Prestress Loss in Externally FRP Reinforced Self Prestressing Concrete Beams

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Abstract

Hybrid fiber-reinforced polymer (FRP) reinforced expansive concrete (EC) structural system shows a good potential for delaying concrete cracking and eliminating steel corrosion. In this study, long-term expansion-shrinkage strain development and prestress loss of the proposed system are investigated. Test results were evaluated based on maximum expansion strain, concrete strength and strain loss. An analytical model consisting of shrinkage, creep of expansive concrete as well as relaxation of steel was developed from GL2000. The comparison of the strain loss between tested results and calculation was presented. Results show that lime-system EC presents a higher prestress strain and lower prestress loss than ettringite-system EC in the long term. Calculated results from the developed model and experimental data show a good agreement.

Keywords: FRP; expansive concrete; shrinkage; creep; prestress loss

1. INTRODUCTION

The major cause of cracking in bridge decks and concrete pavements, as well as slabs on grade, is due to restrained shrinkage of the concrete and warping stress. One possible method of eliminating the cracking and increasing cracking resistance is to use expansive cement concrete known as expansive concrete (EC). Researchers investigated EC using ettringite forming cement during the early 70's. After those early studies on ettringite-system cement, Russell et al. [1] studied lime-system cement EC mixes to develop an expansion between 0.03% and 0.1% while keeping a minimum concrete strength of 27.6 MPa (4000 psi). One problem for lime-system EC is that it has been found difficult to achieve a timely bond from the paste onto the "internal" reinforcement for the EC [1]. Cao and Ma [2-3] proposed a hybrid structural system using a combination of fiber-reinforced polymer (FRP) composites with EC, and conducted a series of expansion and third-point loading experiments to study the short term and long term behavior of the proposed hybrid FRP-EC beams. It was shown that the proposed system developed a residual pre-stressing effect. Tests also showed that the pre-stressing effect from the expansion of EC increases as the axial stiffness of the FRP reinforcement increases [2-3].

The expansion and shrinkage period monitored in Cao and Ma's [2-3] tests was 28 days. However, whether a stable long-term prestress level can be achieved in the FRP-EC structural system has not been studied. Whether and how much the prestress generated by EC expansion and FRP confinement will be lost is critical to evaluate the structural system in the long-term. ACI 209 [4] used simplified methods to predict creep, shrinkage and temperature effects on reinforced and prestressed concrete structures which do not include expansive concrete specimens. Polivka [5] studied various factors influencing the expansion characteristics of ettringite-system expansive cement concretes. It was pointed out that expansive cement concretes are classified as expansive concrete and self-stressing concrete depending on the

1 restrained expansion level or prestress level. The compressive stress level of 0.172 to 0.689
2 MPa (25 to 100 psi) is normally designed in expansive concrete to minimize the cracks due to
3 drying shrinkage. On the other hand, the practical range of self-stressing could be about 1.034
4 to 3.447 MPa (150-500 psi) compressive stress which will let concrete remain in compression
5 after the stress loss due to shrinkage [5]. Benuska et al. [6] studied the effect of different curing
6 schemes on long term prestress condition of eight precast slabs. Test results indicated that the
7 investigated five specimens reached about 1.379 to 2.068 MPa (200-300 psi) prestress level
8 after six months.

9 He et al. [7] studied long-term expansive behavior of self-stressing expansive concrete with
10 combined restrictions of steel fibers and steel bars and concluded that no significant self
11 prestress loss was observed after three-year long-term data recording for all specimens. It was
12 indicated that specimens without steel rebar showed higher expansion strain than those of
13 specimens with rebar. The detailed expansive cement usage and water cement ratio for
14 concrete mix were not reported. Richardson et al. [8] monitored the axial strains in the slabs of
15 a flat-plate post-tensioned EC parking deck. Test results showed that EC experiences a
16 significant less creep and shrinkage than that predicted by design for normal concrete within a
17 two-year period.

18 Since a stable long-term self prestress level is crucial to explore the FRP-EC structural
19 system, a series of tests on the long-term expansion of the proposed FRP-EC beam are
20 conducted in this study. The comparisons of the maximum self prestress strain and prestress
21 loss for different types of concrete and reinforcement are made. Three types of concrete include
22 Portland cement concrete (PCC), ettringite-system EC and lime-system EC. Reinforcement
23 consists of three categories: un-reinforcement, steel reinforcement and CFRP reinforcement.

24 25 **2. RESEARCH SIGNIFICANCE**

Although the long-term expansive behavior of steel reinforced EC has been investigated by previous researchers, the EC system externally reinforced with FRP has not been studied. With the concept of using FRP wrapping around EC proposed by Cao and Ma [2-3], the long-term expansion behavior and prestress loss of the proposed system are conducted in this research. The data generated from this research will contribute to the understanding of whether and how much the existing prestress will be lost in the long term. The results of experiments and the analyses reported in this paper will benefit utilizing of self prestressing effect and future development of design guidelines for the proposed system.

3. EXPERIMENTAL PROGRAM

3.1. Specimen design

Fifteen beams with the same dimensions were fabricated for expansion monitoring and static bending test, with three different concrete materials. In the previous study conducted by Cao and Ma [2-3], the shear-span-to-depth ratio of the tested beam is 1.0. To increase the ratio, the designed length of the beam was increased to 914 mm (36 in.) in this study. **Table 1** lists the experimental matrix of tested beams. Test specimens consist of three types of reinforcement: without reinforcement, steel reinforcement and CFRP reinforcement. The axial reinforcement stiffness (EA) for the five different reinforcement scenarios is also shown in **Table 1**. Each specimen is 914 mm (36 in.) long, 152 mm (6 in.) wide and 152 mm (6 in.) deep. The steel rebar is welded with a head on each end embedded in concrete. The head diameter is 32 mm (1-1/4 in.) and the thickness is 13mm (0.5 in.). The prefabricated CFRP sheets serve as forms for the cast-in-place concrete. Five beams were tested for each concrete mix and three beams were tested for each type of reinforcement. The steel reinforcement used was straight deformed wire reinforcement (DWR) rebar with 16 mm diameter (#5). The DWR specimen has a 25 mm (1 in.) cover at the bottom. **Fig. 1** shows cross sections of three types of specimens.

Strain gages were used to measure the strain in the reinforcement. The strain gages allow for direct strain readings of the rebar and CFRP. One strain gage was installed on the center of steel rebar for steel reinforced specimen. CFRP sheet were used to wrap concrete-core at four sides to make CFRP reinforced specimens. **Fig. 2** shows geometry and instrumentation of CFRP reinforced beam specimens.

3.2. Specimen fabrication

Carbon fiber-reinforced polymer (CFRP) sheets were fabricated by a hand lay-up process in the laboratory. Carbon fiber and epoxy resin as well as resin hardener were used to fabricate CFRP specimen. The molds for CFRP fabrication were internal molds. The mold dimension is 914 mm (36 in.) long by 152 mm (6 in.) wide and 152 mm (6 in.) high. The resin system for CFRP fabrication was epoxy resin mixed well with hardener. The mixed resin was applied to the carbon fiber by squeezing the fiber with a roller for evenly distributing the resin on the fiber. Once the fiber was saturated with resin, the mold was wrapped with the pre-made fiber reinforced polymer. The specimens were kept at room temperature and humidity ($20 \pm 2^\circ\text{C}$, 60% RH) for 24 hours until releasing the molds. After that, the specimens were cured for seven days in the same condition. Three specimens were made and used for testing for each of one-layer, two-layer and three-layer CFRP.

The concrete specimens were fabricated and cured in the laboratory following ASTM 192 [9]. Both ettringite-system cement and lime-system cement were used to produce two kinds of EC. Portland cement concrete (PCC) was used to serve as control specimens. Steel and wood molds were used for pouring control specimens and steel reinforced specimens. CFRP specimens were used as molds for CFRP reinforced specimens. The target concrete compressive strength at 28 days was 41.4 MPa (6000 psi). Concrete cylinders were made concurrently with the pouring of beams. The compressive strength of concrete at 7 days, 28 days and time of beam bending test are shown in **Table 2**.

3.3. Long-term expansion test

Fifteen specimens were tested as shown in **Table 1**. Each beam specimen was fitted with two strain gauges attached at the top and bottom CFRP surface before casting. The gauges were wire connected to a data acquisition system to record the strain (length change rate) over concrete expansion and shrinkage process. Concrete was made and poured into the molds and CFRP specimens. **Fig. 3** shows the picture of the beam specimen after the concrete was casted. After casting, the specimens were cured by covering the top surface with wet burlaps and plastic. Based on the curing scheme, the burlap was kept wet constantly during first 28 days at a room temperature of 73°F and a relative humidity of 74%. After 28 days, burlap was removed and plastic was remained on top of specimens. The strain data on the FRP layer were collected over the entire curing time. The monitoring periods for PCC, ettringite-system EC and lime-system EC specimens were 224 days, 218 days and 154 days respectively.

4. RESULTS AND DISCUSSION

4.1. Expansion strain vs. age

Fig. 4 shows expansion (shrinkage) over time curves for specimens made with ettringite-system EC and lime-system EC. The strains shown on the vertical axis in **Fig. 4** represent the average values from strain gages on both sides of CFRP specimens. The effect of temperature from the heat of hydration on the strains has been corrected in the data acquisition system. In general, lime-system EC shows a higher expansion strain than ettringite-system EC. For lime-system EC specimens, expansive strain increases rapidly in the first 24 hours. Because the concrete mixes for specimen SL and F1L were trial batches, which were different from the mix for F2L and F3L, the comparison of expansion strain over time for specimen F2L and F3L was only plotted in **Fig. 4 (a)**. **Fig. 4 (a)** also shows that as CFRP reinforcement ratio increases from 2-layer to 3-layer reinforcement, the maximum strain decreases. It indicates that the expansion strain on CFRP decreases as axial stiffness (EA)

1 increases. For ettringite-system EC specimens, as can be seen in **Fig. 4 (b)**, expansive strain
2 increases to a maximum value in about 50 to 60 days, then it starts to drop as concrete shrinks.
3 All the expansion strain of specimen F3E loses at the end of 218 days. Compared with
4 ettringite-system EC, lime-system EC specimens maintain a much higher expansion strain
5 during the monitoring period. **Fig. 5** shows the effect of axial reinforcement stiffness on the
6 maximum expansion strain for both ettringite-system EC and lime-system EC. The axial
7 reinforcement stiffness is calculated by multiplying elastic modulus of steel (or CFRP) by the
8 cross sectional area of steel (or CFRP). Also, lime-system EC shows higher maximum
9 expansion strain than ettringite-system EC for the same reinforcement stiffness, which is due to
10 the higher expansion property of lime system expansive cement material.

11 **4.2. Prestress Loss**

12 The relative strain loss was calculated by using the difference between the maximum strain
13 and strain at final (152days) divided by the maximum strain. **Fig. 6** shows the comparison of
14 relative strain loss (percentage loss) for tested reinforced specimens. Three different CFRP
15 reinforcement cases (including 1-layer, 2-layer and 3-layer CFRP) were averaged for
16 comparison with steel reinforcement. As shown, the prestress loss of lime-system EC is 17%
17 for CFRP system and 23% for steel system. They are about one third of the losses of
18 ettringite-system EC, which are 51% and 64% respectively. The error bar added at 5% error
19 value indicates that the difference between the two EC systems is significant. This
20 demonstrates the lower prestress loss potential of lime-system EC and shows the benefit of
21 using lime-system EC. It also demonstrates that the expansion strain losses from FRP
22 specimens are slightly lower than those of steel specimens. It could be explained by the fact
23 that the axial stiffness of steel (40.0 MN) is lower than average stiffness of FRP (50.8MN).

24 The calculated compressive stress after losses is shown in **Table 3**. Compared with the
25 practical criteria of 1.034 to 3.447 MPa (150-500 psi) compressive stress reported by Polivka

[5] and Benuska [6], lime-system EC generates fairly high compressive stress at the end of 152 days. Furthermore, lime-system EC produces a higher prestress than ettringite-system EC due to its higher expansion and lower prestress losses. It can be seen in **Table 4**.

4.3. Analytical model of prestress loss

The prestress was built up through the expansion of concrete and restraint of external FRP. Consequently, the prestress loss of FRP-restrained concrete beam was due to shrinkage of concrete, creep of concrete, and stress relaxation of FRP.

The stress relaxation of FRP is ignored considering the fact that the prestress generated in FRP is comparatively much smaller than the ultimate strength of FRP. It is therefore reasonable to consider shrinkage and creep of concrete as the main factors in the prestress loss analytical model.

GL2000 model [10] is a comparatively accurate model to predict the shrinkage and creep of normal concrete. A modified model based on GL 2000 was proposed in this study considering the characteristics of restrained expansive concrete. As a result, an analytical model was put forward to predict the prestress loss of the FRP reinforced expansive concrete structural system in this research.

4.3.1. Calculation of shrinkage and creep in lime-system expansive concrete

Shrinkage equation:

$$\begin{aligned}\epsilon_{sh} &= \epsilon_{shu} \beta(h) \beta(t) \\ \beta(h) &= (1 - 1.18h^4) \\ \epsilon_{shu} &= 1000K \left(\frac{30}{f_{cm28}} \right)^{0.5} 10^{-6} \\ \beta(t) &= \left(\frac{t - t_c}{t - t_c + 0.15 \left(\frac{V}{S} \right)^2} \right)^{0.5}\end{aligned}\tag{1}$$

The starting date of shrinkage is taken as 28 days as the concrete beam specimens were cured by water spraying until 28 days. The top and bottom surface of concrete were accounted for calculation of S since the four sides of concrete specimens were wrapped with

1 FRP.

2 Creep equation:

3
$$J(t, t_0) = \frac{1}{E_{cm t_0}} + \text{specific creep} \quad (2)$$

4
$$\text{specific creep} = \frac{\Phi_{28}}{E_{cm 28}}$$

5
$$\Phi_{28} = \Phi(t_c) \left[2 \left(\frac{(t-t_0)^{0.3}}{(t-t_0)^{0.3}+14} \right) + \left(\frac{7}{t_0} \right)^{0.5} \left(\frac{t-t_0}{t-t_0+7} \right)^{0.5} + 2.5(1 - 1.086h^2) \left(\frac{t-t_0}{t-t_0+0.15(\frac{V}{S})^2} \right)^{0.5} \right] \quad (3)$$

6

7 Prestress was formed through expansion of expansive concrete which increased gradually

8 from zero. So the first part $\frac{1}{E_{cm t_0}}$ in Eq. (2), which is caused by the instant application of

9 prestress, is ignored. The maximum expansion was achieved at about one day after casting of

10 concrete, therefore starting date of creep was taken as 1 day, i.e., $\Phi(t_c) = 1$. However,

11 expansive concrete was cured by water-spraying during the first 28 days when it continued to

12 expand until 28 days. Expansion data indicated that creep of expansive concrete caused by

13 prestress in 28 days was equivalent to zero, therefore, it can be assumed that the creep was

14 cancelled out by expansion in the first 28 days. The apparent date of creep and shrinkage are

15 defined as the time when prestress starts to decrease which was taken as 28 day. The time

16 parameters used for the analytical model of shrinkage and creep are listed in **Table 5**. The

17 result of analysis can be seen in **Fig. 7** distinctly. The practical creep shown in **Fig. 7** was

18 calculated from the starting date (1 day). It represents the summation of apparent creep and

19 the creep which is cancelled out by expansion. Analytical curve in **Fig. 7** represents the

20 summation of apparent creep and shrinkage. Compared to the traditional creep test, the self

21 prestress load in the proposed structural system decreases in the expansion-shrinkage process

22 and it is not a constant. And since the expansion of concrete is restrained by external FRP, the

23 microstructure of expansive concrete will be different from normal concrete. Therefore,

24 reduction factors α and β are proposed considering its impact on the creep and shrinkage of

25 expansive concrete.

$$\varepsilon_a = \alpha \sigma_c J(t, t_0) + \beta \varepsilon_{sh}$$

where ε_a =Total creep and shrinkage of concrete ;

σ_c =maximum prestress caused by expansive concrete ;

α =creep reduction coefficient of expansive concrete ;

β =shrinkage reduction coefficient of expansive concrete.

By comparing the experimental data of F2L and F3L, the strain losses of F2L and F3L are 190 microstrain and 181 microstrain respectively. The prestress of F2L is 1.66 times of that of F3L, but the prestress loss of F2L is only 1.05 times of that of F3L. This indicates that the creep of expansive concrete accounts for a small portion of prestress loss. So for lime-system expansive concrete, α is taken as 0.2 and β is taken as 0.8 which are both presented in **Table 6**.

The comparison of results between experiments and model predictions is shown in **Fig. 8**, which shows that the strain loss calculated according to the analytical model fits the experimental data quite well. Both F2L and F3L show a very promising prediction with experimental results validated by the fact that they are in the range of $\pm 10\%$ error as shown in **Table 7**.

4.3.2. Shrinkage and creep analytical model of ettringite-system expansive concrete

Similarly to lime-system expansive concrete, the curing scheme for ettringite-system EC was water-spraying during the first 28 days. The starting date of shrinkage was taken as 28 days for ettringite-system concrete. However, it should be noted that the expansion strain of ettringite-system concrete was quite low in the early age, therefore, the starting date for creep was taken as 28 days. Three groups of specimens (F1E, F2E and F3E) were all under ascending stage during the first 60 days, and apparent date of creep and shrinkage are thusly 60 days. α was taken as 1.0 and β was taken as 1.0 which are listed in **Table 6**.

The comparison between analytical results and experimental results is shown in **Fig. 9**. It

1 is concluded that the agreement is good with only F2E outside the range of $\pm 20\%$ as shown
2 in Table 7.

3 **4.3.3. Analysis of steel reinforced expansive concrete beams**

4 Shrinkage and creep of expansive concrete as well as stress relaxation of steel were
5 considered to analyze the steel reinforced expansive concrete beams. Similarly to FRP
6 reinforced lime-system expansive concrete beams, the starting date for calculating the creep
7 of concrete in steel reinforcement system was taken as 1 day, the starting date of shrinkage
8 was taken as 28 days. The apparent date of creep and shrinkage was taken as 28 day. And α
9 was taken as 0.2, β was taken as 0.8. Since concrete was exposed to the air at all surfaces, six
10 sides of concrete were accounted for calculation of "S". For specimen SL, the prestress
11 measured on steel bar is close to yielding strength of steel reinforcement, so the stress
12 relaxation needs to be considered. The Comité Euro-International du Béton (CEB) Model
13 Code 1990 [11] was adopted for analysis of stress relaxation of steel.

14 While for steel reinforced ettringite-system expansive concrete beams, the stress
15 relaxation was not considered due to small prestress level. Similarly to FRP reinforced
16 ettringite-system expansive concrete, the starting date for creep and shrinkage was taken as 28
17 days. Different from FRP reinforcement, steel reinforced expansive concrete specimen
18 reached the maximum prestress level at about 40 days, thusly, the apparent date of creep and
19 shrinkage of expansive concrete was taken as 40 day.

20 The comparison between analytical results and experimental results is shown in **Fig. 10**.
21 Results also show a fairly consistent agreement between calculation and experiment. Table 7
22 shows that specimen SL (0.87%) presents a better fit than SE (19.36%), both of which are in
23 the range of $\pm 20\%$.

24 **5. CONCLUSIONS**

Based on the expansion test and analytical modeling, the following conclusions are made:

(1) Lime-system EC shows a higher expansion strain than ettringite-system EC does. For lime-system EC specimens, expansive strain increases rapidly in the first 24 hours. For ettringite-system EC specimens, expansive strain increase to a maximum value in about 50 to 60 days, then it starts to drop as concrete shrinks.

(2) Lime-system EC shows a higher maximum expansion as well as a lower prestress loss in the long term than ettringite-system EC. The prestress loss of lime-system EC is 17% for FRP system and 23% for steel system. They are about one third of the losses of ettringite-system EC. The expansion strain losses from FRP specimens are lower than those of steel specimens. Overall, lime-system EC specimens demonstrate the highest compressive stress after losses.

(3) A GL2000 modified model was proposed to calculate shrinkage and creep of expansive concrete in FRP reinforced concrete beam specimens. Starting date and apparent date were brought forward conceptually for both creep and shrinkage of expansive concrete in this research. Adjusting factors α and β were also introduced as modification of GL2000 to analyze shrinkage and creep of EC. Comparisons of the tested results with analytical calculations show a good agreement.

(4) The Comité Euro-International du Béton (CEB) Model Code 1990 [11] was adopted for the analysis of stress relaxation in steel reinforced specimens. Tested results compared very well with analytical calculations.

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Table 1 Test Parameters

Reinforcement type	Lime-system EC	Ettringite-system EC	PCC	Reinforcement ratio (%)	Axial reinforcement stiffness EA (kN)
Carbon ERP	F3L	F3E	F3P	2.00(3-layer)	76225
	F2L	F2E	F2P	1.33(2-layer)	50816
	F1L	F1E	F1P	0.67(1-layer)	25408
Steel (DWR)	SL	SE	SP	0.86(#5rebar)	39990
Control	CL	CE	CP		0

3 Note: P: PCC, E: Ettringite-system EC, L: Lime-system EC, C: Control, S: Steel,
4 F1:1-layer CFRP, F2:2-layer CFRP, F3: 3-layer CFRP, 1kN=0.225kip.
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Table 2 Concrete compressive strength

Specimen	PCC	Ettringite-system EC	Lime-system EC
7-Day Test (MPa)	33.7	36.4	29.8
28-Day Test (MPa)	41.9	49.4	41.4
Day of Test (MPa)	52.1 @265 days	59.6 @ 243 days	44.0 @ 196 days

9 Note: 1 psi = 0.00689 MPa.
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Table 3 Calculated compressive stress after losses

Specimen	Compressive stress (MPa)
SE	0.22
F1E	0.26
F2E	0.22
F3E	0
SL	7.17
F1L	0.28
F2L	9.23
F3L	4.98

14 Note: 1 psi = 0.00689 MPa.
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Table 4 Maximum prestress in concrete and reinforcement

Number	F2L	F3L	SL	F1E	F2E	F3E	SE
Max. prestress in concrete (MPa)	9.69	5.83	3.58	0.445	0.572	0.3	0.507
Max. prestress in FRP (MPa)	368.17	204.44	414	16.91	21.74	11.4	58.6

Table 5 Time parameters for shrinkage and creep analysis

Time parameters	Shrinkage		creep	
	Lime	Ettringite	Lime	Ettringite
Starting date (day)	28	28	1	28
Apparent date (day)	28	60	28	60

Table 6 Reduction coefficient for shrinkage and creep of EC

Reduction coefficient	Lime	Ettringite
α - creep	0.2	1.0
β - shrinkage	0.8	1.0

Table 7 Error of strain loss between calculation and test at 150 days

Specimen	F2L	F3L	SL	F1E	F2E	F3E	SE
$(\epsilon_{loss,cal.} - \epsilon_{loss,exp.}) / \epsilon_{loss,exp.}$ (%)	6.26	6.84	0.87	7.33	13.39	27.24	19.36

1	Figure Captions
2	<i>Fig. 1 Cross sections of beam specimens</i>
3	<i>Fig. 2 Geometry and instrumentation of CFRP beam specimens</i>
4	<i>Fig. 3 Beam specimens</i>
5	<i>Fig. 4 Expansion strain versus time curves for EC</i>
6	<i>Fig. 5 Effect of reinforcement stiffness on maximum expansion strain</i>
7	<i>Fig. 6 Comparison of relative strain loss</i>
8	<i>Fig. 7 Analytical curve of F2L</i>
9	<i>Fig. 8 Experimental versus analytical strain loss in lime-system specimens</i>
10	<i>Fig. 9 Experimental versus analytical strain loss in ettringite-system specimens</i>
11	<i>Fig. 10 Experimental versus analytical strain loss in steel reinforced specimens</i>
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(a) Plain concrete

(b) DWR reinforced concrete

(c) CFRP reinforced concrete

Fig. 1. Cross sections of beam specimens

Fig. 2. Geometry and instrumentation of CFRP beam specimens

Fig. 3. Beam specimens

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(a) Lime-system EC for F2L and F3L

(b) Ettringite-system EC

Fig. 4. Expansion strain versus time curves for EC

Fig. 5. Effect of reinforcement stiffness on maximum expansion strain

Fig. 6. Comparison of relative strain loss

Note: The practical creep, apparent creep and shrinkage have been multiplied by α and β .
 "Analytical" represents the summation of "apparent creep" and "shrinkage".

Fig. 7. Analytical curve of F2L

(a) F2L

(b) F3L

Fig. 8. Experimental versus analytical strain loss in lime-system specimens

(a) FIE

(b) F2E

(c) F3E

Fig. 9. Experimental versus analytical strain loss in ettringite-system specimens

(a) SL

(b) SE

Fig. 10. Experimental versus analytical strain loss in steel reinforced specimens