Structures 2 (2015) 50–57

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Prestress losses in pretensioned concrete beams cast with lightweight self-consolidating concrete

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ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 14 January 2015
Accepted 15 January 2015
Available online 22 January 2015

Keywords:
Pretensioned concrete
Prestress loss
Creep
Shrinking
Self-consolidating concrete
Lightweight concrete

ABSTRACT

The use of lightweight self-consolidating concrete (LW-SCC) for pretensioned concrete members offers advantages over the use of conventional, normal weight concrete. This study focused on investigating the prestress losses of 12 pretensioned concrete beams cast with LW-SCC or normal weight SCC (NW-SCC). Two LW-SCC mixtures were developed along with one NW-SCC mixture. The LW-SCC mixtures contained expanded shale or expanded clay coarse aggregates. Prestress losses were measured using vibrating wire strain gauges. The beams were loaded approximately 150 days after casting and losses were measured for an additional 75 days after casting. In addition to prestress losses, the modulus of elasticity (MOE) and shrinkage of the mixtures were measured. Experimental results indicated that the AASHTO-LRFD equation for MOE using a correction factor of 1.0 is appropriate to predict the MOE of LW-SCC. Shrinkage of LW-SCC was less when compared to NW-SCC due to the effect of internal curing. CEB MC90 was the most appropriate model to predict concrete shrinkage. The AASHTO-LRFD methods over-estimated instantaneous and long-time prestress losses. The AASHTO approximate method was more suitable to estimate total prestress losses for the beams using LW-SCC than the AASHTO refined method.

1. Introduction

Self-consolidating concrete (SCC) was developed in the 1980s in Japan due to a lack of skilled workers [1,2]. SCC possesses advanced characteristics over conventional concrete. SCC is a highly flowable mixture which does not need mechanical vibration during placement and consolidation. This concrete flows through narrow areas and fills forms by its self-weight without exhibiting segregation or bleeding. The hardened SCC properties are similar to or better than comparable conventional concrete in terms of strength and durability. Lightweight self-consolidating concrete (LW-SCC) is a type of SCC. LW-SCC possesses all SCC's engineering properties, but lightweight aggregates are used to reduce the concrete's unit weight to approximately 2002 kg/m^3 [3–5]. The use of LW-SCC in construction reduces a structures' self-weight which may decrease member size and foundation size. However, the utilization of LW-SCC has been limited due to a lack of design guidelines regarding the concrete properties, prestress loss, transfer and development length, and shear strength [6,7].

Accurate estimation of prestress losses is important for the design of pretensioned concrete members. The overestimation or underestimation of prestress losses has little effect on the design strength of the members, but impacts service conditions [8–10]. In particular, the overestimation of prestress losses requires a higher prestress force than that which is necessary. This overestimation directly increases camber which may cause cracks in the top fiber of the members. The underestimation of prestress losses, in turn, results in excessive defection which may cause cracking in the bottom fiber of the members. The presence of cracks accelerates concrete deterioration and corrosion of the prestressing strands. These factors reduce the bond between the prestressing strands and concrete which may affect the strength and integrity of pretensioned concrete members [11,12].

Prestress losses can be classified as two types: instantaneous loss or elastic shortening (ES) loss and long-term prestress losses including creep and shrinkage of concrete and steel relaxation [13]. The ES loss depends on the modulus of elasticity (MOE) of concrete and the applied prestress. The steel relaxation (RE) loss depends on properties of prestressing strands, and RE is generally low for low-relaxation prestressing strands. Prestress losses due to creep and shrinkage depend on aggregate stiffness, concrete compressive strength, shape and size of pretensioned concrete members, and temperature and humidity [14,15]. Researchers have proposed several models to estimate prestress losses due to creep and shrinkage [16]. However, concrete creep and shrinkage and their interactions are complicated, making it difficult to establish analytical models for predicting the concrete behavior over time. This difficulty is the reason for the vast number of models and their accuracy, or inaccuracy [14,17].

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http://dx.doi.org/10.1016/j.istruc.2015.01.003
2352-0124/

Creep and shrinkage of the hardened concrete are the major factors affecting long-term prestress losses [18]. These properties can be predicted using proposed models in ACI 209 [16] and AASHTO-LRFD [13]. There is a concern regarding the applicability of the proposed models when applied to LW-SCC [6]. Several studies have come to different conclusions in terms of early age and long term concrete shrinkage. Lopez et al. [19] determined that the shrinkage of high performance lightweight concrete exhibited a slower rate at early ages, but that rate was 20% higher after one year when compared to similar normal weight concrete. In another study, Lopez et al. [20] determined that the internal curing ability of LW-SCC reduced autogenous shrinkage at the early and late ages. Cusson and Hoogeveen [21] had similar conclusions regarding the effects of internal curing in reducing autogenous shrinkage and the risks of concrete cracking at early ages. Davis [22], however, concluded that shrinkage of LW-SCC was slightly higher than the comparable concrete. For creep, a variety of conclusions has been determined by different researchers. The creep of concrete using lightweight aggregates may be higher [19], similar [20], or lower [23,24] than the comparable concrete using normal weight aggregates.

Prestress losses can be predicted using ACI 318 [8] or AASHTO-LRFD [13]. The procedures to predict prestress losses using ACI 318 rely on research conducted by Zia et al. [25]. AASHTO provides two methods for predicting prestress losses: (1) the approximate method (hereafter referred to as AASHTO-AM), and (2) the refined method (hereafter referred to as AASHTO-RM). The AASHTO-RM predicts losses due to creep and shrinkage at various ages. This method is considered more accurate than the AASHTO-AM. Several studies have been conducted to evaluate prestress losses due to creep, shrinkage, and total prestress loss of the pretensioned concrete members using LW-SCC. Researchers have indicated that the measured total losses were less than the predicted losses by 10% to 50% [26–29].

The use of LW-SCC in construction has advantages over other types of concrete. Different conclusions have been determined regarding creep, shrinkage, and prestress losses of the pretensioned concrete members using LW-SCC. In addition, there are no design guidelines regarding concrete properties and their impacts on the structure's performance. This study measured the MOE and shrinkage for two LW-SCC mixtures and one normal weight SCC (NW-SCC) mixture. Twelve pretensioned concrete beams were fabricated to measure prestress losses. Eight beams were cast with LW-SCC, and four beams were cast with NW-SCC. The experimental results were used to evaluate the applicability of using the shrinkage models proposed by ACI 209 and AASHTO-LRFD for LW-SCC. The measured prestress losses were used to assess the most appropriate method for predicting long-term prestress loss for pretensioned concrete members cast with LW-SCC.

2. Experimental investigation

The experimental program included 5 tasks. Task 1 consisted of designing two LW-SCC mixtures and one NW-SCC mixture. Task 2 measured the MOE for the three mixtures at 1 day, 7 days, and 28 days. The results were used to evaluate the applicability of using the MOE equation proposed by AASHTO-LRFD [13] for LW-SCC. The shrinkage of the mixtures was measured and compared to analytical models in Task 3. In Task 4, 12 pretensioned concrete beams were fabricated and the prestress losses were measured for approximately 150 days before loading. The experimental data obtained in Tasks 2 and 3 were used to predict prestress losses. The predicted losses were then compared to predicted values. The final task included loading the beams which simulated the placement of a bridge deck. The prestress losses were measured for approximately 75 days.

2.1. Mix design

The mixture proportions of the two LW-SCC mixtures and one NW-SCC mixture are shown in Table 1. Expanded clay and expanded shale were the lightweight coarse aggregates used for the LW-SCC mixtures which were represented by LW-C and LW-S, respectively. Limestone was the normal weight coarse aggregate for the NW-SCC mixture which was termed as NW-L in Table 1. The mixture proportions were developed as part of an earlier research project at the University of Arkansas [7]. It should be mentioned that the expanded shale and expanded clay are porous lightweight aggregates, and these materials tend to absorb more mixing water. Therefore, the lightweight aggregates were soaked for 24 h and drained immediately prior to mixing.

Table 1
Mix design.

Mixture	LW-C	LW-S	NW-L
Cement (kg/m^3)	479.1 (type III)	493.4 (type III)	489.2 (type I)
Fly ash (kg/m^3)	84.2	87.2	N/A
Coarse aggregate (kg/m^3)	384.9 (Clay)	416.9 (shale)	825.5 (limestone)
Fine aggregate (kg/m^3)	736.5	753.1	832.0
Water (kg/m^3)	197.5	197.5	195.7
w/cm	0.35	0.34	0.4
HRWR (mL)	2272–2631	1913–2392	1196–1435
Number of cylinder for measuring MOE	9	9	9
Number of rectangular prism for measuring shrinkage	4	4	4
Number of beam for measuring prestress losses	4	4	4
Beam designation	LW-C1 to LW-C4	LW-S1 to LW-S4	NW-L1 to NW-L4

(Note: N/A = not applicable).

Several tests were conducted to evaluate the fresh concrete properties. These tests included slump flow [30], J-Ring [31], T_{20} [30], visual stability index (VSI) [30], and unit weight [32]. The test results were summarized in Table 2. The slump flow ranged from 650 mm to 725 mm excluding LW-C1 and LW-C2. The slump flow of LW-C1 and LW-C2 was 50 mm lower than the minimum recommended value for SCC mixtures used in prestressed concrete structures [33]. Therefore, external vibration was applied to facilitate concrete consolidation for those two mixtures. The test results of the J-Ring flow and T_{20} showed a good agreement with the recommended range of 540 mm to 650 mm and 1.5 s to 6 s, respectively.

2.2. Modulus of elasticity

Nine 102 mm by 204 mm cylinders were cast from each concrete mixture (Table 1) to measure MOE. All cylinders were demolded at 24 h and then placed in a water bath conditioned with lime until testing at 1 day, 7 days, and 28 days. These cylinders were used to measure MOE according to ASTM C469 [34]. Fig. 1 illustrates the MOE apparatus within the compression machine. The reported MOE for a given concrete mixture is the average modulus of the three cylinders.

Table 2
Concrete properties.

Beam	Slump flow (mm)	J-Ring flow (mm)	T_{20} (s)	VSI	Unit weight (kg/m^3)
LW-C1	550	470	4.0	1	1957
LW-C2	550	520	2.4	0	2025
LW-C3	700	670	5.2	1	1996
LW-C4	740	620	3.8	1	2005
LW-S1	700	660	4.2	0	1913
LW-S2	750	700	4.0	0	1929
LW-S3	660	650	4.0	0	1887
LW-S4	710	660	2.8	0	1962
NW-L1	750	750	3.4	1	2371
NW-L2	700	710	4.0	1	2379
NW-L3	670	660	4.4	1	2387
NW-L4	650	620	4.6	1	2382

(Note: VSI = visual stability index).