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Prestress loss in externally FRP reinforced self prestressing concrete beams

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HIGHLIGHTS

- Lime-system expansive-concrete (EC) beam achieves a considerable effective prestress level.
- Lime-system EC shows the lowest prestress loss and highest residual compressive stress.
- Shrinkage and creep of expansive concrete were simulated by a modified model.
- Analytical calculation shows good agreement with experimental observation.

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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.

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.

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

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

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

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 13 mm (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 ± 2 °C, 60% RH) for 24 h 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

Table 1
Test parameters.

Reinforcement type	Lime-system EC	Ettringite-system EC	PCC	Reinforcement ratio (%)	Axial reinforcement stiffness EA (kN)
Carbon FRP	F3L	F3E	F3P	2.00(3-layer)	76,225
	F2L	F2E	F2P	1.33(2-layer)	50,816
	F1L	F1E	F1P	0.67(1-layer)	25,408
Steel (DWR)	SL	SE	SP	0.86(#5rebar)	39,990
Control	CL	CE	CP		0

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