FINAL REPORT

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DEVELOPMENT OF A LABORATORY PROCEDURE FOR EVALUATING CONCRETE MIXES FOR RESISTANCE TO SHRINKAGE CRACKING IN SERVICE

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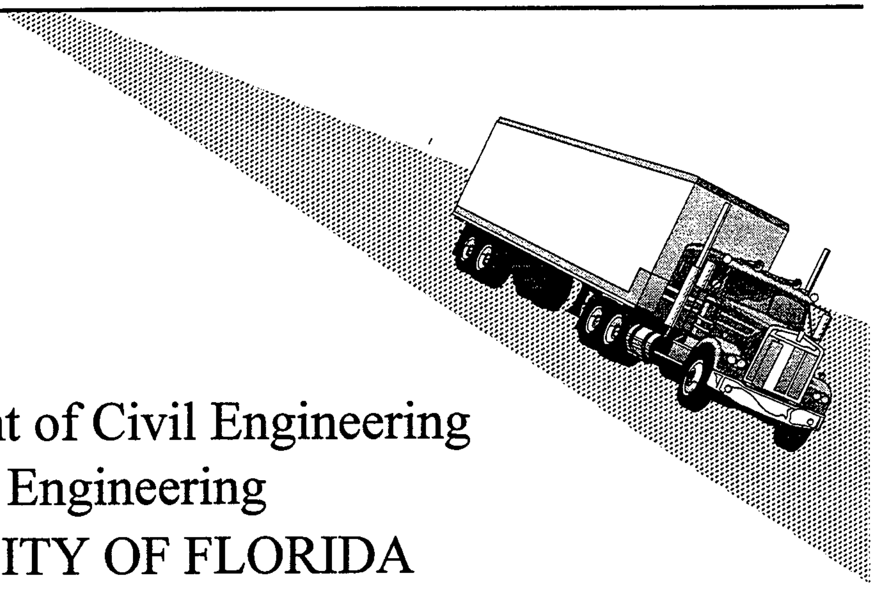

Department of Civil Engineering
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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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TECHNICAL SUMMARY

A laboratory investigation was conducted to develop an effective and convenient laboratory test set-up and procedure for evaluating concrete mixes for their resistance to shrinkage cracking in service. The three methods evaluated in this study include (1) a constrained ring specimen method, (2) a constrained long specimen method, and (3) a constrained plate method. Two different concretes (a Florida Class II & Class IV) which had shown shrinkage cracking problems in service were used to evaluate these test methods.

This research study has resulted in the development of a very promising testing and analysis method for evaluating concrete mixes for resistance to shrinkage cracking in service. Based on the test results from this study, the modified constrained long specimen method appeared to measure reasonable values of stresses and strains. The creep strains that might develop in the concrete during setting could be determined conveniently and effectively by means of this apparatus. Since the creep strain that developed in the concrete had the effect of reducing the induced shrinkage stress, proper determination of creep strain was crucial in the accurate estimation of shrinkage stresses in a concrete. The use of the modified constrained long specimen method makes a realistic determination of the induced shrinkage stresses possible. This testing and analysis method should be further evaluated, refined and implemented as a standard procedure for evaluating shrinkage cracking resistance of concrete used by FDOT, especially for bridge deck applications.

CHAPTER 1
INTRODUCTION

1.1 Background

Shrinkage cracking of concrete bridge decks is a critical problem in Florida and in many states throughout the United States. 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 have indicated that high-performance concretes, which are usually produced by using a 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. Unfortunately, the tendency of a concrete to shrinkage cracking is not just a simple function of its free shrinkage. It 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 stress due to shrinkage. All these pertinent factors need to be fully considered in evaluating a concrete mix for its resistance to shrinkage cracking.

At present, there does not exist an effective and convenient test procedure which could be used to assess the resistance to shrinkage cracking of a concrete in service. Therefore, there is a great need to develop an effective method for this purpose.

1.2 Study Objective

The main objective of this research is to develop an effective and convenient laboratory test set-up and procedure for evaluating concrete mixes for their resistance to shrinkage cracking in service.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of available methods for determining shrinkage cracking potential of concrete in service.

2.2 Constrained Ring Specimen Method

A literature review on methods for evaluating concrete for resistance to shrinkage cracking was conducted. Three test methods of particular interest are summarized in this study. The first test method of interest is a restrained shrinkage cracking test using a constrained ring specimen (Wiegrink et al. 1996). Figure 2.1 illustrates the dimension of the test specimen and the apparatus. The test specimen was made by casting a layer of concrete 35 mm (1.4 in.) in thickness and 140 mm (5.5 in.) in height around a steel ring which had an outer diameter of 205 mm (8 in.). 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 6 hours at 20 °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 observed and used as indicators of shrinkage cracking potential of the concrete.

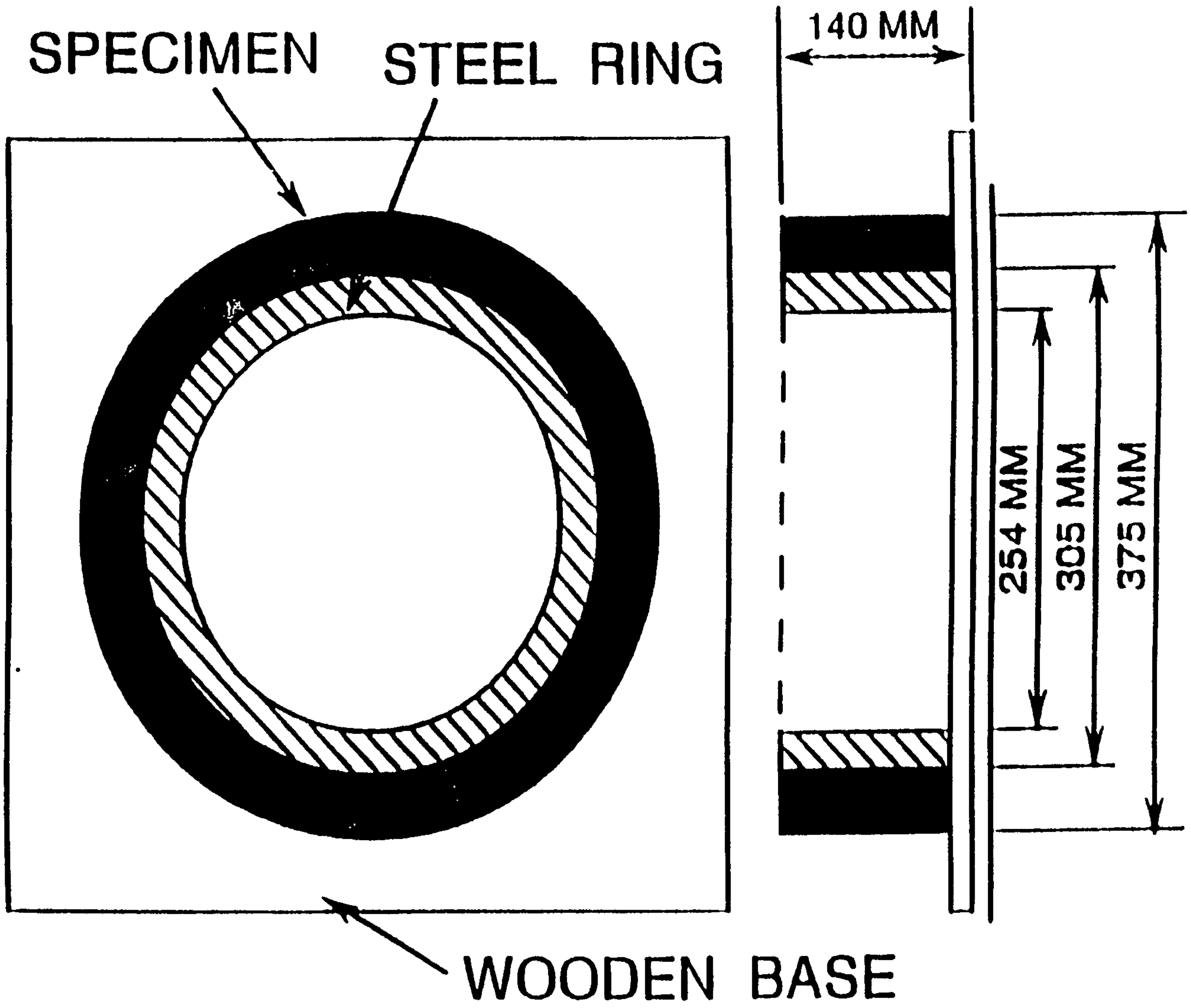

Figure 2.1 Method 1-Constrained Ring Specimen (Wiegrink et al. 1996)

Crack widths were measured by means of a special microscope.

2.3 Constrained Long Specimen Method

The second test method studied was a restrained shrinkage test using a long specimen with flared ends (Bloom et al. 1995). Figure 2.2 illustrates the schematic of the apparatus. The concrete specimen was 40 X 40 mm (1.6 X 1.6 in.) in cross section and 1000 mm (39 in.) long. It increases gradually in width at the two ends, which fit into two end grips. One grip (#1 in figure) was fixed, and the other was free to move and could be monitored by a dial gage (#9). To fabricate a test specimen, the fresh concrete would be casted directly into the apparatus. The two sides (#2) 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 gage (#9) 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 (#7 and #8), connected to the grip (#5) through a load cell (#6), which could measure the load exerted on the concrete. Synthetic resin-coated rails (#3) 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 2 mm (0.08 in.) was provided between the movable grip and the bar supporting the concrete specimen. Dial gages (#9) could be mounted on both sides of the movable grip to monitor the extent of the eccentricity.

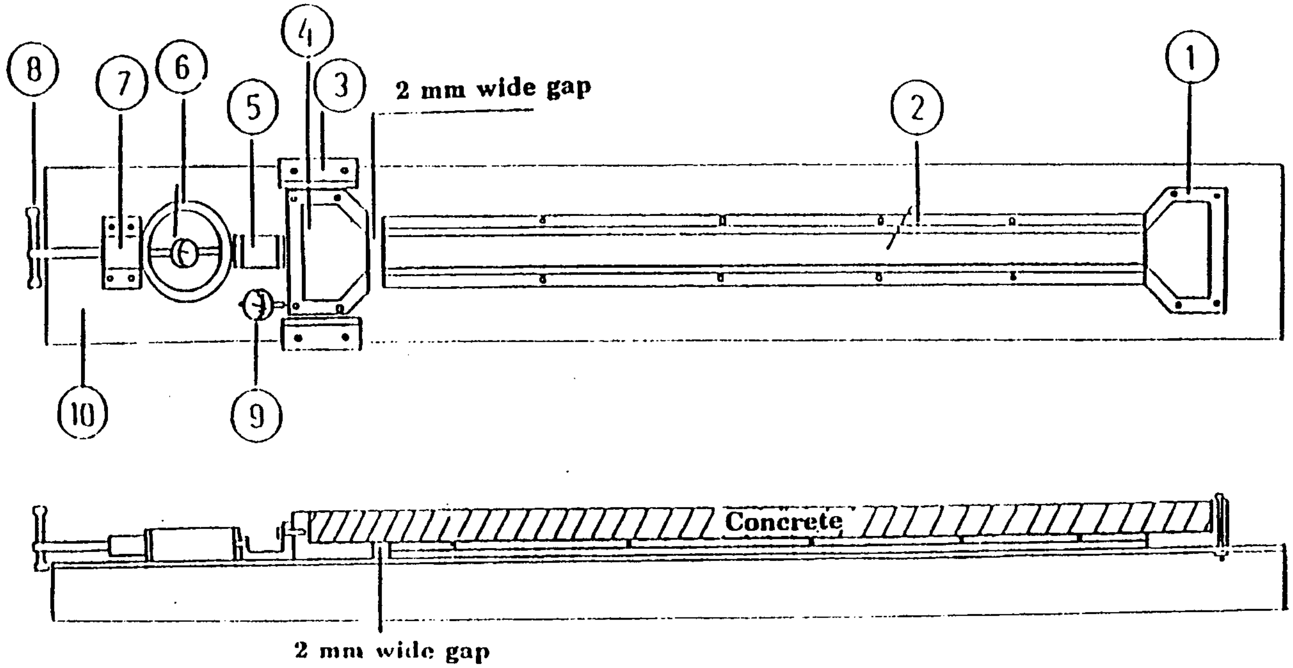

Figure 2.2 Method 2-Constrained Long Specimen With Flared Ends (Bloom et al. 1995)

2.4 Constrained Plate Specimen Method

The third test method is another restrained shrinkage cracking test using rectangular plate specimens, as shown in Figure 2.3 (Shaeles et al. 1988). Specimens were made by casting concrete into forms to produce 610 X 910 mm (24 X 36 in.) rectangular panels with a thickness of 20 mm (3/4 in.). The forms were made of plexiglass to prevent absorption of moisture from the concrete mix. An expended metal lath was attached to the inside perimeter to provide edge restraint to the concrete.

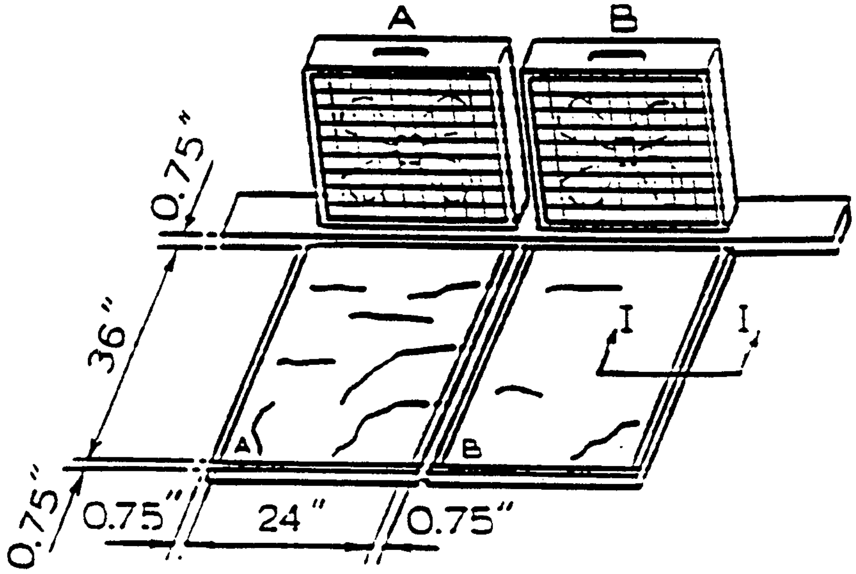

Figure 2.3 Method 3 - Constrained Plate Specimen (Shaeles et al. 1988)

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 3.1 to 3.6 m/sec (7 to 8 mph). The length and average width of the cracks which might develop during the test were recorded and expressed as total crack area in mm^2.

CHAPTER 3
MATERIALS

3.1 Concrete Mixes Used

Mix design information on two concrete mixtures which have experienced shrinkage problems in Florida were provided by the Florida Department of Transportation. These two concrete mixes were to be reproduced in the laboratory and evaluated with the various apparatuses used in this study. The original mix design information for these two concrete mixtures are shown in Tables 3.1 and 3.2. These are Florida Class II and IV concretes which have been used in bridge decks in south Florida. For convenience, a coarse aggregate from a different source (Brooksville #89) was used to produce these mixtures in the laboratory. It is believed that since the aggregate used is also a Florida limestone and thus similar in characteristics to the original one, the shrinkage properties of the concrete should not be changed much by this change of aggregate source. The properties of the aggregates used are displayed in Table 3.3. The chemical composition and physical properties of the cement used along with the requirements for Type I and Type II cements are displayed in Tables 3.4 and 3.5. It can be seen that this cement satisfied both the requirements for Type I and Type II cements. The mix designs for these two concretes were adjusted for the different properties of the aggregates used and are shown in Tables 3.6 and 3.7.

Table 3.1 Mix Design Information on a Class II Concrete (with Shrinkage Problem)

Materials	Types	Weight (lb/yd^3)
Cement	AASHTO M-85 Type I	520.00 lb/yd^3 (309 kg/m^3)
Coarse Aggregate	Crushed Limestone Grade: #57 S.G. (SSD): 2.43	1680.00 lb/yd^3 (998 kg/m^3)
Fine Aggregate	Silica Sand F.M.: 2.20 S.G. (SSD): 2.63	1175.00 lb/yd^3 (698 kg/m^3)
Air Entr. Admixture (DAREX)	AASHTO M-154	0.25 lb/yd^3 (0.15 kg/m^3)
Water Reducing Admixture	AASHTO M-194 Type D	2.79 lb/yd^3 (1.66 kg/m^3)
Fly Ashes	ASTM C-618 Class F	115.00 lb/yd^3 (68 kg/m^3)
Water	-	262.00 lb/yd^3 (156 kg/m^3)
Slump Range	1.50 to 4.50 in. (3.81 to 11.43 cm)	
Air Content	2.4% to 5.6%	
Unit Weight Wet	139.20 lb/ft^3 (2233 kg/m^3)	
Water Cement Ratio	0.41	
Max. Allowable w/c	0.44	

Table 3.2 Mix Design Information on a class IV Concrete (with Shrinkage Problem)

Materials	Types	Weight
Cement	AASHTO M-85 Type I	584 lb/yd^3 (347 kg/m^3)
Coarse Aggregate	Crushed Limestone Grade: #57 S.G. (SSD): 2.43	1708 lb/yd^3 (640 kg/m^3)
Fine Aggregate	Silica Sand F.M.: 2.20 S.G. (SSD): 2.63	1075 lb/yd^3 (638 kg/m^3)
Air Entr. Admixture (DAREX)	AASHTO M-154	0.51 lb/yd^3 (0.30 kg/m^3)
Water Reducing Admixture	AASHTO M-194 Type D	2.57 lb/yd^3 (1.53 kg/m^3)
2ND Admixture	Special Provisions	36 lb/yd^3 (21 kg/m^3)
Fly Ashes	ASTM C-618 Class F	146 lb/yd^3 (87 kg/m^3)
Water	-	231 lb/yd^3 (137 kg/m^3)
Slump Range	1.50 to 4.50 in. (3.81 to 11.43 cm)	
Air Content	2.0% to 6.0%	
Unit Weight Wet	140.10 lb/ft^3 (2246 kg/m^3)	
Water Cement Ratio	0.36	
Max. Allowable w/c	0.41	

Table 3.3 Properties of Aggregates Used

	Coarse Aggregate Brooksville	Fine Aggregate Goldhead
Dry Bulk Spec. Gravity	2.41	2.43
Absorption (%)	4.86	0.56
Natural Moisture Content (%)	0.16	0.20
Dry-Rodded Unit Weight	88.40 lb/ft^3 (52.53 kg/m^3)	-
Max. Size of Aggregate	3/8 in. (9.5 mm)	-
Fineness Modulus	-	2.20

Table 3.4 Chemical Composition and Properties of Type I Portland Cement Used

TESTS PERFORMED BY BROOKSVILLE CEMENT LAB SOUTHDOWN, INC.			Specification Limits			
			Type I		Type II	
Chemical Composition	Test Result		ASTM C-150	ASTM M-85	ASTM C-150	ASTM M-85
% Silicon Dioxide (SiO_2)	20.96	Min %	-	-	20.00	20.00
% Aluminum Oxide (Al_2O_3)	5.01	Max %	-	7.50	6.00	6.00
% Ferric Oxide (Fe_2O_3)	3.92	Max %	-	6.00	6.00	6.00
% Calcium Oxide (CaO)	63.28	-	-	-	-	-
% Magnesium Oxide (MgO)	0.76	Max %	6.00	6.00	6.00	6.00
% Sulfur Trioxide (SO_3) When C_3A is 8.0% or less When C_3A is over 8.0%	2.91	 Max % Max %	 3.00 3.50	 3.00 3.50	 3.00 -	 -
% Tricalcium Silicate (C_3S)	50.56	Max %	-	-	-	55.00
% Tricalcium Aluminate (C_3A)	7.57	Max %	-	-	8.0	8.0
% Alalis (Na_2O+0.658K_2O)	0.49	Max %	-	0.60	-	0.60
% Insoluble Residue	0.24	Max %	0.75	0.75	0.75	0.75
% Loss on Ignition	1.80	Max %	3.00	3.00	3.00	3.00
Physical Properties						
Fineness: Blaine (m^2/kg)	388	Max %	-	400	-	400
Time of Setting (Gillmore): Initial (hr : min) Final (hr : min)	 1:52 3:55	 Min Max	 1:00 10:00	 1:00 10:00	 1:00 10:00	 1:00 10:00
% Air Content	7.31	Max %	12.00	12.00	12.00	12.00
Compressive Strength (MPa) 1 Day:	13.38	-	-	-	-	-
2 Day:	23.16	Min	12.41	12.41	10.34	10.34
7 Day:	30.32	Min	19.30	19.30	19.30	19.30

Table 3.5 Chemical Composition and Properties of Type II Portland Cement Used

TESTS PERFORMED BY STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION			Specification Limits			
			Type I		Type II	
Chemical Composition	Test Result		ASTM C-150	ASTM M-85	ASTM C-150	ASTM M-85
% Silicon Dioxide (SiO_2)	21.70	Min %	-	-	20.00	20.00
% Aluminum Oxide (Al_2O_3)	5.20	Max %	-	7.50	6.00	6.00
% Ferric Oxide (Fe_2O_3)	4.20	Max %	-	6.00	6.00	6.00
% Calcium Oxide (CaO)	-	-	-	-	-	-
% Magnesium Oxide (MgO)	0.77	Max %	6.00	6.00	6.00	6.00
% Sulfur Trioxide (SO_3)	2.60					
When C_3A is 8.0% or less		Max %	3.00	3.00	3.00	-
When C_3A is over 8.0%		Max %	3.50	3.50	-	
% Tricalcium Silicate (C_3S)	41.20	Max %	-	-	-	55.00
% Tricalcium Aluminate (C_3A)	6.70	Max %	-	-	8.0	8.0
% Alalis ($Na_2O+0.658K_2O$)	0.51	Max %	-	0.60	-	0.60
% Insoluble Residue	0.52	Max %	0.75	0.75	0.75	0.75
% Loss on Ignition	1.20	Max %	3.00	3.00	3.00	3.00
Physical Properties						
Fineness: Blaine (m^2/kg)	388	Max %	-	400	-	400
Time of Setting (Gillmore):						
Initial (hr : min)	2:22	Min	1:00	1:00	1:00	1:00
Final (hr : min)	4:14	Max	10:00	10:00	10:00	10:00
% Air Content	-	Max %	12.00	12.00	12.00	12.00
Compressive Strength (MPa)						
1 Day:	-	-	-	-	-	-
3 Day:	19.85	Min	12.41	12.41	10.34	10.34
7 Day:	26.32	Min	19.30	19.30	19.30	19.30

Table 3.6 Mix Design of Concrete Prepared in Laboratory and Properties of Fresh Concrete for Florida Class II Concrete

Materials	Weight
Water	326 lb/yd^3 (194 kg/m^3)
Cement (Type I)	520 lb/yd^3 (309 kg/m^3)
Fly Ash	115 lb/yd^3 (68 kg/m^3)
Coarse Aggregate	1243 lb/yd^3 (738 kg/m^3)
Fine Aggregate	1522 lb/yd^3 (904 kg/m^3)
Air Entr. Admixture (DAREX)	0.27 lb/yd^3 (0.16 kg/m^3)
Water Reducing Admixture (WRDA 64)	2.70 lb/yd^3 (1.60 kg/m^3)
Unit Weight	138 lb/ft^3 (2213 kg/m^3)
Properties of Fresh Concrete	
Slump	1.6 in. (4.1 cm)
Unit Weight	137 lb/ft^3 (2197 kg/m^3)
Air Content	2.6 %

Table 3.7 Mix Design of Concrete Prepared in Laboratory and Properties of Fresh Concrete for Florida Class IV Concrete

Materials	Weight
Water	263 lb/yd^3 (157 kg/m^3)
Cement (Type II)	584 lb/yd^3 (348 kg/m^3)
Fly Ash	146 lb/yd^3 (87 kg/m^3)
Coarse Aggregate	1196 lb/yd^3 (712 kg/m^3)
Fine Aggregate	1625 lb/yd^3 (967 kg/m^3)
Air Entr. Admixture (DAREX)	0.30 lb/yd^3 (0.12 kg/m^3)
Water Reducing Admixture (WRDA 64)	1.51 lb/yd^3 (0.90 kg/m^3)
DCI-S Corrosion Inhibtor Admixture	21.33 lb/yd^3 (12.69 kg/m^3)
Unit Weight	141 lb/ft^3 (2266 kg/m^3)
Properties of Fresh Concrete	
Slump	1.75 in. (4.4 cm)
Unit Weight	139 lb/ft^3 (2233 kg/m^3)
Air Content	2.0 %

3.2 Preparation of Concrete Mixtures

The concrete batches were mixed in a rotary drum mixer. The surface of the mixer was rinsed with water before mixing to avoid water absorption and to ensure the same mixing conditions for all mixes. Water was drained before mixing. First, the coarse aggregates and fine aggregates were mixed for 5 minutes with one-half of mixing water in the mixer to ensure proper dispersion. The cement, fly ashes, air entrained admixture, water reducing admixture and the remaining water were then added, and the mixing was continued for an additional 5 minutes. The mixer was stopped frequently, and the material sticking to the mixer was broken loose to facilitate mixing. After the mix appeared uniformly mixed, slump test was run on the fresh concrete. Additional water reducing agent would be added if the slump was too low.

CHAPTER 4
TEST APPARATUSES TO BE EVALUATED

4.1 Introduction

After a literature review on existing experimental test methods for evaluation of shrinkage cracking resistance of concrete was conducted, three promising methods were selected for evaluation in this study. These three promising methods were the constrained ring specimen (method 1), constrained long specimen (method 2), and constrained plate method (method 3). This chapter presents the modifications of these three test apparatuses to be evaluated.

4.2 Constrained Ring Specimen Method (Method 1)

4.2.1 Design

Two different apparatuses for the constrained ring specimen method (Method 1) were designed and constructed. The schematic of the first apparatus constructed is shown in Figure 4.1. It uses two semicircular steel strips which can be fastened together to form an outer mold with an inner diameter of 356 mm (14 in.). The inner ring was made by a steel pipe with an outer diameter of 299 mm (12 in.) and a height of 140 mm (5.6 in.). Both the inner ring and the outer mold were placed concentrically on a 610 X 610 mm (24 X 24 in.) steel plate and fastened to it through screws and bolts. The inner ring had four pre-drilled threaded holes at the bottom and was fastened to the steel plate by means for four screws through four pre-drilled holes on the plate. The outer mold was fastened

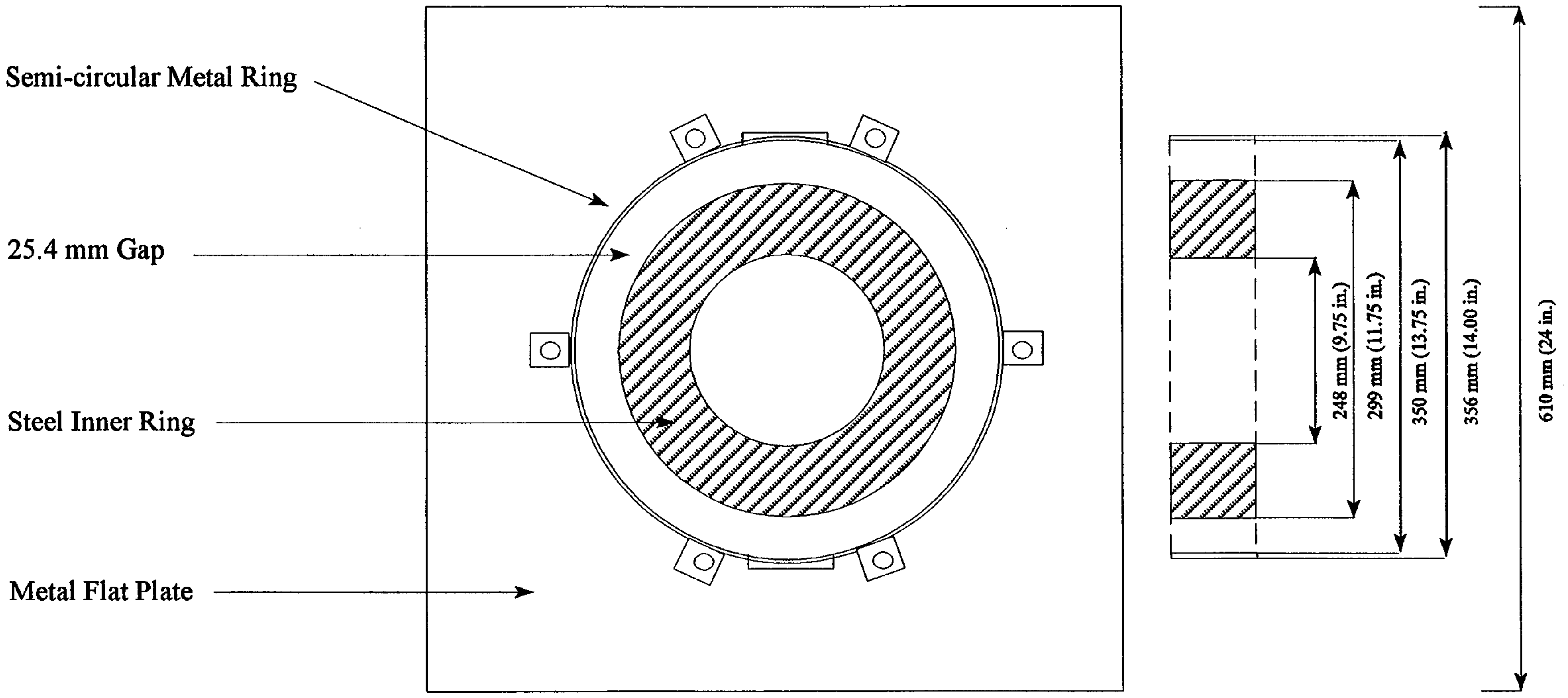

Figure 4.1 Constrained Ring Specimen Using Steel Ring Outer Mold

to the base plate by means of six bolts which were welded to the plate.

The second apparatus constructed was similar to the first apparatus with an exception that a PVC tube, instead of a steel ring, was used as the outer mold. The schematic of the apparatus is shown in Figure 4.2. The inner steel ring was fastened to the steel plate in the same way as for the first apparatus. The PVC outer mold was fixed in position by two wooden guides which were bolted to the steel plate.

4.2.2 Test Procedure

A demolding wax was applied to the inner surface of the outer molds before assembly. After assembling the constrained ring specimen apparatuses, fresh concrete was placed between the outer mold and the inner steel ring to produce ring specimens with a thickness of 25 mm (1 in.). The outer molds were removed after the specimens had set overnight. The top surface of the concrete rings were then sealed off using silicon rubber so that drying would only be allowed only from the outer circumferential surface. The specimen was then subjected to a specified drying condition and cracks that appear on the concrete specimen are to be observed and recorded.

A magnifying lens is used to measure crack widths. The crack widths were reported as an average of three measurements obtained at 1/4, ½, and 3/4 height of the ring. The surface of the specimens is examined for new cracks. The measurements of the widths of existing cracks were performed every 24 hr during the first 14 days after demolding.

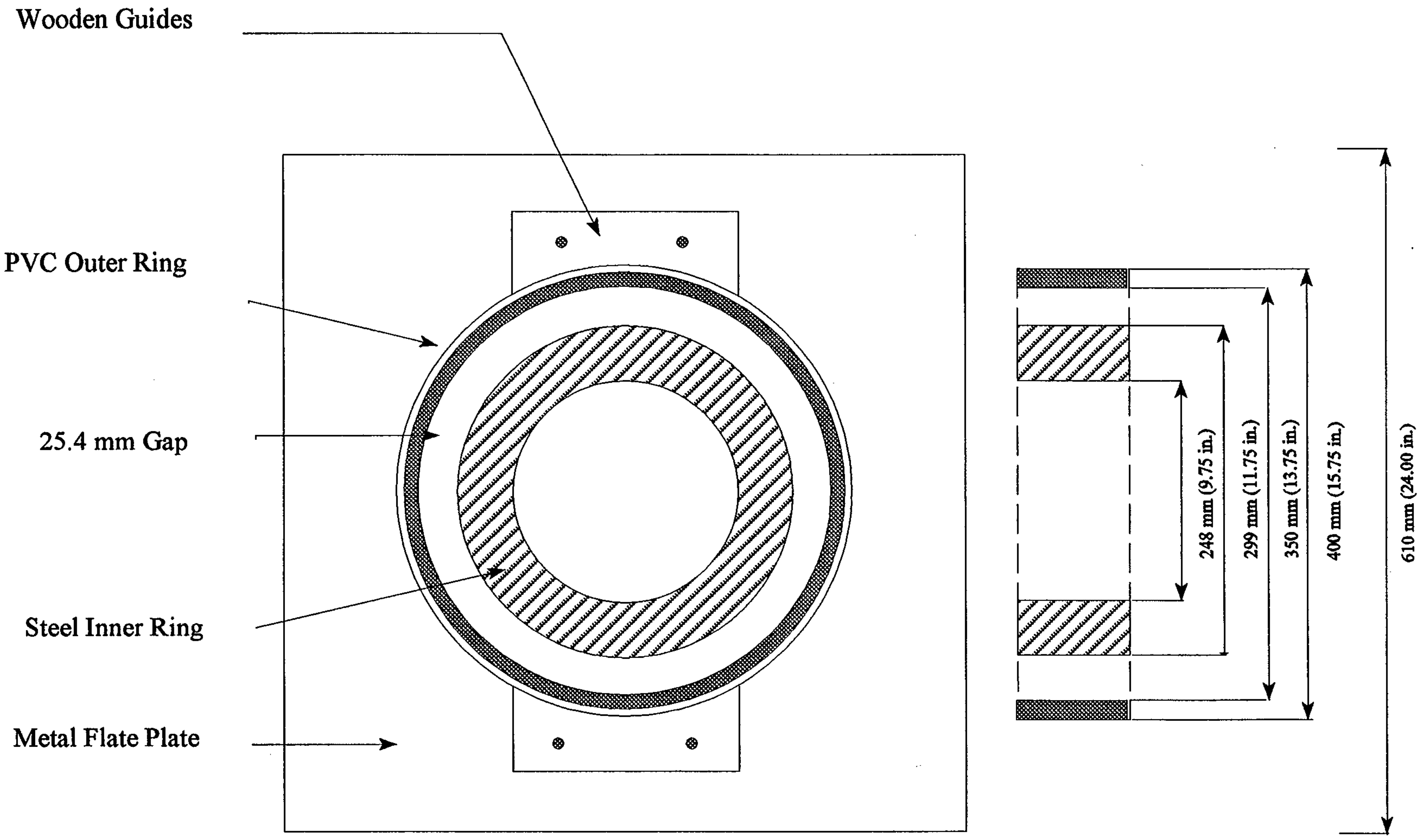

Figure 4.2 Schematic of the Initial Constrained Ring Specimen with PVC Outer Ring

4.3 Constrained Long Specimen Method (Method 2)

4.3.1 Initial Design

The design and construction of an apparatus for a restrained shrinkage test using long specimens with flared ends was based on the method used by Bloom and Bentur (Bloom et al. 1995). The basic principle of operation of this test method has been described in Chapter 2. The adopted design for this apparatus is shown on Figure 4.3. The major differences between this design and that used by Bloom and Bentur are as follows:

1) It used a specimen length of 500 mm (19.7 in.) instead of 1000 mm (39.4 in.). While this modified apparatus would give lower sensitivity in test results due to the shorter specimen length, the test specimen would be much easier to handle and less likely to break.
2) In addition to two dial gauges, two LVDTs were also mounted and used to measure the movement of the specimen. Figure 4.4 is a close-up picture of the apparatus showing the two LVDTs and the two dial gauges used.
3) To reduce friction between the concrete specimen and the plate support, a thin acrylic sheet was placed on top of the plate support so that the concrete specimen would rest on the acrylic surface. To minimize the effect of temperature on the acrylic sheet, the acrylic sheet was bolted firmly to the steel plate, which would restrain it from movement.

4.3.2 Test Procedure

Before casting the concrete mix, a thin layer of demolding wax was applied on

1. Fixed Grip
2. Mold
3. Movable Grip
4. Synthetic Rails
5. Dial Gauges
6. LVDTs
7. Grip
8. Proving Ring
9. Screw Assembly
10. Acrylic Sheet
11. Side of Mold

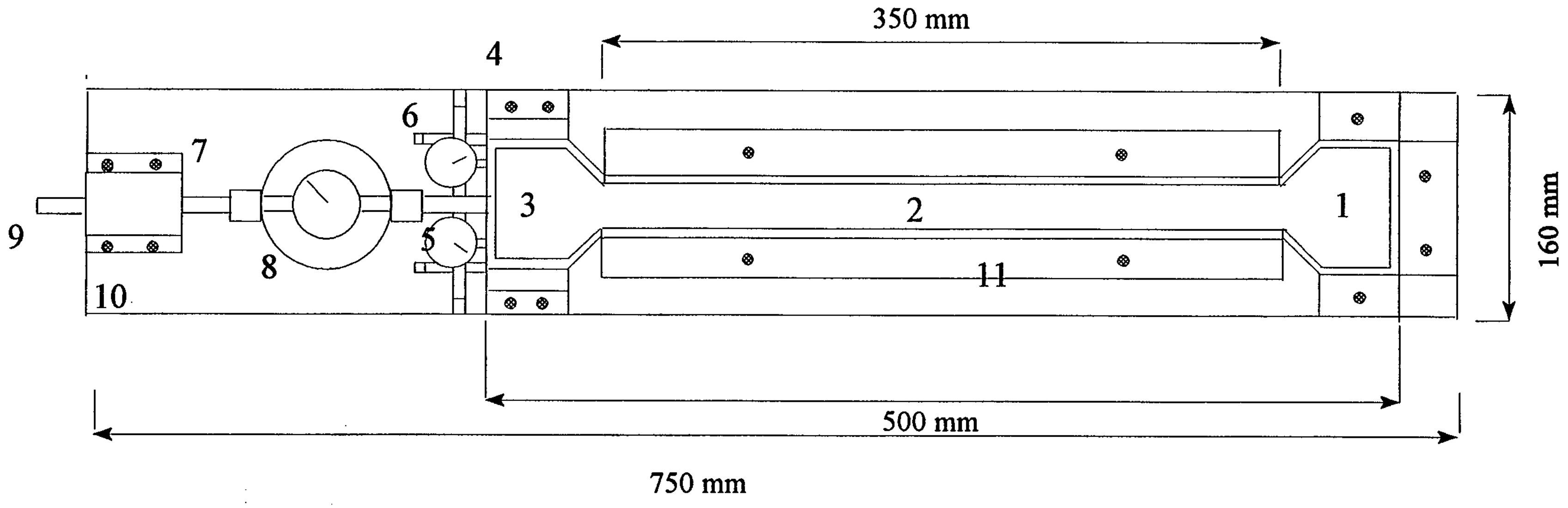

Figure 4.3 Schematic of the Initial Modified Constrained Long Specimen with Flared Ends

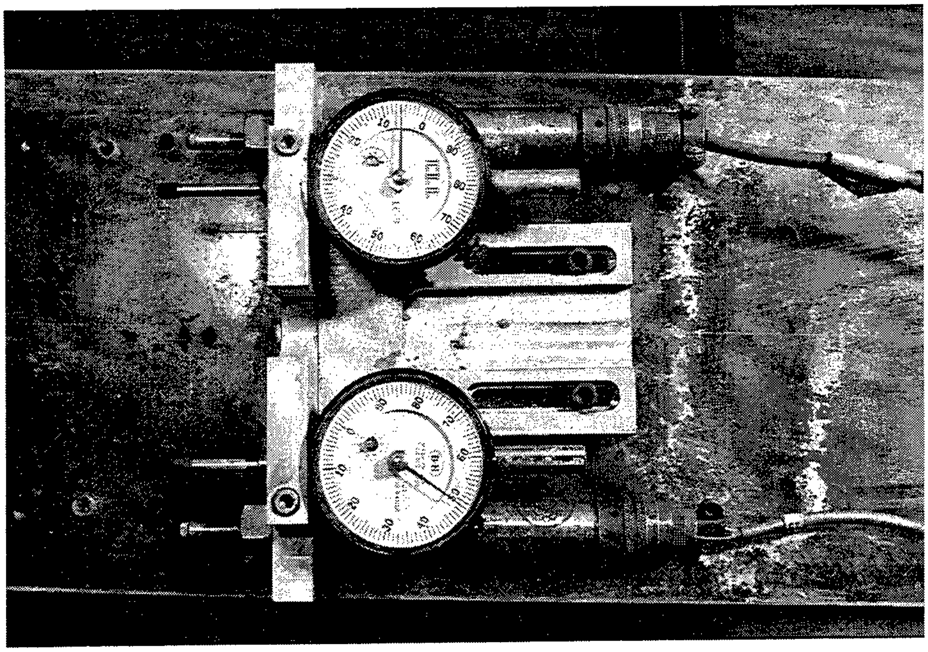

Figure 4.4 Setup of Two LVDTs and Two Dial Gages in the Constrained Long Specimen Method

the surface of the acrylic sheet (#10) and two sides of the specimen mold (#11) to reduce friction. To fabricate a test specimen, the fresh concrete was casted directly into the apparatus. The two sides of the mold were removed after the concrete had set overnight. The two dial gauges (#5) along with the two LVDTs (#6) were used to measure the deformation of the concrete due to shrinkage. After load measurements were taken for a specified period of time by the proving ring (#8), the constraint on the specimen was released by loosening the screw assembly (#9), and the free shrinkage of the specimen can be measured. The constrained long specimen can also be used to measure the stress-strain relationship of the concrete by applying different amounts of strain (as read by the two dial gauges) and measuring the induced stresses (as read by the proving ring) in compression and in tension.

4.4 Constrained Plate Specimen Method (Method 3)

4.4.1 Design

The third test apparatus evaluated was a rectangular plate specimen, which was based on the method used by Kraai (Kraai 1985). Figure 4.5 shows a photo and a drawing of the setup. The forms were made of acrylic sheets to prevent absorption of moisture from the concrete mix. The forms were of the dimensions to produce two 610 X 910 mm (24 X 36 in.) rectangular plate specimens with a thickness of 20 mm (3/4 in.). Instead of using an expended metal lath which was attached to the inside perimeter, the inside side and bottom surfaces of the forms were roughened with sand paper to promote bonding between the concrete specimen and the acrylic surface. Two 508 X 508 mm (20 X 20 in.) electric fans were modified into fans with adjustable speed by attaching a

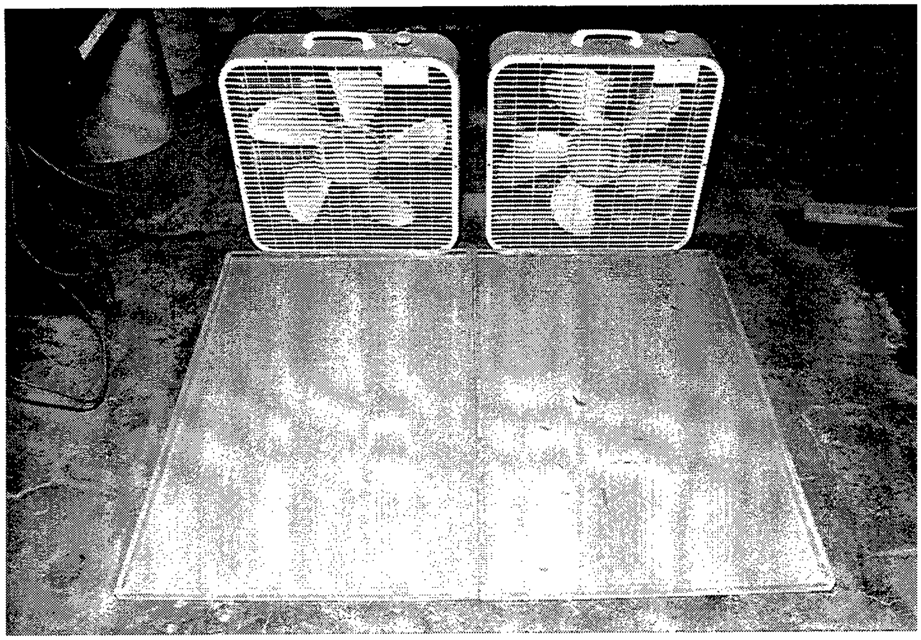

Figure 4.5 Setup of the Constrained Plate Method

variable resistor to each. These two electric fans can also be seen in Figure 4.5.

4.4.2 Test Procedure

After proper mixing, the fresh concrete was placed into the forms and leveled with a dampened, wooden straightedge. The slabs were leveled by holding the straightedge parallel to the 610 mm (24 in.) side and pulling it, without sawing motion, along the 910 mm (36 in.) direction. The fans were turned on 8 minutes after completion of leveling. Temperature, relative humidity, and wind speed were controlled to simulate a hot weather condition. The air temperatures varied from 25 to 35 ^{0}C (77 to 95 ^{0}F), with relative humidities ranging from 25 to 40 percent. The fans generate wind velocities of 3.1 to 3.6 m/s (7 to 8 mph), where were measured 150 mm (6 in.) above the slab surface.

4.5 Shrinkage Measurement Using Length Comparator

4.5.1 Test Equipment

The equipment used to conduct change in length measurements required the use of a length comparator and specimen molds.

4.5.1.1 Length Comparator

The length comparator used was manufactured by the Humboldt Manufacturing Company, Norridge, Chicago, Illinois and is shown in Figure 4.6. It consists of a sensitive dial micrometer mounted on a sturdy upright support which is attached to a solid triangular base. The dial micrometer is graduated to read to a precision of 0.0001 inch (0.00254 mm). The range of the scale is 0.4 inch (10.16 mm). The dial has one large and two small count hands with needle pointers. The scale may be rotated to set for zero at any indication of the large needle pointer where it can then be locked by a set

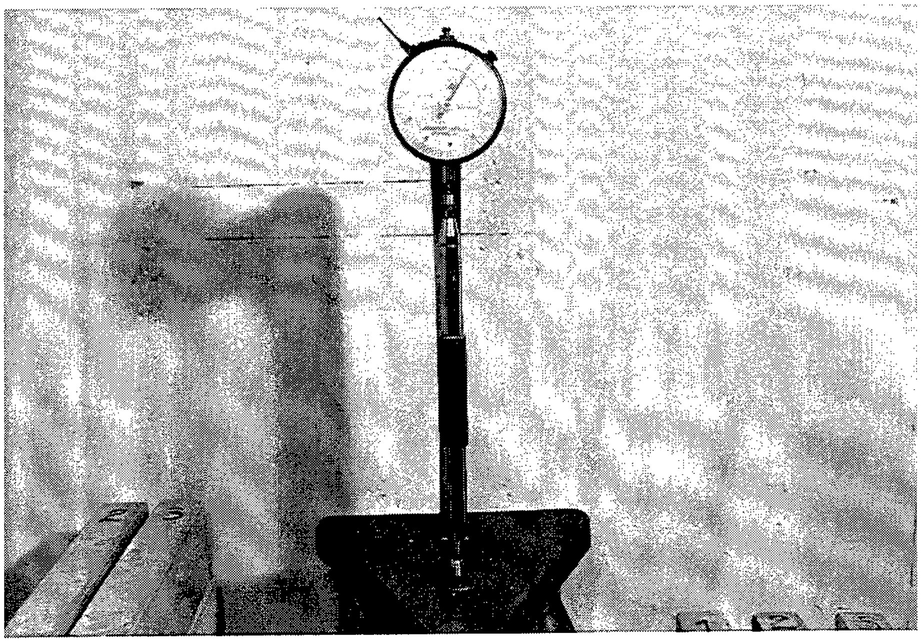

Figure 4.6 Length Comparator and Reference Bar

screw. The two smaller count hands with needle pointers on the face of the large dial show the number of revolutions of the larger pointer. One of the count hands shows the reading in 0.01 inch (0.254 mm), and the other shows it in 0.1 inch (2.54 mm). There are two anvils fitted with collars and shaped to meet the measuring studs cast into the ends of the test concrete bars.

4.5.1.2 Specimen Molds

Three compartment molds with inside dimension of 3 inches (76.2 mm) wide 11.25 inches (285.75 mm) long were used to cast the test specimens. The thickness of the steel mold is 0.5 inch (12.7 mm). Two 0.375 inch (9.53 mm) thick, 3 inches (76.2 mm) square steel end plates with a hole at their centers were used to hold the contact points in place. Figure 4.7 shows a picture of the mold.

4.5.2 Test Procedure

4.5.2.1 Preparation of Molds

Thinly cover the interior surfaces of the molds with a transmission fluid. After this operation, set the gauge studs, taking care to keep them clean, and free of oil, grease and foreign matter.

4.5.2.2 Use of Reference Bar

Check the dial gauge setting of the measuring device by use of the reference bar at the beginning and end of the readings; however, check it more often when kept in a room where the temperature is not constant. Figure 4.6 also shows the setup of the reference bar.

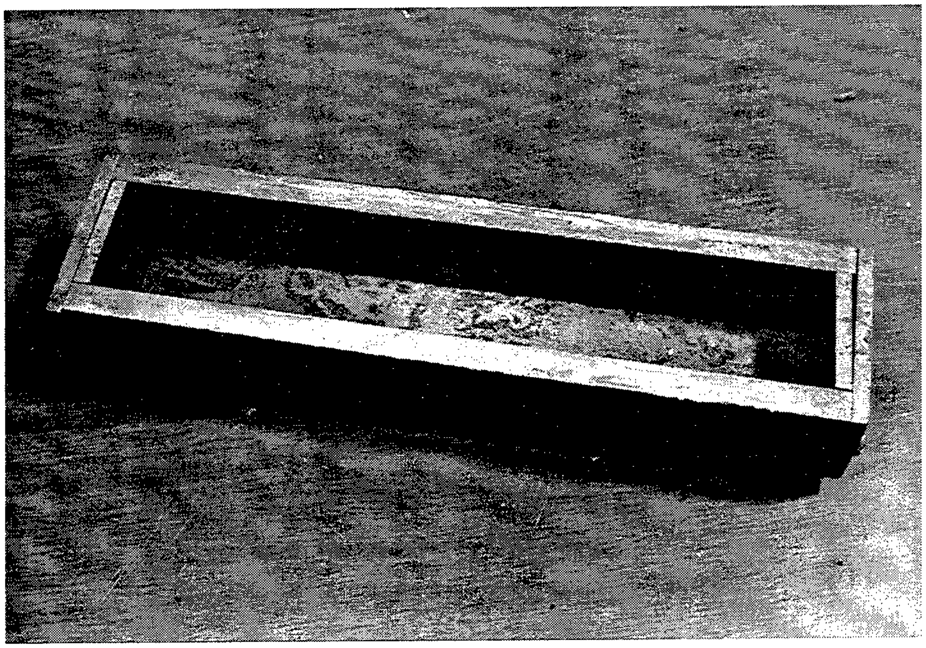

Figure 4.7 Specimen Mold for Free Shrinkage Test Sample

4.5.2.3 Obtaining Comparator Readings

Specimens were demolded overnight and brought to the instrument with the dial indicator retracted. One specimen was left in a moist-curing room, and the other two were left outside for air drying to simulate no-curing condition. The procedure used by Tia et al was followed (Tia et al. 1991). For obtaining comparator readings, a specimen was carefully positioned in the lower anvil, and the indicator was released very slowly and carefully to make contact with the upper anvil. Figure 4.8 shows the setup of the length comparator and a concrete specimen. The specimen was then rotated slowly, and the measurement of the length was then recorded. The mean of the four readings was used as the length reading for that cycle. Two cycles of reading were used. The direction of the rotation of the specimen in the length comparator for cycle 1 was opposite to that used for cycle 2. Two opposite directions were used to reduce the effects of the direction of rotation on the results.

4.5.2.4 Calculation of Length Change

Calculate the length change at any age as follows:

$$L = \frac{(L_i - L_x)}{G} * (0.0001) \qquad (4.1)$$

Where

L = change in length at x age,

L_x = comparator reading of specimen at x age minus comparator reading of reference bar at x age,

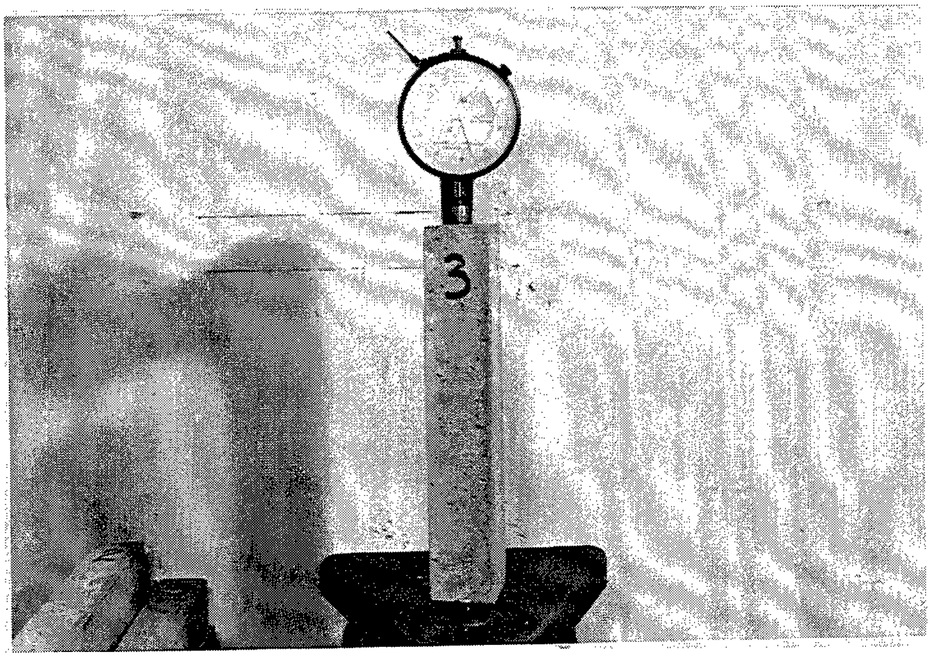

Figure 4.8 Setup of Length Comparator and Specimen

L_i = initial comparator reading of specimen minus comparator reading of reference bar at that same time, and

G = nominal gage length, 10 inches (254 mm).

4.6 Compressive Strength, Elastic Modulus, and Splitting Tensile Strength Tests

4.6.1 Compressive Strength Test

Compressive strength tests were performed according ASTM Standard Test Method C 39-83b for Compressive Strength of Cylindrical Concrete Specimens. Two 6 X 12 in. (152.4 X 304.8 mm) cylindrical specimens per batch per curing condition were used for this test. Figure 4.9 shows the setup for the compressive strength test.

The compressive strength of the specimen was calculated as follows:

$$f_c = \frac{P}{A} \qquad (4.2)$$

Where

P = maximum load attained during the test

A = load area

4.6.2 Elastic Modulus Test

The moduli of elasticity of the concrete specimens were also determined at periods of 1, 2, 7, and 14 days after demolding. A compressometer was used to measure the deformation of cylindrical specimen as it was loaded in compression. The ASTM Standard Method C 469-83 for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression was followed during this test. Figure 4.10 shows the setup for this test.

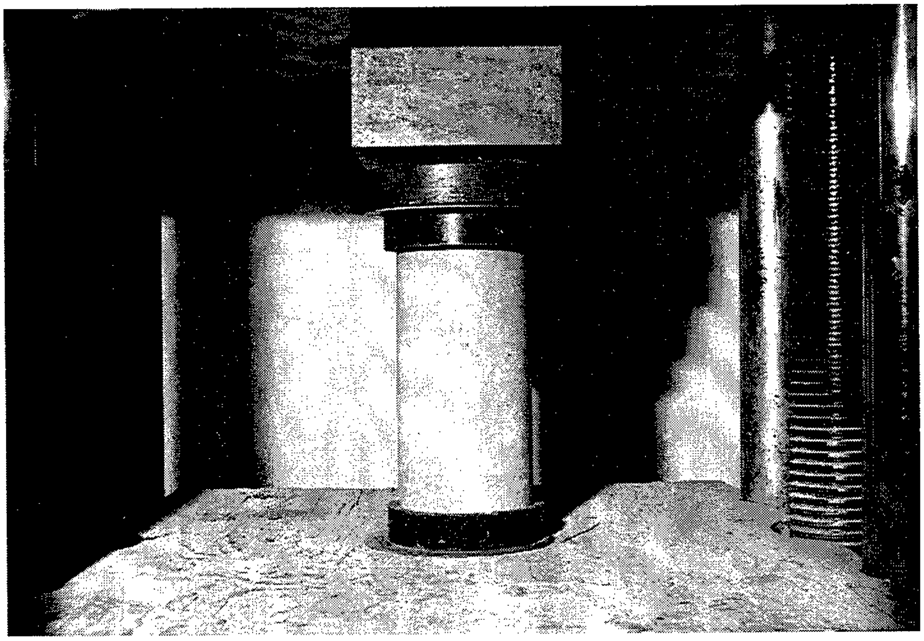

Figure 4.9 Setup of Compressive Strength test

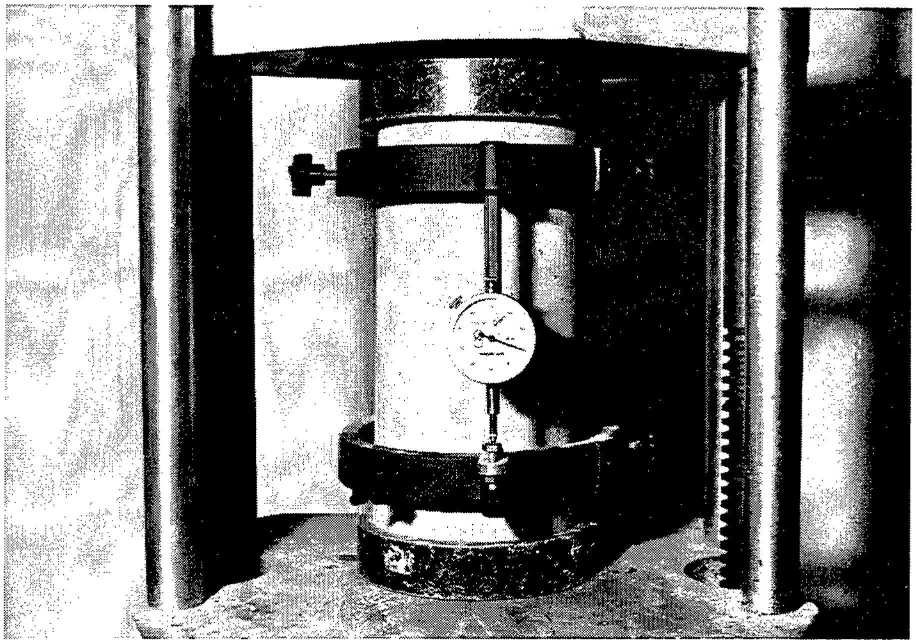

Figure 4.10 Setup for Elastic Modulus Test

Modulus of elasticity was computed as follows:

$$E = \frac{\sigma}{\epsilon} \qquad (4.3)$$

Where

E = modulus of elasticity

σ = stress (load / area)

ϵ = strain (measured deflection / length of specimen)

4.6.3 Splitting Tensile Strength Test

The splitting tensile strength tests were performed in accordance with ASTM Standard Method C496-71 for Splitting Tensile Strength of Cylindrical Concrete Specimens. 6 X 12 in. (152.4 X 304.8 mm) cylindrical specimens were used for this test. Figure 4.11 shows the setup for the Splitting Tensile Strength test.

The splitting tensile strength of the specimen was calculated as follows:

$$f_t = \frac{2P}{\pi l d} \qquad (4.4)$$

Where

f_t = splitting tensile strength

P = maximum applied load

l = length of cylinder

d = diameter of cylinder

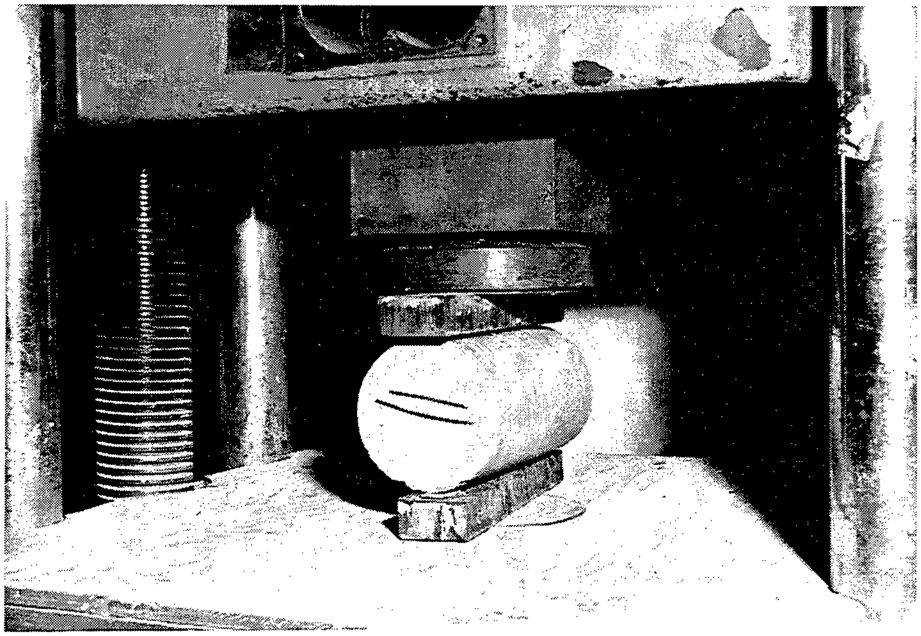

Figure 4.11 Setup for Splitting Tensile Strength Test

CHAPTER 5
PRELIMINARY EVALUATION OF TEST APPARATUS

5.1 Introduction

This chapter presents the preliminary evaluation of the three different test apparatuses. The results of free shrinkage, compressive strength, elastic modulus, and tensile strength tests on the concrete will be also presented. Based on the results of this evaluation, the most effective test method would be selected. Any necessary modification of the selected method would be made and further evaluated to determine its effect on testing measurements.

5.2 Constrained Ring Specimen Method (Method 1)

5.2.1 Ease of Test

The basic principle of operation of this test method has been described in Chapter 4. The first apparatus constructed used two semicircular steel strips which could be fastened together to form an outer mold with an inner diameter of 356 mm (14.0 in.). The second apparatus constructed was similar to the first apparatus with the exception that a PVC tube, instead of a steel ring, was used as the outer mold. Trial concrete specimens made with these two apparatus indicated that, while both devices were feasible for making the constrained ring specimen, both had some deficiencies. The first apparatus required a lot of time to setup, while the PVC outer mold was very difficult to be stripped off from the concrete specimen. They both required two people to lift and place the filled mold on a vibrating table. Modification of the second apparatus (which used a PVC outer mold) was needed to improve the ease of operation.

5.2.2 Test Results of Constrained Ring Specimen Method

The Florida Class II concrete that had shrinkage cracking problem, and which has been described in Chapter 3 was reproduced and used to make two constrained ring specimens. The specimens were left to dry in the laboratory. The first ring specimen was observed to develop two hairline cracks at the 14th day after demolding. One of the two hairline cracks was right under one of the six bolts which were used to fasten the two semicircular steel strips, and it was not possible to measure its crack width by the magnifying lens. The average crack width of the other was measured to be 50 μm (0.002 in.) at the 14th day. No visible crack was observed on the other specimen.

5.2.3 Modification of Constrained Ring Specimen

The second constrained ring specimen method was modified and tested. The schematic of the modified second apparatus is shown in Figure 5.1. The modified second apparatus is similar to the initial apparatus with an exception that two semicircular PVC strips, instead of a PVC tube, were used as outer mold. The two halves of the PVC mold were held together by a hose clamp and can be released from the concrete specimen easily by loosening the clamp. The inner steel ring was fastened to the steel plate in the same way as for the initial apparatus. The PVC outer mold was fixed in the position by two wooden guides which were bolted to the steel plate.

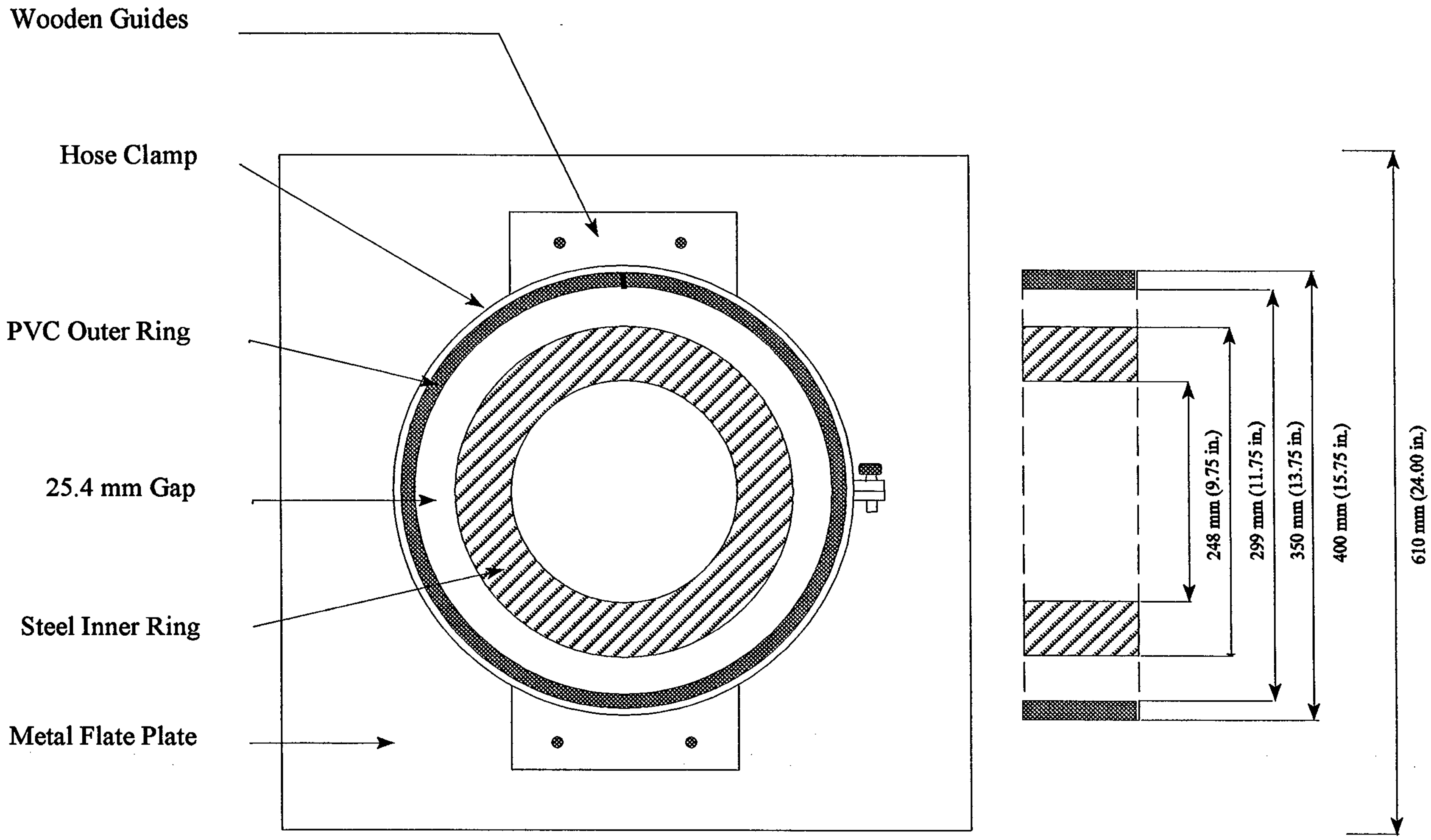

Figure 5.1 Schematic of the Constrained Ring Specimen with PVC Outer Ring

5.2.4 Assessment of Constrained Ring Specimen Method

After modification, the two semicircular PVC strips used as the outer mold were very easy to strip from the concrete specimen. Thus, the second constrained ring specimen method appeared to be superior than the first one.

The major merit of this method is that because of the axisymmetry of the specimen, the geometry and boundaries do not significantly influence the test results. In addition to axisymmetry, it could be assumed that the specimen is essentially subjected to an uniformly distributed uniaxial tension as a result of restraint provided by the steel ring (Grzybowski et al. 1990). Based on the test results, it is clear that the constrained ring specimen method was a good method to evaluate the resistance of a restrained concrete due to shrinkage. However, it could only provide empirical information such as the first crack, the number of cracks, and the average crack width during a test period. This method could not provide more fundamental properties such as the shrinkage strains and elastic strains which could be used to estimate creep strains and shrinkage stresses. Moreover, the total weight of this apparatus with filled fresh concrete was over 114 kg (250 lb), and it required at least two people to lift and place the entire apparatus on a vibrating table. Therefore, due to the limited useful information and inconvenience of operation, the constrained ring specimen method was discontinued for further testing in this study.

5.3 Constrained Long Specimen Method (Method 2)

5.3.1 Ease of Test

The basic principle of operation of this test method has been described in Chapter

4. It took about 5 minutes to set up and required only one person to lift and place the filled mold on a vibrating table. A trial concrete specimen was made using this apparatus. However, after the concrete had set and the two sides of the mold were to be removed, it was found that the sides of the molds could not be removed by sliding them out horizontally. In order to remove the two sides, they had to be lifted up vertically. This process caused the concrete specimen to be lifted up and resulting in cracking the concrete specimen. Due to this problem, the side pieces of the mold need to be made slightly shorter in length so that they would be able to be slid out horizontally. Duck tapes were applied to seal the caps between sides and end grips to prevent leakage of fresh concrete due to vibration.

5.3.2 Test Results of Constrained Long Specimen Method

The constrained long specimen with flared ends were constrained from movement at the two ends and left to dry in the laboratory. The proving ring was used to measure the induced load due to shrinkage of the concrete. However, very little induced load was measured. The amount of load measured corresponds to only about 1 to 2 psi of tensile stress in the concrete. After load measurements were taken up to 7 days, the constraint on the specimen was released.

The constrained long specimen was used to measure the stress-strain relationship of the 7-day old concrete by applying different amounts of strains (read by the two dial gages) and measuring the induced stresses (as read by the proving ring). Figure 5.2 shows a plot of the measured stress-strain relationship of the same specimen in compression. Figure 5.3 shows the measured stress-strain relationship of the same

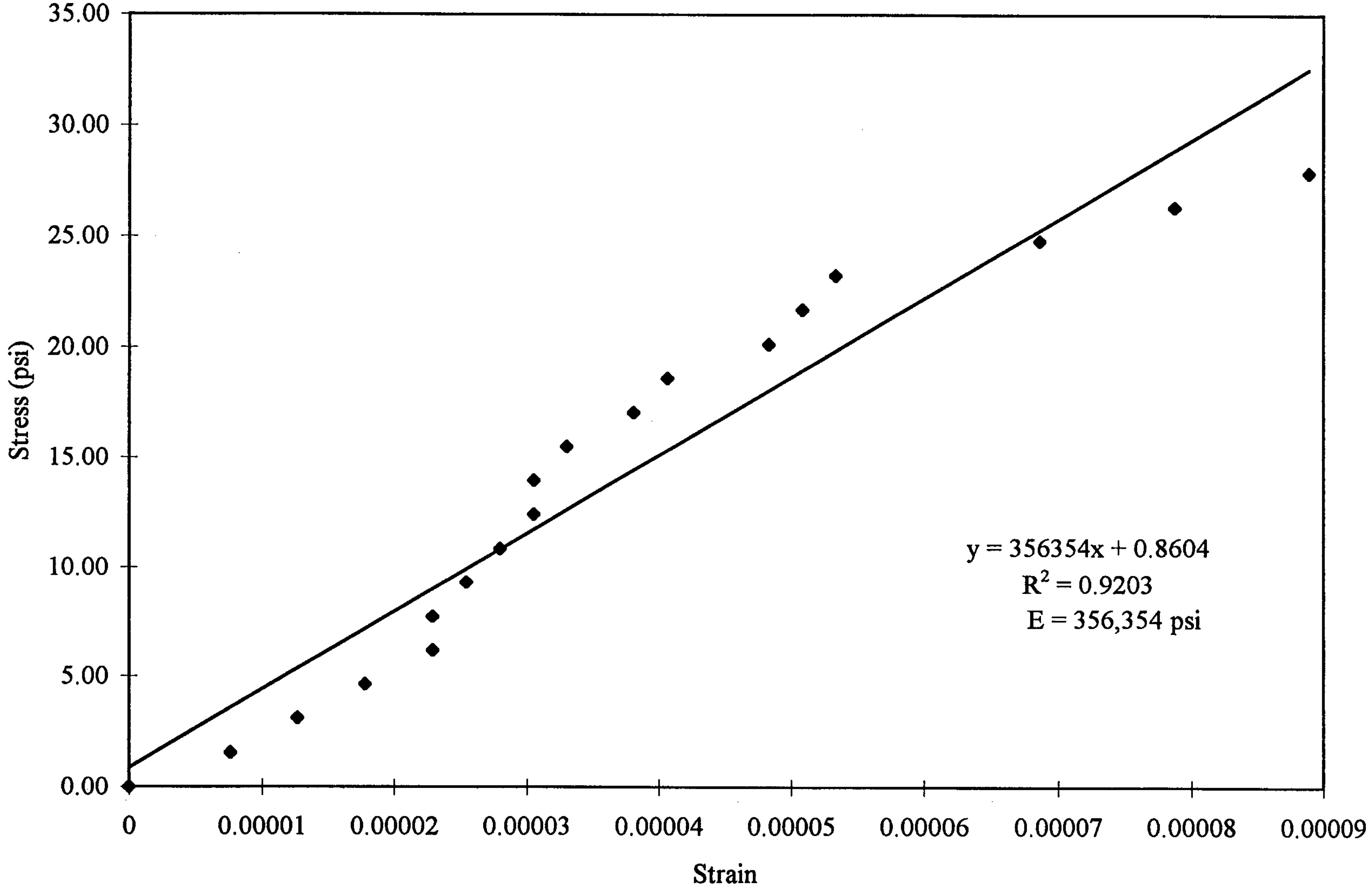

Figure 5.2 Measured Stress vs Strain of Initial Constrained Long Specimen in Compression

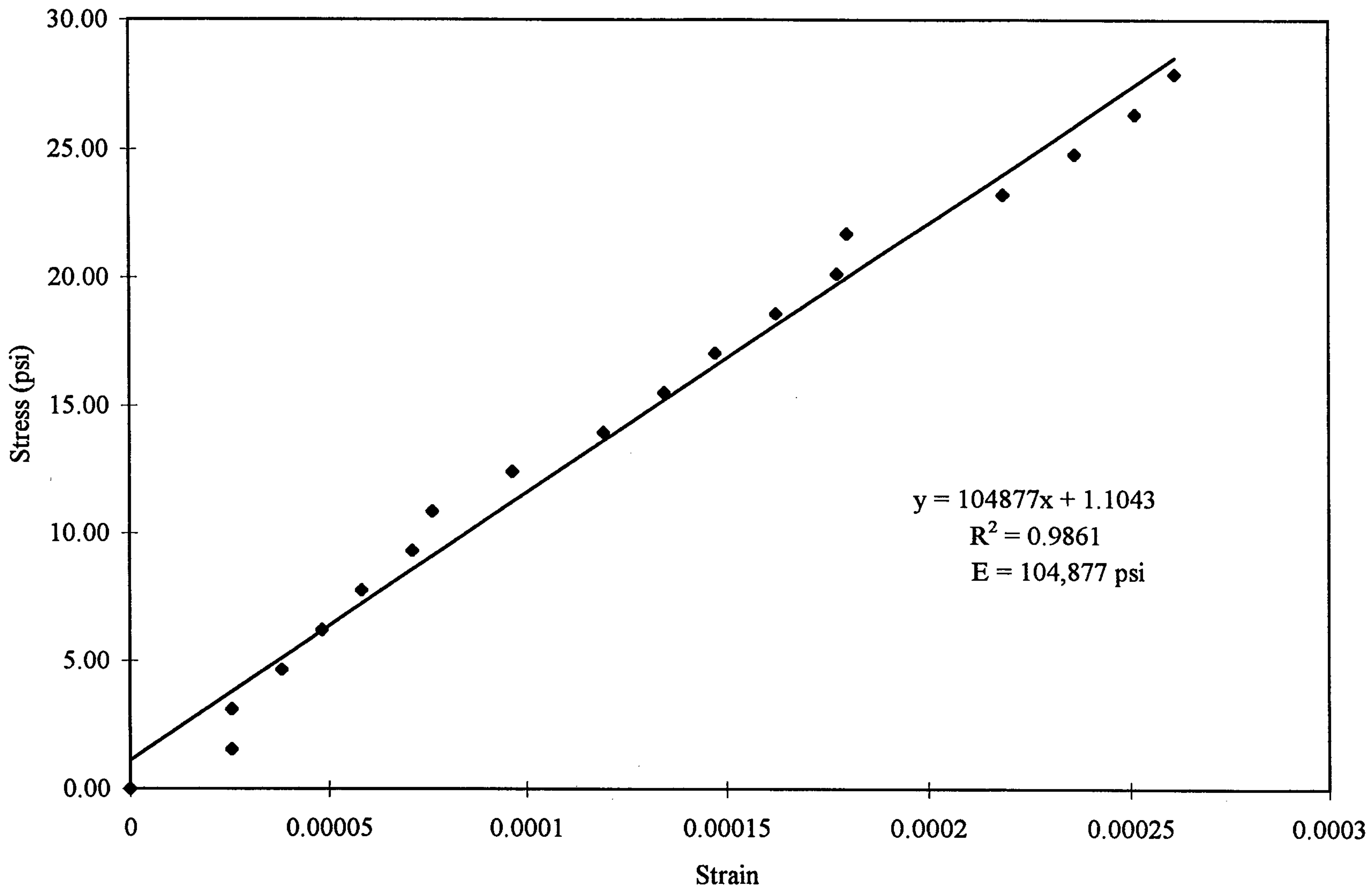

Figure 5.3 Measured Stress vs Strain of Initial Constrained Long Specimen in Tension

specimen in tension. The elastic modulus was determined from a linear regression of the stress-strain plot and is shown on each of these figures. It can be noted that the determined elastic modulus was unreasonably low. It was clear that the measurements were in error. A possible explanation for the erratic measurements is that there might be some slippage of the end grips or breakage of bond between the concrete and end grips, resulting in reduction in induced stresses.

5.3.3 Modification of Constrained Long Specimen Setup

To eliminate the possible errors due to slippage of the end grips or breakage of bond between the concrete and the end grips, the design of the constrained long specimen was modified. The modified design and evaluation of the modified constrained long specimen apparatus will be presented in Chapter 6.

5.4 Constrained Plate Specimen Method (Method 3)

5.4.1 Ease of Test

The principle of operation of the constrained plate specimen test has been described in Chapter 4. Two forms for making the restrained plate specimens were made during the first trial. The setup of this apparatus took less than 2 minutes, but it required two people to lift and place a filled mold on a vibrating table.

5.4.2 Test Results of Constrained Plate Specimen Method

Two trial concrete plate specimens were cast using these two forms. No problem was encountered in the fabrication of these two specimens. No visible cracks were found on these two specimens.

5.4.3 Assessment of Constrained Plate Specimen Method

In the test performed, there was no visible crack found on the constrained plate specimen. It appeared that there was not enough bonding between the concrete and the acrylic molds. The major merit of this method is that the constrained plate specimen method can be used to evaluate the cracking potential of a concrete when it is in the form of a thin plate. Screeding and finishing operations also have significant impact on plastic shrinkage cracking because the screeding direction will influence the direction of cracking (Kraai 1985). This method can be also used evaluate the effect of concrete due to screeding and finishing. However, it is believed that a biaxial state of stress is provided. Consequently, the test results obtained from plate-type specimens may depend on specimen geometry in addition to the material properties (Grzybowski 1990). Similarly, the constrained plate specimen method could not provide more useful information as the constrained long specimen method could. Therefore, this method was discontinued for further testing in this study.

5.5 Test Results from Strength Tests and Free Shrinkage Measurements

5.5.1 Test Results from Strength Tests

Table 5.1 displays the splitting tensile strength and elastic modulus due to air drying at 1, 2, 7 and 14 days for Florida Class II and IV concretes. It also displays the compressive strength at 28 days of moist curing for these two concretes.

5.5.2 Test Results from Free Shrinkage Measurements

Table 5.2 displays the free shrinkage strains due to air drying and moist curing at 1, 2, 7 and 14 days for Florida Class II and IV concretes. Theoretically, if a concrete

Table 5.1 Strength Test Results for Florida Class II and IV Concretes

Florida Class II Concrete					
	1st Day Air Curing	2nd Day Air Curing	7th Day Air Curing	14th Day Air Curing	28th Day Moist Curing
Compressive Strength	-	-	-	-	5608 (lbf/in^2) 40.04 MPa
Splitting Tensile Strength	303.5(lbf/in^2) 2.09MPa	369.6(lbf/in^2) 2.55 MPa	370.0(lbf/in^2) 2.55 MPa	385.9(lbf/in^2) 2.66 MPa	-
Elastic Modulus	2.0E6 (lbf/in^2) 1.4E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	-
Florida Class IV Concrete					
Compressive Strength	-	-	-	-	7256 (lbf/in^2) 51.81 MPa
Splitting Tensile Strength	445.7(lbf/in^2) 3.07 MPa	475.8(lbf/in^2) 3.28 MPa	532.1(lbf/in^2) 3.66 MPa	569.4(lbf/in^2) 3.92 MPa	-
Elastic Modulus	3.0E6 (lbf/in^2) 2.1E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	3.0E6(lbf/in^2) 2.1E4 MPa	-

Table 5.2 Free Shrinkage Test Results For Florida Class II and IV Concretes

Florida Class II Concrete				
	1st Day	2nd Day	7th Day	14th Day
Curing Room Dried (Strain)	0.000026	0.000015	0.000039	0.000055
Air Dried (Strain)	0.000027	0.000063	0.000261	0.000350
Induced Shrinkage Stresses	54 (lbf/in^2) 0.37 MPa	189 (lbf/in^2) 1.30 MPa	783 (lbf/in^2) 5.40 MPa	1050 (lbf/in^2) 7.23 MPa
Florida Class IV Concrete				
Curing Room Dried (Strain)	0.000010	0.000006	0.000025	0.000030
Air Dried (Strain)	0.000074	0.000134	0.000284	0.000414
Induced Shrinkage Stresses	222 (lbf/in^2) 1.53 MPa	402 (lbf/in^2) 2.77 MPa	852 (lbf/in^2) 5.87 MPa	1242 (lbf/in^2) 8.56 MPa

specimen was fully constrained from movement at the two ends, the induced stress would be equal to:

$$\sigma_i = \epsilon_f \ E \qquad (5.1)$$

Where

σ_i = induced stress

ϵ_f = free shrinkage strain

E = elastic modulus

If the induced stress exceeded the tensile strength of the concrete at that point, cracking would occur. The shrinkage stresses of constrained specimens at different times were computed using the measured data for both the air-dried and moist cured specimens. These computed induced shrinkage stresses are also displayed in Table 5.2 and plotted against time in Figures 5.4 and 5.5. The measured tensile strengths are also plotted on the same graph. It could be clearly seen that the computed shrinkage stresses of the air-dried concrete far exceeded their tensile strengths after about three days. This indicates that the concrete would have cracked if left to air drying; however, the concrete would not crack if it was properly cured in curing room.

Figures 5.6 and 5.7 show plots of free shrinkage strains of air-dried and moist cured specimens as a function of time for Florida Class II and IV concretes. Figures 5.8 and 5.9 also show plots of weight loss of air-dried and moist-cured specimens as a function of time. It could be clearly seen that both free shrinkage and weight loss due to air drying became more stable after 14 days. It indicated that free shrinkage and weight

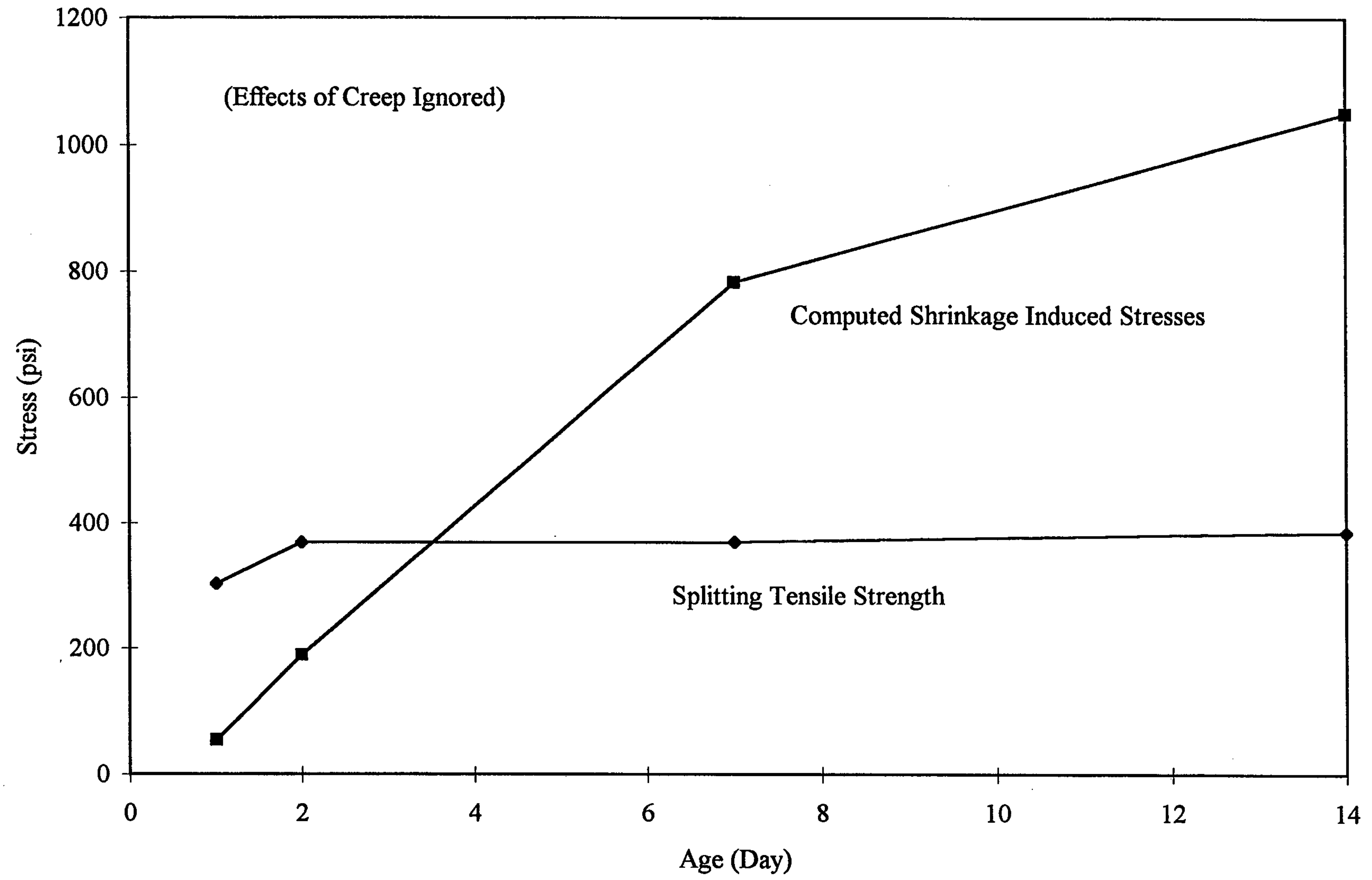

Figure 5.4 Computed Shrinkage Induced Stresses in a Fully Constrained Florida Class II Concrete

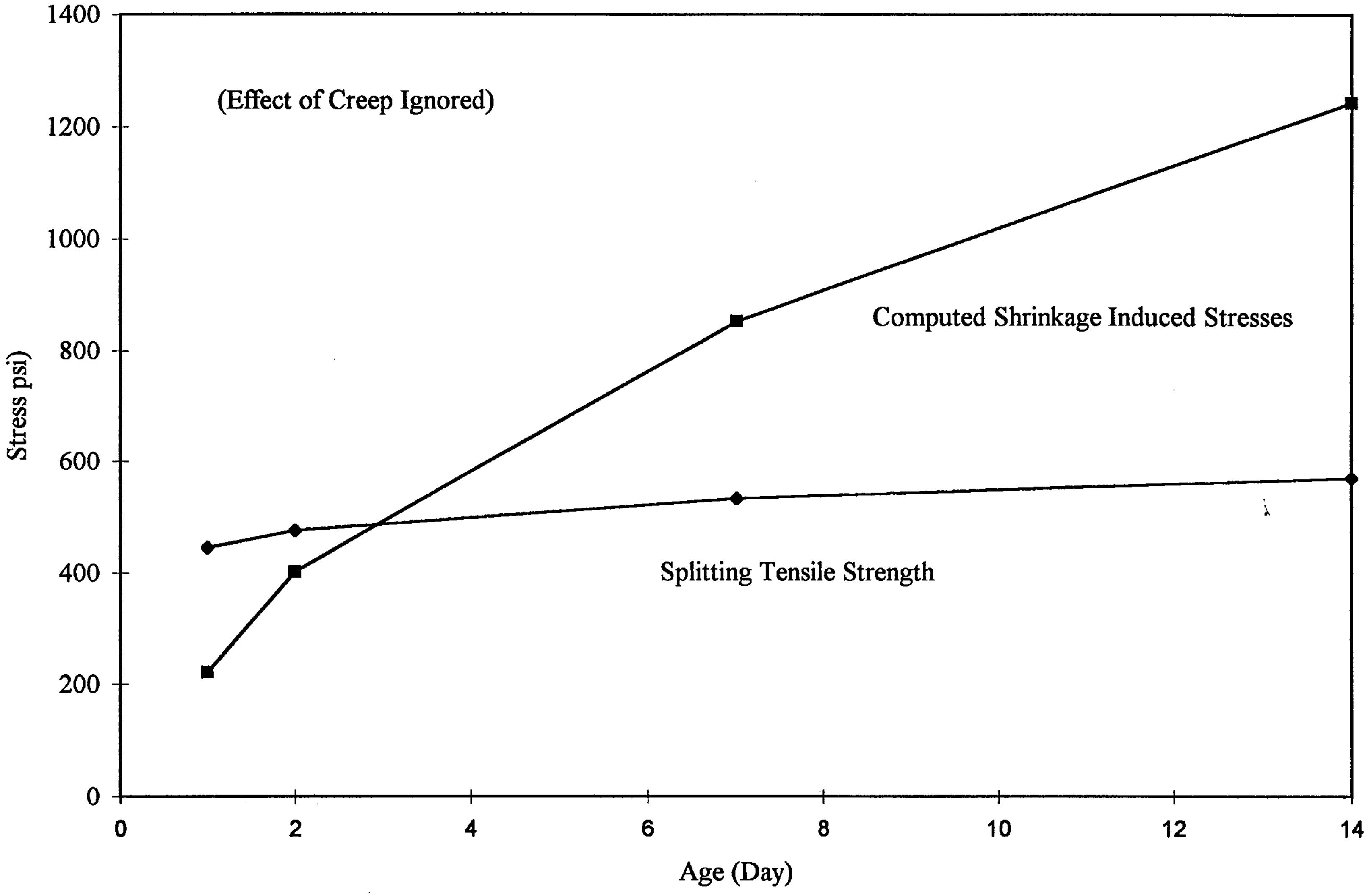

Figure 5.5 Computed Shrinkage Induced Stresses in a Fully Constrained Florida Class IV Concrete

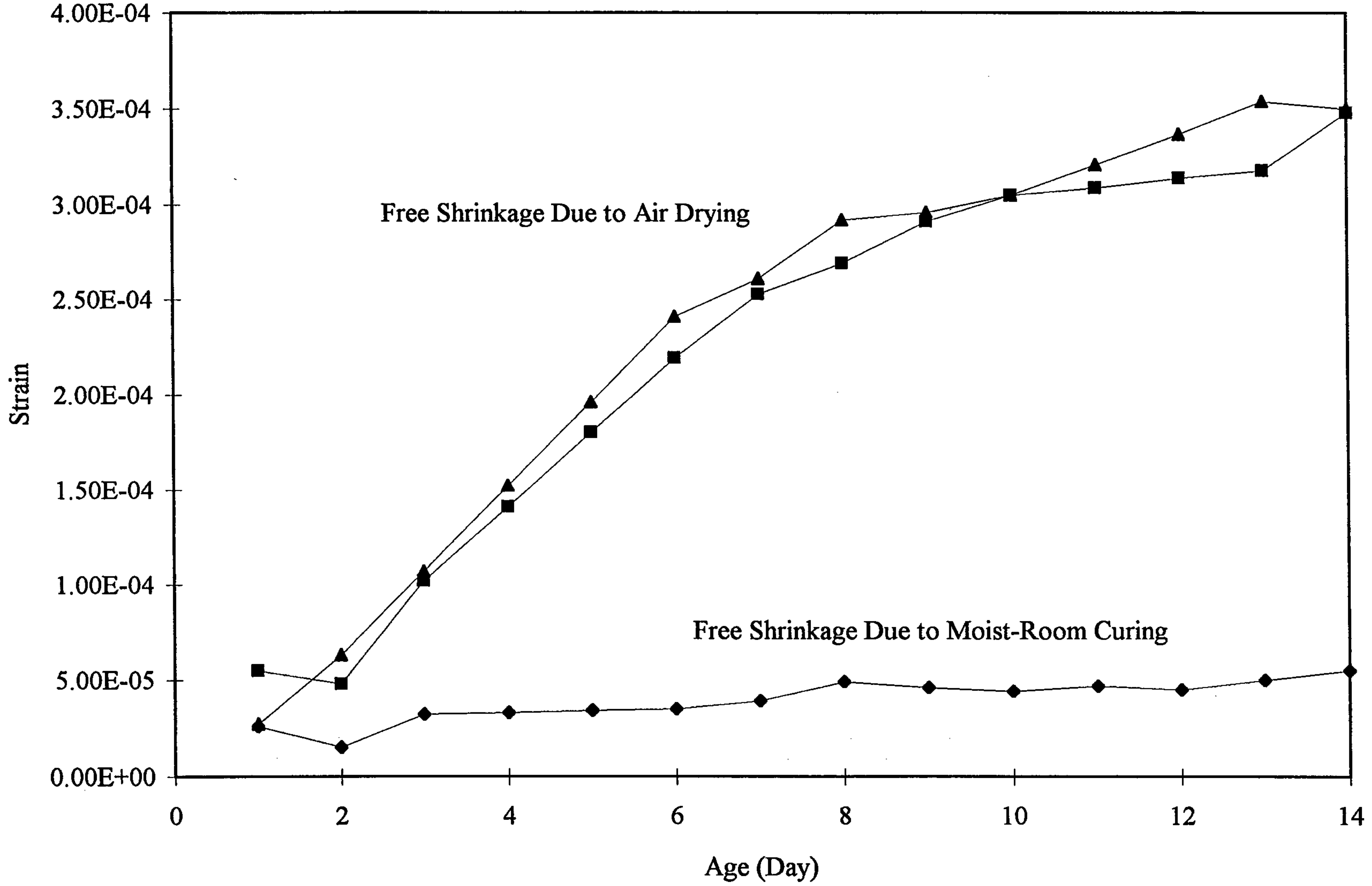

Figure 5.6 Free Shrinkage of Moist-Room-Cured and Air-Dried Specimens for Florida Class II Concrete

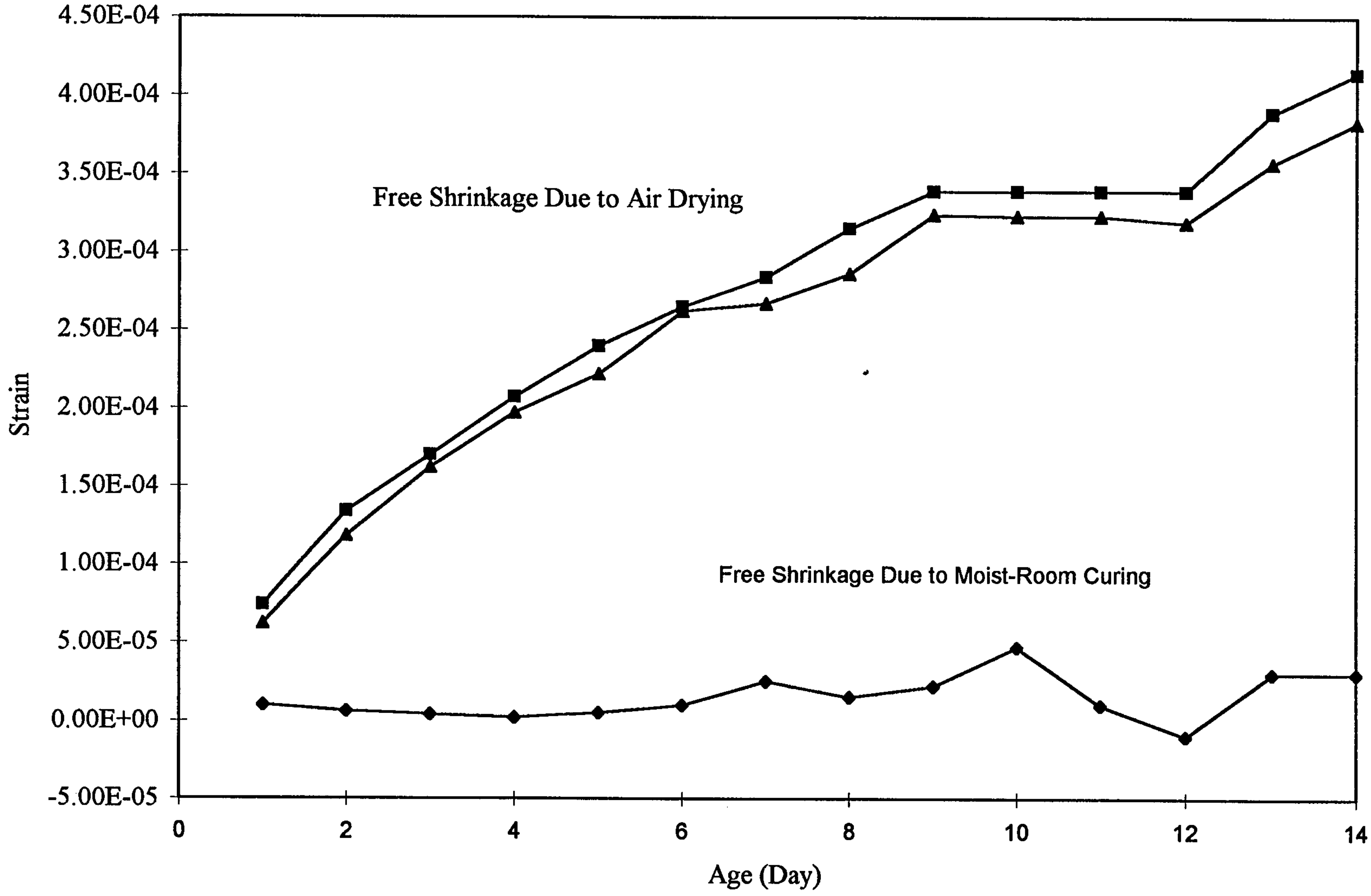

Figure 5.7 Free Shrinkage of Moist-Room-Cured and Air-Dried Specimen for Florida Class IV Concrete

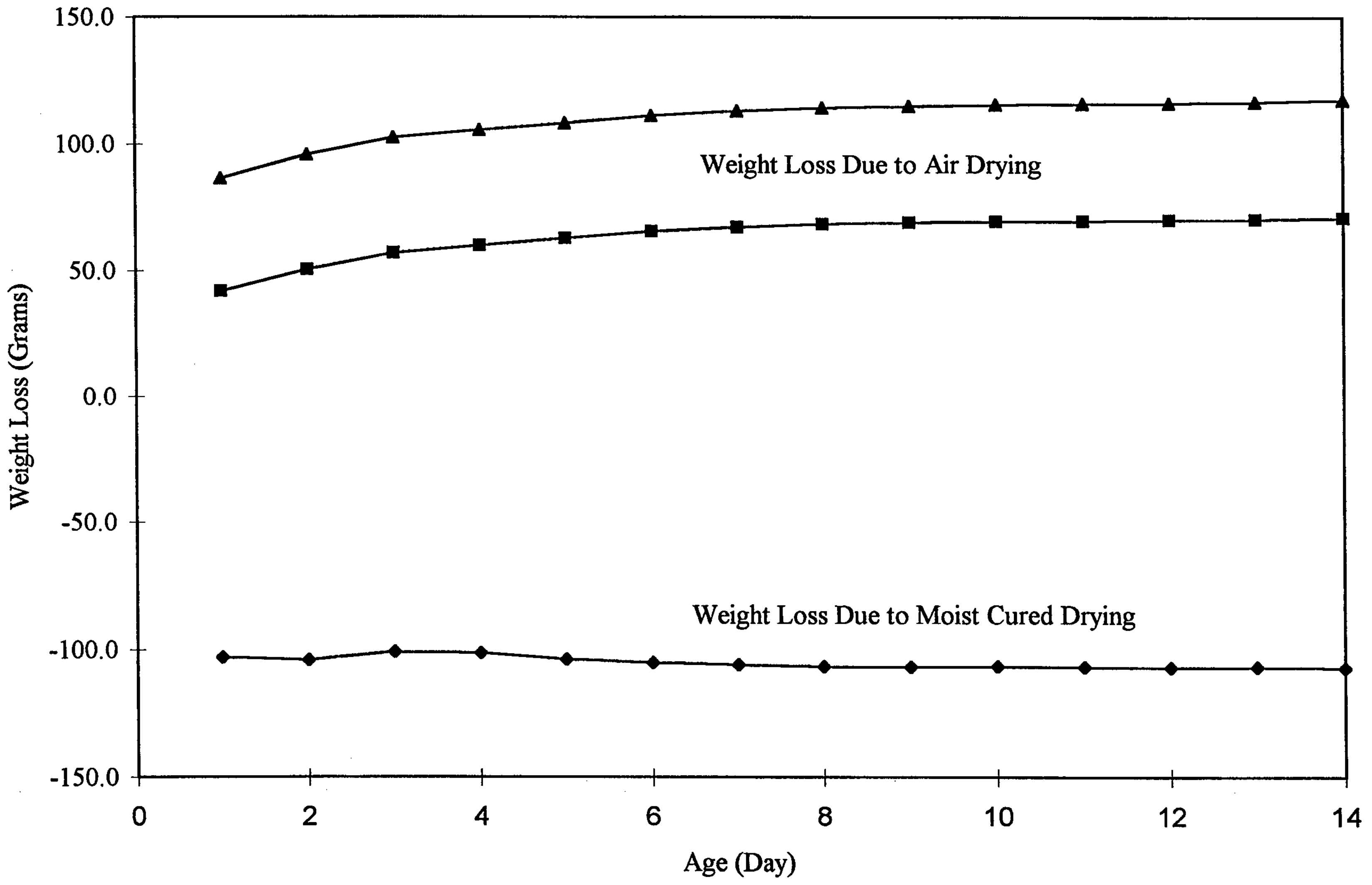

Figure 5.8 Weight Loss of Different Specimen Demolded after 24 Hours For Florida Class II Concrete

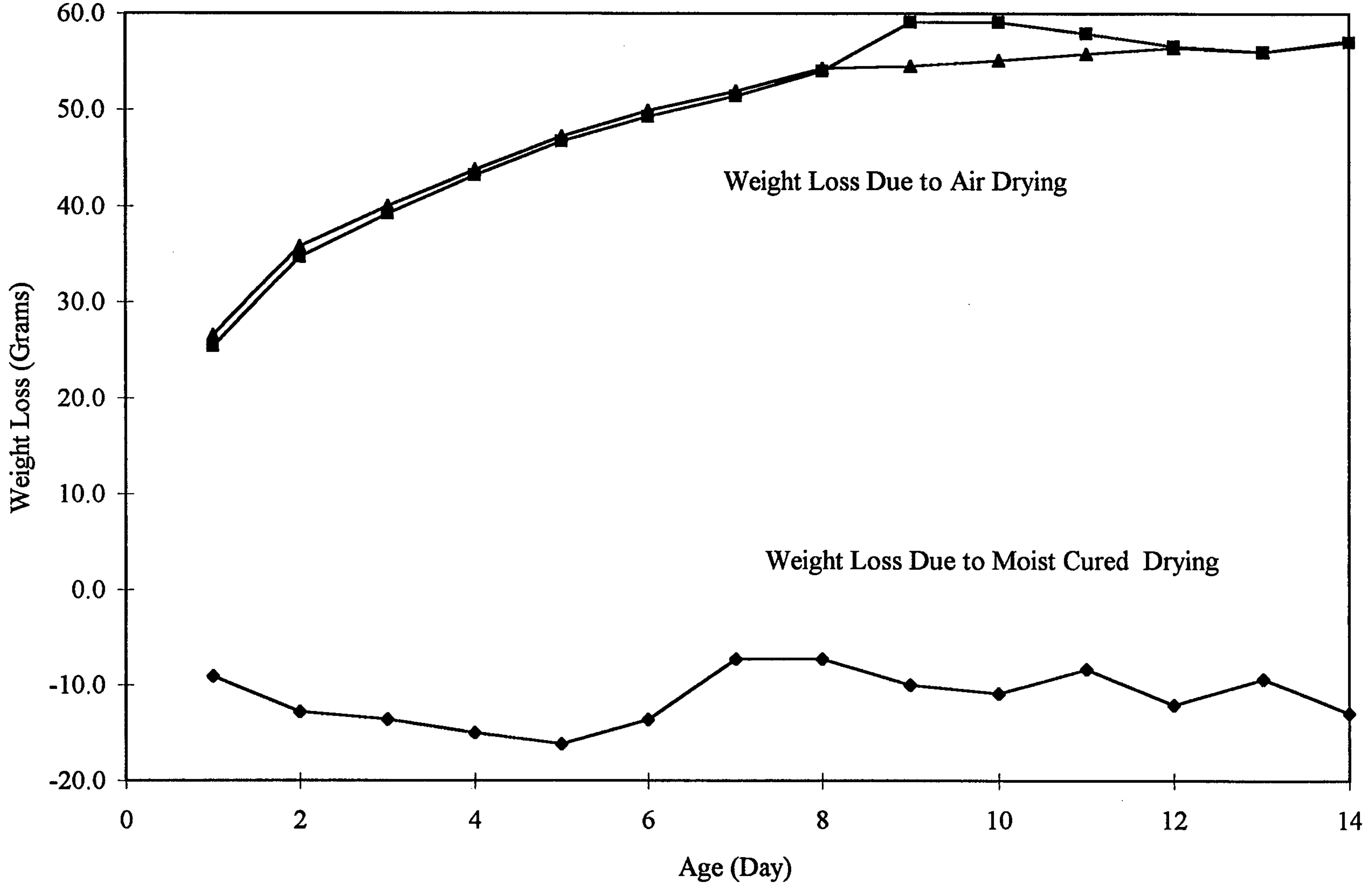

Figure 5.9 Weight Loss of Different Specimen Demolded after 24 Hours for Florida Class IV Concrete

loss due to air drying were a function of time. They were inter-related since the loss of water due to drying was the main reason for shrinkage and weight loss of the specimens.

Creep of concrete which could reduce the induced stresses were ignored in these computations. The actual induced stresses would actually be lower than these computed values. The creep of concrete is considered in the analyses as presented in the next chapter.

CHAPTER 6

EVALUATION OF THE MODIFIED CONSTRAINED LONG SPECIMEN METHOD

6.1 Introduction

This chapter presents the results of an evaluation of the modified constrained long specimen test method. Suggestions for further modification and refinement of the method are also given.

6.2 Modification of the Constrained Long Specimen Apparatus

As reported in Chapter 5, erroneous displacement measurements were obtained from the constrained long specimen in the preliminary tests. It was thought that the erratic measurements might be due to some slippage of the end grips of the apparatus or breakage of bond between the concrete and end grips. Thus, the design of the constrained long specimen was modified. The schematic of the modified design is shown in Figure 6.1. In the modified apparatus, the strain in the concrete specimen is measured by measuring the movements between the two inserts in the concrete by means of a Whittemore gage (dial extensometer). The Whittemore gage was modified such that its two ends could be screwed tightly on the two inserts in the concrete specimen. The Whittemore gage could read to a sensitivity of 0.0001 inch. A picture of the Whittemore gage is shown in Figure 6.2. A schematic drawing showing the modified Whittemore gage and the attachment of the gage to the concrete specimen is shown in Figure 6.3.

1. Fixed Grip
2. Side of Mold
3. Movable Grip
4. Synthetic Rails
5. Proving Ring
6. Grip
7. Screw Assembly
8. Gage Point Inserts
9. Metal Guide for Gauge Point

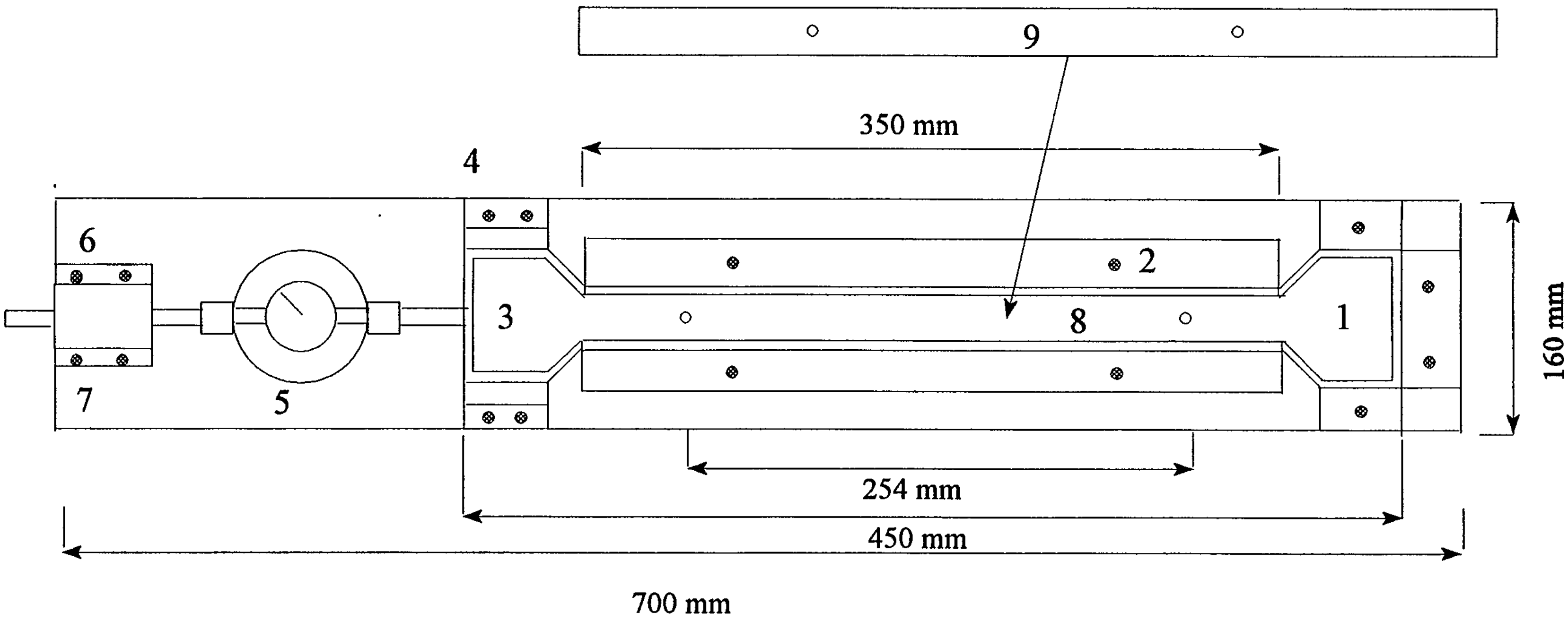

Figure 6.1 Schematic of Modified Constrained Long Specimen with Flared Ends

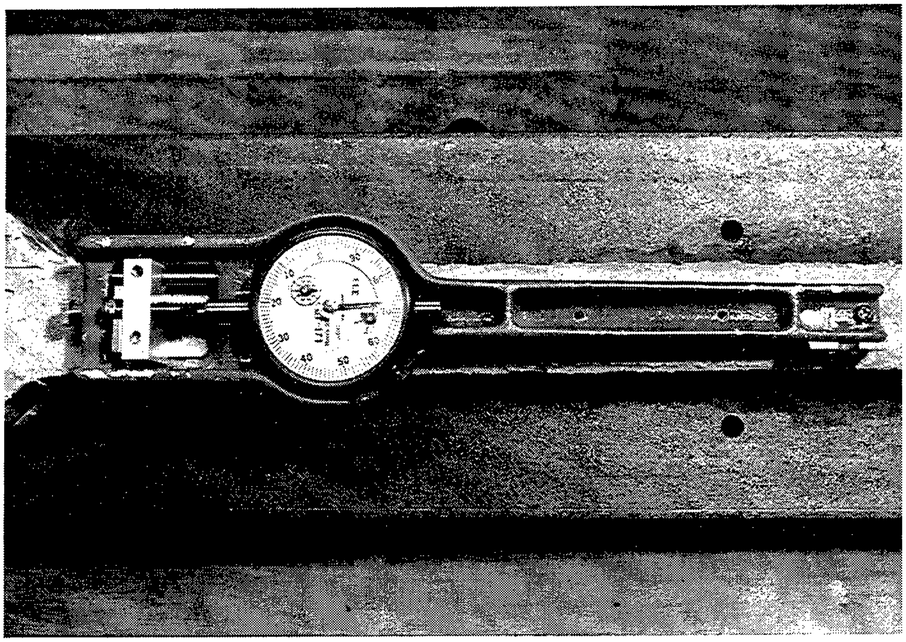

Figure 6.2 Picture of Whittemore Gage

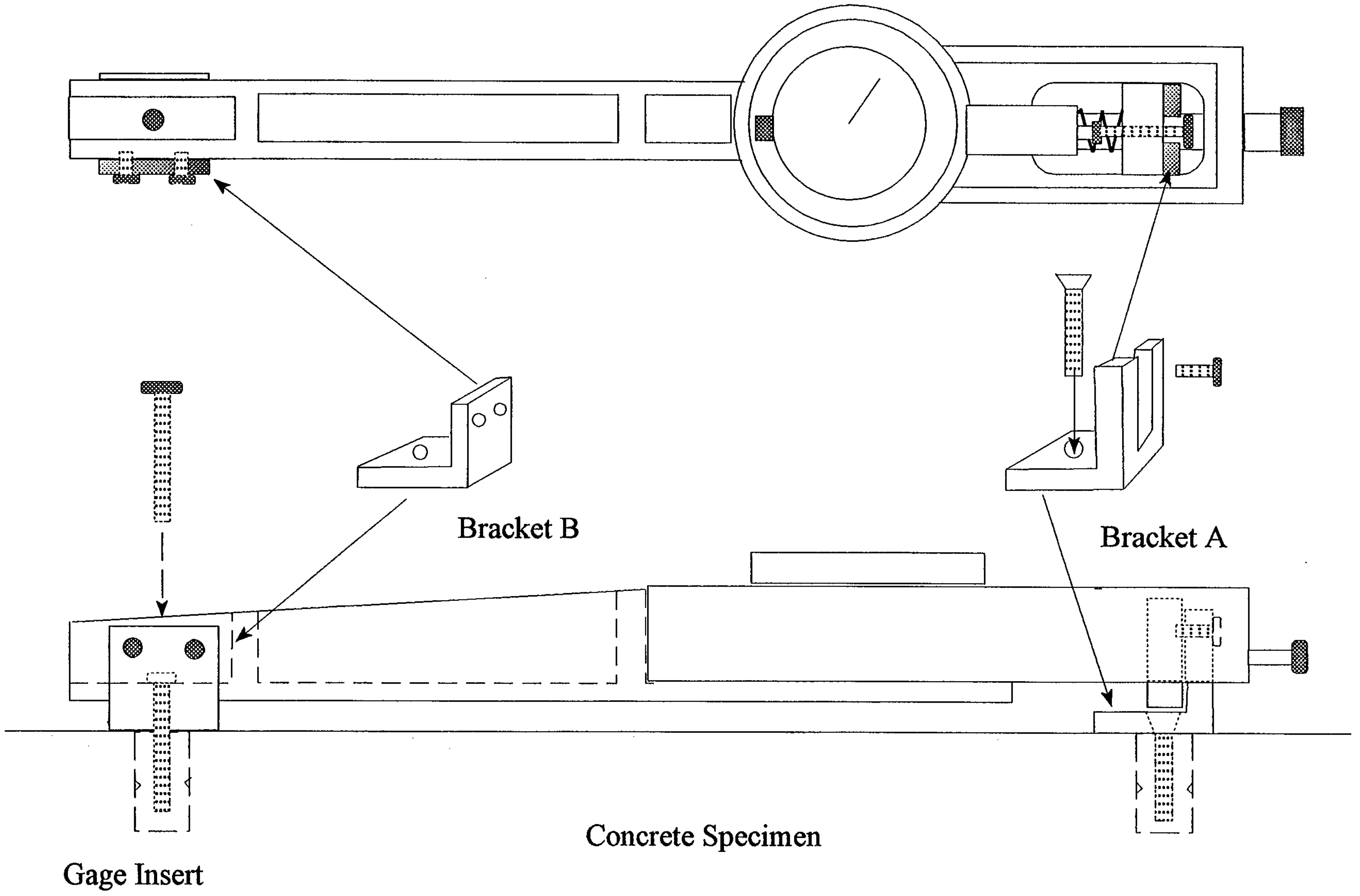

Figure 6.3 Schematic of the Modified Whittemore Gage and the Attachment of the Whittemore gage to the Concrete Specimen

6.3 Preparation of the Constrained Long Specimen

Before the fresh concrete was placed into the mold, a thin layer of transmission fluid was applied on the surface of the plate support and the two sides of the mold to reduce friction. The surface of the metal guide which contacted with the specimen was also applied with a thin layer of transmission fluid. The fresh concrete was then placed into mold. The entire apparatus was then placed on a vibrating table for 1 minute. The two gage point inserts which were attached under the metal guide (#9) were then placed into the concrete specimen. The entire apparatus was again placed on the vibrating table and vibrated for an additional 1 minute. To ensure that the two gage point inserts were fully merged into the concrete, the two inserts need to be firmly pressed down on the concrete by hand during this step. The surface of the specimen was then finished with a hand trowel. After 12 hours, the two side pieces of the mold were removed, and the metal guide was also removed from the gage point inserts. The Whittemore gage was then fastened to the two inserts with 2 screws. The initial readings of both the proving ring and the Whittemore gage were recorded.

6.4 Results from the Modified Constrained Long Specimen Tests

After the removal of the side pieces and the attachment of the Whittemore gage, the induced load was monitored by means of the proving ring, while the movement of the concrete specimen was measured by means of the Whittemore gage for a period of 14 days.

Though the concrete specimen was constrained from movement at the two ends, the Whittemore gage measured a slight shortening of the concrete specimen. This could be explained by the movement of the proving ring as load was induced. Figure 6.4 shows how the movement of the proving ring (δ_{PR}) is equal to the movement of the constrained long specimen (δ_{CL}).

There could be three different components of deformation in the concrete specimen. The first component is the shortening due to shrinkage (δ_{sh}). The second component is the elastic lengthening due to induced tensile stress (δ_E). The third component is the creep due to the induced stresses (δ_{CR}). These three components are related to the total movement of the specimen as follows:

$$\delta_{CL} = \delta_{sh} - \delta_E - \delta_{CR} \qquad (6.1)$$

In terms of strains (ϵ's), the relationship can be written as:

$$\epsilon_{CL} = \epsilon_{sh} - \epsilon_E - \epsilon_{CR} \qquad (6.2)$$

The total strain in the constrained long specimen (ϵ_{CL}) can be calculated from the deformation read by the Whittemore gage (δ_g) as follows:

$$\epsilon_{CL} = \frac{\delta_g}{L_g} \qquad (6.3)$$

Where L_g = gage length = 254 mm (or 10 in.)

The elastic strain (ϵ_E) can be calculated from the induced stress (σ_E) and the elastic modulus of the concrete (E) as follows:

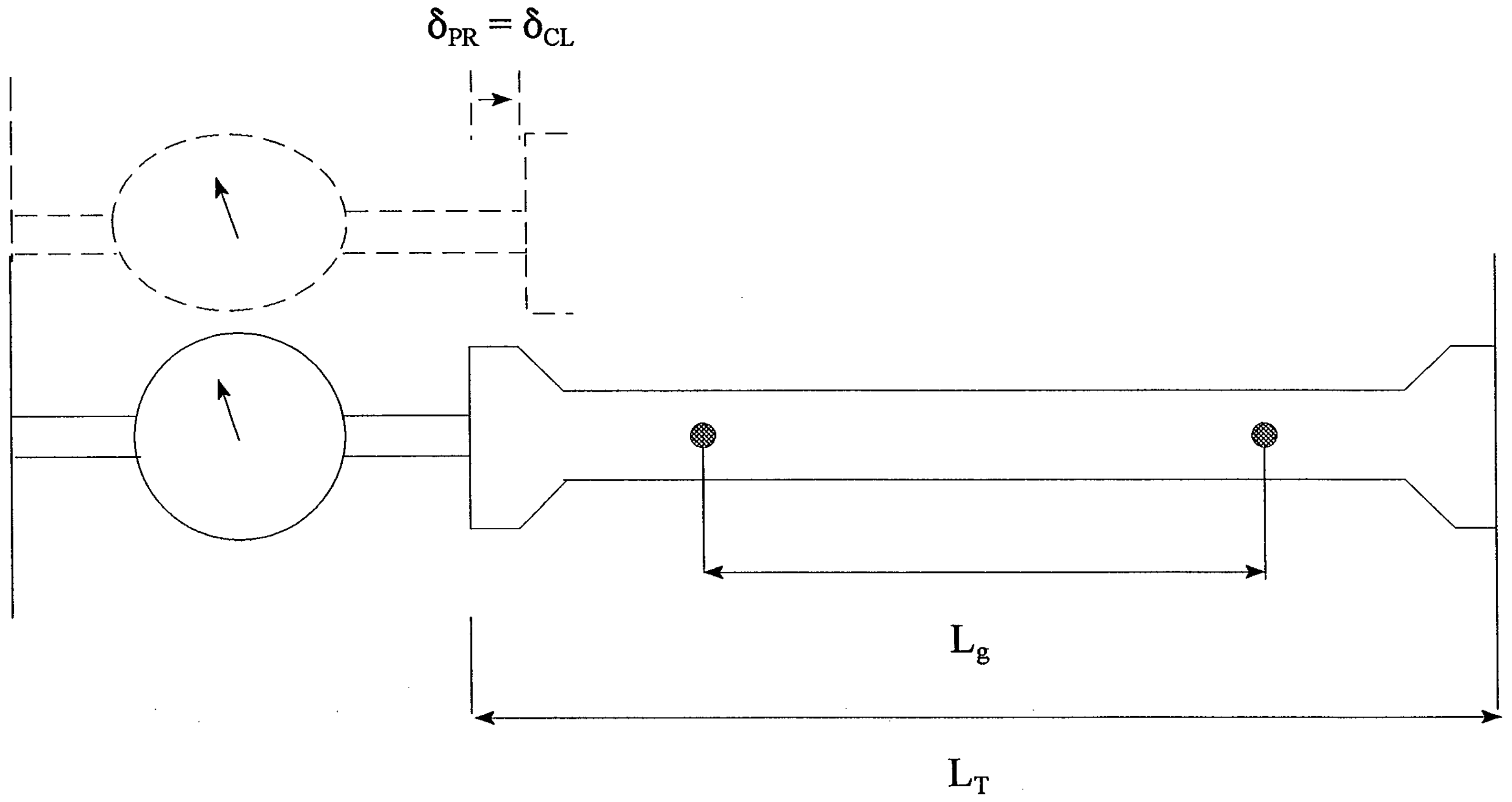

Figure 6.4 Schematic of Restrained Long Specimen

$$\epsilon_E = \frac{\sigma_E}{E} = \frac{F_{PR}}{AE} \qquad (6.4)$$

Where F_{PR} = Force measured by the proving ring

A = cross-sectional area of concrete specimen = 16.0 cm^2 (or 2.48 in.^{2})

The shrinkage strain (ϵ_{sh}) can be assumed to be equal to the free shrinkage strain measured by the length comparator and shown in Figures 5.6 and 5.7 in Chapter 5. From Equation 6.2, the creep strain (ϵ_{CR}) can be calculated from the other strains as:

$$\begin{aligned}\epsilon_{CR} &= \epsilon_{sh} - \epsilon_E - \epsilon_{CL} \\ &= \epsilon_{sh} - \left(\frac{F_{PR}}{AE}\right) - \left(\frac{\delta_g}{L_g}\right) \qquad (6.5)\end{aligned}$$

The first batch of concrete tested was a Florida Class II concrete. Table 6.1 displays the values of (1) the measured shrinkage strains (ϵ_{sh}), (2) the force measured by the proving ring (F_{PR}), (3) the elastic modulus (E), (4) the computed elastic strain (ϵ_E), (5) the measured specimen strain (ϵ_{CL}), and (6) the computed creep strain (ϵ_{CR}) for the Class II concrete. The second batch of concrete tested was a Florida Class IV concrete. Table 6.2 displays the same types of information for the Class IV concrete. The creep strain of the constrained long specimen, as calculated in this fashion, and the elastic strain (ϵ_E) were plotted as a function of time in Figures 6.5 and 6.6 for the Florida Class II and IV concretes.

Table 6.1 Results of Free Shrinkage, Elastic Modulus and Constrained Long Specimen Tests on a Florida Class II Concrete

Day	Shrinkage Strain ϵ_{sh}	Proving Ring F_{PR}	Elastic Modulus E	Elastic Strain ϵ_E	Specimen Strain ϵ_{CL}	Creep Strain ϵ_C
1	3.40E-05	6.29 lbf (27.98 N)	2.00E+06 lbf/in^2 (1.38E+07 kN/m^2)	1.27E-06	2.00E-06	3.07E-05
2	9.70E-05	6.68 lbf (29.71 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	8.97E-07	3.00E-06	9.31E-05
3	1.35E-04	7.06 lbf (31.40 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	9.49E-07	4.00E-06	1.30E-04
4	1.61E-04	7.82 lbf (34.78 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.05E-06	2.50E-05	1.35E-04
5	2.25E-04	10.91 lbf (48.53 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.47E-06	5.00E-05	1.74E-04
6	2.51E-04	13.98 lbf (62.18 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.88E-06	9.00E-05	1.59E-04
7	2.79E-04	14.06 lbf (62.54 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.89E-06	1.20E-04	1.57E-04
12	3.66E-04	14.37 lbf (63.92 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.93E-06	2.00E-04	1.64E-04

Table 6.2 Results of Free Shrinkage, Elastic Modulus and Constrained Long Specimen Tests on Florida Class IV Concrete

Day	Shrinkage Strain ϵ_{sh}	Proving Ring F_{PR}	Elastic Modulus E	Elastic Strain ϵ_E	Specimen Strain ϵ_{CL}	Creep Strain ϵ_C
1	6.20E-05	8.60 lbf (38.26 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.16E-06	1.50E-06	3.07E-05
2	1.18E-04	11.29 lbf (50.22 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.52E-06	7.50E-06	4.15E-05
3	1.62E-04	13.60 lbf (60.50 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	1.83E-06	1.05E-05	5.51E-05
4	1.61E-04	15.37 lbf (68.37 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.07E-06	1.34E-04	6.09E-05
5	2.25E-04	16.52 lbf (73.49 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.22E-06	1.62E-04	5.78E-05
6	2.51E-04	18.21 lbf (81.00 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.45E-06	1.75E-04	8.46E-05
7	2.79E-04	20.14 lbf (89.59 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.71E-06	2.00E-04	6.43E-05
8	2.86E-04	20.91 lbf (93.01 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.81E-06	2.05E-04	7.82E-05
9	3.24E-04	21.29 lbf (94.70 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.86E-06	2.26E-04	9.51E-05
10	3.23E-04	21.45 lbf (95.42 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.88E-06	2.37E-04	8.31E-05
11	3.23E-04	21.52 lbf (95.73 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.89E-06	2.49E-04	7.11E-05
12	3.26E-04	21.68 lbf (96.44 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	2.91E-06	2.60E-04	6.31E-05
13	3.57E-04	23.60 lbf (104.98 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	3.17E-06	2.70E-04	8.38E-05
14	3.83E-04	23.98 lbf (106.67 N)	3.00E+06 lbf/in^2 (2.07E+07 kN/m^2)	3.22E-06	2.75E-04	1.05E-04

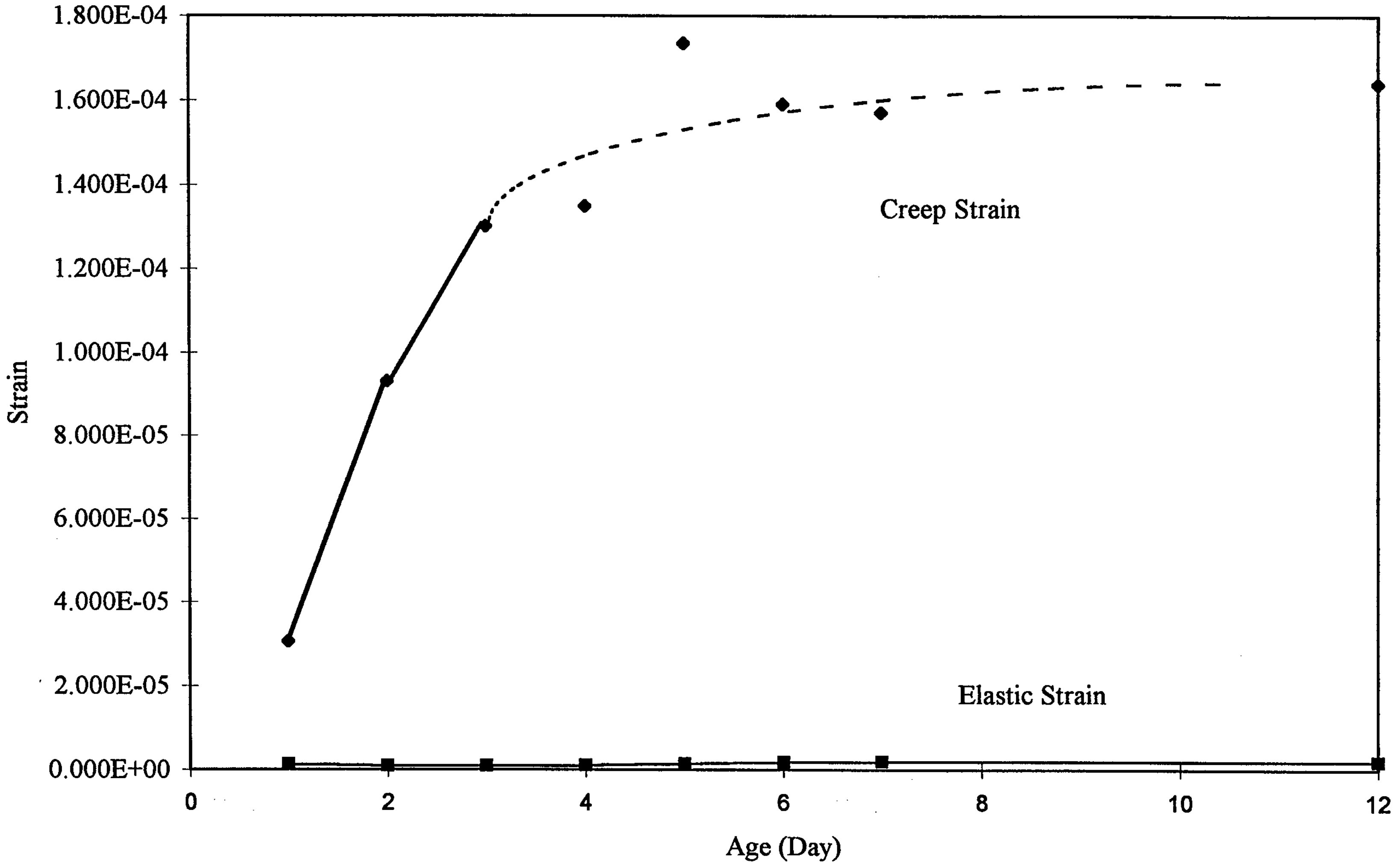

Figure 6.5 Plot of Creep and Elastic Strain Versus Time in Constrained Long Specimen Test for a Florida Class II Concrete

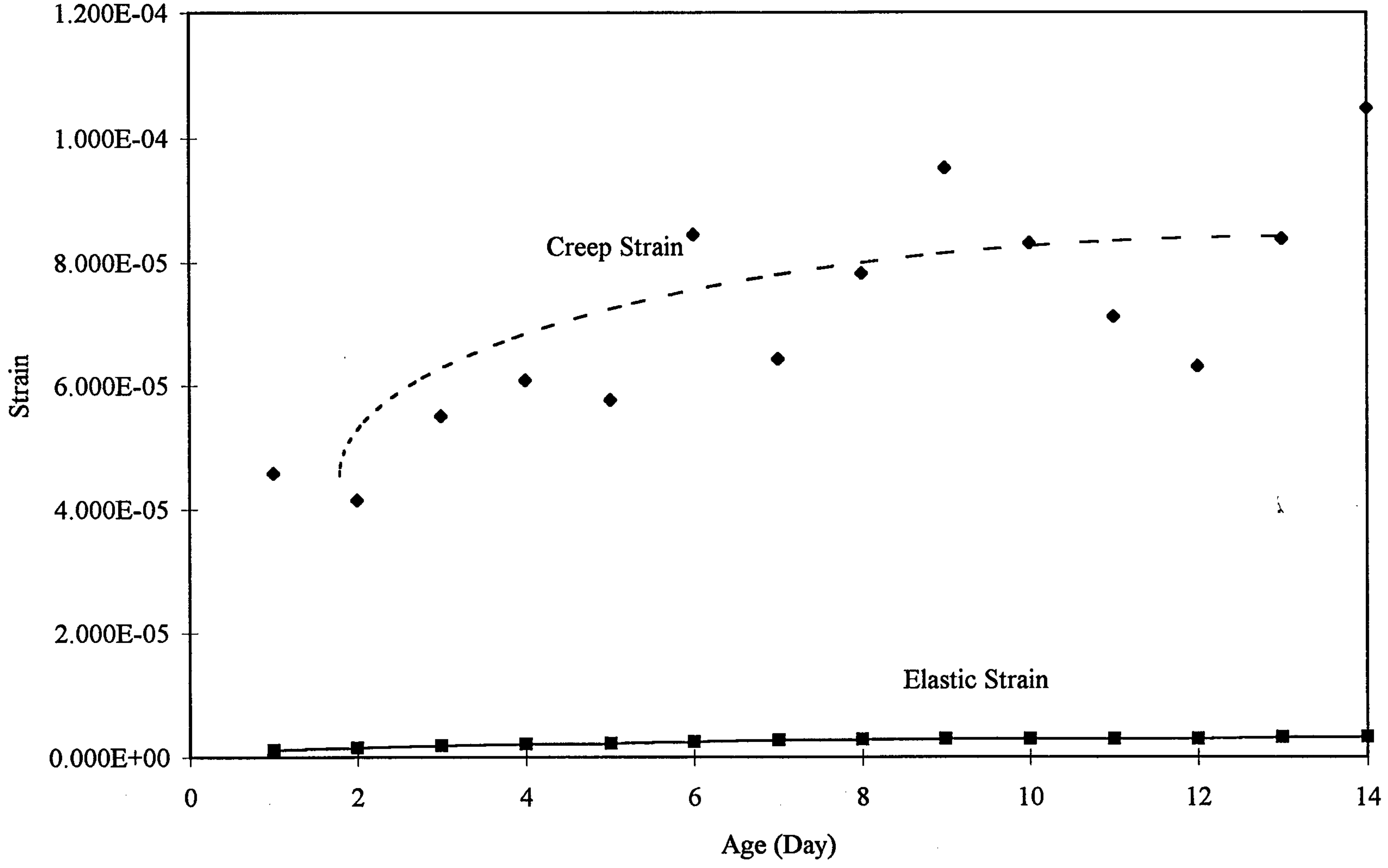

Figure 6.6 Plot of Creep and Elastic Strain Versus Time in Constrained Long Specimen Test for a Florida Class IV Concrete

If a concrete member is fully constrained from movement, the induced stress due to drying shrinkage could be expressed as:

$$\sigma_{FC} = (\epsilon_{sh} - \epsilon_{CR})\, E \qquad (6.6)$$

Where σ_{CF} = induced stress in a fully constrained concrete

The induced stresses in a fully constrained concrete were computed by using the Equation 6.6. The free shrinkage strains as obtained from the free shrinkage measurements by means of the length comparator were used as the shrinkage strain, ϵ_{sh}, while the computed creep strains from the long constrained specimen test were used as the creep strains, ϵ_{CR}. The actual creep strain should be slightly less than the one experienced by the long constrained specimen, since the long constrained specimen was not fully constrained. Thus, using the creep strains from the long constrained specimen would result in a slightly higher (or more conservative) estimation of the induced stresses.

The computed shrinkage induced stresses in the fully constrained Florida Class II and IV concretes are displayed in Table 6.3. The computed shrinkage induced stresses for Florida Class II and IV concretes are plotted as a function of time in Figures 6.7 and 6.8. The splitting tensile strength of the two concretes are also plotted on Figures 6.7 and 6.8. It could be seen from Figure 6.7 that the induced shrinkage stress of Florida Class II concrete could exceed the tensile strength of the concrete at approximately the 10th day. It could be also seen from Figure 6.8 that the induced shrinkage stress of Florida Class IV

Table 6.3 Computed Shrinkage Induced Stresses in the Hypothetical Fully Constrained Florida Class II and IV Concretes in Comparison with Their Tensile Strength

Florida Class II Concrete					
Day	Shrinkage Strain ϵ_{sh}	Creep Strain ϵ_C	Elastic Modulus E	Induced Stress σ_{FC}	Splitting Tensile Strength
1	3.40E-05	3.07E-05	2.00E+06 lb/in^2 (1.38E+07kN/m^2)	6.6 lb/in^2 (45.5 kN/m^2)	328 lb/in^2 (2261 kN/m^2)
2	9.70E-05	9.31E-05	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	11.7 lb/in^2 (80.7 kN/m^2)	456 lb/in^2 (3144 kN/m^2)
7	2.79E-04	1.57E-04	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	366 lb/in^2 (2523 kN/m^2)	460 lb/in^2 (3171 kN/m^2)
12	3.66E-04	1.64E-04	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	606 lb/in^2 (4178 kN/m^2)	535 lb/in^2 (3688 kN/m^2)
Florida Class IV Concrete					
1	6.20E-05	3.07E-05	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	93.9 lb/in^2 (647 kN/m^2)	445.7 lb/in^2 (3072 kN/m^2)
2	1.18E-04	4.15E-05	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	229.5 lb/in^2 (1582 kN/m^2)	475.8 lb/in^2 (3280 kN/m^2)
7	2.79E-04	6.43E-05	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	644.1 lb/in^2 (4441 kN/m^2)	532.1 lb/in^2 (3668 kN/m^2)
14	3.83E-04	1.05E-04	3.00E+06 lb/in^2 (2.07E+07kN/m^2)	834 lb/in^2 (5750 kN/m^2)	569.4 lb/in^2 (3925 kN/m^2)

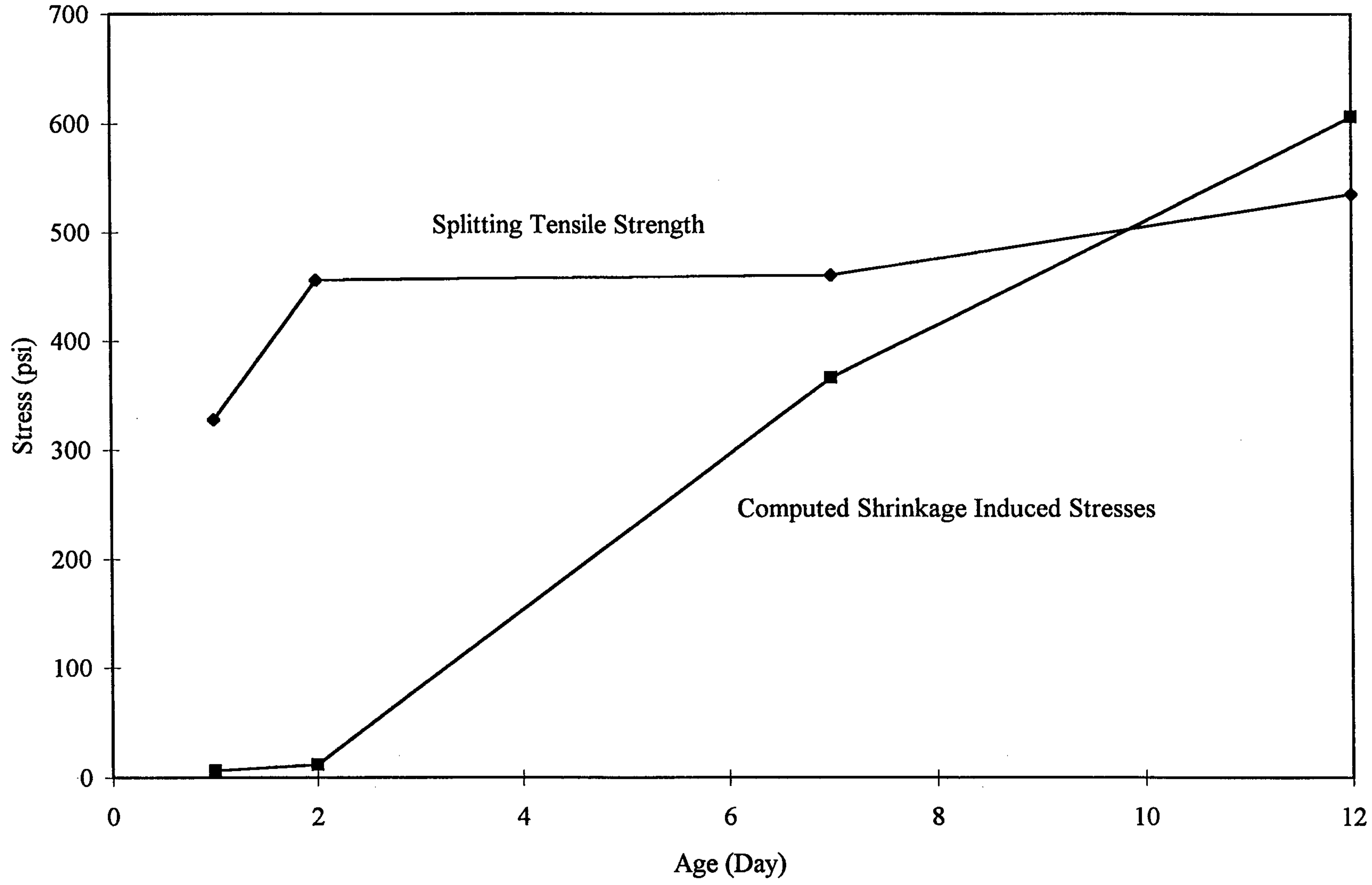

Figure 6.7 Computed Shrinkage Induced Stresses in a Hypothetical Fully Constrained Florida Class II Concrete

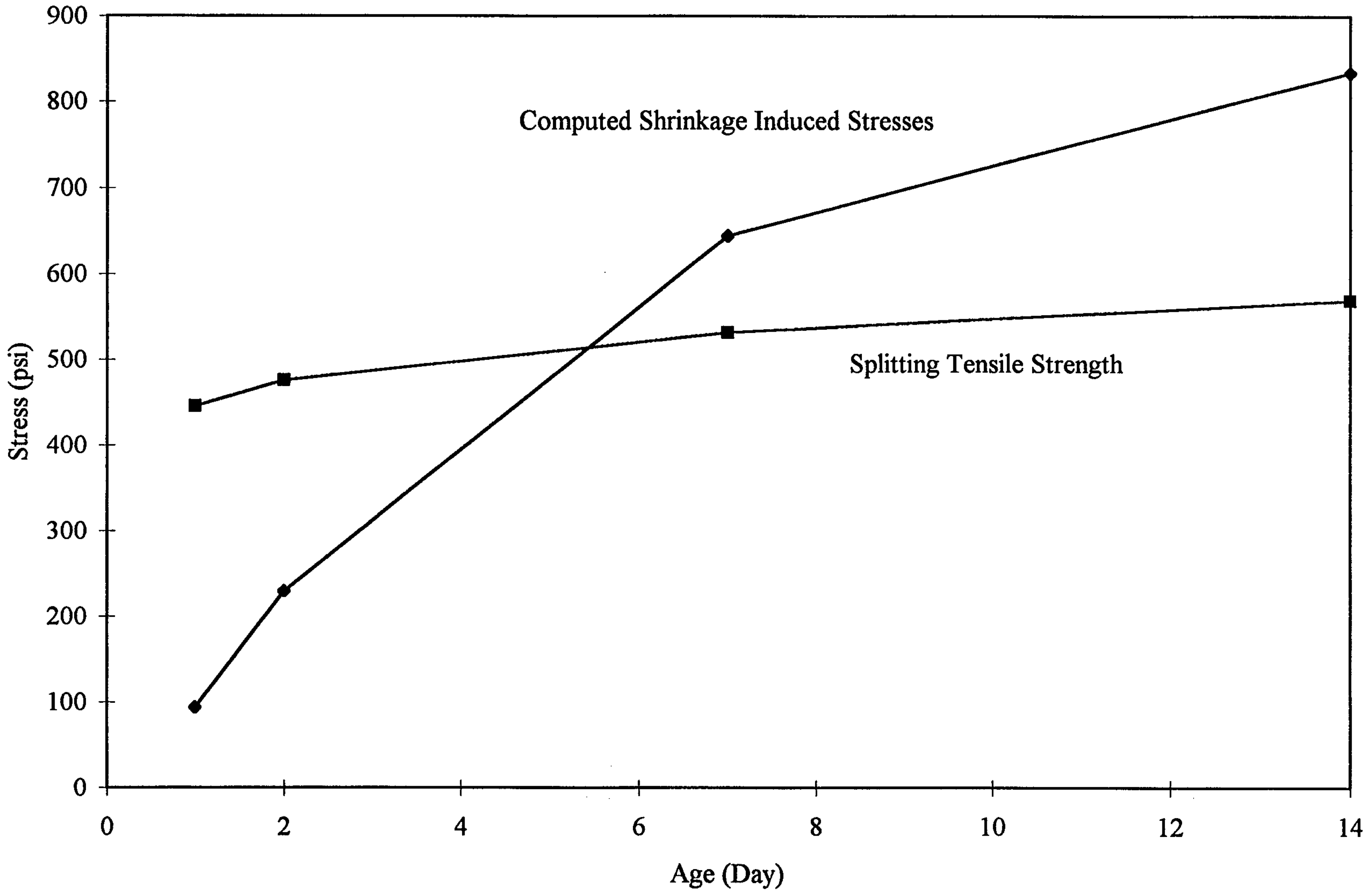

Figure 6.8 Computed Shrinkage Induced Stresses in a Hypothetical Fully Constrained Florida Class IV concrete

concrete could exceed the tensile strength of the concrete at approximately the 6th day.

6.5 Assessment of the Modified Constrained Long Specimen Method

From the data obtained from the two concretes tested in this set of experiment, the modified constrained long specimen method appeared to provide reasonable values of stresses and strains. The use of insert points in the concrete for indication of strains in the concrete is a great improvement over the method of measuring the movement between the two ends of the specimen. The strain measurements would not be affected by the unevenness of the ends of the specimen or the breakage of bond between the specimen and the end grips. The strain data obtained with this method showed a much reduced variability and greater consistency as compared with the data obtained previously when the movements between the two ends of the specimen were measured.

The major merit of this method is that the creep strains that might develop in the concrete during setting could be determined conveniently and effectively. As presented in the previous section, the creep strain can be determined by subtracting the free shrinkage strain and the elastic strain from the total strain as measured by the constrained long specimen method. The creep strain that develops in the concrete has the effect of reducing the induced shrinkage stress in the concrete. Thus, proper determination of creep strains is crucial in the accurate estimation of shrinkage stresses in a concrete. The use of the modified constrained long specimen method makes a realistic determination of the induced shrinkage stresses possible.

CHAPTER 7
RECOMMENDED TESTING PROCEDURE AND ANALYSIS METHOD FOR EVALUATING SHRINKAGE CRACKING POTENTIAL OF CONCRETE

7. 1 Introduction

In order to estimate the shrinkage cracking potential of a concrete under a certain curing environment, the following properties of the concrete under the specified curing environment must be determined:

(1) Free shrinkage strain as a function of time

(2) Creep strain as a function of time

(3) Elastic modulus as a function of time

(4) Tensile strength as a function of time

The free shrinkage, creep and elastic modulus can be used to compute the expected shrinkage stresses at different times. When the computed shrinkage stress exceeds the tensile strength of the concrete, the concrete will likely crack at that time.

This chapter presents the recommended testing procedure for determining these required concrete properties, and the analysis method for determining the expected shrinkage stress in the concrete.

7.2 Recommended Testing Procedure

7.2.1 Tests To Be Performed

For each concrete to be evaluated, it is recommended that the following tests be performed:

(1) Elastic modulus test (ASTM C469) at 1, 2, 7 and 14 days, with 2 replicate samples per condition.

(2) Splitting tensile strength test (ASTM C496) at 1, 2, 7 and 14 days, with 2 replicate samples per condition.

(3) Free shrinkage measurement using length comparator (as described in Section 4.4) at 1 day increments from 1 through 14 days, using 3 replicate samples.

(4) Constrained long specimen test (as described in Sections 6.2 and 6.3) using 2 replicate samples, with force and deformation readings taken at 1 day increments from 1 through 14 days.

(5) Compressive strength test (ASTM C39) at 28 days, with 2 replicate samples per condition.

7.2.1 Curing of Concrete Samples

The concrete samples to be evaluated by tests (1) through (4), as listed in the previous section, should be cured under a condition that would simulate the actual expected curing environment in service. To simulate no moist curing in the field, the samples can be left to dry in the laboratory. Specimens for the compressive strength test should be moist-cured, since the compressive strength test results will be used primarily to check the concrete mix design.

7.3 Recommended Analysis Method

7.3.1 Analysis of Elastic Modulus Data

The averages of the elastic modulus values at the various curing time shall be plotted as a function of time. A best fit curve to show the elastic modulus as a function of curing time can be determined by a regression analysis. This best fit curve shall be used to estimate the elastic modulus of the concrete (E) at different times.

7.3.2 Analysis of Splitting Tensile Strength Data

The averages of the splitting tensile strength values at the various curing time shall be plotted as a function of time. A best fit curve to show the tensile strength as a function of curing time can be determined by a regression analysis. This best fit curve shall be used to estimate the splitting tensile strength of the concrete (σ_t) at different times.

7.3.3 Analysis of Free Shrinkage Data

The averages of the free shrinkage strains as measured by the length comparator at the various curing time shall be plotted as a function of time. A regression analysis can be performed to find the best fit line which would show the free shrinkage strain as a function of curing time. This best fit curve shall be used to estimate the free shrinkage of the concrete (ϵ_{sh}) at different times.

7.3.4 Analysis of Results of Constrained Long Specimen Test

7.3.4.1 Determination of Elastic Strain

The elastic strain (ϵ_E) experienced by the concrete at a specified time shall be computed by dividing the force measured by the proving ring (F_{PR}) by the cross sectional area of the concrete specimen (A) and the average elastic modulus of the concrete (E) at the specified time. It can be expressed as follows:

$$\epsilon_E = F_{PR} / AE \qquad (7.1)$$

7.3.4.2 Determination of Total Strain

The total strain (ϵ_{CL}) experienced by the constrained long specimen shall be computed by dividing the gage-measured deformation (δ_g) by the gage length (L_g) between the two insert points. It can be expressed as follows:

$$\epsilon_{CL} = \delta_g / L_g \qquad (7.2)$$

7.3.4.3 Determination of Creep Strain

The creep strain (ϵ_{CR}) experienced by the concrete specimen shall be calculated as follows:

$$\epsilon_{CR} = \epsilon_{sh} - \epsilon_E - \epsilon_{CL} \qquad (7.3)$$

7.3.5 Computation of Expected Shrinkage Stress

The expected shrinkage stress in a fully constrained concrete (σ_{FC}) can be calculated as follows:

$$\sigma_{FC} = (\epsilon_{sh} - \epsilon_{CR})\, E \qquad (7.4)$$

7.3.6 Assessment of Shrinkage Cracking Potential

When the computed expected shrinkage stress (σ_{FC}) as computed by Equation 7.4 exceeds the expected tensile strength of the concrete (σ_t) at any particular time, the concrete will be likely to crack due to shrinkage stresses at that time.

CHAPTER 8
RECOMMENDATION FOR FURTHER STUDY

This research study has resulted in the development of a very promising testing and analysis method for evaluating concrete mixes for resistance to shrinkage cracking in service. This testing and analysis method should be further evaluated, refined and implemented as a standard procedure for evaluating shrinkage cracking resistance of concrete used by FDOT, especially for bridge deck applications. It is recommended that further study be conducted in order to implement the developed testing and analysis method using constrained long specimen apparatuses as a standardized tool for evaluation of shrinkage cracking resistance of concrete in Florida.

It is recommended that the constrained long specimen apparatus be further refined by automating the data acquisition process. The proving ring, which is used to measure the induced force in the constrained long specimen, can be replaced by a load cell. The load cell will have the advantage of less movement than the proving ring caused by the induced force, and thus the long specimen will be better constrained from movement. The Whittemore gage, which is used to measure the deformation of the specimen, can be replaced by a high-sensitivity DC LVDT. Both the load cell and the LVDT can be connected to a personal computer via a data acquisition board. The schematic of this proposed refined constrained long specimen test apparatus is shown in Figure 8.1. This refined test set-up will be able to provide continual monitoring of load and deformation on the constrained long specimen during the test.

It is also recommended that the same test set-up be used to measure the free shrinkage of the specimen by releasing the constraint on the specimen. In this case, the load cell would not be necessary. For this type of testing, the test set-up can be simplified to the one shown in Figure 8.2.

1. Fixed Grip
2. LVDT
3. Movable Grip
4. Contact Seat
5. Load Cell
6. Grip
7. Screw Assembly
8. Concrete Specimen
9. Data Acquisition System

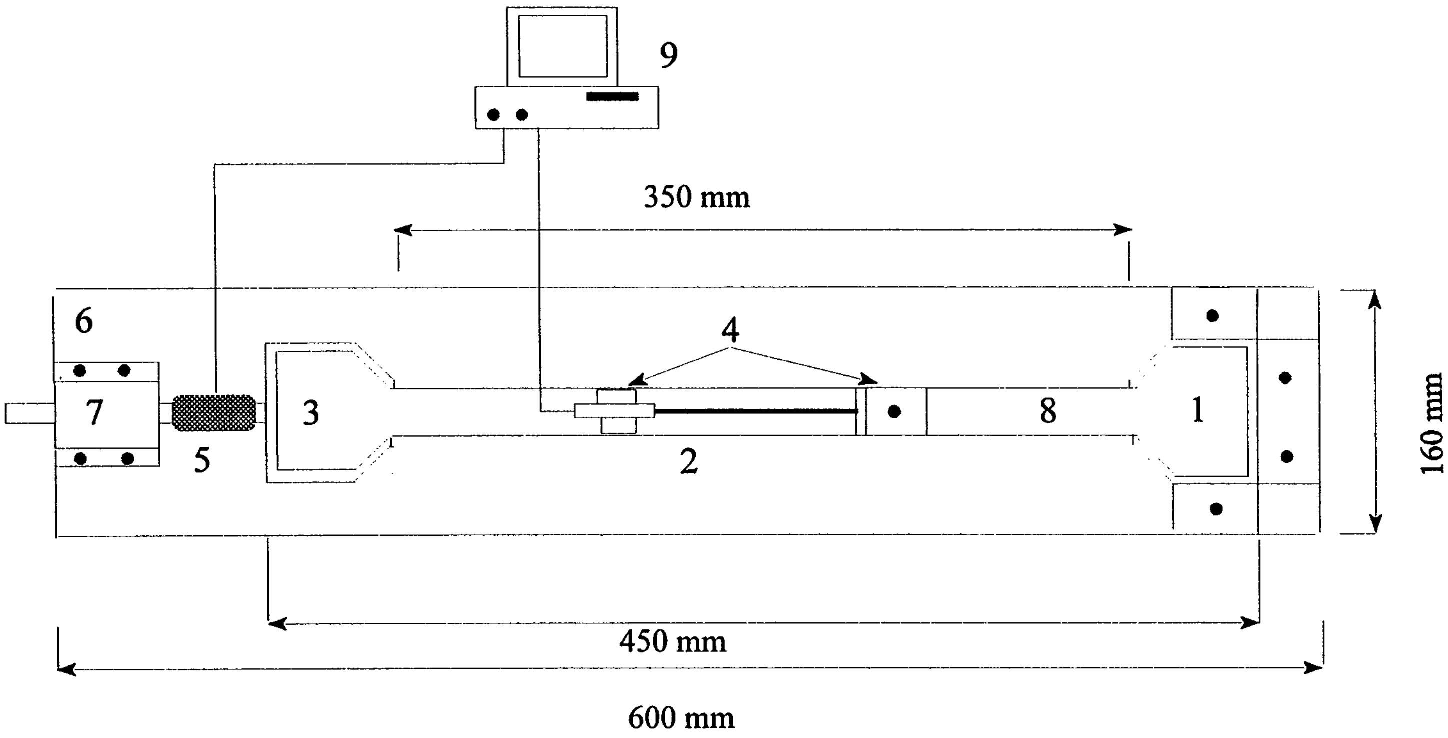

Figure 8.1 Schematic of Proposed Modified Constrained Long Specimen Apparatus for Automatic Measurement of Induced Load and Deformation

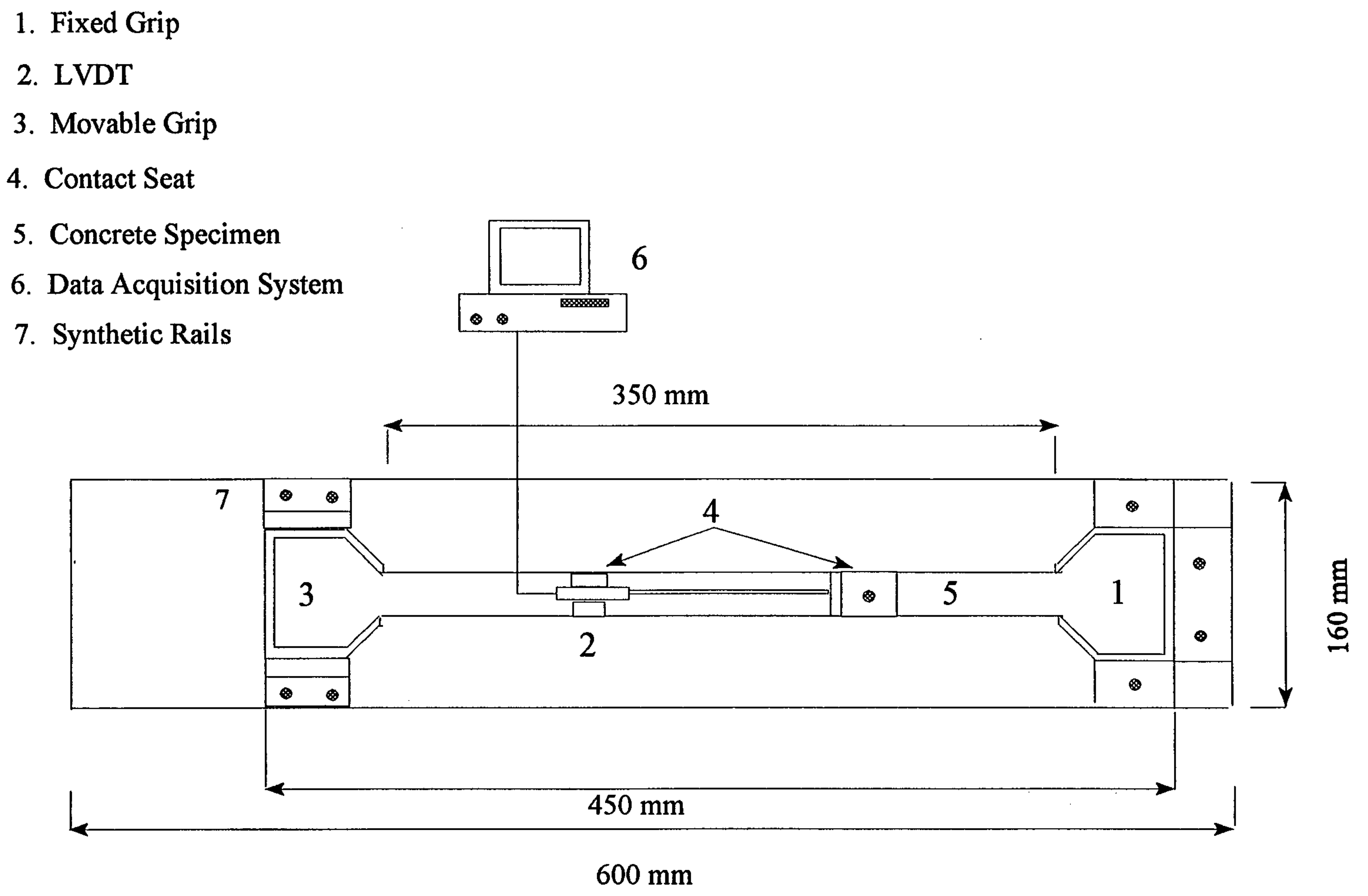

Figure 8.2 Schematic of Proposed Modified Constrained Long Specimen Apparatus for Free Shrinkage Measurement

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