FINAL CONTRACT REPORT

EVAULATION OF MODELS FOR PREDICTING (TOTAL) CREEP OF PRESTRESSED CONCRETE MIXTURES

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ABSTRACT

Concrete experiences volume changes throughout its service life. When loaded, concrete experiences an instantaneous recoverable elastic deformation and a slow inelastic deformation called creep. Creep of concrete is composed of two components, basic creep, or deformation under load without moisture loss and drying creep, or deformation under drying conditions only. Deformation of concrete in the absence of applied load is often called shrinkage.

The deformation due to creep is attributed to the movement of water between the different phases of the concrete. When an external load is applied, it changes the attraction forces between the cement gel particles. This change in the forces causes an imbalance in the attractive and disjoining forces. However, the imbalance is gradually eliminated by the transfer of moisture into the pores in cases of compression, and away from the pores in cases of tension.

Designs typically use one of the two code models to estimate creep and shrinkage strain in concrete, ACI 209 model recommended by the American Concrete Institute or the CEB 90 Eurocode 2 model recommended by the Euro-International Committee. The AASHTO LRFD is based on the ACI 209 model. Three other models are the B3 model, developed by Bazant; the GZ model, developed by Gardner; and the SAK model developed by Sakata.

The objectives of this research was the development of performance limits for compressive creep of concrete mixtures used by the Virginia Department of Transportation, specifically concrete mixtures used for prestressed members (A-5 Concrete) and the determination the accuracy and precision of the creep models presented in the literature.

The CEB 90 Eurocode 2 model for creep and shrinkage is the most precise and accurate predictor. The total creep strain for the VDOT portland cement concrete mixtures discussed in this study were found to be between 1200 ± 110 microstrain at 28 days, and 1600 ± 110 microstrain at 97 days, at a five percent significant level. It is recommended that the CEB 90 model be used in the AASHTO LRFD rather than the ACI 209 model to improve the prediction of prestress loss.

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INTRODUCTION

Concrete experiences volume changes throughout its service life. The total in-service volume change of concrete is the resultant of applied loads and shrinkage. When loaded, concrete experiences an instantaneous recoverable elastic deformation and a slow inelastic deformation. This inelastic deformation, creep, is the concrete property that controls its long-term response when subjected to loads in service, and thus is an important factor in the performance of structural members (Mehta, 1986). Depending on the situation, creep can impart a positive or negative response in the concrete. For example, concrete with sufficient creep can deform in response to long-term tensile stresses resulting from drying and thus avoid cracking. Of more importance for structural concretes, however, is the response of prestressed concrete. Prestressing subjects the concrete member to compressive loads forming the basis for its structural integrity. Excessive creep deformation in prestressed concrete causes a loss in compressive load that reduces the load-carrying capacity of the member. Consequently, creep estimates are necessary when designing prestressed concrete members. Improvements in creep prediction in concert with creep performance limits will allow VDOT to more efficiently design and build structural elements that are less susceptible to cracking or deformation under load, resulting in a longer service life.

Creep of concrete is composed of two components, basic creep, or deformation under load without moisture loss and drying creep, or deformation under drying conditions only. Deformation of concrete in the absence of applied load is often called shrinkage. Creep testing of concrete may be performed on sealed specimens or unsealed specimens. The deformation of sealed-loaded specimens is the result of elastic deformation, water movement from the gel pores to the capillary pores, and autogeneous shrinkage.

The deformation of unsealed-loaded specimens is the result of internal moisture movement, moisture loss, autogeneous shrinkage, and carbonation shrinkage; whereas the deformation of unsealed-unloaded concrete, referred to as drying shrinkage, is the result of moisture loss, autogeneous shrinkage, and carbonation shrinkage. Thus, the difference in deformations between loaded specimens, minus the elastic deformation, and unloaded specimens, is basic creep, which is the resultant of internal moisture movement.

Creep coefficient, specific creep, or creep compliance are generally used to describe creep strain in various mathematical prediction models. The creep coefficient is defined as the ratio of creep strain (basic plus drying creep) at a given time to the initial elastic strain. The specific creep is defined as the creep strain per unit stress. The creep compliance is defined as the creep strain plus elastic strain per unit stress, whereas the elastic strain is defined as the instantaneous recoverable deformation per unit length of a concrete specimen during the initial stage of loading.

Creep of concrete is normally evaluated using unsealed loaded and unloaded companion specimens exposed at a constant drying environment. Thus, the total deformation may be separated into elastic compression, basic creep, and drying creep (moisture loss, autogeneous and carbonation shrinkage). The deformation due to creep is attributed to the movement of water between the different phases of the concrete caused by drying and load stresses. When an external load is applied, it changes the attractive forces between the cement gel particles. This change in the forces causes an imbalance in the attractive and disjoining forces. However, the imbalance is gradually eliminated (basic creep) by the transfer of moisture into the pores in cases of compression, and away from the pores in cases of tension.

Designs typically use one of the two code models to estimate creep and shrinkage strain in concrete, ACI 209 model recommended by the American Concrete Institute or the Eurocode 2 model recommended by the Euro-International Committee. The AASHTO LRFD is based on the ACI 209 model. These models, as well as three others, the B3 model, developed by Bazant; the GZ model, developed by Gardner; and the SAK model, developed by Sakata (Lakshanikantan, 1999) are evaluated in this study for their ability to predict the creep of concretes complying with Virginia Department of Transportation (VDOT) specifications for use in prestressed members.

LLITERATURE REVIEW

Factors that contribute to the dimensional changes include mixture composition, curing conditions, ambient exposure conditions, and element geometry. The following summarizes these influences. See Meyerson (2001) for a more complete evaluation.

Generally, concretes that have aggregates that are hard, dense, and have low absorption and high modulus of elasticity are desirable when concrete with low creep is needed. Aggregates with lower absorption will therefore produce concretes with lower creep and shrinkage characteristics. Concrete with higher elastic modulus will produce lower creep values. Thus, aggregates affect concrete deformation through water demand, aggregate stiffness and volumetric concentration, and paste-aggregate interaction (Troxell et.al., 1968; Han and Walraven, 19XX; Alexander, 1996; Collins, 1989).

High early strength cement typically shrinks and creeps more than normal cement (Troxell et.al., 1968). Low-heat and Portland-pozzolan cement produce larger percentages of gel compared to normal Portland cement, thus causing an increase in shrinkage and creep. Generally, finer cement particles exhibit less shrinkage under moist conditions. The lower the fineness of a low-heat cement, the higher the creep in the concrete. Cement fineness has little influence on the amount of creep of concretes containing ordinary cement.

The addition of ground slag to plain portland cement has the effect of causing an increase in early creep of unsealed specimens, but has a decreasing effect at later ages; significantly reducing creep and shrinkage strains for sealed specimens; reducing the magnitude of the variation within-source, and between-source of Portland cement, thus producing a more consistent product (Mehta, 1986; and Alexander, 1994).

When a constant w/c is maintained, creep increases as the slump and cement content increases or as the amount of cement paste is increased (Troxell et. al., 1968; Wiegrink et.al., 1996). The specific creep and the creep strain per unit of applied stress, decreases with decreasing water content for the conditions of a constant aggregates to cement ratio.

Concretes with 20 %, as well as a 60% FA plus 10 % SF ternary blend were shown to exhibit lower creep values compared with the 100% Portland cement concrete under both sealed and unsealed conditions (Tazawa and Yonekura, 1986; Ghosh and Nasser, 1995; Khatri, et. al., 1995). Addition of SF considerably reduces the specific creep of concrete prepared from ordinary Portland cement. Ternary concretes with 65% slag plus 10% SF, and 35% slag plus 10% SF have marginally lower creep strains than concrete with 100% portland cement (Mehta, 1986; Alexander, 1994). Concrete with lower slag content in its paste will experience lower specific creep than a straight portland cement concrete. Ternary concretes containing 15% or 25% FA along with 10% SF may show far greater reduction in specific creep than portland cement concrete (Tazawa and Yonekura, 1986. The amount of FA, either 15% or 25%, was found to have a negligible effect o creep characteristics of ternary blend concretes (Khatri, et. al., 1995).

The addition of fly ash reduced the creep deformation compared to concrete without fly ash with replacements ranging from 0 to 35% (Mehta, 1986; Tikalsky et. al., 1988;/sivasunduram, et. al., 1990). Class F fly ash may show a greater reduction than Class C fly ash due to a greater pozzolanic nature, which allows the concrete to continue to gain strength over time (Swamy, 1990; Carette and Malhotra, 1997).

Specimens loaded at younger ages exhibited a greater amount of creep for ambient conditions of either 50% or 100% relative humidity. The age of the concrete when loaded significantly affects the magnitude of both the drying creep and basic creep of concrete (Chern and Chan, 1986; Chern et.al., 1988; Carette and Malhotra, 1997).

Temperature and relative humidity affect the shrinkage and creep behavior of concrete (Chern et. al, 1989; Schwesinger et. al., 1987). High temperatures increase creep deformation of concrete, and this is most apparent in concrete that has high slag content. At lower relative humidity more creep and shrinkage occur.

Size and shape of a concrete specimen significantly influence the rate of loss or gain of moisture under given storage conditions and this affects the rate of volume changes as well as the total expansion and contraction (Troxell et. al., 1968). The larger the mass subjected to a sustained loading, the less the creep.

Creep coefficient, specific creep, or creep compliance are generally used to describe creep strain by different models. The creep coefficient is defined as the ratio of creep strain (basic plus drying creep) at a given time to the initial elastic strain. The specific creep is defined at the creep strain per unit stress. The creep compliance is defined as the creep strain plus elastic strain per unit stress, whereas the elastic strain is defined as the instantaneous recoverable deformation of a concrete specimen during the initial stage of loading.

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A recent comparison of four of these models using the distribution of residuals of the creep compliance showed that the ACI 209, B3, Eurocode, and the GZ models over estimated the creep compliance by 23%, 42%, 39%, and 58%, of the total number of data points and underestimated the creep compliance by 77%, 58%, 61%, and 42% respectively (Al-Manaseer and Lakshmikantan, 1999). The mean coefficient of variation for the residuals for the ACI 209, B3, Eurocode, and GZ models were 38.6%, 32%, 31%, and 31% respectively. Model parameters are presented in the appendix.

PURPOSE AND SCOPE

The objective of this research is to develop concrete performance specifications that limit the amount of compressive creep of prestressed concrete mixtures used by the Virginia Department of Transportation, specifically concrete mixtures used for prestressed members. A secondary objective is to assess the accuracy and precision of the creep models presented in the literature. With the development of these concrete performance specifications and the identification of the most accurate and precise creep model, prestress losses can be limited through the application of more rational design and specification.

This study is limited to the testing and evaluation under laboratory conditions of concrete mixtures using a variety of commonly used concrete-making materials available in Virginia. Concrete mixtures were proportioned for compliance with VDOT requirements for prestressed concrete.

METHODS AND MATERIALS

The study variables included two cement types, two pozzolans, and three coarse aggregates with their associated natural fine aggregates. An air entrainment agent and high range water reducer were used to achieve the specified air content and slump.

Aggregate Properties

The three coarse aggregates, a limestone, a quartzose gravel, and a diabase meeting No. 57 grading were used. The fine aggregates used in each mixture corresponded to that of each respective coarse aggregate. All aggregates met the VDOT Road and Bridge 1997 Specifications. The aggregate properties are presented in Table 1.

Cement Properties

The portland cement (PC) was a Type I/II and meet ASTM C 150-98 specifications. A ground granulated blast furnace slag (slag, GGBFS) was also used. The slag was grade 120 and met ASTM C 989-97. Chemical analysis of the PC and slag are presented in Table 2.

Pozzolans

The pozzolans used were a Class F fly ash (FA), and silica fume (SF, MS) meeting ASTM C 618– 97 ASTM C 1240- 97 specifications respectively. Chemical analysis of the FA and MS are presented in Table 3.

Concrete Mixtures

Concrete mixtures were proportioned to comply with VDOT requirements for prestressed concrete. The three basic concrete mixtures consisted of portland cement with the three aggregates, limestone, gravel, and diabase. Three additional limestone concretes were produced in which portion of the portland cement was replaced with fly ash (FA), slag (GGBFS), or silica fume (SF, MS).a Air-entraining and high range water-reducing admixtures were used to achieve the desired properties. Mixture proportions are given in Table 4.

Test Specimens

Concrete batches were mixed in accordance with ASTM C 192-95. Each mixture was batched three times to allow for statistical evaluation. Two creep specimens and eight compressive strength specimens were cast from each batch. Creep test specimens were cast in 150mm x 300mm (6 in x 12 in) steel cylinder molds and compressive strength specimens were cast in 100mm x 200 mm (4 in x 8 in) plastic cylinder molds. Following casting all specimens were moist cured for 7 days in accordance with ASTM C 192-95.

Table 1. Concrete Aggregate Properties

Coarse aggregates

Particle Size	Percent Passing			
mm	Gravel	Limestone	Diabase	VDOT Spec
25	99	100	99	90-100
19	72	81	79	---
12.7	25	19	34	26-60
9.6	12	3	8	---
4.75	2	0	1	Max 7
2.36	0	0	1	Max 3
Unit wt, kg/m^3	1673	1577	1752	---
Dry Bulk SG	2.59	2.81	2.92	---
Absorption, %	0.81	0.36	0.73	---

Fine Aggregates

Particle Size	Percent Passing			
mm	Used w/ Gravel	Used w/ Limestone	Used w/ Diabase	VDOT Spec
9.6	100	100	100	Min 100
4.75	99	97	99	94-100
2.36	90	80	83	80-100
1.18	78	70	68	49-85
0.6	46	53	42	25-59
0.3	17	16	12	8-26
0.15	2	2	4	Max 10
0.075	0.54	0.40	2.0	---
Fineness Modulus	2.68	2.82	2.92	---
Dry Bulk SG	2.55	2.59	2.53	---
Absorption, %	0.75	0.48	1.04	---

Table 2. Cement Properties

Portland Cement Type I/II				
	Percent by Mass			
Oxide	DWM-1	DWM-2		ASTM C 150-98 Type II
SiO_2	21.25	21.17		20.0 min
Al_2O_3	4.49	4.49		6.0 max
Fe_2O_3	3.04	3.03		6.0 max
CaO	63.51	63.41		---
MgO	2.48	2.5		6.0 max
SO_3	2.47	2.46		3.0 max
Na_2O	0.17	0.17		---
K_2O	0.82	0.81		---
TiO_2	0.21	0.22		--
LOI	1.06	1.07		3.0 max
Total	99.83	99.65		---
Total Alkali (Na_2Oeq)	0.72	0.71		*0.6 max
	Compounds, Percent by Mass			
	Bogue Calculation		QXRD	
C_3S	55	56	65	---
C_2S	19	19	16	---
C_3A	7	7	4.2	8.0
C_4AF	9	9	10	---

* Low-alkali cement requirement

Table 3. X-ray Analysis of Silica Fume and Slag

Material	Analysis results
Fly Ash	**No information available**
Silica Fume	**Predominately amorphous silica with possibly a trace amount of merwinite ($Ca_3Mg(SiO_4)_2$)**
Slag	**– Exhibits a broad mid-angle peak that correlates with glass chemistry, a few percent of merwinite and less than one percent of both quartz and calcite. Calcite is probably carbonated from lime**

After the 7-day moist cure, specimens were placed in the creep environmental conditioning room at 50 % ± 4 % relative humidity and 73.4 °F ± 2 °F. All the concrete specimens were capped with sulfur mortar after the curing period according to ASTM C 617-94. Compressive strength tests were conducted according to ASTM C 39-96 to obtain 7, 14, 28, and 56-day strengths. Modulus of elasticity was measured at 7 and 28 days in accordance with ASTM C 469-94.

Two sets of gage points, 200mm (8 in) apart on diametrically opposite sides, were affixed to each creep specimen. The two sets of gage points are referred to as, "Side A" and "Side B".

Creep Testing Cycles

Because of the limited number of load frames, the creep testing was done in cycles. Table 5 presents the specimens for each testing cycle. Test cycle I was comprised of the limestone and limestone-silica fume mixtures. Test cycle II was the gravel and diabase mixtures. Test cycle III was the limestone-fly ash and limestone-slag mixtures.

RESULTS

The fresh concrete properties of the mixtures are shown in Table 6. Table 7 presents the average compressive strength and elastic modulus for all of the prestressed concrete mixtures.

The limestone mixture has a larger compressive strength than the gravel and diabase mixtures likely owing to the lower w/c ratio used in these mixtures. The compressive strengths for the gravel and diabase mixtures are not significantly different.

The limestone SF mixture has the highest compressive strength. The limestone GGBFS and limestone FA mixtures are roughly equivalent and slightly lower than the limestone mixture with portland cement except for the 7-day test where the limestone FA mixture exhibited a significantly lower strength.

The elastic modulus for the limestone mixture with portland cement is similar to the values produced by the mixtures with mineral admixtures, and is higher than that of the gravel mixture. The diabase mixture exhibited an unexplained decrease in elastic modulus between 7 and 28 days.

Table 4. Mixture/Batch Proportion

Material	Limestone	Gravel	Diabase
Cement Type I/II, kg	17.8	18.6	17.9
Water, kg	6.2	7.2	7.0
Coarse aggregate, kg	44.6	48.2	48.2
Fine aggregate, kg	33.4	28.1	28.3
Total kg	102	102	101
Yield, m^3*10^2	4.29	4.16	3.94
AEA, Daravair 1000, ml	(see fresh concrete results, Table 6)		
HRWR, Daracem 19, ml	(see fresh concrete results, Table 6)		

Material	LimestoneSF	LimestoneFA	LimestoneSlag
Cement Type I/II, kg	16.6	15.3	10.8
Mineral admixture, kg (%)	1.3 (7.25)	3.6 (19)	7.2 (40)
Water, kg	6.3	6.3	6.3
Coarse aggregate, kg	44.8	45.1	44.8
Fine aggregate, kg	33.1	31.8	33.1
Total kg	102	102	102
Yield, m^3*10^2	4.31	4.33	4.31
AEA, Daravair 1000, ml	(see fresh concrete results, Table 6)		
HRWR, Daracem 19, ml	(see fresh concrete results, Table 6)		

Table 5. Creep Testing Cycles

Frame 1	Frame 2	Frame 3	Frame 4
Test Cycle 1			
Limestone-SF B1-S1	Limestone B1-S2	Limestone-SF B2-S1	Limestone-SF B3-S2
Limestone B2-S1	Limestone B2-S2	Limestone-SF B3-S1	Limestone-SF B2-S2
Limestone B1-S1	Limestone-SF B1-S2	Limestone B3-S1	Limestone B3-S2
Test Cycle 2			
Diabase B2-S1	Diabase B1-S2	Gravel B2-S1	Gravel B2-S2
Gravel B1-S1	Gravel B1-S2	Gravel B3-S1	Diabase B3-S2
Diabase B1-S1	Diabase B2-S2	Diabase B3-S1	Gravel B3-S2
Test Cycle 3			
Limestone-Slag B1-S1	Limestone-Slag B2-S2	Limestone-Slag B3-S1	Limestone-Slag B3-S2
Limestone-FA B1-S1	Limestone-FA B1-S2	Limestone-FA B2-S1	Limestone-FA B2-S2
Limestone-Slag B2-S1	Limestone-Slag B1-S2	Limestone-FA B3-S1	Limestone-FA B3-S2

Specimen labeling – (aggregate type – mineral admixture (where applicable) – batch number – specimen number)

Creep Testing

Drying shrinkage, applied load, and total strain values for all mixtures can be found in Meyerson (2001). Most notable in this data is the relatively high variability of the shrinkage and total strain for the limestone and limestone-SF mixtures. These mixtures were tested in the first cycle, and the high variability is attributable to learning-curve factors with the experimental set-up and conditioning equipment. See Meyerson (2001) for a complete discussion of the experimental variability. Average total strain values for the mixtures are presented in Figures 1 and 2. Average total strain was significantly higher for the limestone-PC mixture (2500 microstrain) than the others (approximately 1500-1750 microstrain). Regarding the portland cement mixtures, lower total strain for the gravel and diabase aggregates are attributable to the relative stiffness of these aggregate types. The limestone aggregate was used in mixtures with portland cement and portland cement plus pozzolan (fly ash or silica fume) as well as slag. Lower strain in the pozzolan and slag mixtures can be attributed to the stiffening effect of these materials on the paste.

Table 6. Fresh Concrete Properties

Mixture	Gravel			Diabase			Limestone			Lmstn.SF			Lmstn.FA			Lmstn.Slag		
W/C	0.35			0.39			0.33			0.31			0.32			0.33		
Batch	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Temp. ^{o}C	22	22	22	22	21	22	22	21	22	22	22	22	28	26	25	27	27	25
Slump, mm	65	90	90	75	90	75	100	90	75	75	100	75	150	65	125	65	150	50
Un Wt. kg/m^3 P	2451	2451	2451	2563	2563	2563	2377	2377	2377	2368	2368	2368	2355	2355	2355	2367	2367	2367
Un Wt., kg/m^{3}M	2387	2355	2355	2515	2499	2483	2465	2454	2435	2441	2435	2478	2377	2426	2399	2410	2379	2444
Yield, (P/M)	1.03	1.04	1.04	1.02	1.03	1.03	0.963	0.970	0.976	0.970	0.972	0.955	0.991	0.971	0.982	0.982	0.995	0.969
AC, %	3.5	4.5	5.3	3.1	3.1	3.7	5.0	4.5	5.1	4.5	4.4	3.8	5.8	4.3	5.3	4.8	6.8	4.2
AEA, ml	9	9	9	9	9	9	9	9	9	9	9	9	10	10	10	10	9	9
HRWR, ml	100	100	100	60	60	100	225	188	174	236	264	304	125	100	110	120	140	130

P –as proportioned; M – measured

Table 7. Compressive Strength and Elastic Modulus of Concrete Mixtures

Mixture	Gravel	Diabase	Limestone	Lmstn.SF	Lmstn.FA	Lmstn.Slag
Test age, d			Compressive strength results, MPa			
7	33	36	44	50	34	41
14	37	40	49	56	42	48
28	42	42	51	63	46	50
56	41	43	52	65	46	47
Test age, d			Elastic modulus, GPa			
7	32	41	41	40	39	41
28	34	36	41	41	38	38

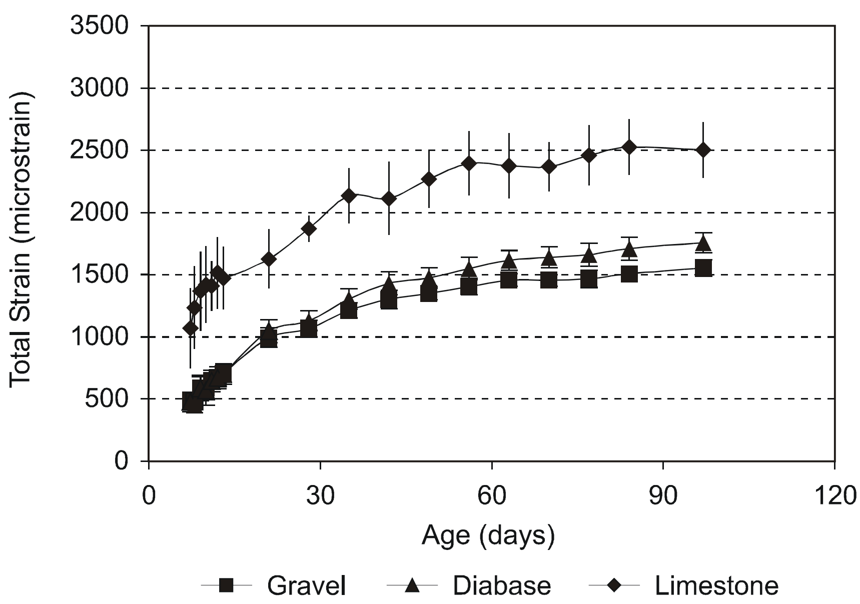

Figure 1. Average total strain for portland cement concretes. Error bars indicate confidence interval (α = 0.05)

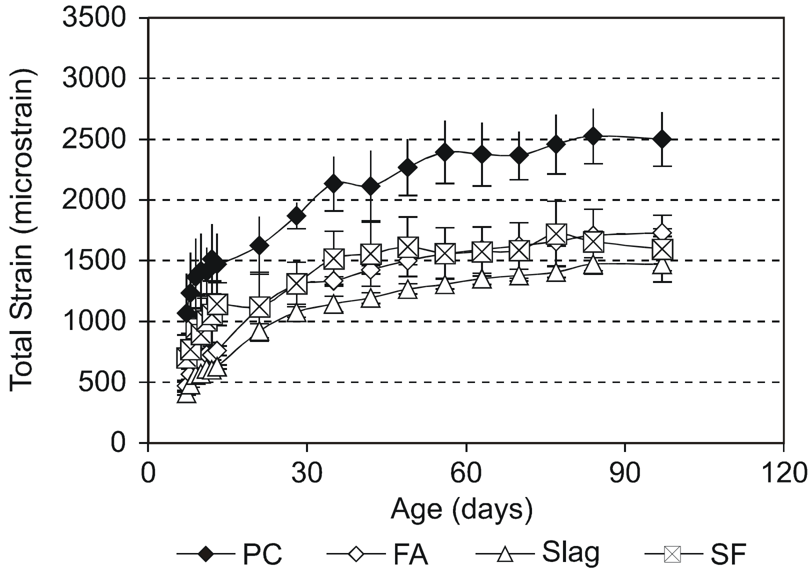

Figure 2. Average total strain for concretes containing limestone aggregates. Error bars indicate confidence interval ($\alpha = 0.05$)

Creep Model Evaluation

The creep models examined, ACI 209, Eurocode CEB 90, Bazant B3, Gardner GZ, and Sakata SAK are describe in Appendix A. The model results are presented as residuals, the difference between the experimental mean and the model value. If the model is under predicting the experimental mean, the residual has a positive value. If the model is over predicting the experimental mean, the residual has a negative residual. All five models predict the total strain as the sum of the drying shrinkage strain and basic creep. The models are limited to concrete mixtures without mineral admixtures, therefore the figures were arranged such that the mixtures with portland cement concrete are presented as one group, and mixtures with portland cement plus mineral admixture concrete are presented as another group.

ACI 209

Portland Cement Concrete Mixtures

Figures 3 through 5 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures for the ACI 209 model. For total strain, the ACI 209 model is a better predictor at early ages for the limestone, diabase, and gravel mixtures. At later ages, after 28 days, the model under predicts and becomes less accurate. The limestone mixture exhibits a larger variability at the five percent significance level than the diabase and gravel mixtures. The results for the diabase and gravel mixtures were similar. The model under predicts the drying shrinkage strain to the same degree for each of the mixtures, and becomes less accurate after 28 days

The basic creep of each mixture is over predicted to the same degree and the model becomes more accurate after 28 days.

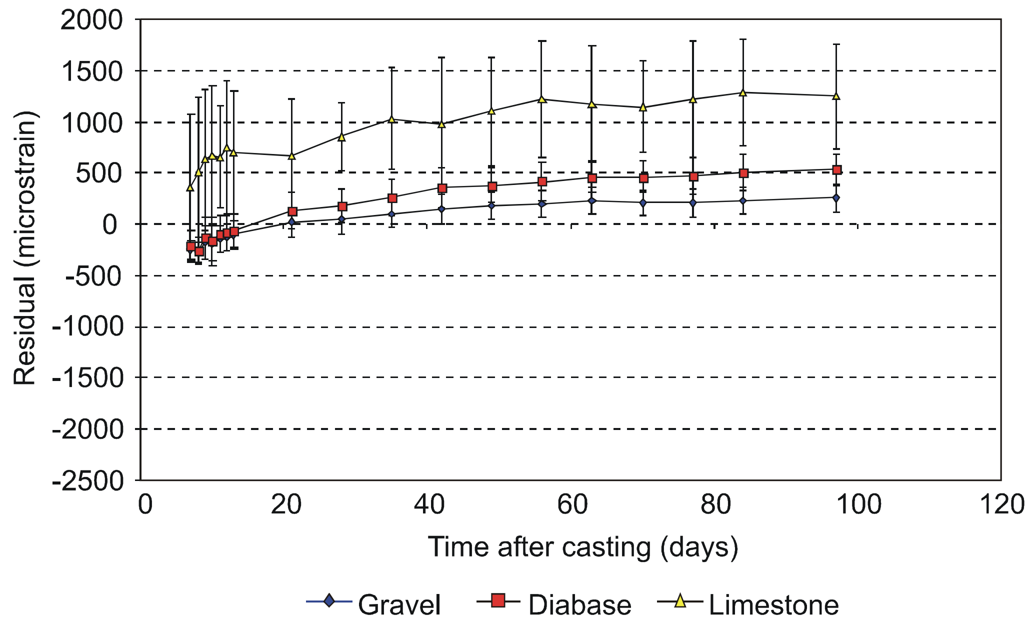

Figure 3. Residuals of Total Strain of Portland Cement Concrete with the ACI 209 Model (Each data point for a specified time is an average of three measurements. The error bars represent the 95 % confidence interval.)

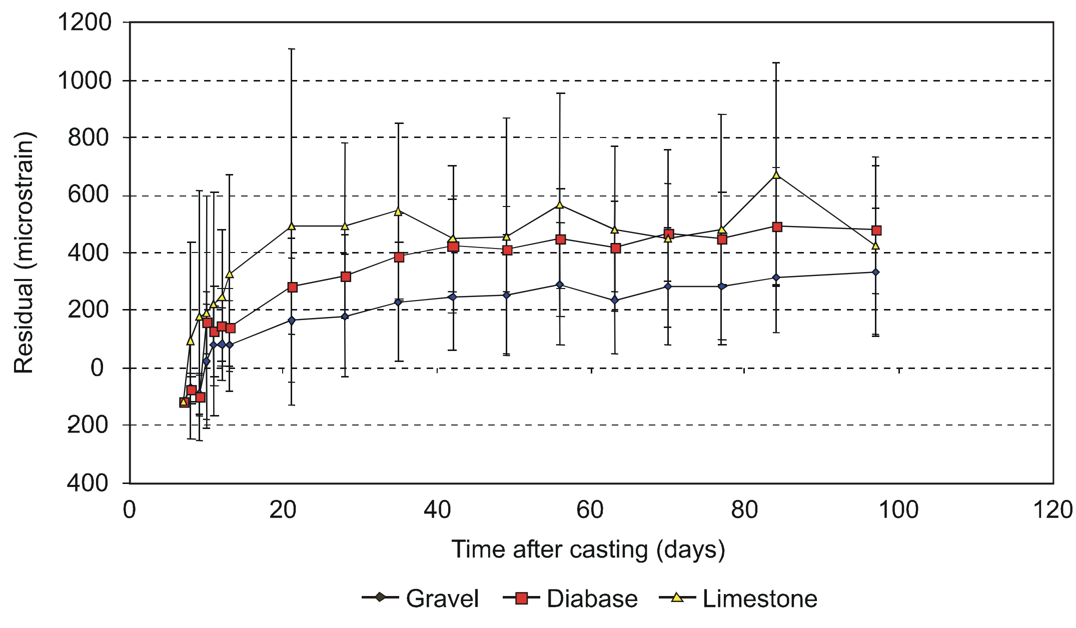

Figure 4. Residuals of Drying Shrinkage of Portland Cement Concrete and ACI 209 Model

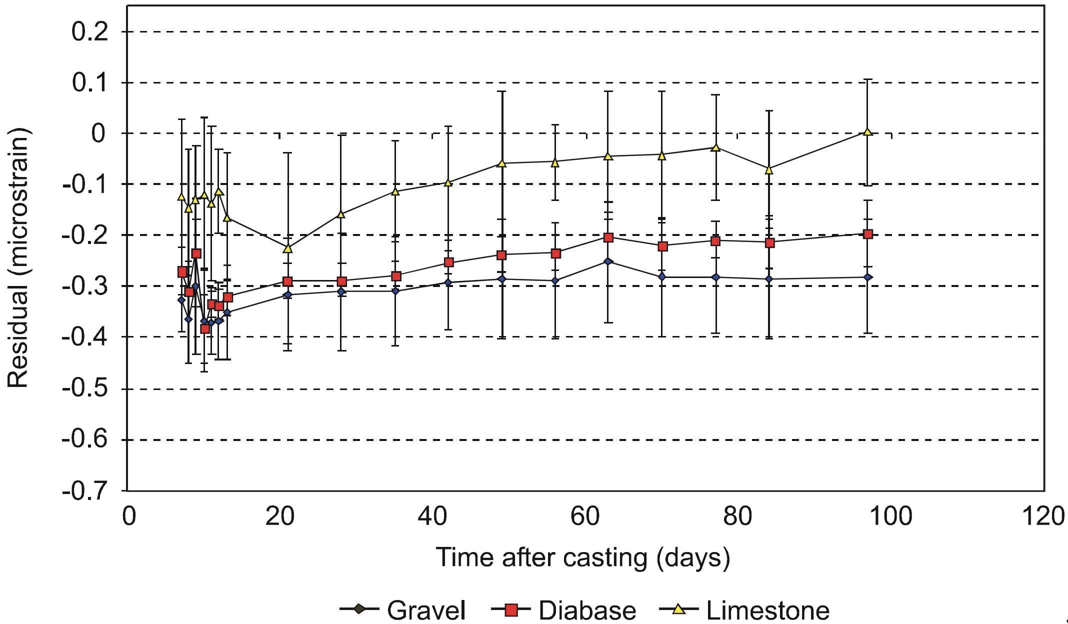

Figure 5. Residuals of Basic Creep of Portland Cement Concrete and ACI 209 Model

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 6 through 8 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures for the ACI 209 model. For total strain, the ACI 209 model is a better predictor at early ages for the limestone FA, limestone GGBFS, and limestone MS mixtures. After 28 days the model under predicts and becomes less accurate. The model under predicts the drying shrinkage strain to the same degree for each of the mixtures, and becomes less accurate after 28 days. The limestone MS mixture has a larger variability than the other mixtures.

The basic creep is over predicted to the same degree for each of the mixtures, but the precision remains the same over time.

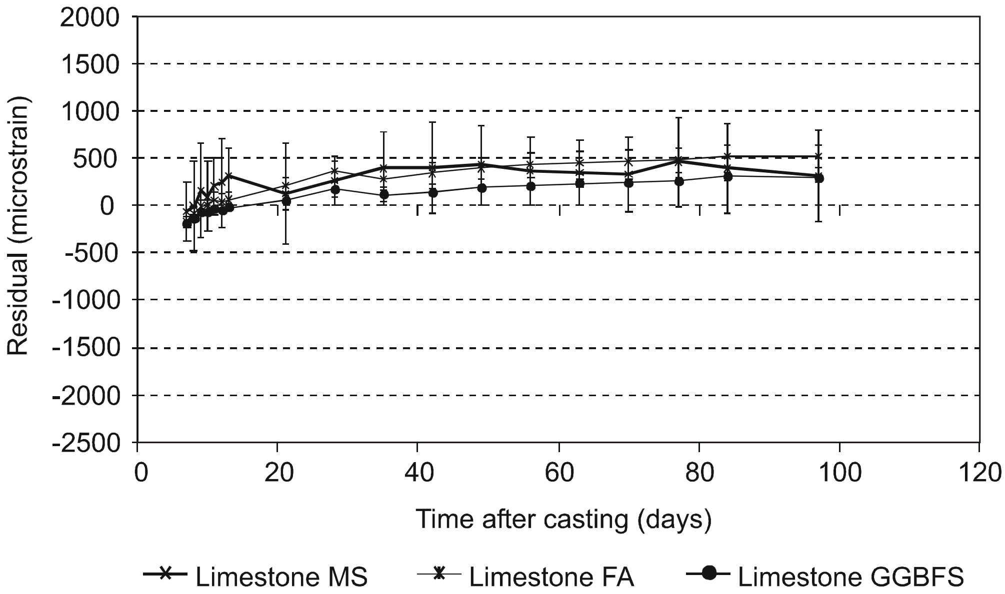

Figure 6. Residuals of Total Strain of Portland Cement plus Mineral Admixture Concrete and ACI 209 Model

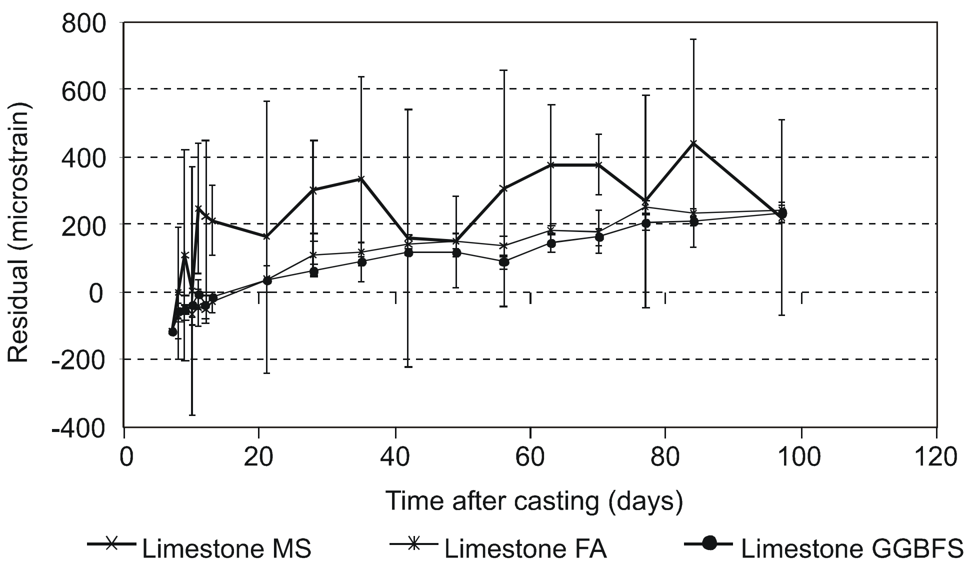

Figure 7. Residuals of Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete and ACI 209 Model

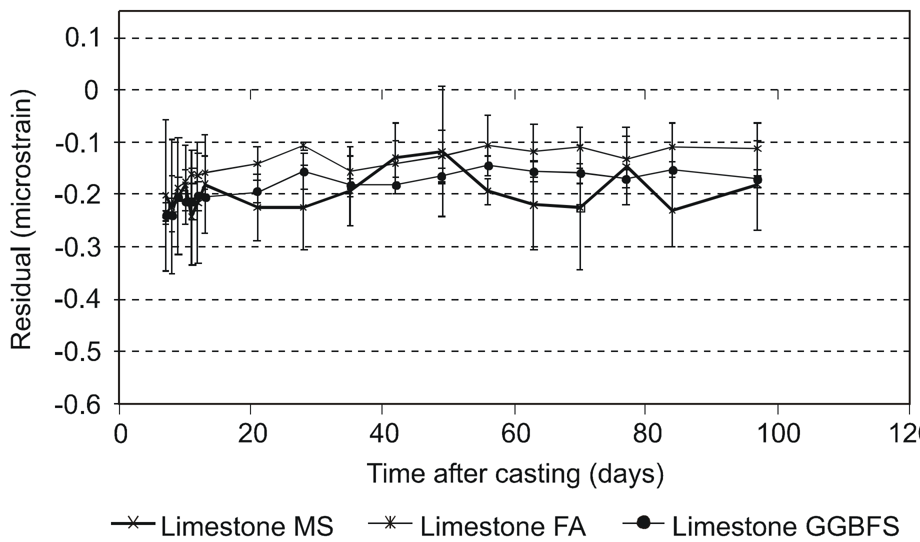

Figure 8. Residuals of Basic Creep of Portland Cement Plus Mineral Admixture with the ACI 209 Model

CEB 90 Euro-Code

Portland Cement Concrete Mixtures

Figures 9 through 11 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures for the CEB 90 Euro-Code. For total strain, the CEB 90 model is a good predictor. The limestone mixture exhibits a larger variability at the five percent significance level than the diabase and gravel mixtures. The predictions for the diabase and gravel mixtures were similar.

The model under predicts the drying shrinkage strain, with little difference between the gravel, limestone, and diabase mixtures.

The model over predicts the basic creep to the same degree for each of the mixtures.

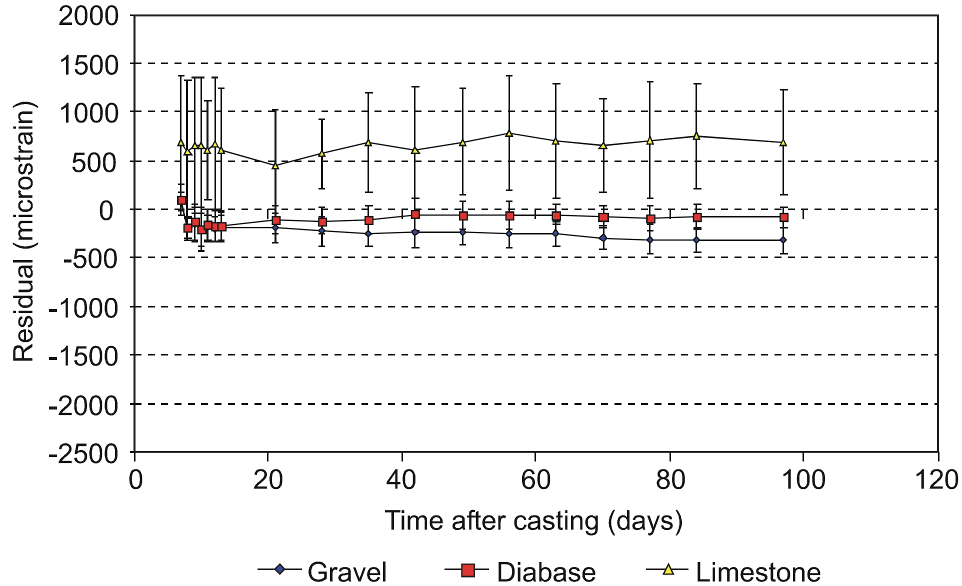

Figure 9. Residuals of Total Strain of Portland Cement Concrete and CEB 90 Model

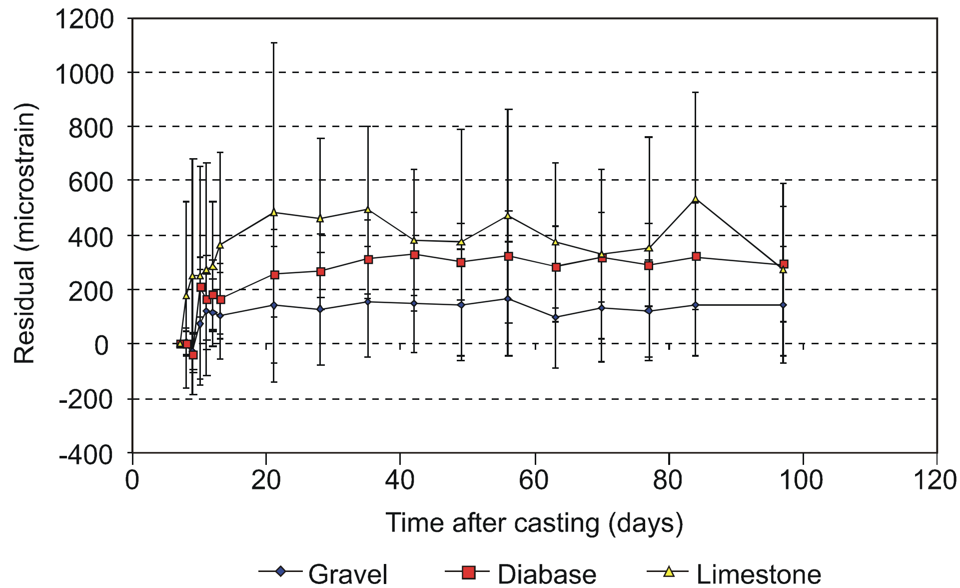

Figure 10. Residuals of Drying Shrinkage of Portland Cement Concrete and CEB 90 Model

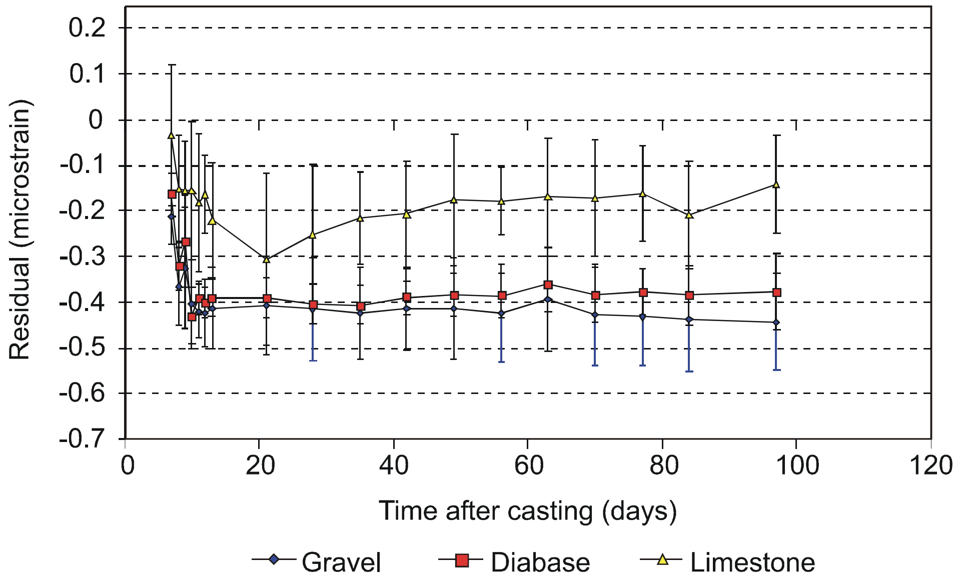

Figure 11. Residuals of Basic Creep of Portland Cement Concrete

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 12 through 14 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures for the CEB 90 Euro-Code model. For total strain, the CEB 90 model is a good predictor for the limestone FA, limestone GGBFS, and limestone MS mixtures.

The model under predicts the drying shrinkage strain for each of the mixtures to the same degree. The limestone MS mixture has a larger variability than the other mixtures.

For each of the mixtures, the basic creep is over predicted and the accuracy slightly decreases over time

Bazant Model

Portland Cement Concrete Mixtures

Figures 15 through 17 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures for the Bazant Model. For total strain, the Bazant model over predicts the diabase and gravel mixtures to a similar degree. The model under predicts the limestone mixture, and exhibits a larger variability at the five percent significance level than the diabase and gravel mixtures

The model under predicts the drying shrinkage strain for each mixture to a similar degree. The model over predicts the basic creep of each mixture to the same degree, becoming a better predictor after 28 days.

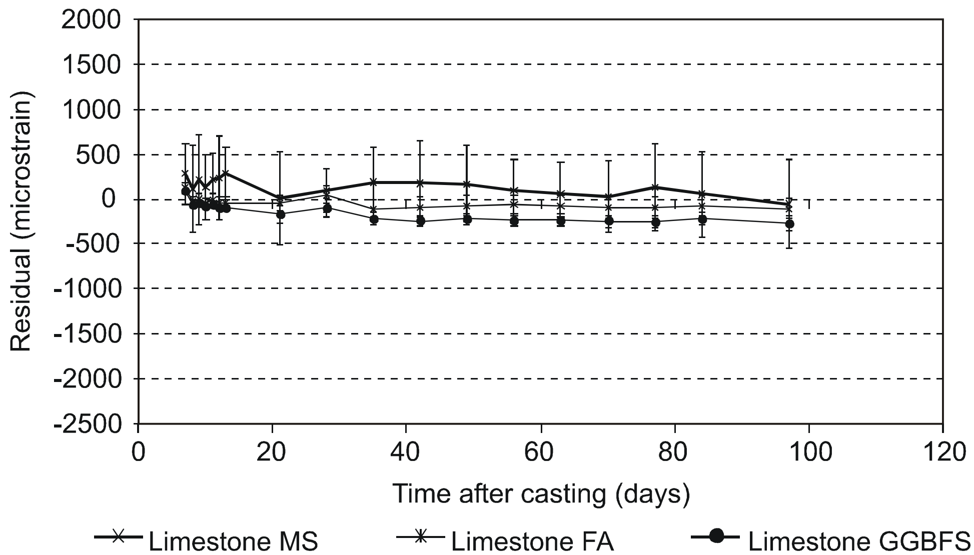

Figure 12. Residuals of Total Strain of Portland Cement plus Mineral Admixture Concrete and CEB 90 Model

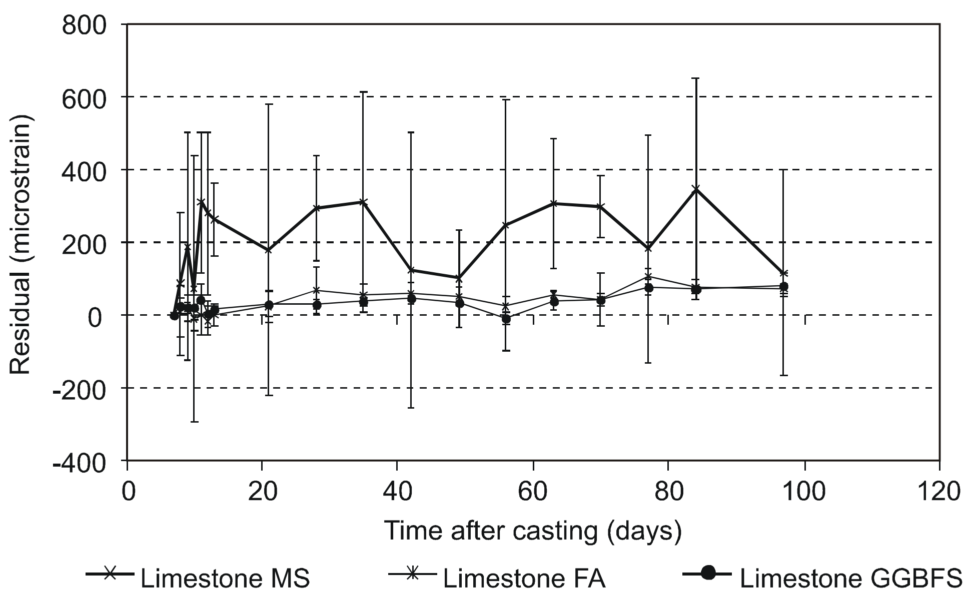

Figure 13. Residuals of Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete and CEB 90 Model

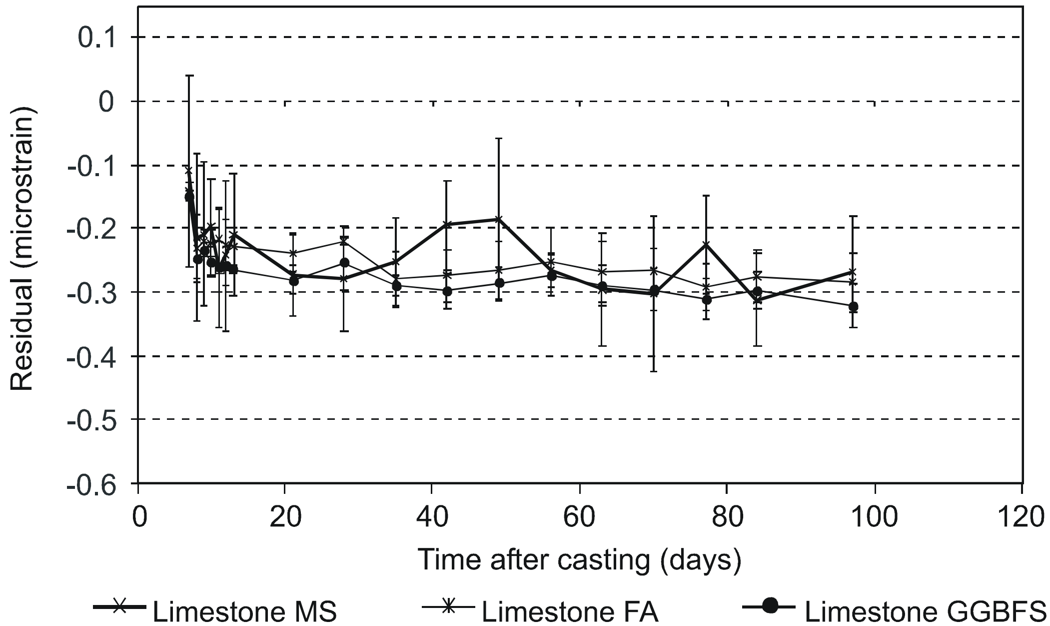

Figure 14. Residuals of Basic Creep of Portland Cement plus Mineral Admixture Concrete and CEB 90 Model

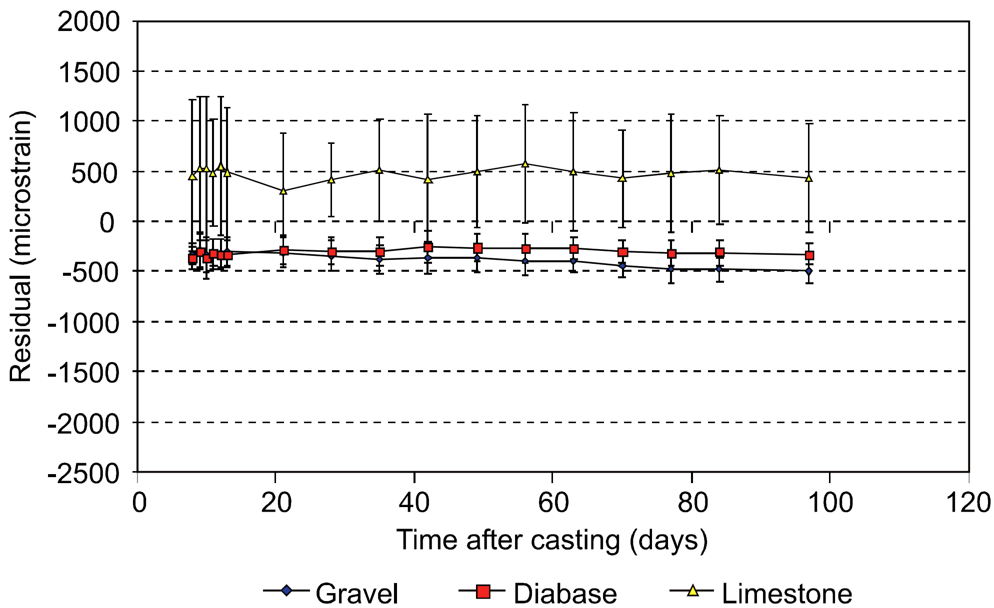

Figure 15. Residuals of Total Strain of Portland Cement Concrete and Bazant Model

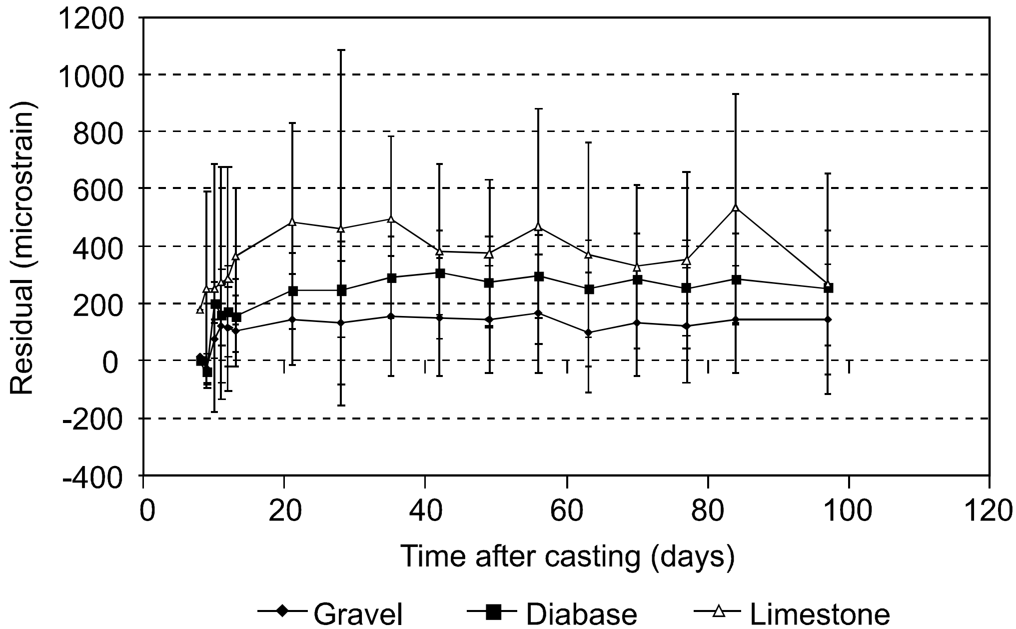

Figure 16. Residuals of Drying Shrinkage of Portland Cement Concrete and Bazant Model

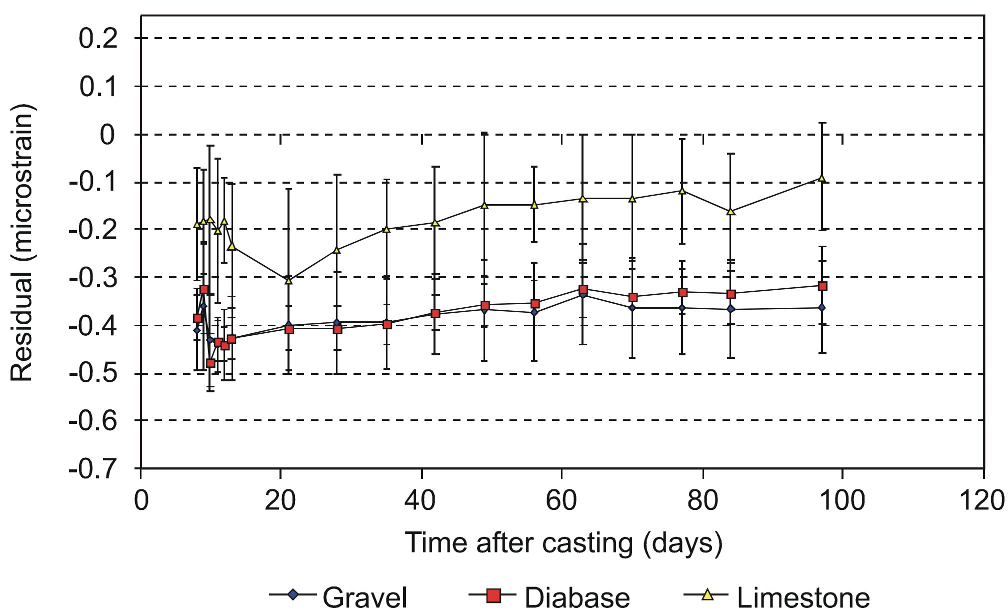

Figure 17. Residuals of Basic Creep of Portland Cement Concrete and Bazant Model

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 18 through 20 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures for the Bazant model. For total strain, the Bazant model is a good predictor for the limestone FA, limestone GGBFS, and limestone MS mixtures, with minimal differences between the different mixtures. . At later ages, after 40 days, the model over predicts the total strain.

The model under predicts the drying shrinkage strain with little difference between the mixtures. The limestone MS mixture has a larger variability than the other mixtures.

The model over predicts the basic creep, and the precision remains constant over time with little difference between the mixtures.

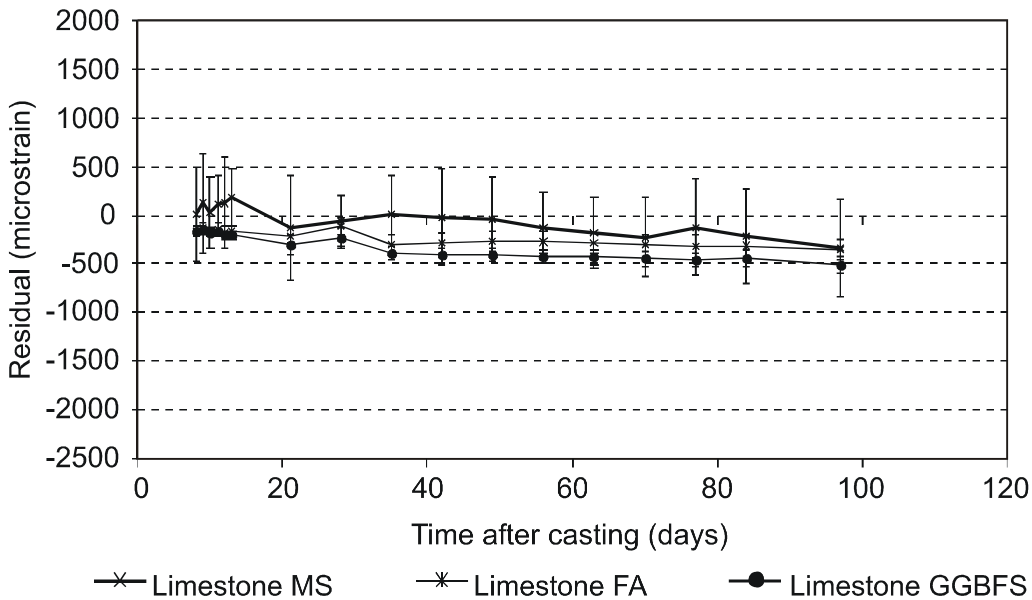

Figure 18. Residuals of Total Strain of Portland Cement plus Mineral Admixture Concrete and Bazant Model

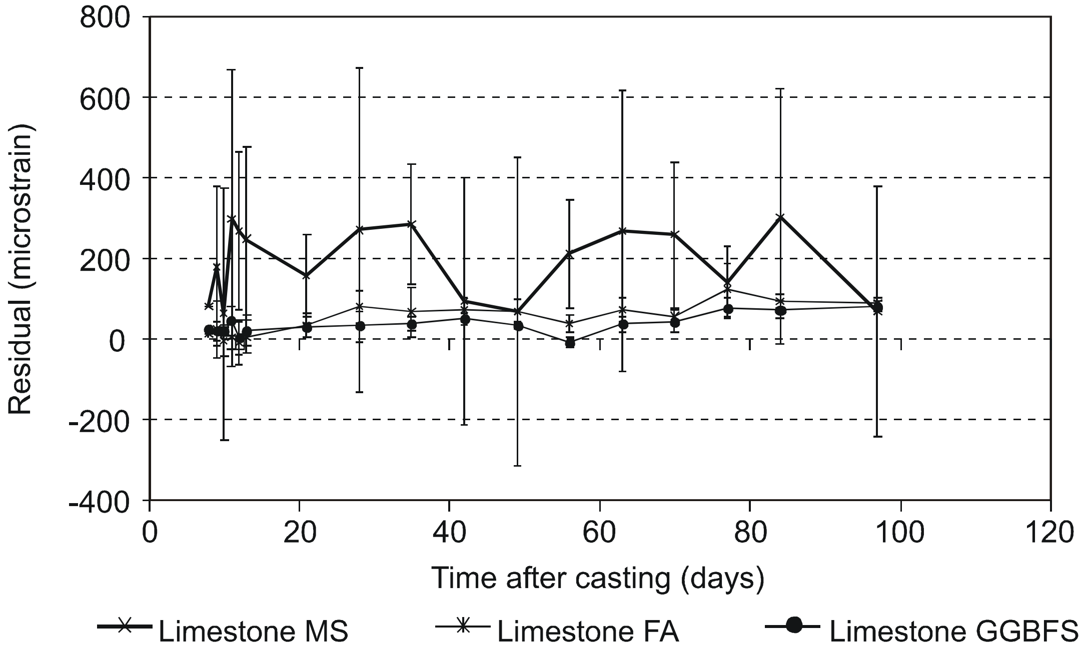

Figure 19. Residuals of Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete and Bazant Model

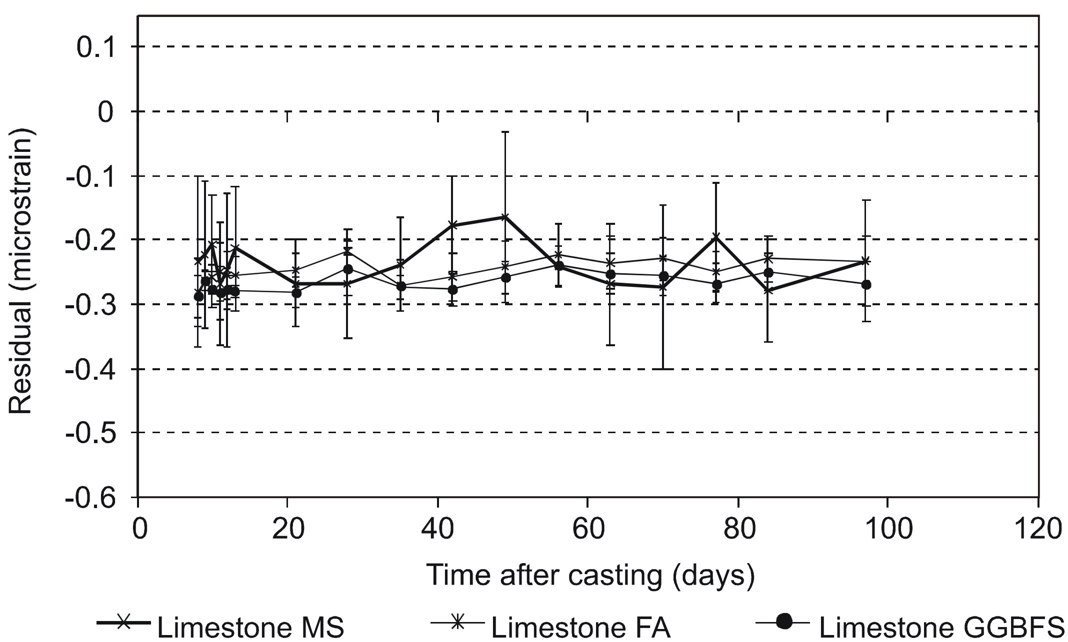

Figure 20. Residuals of Basic Creep of Portland Cement plus Mineral Admixture Concrete and Bazant Model

Gardner Model

Portland Cement Concrete Mixtures

Figures 21 through 23 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures for the Gardner Model. For total strain, the Gardner model over predicts the diabase and gravel mixtures. The model under predicts the experimental mean of the limestone mixture, but exhibits a larger variability at the five percent significance level than the diabase and gravel mixtures. The diabase and gravel mixtures behaved in a similar fashion to each other.

The model under predicts the drying shrinkage strain in a manner similar for the gravel, limestone, and diabase mixtures. The model over predicts the basic creep to the same degree for each of the mixtures.

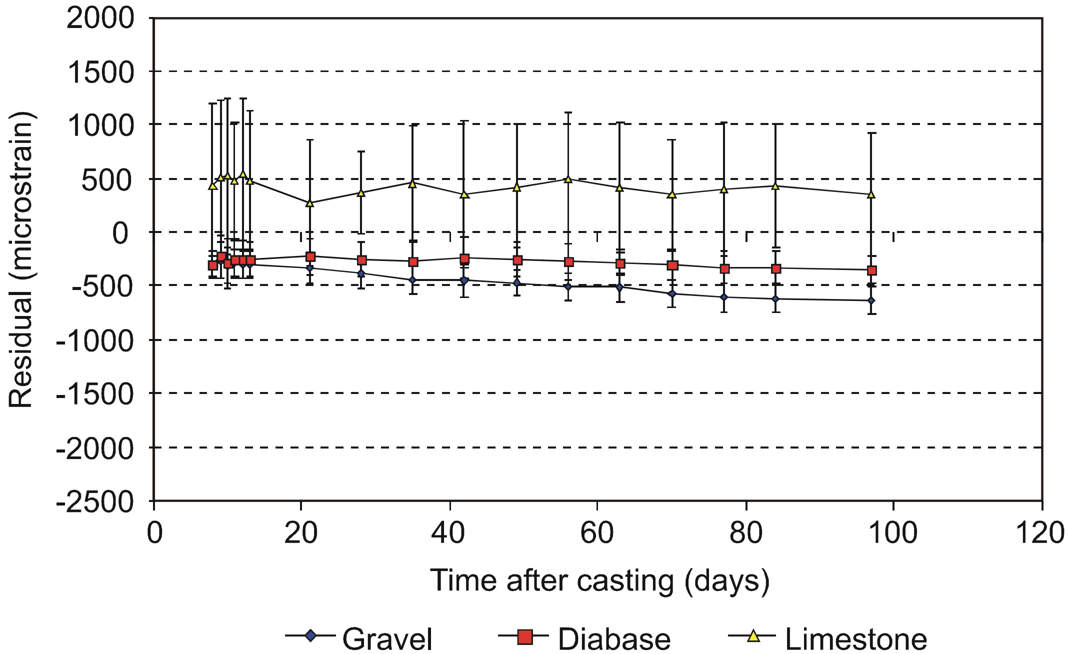

Figure 21. Residuals of Total Strain of Portland Cement Concrete and Gardner Model

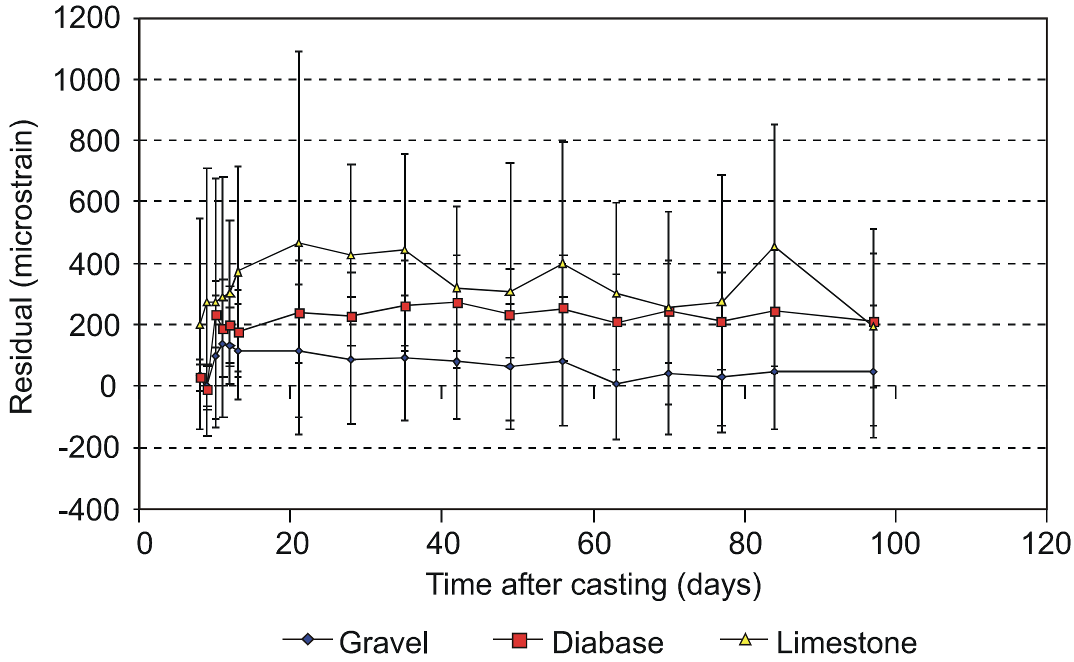

Figure 22. Residuals of Drying Shrinkage of Portland Cement Concrete and Gardner Model

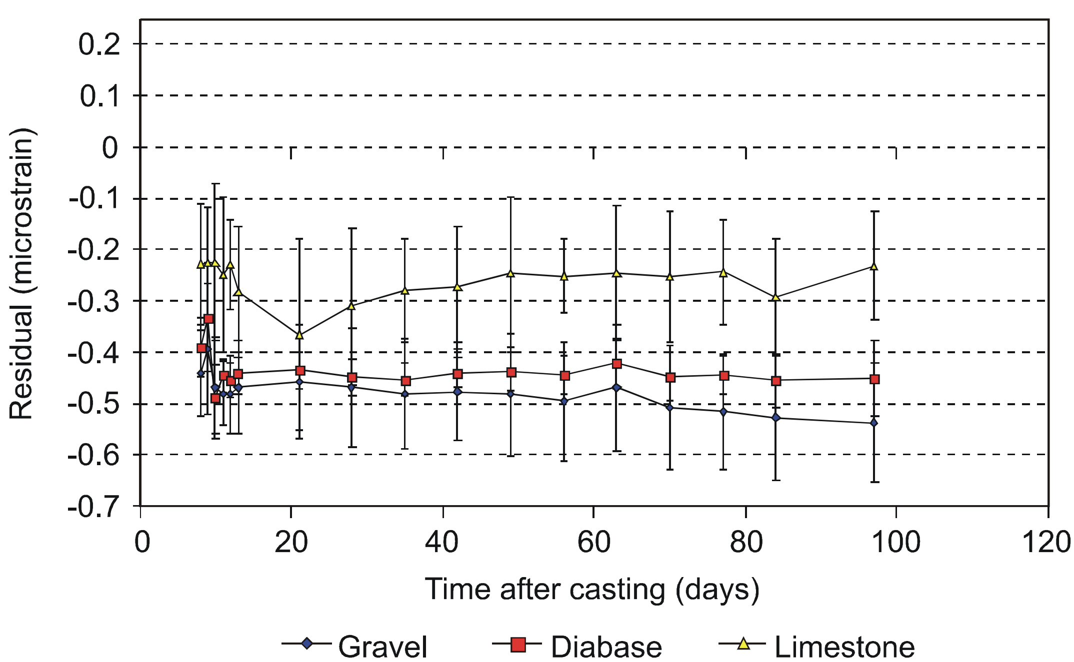

Figure 23. Residuals of Basic Creep of Portland Cement Concrete and Gardner Model

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 24 through 26 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures for the Gardner model. For total strain, the Gardner model over predicts the experimental mean for the limestone FA, limestone GGBFS, and limestone MS mixtures, and becomes less accurate over time. There is no significant difference between the limestone FA, limestone GGBFS, and limestone MS mixtures.

The model under predicts the drying shrinkage strain, and the behavior of the mixtures is similar. The limestone MS mixture has a larger variability than the other mixtures.

The model over predicts the basic creep, and becomes less accurate over time The behavior of the different mixtures is similar for the prediction of basic creep.

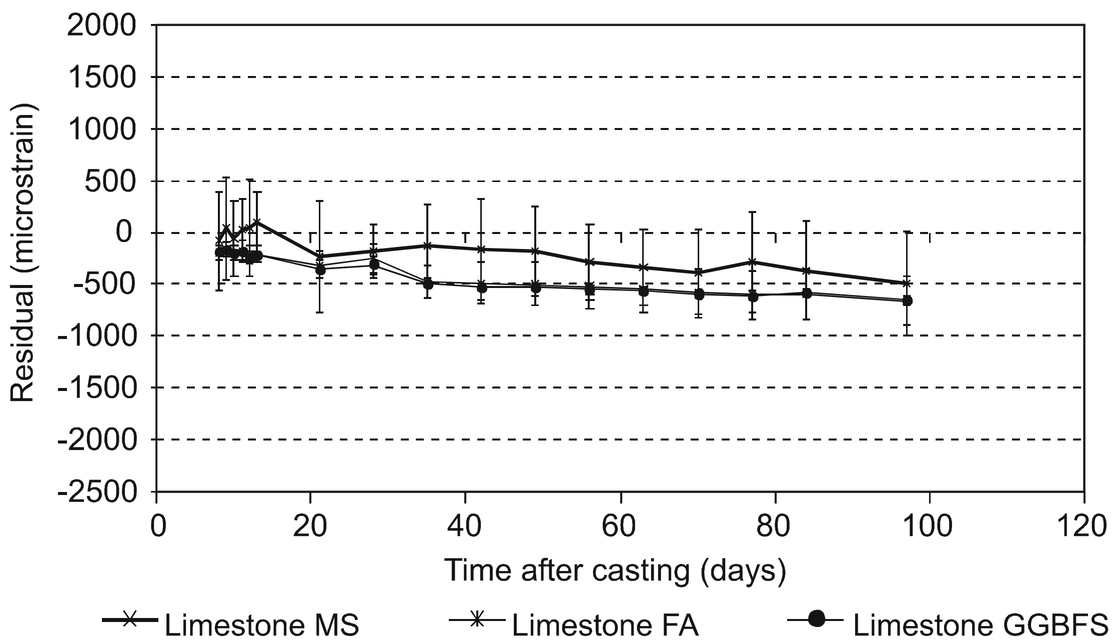

Figure 24. Residuals of Total Strain of Portland Cement plus Mineral Admixture Concrete and Gardner Model

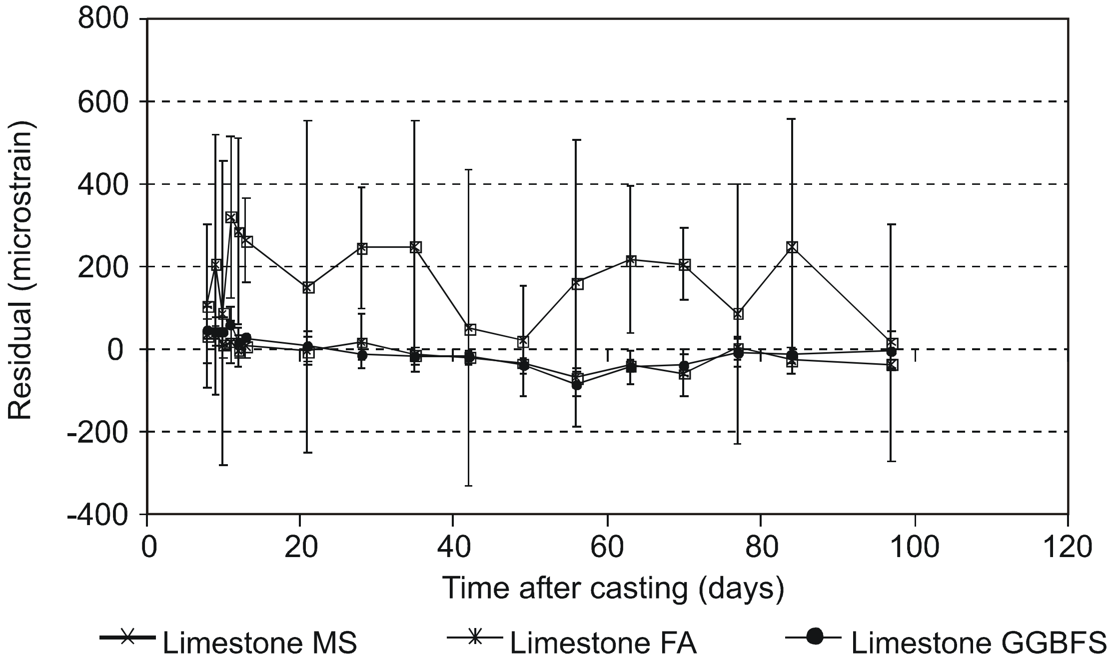

Figure 25. Residuals of Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete and Gardner Model

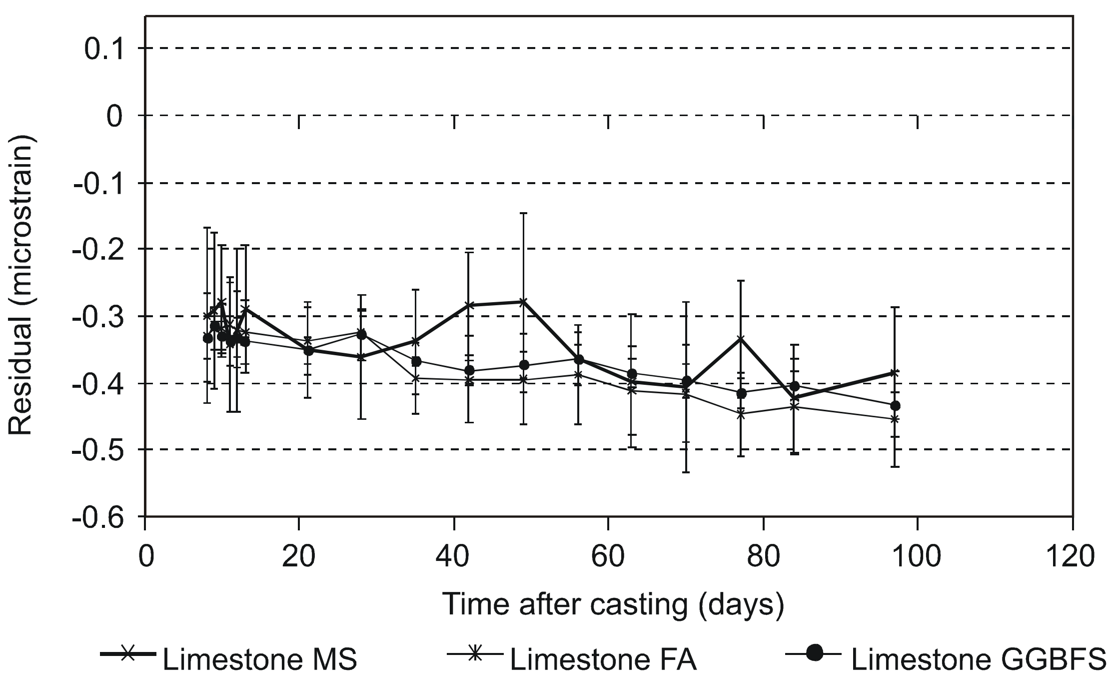

Figure 26. Residuals of Basic Creep of Portland Cement plus Mineral Admixture Concrete and Gardner Model

Sakata Model

Portland Cement Concrete Mixtures

Figures 27 through 29 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures for the Sakata Model. For total strain, the Sakata model is a good predictor for the diabase and gravel mixtures. The model under predicts the experimental mean for the limestone mixture, but exhibits a larger variability at the five percent significance level than the diabase and gravel mixtures. The behavior of the diabase and gravel mixtures was similar.

The model is a good predictor for the drying shrinkage strain. The behavior of the gravel, limestone, and diabase mixtures for the prediction of drying shrinkage was similar. The model slightly under predicts the limestone mixture, while the gravel mixture is slightly over predicted, and the model is a good predictor for the diabase mixture.

The model over predicts the basic creep for the gravel and diabase mixtures. The model over predicts the basic creep for the limestone mixture at early ages. After 28 days, the model under predicts the basic creep values. The gravel and diabase mixtures had similar responses for the prediction of basic creep.

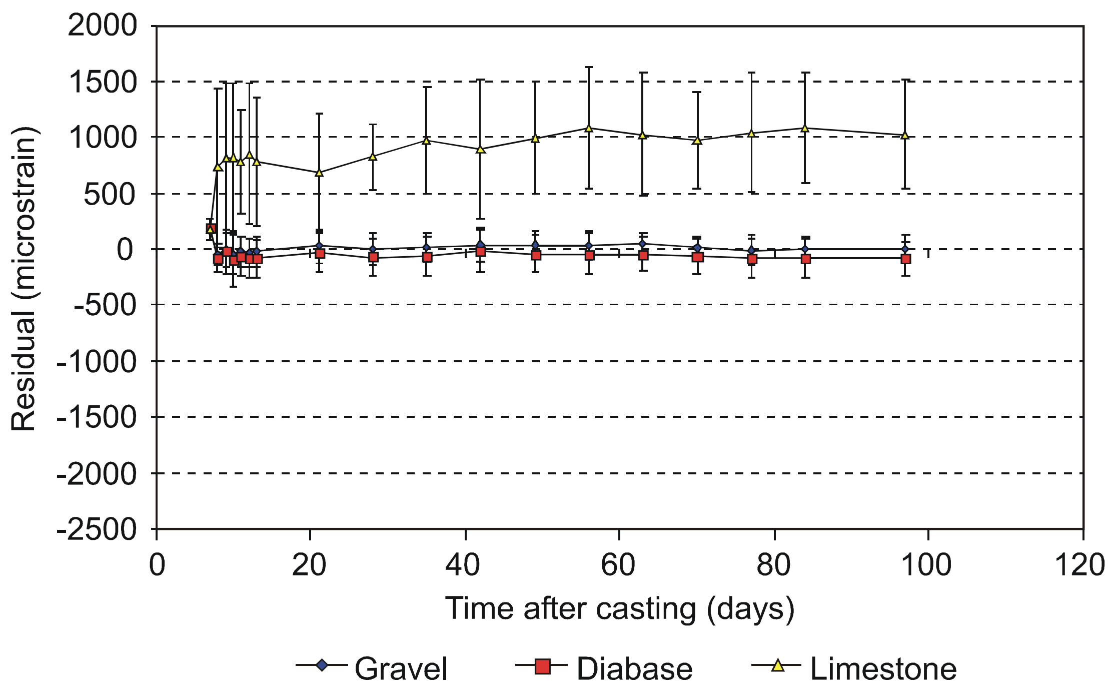

Figure 27. Residuals of Total Strain of Portland Cement Concrete and Sakata Model

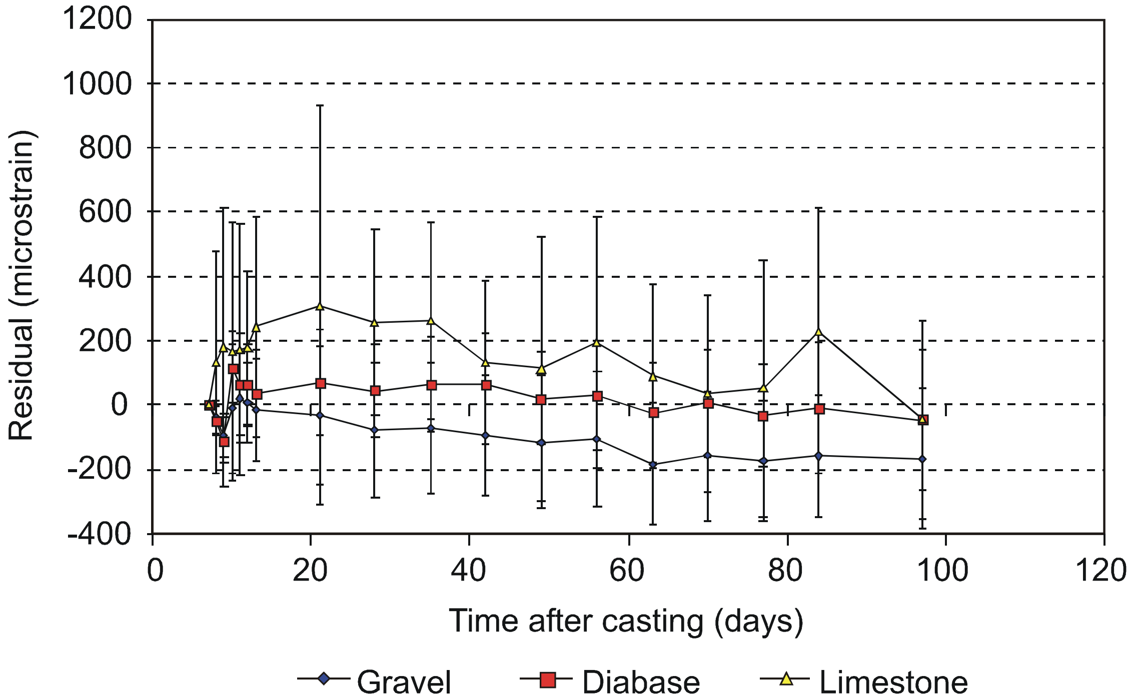

Figure 28. Residuals of Drying Shrinkage of Portland Cement Concrete and Sakata Model

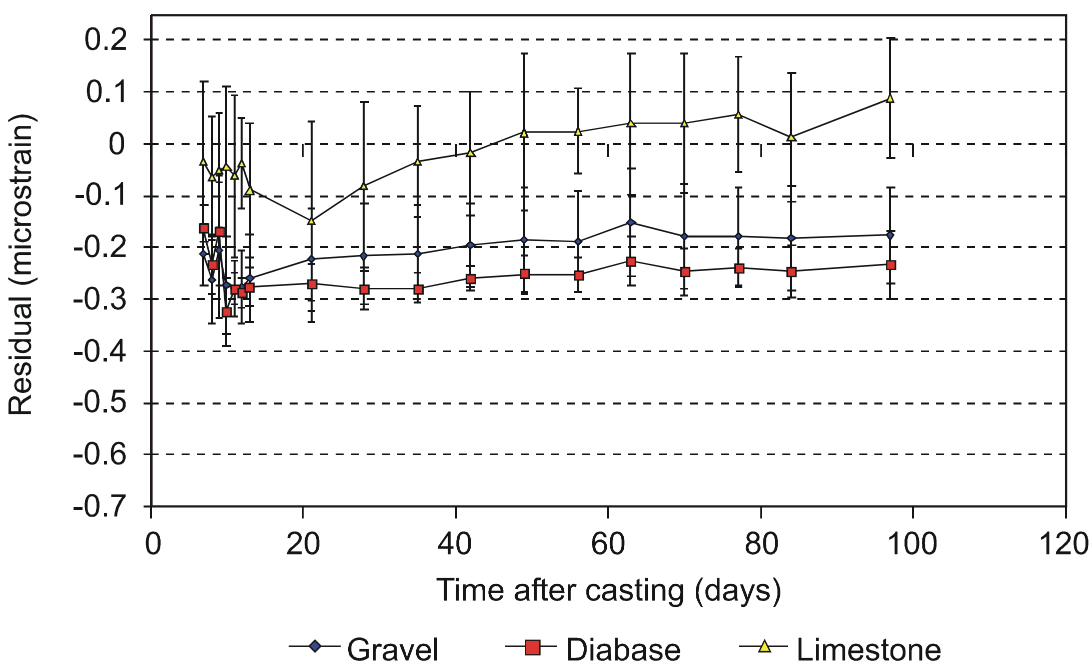

Figure 29. Residuals of Basic Creep of Portland Cement Concrete and Sakata Model

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 30 through 32 present the residuals of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures for the Sakata model. For total strain, the Sakata model is a good predictor for the limestone FA, limestone GGBFS, and limestone MS mixtures. The behavior of the limestone FA, limestone GGBFS, and limestone MS mixtures was similar.

The model under predicts the drying shrinkage strain, and becomes less accurate over time. Again, the mixtures behaved similarly. The limestone MS mixture has a larger variability than the other mixtures.

The model over predicts the basic creep, and becomes more accurate over time. The prediction of basic creep did not differ between mixtures.

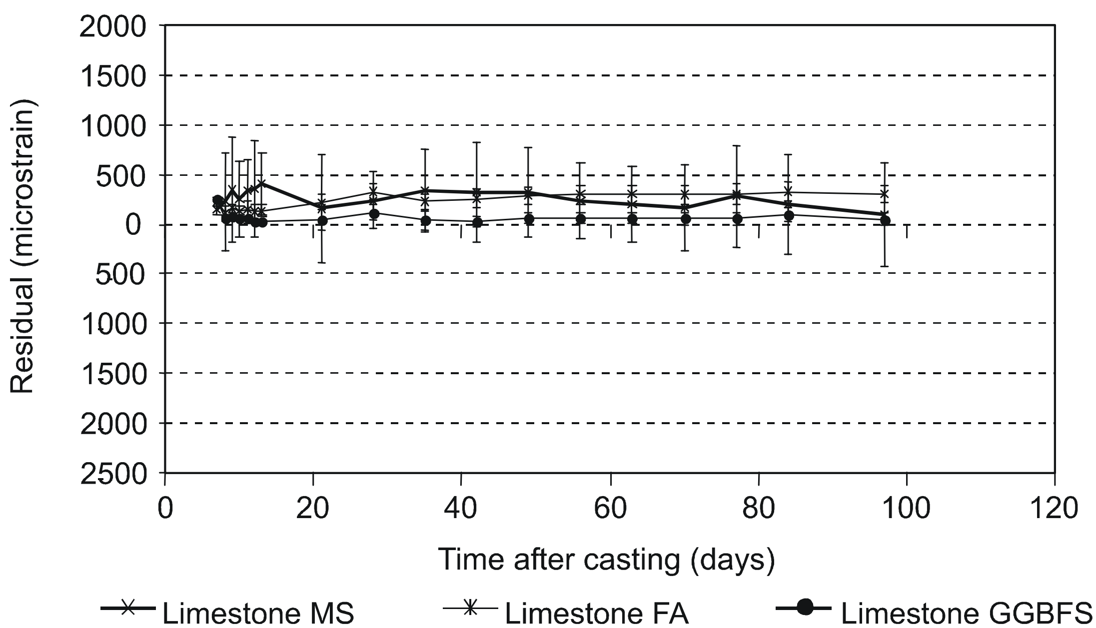

Figure 30. Residuals of Total Strain of Portland Cement plus Mineral Admixture Concrete and Sakata Model

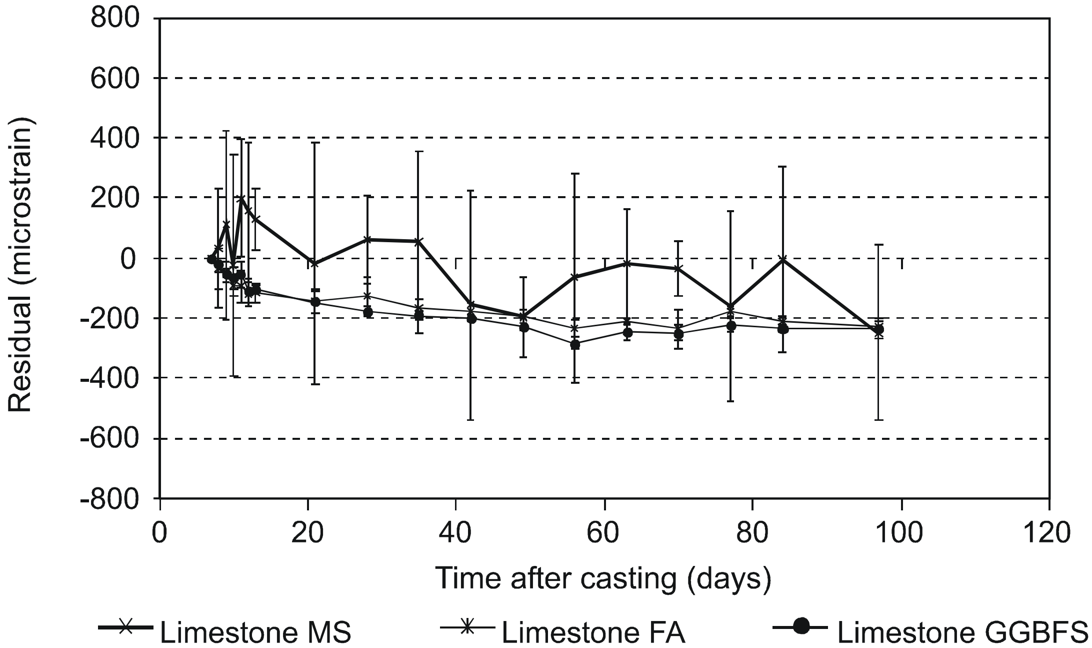

Figure 31. Residuals of Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete and Sakata Model

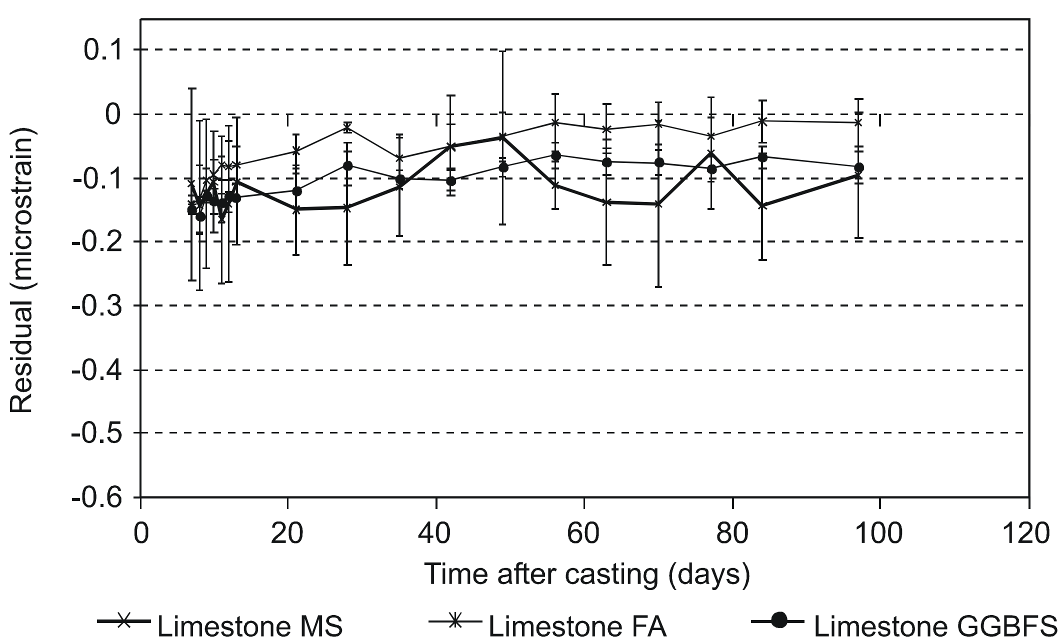

Figure 32. Residuals of Basic Creep of Portland Cement plus Mineral Admixture Concrete and Sakata Model

MODEL COMPARISON

The *residual sum of squares* (RSS) of the experimental mean and the model predicted value was used to comparatively evaluate the models. The model with the smallest test statistic is the best predictor. The models were divided into the total strain, the drying shrinkage strain, and the basic creep. The 28 day and 97 day residual values were examined to better understand the short-term, and the long-term behavior of each model.

Short term – 28 Days

Portland Cement Concrete Mixtures

Figures 33 through 35 present the RSS values of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures. The models that predict the total strain best, in order of accuracy, are the Sakata, ACI 209, and CEB 90 models. The Bazant and Gardner models are the least accurate predictors for the total strain. The limestone mixture has the least accurate prediction of the mixtures.

The drying shrinkage predicted by the Sakata, Gardner, Bazant, and CEB 90 models, are the most accurate. The ACI 209 model does not predict the drying shrinkage accurately.

The Sakata, ACI 209, Bazant, and CEB 90 models predict the basic creep more accurately than the Gardner model.

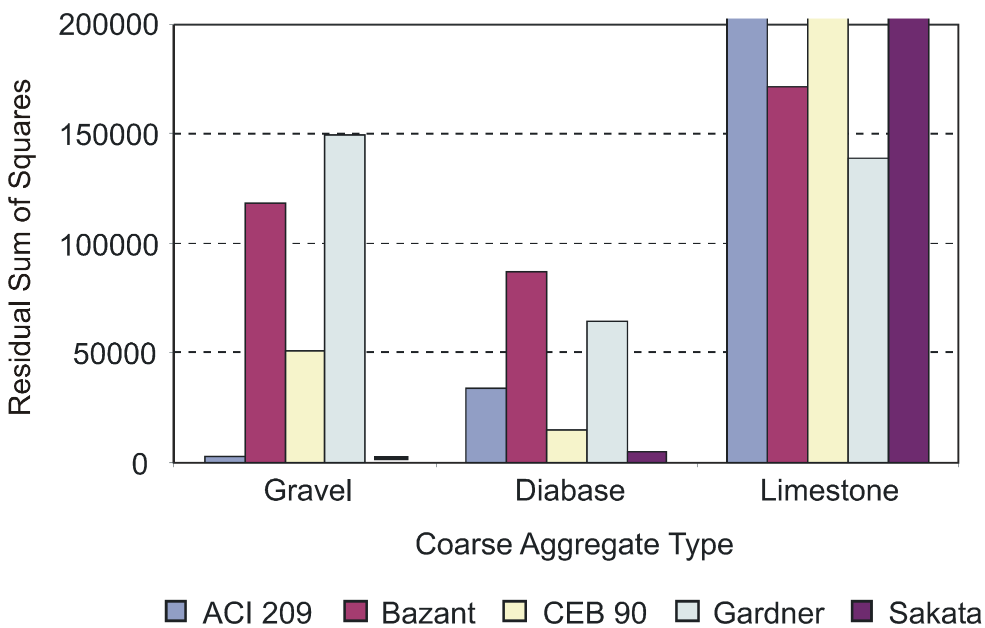

Figure 33. RSS Analysis for Total Strain of Portland Cement Concrete at 28 Days After Casting (The residual is an average of three values)

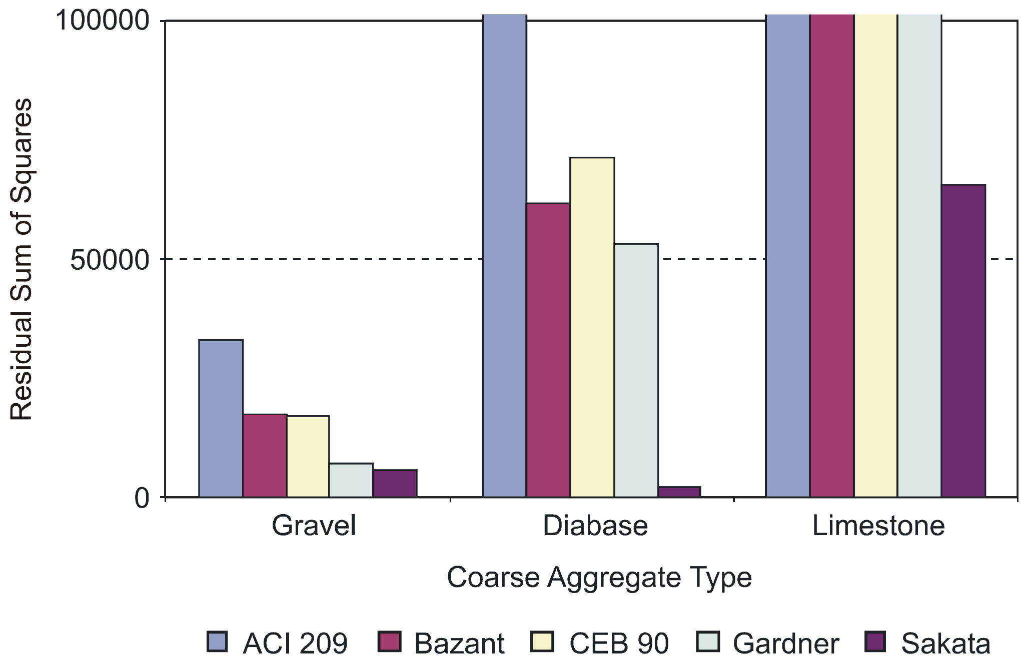

Figure 34. RSS Analysis for Drying Shrinkage of Portland Cement Concrete at 28 Days After

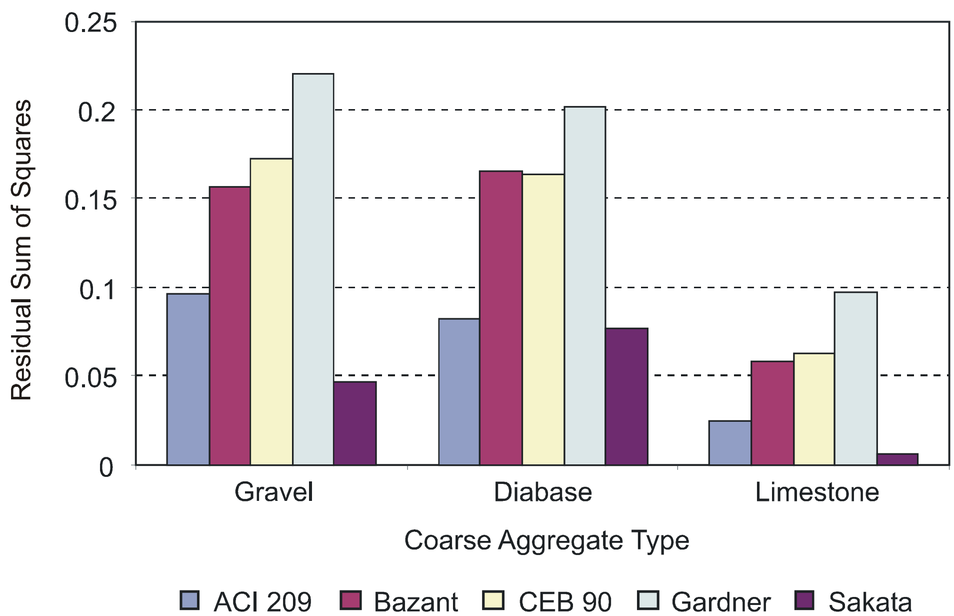

Figure 35. RSS Analysis for Basic Creep of Portland Cement Concrete at 28 Days After Casting

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 36 through 38 present the RSS values of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures. In general, the mineral admixture concrete mixtures are more precise than the mixtures with the portland cement.

The model that predicts the total strain with the most precision and accuracy is the CEB 90 model. The Bazant, the Gardner, ACI 209, and Sakata all predict the total strain fairly accurately, but are not as precise as the CEB 90 model.

The models, with the exception of the Sakata model, predict the drying shrinkage strain more precisely and accurately for concretes containing fly ash or slag than silica fume.

The Gardner model is the least accurate when predicting the basic creep. The Sakata, ACI 209, Bazant, and CEB 90 models are similar in precision and accuracy for the prediction of basic creep.

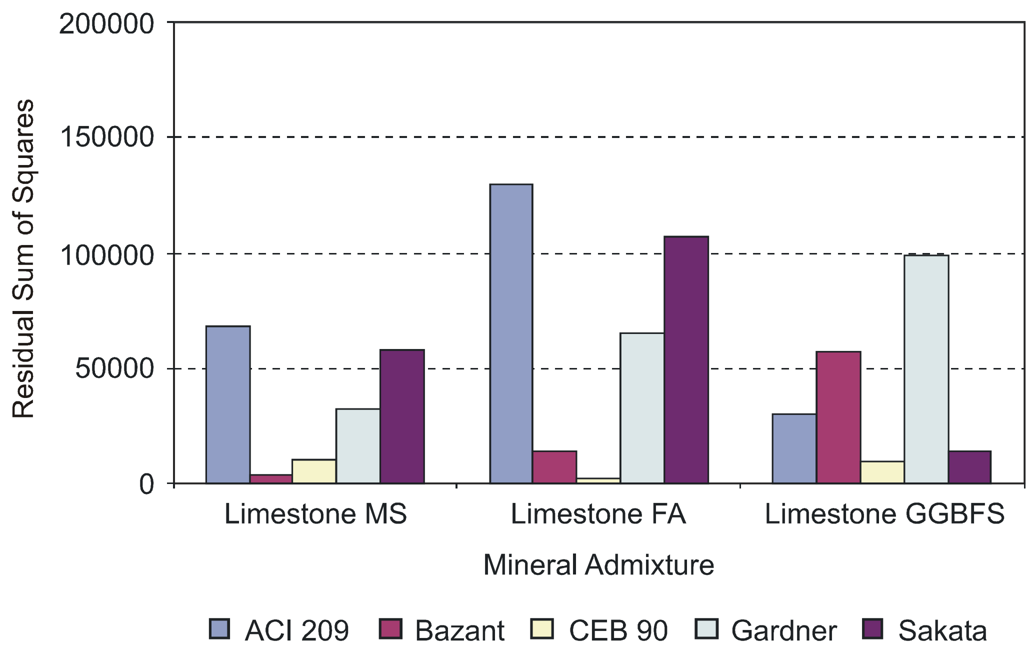

Figure 36. RSS Analysis for Total Strain of Portland Cement plus Mineral Admixture Concrete at 28 Days After Casting

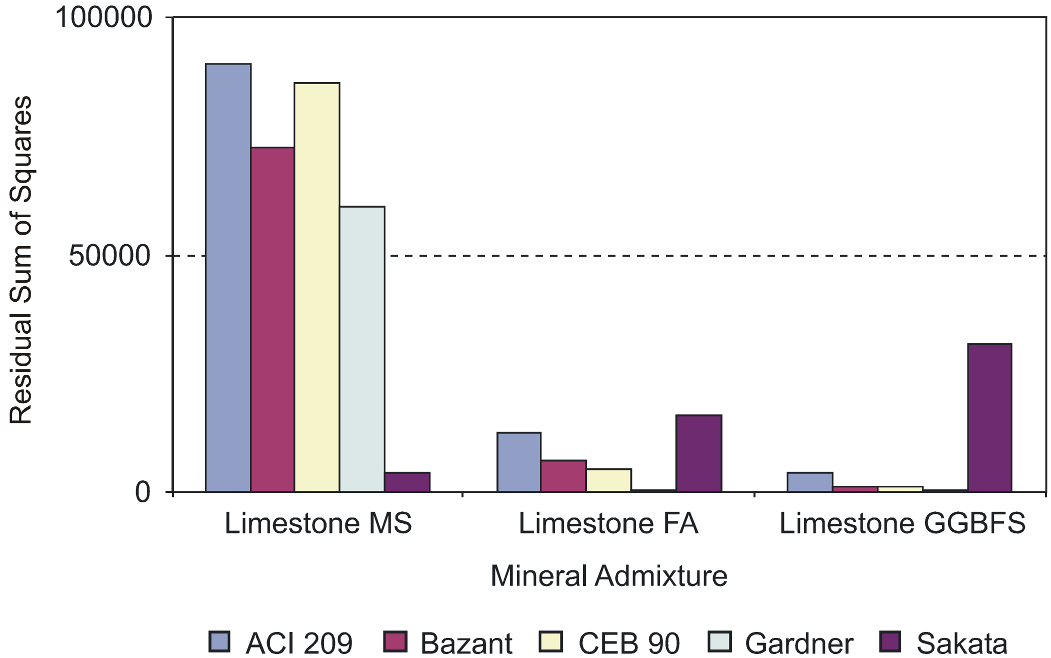

Figure 37. RSS Analysis for Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete at 28 Days After Casting

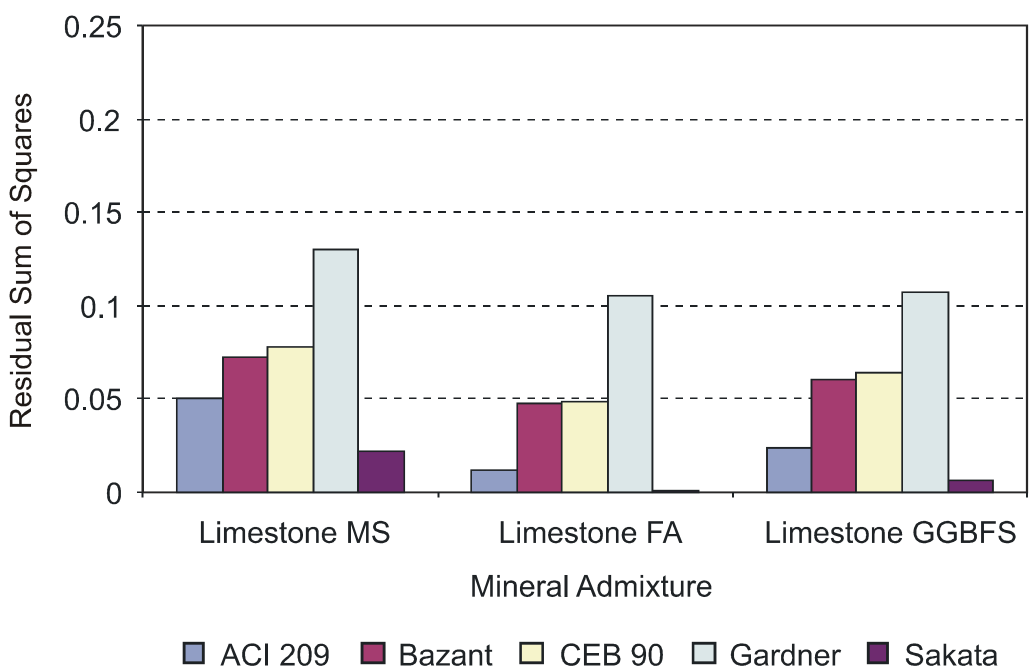

Figure 38. RSS Analysis for Basic Creep of Portland Cement plus Mineral Admixture Concrete at 28 Days After Casting

Long term – 97 Days

Portland Cement Concrete Mixtures

Figures 39 through 41 present the RSS values of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement concrete mixtures. The models that predict the total strain in the order of accuracy are the Sakata, CEB 90, and ACI 209 models. The Bazant and Gardner models are the least accurate predictors for the total strain. All the models predict the limestone mixture with the least accuracy.

The drying shrinkage predicted by the Sakata, Gardner, Bazant, and CEB 90 models, are the most accurate. The ACI 209 model does not predict the drying shrinkage accurately.

The ACI 209, Sakata, Bazant, and CEB 90 models predict the basic creep more accurately than the Gardner model.

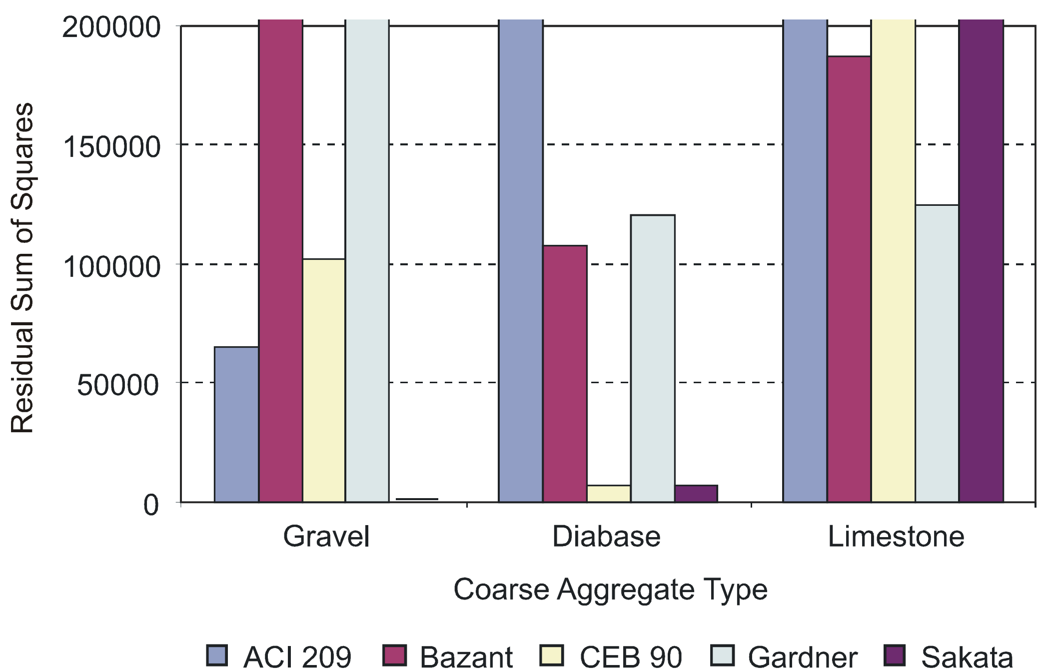

Figure 39. RSS Analysis for Total Strain of Portland Cement Concrete at 97 Days After Casting

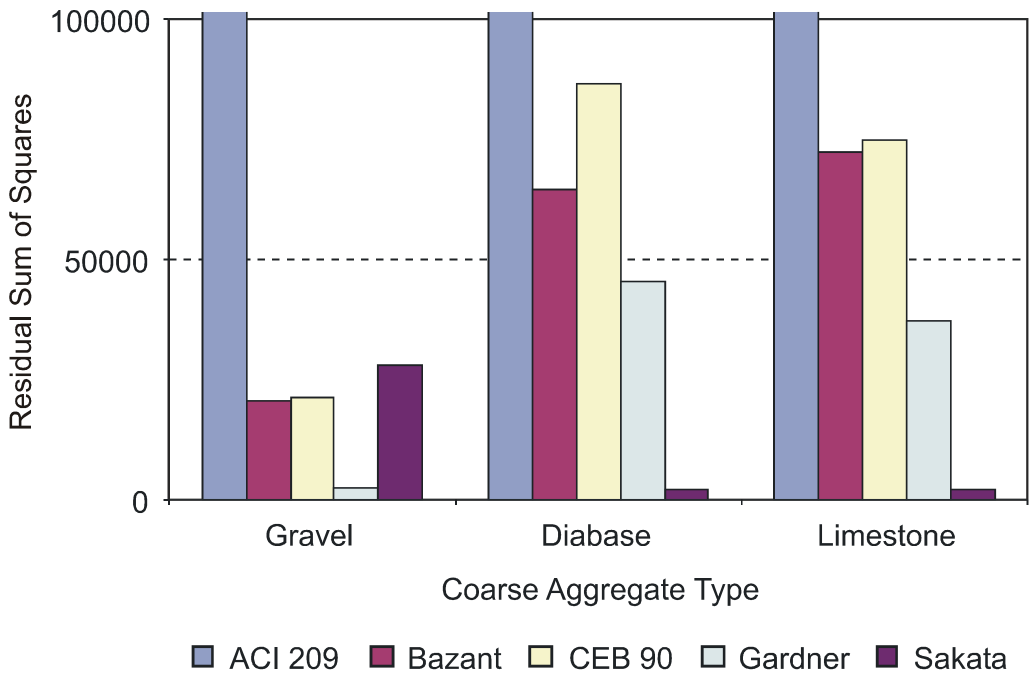

Figure 40. RSS Analysis for Drying Shrinkage of Portland Cement Concrete at 97 Days After Casting

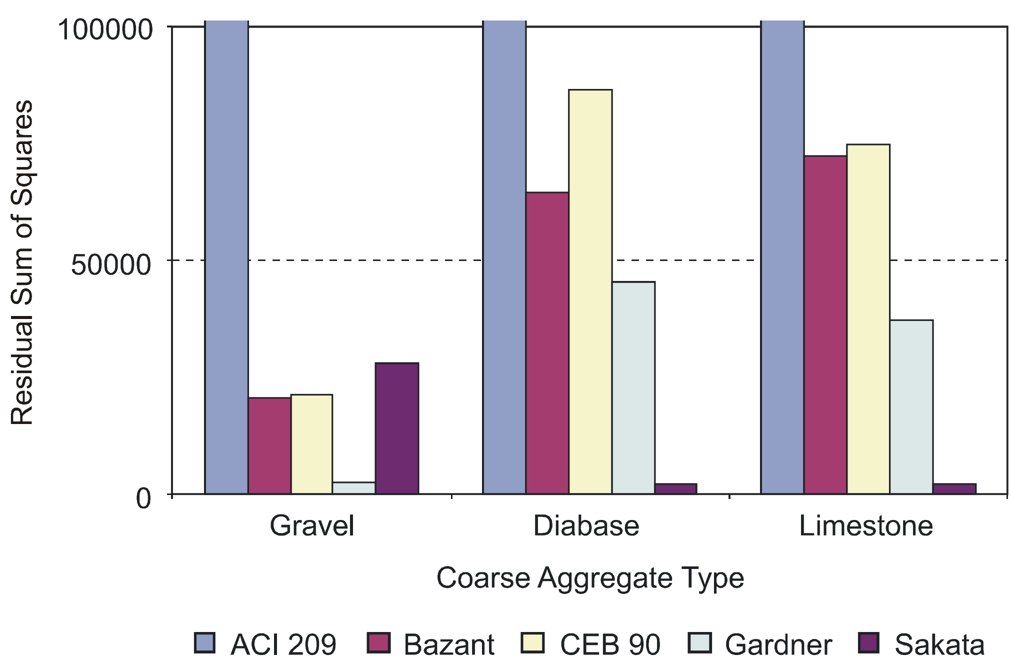

Figure 41. RSS Analysis for Basic Creep of Portland Cement Concrete at 97 Days After Casting

Portland Cement plus Mineral Admixture Concrete Mixtures

Figures 42 through 44 present the RSS values of the total strain, drying shrinkage strain, and basic creep, respectively, of the portland cement plus mineral admixture concrete mixtures. In general, the mineral admixture concrete mixtures are more precise than the mixtures with the portland cement.

The model that predicts the total strain with the most precision and accuracy is the CEB 90 model. The Sakata, Bazant, and ACI 209, all predict the total strain accurately. The Gardner model is inaccurate when predicting the total strain.

The Gardner, CEB 90, and Bazant models predict the drying shrinkage strain more precisely and accurately than the Sakata and ACI 209 models.

The Gardner model is the least accurate when predicting the basic creep. The Sakata, ACI 209, Bazant, and CEB 90 models are similar in precision and accuracy for the prediction of basic creep.

In general, the limestone portland cement concrete mixture has the most variability and least precision than the other mixtures. When comparing the models for short and long term accuracy and precision, the models for the short term time periods are better predictors.

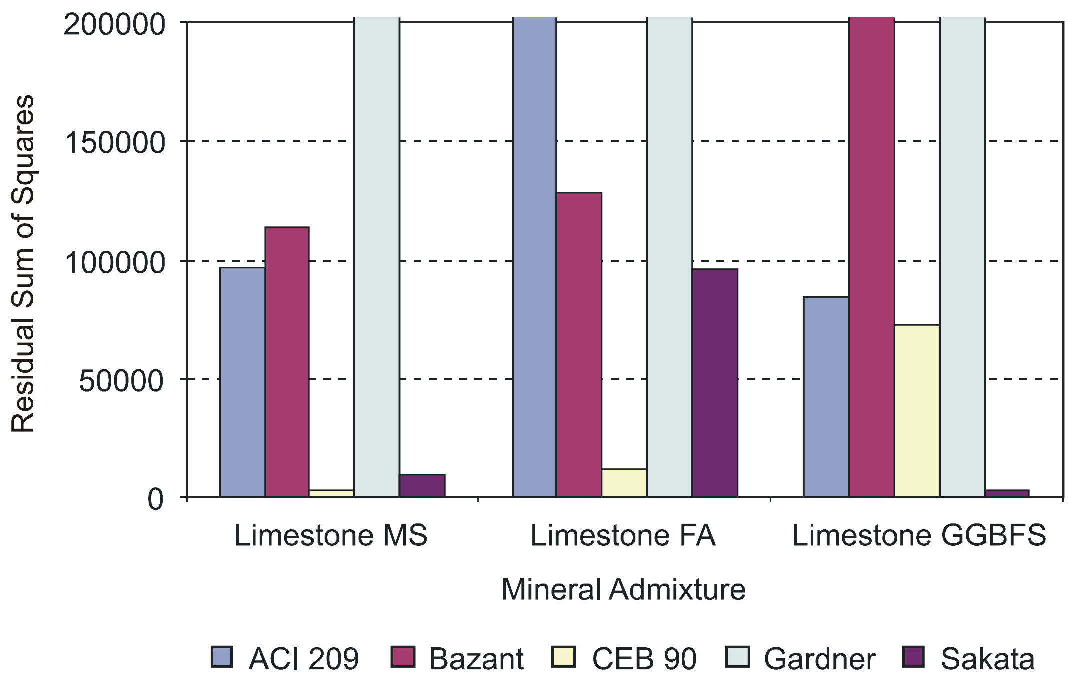

Figure 42. RSS Analysis for Total Strain of Portland Cement plus Mineral Admixture Concrete at 97 Days After Casting

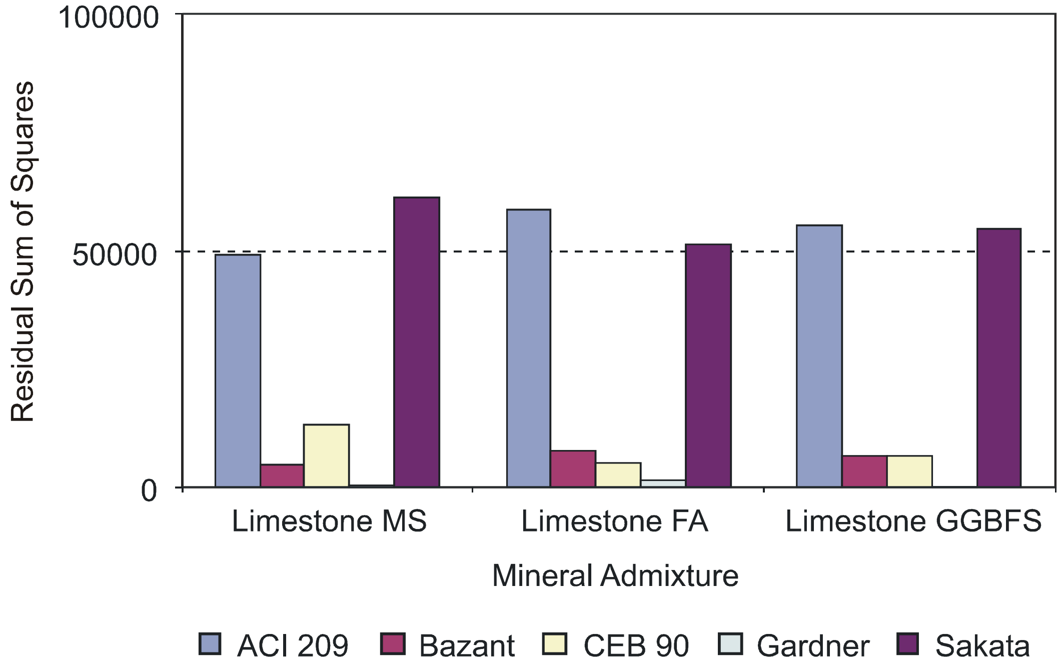

Figure 43. RSS Analysis for Drying Shrinkage of Portland Cement plus Mineral Admixture Concrete at 97 Days After Casting

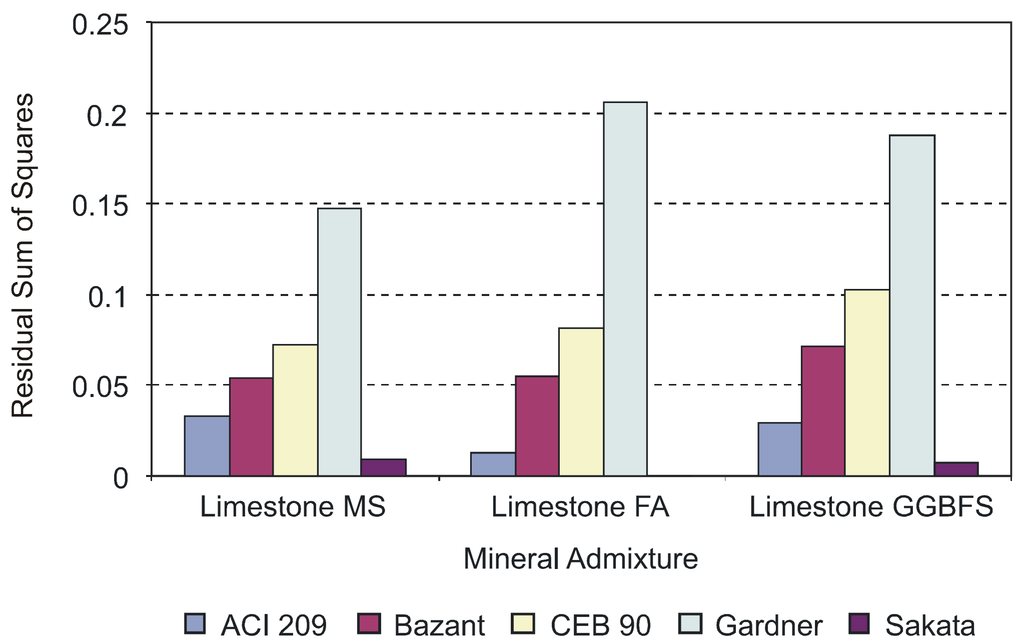

Figure 44. RSS Analysis for Basic Creep of Portland Cement plus Mineral Admixture Concrete at 97 Days After Casting

Figures 45 and 46 present the difference between the prediction models and the AASHTO LRFD design for basic creep strain. Values were calculated by the following equation:

(AASHTO – Model) / Model x 100

The model value was calculated by taking the average prediction values of all the mixtures. The CEB 90, Bazant, and Gardner models ranged from –50% to approximately 150% difference over time. The ACI 209 and Sakata models ranged from –50% to approximately 250% difference over time. A positive value represents the model under predicting the AASHTO design. The percent differences increase as time progresses.

DISCUSSION

This section discusses the results of the ASTM C 39-96 and ASTM C 469-94 test methods, the variability of total strain between and within the batches, and the residuals of the experimental data and each prediction model: the ACI 209, CEB 90 Euro-Code, Bazant Model, Gardner Model, and Sakata Model.

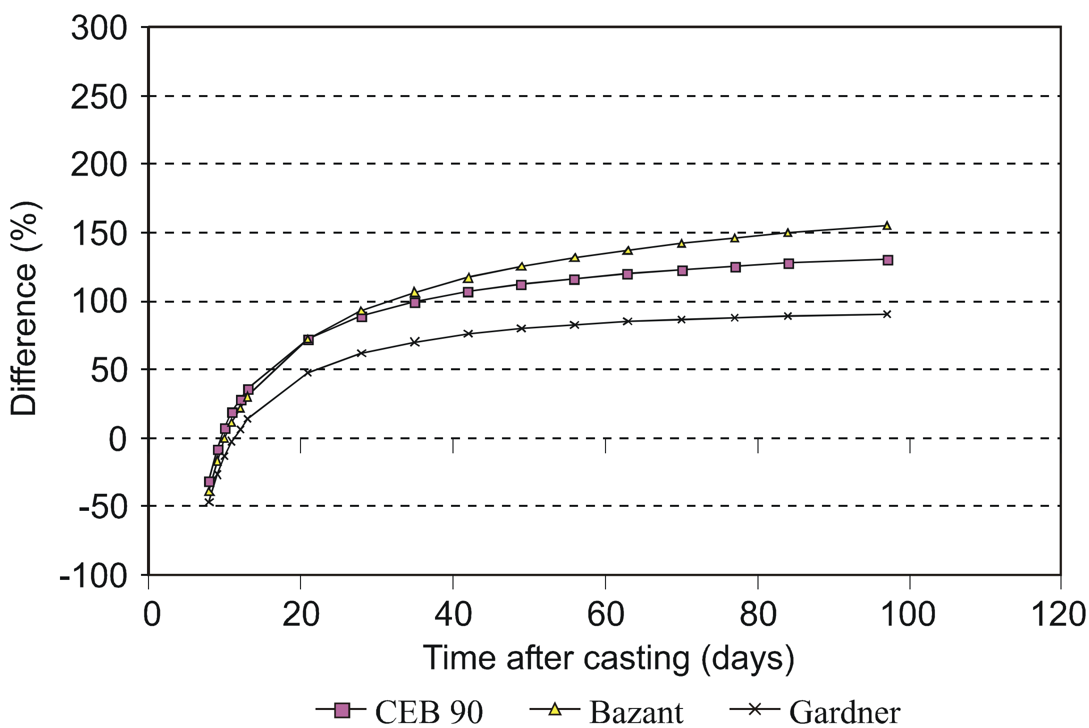

Figure 45. Percent Difference between AASHTO LRFD Design Values and Model Prediction, for Creep Strain (Percent)

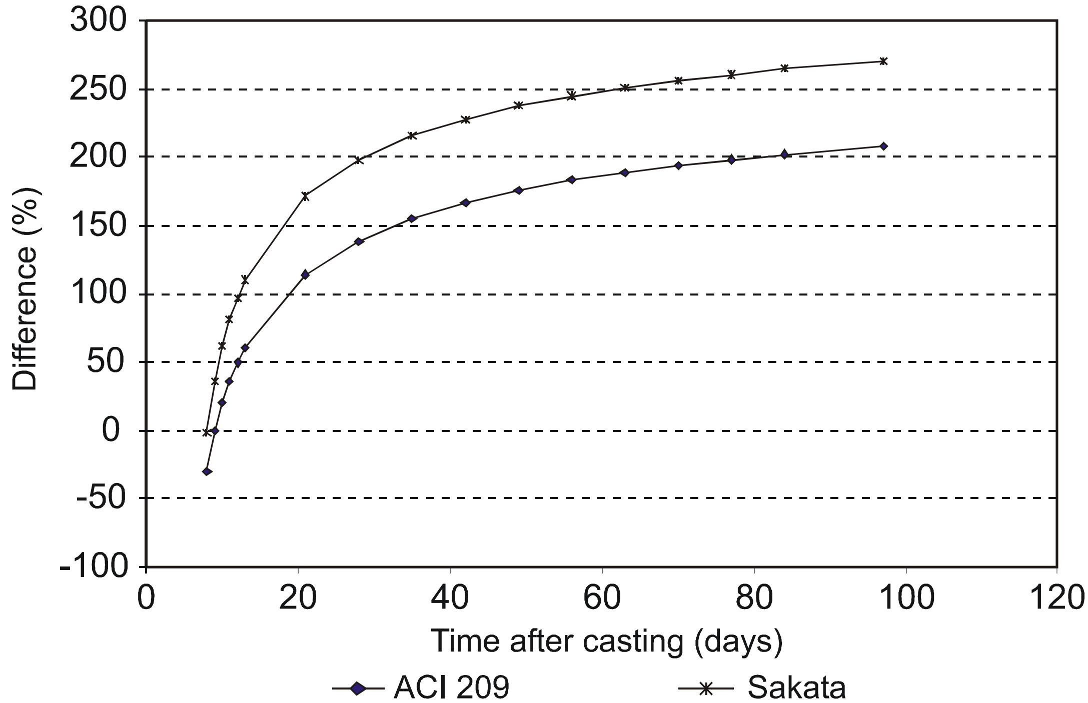

Figure 46. Percent Difference between AASHTO LRFD Design Values and Model Prediction for Creep Strain (Percent)

Compressive Strength and Modulus

ASTM C 39-96

The limestone mixture has a higher compressive strength and lower w/c ratio than the gravel and diabase mixtures. As the w/c ratio decreases, the compressive strength increases for a mixture with the same aggregate. The compressive strengths for the gravel and diabase mixtures are not significantly different, although the gravel mixture has a lower w/c ratio. This is a result of the surface mechanics of the aggregate. The gravel aggregate has fewer fracture surfaces than the diabase aggregate, and this likely affects the mechanical bond between the aggregate and the cement paste.

The limestone-SF mixture has a higher compressive strength and lower w/c ratio than the limestone-Slag and limestone-FA mixtures. The compressive strength for the limestone-SF mixture is larger than the compressive strength of the limestone mixture without a mineral admixture. This is a result of the SF having a finer particle distribution. The finer particles allow the cement paste to hydrate at a faster rate than normal portland cement. The desired compressive strength is reached at earlier ages. The addition of SF in a concrete mixture will increase the compressive strength at all ages of the concrete compared to the compressive strength of a mixture with normal portland cement.

The compressive strengths for the limestone-Slag and limestone-FA mixtures are not significantly different. The limestone-Slag mixture has a slightly lower compressive strength than the limestone mixture without a mineral admixture. The limestone-FA mixture at early ages has a considerable lower compressive strength than the limestone mixture with portland cement. As the concrete ages, the limestone-FA compressive strength increases nearing the strength of the limestone mixture with portland cement. The two mineral admixtures, when added to the mixture, slow the hydration of the cement paste, and the desired compressive strength is reached at later ages.

When compared to the compressive strength of normal portland cement concrete, the addition of Slag or FA to a concrete mixture decreases the 7-day compressive strength, and become uniform at later ages.

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The seven-day and 28-day modulus for the gravel mixture is lower than the modulus for the limestone and diabase mixtures. The surface area on the gravel aggregate is less than the surface area of the limestone and diabase aggregates. The area of contact between the gravel aggregate and the cement paste is less, resulting in a lower modulus. The 28-day modulus for the diabase mixture decreased, due to variability in the testing procedure.

The modulus for the limestone-Slag, limestone-SF, and limestone-FA concrete mixtures are not significantly different. The elastic modulus for the limestone mixture with portland cement is similar to the values produced by the mixtures with mineral admixtures.

Variability of the Total Strain Batch Data

The variability of total strain between the batches is the variation of the process from day-to-day, or batch-to-batch, batching and mixing combined. The variability within the batch is the inherent variation of experimental error. The experimental error represents the variability of each strain reading for one test cycle.

Portland Cement Concrete Mixtures

The limestone, diabase, and gravel total strain variability between batches is approximately 75%, 65%, and 45% respectively. The limestone mixture has the largest between batch variability. The limestone mixture was tested in the first testing cycle. The error due to learning the day-to-day methodology of the test is most likely the cause of the higher variability. The diabase and gravel mixtures were prepared in the second testing cycle and exhibit a lower variability between the batches.

The limestone, diabase, and gravel total strain variability within batches is approximately 25%, 35%, and 55% respectively. The variability of the limestone mixture within the batch is the lowest, because the majority of the variability is between the batches due to learning error. The diabase mixture has a lower within batch variability than the between batch variability, which is to be expected. The gravel mixture variability within and between batches is similar, due to the inherent variability of the material, and the testing procedure.

Portland Cement plus Mineral Admixture Concrete Mixtures

The limestone-SF, limestone-FA, and limestone-Slag total strain variability between batches is approximately 90%, 70%, and 60% respectively. The variability between the batches for the limestone-SF is particularly high. The limestone-SF mixture was also tested in the first testing cycle. Error due to learning the day-to-day methodology in the test is the result of the higher variability. The limestone-FA and limestone-Slag mixtures have similar between batch variability. Both mixtures were tested in the third testing cycle.

The limestone-SF, limestone-FA, and limestone-Slag total strain variability within batches is approximately 10%, 30%, and 40% respectively. The variability of the limestone MS mixture within the batch is the lowest, because the majority of the variability is between the batches due to learning error. The limestone-FA and limestone-Slag mixtures have a lower within batch variability than the between batch variability, which is to be expected.

Creep Prediction Models

The models have various factors that contribute to an accurate prediction of creep and shrinkage. Each parameter limitation is further explained in the Model Limitations found elsewhere (Meyerson, 2001). The most influential model parameter, in the case of the VDOT mixtures is the w/c ratio. The Bazant model was developed using w/c ratios of 0.35 to 0.85, and the Sakata model was developed using w/c ratios of 0.4 to 0.6. The concrete mixtures used have w/c ratios lower than what is required by the model. This must be taken into consideration when looking for the best prediction model.

The model prediction results are presented as residuals, the difference between the experimental mean and the model value. If the model is under predicting the experimental mean, the residual will have a positive value. If the model is over predicting the experimental mean, the residual will have a negative value. All five models predict the total strain as the sum of the drying shrinkage strain and basic creep.

The limestone mixture has a larger variability than the other mixtures due to learning error. Therefore, the limestone mixture values will not have much weight when deciding which model is the best predictor.

Each model under predicts the drying shrinkage and over predicts the basic creep, resulting in a good prediction of the total strain, some models being more accurate than others. In the context of the models, basic creep is the difference between the total strain and the drying shrinkage. All of the models under predict the drying shrinkage. This calls to question the ability of the test method to predict the drying shrinkage. If the measured drying shrinkage is higher than predicted due to the testing procedure, then the basic creep should be less than predicted. This is the case for the ACI 209, CEB 90, Bazant, Gardner, and Sakata models.

There is no difference between the residuals when comparing mixtures with or without mineral admixtures. The variability of the results is less for the mixtures with mineral admixtures. The mineral admixture concrete mixtures were tested in the third testing cycle. The variability in the third testing cycle appears to be much less than that of the first testing cycle.

Based on average RSS analysis results, the following rankings can be made for the models:

- At 28 days, the order of best prediction of total strain is the CEB 90, Sakata, ACI 209, Bazant, and Gardner models respectively. At 97 days, the order of best prediction of total strain is the Sakata, CEB 90, ACI 209, Bazant, and Gardner models respectively.

- At 28 days, the order of best prediction of drying shrinkage strain is the Sakata, Gardner, Bazant, CEB 90, and ACI 209 models respectively. At 97 days, the order of best prediction of drying shrinkage strain is the Gardner, Bazant, CEB 90, Sakata, and ACI 209 models respectively.

- At 28 days, the order of best prediction of basic creep strain is the Sakata, ACI 209, Bazant, CEB 90, and Gardner models respectively. At 97 days, the order of best prediction of basic creep strain is the Sakata, ACI 209, Bazant, CEB 90, and Gardner models respectively.

It can be concluded that the CEB 90 model is the best predictor for total strain up to 97 days for concrete mixtures with or with out mineral admixtures. Total strain is the most relevant parameter for prestress loss, because it accounts for the combined effects of both compressive creep and shrinkage. Hence, of the models examined, the CEB 90 is best suited for use in estimating prestress loss. The later ages of the prediction are less accurate. The CEB 90 model for example has a 28-day RSS value of 17300, and a 97-day RSS value of 39100. This is also true for the ACI 209, Bazant, and Gardner models. The Sakata model remains consistent over time.

Creep Models and the AASHTO LRFD

The performance specifications are limited to all of the mixtures examined in this study. Due to the large error in the limestone mixture, the total strain values will be disregarded when determining the performance limits for the mixtures. Since there is no significant difference between the mixtures at a five percent significant level, the average of the total strain at 28 and 97 days for all the mixtures, except the limestone mixture, will be used.

The total strain for the VDOT portland cement concrete mixtures discussed in this study should be between 1180 ± 110 microstrain at 28 days, and 1620 ± 110 microstrain at 97 days, at a five percent significant level.

The CEB 90 model is the best model to apply to prestress losses. Values obtained apply for the losses due to creep and shrinkage.

The ultimate creep coefficient C_u is defined as the product of the basic creep per unit stress and the elastic modulus of the concrete. The stress losses due to creep is defined as the product of the ultimate creep coefficient, C_u, the ratio of the elastic modulus of the prestressing steel and the elastic modulus of concrete, and the stress of the prestressing steel at the level of the steel centroid. The CEB 90 model accounts for the prediction of the basic creep.

The losses due to shrinkage are expressed as the product of the elastic modulus of the prestressing steel and the shrinkage strain. The CEB 90 model predicts the shrinkage strain and there is a direct correlation between the model and prestress losses.

The prediction of creep and shrinkage combined, apply to the total affects of the losses of prestressing force in prestressed beams.

Figures 45 and 46 present the difference between the AASHTO LRFD design and the prediction models for basic creep strain (Barker and Puckett, 1997). Values were calculated by the following equation:

$$(\text{AASHTO} - \text{Model}) / \text{Model} \times 100$$

The model value was calculated by taking the average prediction values of all the mixtures. The CEB 90, Bazant, and Gardner models ranged from –50% to approximately 150% difference over time. The ACI 209 and Sakata models ranged from –50% to approximately 250% difference over time. A positive value represents the model under predicting the AASHTO design. The percent differences increase as time progresses. The prediction errors arise from the limited mixture parameters that can be used in developing any single model and add to the conservative nature of structural design. Despite the errors, the models have utility in the design process when compared to the alternative of measuring creep on a near infinite number of concrete mixtures available. Identifying a more accurate model, for instance the CEB 90, for use in the AASHTO LRFD rather than the currently used ACI 209 model will permit more efficient use of materials.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The CEB 90 Model predicts the creep and shrinkage strain of prestressed concrete with the best precision and accuracy for the VDOT approved mixtures examined in this study.

The prediction of basic creep should be applied to the calculation of prestress losses due to creep, and the prediction of shrinkage strain should be applied to the calculation of prestress losses due to shrinkage.

There is no significant difference in creep between mixtures with or without mineral admixtures.

The total strain for the VDOT portland cement concrete mixtures discussed in this study were found to be 1200 ± 110 microstrain at 28 days, and 1600 ± 110 microstrain at 97 days, at a five percent significant level.

Recommendations

- The CEB 90 model should be used to calculate prestress loss for structural design purposes.
- When running a creep test cycle, no fewer than two batches of the same mixture should be used to reduce the influence of testing variability.
- Further research should be conducted on the Bazant and Sakata prediction models to allow for limitations of w/c ratio to be lower than the ranges specified by the models.
- Future research should be conducted on the effect of shrinkage reducing admixtures on the compressive creep of concrete mixtures.

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APPENDIX A: MODEL PARAMETERS

Model Limitations

Each model has various complexity and limitations. The table below presents each model variable and the corresponding limitations.

Variable	ACI 209	CEB 90	Bazant	Gardner	Sakata
f_{cm} (psi)	-	2,900-13,000	2,500–10,000	2,900-10,000	-
a/c	-	-	2.5-13.5	-	-
c (lbs/ft^3)	-	-	10-45	-	16-31
w/c	-	-	0.35-0.85	0-0.6	0.4-0.6
H (%)	40-100	40-100	40-100	40-100	40-80
Cement Type	I or III	R, SL or RS	I, II or III	I, II or III	I or III
t_o or t_s (moist cured)	≥ 7 days	-	$t_s \leq t_o$	≥ 2 days	≥ 7 days
t_o or t_s (steam cured)	≥ 1-3 days	-	$t_s \leq t_o$	≥ 2 days	≥ 7 days

Where;

f_{cm} = 28 day mean compressive strength

a/c = Aggregate to cement ratio (by weight) c = Cement content

w/c = water to cement ratio (by weight)

H = Relative humidity

Cement Type

ASTM Type I = Normal portland cement

ASTM Type II = Moderate sulfate resistance cement

ASTM Type III = High early strength cement

R = Equivalent to ASTM Type I

SL = Equivalent to ASTM Type II

RS = Equivalent to ASTM Type III

t_o = Age of concrete at loading

t_s = Age of concrete at the beginning of shrinkage