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The ALSN 2004 model to predict shrinkage of concrete containing SRA

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**THE ALSN 2004 MODEL TO PREDICT SHRINKAGE OF CONCRETE
CONTAINING SRA**

A Thesis

Presented to

The Faculty of the Department of Civil and Environmental Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Snezana Ristanovic

December 2005

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ABSTRACT

THE ALSN 2004 MODEL TO PREDICT DRYING SHRINKAGE OF CONCRETE CONTAINING SRA

by Snezana Ristanovic

This thesis describes a new equation, referenced as the ALSN (Al-Manaseer and Snezana) 2004, to predict the shrinkage of concrete containing shrinkage reducing admixture (SRA) (i.e., a chemical admixture that reduces drying shrinkage of concrete). The equation is a modified version of the GL 2000 shrinkage model. The equation was tested for concrete mixes containing SRA in the range of 0.5–2.5% by mass of cementitious materials. The ALSN 2004 model was compared with the GL 2000 model and the CEB-FIP MC 90-99 utilizing the residual method, average and standard deviation of residuals, the CEB coefficient of variation method, the CEB mean square error method, and the CEB mean deviation method. The results show that the ALSN 2004 has improved the shrinkage prediction of concrete containing SRA. To date no known model has been published to predict the drying shrinkage of concrete containing SRA.

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NOMENCLATURE

A. Organizations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
CEB-FIP MC	The Committee Euro-International du Beton/Federation International de la Precontrainte-Europe Model Code
RILEM	Réunion Internationale des Laboratoires et Experts des Matériaux, Systèmes de Constructions et Ouvrages

B. General Abbreviations and Symbols

A/cm	Aggregate-to-cementitious material ratio
CA	Coarse aggregate
FA	Fine aggregate
G	Grace
HRWR	High-range water reducer
LRWR	Low-range water reducer
MB	Master Builder
SRA	Shrinkage Reducing Admixture
w/cm	Water-to-cementitious material ratio

C. Abbreviations and Symbols for Models

C.1. The GL 2000 and ALSN 2004 Model

f_{cm28}	Average 28-day concrete compressive strength [Mpa]
H	Relative humidity [%]
K	Shrinkage constant which depends on cement type
t	Age of concrete [days]
t_c	Age of concrete at the end of water or steam curing (i.e. beginning of drying)[days]
V/S	Volume-to surface area ratio [mm]
$\beta(h)$	Humidity correction factor
$\beta(SRA)$	SRA correction factor
$\beta(t)$	Age correction factor
ε_{shu}	Ultimate shrinkage strain

C.2. The CEB-FIP MC 90-99

A_c	The cross-section [mm ²]
f_{cm28}	Mean compressive strength of concrete at an age of 28 days [MPa]
H	Ambient relative humidity [%]
h_e	Notional size of member [mm]
t	Age of concrete [days]
t_c	Concrete age at the beginning of drying [days]

u	Perimeter of the member in contact with the atmosphere [mm]
α_{as}	Coefficient that depends on type of cement
α_{ds1}	Coefficient that depends on type of cement
α_{ds2}	Coefficient that depends on type of cement
$\beta_{as}(t)$	Function to describe the time-development of autogenous shrinkage
$\beta_{ds}(t-t_c)$	Function to describe the time-development of drying shrinkage
$\beta_{RH}(H)$	Coefficient to take into account the effect of relative humidity on drying shrinkage
β_{s1}	Coefficient to take into account the self-desiccation in high-performance concrete
$\varepsilon_{as}(t)$	Autogenous shrinkage at time t
$\varepsilon_{as0}(f_{cm28})$	Notional autogenous shrinkage coefficient
$\varepsilon_{ds}(t, t_c)$	Drying shrinkage at time t
$\varepsilon_{ds0}(f_{cm28})$	Notional drying shrinkage coefficient

D. Abbreviations and Symbols for Statistical Methods

D.1. The Average and Standard Deviation of Residuals

A_j	Average of residuals for fixed time, j
-------	--

n	Total number of data points considered at a fixed time
S_j	Standard deviation of residuals for fixed time j
X_i	Residual value of i^{th} data point in a fixed time, j

D.2. The CEB Coefficient of Variation Method

n	Number of data points taken
N	Total number of data sets considered
S_i	Standard error determined from ΔY_{ij} for experiment i
V_i	Coefficient of variation of experiment i
V_{CEB}	Mean coefficient of variation
Y_i	Mean shrinkage strain of experiment i
Y_{ij}	Observed shrinkage strain at time j of experiment i
ΔY_{ij}	Difference between measured and predicted shrinkage strains at time j of experiment i

D.3. The CEB Mean Square Error Method

$CalX_{ij}$	Predicted shrinkage strain at time j of experiment i
$ObsX_{ij}$	Experimental shrinkage strain at time j of experiment I
f_j	Percent difference between calculated and observed data point j

F_{CEB}	Mean square error
n	Total number of values j of experiment i considered at a fixed time
N	Total number of data sets considered

D.4. The CEB Mean Deviation Method

$CalX_{ij}$	Predicted shrinkage strain at time j of experiment i
$ObsX_{ij}$	Experimental shrinkage strain at time j of experiment i
M_i	Deviation between predicted and experimental values of experiment i
M_{CEB}	Mean deviation
n	Total number of values j of experiment i considered at a fixed time
N	Total number of data sets considered

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Chapter 1

Introduction

1.1 General

Concrete changes its volume, even when no external loads are applied. The reduction in volume is known as shrinkage. Shrinkage in concrete can be attributed to: loss of moisture content, chemical reactions of the cement with water, variations in temperature, and chemical reactions of the cement with atmospheric carbon dioxide. As concrete hardens, shrinkage can produce cracking. Cracking directly influences the durability and serviceability of concrete structures. Accurate estimation of concrete shrinkage is significant to the design of concrete structures. Benefits of an accurate prediction model can yield a structure with minimal cracking, extended life and durability. In addition, a precise model can reduce the cost incurred from over-design of concrete members.

1.2 Shrinkage of Concrete

The shrinkage of concrete is an important factor for the performance and quality of concrete structures. Completely independent of any action of stresses, shrinkage of concrete is a very complex phenomena that cannot be explained completely. Many factors influence shrinkage, such as ambient conditions, the age of concrete, the mix composition, the method of preparation of concrete, curing, the dimensions of the structural member, and many other factors. There are several types of shrinkage: plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage.

Plastic shrinkage occurs as fresh concrete loses moisture before placement and before any strength development occurs. Cracks occur at the surface of the fresh concrete after it is placed and while it is still plastic. Mostly, cracks appear at the horizontal surfaces, as a result of rapid evaporation of water from the surface of concrete before it has set. Particles of water under the surface of concrete forms menisci between the fine particles of cement and aggregate causing tensile forces to develop in the surface layers. If the concrete surface has developed sufficient tensile strength to resist the tensile forces cracks do not form. Factors that influence the high evaporation rate from the surface of concrete are high wind velocity, low relative humidity, and high ambient and/or concrete temperatures. Plastic cracking can be minimized with the proper curing of concrete during placing and finishing of concrete.¹

Autogenous shrinkage results from the Portland cement hydration. Chemical reactions occur in the cement paste, the reaction products occupy less space than the original reactants and so-called chemical shrinkage occurs. Once the cement has set, this shrinkage is resisted and porosity is created within the capillary pore system of the cement paste microstructure. The water or air menisci created in these empty pores induce an autogenous shrinkage that may result in cracking if the tensile strength of material is exceeded.²

Carbonation shrinkage is due to the carbonation process in cement hydration products. It occurs when hydrated cement reacts with atmospheric carbon dioxide. This leads to the formation of calcium carbonate and water and consequently a reduction in volume.²

Drying shrinkage occurs when hardened concrete is exposed to air with relative humidity less than one hundred percent. The surface near regions of concrete reaches a state of moisture equilibrium with the surrounding environment after a short period of time. However, with increasing distance from the concrete surface, the moisture of concrete increases. As a result, exterior concrete shrinks more rapidly than the interior concrete. This leads to tensile stresses in outer skin of the concrete and compressive stresses in the interior. If these tensile stresses exceed the tensile strength of concrete, the concrete will crack. Parameters that most influence drying shrinkage are the amount and size of reinforcement, size and shape of concrete member, and surface area to volume ratio of concrete member. Reinforced concrete will shrink less than plain concrete in the same ambient conditions, a small concrete member will shrink more than large member, greater surface area to volume results in greater shrinkage.³

Cracks in concrete members provide easy access for oxygen, moisture, chlorides, and other aggressive chemicals and agents into the concrete, and can impact durability of concrete. The cracking of concrete can be minimized if it is properly designed for the environment to which it is to be exposed to.

Drying shrinkage is major engineering problem because it can produce the cracks into hardened concrete, and reduce the resistance of the concrete. With the development of new technologies and materials, a new admixture for reducing the drying shrinkage in concrete was invented.

1.3 Shrinkage Reducing Admixture (SRA)

The usage of shrinkage reducing admixture in concrete mix has been introduced as a very effective method for reducing drying shrinkage. SRA reduces the capillary tension of the water within the concrete pores as it dries.

SRA was first developed and made commercially available in 1982 in Japan in a partnership between Nihon Cement Co., Ltd. and Sanyo Chemical Industries, Ltd.^{4, 5} The first U.S. patent for this type of invention was awarded to Goto et al. in 1985. The main component of their SRA was polyoxyalkylene alkyl ether, a lower alcohol alkyleneoxid adduct.⁶ Later in 1996, another U.S. patent was also awarded for the development of an SRA with similar components to Berke et al.⁷

SRAs are non-corrosive, low viscosity, water-soluble liquids that reduce shrinkage by reducing capillary tension within the pores of concrete as it dries. With the exception of the added SRA, concrete mixture proportions and mixing requirements remain relatively unchanged when compared to concrete mixes without SAR. Thus, drying shrinkage can be reduced for essentially any currently used concrete. It was found that the effectiveness of the SRA mixture increases with the increase of SRA concentration to the water content.

1.4 Objective

The purpose of this study was to improve the GL 2000 model prediction for concrete containing SRA. The GL 2000 model was modified by adding a new parameter, $\beta(\text{SRA})$, that accounts for effects of SRA in the mix. The new model, called ALSN 2004, was developed and evaluated utilizing experimental data obtained from 17 concrete mixes

with percentage of SRA in the range of 0.5-2.5%. The adequacy of the new equation was established by comparing its predicted values with the values obtained from the GL 2000 and the CEB-FIP MC 90-99 model equations.

Three different approaches in analysis of the predicted values were used:

- The values of measured and predicted shrinkage strain were plotted on the same graph for each concrete mix. The deviation of predicted values from measured values can be easily observed for each model.
- Analysis of residuals was performed.
- Four statistical methods for evaluation of the models were used.

It is shown that the ALSN 2004 gives better prediction than GL 2000 model and CEB-FIP MC 90-99 model for concrete containing SRA.

1.5 Thesis Outline

This thesis consists of five chapters. Chapter 1 includes the introduction on concrete shrinkage and shrinkage reducing admixture. Chapter 2 presents the ALSN 2004 Model for predicting the shrinkage of concrete containing SRA. Chapter 3 describes the concrete mixes used in calibration and evaluation of the new model. Also, it explains the procedure used to develop the new equation. Chapter 4 includes the evaluation of the new model. Chapter 5 provides conclusions and recommendations.

Chapter 2

ALSN 2004 Equation to Predict Drying Shrinkage of Concrete Containing Shrinkage Reducing Admixture

2.1 Introduction

Over the past 30 years several models for predicting drying shrinkage of concrete have been developed. One of the primary needs is a model that is accurate and simple to use. The American Concrete Institute (ACI) and the Euro-International Concrete Committee have accepted and published several models for estimating the shrinkage of concrete. One of the models for predicting shrinkage of concrete that was accepted by ACI committee is the GL 2000 Model. The level of accuracy of this model was established by comparing the calculated values with experimental values from RILEM data bank. This model was evaluated as one of the best from the point of accuracy and simplicity.⁸ The GL 2000 Model includes factors such as relative humidity, concrete member size, cement type, age at end of curing and strength. However, with the development of SRA, that reduces the shrinkage of concrete, the prediction of shrinkage of concrete became less accurate. The GL 2000 model does not account for the effect of SRA. Therefore, its accuracy decreases with increased SRA content.

2.2 The ALSN 2004 Model

The proposed model, ALSN 2004, is a modified version of the GL 2000 equation developed by Gardner.⁹ The GL 2000 model includes factors such as relative humidity, concrete member size, cement type, age at end of curing and 28-day strength. However, it does not account for the effect of SRA, therefore its accuracy decreases with increased

SRA content. The ALSN 2004 equation introduces a new parameter $\beta(SRA)$ that accounts for effects of SRA in the mix. For concrete with 0 % SRA, $\beta(SRA)$ coefficient is equal to 1 and the predicted values of shrinkage are the same for the GL 2000 and ALSN 2004 Models. The proposed ALSN 2004 equation for computing drying shrinkage $\varepsilon_s(t)$ is:

$$\varepsilon_s(t) = \varepsilon_{shu} \beta(h) \beta(t) \beta(SRA) \quad (1)$$

$$\varepsilon_{shu} = (900) K \left(\frac{30}{f_{cm28}} \right)^{1/2} \times 10^{-6} \quad (2)$$

$$\beta(h) = 1 - 1.18 \left(\frac{H}{100} \right)^4 \quad (3)$$

$$\beta(t) = \left(\frac{t - t_c}{t - t_c + 0.12 (V/S)^2} \right)^{1/2} \quad (4)$$

$$\beta(SRA) = \frac{2}{2 + SRA^{0.7}} \quad (5)$$

Where,

ε_{shu} = Ultimate shrinkage strain

$\beta(h)$ = Humidity correction factor

$\beta(t)$ = Age correction factor

$\beta(SRA)$ = SRA correction factor

K = Shrinkage constant which depends on cement type (Appendix A.1)

f_{cm28} = Average 28-day concrete compressive strength [MPa]

H = Relative humidity [%]

t = Age of concrete [days]

t_c = Age of concrete at the end of water or steam curing (i.e. beginning of drying) [days]

V/S = Volume-to surface area ratio [mm]

SRA = Percentage of SRA between [0-2.5%]

The limitations of the ALSN 2004 model are similar to the limitations of the GL 2000 model, and they are:

- Average compressive strength ranges from 16 MPa to 82 MPa.
- Relative humidity is between 20% and 100%.
- Volume to surface ratio is greater than 19 mm.
- Age of concrete drying commenced is greater than 1 day.
- The mixes used for the calibration and evaluation of the model have the same materials and same w/cm ratio. The equation was not tested for different w/cm ratios and is limited to a maximum SRA dosage of 2.5%.

Chapter 3

Experimental

3.1 Introduction

This chapter describes the concrete mixes used for the calibration and evaluation of the ALSN 2004 model. Mix proportions as well as mechanical properties including strength are given. The chapter describes the preparation, curing, and testing procedure for the concrete mixes. The procedure used to develop the new equation is also presented.

3.2 Mixture Components

The mixture components used in the preparation of concrete are: water, cement, aggregate, mineral admixtures, and chemical admixtures.

Cement used in the preparation of concrete is ASTM type II Portland cement that met the ASTM C 150 specifications. The equivalent European cement type is slow hardening (SL) cement. Chemical compositions and physical properties of cement are given in Table 3.1.

The coarse aggregate used was composed of limestone and crushed granite. The coarse aggregate had a maximum size of $\frac{1}{2}$ in. The fine aggregate has a fineness modulus of 2.77. Sieve analysis for the coarse and fine aggregate was performed in accordance to ASTM C 33 and is shown in Table 3.2. Physical properties of the coarse and fine aggregate are presented in Table 3.3.

Mineral admixtures used to prepare the concrete mixes are: fly ash class F, silica fume, and metakaolin class N. The chemical and physical compositions of the mineral admixtures can be found in Tables 3.4, 3.5, and 3.6.

Chemical admixtures used to prepare the concrete mixes are: shrinkage reducing admixture produced by Grace (SRA-G, Eclipse), shrinkage reducing admixture produced by Master Builder (SRA-MB, Tetraguard-AS20), high-range water reducing admixture produced by Grace (HRWR-G, ADVA-100), high-range water reducing admixture produced by Master Builder (HRWR-MB, Rheobuild-3000 FC), low-range water reducing admixture produced by Grace (LRWR-G, WRAD-64), and low-range water reducing admixture produced by Master Builder (LRWR-MB, Pozzolith 200N).

The concrete mix was designed to have a water-to-cementitious materials ratio (w/cm) of 0.33 by mass of cementitious materials.

Table 3.7 lists the proportions of concrete components and the 28-day compressive strength for the 17 mixes that were used in this study. These mixes contained SRA component in the range of 0.5-2.5% by mass of cementitious materials.

3.3 Preparation and Curing of Concrete Specimens

Three concrete prisms, 3 x 3 x 11 ¼ in. (75 x 75 x 285 mm) having a 10 in. (250 mm) gage length, are made for each mix to determine the shrinkage values according to ASTM C 490. Also, twelve 4 x 8 in. (100 x 200 mm) cylinders were prepared to determine the compressive strength. The concrete prisms and cylinders were placed in the humidity room at a relative humidity of 100 percent. After twenty-four hours concrete prisms were demolded and initial readings were taken. The specimens were

then cured in water for six days and then placed in a controlled room at $73.4^{\circ} \pm 3^{\circ}\text{F}$ and relative humidity of $50\% \pm 4\%$.

3.4 Shrinkage Measurements

Shrinkage was measured at regular intervals every 7 days up to 180 days and after that every 60 days up to 800 days. The apparatus used for measuring the shrinkage strain is HUMBOLDT H-3250 comparator with accuracy of 0.0001 in.

For each mix the value of shrinkage in the given time interval was determined as the average of three measured values obtained from the three concrete prisms. A total of 502 data points were collected from the 17 mixes and are presented in Appendix B.

3.5 Procedure to Develop the New Equation

This procedure consisted of four steps:

Step 1: Shrinkage of concrete mixes with different percentage of SRA was plotted and compared as shown in Figure 3.1. The figure shows that the shrinkage decreases with increased SRA content.

Step 2: Shrinkage values obtained from the GL 2000 model were compared with previously measured experimental values. The difference between predicted and experimental values was found to increase with increased SRA content as shown in Table 3.8. It can be observed from the table that the maximum deviation between the predicted and measured values was obtained for 2.5% SRA. These observations led to the conclusion that the new parameter should be a function of the SRA content such that its value will increase with reduction of SRA content, reduce with increasing SRA content and be equal to 1 for 0% of SRA.

Step 3. Five mixes with different SRA percentage (0.5%, 1%, 1.5%, 2% and 2.5% SRA) were randomly chosen to calibrate the model. These mixes were 14/24, 6/13, 15/28, 12/21, and 13/22 as shown in Table 3.7. The form of the new parameter was determined and incorporated in the GL 2000 model equation. By multiplying the GL 2000 equation with the new parameter (Equation 2.2-1) the predicted values were found to fit the experimental data as shown in Figures 3.2-3.6. It should be noted that all mixes had the same cement and aggregate types, water-to-cementitious materials ratio (w/cm) and same aggregate-to-cementitious materials ratio (A/cm).

Step 4: The adequacy of the new equation was tested for the total number of data points (i.e. 502 points). The model was compared with the GL 2000 and European CEB-FIP MC 90-99 model. Chapter 4 gives detailed analysis and evaluation of the ALSN 2004 model.

Table 3.1: Chemical Composition and Physical Properties of Type II Portland Cement

Chemical Composition %	Type II Cement	ASTM C 150 Specifications for Type I Cement	ASTM C 150 Specifications for Type II Cement
Silicon Dioxide (SiO ₂)	21.73	----	20.0 min
Aluminum Oxide (Al ₂ O ₃)	4.12	----	6.0 max
Ferric Oxide (Fe ₂ O ₃)	3.48	----	6.0 max
Calcium Oxide (CaO)	63.75	----	----
Magnesium Oxide (MgO)	1.72	6.0 max	6.0 max
Sulfur Trioxide (SO ₃)	2.59	3.0 max	3.0 max
Loss on ignition	1.33	3.0 max	3.0 max
Sodium Oxide (Na ₂ O)	0.31	----	----
Potassium Oxide (K ₂ O)	0.44	----	----
Equivalent Alkalies (Na ₂ O+ 0.658 K ₂ O)	0.6	0.6 max	0.6 max
Insoluble Residue	0.23	0.75 max	0.75 max
Compound Composition %			
Dicalcium Silicate (C ₂ S)	21.31	----	----
Tricalcium Silicate (C ₃ S)	54.34	----	----
Tricalcium Aluminate (C ₃ A)	5.01	----	8.0 max
Sum of Tricalcium Silicate and Tricalcium Aluminate	59.35	----	58.0 max
Tetracalcium Aluminoferrite (C ₄ AF)	10.6	----	----
Physical Properties			
Blaine fineness, m ² /kg	3772	160 min	160 min
No 325 fineness	92.7	----	----
Autoclave expansion, %	0.053	0.8 max	0.8 max
Setting time, Gilmore needless (min.):			
Initial	133	60 min	60 min
Final	259	600 max	600 max
Setting time, Vicat (min.):			
Initial	61	45 min	45 min
Final	169	375 max	375 max
Air content of mortar, volume %	7.2	12 max	12 max
Compressive strength (psi) at:			
1 Day	1702	----	----
3 Days	2969	1740 min	1740 min
7 Days	3886	2760 min	2760 min
28 Days	5517	4060 min	4060 min

Table 3.2: Results of the Sieve Analysis (Hanson Aggregate)

1/2 in. Coarse Aggregate				Fine Aggregate			
ASTM C 33 Sieve Analysis	Percent Passing		ASTM C 33 Spec. Size 7	ASTM C 33 Sieve Analysis	Percent Passing		ASTM C 33 Spec.
	Sechelt 1/2"x #4	Caltrans 1/2"x #4			Sechelt Conc.Sand	Caltrans Spec. Sec. 90	
3/4"	100	100	100	3/8"	100	100	100
1/2"	95	82 - 100	90 - 100	No. 4	99	95 - 100	95 - 100
3/8"	63	40 - 78	40 - 70	No. 8	89	65 - 95	80 - 100
No. 4	2	0 - 15	0 - 15	No.16	70	55 - 75	50 - 85
No. 8	1	0 - 6	0 - 5	No. 30	47	34 - 46	25 - 60
				No. 50	19	16 - 29	10 - 30
				No. 100	5	2 - 12	2 - 10
				No. 200	1	0 - 8	0 - 3

Table 3.3: Physical Properties of Aggregate (Hanson Aggregate)

Coarse Aggregate		Fine Aggregate	
Bulk Specific Gravity (SSD)	2.69	Bulk Specific Gravity (SSD)	2.65
Absorption, %	0.8	Fineness Modulus	2.77
		Absorption, %	0.9

Table 3.4: Chemical and Physical Analysis of Fly Ash*

Chemical Composition, %	Class F	ASTM C 618-97 Specifications	
		Class F	Class C
Total Silica, Aluminum, Iron	81	70 min	50min
Silicon Dioxide	57.1	-----	-----
Aluminum Oxide	18.7	-----	-----
Iron Oxide	5.2	-----	-----
Sulfur Trioxide	0.7	5.0 max	5.0 max
Calcium Oxide	8.3	-----	-----
Moisture Content	0.4	3.0 max	3.0 max
Loss on Ignition	0.4	6.0 max	6.0 max
Physical Test Results			
Fineness, Retained on # 325 Sieve (%)	26.5	34 max	34 max
Strength Activity with Portland Cement:			
7 Day, % of Control	80.3	-----	-----
28 Day, % of Control	94.2	75 min	75 min
Water Requirement, % of Control	92.1	105 max	105 max
Soundness, Autoclave Expansion (%)	0.01	0.8 max	0.8 max
Density	2.38	-----	-----

* Chemical composition and physical data were provided by ISG Resources, INC. Western Region.

Table 3.5: Chemical Composition and Physical Properties of Silica Fume*

Chemical Composition	Percentage by Dry Mass
Silicon Dioxide (SiO ₂)	93.08
CL	0.19
Aluminum Oxide (Al ₂ O ₃)	1.17
Ferric Oxide (Fe ₂ O ₃)	0.19
Calcium Oxide (CaO)	0.43
Magnesium Oxide (MgO)	0.53
Sulfur Trioxide (SO ₃)	0.22
Sodium Oxide (Na ₂ O)	0.42
Potassium Oxide (K ₂ O)	1.18
Available Alkalies	1.27
Carbon (C)	3.47
Loss on Ignition	4.47
Physical Properties	
325 Sieve Retained (%)	3.44
Specific Gravity	2.2
Density - Fluffy (pcf)	10.5
Moisture Content (%)	0.14

* Chemical compositions and physical data were provided by Norchem Concrete Products Inc. in Fort Pierce, Florida.

Table 3.6: Chemical and Physical Analysis of Metakaolin*

Chemical Analysis	Class N	ASTM C 618 Limits Class N	ASTM Test Method
Silicon Dioxide (SiO ₂)	53.40%	-----	-----
Aluminum Oxide (Al ₂ O ₃)	41.10%	-----	-----
Iron Oxide (Fe ₂ O ₃)	1.06%	-----	-----
Sum of Constituents	95.58%	70.0% min	D4326
Sulfur Trioxide (SO ₃)	0.09%	4.0% max	D4326
Calcium Oxide (CaO)	0.09%		D4326
Moisture Content	0.49%	3.0% max	C311
Loss on Ignition, % carbon	0.048%	10.0% max	C311
Available Alkalies, as Na ₂ O	0.0111%	1.5% max	C311
Physical Analysis			
Fineness, % Retained on # 325 Sieve	6.90%	-----	C311, C430
Strength Activity with Portland Cement:			C311, C109
7 Day, % of Control	106%	75% min	
28 Day, % of Control	124%	75% min	
Water Requirement, % Control	115%	115% max	-----
Autoclave Soundness	-0.05%	0.8% max	C311, C151
True Particle Density	2.29	-----	-----

* Chemical composition and physical data were provided by ISG Resources, INC. Western Region.

Table 3.7: Concrete Mixes With SRA Percentage Varying From 0.5 to 2.5 %

Mix Label *	28-day Strength [MPa]	w/cm **	A/cm ***	CA/FA ****	Cement Content [Kg/m ³]	Fly Ash Class F [%]	Silica Fume [%]	Meta-Kaolin Class N [%]	HRWR (G) [%]	HRWR (MB) [%]	LRWR (G) [%]	LRWR (MB) [%]	SRA (G) [%]	SRA (MB) [%]
1/4	73.4	0.33	5.25	1.12	280.6	20		5	0.60				0.50	
2/7	71.3				262	25	5		0.60				0.50	
3/8	59.0				262	25		5	0.60				0.50	
4/11	58.3				243.3	30		5	0.60				0.50	
5/12	68.0				243.3	30	5		0.60				0.50	
6/13	53.2				262	25	5		0.60				1.00	
7/14	56.8				262	25	5		0.60				1.50	
8/15	53.0				262	25	5		0.60				2.00	
9/16	49.5				262	25	5		0.40				2.50	
10/18	52.4				262	25	5		0.40		0.20		0.50	
11/19	64.9				262	25	5		0.40		0.20		1.00	
12/21	64.7				262	25	5		0.40		0.20		2.00	
13/22	57.2				262	25	5		0.40		0.20		2.50	
14/24	78.0				262	25	5			0.60				0.50
15/28	70.5				262	25	5			0.40		0.20		1.50
16/29	68.7				262	25	5			0.40		0.20		2.00
17/30	65.4				262	25	5			0.40		0.20		2.50

* Second number indicates the mix label under which the mix is defined in Reference 10.

** w/cm = Water-to-cementitious materials ratio by mass

*** A/cm = Aggregate-to-cementitious materials ratio by mass

**** CA/FA = Coarse aggregate-to-fine aggregate ratio by mass

Table 3.8: Deviation Between Measured and the GL 2000 Predicted Values of Shrinkage

Time interval [Days]	Average of residuals in microstrains (number of data points used in the analysis)				
	SRA content				
	0.5%	1.0%	1.5%	2.0%	2.5%
0-28	80 microstr. (22)	71 microstr. (7)	121 microstr. (8)	137 microstr. (12)	144 microstr. (12)
29-100	65 microstr. (37)	67 microstr. (10)	138 microstr. (11)	159 microstr. (17)	162 microstr. (16)
101-190	94 microstr. (79)	109 microstr. (20)	166 microstr. (22)	177 microstr. (35)	184 microstr. (34)
191-800	122 microstr. (68)	113 microstr. (19)	184 microstr. (22)	197 microstr. (77)	203 microstr. (24)

Figure 3.1: Comparison of Shrinkage Strain for Concrete Mixes With Different SRA %

Figure 3.2: Comparison Between Experimental Values and the ALSN 2004 Model Predicted Values for Concrete with 0.5% SRA (Mix 14/24).

Figure 3.3: Comparison Between Experimental Values and the ALSN 2004 Model Predicted Values for Concrete with 1.0% SRA (Mix 6/13).

Figure 3.4: Comparison Between Experimental Values and the ALSN 2004 Model Predicted Values for Concrete with 1.5% SRA (Mix 15/28).

Figure 3.5: Comparison Between Experimental Values and the ALSN 2004 Model Predicted Values for Concrete with 2.0% SRA (Mix 12/21).

Figure 3.6: Comparison Between Experimental Values and the ALSN 2004 Model Predicted Values for Concrete with 2.5% SRA (Mix 13/22).

Chapter 4

Validation of the Accuracy of the ALSN 2004 Model

4.1 Introduction

The goal of this chapter is to determine the accuracy of the ALSN 2004 model by comparing its predicted values against measured values. Also, the performance of the model was established by comparing its accuracy with the accuracy of the GL 2000 and CEB-FIP MC 90-99 models. Three different approaches were utilized:

The values of predicted and measured shrinkage strain were plotted on the same graph for each concrete mix. Predicted values were calculated using the GL 2000, CEB-FIP MC 90-99 and ALSN 2004 equations. These graphs are shown in the Figures 4.1 to 4.17.

Analysis of residuals was performed to validate the model's accuracy. The residuals were plotted versus duration of drying (i.e. 800 days) for each model as shown in Figures 4.18. The results of the analysis are presented in Tables 4.1-4.3 and plotted in Figures 4.19-4.21.

Four statistical methods for evaluation of the model accuracy were used: The mean and Standard Deviation of Residuals, The CEB Coefficient of Variation Method, The CEB Mean Square Error Method, and The CEB Mean Deviation Method. The results of statistical analysis are presented in Tables 4.4-4.9.

Experimental shrinkage data used in the analysis (i.e., 502 data points) are given in Appendix B.

4.2 Comparison of the Plotted Shrinkage Strain

The predicted and measured values of drying shrinkage were plotted versus duration of drying for each mix as shown in Figures 4.1-4.17. It can be observed that the ALSN 2004 predicted values are closer to the experimental values and overestimate shrinkage strain for the majority of mixes. The GL 2000 and CEB-FIP MC 90-99 model overestimate shrinkage for all mixes, and deviate significantly from the measured values.

4.3 Residual Method

4.3.1 Introduction

Residual value is defined as the difference between measured and predicted value (i.e. $residual = measured - predicted$). A positive value for residual implies that the model overestimates the shrinkage strain and a negative value for residual implies that the model underestimates the shrinkage strain value.

The prediction model is considered accurate and adequate if residuals are balanced on the positive and negative side and in the range of ± 100 microstrains.

The analysis of residuals was performed as follows:

1. The duration of drying was divided into four time intervals of 0-28 days, 29-100 days, 101-190 days, and 191-800 days. For each model the percentage of positive and negative residuals in different time intervals was determined and compared as shown in Table 4.1 and Figure 4.19.
2. The distributions of positive residuals in the range of 0 to +20, 0 to +50, 0 to +100, and 0 to +300 microstrains and similarly in the negative residual

ranges are calculated up to 800 days as shown in Tables 4.2 and 4.3 and plotted in Figures 4.20 and 4.21.

4.3.2 Distribution of Residuals in Positive and Negative Ranges

Comparing the residuals for different models as shown in Figure 4.18, it can be observed that the ALSN 2004 model residuals are concentrated around “zero axis” while the GL 2000 and CEB-FIP MC 90-99 residuals show overestimating models with 100% of residuals in the range of 0 to +300 microstrains as detailed in Tables 4.1-4.3 and shown in Figures 4.19-4.21. It can also be observed that the residual boundaries are almost constant and do not change as a function of time.

The following observations can be made from the result listed in Table 4.1 and shown in Figure 4.20:

1. The values predicted by the GL 2000 model and overestimate the shrinkage strain with 100% positive residuals for all time ranges.
2. The CEB-FIP MC 90-99 residual distribution shows that the model overestimates shrinkage strain with 100% of positive residuals for all time ranges.
3. The values predicted by the ALSN 2004 Model have a tendency to overestimate the shrinkage strain with different percentage of positive residuals. The ALSN 2004 model residuals are balanced on the positive and negative side for all time ranges. For the time interval of 0 to 28 days the ALSN 2004 model overestimated shrinkage strain with 87% of residuals on positive side and 13% of residuals on negative side. For the time interval of

29 to 100 days the ALSN 2004 model overestimated the shrinkage strain with 53% of positive residuals. For the third time interval of 101 to 190 days, the ALSN 2004 overestimated the shrinkage strain with 59% of positive residuals and 41% of negative residuals. For the interval of 190 to 800 days, the ALSN 2004 model overestimated the shrinkage strain with 67% of positive residuals. For the time interval of 0 to 800 days the ALSN 2004 model overestimated shrinkage strain with 64% of positive residuals.

4.3.3 Distribution of Residuals in Different Ranges of Microstrains

The distributions of residuals in the ranges of: 0 to 20, 0 to 50, 0 to 100, 0 to 300 and 0 to -20, 0 to -50, 0 to -100, 0 to -300 microstrains are presented in Tables 4.2 and 4.3 and plotted in Figures 4.20 and 4.21. The following observations can be made:

1. The ALSN 2004 model residuals are much closer to the “zero axes” than the GL 2000 or the CEB-FIP MC 90-99 residuals. The ALSN 2004 model has 37% of residuals in the range of -20 to +20 microstrains, where 21% are positive and 16% are negative residuals, while the GL 2000 has only 2% of positive residuals in this range. The CEB-FIP MC 90-99 does not have residuals in this range.
2. The percentage of the residuals in the range of -50 to +50 microstrains for the ALSN 2004 model is 72%, with 44% of positive and 28% of negative residuals. This percentage is 9 times greater than that for the GL 2000 model (i.e., 8%) or 36 times greater than that for the CEB-FIP MC 90-99 (i.e., 2%).

3. The ALSN 2004 model has 97% of residuals in the range of ± 100 microstrains, where 61% are positive and 36% are negative residuals while the GL 2000 Model has 31% and the CEB-FIP MC 90-99 has 15% of the residuals, and they are all positive.
4. The GL 2000 model overestimated shrinkage strains with 69% of residuals in the range of +100 to +300 microstrains. Also, the CEB-FIP MC 90-99 overestimated shrinkage strains with 85% of residuals, while the ALSN 2004 model has only 3% of residuals in this range and 0% of residuals in the range of -100 to -300 microstrains.

4.4. Statistical Analysis

4.4.1 The Average and Standard Deviation of Residuals

The average is the point on the scale of measures where the data are centered. The standard deviation of residuals is a statistic that indicates how tightly all the data points are clustered around the mean in a set of data. The equations used to determine average and standard deviation are given in Appendix C.1.

The average and standard deviation of residuals are calculated for five time intervals: 0 to 28 days, 29 to 100 days and 101 to 190 days, 191 to 800 days and 0 to 800 days. The results of the analysis for the GL 2000 model, the ALSN 2004 model and CEB-FIP MC 90-99 are presented in Tables 4.4 and 4.5. The following observations can be made:

1. The average of residuals for the ALSN 2004 model is smaller than the average of residuals for the GL 2000 model and the CEB-FIP MC 90-99 for

all time intervals, which indicate that the predicted values using the ALSN 2004 model are closer to the measured values.

2. The average of the residuals up to 800 days for the ALSN 2004 model is 14 microstrains, while for the GL 2000 model is 134 and for the CEB-FIP MC 90-99 is 181 microstrains. The mean average is slightly different and has values of 16 microstrains for the ALSN 2004 model, 127 microstrains for the GL 2000 model and 172 microstrains for the CEB-FIP MC 90-99.
3. The ALSN 2004 model has lower standard deviation for all time intervals comparing to the GL 2000 model and CEB-FIP MC 90-99 model, which indicate that the data are more clustered around the mean value.
4. The standard deviation of the residuals up to 800 days for the ALSN 2004 model is 43 microstrains, while for the GL 2000 model is 62 and for the CEB-FIP MC 90-99 is 51 microstrains. The mean average has values of 39 microstrains for the ALSN 2004 model, 56 microstrains for the GL 2000 model and 51 microstrains for the CEB-FIP MC 90-99.

Mean and standard deviation are parameters that define normal distribution. A normal distribution is a theoretical bell-shaped curve that is defined by a specific equation called the normal probability density function. Normal distribution curves for the GL 2000, ALSN 2004 and CEB-FIP MC 90-99 models are given in Figures 4.22, 4.23 and 4.24. For the data sets that are normally distributed approximately 68% of data lies in the interval of mean $\pm$ one standard deviation, 95% of the data lies in the interval

of mean $\pm$ two standard deviations and 99.7% of data lies in the interval of mean $\pm$ three standard deviations.

According to the normal distribution curves presented in Figures 4.22, 4.23 and 4.24 it can be observed that:

1. The GL 2000 model has 68% of shrinkage strain residuals is in the range of 78 to 190 microstrains, 95% is in the range of 22 to 246 microstrains and 99.7% is in the range of -34 to 302 microstrains. (Figure 4.22)
2. The ALSN 2004 has 68% of shrinkage strain residuals is in the range of -25 to 53 microstrains, 95% is in the range of -64 to 92 microstrains and 99.7% is in the range of -103 to 131 microstrains. (Figure 4.23)
3. The CEB-FIP MC 90-99 has 68% of shrinkage strain residuals is in the range of 121 to 223 microstrains, 95% is in the range of 70 to 274 microstrains and 99.7% is in the range of -19 to 325 microstrains. (Figure 4.24)

Figure 4.25 compare all three normal distribution curves. The area under the curve bounded by the $\pm$ one standard deviation indicate the probability of getting the experimental data in the range of one standard deviation from the mean. It can be observed from Figure 4.25 that the area under the ALSN 2004 curve is the largest. The probability of getting the experimental data in the range of $\pm$ standard deviation from the mean is the highest for the ALSN 2004 model. The ALSN 2004 has the greater level of confidence in the experimental results than the GL 2000 or CEB-FIP MC 90-99 model.

4.4.2 The CEB Coefficient of Variation Method

The coefficient of variation is defined as standard deviation divided by mean. High coefficient of variation indicates high variability of data. The equations used for calculation of the coefficient of variation " V_i " and the mean coefficient of variation " V_{CEB} " are given in Appendix C.2.

The coefficient of variation is calculated in 4 time ranges, which are: 0-28, 29-100, 101-190, 191-800 days. " V_{CEB} ," is also determined. The results are given in Table 4.6. The following observations can be made:

1. The coefficient of variation " V_i " for the ALSN 2004 model has the smaller value than the coefficient of variation for the GL 2000 model and the CEB-FIP MC 90-99 for all time intervals.
2. The value of the mean coefficient of variation " V_{CEB} " for the ALSN 2004 model is 24%, which is almost twice smaller compared to the GL 2000 model or the CEB-FIP MC 90-99.

4.4.3 The CEB Mean Square Error Method

Equations used for this statistical method are presented in Appendix C.3. Table 4.7 gives the average of the relative error of shrinkage strain prediction, " f_j " (Equation C.3-1) for the different age of concrete. The values of error are plotted versus time and shown in Figure 4.26. The following observations can be made:

1. The GL 2000 model and the CEB-FIP MC 90-99 produce higher error for all time intervals than the ALSN 2004 model.

2. The error in the prediction of shrinkage up to 42 days is higher for the three models when compared to ages 42 days and above.
3. The average values of errors for the different shrinkage durations using the GL 2000 model and the CEB-FIP MC 90-99 are 81% and 106% respectively, which is much greater than the average error of 14% made by using the ALSN 2004 model.

The results of the CEB Mean Square Error method are presented in Table 4.8. The square error " F_i " is calculated in 4 time intervals: 0-28, 29-100, 101-190, and 191-800 days. Mean square error " F_{CEB} " is also determined. The following observations can be made:

The values of square error for the GL 2000 model and the CEB-FIP MC 90-99 are greater than the value of square error for the ALSN 2004 model for all time ranges.

The values of mean square error for the GL 2000 model and the CEB-FIP MC 90-99 are 138% and 170% respectively, which is more than two and three times greater than the value of mean square error of 59% for the ALSN 2004 model.

4.4.4 The CEB Mean Deviation Method

This method indicates the systematic overestimation or underestimation of a given model. The equation used for calculation of deviation M_i and mean deviation, M_{CEB} are presented in Appendix C.4.

The ideal value for M_i and M_{CEB} is 1 because this indicates that the predicted and the measured values are the same. If the value is greater than 1 model tends to overestimate the shrinkage of concrete, and if the value is less than 1 then the model tends to

underestimate the shrinkage strain. Table 4.9 gives the results of the statistical analysis.

The following observations can be made:

1. The values of deviation for the GL 2000 model and the CEB-FIP MC 90-99 are greater than the value of deviation for the ALSN 2004 model for all time ranges which means that the ALSN 2004 predicted values are closer to the measured shrinkage.
2. The values of mean deviation for the GL 2000 model and the CEB-FIP MC 90-99 are 4.76 and 6.26 respectively, which is much greater than the value of mean deviation of 1.77 for the ALSN 2004 model.

Table 4.1: Distribution of Residuals in Positive and Negative Ranges

Time range [days]	Number of Data points in the range	Percentage of “+” residuals in the range			Percentage of “-“ residuals in the range		
		GL 2000	ALSN 2004	FIB-CEB MC 90-99	GL 2000	ALSN 2004	FIB-CEB MC 90-99
0-28	61	100	87	100	0	13	0
28-100	91	100	53	100	0	47	0
100-190	190	100	59	100	0	41	0
190-800	160	100	67	100	0	33	0
0-800	502	100	64	100	0	36	0

“+” residuals indicate that the predicted value overestimate measured value

“-“ residuals indicate that the predicted value underestimate measured value

Table 4.2: Distribution of Positive Residuals in the Different Ranges of Microstrains for the Time Interval of 0 to 800 Days.

Number of positive residuals			Range [microstrains]	Percentage of positive residuals in the range		
GL 2000	ALSN 2004	CEB-FIP MC 90-99		GL 2000	ALSN 2004	CEB-FIP MC 90-99
502	321	502	0 to +20	2%	21%	0%
			0 to +50	8%	44%	2%
			0 to +100	31%	61%	15%
			0 to +300	69%	3%	85%

Table 4.3: Distribution of Negative Residuals in the Different Ranges of Microstrains for the Time Interval of 0 to 800 Days.

Number of negative residuals			Range [microstrains]	Percentage of negative residuals in the range		
GL 2000	ALSN 2004	CEB-FIP MC 90-99		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0	181	0	0 to -20	0%	16%	0%
			0 to -50	0%	28%	0%
			0 to -100	0%	36%	0%
			0 to -300	0%	0%	0%

Table 4.4: Average of Residuals for Different Time Intervals

Time Range [days]	Number of data points in the range	Average of residuals [microstrains]		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0 to 28	61	108	32	143
29 to 100	91	110	-1	151
101 to 190	190	136	11	184
191 to 800	160	155	20	209
Mean Average	502	127	16	172
0 to 800	502	134	14	181

Table 4.5: Standard Deviation of Residuals for Different Time Intervals

Time Range [days]	Number of data points in the range	Standard Deviation of Residuals [microstrains]		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0 to 28	61	42	29	39
29 to 100	91	60	39	54
101 to 190	190	61	43	55
191 to 800	160	62	46	54
Mean Average	502	56	39	51
0 to 800	502	62	43	58

Table 4.6: The CEB Coefficient of Variation Method Results

Time range [Days]	Number of data points in the range	Coefficient of variation, Vi [%]		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0-28	61	56	33	62
28-100	91	41	20	44
101-190	190	42	19	45
191- 800	160	43	20	48
Mean coefficient of variation, V_{CEB} [%]		46	24	50

Table 4.7: Error of Prediction of Concrete Shrinkage at Different Concrete Age

Shrinkage Duration (t-t _c) [days]	Number of data points	Relative Error [%]		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
7	17	268	128	351
14	15	130	41	169
21	14	117	30	145
28	15	108	30	136
35	9	118	29	145
42	9	97	21	116
49	10	50	0	73
56	7	54	3	74
63	10	59	2	77
70	10	59	-1	78
77	5	53	-4	82
84	11	41	-8	63
91	10	67	2	83
98	10	77	6	99
112	14	57	2	80
119	14	74	9	96
126	13	85	10	107
133	17	74	10	96
140	16	76	11	98
147	17	72	10	95
154	17	69	8	92
161	17	71	8	93
168	17	74	10	97
175	17	73	9	96
182	17	74	11	97
189	6	56	5	78
245	17	79	15	104
305	17	69	8	92
365	17	69	8	92
425	17	69	8	92
485	14	66	9	91
547	17	79	14	103
608	17	80	14	104
669	17	78	13	102
731	17	80	14	104
791	10	84	22	106
Average Error [%]		81	14	106

Table 4.8: The CEB Mean Square Method Results

Time range [Days]	Number of data points in the range	Square error, Fi [%]		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0-28	61	231	109	283
28-100	91	88	25	130
101-190	190	85	24	80
191-791	160	88	26	109
Mean square error, F _{CEB} [%]		138	59	170

Table 4.9: The CEB Mean Deviation Method Results

Time range [Days]	Number of data points in the range	Deviation, Mi		
		GL 2000	ALSN 2004	CEB-FIP MC 90-99
0-28	61	9.47	3.37	13.00
28-100	91	3.12	1.16	3.89
101-190	190	3.17	1.23	4.00
191-791	160	3.26	1.31	4.15
Mean deviation, M_{CEB}		4.76	1.77	6.26

Figure 4.1: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 1/4).

Figure 4.2: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 2/7).

Figure 4.3: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 3/8).

Figure 4.4: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 4/11).

Figure 4.5: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 5/12).

Figure 4.6: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 10/18).

Figure 4.7: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 0.5% SRA (Mix # 14/24).

Figure 4.8: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 1.0% SRA (Mix # 6/13).

Figure 4.9: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 1.0% SRA (Mix # 11/19).

Figure 4.10: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 1.5% SRA (Mix # 7/14).

Figure 4.11: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 1.5% SRA (Mix # 15/28).

Figure 4.12: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.0% SRA (Mix # 8/15).

Figure 4.13: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.0% SRA (Mix # 12/21).

Figure 4.14: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.0% SRA (Mix # 16/29).

Figure 4.15: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.5% SRA (Mix # 9/16).

Figure 4.16: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.5% SRA (Mix 13/22).

Figure 4.17: Comparison of Experimental Shrinkage Data with Models Prediction for Concrete with 2.5% SRA (Mix 17/30).

Figure 4.18: Comparison of Shrinkage Strain Residuals for the GL 2000, ALSN 2004 and CEB-FIP MC 90-99 Models.

Figure 4.19: Percentage of Residuals in the Positive and Negative Ranges.

Figure 4.20: Distribution of Positive and Negative Residuals for the Time Interval of 0 to 800 days.

Figure 4.21: Percentage of Residuals in Different Ranges of Microstrains.

Figure 4.22: Normal Distribution Curve for the GL 2000 Model.

Figure 4.23: Normal Distribution Curve for the ALSN 2004 Model.

Figure 4.24: Normal Distribution Curve for the CEB-FIP MC 90-99 Model.

Figure 4.25: Comparison of the Normal Distribution Curves.

Figure 4.26: Error of Shrinkage Prediction at Different Concrete Age.

Chapter 5

Conclusions and Recommendations

5.1 Introduction

The goal of this study was to modify the GL 2000 prediction equation to include a factor to account for the SRA in concrete. The modified version of the GL 2000 model introduces a new SRA parameter, called $\beta(\text{SRA})$. To determine the level of accuracy of the model, experimental data were utilized for concrete containing SRA. The new model was compared with the GL 2000 model and the CEB-FIP MC 90-99. Statistical analysis was performed using the following methods:

- Residual method.
- Mean and standard deviation of residuals method.
- The CEB mean coefficient of variation method.
- The CEB mean square error method.
- The CEB mean deviation method.

The total number of data points used to analyze the new model was 502 points. It should be noted that the ALSN 2004 model is tested only for concrete with the same cement and aggregate types. The value of w/cm is limited to 0.33 and the SRA is limited up to 2.5%.

5.2 Conclusions

A new equation called the ALSN 2004 is presented in this thesis. The new equation gives a more accurate prediction than the GL 2000 model and the CEB-FIP MC 90-99 for concrete containing SRA. The conclusion was made based on the following evaluations:

The distributions of residuals for all three models are listed in Table 5.1.

Table 5.1: Distribution of Residuals for Time Range 0-800 Days.

Category	GL 2000	ALSN 2004	CEB-FIP MC 90-99
Model overestimate	100%	64%	100%
Model under-estimate	0%	36%	0%
Residuals in the range of +100 microstrains	31%	61%	15%
Residuals in the range of -100 microstrains	0%	36%	0%
Residuals > +100 microstrains	69%	3%	85%
Residuals > -100 microstrains	0%	0%	0%

The GL 2000 and CEB-FIP MC 90-99 models were found to grossly overestimate while the ALSN 2004 is more balanced with tendency to overestimate. The table shows that the ALSN 2004 model has 97% of the residuals in the range of ± 100 microstrains while the GL 2000 and the CEB-FIP MC 90-99 has 31% and 15% respectively. The GL 2000 and the CEB-FIP MC 90-99 models overestimate shrinkage strain with 69% and

85% of residuals greater than 100 microstrains while the ALSN 2004 over estimate by 3%.

Statistical analysis performed to calculate the average of residuals, standard deviation of residuals, mean coefficient of variation, mean square error, and mean deviation. The data is summarized in Table 5.2:

Table 5.2: Summary of Statistical Analysis.

Category	Time Range	GL 2000	ALSN 2004	CEB-FIP MC 90-99
Average of residuals	0-800 days	134 microstrains	14 microstrains	181 microstrains
Standard deviation of residuals	0-800 days	62 microstrains	43 microstrains	58 microstrains
Mean coefficient of variation, V_{CEB} %	4 time ranges	46%	24%	50%
Mean square error, F_{CEB} %	4 time ranges	138%	59%	170%
Mean Deviation, M_{CEB}	4 time ranges	4.76	1.77	6.26

It can be observed that the ALSN 2004 gives the best prediction in all categories. The smaller number in the table indicates a better prediction in a given category.

5.3 Recommendations for Future Research

Future research should include testing the ALSN 2004 model for concrete with different water-to-cementitious material ratios, different chemical and mineral

admixtures, mixed components and its proportions. Also, the equation should be tested for concrete containing SRA at dosages greater than 2.5%.

Future research can be conducted on the CEB-FIP MC 90-99 to include the effect of SRA and to evaluate the combined effect of SRA with other admixtures such as fly ash, metakaolin, high-range water reducers, and low-range water reducers.

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Appendix A –Models for Shrinkage Prediction

A.1. The GL 2000 Model

The GL 2000 model is modified Atlanta 97 Model that was proposed by Gardner and Zhao in 1993. Parameters required for calculation of shrinkage strain using the GL 2000 Model are: mean 28-day concrete compressive strength, relative humidity, age of concrete at the beginning of shrinkage, type of cement, specimen shape.

The shrinkage strain can be calculated using the following equation:

$$\varepsilon_s(t) = \varepsilon_{shu} \beta(h) \beta(t) \quad (\text{A.1-1})$$

Where,

ε_{shu} = Ultimate shrinkage strain

$\beta(h)$ = Correction term for effect of humidity

$\beta(t)$ = Correction term for effect of time

Ultimate shrinkage strain should be calculated from the equation:

$$\varepsilon_{shu} = (900) K \left(\frac{30}{f_{cm28}} \right)^{1/2} \times 10^{-6} \quad (\text{A.1-2})$$

Where,

K = Shrinkage constant which depends on cement type as shown in Table A.1

f_{cm28} = Mean 28-day concrete compressive strength [MPa]

Table A.1. Shrinkage Constant K as a Function of Cement Type:

Type of Cement	K
I	1.00
II	0.75
III	1.15

Correction term for effect of humidity should be calculated as shown:

$$\beta(h) = 1 - 1.18 \left(\frac{H}{100} \right)^4 \quad (\text{A.1-3})$$

Where,

H = Relative humidity in [%]

Correction term for effect of time should be determined as follows:

$$\beta(t) = \left(\frac{t - t_c}{t - t_c + 0.12(V/S)^2} \right)^{1/2} \quad (\text{A.1-4})$$

Where,

t = Age of concrete after casting [days]

t_c = Age of concrete at the beginning of shrinkage [days]

V/S = Volume-to surface area ratio [mm]

A.2. The CEB-FIP MC 90-99 Model

In this model the total shrinkage is the sum of autogenous and drying shrinkage component. This approach was necessary so that shrinkage of normal as well as high performance concrete can be predicted with sufficient accuracy. Parameters required for calculation of shrinkage strain using the CEB-FIP MC 90-99 model are: mean 28-day concrete compressive strength, relative humidity, age of concrete at the beginning of shrinkage, type of cement, specimen shape.

Total shrinkage strain can be calculated using the following equation:

$$\varepsilon_s(t, t_c) = \varepsilon_{as}(t) + \varepsilon_{ds}(t, t_c) \quad (\text{A.2-1})$$

Where,

$$\varepsilon_{as}(t) = \text{Autogenous shrinkage at time } t$$

$$\varepsilon_{ds}(t, t_c) = \text{Drying shrinkage at time } t$$

Autogenous shrinkage, $\varepsilon_{as}(t)$, should be calculated as follows:

$$\varepsilon_{as}(t) = \varepsilon_{as0}(f_{cm_{28}}) \beta_{as}(t) \quad (\text{A.2-2})$$

Where,

$$\varepsilon_{as0}(f_{cm_{28}}) = \text{Notional autogenous shrinkage coefficient}$$

$$\beta_{as}(t) = \text{Function to describe the time-development of autogenous shrinkage}$$

Notional autogenous shrinkage coefficient, $\varepsilon_{cas0}(f_{cm})$, can be calculated as follows:

$$\varepsilon_{cas0}(f_{cm_{28}}) = -\alpha_{as} \left(\frac{f_{cm_{28}}/10}{6 + f_{cm_{28}}/10} \right)^{2.5} \times 10^{-6} \quad (\text{A.2-3})$$

Where,

α_{as} = Coefficient that depends on type of cement

= 800 for slowly hardening cements

= 700 for normal or rapidly hardening cements

= 600 for rapidly hardening high-strength cements

f_{cm28} = Mean compressive strength of concrete at an age of 28 days [MPa]

Function $\beta_{as}(t)$ should be calculated using the following equation:

$$\beta_{as}(t) = 1 - \exp[-0.2(t)^{0.5}] \quad (\text{A.2-4})$$

Where,

t = Age of concrete [days]

Drying shrinkage $\varepsilon_{ds}(t, t_c)$ can be estimated by equation:

$$\varepsilon_{ds}(t, t_c) = \varepsilon_{ds0}(f_{cm28}) \beta_{RH}(H) \beta_{ds}(t - t_c) \quad (\text{A.2-5})$$

Where,

$\varepsilon_{ds0}(f_{cm28})$ = Notional drying shrinkage coefficient

$\beta_{RH}(H)$ = Coefficient to take into account the effect of relative humidity on drying

shrinkage

$\beta_{ds}(t - t_c)$ = Function to describe the time-development of drying shrinkage

Notional drying shrinkage coefficient $\varepsilon_{ds0}(f_{cm28})$ may be calculated from equation:

$$\varepsilon_{ds0}(f_{cm28}) = [(220 + 110\alpha_{ds1}) \exp(-\alpha_{ds2} f_{cm28}/10)] \times 10^{-6} \quad (\text{A.2-6})$$

Where,

α_{ds1} = Coefficient that depends on type of cement:

= 3 for slowly hardening cements

= 4 for normal or rapidly hardening cements

= 6 for rapidly hardening high-strength cements

α_{ds2} = Coefficient that depends on type of cement:

= 0.13 for slowly hardening cements

= 0.11 for normal or rapidly hardening cements

= 0.12 for rapidly hardening high-strength cements

Coefficient $\beta_{RH}(H)$ should be calculated as follows:

$$\beta_{RH} = \begin{cases} -1.55 \left[1 - \left(\frac{H}{100} \right)^3 \right] & \text{for } 40\% \leq H < 99\% \times \beta_{s1} \\ 0.25 & \text{for } H \geq 99\% \times \beta_{s1} \end{cases} \quad (\text{A.2-7})$$

Where,

H = Ambient relative humidity [%]

β_{s1} = Coefficient to take into account the self-desiccation in high-performance

concrete. It can be determined as follows:

$$\beta_{s1} = \left(\frac{35}{f_{cm28}} \right)^{0.1} \leq 1.0 \quad (\text{A.2-8})$$

Function $\beta_{ds}(t - t_c)$ may be estimated as follows:

$$\beta_{ds}(t-t_c) = \left(\frac{(t-t_c)}{0.56(h_e/4)^2 + (t-t_c)} \right)^{0.5} \quad (\text{A.2-9})$$

Where,

t_c = Concrete age at the beginning of drying [days]

$h_e = \frac{2A_c}{u}$ = Notional size of member [mm], where A_c is the cross-section [mm²] and

u is the perimeter of the member in contact with the atmosphere [mm].

Appendix B – Shrinkage Experimental Data

Table B.1: Environment Conditions and Concrete Properties.

Mix Label	f_{cm28} [Mpa]	Humidity [%]	American cement type	Equivalent European cement type	V/S [mm]	Type of curing	Duration of curing, t_c [days]
1/4	73.4	50 ± 4	2	SL	19.05	Water cured	7
2/7	71.3	50 ± 4	2	SL	19.05	Water cured	7
3/8	59.0	50 ± 4	2	SL	19.05	Water cured	7
4/11	58.3	50 ± 4	2	SL	19.05	Water cured	7
5/12	68.0	50 ± 4	2	SL	19.05	Water cured	7
6/13	53.2	50 ± 4	2	SL	19.05	Water cured	7
7/14	56.8	50 ± 4	2	SL	19.05	Water cured	7
8/15	53.0	50 ± 4	2	SL	19.05	Water cured	7
9/16	49.5	50 ± 4	2	SL	19.05	Water cured	7
10/18	52.4	50 ± 4	2	SL	19.05	Water cured	7
11/19	64.9	50 ± 4	2	SL	19.05	Water cured	7
12/21	64.7	50 ± 4	2	SL	19.05	Water cured	7
13/22	57.2	50 ± 4	2	SL	19.05	Water cured	7
14/24	78.0	50 ± 4	2	SL	19.05	Water cured	7
15/28	70.5	50 ± 4	2	SL	19.05	Water cured	7
16/29	68.7	50 ± 4	2	SL	19.05	Water cured	7
17/30	65.4	50 ± 4	2	SL	19.05	Water cured	7

Appendix B (a): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 1/4 Prepared 1/23/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age, t	BAR #1	BAR #2	BAR #3	Average	Age, t-t _c	BAR #1	BAR #2	BAR #3	Average
1/24/2002	-0.0371	-0.0101	-0.0097	0	0	0	0	0	...				...
1/30/2002	-0.0366	-0.0098	-0.0089	7	0.005	0.003	0.008	0.005333	0	0	0	0	0
2/6/2002	-0.0373	-0.0107	-0.0099	14	-0.002	-0.006	-0.002	-0.00333	7	-0.007	-0.009	-0.01	-0.00867
2/13/2002	-0.0374	-0.0112	-0.0104	21	-0.003	-0.011	-0.007	-0.007	14	-0.008	-0.014	-0.015	-0.01233
28-Feb	-0.0376	-0.0113	-0.0106	36	-0.005	-0.012	-0.009	-0.00867	29	-0.01	-0.015	-0.017	-0.014
3/7/2002	-0.0378	-0.0115	-0.0105	42	-0.007	-0.014	-0.008	-0.00967	36	-0.012	-0.017	-0.016	-0.015
3/13/2002	-0.0384	-0.0123	-0.0112	49	-0.013	-0.022	-0.015	-0.01667	42	-0.018	-0.025	-0.023	-0.022
3/27/2002	-0.0383	-0.0122	-0.0111	63	-0.012	-0.021	-0.014	-0.01567	56	-0.017	-0.024	-0.022	-0.021
4/7/2002	-0.0384	-0.0121	-0.011	74	-0.013	-0.02	-0.013	-0.01533	67	-0.018	-0.023	-0.021	-0.02067
4/16/2002	-0.0384	-0.0127	-0.011	83	-0.013	-0.026	-0.013	-0.01733	76	-0.018	-0.029	-0.021	-0.02267
4/23/2002	-0.0389	-0.0127	-0.0121	90	-0.018	-0.026	-0.024	-0.02267	83	-0.023	-0.029	-0.032	-0.028
5/7/2002	-0.0389	-0.0127	-0.0117	104	-0.018	-0.026	-0.02	-0.02133	97	-0.023	-0.029	-0.028	-0.02667
5/28/2002	-0.039	-0.0128	-0.0118	125	-0.019	-0.027	-0.021	-0.02233	118	-0.024	-0.03	-0.029	-0.02767
6/4/2002	-0.0389	-0.0127	-0.0117	132	-0.018	-0.026	-0.02	-0.02133	125	-0.023	-0.029	-0.028	-0.02667
6/13/2002	-0.0388	-0.0125	-0.0116	141	-0.017	-0.024	-0.019	-0.02	134	-0.022	-0.027	-0.027	-0.02533
6/25/2002	-0.0387	-0.0125	-0.0116	153	-0.016	-0.024	-0.019	-0.01967	146	-0.021	-0.027	-0.027	-0.025
7/2/2002	-0.0387	-0.0125	-0.0115	160	-0.016	-0.024	-0.018	-0.01933	153	-0.021	-0.027	-0.026	-0.02467
7/9/2002	-0.0388	-0.0125	-0.0115	167	-0.017	-0.024	-0.018	-0.01967	160	-0.022	-0.027	-0.026	-0.025
7/16/2002	-0.0389	-0.0124	-0.0116	174	-0.018	-0.023	-0.019	-0.02	167	-0.023	-0.026	-0.027	-0.02533
7/23/2002	-0.039	-0.0125	-0.0116	181	-0.019	-0.024	-0.019	-0.02067	174	-0.024	-0.027	-0.027	-0.026
7/30/2002	-0.039	-0.0126	-0.0116	188	-0.019	-0.025	-0.019	-0.021	181	-0.024	-0.028	-0.027	-0.02633
8/6/2002	-0.0388	-0.0125	-0.0115	195	-0.017	-0.024	-0.018	-0.01967	188	-0.022	-0.027	-0.026	-0.025
9/30/2002	-0.0387	-0.0125	-0.0114	249	-0.016	-0.024	-0.017	-0.019	243	-0.021	-0.027	-0.025	-0.02433
11/30/2002	-0.0389	-0.0127	-0.0116	310	-0.018	-0.026	-0.019	-0.021	304	-0.023	-0.029	-0.027	-0.02633
1/31/2003	-0.039	-0.0129	-0.0114	372	-0.019	-0.028	-0.017	-0.02133	366	-0.024	-0.031	-0.025	-0.02667
3/31/2003	-0.0391	-0.0133	-0.0115	431	-0.02	-0.032	-0.018	-0.02333	425	-0.025	-0.035	-0.026	-0.02867
5/31/2003	-0.0392	-0.0134	-0.0116	492	-0.021	-0.033	-0.019	-0.02433	486	-0.026	-0.036	-0.027	-0.02967
7/30/2003	-0.0391	-0.0134	-0.0116	552	-0.02	-0.033	-0.019	-0.024	547	-0.025	-0.036	-0.027	-0.02933
9/30/2003	-0.0391	-0.0133	-0.0114	614	-0.02	-0.032	-0.017	-0.023	608	-0.025	-0.035	-0.025	-0.02833
11/30/2003	-0.0391	-0.0134	-0.0114	675	-0.02	-0.033	-0.017	-0.02333	669	-0.025	-0.036	-0.025	-0.02867
1/31/2004	-0.0391	-0.0133	-0.0114	737	-0.02	-0.032	-0.017	-0.023	731	-0.025	-0.035	-0.025	-0.02833
3/31/2004	-0.0391	-0.0134	-0.0114	797	-0.02	-0.033	-0.017	-0.02333	791	-0.025	-0.036	-0.025	-0.02867

Appendix B (b): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 2/7 Prepared 1/26/2002												
DATE	Readings			Shrinkage [%]				Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age, t [Days]	BAR #1	BAR #2	Average	Age, t _c [Days]	BAR #1	BAR #2	BAR #3	Average
1/27/2002	0.0076	-0.0855	-0.0905	0	0	0	0	...	...	...		...
2/2/2002	0.0087	-0.0843	-0.0899	7	0.011	0.012	0.0115	0	0	0	Bad Sample	0
2/9/2002	0.0083	-0.0848	-0.09	14	0.007	0.007	0.007	7	-0.004	-0.005		-0.0045
2/16/2002	0.0077	-0.0851	-0.0943	21	0.001	0.004	0.0025	14	-0.01	-0.008		-0.009
3/2/2002	0.007	-0.0856	-0.0947	35	-0.006	-0.001	-0.0035	28	-0.017	-0.013		-0.015
3/23/2002	0.0066	-0.0864	Bad Sample	56	-0.01	-0.009	-0.0095	49	-0.021	-0.021		-0.021
4/1/2002	0.0065	-0.0865		65	-0.011	-0.01	-0.0105	58	-0.022	-0.022		-0.022
4/25/2002	0.0063	-0.0865		89	-0.013	-0.01	-0.0115	82	-0.024	-0.022		-0.023
5/7/2002	0.0061	-0.0867	-0.1074	101	-0.015	-0.012	-0.0135	94	-0.026	-0.024		-0.025
5/28/2002	0.006	-0.0868	-0.1076	122	-0.016	-0.013	-0.0145	115	-0.027	-0.025		-0.026
6/4/2002	0.0061	-0.0867	-0.1076	129	-0.015	-0.012	-0.0135	122	-0.026	-0.024		-0.025
6/12/2002	0.0063	-0.0866	-0.1077	137	-0.013	-0.011	-0.012	130	-0.024	-0.023		-0.0235
6/25/2002	0.0063	-0.0864	-0.1072	150	-0.013	-0.009	-0.011	143	-0.024	-0.021		-0.0225
7/2/2002	0.0063	-0.0864	-0.1072	157	-0.013	-0.009	-0.011	150	-0.024	-0.021		-0.0225
7/9/2002	0.0063	-0.0865	-0.1072	164	-0.013	-0.01	-0.0115	157	-0.024	-0.022		-0.023
7/16/2002	0.0062	-0.0866	-0.1075	171	-0.014	-0.011	-0.0125	164	-0.025	-0.023		-0.024
7/23/2002	0.006	-0.0868	-0.1077	178	-0.016	-0.013	-0.0145	171	-0.027	-0.025		-0.026
7/30/2002	0.006	-0.0868	-0.1074	185	-0.016	-0.013	-0.0145	178	-0.027	-0.025		-0.026
8/6/2002	0.0062	-0.0867	-0.1074	192	-0.014	-0.012	-0.013	185	-0.025	-0.024		-0.0245
8/13/2002	0.0059	-0.0869	-0.1076	199	-0.017	-0.014	-0.0155	192	-0.028	-0.026		-0.027
10/6/2002	0.0064	-0.0865	-0.1073	252	-0.012	-0.01	-0.011	246	-0.023	-0.022		-0.0225
12/6/2002	0.0062	-0.0867	-0.1075	313	-0.014	-0.012	-0.013	307	-0.025	-0.024		-0.0245
2/6/2003	0.0061	-0.0865	-0.1074	375	-0.015	-0.01	-0.0125	369	-0.026	-0.022		-0.024
4/6/2003	0.0062	-0.0865	-0.1074	434	-0.014	-0.01	-0.012	428	-0.025	-0.022		-0.0235
6/6/2003	0.0062	-0.0867	-0.1072	495	-0.014	-0.012	-0.013	489	-0.025	-0.024		-0.0245
8/6/2003	0.0061	-0.0865	-0.1074	556	-0.015	-0.01	-0.0125	550	-0.026	-0.022		-0.024
10/6/2003	0.0062	-0.0867	-0.1074	617	-0.014	-0.012	-0.013	611	-0.025	-0.024		-0.0245
12/6/2003	0.0061	-0.0865	-0.1073	678	-0.015	-0.01	-0.0125	672	-0.026	-0.022		-0.024
2/6/2004	0.0061	-0.0866	-0.1073	740	-0.015	-0.011	-0.013	734	-0.026	-0.023		-0.0245
4/6/2004	0.0062	-0.0865	-0.1074	800	-0.014	-0.01	-0.012	794	-0.025	-0.022		-0.0235

Appendix B (c): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 3/8 Prepared 1/26/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age, t [Days]	BAR #1	BAR #2	BAR #3	Average	Age, t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
1/27/2002	0.0888	0.0301	-0.0104	0	0	0	0	0	...	...	...	...	...
2/2/2002	0.0896	0.0304	-0.0098	7	0.008	0.003	0.006	0.005667	0	0	0	0	0
2/9/2002	0.0888	0.0296	-0.0104	14	0	-0.005	0	-0.00167	7	-0.008	-0.008	-0.006	-0.00733
2/15/2002	0.0884	0.0298	-0.0109	20	-0.004	-0.003	-0.005	-0.004	13	-0.012	-0.006	-0.011	-0.00967
3/2/2002	0.0881	0.0292	-0.0107	35	-0.007	-0.009	-0.003	-0.00633	28	-0.015	-0.012	-0.009	-0.012
3/23/2002	0.0879	0.0285	-0.0117	56	-0.009	-0.016	-0.013	-0.01267	49	-0.017	-0.019	-0.019	-0.01833
4/1/2002	0.0879	0.0285	-0.0117	65	-0.009	-0.016	-0.013	-0.01267	58	-0.018	-0.019	-0.019	-0.01867
4/7/2002	0.0878	0.0286	-0.0116	71	-0.01	-0.015	-0.012	-0.01233	64	-0.018	-0.018	-0.018	-0.018
4/25/2002	0.0874	0.0284	-0.0117	89	-0.014	-0.017	-0.013	-0.01467	82	-0.022	-0.02	-0.019	-0.0203
5/7/2002	0.0867	0.0284	-0.0119	101	-0.021	-0.017	-0.015	-0.01767	94	-0.029	-0.02	-0.021	-0.0233
5/28/2002	0.0875	0.0282	-0.012	122	-0.013	-0.019	-0.016	-0.016	115	-0.021	-0.022	-0.022	-0.0217
6/4/2002	0.0876	0.0285	-0.0119	129	-0.012	-0.016	-0.015	-0.01433	122	-0.02	-0.019	-0.021	-0.0200
6/12/2002	0.0877	0.0284	-0.0121	137	-0.011	-0.017	-0.017	-0.015	130	-0.019	-0.02	-0.023	-0.0207
6/25/2002	0.0878	0.0288	-0.0116	150	-0.01	-0.013	-0.012	-0.01167	143	-0.018	-0.016	-0.018	-0.0173
7/2/2002	0.0879	0.0288	-0.0116	157	-0.009	-0.013	-0.012	-0.01133	150	-0.017	-0.016	-0.018	-0.0170
7/9/2002	0.0878	0.0288	-0.0116	164	-0.01	-0.013	-0.012	-0.01167	157	-0.018	-0.016	-0.018	-0.0173
7/16/2002	0.0878	0.0286	-0.0117	171	-0.01	-0.015	-0.013	-0.01267	164	-0.018	-0.018	-0.019	-0.0183
7/23/2002	0.0875	0.0284	-0.0117	178	-0.013	-0.017	-0.013	-0.01433	171	-0.021	-0.02	-0.019	-0.0200
7/30/2002	0.0875	0.0284	-0.0118	185	-0.013	-0.017	-0.014	-0.01467	178	-0.021	-0.02	-0.02	-0.0203
8/6/2002	0.0876	0.0285	-0.0118	192	-0.012	-0.016	-0.014	-0.014	185	-0.02	-0.019	-0.02	-0.0197
8/13/2002	0.0876	0.0284	-0.0119	199	-0.012	-0.017	-0.015	-0.01467	192	-0.02	-0.02	-0.021	-0.0203
10/6/2002	0.0877	0.0288	-0.0115	252	-0.011	-0.013	-0.011	-0.01167	246	-0.019	-0.016	-0.017	-0.0173
12/6/2002	0.0876	0.0287	-0.0116	313	-0.012	-0.014	-0.012	-0.01267	307	-0.02	-0.017	-0.018	-0.0183
2/6/2003	0.0877	0.0287	-0.0117	375	-0.011	-0.014	-0.013	-0.01267	369	-0.019	-0.017	-0.019	-0.0183
4/6/2003	0.0877	0.0287	-0.0117	434	-0.011	-0.014	-0.013	-0.01267	428	-0.019	-0.017	-0.019	-0.0183
6/6/2003	0.0878	0.0286	-0.0117	495	-0.01	-0.015	-0.013	-0.01267	489	-0.018	-0.018	-0.019	-0.0183
8/6/2003	0.0877	0.0287	-0.0116	556	-0.011	-0.014	-0.012	-0.01233	550	-0.019	-0.017	-0.018	-0.0180
10/6/2003	0.0878	0.0286	-0.0117	617	-0.01	-0.015	-0.013	-0.01267	611	-0.018	-0.018	-0.019	-0.0183
12/6/2003	0.0878	0.0287	-0.0116	678	-0.01	-0.014	-0.012	-0.012	672	-0.018	-0.017	-0.018	-0.0177
2/6/2004	0.0878	0.0286	-0.0117	740	-0.01	-0.015	-0.013	-0.01267	734	-0.018	-0.018	-0.019	-0.0183
4/6/2004	0.0877	0.0286	-0.0117	800	-0.011	-0.015	-0.013	-0.013	794	-0.019	-0.018	-0.019	-0.0187

Appendix B (d): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 4/11 Prepared 2/5/2002

DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age, t [Days]	BAR #1	BAR #2	BAR #3	Average	Age, t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/6/2002	0.1039	0.0948	0.038	0	0	0	0	0	...	...	...	...	...
2/12/2002	0.1042	0.0951	0.0383	7	0.003	0.003	0.003	0.003	0	0	0	0	0
2/19/2002	0.104	0.0945	0.0382	14	0.001	-0.003	0.002	0	7	-0.002	-0.006	-0.001	-0.003
3/5/2002	0.1028	0.0928	0.0375	28	-0.011	-0.02	-0.005	-0.012	21	-0.014	-0.023	-0.008	-0.015
3/13/2002	0.1027	0.0928	0.0373	36	-0.012	-0.02	-0.007	-0.013	29	-0.015	-0.023	-0.01	-0.016
3/27/2002	0.1025	0.0925	0.0375	50	-0.014	-0.023	-0.005	-0.014	43	-0.017	-0.026	-0.008	-0.017
4/2/2002	0.1024	0.0923	0.0369	56	-0.015	-0.025	-0.011	-0.017	49	-0.018	-0.028	-0.014	-0.02
4/7/2002	0.1019	0.092	0.0364	61	-0.02	-0.028	-0.016	-0.02133	54	-0.023	-0.031	-0.019	-0.0243
4/25/2002	0.1018	0.0918	0.036	79	-0.021	-0.03	-0.02	-0.02367	72	-0.024	-0.033	-0.023	-0.0267
5/7/2002	0.102	0.091	0.036	91	-0.019	-0.038	-0.02	-0.02567	84	-0.022	-0.041	-0.023	-0.0287
5/28/2002	0.1019	0.0919	0.0359	112	-0.02	-0.029	-0.021	-0.02333	105	-0.023	-0.032	-0.024	-0.0263
6/4/2002	0.102	0.0919	0.0361	119	-0.019	-0.029	-0.019	-0.02233	112	-0.022	-0.032	-0.022	-0.0253
6/13/2002	0.1022	0.0921	0.0365	128	-0.017	-0.027	-0.015	-0.01967	121	-0.02	-0.03	-0.018	-0.0227
6/25/2002	0.1024	0.0922	0.0364	140	-0.015	-0.026	-0.016	-0.019	133	-0.018	-0.029	-0.019	-0.0220
7/2/2002	0.1024	0.0922	0.0364	147	-0.015	-0.026	-0.016	-0.019	140	-0.018	-0.029	-0.019	-0.0220
7/9/2002	0.1024	0.0922	0.0364	154	-0.015	-0.026	-0.016	-0.019	147	-0.018	-0.029	-0.019	-0.0220
7/16/2002	0.1022	0.0921	0.0362	161	-0.017	-0.027	-0.018	-0.02067	154	-0.02	-0.03	-0.021	-0.0237
7/23/2002	0.102	0.092	0.0362	168	-0.019	-0.028	-0.018	-0.02167	161	-0.022	-0.031	-0.021	-0.0247
7/30/2002	0.1021	0.092	0.0361	175	-0.018	-0.028	-0.019	-0.02167	168	-0.021	-0.031	-0.022	-0.0247
8/6/2002	0.1021	0.092	0.0361	182	-0.018	-0.028	-0.019	-0.02167	175	-0.021	-0.031	-0.022	-0.0247
8/13/2002	0.1021	0.0921	0.0362	189	-0.018	-0.027	-0.018	-0.021	182	-0.021	-0.03	-0.021	-0.0240
10/13/2002	0.1024	0.0922	0.0365	249	-0.015	-0.026	-0.015	-0.01867	243	-0.018	-0.029	-0.018	-0.0217
12/13/2002	0.1021	0.0919	0.0362	310	-0.018	-0.029	-0.018	-0.02167	304	-0.021	-0.032	-0.021	-0.0247
2/13/2003	0.1021	0.092	0.0362	372	-0.018	-0.028	-0.018	-0.02133	366	-0.021	-0.031	-0.021	-0.0243
4/13/2003	0.1021	0.0919	0.036	431	-0.018	-0.029	-0.02	-0.02233	425	-0.021	-0.032	-0.023	-0.0253
6/13/2003	0.1022	0.0916	0.0358	492	-0.017	-0.032	-0.022	-0.02367	486	-0.02	-0.035	-0.025	-0.0267
8/13/2003	0.1021	0.092	0.036	553	-0.018	-0.028	-0.02	-0.022	547	-0.021	-0.031	-0.023	-0.0250
10/13/2003	0.1022	0.0919	0.0362	614	-0.017	-0.029	-0.018	-0.02133	608	-0.02	-0.032	-0.021	-0.0243
12/13/2003	0.1021	0.092	0.0358	675	-0.018	-0.028	-0.022	-0.02267	669	-0.021	-0.031	-0.025	-0.0257
2/13/2004	0.1021	0.0919	0.036	737	-0.018	-0.029	-0.02	-0.02233	731	-0.021	-0.032	-0.023	-0.0253
4/13/2004	0.1021	0.0916	0.036	797	-0.018	-0.032	-0.02	-0.02333	791	-0.021	-0.035	-0.023	-0.0263

Appendix B (e): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 5/12 Prepared 2/5/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/6/2002	-0.0067	0.0179	0.0183	0	0	0	0	0	...	...	...	...	...
2/12/2002	-0.0064	0.0183	0.0186	7	0.003	0.004	0.003	0.003333	0	0	0	0	0
2/19/2002	-0.0069	0.0181	0.0183	14	-0.002	0.002	0	0	7	-0.005	-0.002	-0.003	-0.0033
3/5/2002	-0.0081	0.0173	0.0174	28	-0.014	-0.006	-0.009	-0.00967	21	-0.017	-0.01	-0.012	-0.013
3/13/2002	-0.0082	0.0168	0.017	36	-0.015	-0.011	-0.013	-0.013	29	-0.018	-0.015	-0.016	-0.0163
3/27/2002	-0.0085	0.0163	0.0165	50	-0.018	-0.016	-0.018	-0.01733	43	-0.021	-0.02	-0.021	-0.0207
4/2/2002	-0.0087	0.0161	0.0164	56	-0.02	-0.018	-0.019	-0.019	49	-0.023	-0.022	-0.022	-0.0223
4/7/2002	-0.009	0.0158	0.016	61	-0.023	-0.021	-0.023	-0.02233	54	-0.026	-0.025	-0.026	-0.0257
4/25/2002	-0.0091	0.0157	0.016	79	-0.024	-0.022	-0.023	-0.023	72	-0.027	-0.026	-0.026	-0.0263
5/7/2002	-0.0091	0.0156	0.016	91	-0.024	-0.023	-0.023	-0.02333	84	-0.027	-0.027	-0.026	-0.0267
5/28/2002	-0.0091	0.0157	0.016	112	-0.024	-0.022	-0.023	-0.023	105	-0.027	-0.026	-0.026	-0.0263
6/4/2002	-0.0091	0.0159	0.016	119	-0.024	-0.02	-0.023	-0.02233	112	-0.027	-0.024	-0.026	-0.0257
6/12/2002	-0.009	0.0155	0.0162	127	-0.023	-0.024	-0.021	-0.02267	120	-0.026	-0.028	-0.024	-0.0260
6/25/2002	-0.0087	0.0159	0.0164	140	-0.02	-0.02	-0.019	-0.01967	133	-0.023	-0.024	-0.022	-0.0230
7/2/2002	-0.0085	0.016	0.0164	147	-0.018	-0.019	-0.019	-0.01867	140	-0.021	-0.023	-0.022	-0.0220
7/9/2002	-0.0085	0.016	0.0164	154	-0.018	-0.019	-0.019	-0.01867	147	-0.021	-0.023	-0.022	-0.0220
7/16/2002	-0.0088	0.0159	0.0163	161	-0.021	-0.02	-0.02	-0.02033	154	-0.024	-0.024	-0.023	-0.0237
7/23/2002	-0.0089	0.0158	0.0161	168	-0.022	-0.021	-0.022	-0.02167	161	-0.025	-0.025	-0.025	-0.0250
7/30/2002	-0.0088	0.0158	0.0162	175	-0.021	-0.021	-0.021	-0.021	168	-0.024	-0.025	-0.024	-0.0243
8/6/2002	-0.0088	0.0157	0.0161	182	-0.021	-0.022	-0.022	-0.02167	175	-0.024	-0.026	-0.025	-0.0250
8/13/2002	-0.0088	0.0158	0.0162	189	-0.021	-0.021	-0.021	-0.021	182	-0.024	-0.025	-0.024	-0.0243
10/13/2002	-0.0085	0.016	0.0163	249	-0.018	-0.019	-0.02	-0.019	243	-0.021	-0.023	-0.023	-0.0223
12/13/2002	-0.0089	0.0156	0.016	310	-0.022	-0.023	-0.023	-0.02267	304	-0.025	-0.027	-0.026	-0.0260
2/13/2003	-0.0088	0.0156	0.016	372	-0.021	-0.023	-0.023	-0.02233	366	-0.024	-0.027	-0.026	-0.0257
4/13/2003	-0.0088	0.0157	0.016	431	-0.021	-0.022	-0.023	-0.022	425	-0.024	-0.026	-0.026	-0.0253
6/13/2003	-0.0086	0.0158	0.016	492	-0.019	-0.021	-0.023	-0.021	486	-0.022	-0.025	-0.026	-0.0243
8/13/2003	-0.0086	0.0157	0.016	553	-0.019	-0.022	-0.023	-0.02133	547	-0.022	-0.026	-0.026	-0.0247
10/13/2003	-0.0087	0.0158	0.0161	614	-0.02	-0.021	-0.022	-0.021	608	-0.023	-0.025	-0.025	-0.0243
12/13/2003	-0.0087	0.0157	0.0161	675	-0.02	-0.022	-0.022	-0.02133	669	-0.023	-0.026	-0.025	-0.0247
2/13/2004	-0.0086	0.0157	0.016	737	-0.019	-0.022	-0.023	-0.02133	731	-0.022	-0.026	-0.026	-0.0247
4/13/2004	-0.0086	0.0158	0.016	797	-0.019	-0.021	-0.023	-0.021	791	-0.022	-0.025	-0.026	-0.0243
6/13/2003	-0.0086	0.0158	0.016	492	-0.019	-0.021	-0.023	-0.021	486	-0.022	-0.025	-0.026	-0.0243
8/13/2003	-0.0087	0.0158	0.0161	553	-0.02	-0.021	-0.022	-0.021	547	-0.023	-0.025	-0.025	-0.0243
10/13/2003	-0.0086	0.0157	0.016	614	-0.019	-0.022	-0.023	-0.02133	608	-0.022	-0.026	-0.026	-0.0247
12/13/2003	-0.0087	0.0158	0.016	675	-0.02	-0.021	-0.023	-0.02133	669	-0.023	-0.025	-0.026	-0.0247
2/13/2004	-0.0086	0.0156	0.0161	737	-0.019	-0.023	-0.022	-0.02133	731	-0.022	-0.027	-0.025	-0.0247
4/13/2004	-0.0086	0.0158	0.016	797	-0.019	-0.021	-0.023	-0.021	791	-0.022	-0.025	-0.026	-0.0243

Appendix B (f): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 6/13 Prepared 2/16/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/17/2002	-0.0018	0.056	0.0211	0	0	0	0	0	...	...	...	...	...
2/22/2002	-0.002	0.0562	0.0214	6	-0.002	0.002	0.003	0.001	0	0	0	0	0
3/2/2002	-0.0028	0.0551	0.0205	14	-0.01	-0.009	-0.006	-0.00833	8	-0.008	-0.011	-0.009	-0.0093
3/9/2002	-0.0031	0.0549	0.0203	21	-0.013	-0.011	-0.008	-0.01067	15	-0.011	-0.013	-0.011	-0.0117
3/16/2002	-0.0033	0.0548	0.0199	28	-0.015	-0.012	-0.012	-0.013	22	-0.013	-0.014	-0.015	-0.014
3/23/2002	-0.0038	0.0542	0.0196	35	-0.02	-0.018	-0.015	-0.01767	29	-0.018	-0.02	-0.018	-0.0187
4/7/2002	-0.0042	0.0541	0.0196	50	-0.024	-0.019	-0.015	-0.01933	44	-0.022	-0.021	-0.018	-0.0203
4/25/2002	-0.0047	0.0538	0.0193	68	-0.029	-0.022	-0.018	-0.023	62	-0.027	-0.024	-0.021	-0.024
5/7/2002	-0.0045	0.0537	0.0193	80	-0.027	-0.023	-0.018	-0.02267	74	-0.025	-0.025	-0.021	-0.0237
5/28/2002	-0.0048	0.0535	0.0189	101	-0.03	-0.025	-0.022	-0.02567	95	-0.028	-0.027	-0.025	-0.0267
6/4/2002	-0.0047	0.0537	0.0191	108	-0.029	-0.023	-0.02	-0.024	102	-0.027	-0.025	-0.023	-0.0250
6/12/2002	-0.0048	0.0533	0.0191	116	-0.03	-0.027	-0.02	-0.02567	110	-0.028	-0.029	-0.023	-0.0267
6/25/2002	-0.0042	0.0541	0.0196	129	-0.024	-0.019	-0.015	-0.01933	123	-0.022	-0.021	-0.018	-0.0203
7/2/2002	-0.0043	0.0539	0.0194	136	-0.025	-0.021	-0.017	-0.021	130	-0.023	-0.023	-0.02	-0.0220
7/9/2002	-0.0042	0.054	0.0194	145	-0.024	-0.02	-0.017	-0.02033	137	-0.022	-0.022	-0.02	-0.0213
7/16/2002	-0.0045	0.0539	0.0193	152	-0.027	-0.021	-0.018	-0.022	144	-0.025	-0.023	-0.021	-0.0230
7/23/2002	-0.0045	0.0539	0.0191	159	-0.027	-0.021	-0.02	-0.02267	151	-0.025	-0.023	-0.023	-0.0237
7/30/2002	-0.0045	0.0539	0.0192	166	-0.027	-0.021	-0.019	-0.02233	158	-0.025	-0.023	-0.022	-0.0233
8/6/2002	-0.0045	0.0539	0.0192	173	-0.027	-0.021	-0.019	-0.02233	165	-0.025	-0.023	-0.022	-0.0233
8/13/2002	-0.0045	0.054	0.0193	180	-0.027	-0.02	-0.018	-0.02167	172	-0.025	-0.022	-0.021	-0.0227
8/20/2002	-0.0045	0.0539	0.0192	187	-0.027	-0.021	-0.019	-0.02233	179	-0.025	-0.023	-0.022	-0.0233
10/20/2002	-0.0046	0.0537	0.0192	245	-0.028	-0.023	-0.019	-0.02333	240	-0.026	-0.025	-0.022	-0.0243
12/20/2002	-0.0047	0.0535	0.0186	306	-0.029	-0.025	-0.025	-0.02633	301	-0.027	-0.027	-0.028	-0.0273
2/20/2003	-0.0048	0.0537	0.0188	368	-0.03	-0.023	-0.023	-0.02533	363	-0.028	-0.025	-0.026	-0.0263
4/20/2003	-0.0047	0.0535	0.0187	427	-0.029	-0.025	-0.024	-0.026	422	-0.027	-0.027	-0.027	-0.0270
6/20/2003	-0.0046	0.0533	0.0186	488	-0.028	-0.027	-0.025	-0.02667	483	-0.026	-0.029	-0.028	-0.0277
8/20/2003	-0.0046	0.0535	0.0188	549	-0.028	-0.025	-0.023	-0.02533	544	-0.026	-0.027	-0.026	-0.0263
10/20/2003	-0.0047	0.0535	0.0187	610	-0.029	-0.025	-0.024	-0.026	605	-0.027	-0.027	-0.027	-0.0270
12/20/2003	-0.0047	0.0535	0.0188	671	-0.029	-0.025	-0.023	-0.02567	666	-0.027	-0.027	-0.026	-0.0267
2/20/2004	-0.0046	0.0535	0.0187	733	-0.028	-0.025	-0.024	-0.02567	728	-0.026	-0.027	-0.027	-0.0267
4/20/2004	-0.0048	0.0537	0.0188	793	-0.03	-0.023	-0.023	-0.02533	788	-0.028	-0.025	-0.026	-0.0263

Appendix B (g): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 7/14 Prepared 2/16/2002

DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/17/2002	-0.0077	0.0152	0.0226	0	0	0	0	0	...	...	...	...	...
2/22/2002	-0.0075	0.0154	0.0229	6	0.002	0.002	0.003	0.002333	0	0	0	0	0
3/2/2002	-0.008	0.0148	0.0223	14	-0.003	-0.004	-0.003	-0.00333	8	-0.005	-0.006	-0.006	-0.0057
3/9/2002	-0.0083	0.0145	0.0221	21	-0.006	-0.007	-0.005	-0.006	15	-0.008	-0.009	-0.008	-0.0083
3/16/2002	-0.0085	0.0143	0.0218	28	-0.008	-0.009	-0.008	-0.00833	22	-0.01	-0.011	-0.011	-0.0107
3/23/2002	-0.0089	0.0141	0.0214	35	-0.012	-0.011	-0.012	-0.01167	29	-0.014	-0.013	-0.015	-0.014
4/7/2002	-0.009	0.0142	0.0214	50	-0.013	-0.01	-0.012	-0.01167	44	-0.015	-0.012	-0.015	-0.014
4/25/2002	-0.0093	0.0137	0.0209	68	-0.016	-0.015	-0.017	-0.016	62	-0.018	-0.017	-0.02	-0.0183
5/7/2002	-0.0095	0.0137	0.0209	80	-0.018	-0.015	-0.017	-0.01667	74	-0.02	-0.017	-0.02	-0.019
5/28/2002	-0.0096	0.0136	0.0209	101	-0.019	-0.016	-0.017	-0.01733	95	-0.021	-0.018	-0.02	-0.0197
6/4/2002	-0.0096	0.0137	0.0208	108	-0.019	-0.015	-0.018	-0.01733	102	-0.021	-0.017	-0.021	-0.0197
6/12/2002	-0.0097	0.0139	0.0211	116	-0.02	-0.013	-0.015	-0.016	110	-0.022	-0.015	-0.018	-0.0183
6/25/2002	-0.0092	0.014	0.0211	129	-0.015	-0.012	-0.015	-0.014	123	-0.017	-0.014	-0.018	-0.0163
7/2/2002	-0.0092	0.014	0.0212	136	-0.015	-0.012	-0.014	-0.01367	130	-0.017	-0.014	-0.017	-0.0160
7/9/2002	-0.0093	0.0141	0.0211	145	-0.016	-0.011	-0.015	-0.014	137	-0.018	-0.013	-0.018	-0.0163
7/16/2002	-0.0093	0.0138	0.021	152	-0.016	-0.014	-0.016	-0.01533	144	-0.018	-0.016	-0.019	-0.0177
7/23/2002	-0.0095	0.0136	0.021	159	-0.018	-0.016	-0.016	-0.01667	151	-0.02	-0.018	-0.019	-0.0190
7/30/2002	-0.0094	0.0138	0.021	166	-0.017	-0.014	-0.016	-0.01567	158	-0.019	-0.016	-0.019	-0.0180
8/6/2002	-0.0094	0.0137	0.021	173	-0.017	-0.015	-0.016	-0.016	165	-0.019	-0.017	-0.019	-0.0183
8/13/2002	-0.0092	0.0138	0.021	180	-0.015	-0.014	-0.016	-0.015	172	-0.017	-0.016	-0.019	-0.0173
8/20/2002	-0.0092	0.0138	0.0211	187	-0.015	-0.014	-0.015	-0.01467	179	-0.017	-0.016	-0.018	-0.0170
10/20/2002	-0.0093	0.0139	0.0209	245	-0.016	-0.013	-0.017	-0.01533	240	-0.018	-0.015	-0.02	-0.0177
12/20/2002	-0.0096	0.0135	0.0205	306	-0.019	-0.017	-0.021	-0.019	301	-0.021	-0.019	-0.024	-0.0213
2/20/2003	-0.0096	0.0135	0.0207	368	-0.019	-0.017	-0.019	-0.01833	363	-0.021	-0.019	-0.022	-0.0207
4/20/2003	-0.0096	0.0135	0.0207	427	-0.019	-0.017	-0.019	-0.01833	422	-0.021	-0.019	-0.022	-0.0207
6/20/2003	-0.0096	0.0136	0.0208	488	-0.019	-0.016	-0.018	-0.01767	483	-0.021	-0.018	-0.021	-0.0200
8/20/2003	-0.0092	0.0136	0.0211	549	-0.015	-0.016	-0.015	-0.01533	544	-0.017	-0.018	-0.018	-0.0177
10/20/2003	-0.0093	0.0135	0.0205	610	-0.016	-0.017	-0.021	-0.018	605	-0.018	-0.019	-0.024	-0.0203
12/20/2003	-0.0096	0.0138	0.0207	671	-0.019	-0.014	-0.019	-0.01733	666	-0.021	-0.016	-0.022	-0.0197
2/20/2004	-0.0096	0.0139	0.0207	733	-0.019	-0.013	-0.019	-0.017	728	-0.021	-0.015	-0.022	-0.0193
4/20/2004	-0.0096	0.0135	0.0208	793	-0.019	-0.017	-0.018	-0.018	788	-0.021	-0.019	-0.021	-0.0203

Appendix B (h): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 8/15 Prepared 2/17/2002

DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/18/2002	0.1048	0.0675	0.0748	0	0	0	0	0	...	...	...	...	...
2/24/2002	0.1045	0.067	0.0717	7	-0.003	-0.005	-0.031	-0.013	0	0	0	0	0
3/3/2002	0.1041	0.0667	0.072	14	-0.007	-0.008	-0.028	-0.01433	7	-0.004	-0.003	0.003	-0.00133
3/10/2002	0.1036	0.0663	0.0715	21	-0.012	-0.012	-0.033	-0.019	14	-0.009	-0.007	-0.002	-0.006
3/18/2002	0.1036	0.0663	0.0715	29	-0.012	-0.012	-0.033	-0.019	22	-0.009	-0.007	-0.002	-0.006
3/24/2002	0.1035	0.0662	0.0711	35	-0.013	-0.013	-0.037	-0.021	28	-0.01	-0.008	-0.006	-0.008
4/1/2002	0.1034	0.0661	0.0711	43	-0.014	-0.014	-0.037	-0.02167	36	-0.011	-0.009	-0.006	-0.00867
4/7/2002	0.1035	0.0661	0.071	49	-0.013	-0.014	-0.038	-0.02167	42	-0.01	-0.009	-0.007	-0.00867
4/25/2002	0.103	0.0655	0.0702	67	-0.018	-0.02	-0.046	-0.028	60	-0.015	-0.015	-0.015	-0.015
5/7/2002	0.1029	0.0654	0.0701	79	-0.019	-0.021	-0.047	-0.029	72	-0.016	-0.016	-0.016	-0.016
5/28/2002	0.1028	0.0656	0.0703	100	-0.02	-0.019	-0.045	-0.028	93	-0.017	-0.014	-0.014	-0.015
6/4/2002	0.1028	0.0655	0.0705	107	-0.02	-0.02	-0.043	-0.02767	100	-0.017	-0.015	-0.012	-0.01467
6/25/2002	0.1031	0.0656	0.0705	128	-0.017	-0.019	-0.043	-0.02633	121	-0.014	-0.014	-0.012	-0.01333
7/2/2002	0.1032	0.0657	0.0707	135	-0.016	-0.018	-0.041	-0.025	128	-0.013	-0.013	-0.01	-0.012
7/9/2002	0.1031	0.0656	0.0707	142	-0.017	-0.019	-0.041	-0.02567	135	-0.014	-0.014	-0.01	-0.01267
7/16/2002	0.1032	0.0654	0.0701	149	-0.016	-0.021	-0.047	-0.028	142	-0.013	-0.016	-0.016	-0.015
7/23/2002	0.103	0.0655	0.0704	156	-0.018	-0.02	-0.044	-0.02733	149	-0.015	-0.015	-0.013	-0.01433
7/30/2002	0.103	0.0653	0.0704	163	-0.018	-0.022	-0.044	-0.028	156	-0.015	-0.017	-0.013	-0.015
8/6/2002	0.103	0.0655	0.0705	170	-0.018	-0.02	-0.043	-0.027	163	-0.015	-0.015	-0.012	-0.014
8/13/2002	0.1032	0.0656	0.0705	177	-0.016	-0.019	-0.043	-0.026	170	-0.013	-0.014	-0.012	-0.013
8/20/2002	0.1032	0.0656	0.0705	184	-0.016	-0.019	-0.043	-0.026	177	-0.013	-0.014	-0.012	-0.013
8/27/2002	0.1031	0.0654	0.0705	191	-0.017	-0.021	-0.043	-0.027	184	-0.014	-0.016	-0.012	-0.014
10/27/2002	0.1031	0.0653	0.0704	251	-0.017	-0.022	-0.044	-0.02767	245	-0.014	-0.017	-0.013	-0.01467
12/27/2002	0.103	0.0651	0.0702	312	-0.018	-0.024	-0.046	-0.02933	306	-0.015	-0.019	-0.015	-0.01633
2/27/2003	0.1029	0.0653	0.0701	374	-0.019	-0.022	-0.047	-0.02933	368	-0.016	-0.017	-0.016	-0.01633
4/27/2003	0.1031	0.0652	0.0703	433	-0.017	-0.023	-0.045	-0.02833	427	-0.014	-0.018	-0.014	-0.01533
6/27/2003	0.1031	0.0655	0.0705	494	-0.017	-0.02	-0.043	-0.02667	488	-0.014	-0.015	-0.012	-0.01367
8/27/2003	0.103	0.0656	0.0705	555	-0.018	-0.019	-0.043	-0.02667	549	-0.015	-0.014	-0.012	-0.01367
10/27/2003	0.1029	0.0656	0.0705	616	-0.019	-0.019	-0.043	-0.027	610	-0.016	-0.014	-0.012	-0.014
12/27/2003	0.1031	0.0654	0.0703	677	-0.017	-0.021	-0.045	-0.02767	671	-0.014	-0.016	-0.014	-0.01467
2/27/2004	0.1031	0.0654	0.0703	739	-0.017	-0.021	-0.045	-0.02767	733	-0.014	-0.016	-0.014	-0.01467
4/27/2004	0.1031	0.0651	0.0703	799	-0.017	-0.024	-0.045	-0.02867	793	-0.014	-0.019	-0.014	-0.01567

Appendix B (i): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 9/16 Prepared 2/17/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/18/2002	0.0305	-0.0151	0.0234	0	0	0	0	0	...	...	...	...	...
2/24/2002	0.0296	-0.0153	0.0234	7	-0.009	-0.002	0	-0.00367	0	0	0	0	0
3/3/2002	0.0293	-0.0157	0.0233	14	-0.012	-0.006	-0.001	-0.00633	7	-0.003	-0.004	-0.001	-0.00267
3/10/2002	0.0289	-0.0159	0.0228	21	-0.016	-0.008	-0.006	-0.01	14	-0.007	-0.006	-0.006	-0.00633
3/18/2002	0.0288	-0.0159	0.0228	29	-0.017	-0.008	-0.006	-0.01033	22	-0.008	-0.006	-0.006	-0.00667
3/24/2002	0.0287	-0.0162	0.0225	35	-0.018	-0.011	-0.009	-0.01267	28	-0.009	-0.009	-0.009	-0.009
4/1/2002	0.0287	-0.0162	0.0226	43	-0.018	-0.011	-0.008	-0.01233	36	-0.009	-0.009	-0.008	-0.00867
4/7/2002	0.0287	-0.0163	0.0226	49	-0.018	-0.012	-0.008	-0.01267	42	-0.009	-0.01	-0.008	-0.009
4/25/2002	0.0282	-0.0167	0.022	65	-0.023	-0.016	-0.014	-0.01767	58	-0.014	-0.014	-0.014	-0.014
5/7/2002	0.0281	-0.0167	0.0219	77	-0.024	-0.016	-0.015	-0.01833	70	-0.015	-0.014	-0.015	-0.01467
5/28/2002	0.0279	-0.0167	0.0219	98	-0.026	-0.016	-0.015	-0.019	91	-0.017	-0.014	-0.015	-0.01533
6/4/2002	0.0281	-0.0167	0.0221	105	-0.024	-0.016	-0.013	-0.01767	98	-0.015	-0.014	-0.013	-0.014
6/25/2002	0.0282	-0.0166	0.0223	126	-0.023	-0.015	-0.011	-0.01633	119	-0.014	-0.013	-0.011	-0.01267
7/2/2002	0.0283	-0.0165	0.0223	133	-0.022	-0.014	-0.011	-0.01567	126	-0.013	-0.012	-0.011	-0.012
7/9/2002	0.0281	-0.0166	0.0221	140	-0.024	-0.015	-0.013	-0.01733	133	-0.015	-0.013	-0.013	-0.01367
7/16/2002	0.028	-0.0168	0.022	147	-0.025	-0.017	-0.014	-0.01867	140	-0.016	-0.015	-0.014	-0.015
7/23/2002	0.0278	-0.017	0.0218	154	-0.027	-0.019	-0.016	-0.02067	147	-0.018	-0.017	-0.016	-0.017
7/30/2002	0.0279	-0.0168	0.0218	161	-0.026	-0.017	-0.016	-0.01967	154	-0.017	-0.015	-0.016	-0.016
8/6/2002	0.028	-0.0168	0.0217	168	-0.025	-0.017	-0.017	-0.01967	161	-0.016	-0.015	-0.017	-0.016
8/13/2002	0.0282	-0.0167	0.022	175	-0.023	-0.016	-0.014	-0.01767	168	-0.014	-0.014	-0.014	-0.014
8/20/2002	0.0281	-0.0168	0.022	182	-0.024	-0.017	-0.014	-0.01833	175	-0.015	-0.015	-0.014	-0.01467
8/27/2002	0.0279	-0.0169	0.0218	189	-0.026	-0.018	-0.016	-0.02	182	-0.017	-0.016	-0.016	-0.01633
10/27/2002	0.028	-0.0169	0.0218	251	-0.025	-0.018	-0.016	-0.01967	245	-0.016	-0.016	-0.016	-0.016
12/27/2002	0.0279	-0.0168	0.0217	312	-0.026	-0.017	-0.017	-0.02	306	-0.017	-0.015	-0.017	-0.01633
2/27/2003	0.0279	-0.017	0.0216	374	-0.026	-0.019	-0.018	-0.021	368	-0.017	-0.017	-0.018	-0.01733
4/27/2003	0.0278	-0.0168	0.0216	433	-0.027	-0.017	-0.018	-0.02067	427	-0.018	-0.015	-0.018	-0.017
6/27/2003	0.0278	-0.0168	0.0216	494	-0.027	-0.017	-0.018	-0.02067	488	-0.018	-0.015	-0.018	-0.017
8/27/2003	0.0279	-0.0171	0.0216	555	-0.026	-0.02	-0.018	-0.02133	549	-0.017	-0.018	-0.018	-0.01767
10/27/2003	0.028	-0.0168	0.0218	616	-0.025	-0.017	-0.016	-0.01933	610	-0.016	-0.015	-0.016	-0.01567
12/27/2003	0.0279	-0.0169	0.0216	677	-0.026	-0.018	-0.018	-0.02067	671	-0.017	-0.016	-0.018	-0.017
2/27/2004	0.0279	-0.0168	0.0217	739	-0.026	-0.017	-0.017	-0.02	733	-0.017	-0.015	-0.017	-0.01633
4/27/2004	0.0279	-0.0169	0.0217	799	-0.026	-0.018	-0.017	-0.02033	793	-0.017	-0.016	-0.017	-0.01667

Appendix B (j): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 10/18 Prepared 2/24/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/25/2002	0.0139	-0.0473	-0.0076	0	0	0	0	0	...	...	...	...	...
3/3/2002	0.0151	-0.0466	-0.0069	7	0.012	0.007	0.007	0.008667	0	0	0	0	0
3/10/2002	0.0142	-0.0475	-0.0079	14	0.003	-0.002	-0.003	-0.00067	7	-0.009	-0.009	-0.01	-0.00933
3/18/2002	0.0134	-0.0485	-0.0085	22	-0.005	-0.012	-0.009	-0.00867	15	-0.017	-0.019	-0.016	-0.01733
3/24/2002	0.0128	-0.049	-0.0091	28	-0.011	-0.017	-0.015	-0.01433	21	-0.023	-0.024	-0.022	-0.023
4/1/2002	0.0126	-0.0492	-0.0094	36	-0.013	-0.019	-0.018	-0.01667	29	-0.025	-0.026	-0.025	-0.0253
4/7/2002	0.0125	-0.0495	-0.0095	42	-0.014	-0.022	-0.019	-0.01833	35	-0.026	-0.029	-0.026	-0.027
4/25/2002	0.012	-0.05	-0.01	60	-0.019	-0.027	-0.024	-0.02333	53	-0.031	-0.034	-0.031	-0.032
5/7/2002	0.012	-0.0501	-0.0104	72	-0.019	-0.028	-0.028	-0.025	65	-0.031	-0.035	-0.035	-0.034
5/28/2002	0.0119	-0.0504	-0.0104	93	-0.02	-0.031	-0.028	-0.02633	86	-0.032	-0.038	-0.035	-0.035
6/4/2002	0.0118	-0.0502	-0.0105	100	-0.021	-0.029	-0.029	-0.02633	93	-0.033	-0.036	-0.036	-0.035
6/12/2002	0.012	-0.05	-0.0103	109	-0.019	-0.027	-0.027	-0.02433	102	-0.031	-0.034	-0.034	-0.033
6/25/2002	0.012	-0.0501	-0.0102	121	-0.019	-0.028	-0.026	-0.02433	114	-0.031	-0.035	-0.033	-0.033
7/2/2002	0.012	-0.05	-0.0103	128	-0.019	-0.027	-0.027	-0.02433	121	-0.031	-0.034	-0.034	-0.033
7/9/2002	0.0119	-0.0504	-0.0104	135	-0.02	-0.031	-0.028	-0.02633	128	-0.032	-0.038	-0.035	-0.035
7/16/2002	0.0118	-0.0505	-0.0106	142	-0.021	-0.032	-0.03	-0.02767	135	-0.033	-0.039	-0.037	-0.036
7/23/2002	0.0114	-0.0506	-0.0107	149	-0.025	-0.033	-0.031	-0.02967	142	-0.037	-0.04	-0.038	-0.038
7/30/2002	0.0115	-0.0505	-0.0107	156	-0.024	-0.032	-0.031	-0.029	149	-0.036	-0.039	-0.038	-0.038
8/6/2002	0.0115	-0.0505	-0.0107	163	-0.024	-0.032	-0.031	-0.029	156	-0.036	-0.039	-0.038	-0.038
8/13/2002	0.0116	-0.0503	-0.0104	170	-0.023	-0.03	-0.028	-0.027	163	-0.035	-0.037	-0.035	-0.036
8/20/2002	0.0116	-0.0504	-0.0105	177	-0.023	-0.031	-0.029	-0.02767	170	-0.035	-0.038	-0.036	-0.036
8/27/2002	0.0115	-0.0505	-0.0106	184	-0.024	-0.032	-0.03	-0.02867	177	-0.036	-0.039	-0.037	-0.037
9/3/2002	0.0117	-0.0503	-0.0104	191	-0.022	-0.03	-0.028	-0.02667	184	-0.034	-0.037	-0.035	-0.035
9/10/2002	0.0116	-0.0504	-0.0104	198	-0.023	-0.031	-0.028	-0.02733	191	-0.035	-0.038	-0.035	-0.036
11/3/2002	0.0116	-0.0504	-0.0109	251	-0.023	-0.031	-0.033	-0.029	245	-0.035	-0.038	-0.04	-0.038
1/3/2003	0.0114	-0.0503	-0.0106	312	-0.025	-0.03	-0.03	-0.02833	306	-0.037	-0.037	-0.037	-0.037
3/3/2003	0.0116	-0.0503	-0.0106	371	-0.023	-0.03	-0.03	-0.02767	365	-0.035	-0.037	-0.037	-0.036
5/3/2003	0.0117	-0.0504	-0.0106	432	-0.022	-0.031	-0.03	-0.02767	426	-0.034	-0.038	-0.037	-0.036
7/3/2003	0.0116	-0.0504	-0.0106	493	-0.023	-0.031	-0.03	-0.028	487	-0.035	-0.038	-0.037	-0.037
9/3/2003	0.0116	-0.0503	-0.0106	555	-0.023	-0.03	-0.03	-0.02767	549	-0.035	-0.037	-0.037	-0.036
11/3/2003	0.0114	-0.0504	-0.0105	616	-0.025	-0.031	-0.029	-0.02833	610	-0.037	-0.038	-0.036	-0.037
1/3/2004	0.0117	-0.0503	-0.0105	677	-0.022	-0.03	-0.029	-0.027	671	-0.034	-0.037	-0.036	-0.036
3/3/2004	0.0117	-0.0504	-0.0106	737	-0.022	-0.031	-0.03	-0.02767	731	-0.034	-0.038	-0.037	-0.036

Appendix B (k): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 11/19 Prepared 2/14/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/15/2002	0.021	-0.0066	0.0131	0	0	0	0	0	...	...	...	...	...
2/22/2002	0.0217	-0.0061	0.0133	8	0.007	0.005	0.002	0.004667	0	0	0	0	0
2/28/2002	0.0204	-0.0071	0.0125	14	-0.006	-0.005	-0.006	-0.00567	6	-0.013	-0.01	-0.008	-0.0103
3/7/2002	0.0201	-0.0074	0.0121	21	-0.009	-0.008	-0.01	-0.009	13	-0.016	-0.013	-0.012	-0.0137
3/16/2002	0.0195	-0.0082	0.0112	30	-0.015	-0.016	-0.019	-0.01667	22	-0.022	-0.021	-0.021	-0.0213
4/7/2002	0.0191	-0.0086	0.011	52	-0.019	-0.02	-0.021	-0.02	44	-0.026	-0.025	-0.023	-0.0247
4/25/2002	0.0189	-0.0087	0.0107	70	-0.021	-0.021	-0.024	-0.022	62	-0.028	-0.026	-0.026	-0.0267
5/7/2002	0.0187	-0.0091	0.0106	82	-0.023	-0.025	-0.025	-0.02433	74	-0.03	-0.03	-0.027	-0.0290
5/28/2002	0.0185	-0.0091	0.0104	103	-0.025	-0.025	-0.027	-0.02567	95	-0.032	-0.03	-0.029	-0.0303
6/4/2002	0.0185	-0.0091	0.0105	110	-0.025	-0.025	-0.026	-0.02533	102	-0.032	-0.03	-0.028	-0.0300
6/12/2002	0.0184	-0.0089	0.0104	118	-0.026	-0.023	-0.027	-0.02533	110	-0.033	-0.028	-0.029	-0.0300
6/25/2002	0.0186	-0.0088	0.0108	131	-0.024	-0.022	-0.023	-0.023	123	-0.031	-0.027	-0.025	-0.0277
7/2/2002	0.0188	-0.0086	0.0108	138	-0.022	-0.02	-0.023	-0.02167	130	-0.029	-0.025	-0.025	-0.0263
7/9/2002	0.0187	-0.0086	0.0108	145	-0.023	-0.02	-0.023	-0.022	137	-0.03	-0.025	-0.025	-0.0267
7/16/2002	0.0185	-0.0086	0.0106	152	-0.025	-0.02	-0.025	-0.02333	144	-0.032	-0.025	-0.027	-0.0280
7/23/2002	0.0184	-0.0089	0.0104	159	-0.026	-0.023	-0.027	-0.02533	151	-0.033	-0.028	-0.029	-0.0300
7/30/2002	0.0185	-0.0089	0.0105	166	-0.025	-0.023	-0.026	-0.02467	158	-0.032	-0.028	-0.028	-0.0293
8/6/2002	0.0185	-0.0088	0.0105	173	-0.025	-0.022	-0.026	-0.02433	165	-0.032	-0.027	-0.028	-0.0290
8/13/2002	0.0185	-0.0088	0.0106	180	-0.025	-0.022	-0.025	-0.024	172	-0.032	-0.027	-0.027	-0.0287
8/20/2002	0.0185	-0.0089	0.0104	187	-0.025	-0.023	-0.027	-0.025	179	-0.032	-0.028	-0.029	-0.0297
10/20/2002	0.0187	-0.0087	0.0106	247	-0.023	-0.021	-0.025	-0.023	240	-0.03	-0.026	-0.027	-0.0277
12/20/2002	0.0183	-0.0091	0.0103	308	-0.027	-0.025	-0.028	-0.02667	301	-0.034	-0.03	-0.03	-0.0313
2/20/2003	0.0181	-0.0091	0.0103	370	-0.029	-0.025	-0.028	-0.02733	363	-0.036	-0.03	-0.03	-0.0320
4/20/2003	0.0183	-0.0092	0.0102	429	-0.027	-0.026	-0.029	-0.02733	422	-0.034	-0.031	-0.031	-0.0320
6/20/2003	0.0183	-0.0091	0.0102	490	-0.027	-0.025	-0.029	-0.027	483	-0.034	-0.03	-0.031	-0.0317
8/20/2003	0.0183	-0.0092	0.0102	551	-0.027	-0.026	-0.029	-0.02733	544	-0.034	-0.031	-0.031	-0.0320
10/20/2003	0.0183	-0.0089	0.0102	612	-0.027	-0.023	-0.029	-0.02633	605	-0.034	-0.028	-0.031	-0.0310
12/20/2003	0.0182	-0.0091	0.0103	673	-0.028	-0.025	-0.028	-0.027	666	-0.035	-0.03	-0.03	-0.0317
2/20/2004	0.0183	-0.0092	0.0102	735	-0.027	-0.026	-0.029	-0.02733	728	-0.034	-0.031	-0.031	-0.0320
4/20/2004	0.0182	-0.009	0.0103	795	-0.028	-0.024	-0.028	-0.02667	788	-0.035	-0.029	-0.03	-0.0313

Appendix B (I): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 12/21 Prepared 2/24/2002

DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/25/2002	0.019	0.0698	0.0528	0	0	0	0	0	...	...	...	...	...
3/3/2002	0.0192	0.07	0.053	7	0.002	0.002	0.002	0.002	0	0	0	0	0
3/10/2002	0.0189	0.0698	0.0526	14	-0.001	0	-0.002	-0.001	7	-0.003	-0.002	-0.004	-0.003
3/18/2002	0.0183	0.0696	0.0523	22	-0.007	-0.002	-0.005	-0.00467	15	-0.009	-0.004	-0.007	-0.0067
3/24/2002	0.0182	0.069	0.052	28	-0.008	-0.008	-0.008	-0.008	21	-0.01	-0.01	-0.01	-0.01
4/1/2002	0.0181	0.0689	0.0519	36	-0.009	-0.009	-0.009	-0.009	29	-0.011	-0.011	-0.011	-0.011
4/7/2002	0.0178	0.0687	0.0517	42	-0.012	-0.011	-0.011	-0.01133	35	-0.014	-0.013	-0.013	-0.0133
4/25/2002	0.0172	0.0683	0.0514	60	-0.018	-0.015	-0.014	-0.01567	53	-0.02	-0.017	-0.016	-0.0177
5/7/2002	0.0174	0.0684	0.0512	72	-0.016	-0.014	-0.016	-0.01533	65	-0.018	-0.016	-0.018	-0.0173
5/28/2002	0.0173	0.0682	0.0511	93	-0.017	-0.016	-0.017	-0.01667	86	-0.019	-0.018	-0.019	-0.0187
6/4/2002	0.0174	0.0684	0.0513	100	-0.016	-0.014	-0.015	-0.015	93	-0.018	-0.016	-0.017	-0.0170
6/13/2002	0.0173	0.0684	0.0513	109	-0.017	-0.014	-0.015	-0.01533	102	-0.019	-0.016	-0.017	-0.0173
6/25/2002	0.0176	0.0685	0.0514	121	-0.014	-0.013	-0.014	-0.01367	114	-0.016	-0.015	-0.016	-0.0157
7/2/2002	0.0175	0.068	0.0514	128	-0.015	-0.018	-0.014	-0.01567	121	-0.017	-0.02	-0.016	-0.0177
7/9/2002	0.0175	0.068	0.0514	135	-0.015	-0.018	-0.014	-0.01567	128	-0.017	-0.02	-0.016	-0.0177
7/16/2002	0.0174	0.0678	0.0511	142	-0.016	-0.02	-0.017	-0.01767	135	-0.018	-0.022	-0.019	-0.0197
7/23/2002	0.0172	0.0677	0.0511	149	-0.018	-0.021	-0.017	-0.01867	142	-0.02	-0.023	-0.019	-0.0207
7/30/2002	0.0172	0.0678	0.051	156	-0.018	-0.02	-0.018	-0.01867	149	-0.02	-0.022	-0.02	-0.0207
8/6/2002	0.0172	0.0678	0.051	163	-0.018	-0.02	-0.018	-0.01867	156	-0.02	-0.022	-0.02	-0.0207
8/13/2002	0.0174	0.0678	0.0511	170	-0.016	-0.02	-0.017	-0.01767	163	-0.018	-0.022	-0.019	-0.0197
8/20/2002	0.0173	0.0678	0.0511	177	-0.017	-0.02	-0.017	-0.018	170	-0.019	-0.022	-0.019	-0.0200
8/27/2002	0.0172	0.0677	0.051	184	-0.018	-0.021	-0.018	-0.019	177	-0.02	-0.023	-0.02	-0.0210
9/3/2002	0.0173	0.0678	0.0512	191	-0.017	-0.02	-0.016	-0.01767	184	-0.019	-0.022	-0.018	-0.0197
9/10/2002	0.0174	0.0678	0.051	198	-0.016	-0.02	-0.018	-0.018	191	-0.018	-0.022	-0.02	-0.0200
11/3/2002	0.0174	0.0677	0.051	251	-0.016	-0.021	-0.018	-0.01833	245	-0.018	-0.023	-0.02	-0.0203
1/3/2003	0.0174	0.0677	0.051	312	-0.016	-0.021	-0.018	-0.01833	306	-0.018	-0.023	-0.02	-0.0203
3/3/2003	0.0173	0.0676	0.0509	371	-0.017	-0.022	-0.019	-0.01933	365	-0.019	-0.024	-0.021	-0.0213
5/3/2003	0.0172	0.0676	0.0507	432	-0.018	-0.022	-0.021	-0.02033	426	-0.02	-0.024	-0.023	-0.0223
7/3/2003	0.0173	0.0677	0.0509	493	-0.017	-0.021	-0.019	-0.019	487	-0.019	-0.023	-0.021	-0.0210
9/3/2003	0.0172	0.0677	0.0508	555	-0.018	-0.021	-0.02	-0.01967	549	-0.02	-0.023	-0.022	-0.0217
11/3/2003	0.0172	0.0677	0.0507	616	-0.018	-0.021	-0.021	-0.02	610	-0.02	-0.023	-0.023	-0.0220
1/3/2004	0.0173	0.0678	0.051	677	-0.017	-0.02	-0.018	-0.01833	671	-0.019	-0.022	-0.02	-0.0203
3/3/2004	0.0171	0.0677	0.0507	737	-0.019	-0.021	-0.021	-0.02033	731	-0.021	-0.023	-0.023	-0.0223

Appendix B (m): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 13/22 Prepared 2/26/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
2/27/2002	0.0582	0.0824	0.0581	0	0	0	0	0	...	...	...	...	...
3/5/2002	0.0584	0.0829	0.0578	7	0.002	0.005	-0.003	0.00133	0	0	0	0	0
3/13/2002	0.0578	0.0824	0.0573	15	-0.004	0	-0.008	-0.004	8	-0.006	-0.005	-0.005	-0.005
3/20/2002	0.0575	0.0822	0.0571	22	-0.007	-0.002	-0.01	-0.0063	15	-0.009	-0.007	-0.007	-0.0077
3/27/2002	0.0573	0.0821	0.0569	29	-0.009	-0.003	-0.012	-0.008	22	-0.011	-0.008	-0.009	-0.0093
4/2/2002	0.057	0.0819	0.0567	35	-0.012	-0.005	-0.014	-0.0103	28	-0.014	-0.01	-0.011	-0.0117
4/7/2002	0.0571	0.0819	0.0567	40	-0.011	-0.005	-0.014	-0.010	33	-0.013	-0.01	-0.011	-0.0113
4/25/2002	0.0566	0.0811	0.0561	56	-0.016	-0.013	-0.02	-0.0163	49	-0.018	-0.018	-0.017	-0.0177
5/7/2002	0.0567	0.0814	0.0563	68	-0.015	-0.01	-0.018	-0.0143	61	-0.017	-0.015	-0.015	-0.0157
5/28/2002	0.056	0.0811	0.0561	89	-0.022	-0.013	-0.02	-0.0183	82	-0.024	-0.018	-0.017	-0.0197
6/4/2002	0.0561	0.0813	0.0562	96	-0.021	-0.011	-0.019	-0.017	89	-0.023	-0.016	-0.016	-0.0183
6/12/2002	0.0561	0.0813	0.0561	104	-0.021	-0.011	-0.02	-0.0173	97	-0.023	-0.016	-0.017	-0.0187
6/25/2002	0.0563	0.0814	0.0563	117	-0.019	-0.01	-0.018	-0.0157	110	-0.021	-0.015	-0.015	-0.0170
7/2/2002	0.0564	0.0813	0.0561	124	-0.018	-0.011	-0.02	-0.0163	117	-0.02	-0.016	-0.017	-0.0177
7/9/2002	0.0564	0.0813	0.0561	131	-0.018	-0.011	-0.02	-0.0163	124	-0.02	-0.016	-0.017	-0.0177
7/16/2002	0.0562	0.0812	0.0558	138	-0.02	-0.012	-0.023	-0.0183	131	-0.022	-0.017	-0.02	-0.0197
7/23/2002	0.0563	0.0813	0.0556	145	-0.019	-0.011	-0.025	-0.0183	138	-0.021	-0.016	-0.022	-0.0197
7/30/2002	0.0562	0.0813	0.0556	152	-0.02	-0.011	-0.025	-0.0187	145	-0.022	-0.016	-0.022	-0.0200
8/6/2002	0.0561	0.0814	0.0557	159	-0.021	-0.01	-0.024	-0.0183	152	-0.023	-0.015	-0.021	-0.0197
8/13/2002	0.0562	0.0815	0.056	166	-0.02	-0.009	-0.021	-0.0167	159	-0.022	-0.014	-0.018	-0.0180
8/20/2002	0.0562	0.0815	0.0558	173	-0.02	-0.009	-0.023	-0.0173	166	-0.022	-0.014	-0.02	-0.0187
8/27/2002	0.0559	0.0813	0.0558	180	-0.023	-0.011	-0.023	-0.0190	173	-0.025	-0.016	-0.02	-0.0203
9/3/2002	0.0561	0.0813	0.0561	187	-0.021	-0.011	-0.02	-0.0173	180	-0.023	-0.016	-0.017	-0.0187
9/10/2002	0.0561	0.0814	0.0559	194	-0.021	-0.01	-0.022	-0.0177	187	-0.023	-0.015	-0.019	-0.0190
11/3/2002	0.056	0.0813	0.0558	249	-0.022	-0.011	-0.023	-0.0187	243	-0.024	-0.016	-0.02	-0.0200
1/3/2003	0.056	0.0812	0.0556	310	-0.022	-0.012	-0.025	-0.0197	304	-0.024	-0.017	-0.022	-0.0210
3/3/2003	0.0559	0.0812	0.0557	369	-0.023	-0.012	-0.024	-0.0197	363	-0.025	-0.017	-0.021	-0.0210
5/3/2003	0.0559	0.0811	0.0556	430	-0.023	-0.013	-0.025	-0.0203	424	-0.025	-0.018	-0.022	-0.0217
7/3/2003	0.0559	0.0812	0.0556	491	-0.023	-0.012	-0.025	-0.0200	485	-0.025	-0.017	-0.022	-0.0213
9/3/2003	0.056	0.0814	0.0559	553	-0.022	-0.01	-0.022	-0.0180	547	-0.024	-0.015	-0.019	-0.0193
11/3/2003	0.056	0.0813	0.0556	614	-0.022	-0.011	-0.025	-0.0193	608	-0.024	-0.016	-0.022	-0.0207
1/3/2004	0.0563	0.0812	0.0556	675	-0.019	-0.012	-0.025	-0.0187	669	-0.021	-0.017	-0.022	-0.0200
3/3/2004	0.0562	0.0811	0.0555	735	-0.02	-0.013	-0.026	-0.0197	729	-0.022	-0.018	-0.023	-0.0210

Appendix B (n): Shrinkage Data for Concrete Mixes Containing SRA

Mix #14/24 Prepared 3/9/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
3/10/2002	0.0768	0.0268	0.0424	0	0	0	0	0	...	...	...	...	...
3/16/2002	0.0772	0.0269	0.0426	7	0.004	0.001	0.002	0.0023	0	0	0	0	0
3/23/2002	0.0763	0.026	0.0416	14	-0.005	-0.008	-0.008	-0.0070	7	-0.009	-0.009	-0.01	-0.0093
4/1/2002	0.0761	0.0257	0.0413	23	-0.007	-0.011	-0.011	-0.0097	16	-0.011	-0.012	-0.013	-0.012
4/7/2002	0.0758	0.0255	0.0412	29	-0.01	-0.013	-0.012	-0.0117	22	-0.014	-0.014	-0.014	-0.014
4/25/2002	0.0753	0.0252	0.0408	45	-0.015	-0.016	-0.016	-0.01567	38	-0.019	-0.017	-0.018	-0.018
5/3/2002	0.0746	0.0242	0.0406	53	-0.022	-0.026	-0.018	-0.0220	46	-0.026	-0.027	-0.02	-0.0243
5/28/2002	0.0748	0.0245	0.0402	78	-0.02	-0.023	-0.022	-0.0217	71	-0.024	-0.024	-0.024	-0.024
6/4/2002	0.075	0.0246	0.0401	85	-0.018	-0.022	-0.023	-0.0210	78	-0.022	-0.023	-0.025	-0.0233
6/12/2002	0.0749	0.0249	0.0404	93	-0.019	-0.019	-0.02	-0.0193	86	-0.023	-0.02	-0.022	-0.0217
6/25/2002	0.0752	0.0248	0.0404	106	-0.016	-0.02	-0.02	-0.0187	99	-0.02	-0.021	-0.022	-0.0210
7/2/2002	0.075	0.0247	0.0403	113	-0.018	-0.021	-0.021	-0.0200	106	-0.022	-0.022	-0.023	-0.0223
7/9/2002	0.0751	0.0247	0.0404	120	-0.017	-0.021	-0.02	-0.0193	113	-0.021	-0.022	-0.022	-0.0217
7/16/2002	0.075	0.0245	0.0401	127	-0.018	-0.023	-0.023	-0.0213	120	-0.022	-0.024	-0.025	-0.0237
7/23/2002	0.0748	0.0244	0.0402	134	-0.02	-0.024	-0.022	-0.0220	127	-0.024	-0.025	-0.024	-0.0243
7/30/2002	0.0748	0.0245	0.0402	141	-0.02	-0.023	-0.022	-0.0217	134	-0.024	-0.024	-0.024	-0.0240
8/6/2002	0.0748	0.0245	0.0402	148	-0.02	-0.023	-0.022	-0.0217	141	-0.024	-0.024	-0.024	-0.0240
8/13/2002	0.0748	0.0246	0.0402	155	-0.02	-0.022	-0.022	-0.0213	148	-0.024	-0.023	-0.024	-0.0237
8/20/2002	0.0749	0.0245	0.0402	162	-0.019	-0.023	-0.022	-0.0213	155	-0.023	-0.024	-0.024	-0.0237
8/27/2002	0.0747	0.0244	0.04	169	-0.021	-0.024	-0.024	-0.0230	162	-0.025	-0.025	-0.026	-0.0253
9/3/2002	0.0749	0.0245	0.0403	176	-0.019	-0.023	-0.021	-0.0210	169	-0.023	-0.024	-0.023	-0.0233
9/10/2002	0.0749	0.0245	0.0401	183	-0.019	-0.023	-0.023	-0.0217	176	-0.023	-0.024	-0.025	-0.0240
9/17/2002	0.0749	0.0245	0.0402	190	-0.019	-0.023	-0.022	-0.0213	183	-0.023	-0.024	-0.024	-0.0237
11/10/2002	0.0748	0.0244	0.0402	245	-0.02	-0.024	-0.022	-0.0220	239	-0.024	-0.025	-0.024	-0.0243
1/10/2003	0.0748	0.0244	0.0401	306	-0.02	-0.024	-0.023	-0.0223	300	-0.024	-0.025	-0.025	-0.0247
3/10/2003	0.0748	0.0242	0.0401	365	-0.02	-0.026	-0.023	-0.0230	359	-0.024	-0.027	-0.025	-0.0253
5/10/2003	0.0748	0.0242	0.04	426	-0.02	-0.026	-0.024	-0.0233	420	-0.024	-0.027	-0.026	-0.0257
7/10/2003	0.0748	0.0242	0.04	487	-0.02	-0.026	-0.024	-0.0233	481	-0.024	-0.027	-0.026	-0.0257
9/10/2003	0.0749	0.0245	0.0402	549	-0.019	-0.023	-0.022	-0.0213	543	-0.023	-0.024	-0.024	-0.0237
11/10/2003	0.0749	0.0245	0.0401	610	-0.019	-0.023	-0.023	-0.0217	604	-0.023	-0.024	-0.025	-0.0240
1/10/2004	0.0748	0.0242	0.04	671	-0.02	-0.026	-0.024	-0.0233	665	-0.024	-0.027	-0.026	-0.0257
3/10/2004	0.0748	0.0245	0.0402	731	-0.02	-0.023	-0.022	-0.0217	725	-0.024	-0.024	-0.024	-0.0240

Appendix B (o): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 15/28 Prepared 3/12/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
3/13/2002	0.0709	0.063	0.0844	0	0	0	0	0	...	...	...	...	...
3/20/2002	0.0703	0.0625	0.0843	8	-0.006	-0.005	-0.001	-0.004	0	0	0	0	0
3/27/2002	0.0699	0.0621	0.0836	15	-0.01	-0.009	-0.008	-0.009	7	-0.004	-0.004	-0.007	-0.005
4/2/2002	0.0697	0.0619	0.0833	21	-0.012	-0.011	-0.011	-0.01133	13	-0.006	-0.006	-0.01	-0.0073
4/7/2002	0.0693	0.0616	0.0832	26	-0.016	-0.014	-0.012	-0.014	18	-0.01	-0.009	-0.011	-0.01
4/16/2002	0.0695	0.0618	0.0833	35	-0.014	-0.012	-0.011	-0.01233	27	-0.008	-0.007	-0.01	-0.0083
4/25/2002	0.069	0.0615	0.0831	44	-0.019	-0.015	-0.013	-0.01567	36	-0.013	-0.01	-0.012	-0.0117
5/7/2002	0.0687	0.0611	0.0825	56	-0.022	-0.019	-0.019	-0.02	48	-0.016	-0.014	-0.018	-0.016
5/28/2002	0.0687	0.061	0.0823	75	-0.022	-0.02	-0.021	-0.021	69	-0.016	-0.015	-0.02	-0.017
6/4/2002	0.0687	0.061	0.0823	82	-0.022	-0.02	-0.021	-0.021	76	-0.016	-0.016	-0.019	-0.017
6/12/2002	0.0687	0.061	0.0823	90	-0.022	-0.02	-0.021	-0.021	84	-0.016	-0.016	-0.019	-0.017
6/25/2002	0.0686	0.0609	0.0824	103	-0.023	-0.021	-0.02	-0.02133	97	-0.017	-0.016	-0.019	-0.01733
7/2/2002	0.0686	0.0609	0.0824	110	-0.023	-0.021	-0.02	-0.02133	104	-0.017	-0.016	-0.019	-0.01733
7/9/2002	0.0684	0.0608	0.0824	117	-0.025	-0.022	-0.02	-0.02233	111	-0.019	-0.017	-0.019	-0.01833
7/16/2002	0.0682	0.0606	0.0822	124	-0.027	-0.024	-0.022	-0.02433	118	-0.021	-0.019	-0.021	-0.02033
7/23/2002	0.0684	0.0605	0.0821	131	-0.025	-0.025	-0.023	-0.02433	125	-0.019	-0.02	-0.022	-0.02033
7/30/2002	0.0684	0.0607	0.0822	138	-0.025	-0.023	-0.022	-0.02333	132	-0.019	-0.018	-0.021	-0.01933
8/6/2002	0.0683	0.0608	0.0822	145	-0.026	-0.022	-0.022	-0.02333	139	-0.02	-0.017	-0.021	-0.01933
8/13/2002	0.0683	0.0607	0.0822	152	-0.026	-0.023	-0.022	-0.02367	146	-0.02	-0.018	-0.021	-0.01967
8/20/2002	0.0684	0.0607	0.0822	159	-0.025	-0.023	-0.022	-0.02333	153	-0.019	-0.018	-0.021	-0.01933
8/27/2002	0.0682	0.0606	0.0821	166	-0.027	-0.024	-0.023	-0.02467	160	-0.021	-0.019	-0.022	-0.02067
9/3/2002	0.0683	0.0607	0.0822	173	-0.026	-0.023	-0.022	-0.02367	167	-0.02	-0.018	-0.021	-0.01967
9/10/2002	0.0684	0.0606	0.0822	180	-0.025	-0.024	-0.022	-0.02367	174	-0.019	-0.019	-0.021	-0.01967
9/17/2002	0.0684	0.0607	0.0823	187	-0.025	-0.023	-0.021	-0.023	181	-0.019	-0.018	-0.02	-0.019
11/17/2002	0.0683	0.0606	0.0822	249	-0.026	-0.024	-0.022	-0.024	242	-0.02	-0.019	-0.021	-0.02
1/17/2003	0.0682	0.0605	0.0822	310	-0.027	-0.025	-0.022	-0.02467	303	-0.021	-0.02	-0.021	-0.02067
3/17/2003	0.0682	0.0605	0.082	369	-0.027	-0.025	-0.024	-0.02533	362	-0.021	-0.02	-0.023	-0.02133
5/17/2003	0.068	0.0604	0.082	430	-0.029	-0.026	-0.024	-0.02633	423	-0.023	-0.021	-0.023	-0.02233
7/17/2003	0.0684	0.0607	0.0822	491	-0.025	-0.023	-0.022	-0.02333	484	-0.019	-0.018	-0.021	-0.01933
9/17/2003	0.068	0.0604	0.082	553	-0.029	-0.026	-0.024	-0.02633	546	-0.023	-0.021	-0.023	-0.02233
11/17/2003	0.0682	0.0606	0.0821	614	-0.027	-0.024	-0.023	-0.02467	607	-0.021	-0.019	-0.022	-0.02067
1/17/2004	0.0684	0.0607	0.0823	675	-0.025	-0.023	-0.021	-0.023	668	-0.019	-0.018	-0.02	-0.019
3/17/2004	0.0683	0.0606	0.0822	735	-0.026	-0.024	-0.022	-0.024	728	-0.02	-0.019	-0.021	-0.02

Appendix B (p): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 16/29 Prepared 3/10/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
3/11/2002	0.0272	0.0463	0.0357	0	0	0	0	0	...	...	...	...	...
3/18/2002	0.0286	0.047	0.0364	8	0.014	0.007	0.007	0.0093	0	0	0	0	0
3/24/2002	0.0283	0.0463	0.0361	14	0.011	0	0.004	0.0050	6	-0.003	-0.007	-0.003	-0.0043
4/1/2002	0.0281	0.0459	0.0356	22	0.009	-0.004	-0.001	0.0013	14	-0.005	-0.011	-0.008	-0.008
4/7/2002	0.0276	0.0456	0.0349	28	0.004	-0.007	-0.008	-0.0037	20	-0.01	-0.014	-0.015	-0.013
4/16/2002	0.0278	0.0457	0.0352	37	0.006	-0.006	-0.005	-0.00167	29	-0.008	-0.013	-0.012	-0.011
4/25/2002	0.0275	0.0455	0.0348	46	0.003	-0.008	-0.009	-0.0047	38	-0.011	-0.015	-0.016	-0.014
5/3/2002	0.0277	0.0456	0.0347	54	0.005	-0.007	-0.01	-0.0040	46	-0.009	-0.014	-0.017	-0.0133
5/28/2002	0.0271	0.045	0.0344	79	-0.001	-0.013	-0.013	-0.0090	71	-0.015	-0.02	-0.02	-0.0183
6/4/2002	0.0272	0.0452	0.0345	86	0	-0.011	-0.012	-0.0077	77	-0.014	-0.018	-0.019	-0.0170
6/12/2002	0.0269	0.0448	0.0342	94	-0.003	-0.015	-0.015	-0.0110	85	-0.017	-0.022	-0.022	-0.0203
6/25/2002	0.0272	0.0451	0.0344	107	0	-0.012	-0.013	-0.0083	98	-0.014	-0.019	-0.02	-0.0177
7/2/2002	0.0271	0.0452	0.0344	114	-0.001	-0.011	-0.013	-0.0083	105	-0.015	-0.018	-0.02	-0.0177
7/9/2002	0.0271	0.045	0.0343	121	-0.001	-0.013	-0.014	-0.0093	112	-0.015	-0.02	-0.021	-0.0187
7/16/2002	0.0269	0.0447	0.0341	128	-0.003	-0.016	-0.016	-0.0117	119	-0.017	-0.023	-0.023	-0.0210
7/23/2002	0.0268	0.0447	0.0341	135	-0.004	-0.016	-0.016	-0.0120	126	-0.018	-0.023	-0.023	-0.0213
7/30/2002	0.0269	0.0448	0.0342	142	-0.003	-0.015	-0.015	-0.0110	133	-0.017	-0.022	-0.022	-0.0203
8/6/2002	0.027	0.0448	0.0341	149	-0.002	-0.015	-0.016	-0.0110	140	-0.016	-0.022	-0.023	-0.0203
8/13/2002	0.0271	0.0449	0.0343	156	-0.001	-0.014	-0.014	-0.0097	147	-0.015	-0.021	-0.021	-0.0190
8/20/2002	0.0269	0.0448	0.0341	163	-0.003	-0.015	-0.016	-0.0113	154	-0.017	-0.022	-0.023	-0.0207
8/27/2002	0.0269	0.0447	0.034	170	-0.003	-0.016	-0.017	-0.0120	163	-0.017	-0.023	-0.024	-0.0213
9/3/2002	0.0271	0.0449	0.0343	177	-0.001	-0.014	-0.014	-0.0097	170	-0.015	-0.021	-0.021	-0.0190
9/10/2002	0.0271	0.0448	0.0342	184	-0.001	-0.015	-0.015	-0.0103	177	-0.015	-0.022	-0.022	-0.0197
9/17/2002	0.0271	0.0449	0.0342	191	-0.001	-0.014	-0.015	-0.0100	184	-0.015	-0.021	-0.022	-0.0193
11/17/2002	0.0269	0.0448	0.0343	251	-0.003	-0.015	-0.014	-0.0107	244	-0.017	-0.022	-0.021	-0.0200
1/17/2003	0.0266	0.0446	0.0342	312	-0.006	-0.017	-0.015	-0.0127	305	-0.02	-0.024	-0.022	-0.0220
3/17/2003	0.0266	0.0446	0.0341	371	-0.006	-0.017	-0.016	-0.0130	364	-0.02	-0.024	-0.023	-0.0223
5/17/2003	0.0264	0.0445	0.0341	432	-0.008	-0.018	-0.016	-0.0140	425	-0.022	-0.025	-0.023	-0.0233
7/17/2003	0.0271	0.0449	0.0342	493	-0.001	-0.014	-0.015	-0.0100	486	-0.015	-0.021	-0.022	-0.0193
9/17/2003	0.0266	0.0446	0.0342	555	-0.006	-0.017	-0.015	-0.0127	548	-0.02	-0.024	-0.022	-0.0220
11/17/2003	0.0271	0.0448	0.0342	616	-0.001	-0.015	-0.015	-0.0103	609	-0.015	-0.022	-0.022	-0.0197
1/17/2004	0.0264	0.0445	0.0341	677	-0.008	-0.018	-0.016	-0.0140	670	-0.022	-0.025	-0.023	-0.0233
3/17/2004	0.0271	0.0449	0.0342	737	-0.001	-0.014	-0.015	-0.0100	730	-0.015	-0.021	-0.022	-0.0193

Appendix B (q): Shrinkage Data for Concrete Mixes Containing SRA

Mix # 17/30 Prepared 3/3/2002													
DATE	Readings			Shrinkage [%]					Shrinkage after curing in water [%]				
	BAR #1	BAR #2	BAR #3	Age t [Days]	BAR #1	BAR #2	BAR #3	Average	Age t-t _c [Days]	BAR #1	BAR #2	BAR #3	Average
3/4/2002	0.042	0.0342	0.1336	0	0	0	0	0	...	...	...	...	...
3/10/2002	0.0427	0.035	0.1352	7	0.007	0.008	0.016	0.0103	0	0	0	0	0
3/18/2002	0.0424	0.0345	0.1348	15	0.004	0.003	0.012	0.0063	8	-0.003	-0.005	-0.004	-0.004
3/24/2002	0.042	0.034	0.1344	21	0	-0.002	0.008	0.0020	14	-0.007	-0.01	-0.008	-0.0083
4/1/2002	0.0419	0.034	0.1342	29	-0.001	-0.002	0.006	0.0010	22	-0.008	-0.01	-0.01	-0.0093
4/7/2002	0.0416	0.0338	0.1337	35	-0.004	-0.004	0.001	-0.00233	28	-0.011	-0.012	-0.015	-0.0127
4/25/2002	0.0411	0.0332	0.1332	53	-0.009	-0.01	-0.004	-0.0077	46	-0.016	-0.018	-0.02	-0.018
5/7/2002	0.041	0.0331	0.1332	65	-0.01	-0.011	-0.004	-0.0083	58	-0.017	-0.019	-0.02	-0.0187
5/28/2002	0.0407	0.0328	0.133	86	-0.013	-0.014	-0.006	-0.0110	79	-0.02	-0.022	-0.022	-0.0213
6/4/2002	0.0409	0.0329	0.133	93	-0.011	-0.013	-0.006	-0.0100	86	-0.018	-0.021	-0.022	-0.0203
6/25/2002	0.0409	0.033	0.1333	114	-0.011	-0.012	-0.003	-0.0087	107	-0.018	-0.02	-0.019	-0.0190
7/2/2002	0.0407	0.0329	0.1332	121	-0.013	-0.013	-0.004	-0.0100	114	-0.02	-0.021	-0.02	-0.0203
7/9/2002	0.0407	0.0329	0.1332	128	-0.013	-0.013	-0.004	-0.0100	121	-0.02	-0.021	-0.02	-0.0203
7/16/2002	0.0405	0.0327	0.133	135	-0.015	-0.015	-0.006	-0.0120	128	-0.022	-0.023	-0.022	-0.0223
7/23/2002	0.0403	0.0325	0.1329	142	-0.017	-0.017	-0.007	-0.0137	135	-0.024	-0.025	-0.023	-0.0240
7/30/2002	0.0404	0.0326	0.133	149	-0.016	-0.016	-0.006	-0.0127	142	-0.023	-0.024	-0.022	-0.0230
8/6/2002	0.0404	0.0327	0.133	156	-0.016	-0.015	-0.006	-0.0123	149	-0.023	-0.023	-0.022	-0.0227
8/13/2002	0.0406	0.0327	0.1331	163	-0.014	-0.015	-0.005	-0.0113	156	-0.021	-0.023	-0.021	-0.0217
8/20/2002	0.0405	0.0327	0.1331	170	-0.015	-0.015	-0.005	-0.0117	163	-0.022	-0.023	-0.021	-0.0220
8/27/2002	0.0403	0.0326	0.133	177	-0.017	-0.016	-0.006	-0.0130	170	-0.024	-0.024	-0.022	-0.0233
9/3/2002	0.0406	0.0327	0.1332	184	-0.014	-0.015	-0.004	-0.0110	177	-0.021	-0.023	-0.02	-0.0213
9/10/2002	0.0405	0.0328	0.1331	191	-0.015	-0.014	-0.005	-0.0113	184	-0.022	-0.022	-0.021	-0.0217
11/10/2002	0.0405	0.0326	0.133	251	-0.015	-0.016	-0.006	-0.0123	245	-0.022	-0.024	-0.022	-0.0227
1/10/2003	0.0405	0.0326	0.133	312	-0.015	-0.016	-0.006	-0.0123	306	-0.022	-0.024	-0.022	-0.0227
3/10/2003	0.0403	0.0324	0.1329	371	-0.017	-0.018	-0.007	-0.0140	365	-0.024	-0.026	-0.023	-0.0243
5/10/2003	0.0403	0.0324	0.1327	432	-0.017	-0.018	-0.009	-0.0147	426	-0.024	-0.026	-0.025	-0.0250
7/10/2003	0.0405	0.0328	0.1331	493	-0.015	-0.014	-0.005	-0.0113	487	-0.022	-0.022	-0.021	-0.0217
9/10/2003	0.0405	0.0326	0.133	555	-0.015	-0.016	-0.006	-0.0123	549	-0.022	-0.024	-0.022	-0.0227
11/10/2003	0.0405	0.0326	0.133	616	-0.015	-0.016	-0.006	-0.0123	610	-0.022	-0.024	-0.022	-0.0227
1/10/2004	0.0403	0.0324	0.1327	677	-0.017	-0.018	-0.009	-0.0147	671	-0.024	-0.026	-0.025	-0.0250
3/10/2004	0.0405	0.0326	0.133	737	-0.015	-0.016	-0.006	-0.0123	731	-0.022	-0.024	-0.022	-0.0227

Appendix C – Statistical Methods

C.1. Average and Standard Deviation of Residuals

This statistical method is based on the following equations:

$$A_j = \frac{\sum_{i=1}^n X_i}{n} \quad (C.1-1)$$

$$S_j = \sqrt{\frac{n \sum_{i=1}^n X_i^2 - \left(\sum_{i=1}^n X_i \right)^2}{n(n-1)}} \quad (C.1-2)$$

Where,

A_j = Average of residuals for fixed time, j

X_i = Residual value of i^{th} data point in a fixed time, j

n = Total number of data points considered at a fixed time

S_j = Standard deviation of residuals for fixed time j

C.2. The CEB Coefficient of Variation Method

The equations utilized in this method are:

$$Y_i = \frac{\sum_{j=1}^n Y_{ij}}{n} \quad (\text{C.2-1})$$

$$S_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (\Delta Y_{ij})^2} \quad (\text{C.2-2})$$

$$V_i = \frac{S_i}{Y_i} \times 100 \quad (\text{C.2-3})$$

$$V_{CEB} = \sqrt{\frac{1}{N} \sum_{i=1}^N V_i^2} \quad (\text{C.2-4})$$

Where,

n = Number of data points taken

N = Total number of data sets considered

S_i = Standard error determined from ΔY_{ij} for experiment i

V_i = Coefficient of variation of experiment i

V_{CEB} = Mean coefficient of variation

Y_i = Mean shrinkage strain of experiment i

Y_{ij} = Observed shrinkage strain at time j of experiment i

ΔY_{ij} = Difference between measured and predicted shrinkage strains at time j of experiment i

C.3. The CEB Mean Square Error Method

Equations used in this analysis are given below

$$f_j = \frac{CalX_{ij} - ObsX_{ij}}{ObsX_{ij}} \times 100 \quad (C.3-1)$$

$$F_i = \sqrt{\frac{1}{n-1} \sum_{j=1}^n f_j^2} \quad (C.3-2)$$

$$F_{CEB} = \sqrt{\frac{1}{N} \sum_{i=1}^N F_i^2} \quad (C.3-3)$$

Where,

$CalX_{ij}$ = Predicted shrinkage strain at time j of experiment i

$ObsX_{ij}$ = Experimental shrinkage strain at time j of experiment i

f_j = Percent difference between calculated and observed data point j

F_{CEB} = Mean square error

n = Total number of values j of experiment i considered at a fixed time

N = Total number of data sets considered

C.4. The CEB Mean Deviation Method

Equations used in this method are:

$$M_i = \frac{1}{n} \sum_{j=1}^n \frac{CalX_{ij}}{ObsX_{ij}} \quad (C.4-1)$$

$$M_{CEB} = \frac{\sum_{i=1}^N M_i}{N} \quad (C.4-2)$$

Where,

$CalX_{ij}$ = Predicted shrinkage strain at time j of experiment i

$ObsX_{ij}$ = Experimental shrinkage strains at time j of experiment i

M_i = Deviation between predicted and experimental values of experiment I

M_{CEB} = Mean deviation

n = Total number of values j of experiment i considered at a fixed time

N = Total number of data sets considered

Appendix D - Examples of Shrinkage Strain Calculation Using the GL 2000, ALSN 2004, and CEB-FIP MC 90-99 Models

Example D.1. Calculate shrinkage strain of concrete mix # 4/11 at 103 days from the beginning of drying. Use the GL 2000, ALSN 2004 and CEB-FIP MC 90-99 prediction models.

Given factors:

Humidity = 55 %

$V/S = A_c/u = 19.05$ mm

$f_{cm28} = 61.9$ MPa

$t - t_c = 103$ days

$t_c = 7$ days

Cement type II

Water cured concrete

SRA = 0.5%

Measured value of shrinkage strain at 103 days from the beginning of drying (i.e., $t - t_c$) is 263×10^{-6} mm/mm.

Solution

The GL 2000 Model Solution:

$$\varepsilon_s(t) = \varepsilon_{shu}(h) \beta(t)$$

Calculation of ε_{shu} :

$K = 0.75$ (Table A.1.)

$$\varepsilon_{shu} = -(900)K\left(\frac{30}{f_{cm28}}\right)^{1/2} \times 10^{-6} = -(900)(0.75)\left(\frac{30}{61.9}\right)^{1/2} \times 10^{-6} = -469.9 \times 10^{-6} \text{ mm/mm}$$

Calculation of $\beta(h)$:

$$\beta(h) = 1 - 1.18\left(\frac{H}{100}\right)^4 = 1 - 1.18\left(\frac{55}{100}\right)^4 = 0.892$$

Calculation of $\beta(t)$:

$$\beta(t) = \left(\frac{t - t_c}{t - t_c + 0.12(V/S)^2}\right)^{1/2} = \left(\frac{103}{103 + 0.12(19.05)^2}\right)^{1/2} = 0.838$$

Predicted value of shrinkage strain is:

$$\varepsilon_s(t) = \varepsilon_{shu}\beta(h)\beta(t) = (-469.9 \times 10^{-6})(0.892)(0.838) = -351 \times 10^{-6} \text{ mm/mm}$$

Deviation from the measured value:

Deviation = Measured- Predicted =

$$(-263 \times 10^{-6}) - (-351 \times 10^{-6}) = 88 \times 10^{-6} = 88 \text{ microstrains}$$

The ALSN 2004 Model Solution:

The value of $\varepsilon_s(t)$ calculated using the GL 2000 model is:

$$\varepsilon_s(t) = 263 \times 10^{-6} = 351 \times 10^{-6} \text{ mm/mm}$$

The effect of SRA on concrete shrinkage is determined as follows:

$$\beta(SRA) = \frac{2}{2 + (SRA)^{0.7}} = \frac{2}{2 + (0.5)^{0.7}} = 0.765$$

Predicted value of shrinkage strain is:

$$\varepsilon_s(t) = (351 \times 10^{-6}) \times 0.765 = 269 \times 10^{-6} \text{ mm/mm}$$

Deviation from the measured value:

Deviation = Measured- Predicted =

$$(-263 \times 10^{-6}) - (-269 \times 10^{-6}) = 6 \times 10^{-6} = 6 \text{ microstrains}$$

The CEB-FIP MC 90-99 Model Solution:

$$\varepsilon_s(t, t_c) = \varepsilon_{as}(t) + \varepsilon_{ds}(t, t_c)$$

$$\alpha_{as} = 800$$

$$\alpha_{ds1} = 3$$

$$\alpha_{ds2} = 0.13$$

$$h_e = \frac{2A_c}{u} = \frac{2V}{S} = 38.1 \text{ mm}$$

Calculation of $\varepsilon_{as}(t)$:

$$\varepsilon_{as0}(f_{cm28}) = -\alpha_{as} \left(\frac{f_{cm28}/10}{6 + f_{cm28}/10} \right)^{2.5} \times 10^{-6} = -800 \times \left(\frac{61.9/10}{6 + 61.9/10} \right)^{2.5} \times 10^{-6} = -147 \times 10^{-6} \text{ mm/mm}$$

$$\beta_{as}(t) = 1 - \exp[-0.2(t)^{0.5}] = 1 - \exp[-0.2(110)^{0.5}] = 0.88$$

$$\varepsilon_{as}(t) = \varepsilon_{as0}(f_{cm28}) \beta_{as}(t) = (-147 \times 10^{-6}) \times 0.88 = -129 \times 10^{-6} \text{ mm/mm}$$

Calculation of $\varepsilon_{ds}(t, t_c)$:

$$\varepsilon_{ds0}(f_{cm28}) = [(220 + 110\alpha_{ds1}) \exp(-\alpha_{ds2} f_{cm28}/10)] \times 10^{-6} =$$

$$[(220 + 110 \times 3) \exp(-0.13 \times 61.9/10)] \times 10^{-6} = 246 \times 10^{-6} \text{ mm/mm}$$

$$\beta_{s1} = \left(\frac{35}{f_{cm28}} \right)^{0.1} = \left(\frac{35}{61.9} \right)^{0.1} = 0.945 < 1$$

$$40\% \leq 55\% < 99\% \times \beta_{s1} = 99\% \times 0.945 = 93.5\%$$

Therefore,

$$\beta_{RH} = -1.55 \left[1 - \left(\frac{H}{100} \right)^3 \right] = -1.55 \left[1 - \left(\frac{55}{100} \right)^3 \right] = -1.292$$

$$\beta_{ds}(t - t_c) = \left(\frac{(t - t_c)}{0.56(h_e/4)^2 + (t - t_c)} \right)^{0.5} = \left(\frac{103}{0.56(38.1/4)^2 + 103} \right)^{0.5} = 0.818$$

$$\varepsilon_{ds}(t, t_c) = \varepsilon_{ds0}(f_{cm28}) \beta_{RH}(H) \beta_{ds}(t - t_c) = (246 \times 10^{-6}) \times (-1.292) \times (0.818) = -260 \times 10^{-6} \text{ mm/mm}$$

Predicted value of shrinkage strain is:

$$\varepsilon_s(t, t_c) = \varepsilon_{as}(t) + \varepsilon_{ds}(t, t_c) = (260 + 129) \times 10^{-6} = 389 \times 10^{-6} \text{ mm/mm}$$

Deviation from the measured value:

Deviation = Measured- Predicted =

$$(-263 \times 10^{-6}) - (-389 \times 10^{-6}) = 126 \times 10^{-6} = 126 \text{ microstrains}$$