710	8591	509	562	646	572
	28	5177606	5134069	5155838	9044	9148	9108	9100	789	599	629	672
Mix-14 (C-65, F-35), Std (w/c - 0.30)	3	3858952	3826463	3842707	3475	3523	3378	3459	287	383	367	346
	7	3886822	2911755	3886822	4542	4470	4311	4441	467	436	453	452
	14	4423983	4366718	4395351	5505	5377	5170	5351	515	533	545	531
	28	5580151	4812471	5196311	7239	7382	6928	7183	611	509	723	615
Mix -14 (C-65, F-35), Ecl (w/c - 0.30)	3	3556466	3341947	3449206	3043	2954	2980	2993	313	327	331	324
	7	3965263	4036854	4001058	4176	4073	4120	4123	475	416	396	429
	14	4441069	4218399	4329734	5003	5338	4828	5056	481	515	561	519
	28	4592010	4711529	4651769	6618	6570	6284	6491	526	508	507	514
Mix-15 (C-100), Std (w/c - 0.29)	3	3803863	4510687	4157275	7764	8082	7835	7894	618	622	702	647
	7	5039900	5039900	5039900	10047	9561	9713	9773	651	722	722	698
	14	5315464	5123516	5219490	11192	10595	10206	10664	769	768	611	716
	28	5322837	5471778	5397307	11089	11526	11574	11396	597	692	716	668
Mix-15 (C-100), Ecl (w/c - 0.29)	3	4408573	4323830	4366202	6109	6173	6109	6130	528	472	585	528
	7	3366304	4917633	4917633	7692	7589	7772	7684	696	679	745	707
	14	5035781	5669101	5352441	9052	8480	8480	8670	627	504	532	554
	28	5234741	5439419	5337080	9076	9386	9593	9352	730	678	571	660

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Biographies

RAJARAJAN SUBRAMANIAN is a lecturer in the Civil Engineering Department at the Pennsylvania State University at Harrisburg. Dr. Subramanian graduated with a bachelor's degree in Civil and Structural Engineering from Annamalai University in India. He obtained his master's and doctoral degrees from the University of Florida. He has over 25 years of experience working for government, industry, and academia. Dr. Subramanian may be reached at rus30@psu.edu

MANG TIA is a professor of Civil Engineering at the Engineering School of Sustainable Infrastructure and Environment, University of Florida. Dr. Tia has more than 30 years of experience as an academician. His research interests include Portland cement concrete and asphalt concrete. He has published more than 50 technical journal and conference papers and currently is the Graduate Coordinator of the Civil and Coastal Engineering Department at the University of Florida. Dr. Tia may be reached at tia.ce@ufl.edu

MICHAEL J. BERGIN has 25 years of working experience with the Florida Department of Transportation as a Materials Engineer. Prior to his working at FDOT, Mr. Bergin was working residential and commercial construction for 10 years. He graduated with a bachelor's degree in Civil Engineering from the University of Florida. At the national level, he is actively involved in the FHWA High Performance Concrete Technical Delivery Team, and serves as a member of a task team harmonizing the AASHTO and ASTM Cement Specifications. Within the Department, he is a member of the Construction Technical Review Team for concrete qualifications required for testing and inspection. Mr. Bergin may be reached at michael.bergin@dot.state.fl.us

CHARLES A. ISHEE is currently working with Applied Research Associates, Inc., as a materials engineer. Prior to his working at ARA, he worked as a concrete materials engineer at the Florida Department of Transportation for more than 10 years. Mr. Ishee may be reached at charles.ishee@ara.com