Journal of Building Engineering 7 (2016) 133–142

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Prestress losses of double-tee girders cast with lightweight self-consolidating concrete

Dustin B. Ward [a], Canh N. Dang [b], Royce W. Floyd [c], W. Micah Hale [b,*]

[a] B & F Engineering, 928 Airport Rd, Hot Springs, AR 71913, USA
[b] University of Arkansas, Department of Civil Engineering, 4190 Bell Engineering Center Fayetteville, AR 72701, USA
[c] University of Oklahoma, School of Civil Engineering and Environmental Science, 202 W. Boyd St., Norman, OK 73019, USA

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form
6 June 2016
Accepted 6 June 2016
Available online 7 June 2016

Keywords:
Pretensioned concrete
Prestress loss
Creep
Shrinkage
Elastic shortening
Lightweight concrete
Self-consolidating concrete

ABSTRACT

Prestress loss estimation is a necessary and important procedure in design of pretensioned concrete girders. The current specifications were developed from the experimental results of normal-weight concrete that are possibly inaccurate in estimating prestress losses for members cast with lightweight self-consolidating concrete (SCC). This study measures prestress losses for two full-scale double-tee girders cast with sand-lightweight SCC. Expanded clay, which had a specific gravity of 1.25 and an absorption capacity of 15%, was used as the lightweight coarse aggregate for the designed concrete mixture. The prestress losses were measured for 26 days and at 83 days using vibrating wire strain gauges attached to prestressing strands, after which the tested girders were then used in the construction of a parking garage. The experimental results indicated that the modulus of elasticity of lightweight SCC can be predicted using a correction factor of 0.99. The measured elastic-shortening loss was slightly lower than the predicted values. The predicted time-dependent losses, however, significantly over-estimated the measured results, which yielded the over-estimation of total prestress losses that varied from 86% to 153%.

1. Introduction

Pretensioned concrete members are widely used in the construction of buildings, parking garages, and bridges. Prestress losses occur throughout the life of pretensioned concrete members, and have significant impact on the design for long-term effects [1–4]. In the design period, structural engineers rely on the existing empirical formulas to calculate prestress losses. The variability in predicting prestress losses directly causes the inaccuracy in estimating the camber and long-term deflection of pretensioned concrete members. At erection, the under- or over-estimation of camber increases the possibility of construction-related problems, which increases the construction cost, delays the project, or affects the structural performance. The inaccuracy in predicting the long-term deflection reduces the riding quality if the deflection is over-estimated, or rises the public concern and affects the structural durability if the deflection is under-estimated.

The use of self-consolidating concrete (SCC) for pretensioned concrete members is advantageous when compared to conventional or vibrated concrete. The fresh SCC has high flowability and deformability, so it can flow through narrow regions and fill the formwork by its self-weight without segregation or bleeding. This feature particularly benefits at the anchorage zone of pretensioned concrete members that normally contain congested reinforcement, or thin elements like double-tee girders that are widely used in the United States [5]. The use of lightweight aggregates in SCC offers further advantages for the concrete technology [6–8]. First, the use of lightweight concrete can reduce the self-weight of structures up to 20%, which decreases the dimensions of concrete members and vertical load on foundations [6,9]. Second, internal curing techniques can be employed for lightweight concrete to enhance the durability and resilience of concrete structures [10–14]. In summary, the use of lightweight SCC not only furthers the advantages of SCC but also improves the long-term performance for pretensioned concrete members.

The use of lightweight SCC in pretensioned concrete members may present several challenges. First, lightweight SCC contains a high volume of paste, which may increase concrete shrinkage and affect time-dependent losses [15]. The high flowability of lightweight SCC may also reduce the concrete stiffness at the interface of prestressing strands and concrete, which consequently weakens the bond between the two materials [15–23]. Second, the reduced stiffness of lightweight aggregates decreases concrete stiffness,

* Corresponding author.
E-mail address: micah@uark.edu (W.M. Hale).

http://dx.doi.org/10.1016/j.jobe.2016.06.004
2352-7102/

which affects instantaneous and time-dependent losses [24]. Finally, the absorption capacity of lightweight aggregates is greater than normal-weight aggregates, which can reduce concrete shrinkage due to the effect of internal curing. The contribution of these factors can affect the prediction of prestressed losses for pretensioned concrete members cast with lightweight SCC.

2. Literature review

The modulus of elasticity (MOE) of concrete is necessary for estimating the instantaneous loss or elastic-shortening loss. The MOE of lightweight concrete may be lower than that of comparable, normal-weight concrete since the stiffness of lightweight aggregates is generally lower than that of normal-weight aggregates [25]. The MOE of normal-weight concrete can be predicted using Eq. (1). The American Concrete Institute – *Building Code Requirements for Structural Concrete and Commentary* (herein referred as ACI 318-14) [1] incorporates a modification factor of 0.85 for sand-lightweight concrete and 0.75 for all-lightweight concrete. AASHTO LRFD *Bridge Design Specifications* (herein referred as AASHTO) [26], however, uses a correction factor K_1 to consider the effect of aggregate stiffness on the MOE of concrete. Cousins et al. [6] determined that a factor K_1 of 1.0 is appropriate for predicting the MOE of sand-lightweight concrete. In other words, the use of lightweight coarse aggregates has minimal effect on the MOE.

$$E_c = 0.043 w_c^{1.5}\sqrt{f'_c}\ \left(w_c \text{ in } kg/m^3 \text{ and } f'_c \text{in MPa}\right) \tag{1}$$

where E_c is the modulus of elasticity of concrete; w_c is the concrete unit weight; f'_c is concrete compressive strength.

Concrete creep and shrinkage are important factors affecting the time-dependent losses [27,28]. Creep and shrinkage of lightweight concrete are different from those of comparable, normal-weight concrete because of the difference in aggregate stiffness and absorption capacity [29–31]. The aggregate stiffness is a main factor affecting concrete creep, while the aggregate absorption capacity and amount of paste affect concrete shrinkage [32,33]. Technically, concrete creep and shrinkage of normal-weight concrete can be predicted by empirical models proposed by Precast/Prestressed Concrete Institute (PCI) [34], Model Code 2010 [35], ACI 209 [36], and AASHTO [26]. However, there is little to no recommendation regarding a suitable model to predict creep and shrinkage for lightweight SCC [6]. Therefore, more research is needed to evaluate the applicability of using existing empirical formulas, which were developed based on the experimental results of normal-weight concrete, to predict the instantaneous and time-dependent prestress losses for pretensioned concrete members cast with lightweight SCC.

A number of studies have been conducted to evaluate prestress losses of pretensioned concrete girders using lightweight concrete. Different conclusions have been made regarding the accuracy of using existing formulas in predicting prestress losses of pretensioned concrete members. Holste et al. [30] measured prestress losses for inverted-tee beams cast with lightweight SCC for one year. The total measured loss is 490 MPa which is 20% greater than the predicted value of 407 MPa using AASHTO specifications [37]. Dymond [38], however, presented a contrary conclusion when evaluating prestress losses over a 4-month period for a full-scale 19.8-m long PCBT-53 girder. The total measured loss is 179 MPa, which is 30% lower than the total predicted value of 255 MPa using AASHTO-Refined method [26]. Ziehl et al. [39] had a similar conclusion to Dymond when measuring prestress losses of thee AASHTO Type III girders. The total measured loss is 207 MPa, which is 21% lower than the predicted value of 262 MPa.

A trend in over-estimating prestress losses for pretensioned concrete girders cast with high performance lightweight concrete has been recognized. Cousins and Nassar [40] measured prestress losses for two AASHTO Type IV girders for 9 months. The experimental results indicated the total predicted loss using the PCI [34] and the ACI 209 [36] specification over-estimates the measured values by 9% and 51%, respectively. Lopez and Kahn [41] stated that AASHTO-Refined method [26] over-estimates the measured prestress losses by 40% and 80% for two AASHTO Type II girders, which are measured for 4 months. The over-estimation was about 20% and 40% when the ACI 209 [36] is used for predicting prestress losses.

In summary, a number of concerns regarding the use of lightweight SCC for pretensioned concrete members have been determined. The current specifications, in fact, were primarily developed for normal-weight concrete. Researchers and engineers generally extend these specifications for lightweight concrete. This practice leads to a high variability in estimating prestress losses for pretensioned concrete members. This project examines the applicability of using the existing specifications in predicting prestress losses for two full-scale double-tee girders cast with lightweight SCC. In the experimental investigation, the prestress losses were measured continuously for 26 days and at 83 days, while the girders were stored at the precast facility. The measured instantaneous and time-dependent prestress losses were compared to the predicted values in the analytical investigation, and a number of assessments and recommendations regarding predicting the prestress losses were provided in the remaining sections of the paper.

3. Experimental investigation

3.1. Girder fabrication

This project monitored prestress losses for two out of several full-scale double-tee girders, which were cast at the Coreslab Structures, Arkansas, USA. The girders were used to construct a parking garage. Both girders had an identical depth of 660 mm. These girders were identified as DT-A and DT-B, which had a length of 9.72 m and 17.85 m, respectively. Girder DT-A consisted of ten fully bonded, 12.7-mm, Grade 1860, low-relaxation prestressing strands that were tensioned to $0.65f_{pu}$ (where f_{pu} is the ultimate strand strength) or 1212 MPa. All the prestressing strands were straight, and Fig. 1 shows the strand pattern of girder DT-A. Girder DT-B used an identical number of prestressing strands and the prestress level as girder DT-A, but the prestressing strands were depressed in the midspan. Figs. 2 and 3 show the strand pattern at the ends and midspan of girder DT-B, respectively. These girders were two of several girders cast in the 152-m prestressing bed.

Vibrating wire strain gauges (VWSGs) were embedded in the girders to measure strains caused by prestress losses. Each girder included four VWSGs in which two VWSGs were placed at or near the center of gravity of the prestressing strands, and the other VWSGs were placed at the location where the stems meet the flange for each girder. For girder DT-A, two VWSGs were placed at the center of gravity of the prestressing strands of 175 mm, and the others were placed at a distance of 655 mm from the bottom fiber of the girder. Fig. 1 illustrates the placement of these VWSGs. For girder DT-B, the first two VWSG were offset 0.61 m from the midspan to avoid damage from the depression equipment. These VWSGs were placed at the center of gravity of the prestressing strands of 75 mm. The others VWSGs were placed at a distance of 655 mm and 665 mm from the bottom fiber of the girder as shown in Fig. 3.