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

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A B S T R A C T

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,

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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.

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

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 $0.65 f_{pu}$ (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.

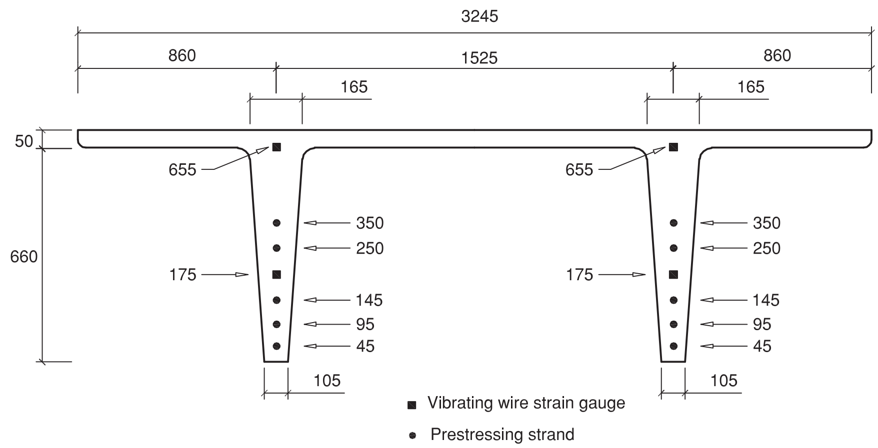

Fig. 1. DT-A cross section at midspan* and at ends. (Note: * = vibrating strain gauges were only attached in the midspan).

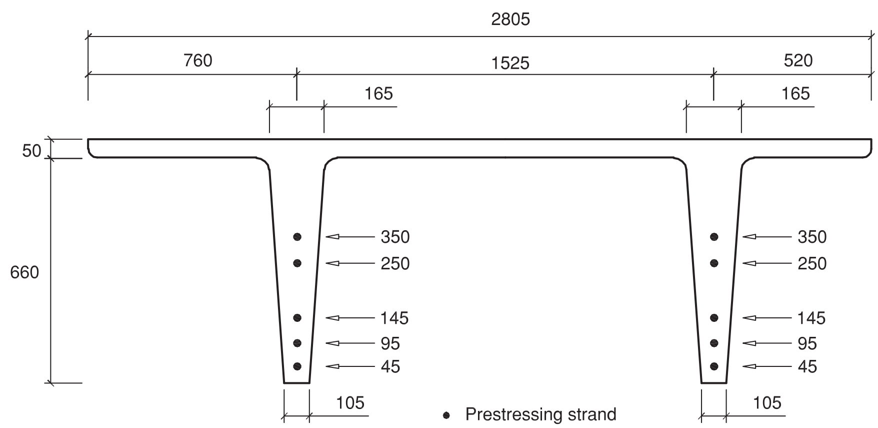

Fig. 2. DT-B cross section at ends.

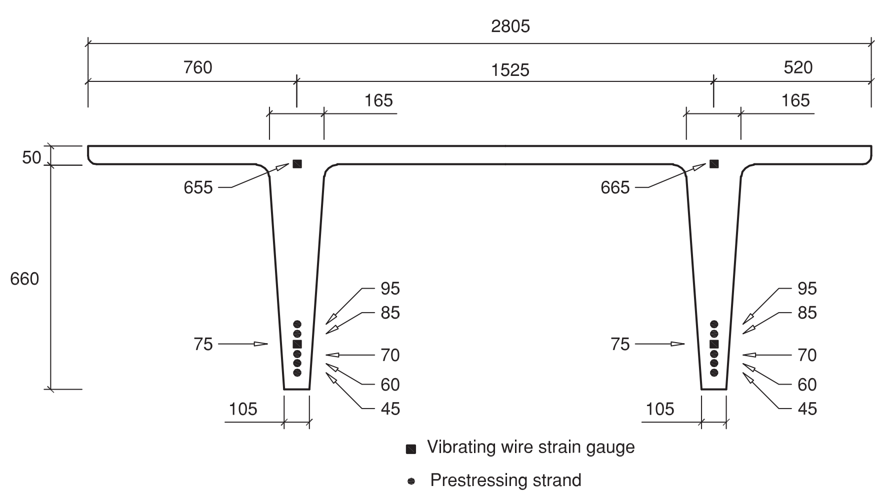

Fig. 3. DT-B cross section at midspan*. (Note: * = vibrating strain gauges were offset 0.61 m from the midspan).

All VWSGs were connected to a data-acquisition system. The strain and temperature of each VWSG were continuously monitored at 3-min intervals after transfer and at 15-min intervals when the girders were placed in storage location. The VWSG readings require temperature correction. The results presented in the following sections were the corrected data, which were calculated from the calibration temperature provided by the manufacturer and the measured temperature of each VWSG.

3.2. Concrete mixture proportion, placement, and testing

The girders DT-A and DT-B were cast using the same lightweight SCC mixture. A Type I portland cement and normal weight river sand were used in the concrete. The lightweight coarse aggregate consisted of expanded clay aggregate that had a specific gravity of 1.25 and an absorption capacity of 15%. Table 1 shows the concrete mixture proportion. The fresh concrete properties

Table 1
Concrete mixture proportion and fresh concrete properties.

Material	Parameter
Cement (kg/m^3)	469
Normal weight, fine aggregate (kg/m^3)	762
Lightweight, coarse aggregate (kg/m^3)	438
Water (kg/m^3)	178
Water/Cement ratio	0.38
Concrete properties	
Slump flow (mm)	780
Visual Stability Index	1.5
Unit weight (kg/m^3)	1922
Air content (%)	0.5

Table 2
Properties of girders DT-A and DT-B.

Properties	DT-A	DT-B
Gross Section Properties		
A_g (mm^2)	343,225	320,645
I_g (mm^4)	1.579E+10	1.507E+10
Exposed perimeter (mm)	9246	8357
V/S (mm)	37	38
Girder length (m)	9.72	17.85
Weight (kN/m)	6.465	6.040
M_g (kN-m)	76.9	244.4
y_g (mm)	514	502
e (mm)	338	432
n	8.0	8.58
n_i	12.4	12.4
Transformed Section Properties at Release		
A_{ti} (mm^2)	354,451	331,870
I_{ti} (mm^4)	1.699E+10	1.702E+10
y_{ti} (mm)	503	488
e_{ti} (mm)	628	417

(Note: A_g=gross area of section; I_g=moment of inertia of the gross concrete section about the centroid axis, neglecting the reinforcement or prestressing strands; V/S=volume-to-surface ratio; M_g=midspan moment due to member self-weight; y_g=distance from the neutral axis to the extreme tension fiber for gross section; e=eccentricity of strands with respect to centroid of girder for gross section; n=modular ratio (E_s/E_c); n_i=modular ratio (E_s/E_{ci}); A_{ti}=transformed area of section; I_{ti}=moment of inertia of the transformed concrete section about the centroid axis, neglecting the reinforcement or prestressing strands; y_{ti}=distance from the neutral axis to the extreme tension fiber for transformed section; e_{ti}=eccentricity of strands with respect to centroid of girder for transformed section)

Table 3
Inputs for AASHTO-Approximate and Refined methods.

Properties	DT-A		DT-B	
AASHTO-Approximate Method				
H (%)	70		70	
γ_{st}	1.006		1.006	
γ_h	1.000		1.000	
f_{cgp} (MPa)	9.419		9.874	
AASHTO-Refined Method				
t_f (day)	26	83	26	83
t_i (day)	0.667	0.667	0.667	0.667
k_s	1.260	1.260	1.254	1.254
k_f	1.001	1.006	1.006	1.006
k_{hc}	1.000	1.000	1.000	1.000
k_{hs}	1.020	1.020	1.020	1.020
k_{td}	0.359	0.646	0.359	0.646
$\Psi_b(t_f, t_i)$	0.908	1.632	0.904	1.624
K_{id}	0.846	0.807	0.791	0.742
f_{pt} (MPa)	1095.4	1095.4	1089.8	1089.8
K_L	30	30	30.0	30.0
f_{py} (MPa)	1675	1675	1675	1675

(Note: H=relative humidity; γ_{st}=a coefficient (AASHTO, Eq. 5.9.5.3-2); γ_h=a coefficient (AASHTO-LRFD, Eq. 5.9.5.3-3); f_{cgp}=concrete stress at the center of gravity of prestressing tendons, that results from the prestressing force at either transfer or jacking and the self-weight of the member at sections of maximum moment; t_f=final age; t_i=age of concrete when load is initially applied; k_s=factor for the effect of the volume-to-surface ratio; k_f=factor for the effect of concrete strength; k_{hc}=humidity factor for creep; k_{hs}=humidity factor for shrinkage; k_{td}= time development factor; $\Psi_b(t_f,t_i)$=girder creep coefficient at final time due to loading introduced at transfer; K_{id}=transformed section coefficient that accounts for time-dependent interaction between concrete and bonded steel in the section being considered for time period between transfer and deck placement; f_{pt}=stress in prestressing steel immediately after transfer; K_L=factor accounting for type of steel taken as 30 for low relaxation strands; f_{py}=yield strength of prestressing steel).

were measured from a sample taken prior to casting the double-tee girders. Table 1 also summarizes the measured slump flow and Visual Stability Index [42], unit weight [43], and air content [44]. The slump flow and Visual Stability Index were slightly greater than the recommended thresholds of 730 mm and 1.0, respectively [45]. However, there were no signs of segregation in the girders during casting or in the cylinders after measuring compressive strength.

The concrete was batched in a central batch plant at the precast facility and transported to the formwork in ready-mix trucks. The concrete was first placed in stems of the girders and then the flanges. After placement, a tarp was placed over the girders to prevent rapid moisture loss. The strands were detensioned 16 h after casting. In the detensioning process, each strand was flame cut simultaneously at the ends of the prestressing bed. After the ten strands were cut at the bed ends, individual girders were then detensioned using the same procedure. The girders were then removed from the bed, inspected, and moved to the storage yard at the precast facility until transported to the construction site.

4. Analytical investigation

An in-house computer program was used to calculate prestress losses according to three methods: Zia et al. [46] study, AASHTO-Approximate method [26], and AASHTO-Refined method [26]. The AASHTO-Approximate and the AASHTO-Refined methods have the same procedures to estimate elastic shortening loss, but the procedures used to estimate term-dependent losses are different. The program includes three parts for: (1) *input*, (2) *calculation*, and (3) *results*. Table 2 shows parameters necessary for the *input* part. The *calculation* part computes related equations of the mentioned methods. The *results* part presents intermediate parameters as summarized in Table 3 and results of prestress losses. This computer program has been verified by several studies [9,47–49].

5. Experimental results and discussion

5.1. Concrete properties

The hardened concrete properties were measured from a sample taken from a diverted stream of concrete during the placement of each double-tee girder. The specimens were cured with the double-tee girders until testing. Compressive strength [50] and modulus of elasticity [51] were measured at strand release (16 h), and at 7, 28, and 90 days of age. Three specimens were tested for each concrete property at a specific age.

Table 4 shows the concrete compressive strengths. At release, the precast facility used one sample from both girders to measure compressive strength, which is why the 16-h tests are identical. Separate samples were produced from diverted flows during placement of each individual girder for compressive strength and modulus of elasticity testing at 7, 28, and 90 days of age. The

Table 4
Concrete compressive strength.

Age	DT-A	DT-B
16 h (MPa)	27.4	27.4
7 days (MPa)	38.5	37.0
28 days (MPa)	42.7	48.1
90 days (MPa)	47.2	46.6

required compressive strength at release was 24.1 MPa and the specified 28-day compressive strength was 34.5 MPa. The designed concrete mixture achieved the required and specified concrete compressive strength. For girder DT-A, the concrete compressive strengths continued to increase up to 90 days of age. For girder DT-B, the 90-day compressive strength was 4% less than the 28-day compressive strength. This deviation is possibly attributed to the slight inconsistence of the samples taken from a diverted stream of concrete.

The precast facility did not have the capabilities to measure the MOE of concrete, therefore the 16-h MOE test was conducted on an identical mixture cast at the laboratory at the University of Arkansas. Fig. 4 shows the measured MOE values for each girder. Least-squares estimation method was used to determine the most fitting correction factor K_1 of the AASHTO equation for predicting the MOE that based on the measured concrete unit weight and compressive strength. An iterative procedure was used for the determination of K_1 factor. The trial factors were varied from 0.8 to 1.2, and the coefficient of determination R^2 was calculated for each iteration. For the trial factors in a range of 0.8–0.84 and 1.15–1.2, the values of R^2 were negative, which meant the predicted and the measured MOE values had no correlation. For the trial factors in a range of 0.84–1.15, a maximum R^2 of 0.722 was achieved at a K_1 factor of 0.99. This best fitting correction factor was approximately equal to a factor of 1.0 reported by Bymaster et al. [9]. The determined factor was also 5% less than a value of 1.035 reported by Noguchi and Nemati [52] for sand-lightweight concrete. The difference in aggregate sources was the main element contributing to this deviation.

Fig. 4 shows the variability in the measured MOE values in conjunction to the predicted values using the AASHTO equation with a correction factor K_1 of 0.99. For girder DT-A, the AASHTO equation over-estimated the measured MOE values at release and at 7 days by 16% and 7%, respectively. At 28 days and 90 days, the AASHTO equation, however, under-estimated the measured MOE values by 4% and 7%, respectively. The measured MOE values of girder DT-B shows a trend different from that of girder DT-A. The measured MOE at 7 days was 2% greater than the predicted value while the measured MOE at 28 days was 8% lower than the predicted value. These deviations were attributed to the variability in lightweight concrete mixture.

The hatched region in Fig. 4 represents the predicted MOE values with $\pm 10\%$ error. In other words, the lower and upper bounds of the hatched region were 90% and 110% of the predicted MOE values, respectively. The figure indicates that the AASHTO equation with a correction factor K_1 of 0.99 provides a good prediction for the measured MOE values within an error of 10%. The predicted region only over-estimated the measured MOE values at release by 6% for both girders and under-estimated the measured MOE value at 90 days by 3% for girder DT-B.

5.2. Measured prestress losses

Fig. 5 shows the measured prestress losses for both girders. Prestress loss data were determined by multiplying the corrected strain gage readings, which were placed at the center of gravity of the prestressing steel, by the MOE of the prestressing strand. The prestress losses shown in Fig. 5 and in the following figures are the averages of the losses measured in each stem of the double-tee girders. Prestress losses were continuously measured for 26 days while the girders were stored at the precast facility. Fig. 5 indicates that the majority of the losses occurred at release. On average, the losses increased approximately 25.6 MPa over the next 26 days. The prestress losses over the 26-day period were 121.6 MPa for girder DT-A and 107.1 MPa for girder DT-B. It should be mentioned that these losses do not include prestress loss due to steel relaxation, since the strain gages used in this study could not detect the changes in strains caused by relaxation in prestressing steel.

Once the double-tee girders were erected in the parking garage, which was at 83 days of age, prestress losses were again measured before the topping slab was placed. During construction of the parking garage, the VWSG wires were accessible, and a hand held reader was used to measure concrete strains. At 83 days of age, the measured losses were 147.8 MPa and 121.7 MPa for girders DT-A and DT-B, respectively. When compared to the 26-day readings, losses increased approximately 26.2 MPa for girder DT-A and 14.6 MPa for girder DT-B. This increase in prestress losses during this period was comparable to the experimental laboratory study reported by Bymaster et al. [9]. The researcher stated the maximum increase of prestress losses for 7 months, after 28 days

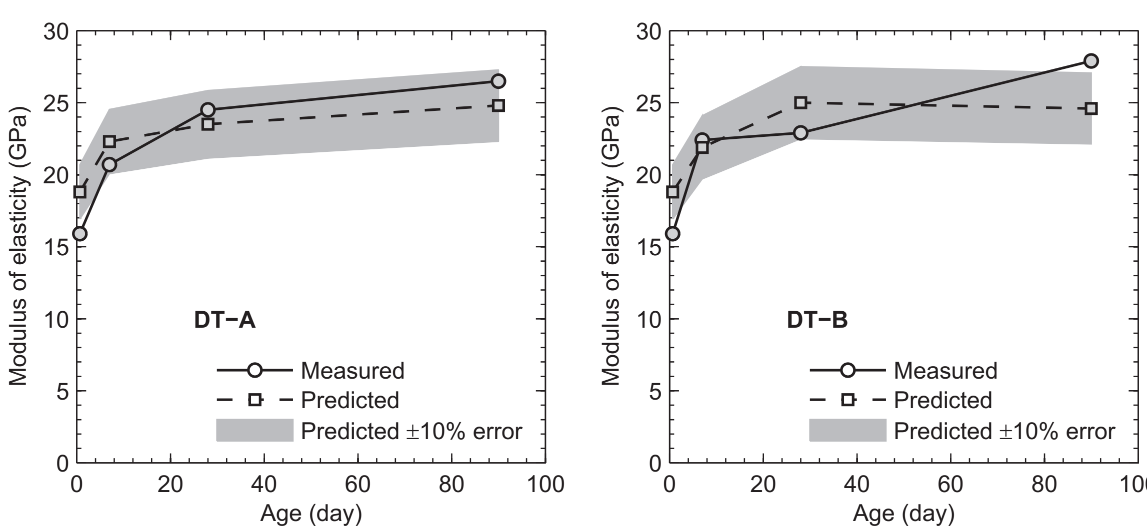

Fig. 4. Measured and predicted modulus of elasticity.

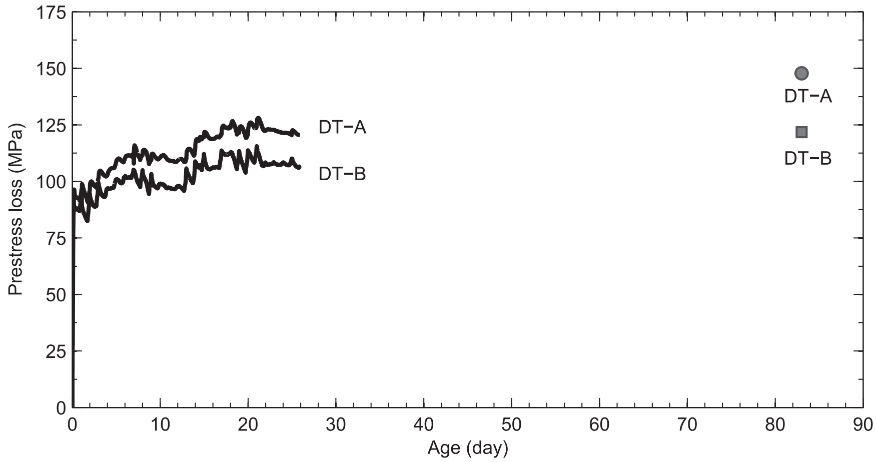

Fig. 5. Measured prestress losses of DT-A and DT-B.

of age, ranged from 21.7 MPa to 27.0 MPa. This comparability was attributed to the use of similar lightweight SCC in both studies.

Prestress losses of pretensioned concrete members may be significant for first several months or the first year after casting [24]. In this study, however, prestress losses were unable to be measured after 83 days of age since the tested girders were used for construction of a parking garage. This duration may not long enough to evaluate the time-dependent losses in comparison with the members' service life. When quantifying prestress losses for pretensioned concrete beams cast with lightweight SCC, Bymaster et al. [9] found that the prestress losses show little changes after 75 days of age. As shown in Fig. 5, prestress losses may occur after 83 days, possibly at a slow rate. When the topping slab is placed, the girders can gain elastic shortening prestress that can compensate for the time-dependent losses occurring after 83 days of age.

5.3. Elastic-shortening loss

An increase in elastic-shortening loss was observed when the strands were cut at the ends of each girder, and after the girders were removed from the prestressing bed (5 h after strands were cut). After the strands were cut at girder ends, the elastic-shortening loss was 73.6 MPa and 28.0 MPa for DT-A and DT-B, respectively. After the girders were removed from prestressing bed, the elastic-shortening loss increased to 96.2 MPa and 88.8 MPa for girders DT-A and DT-B, respectively. A possible explanation of the increase in prestress losses is the large frictional force of a long prestressing bed acting on the concrete, reducing elastic shortening of the concrete. If friction reduces the ability for the concrete to shorten under transfer, then elastic shortening may not fully occur until the frictional restraint is removed. Cook et al. [53] reported that they observed a significant increase in camber after the girders in their study were removed from the bed, likely because of the frictional force present between the bed liner and the girder. They also reported this effect would be more pronounced on longer girders. A large frictional force could lead to less than expected values in both elastic prestress losses and initial camber.

Fig. 6 shows the ratios of the predicted prestress losses using Zia et al. study [46] and AASHTO specifications [26] to the measured elastic-shortening loss when the girders were removed from prestressing bed. The basic mechanism of elastic-shortening loss shown in Eq. (2) is to relate the concrete stress at the centroid of the prestressing strands (f_{cpg}) at prestress transfer to the elastic-shortening loss through the modular ratio (E_p/E_{ci}). Zia et al. proposed to calculate f_{cpg} using gross-section properties, and the prestress after transfer (f_{pt}) is assumed to be 90% of the prestress

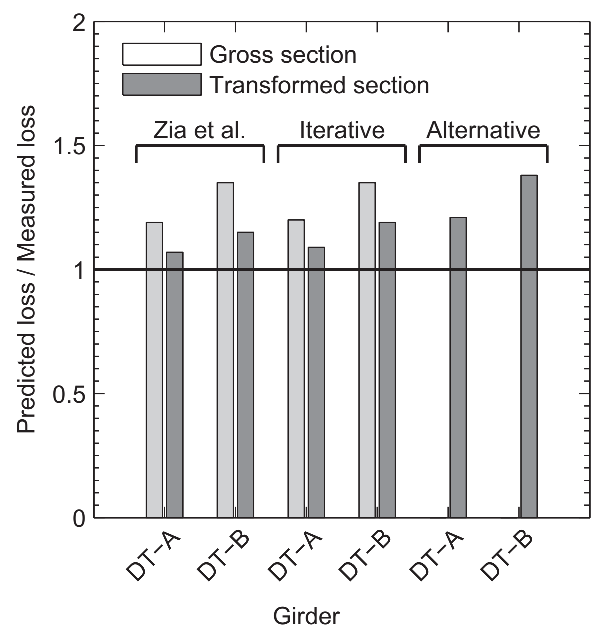

Fig. 6. Ratios of predicted elastic-shortening loss using Zia et al. study, AASHTO iterative procedure, and AASHTO alternative procedure to the measured elastic-shortening loss.

prior to transfer (f_{pj}). This procedure resulted in elastic-shortening loss of 114.8 MPa for girder DT-A and 120.1 MPa for girder DT-B, which over-estimated the measured results by 19% and 35%.

$$\Delta f_{pES} = \frac{E_p}{E_{ci}} f_{cgp} \tag{2}$$

where Δf_{pES} is elastic-shortening loss; E_p is modulus of elasticity of prestressing strands (196.5 GPa); E_{ci} is the modulus of elasticity of concrete at release; f_{cpg} is the concrete stress at the centroid of the prestressing strands at prestress transfer.

AASHTO [26] refined the procedure proposed by Zia et al. by including a number of iterations to calculate f_{pt}. Variable f_{pt} is firstly assumed to be 90% of f_{pj}, and iterated until an acceptable accuracy is attained. In this study, the iterations were stopped when f_{pt} was 90.5% and 90.1% of f_{pj} for girders DT-A and DT-B, respectively. These values were approximately equal to the assumed value by Zia et al. The predicted elastic-shortening loss using AASHTO was similar to that predicted by Zia et al., which was 115.5 MPa for girder DT-A and 120.3 MPa for girder DT-B. The

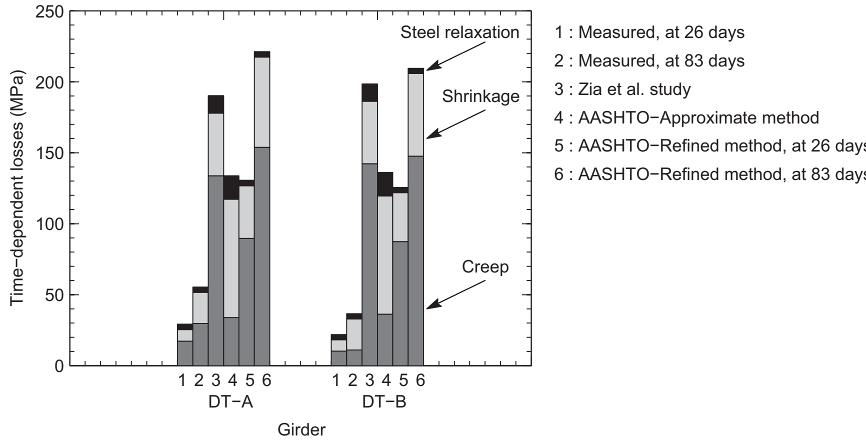

Fig. 7. Measured and predicted time-dependent prestress losses.

results of this technique are shown as "Iterative" in Fig. 6. To avoid the iteration, AASHTO proposes an alternative procedure that uses transformed-section properties as stated in Eq. (C5.9.5.2.3a-1) of the Article 5.9.2.3 of the AASHTO specifications. The predicted elastic-shortening loss using the alternative procedure was 116.7 MPa for girder DT-A and 122.1 MPa for girder DT-B, which over-estimated the measured values by 21% and 38%.

To increase the accuracy in estimating elastic-shortening loss, the authors propose to use transformed-section properties for the procedure proposed by Zia et al. and AASHTO iterative procedure. For Zia et al., the predicted loss was 103.2 MPa for girder DT-A and 102.5 MPa for girder DT-B. These values showed a good agreement with the experimental results in which the over-estimation ranged from 7.0 MPa to 13.7 MPa. For the AASHTO iterative procedure, the iterations were stopped when f_{pt} was 91.4% of f_{pj} for both girders DT-A and DT-B. The predicted elastic-shortening loss was 105.1 MPa for girder DT-A and 105.2 for girder DT-B. These values were similar to those predicted by Zia et al., and over-estimated the measured results by 9% and 19% for girders DT-A and DT-B, respectively.

5.4. Time-dependent losses

Fig. 7 shows the time-dependent prestress losses due to concrete creep and shrinkage and steel relaxation. At 26 days, the measured time-dependent losses were 29.2 MPa and 21.9 MPa for girders DT-A and DT-B, respectively. At 83 days, the measured time-dependent losses increased to 55.4 MPa for girder DT-A and 36.6 MPa for girder DT-B. It should be mentioned that these values included the prestress loss due to steel relaxation that was calculated using the AASHTO-Refined method [26], which ranged from 3.6 to 3.8 MPa. As shown in Fig. 7, the measured time-dependent losses of girder DT-A were greater than girder DT-B. This was possibly due to the variability in creep loss, which was attributed to the different in the concrete stresses due to permanent loading in pretensioned concrete girders [54]. The shrinkage loss of the two girders was expected to be comparable due to these girders experiencing the similar environmental conditions.

The Zia et al. study [46], AASHTO-Approximate method [26], and AASHTO-Refined method [26] over-estimated the measured time-dependent losses, either at 26 or 83 days. Zia et al. method and AASHTO-Approximate method predict the time-dependent prestress losses that occur throughout the life of the girders. According to Zia et al. study, the time-dependent prestress losses of girders DT-A and DT-B were 190.2 MPa and 198.7 MPa, respectively. The AASHTO-Approximate method predicts lower prestress losses that were 133.8 MPa for girder DT-A and 136.1 MPa for girder DT-B. The AASHTO-Refined method, however, specifies the time-dependent losses at 26 and 83 days. The predicted losses at 26 days using the AASHTO-Refined method were approximately the same as those predicted using the AASHTO-Approximate method for the entire life of the girders. At 83 days, the AASHTO-Refined method predicted prestress losses of 221.2 MPa for girder DT-A and 209.5 MPa for girder DT-B. Each method uses different coefficients in estimating prestress that were derived from experimental results of various types of normal-weight concrete. Therefore, the degree of over-estimation is varied when extending these methods to predict prestress losses for pretensioned concrete members cast with lightweight SCC.

The use of VWSGs is a reliable technique to measure prestress losses. However, this technique could not separate the prestress losses caused by concrete creep and shrinkage, while the understanding regarding the contribution of each component is important for the design of pretensioned concrete members [54]. Therefore, the measured shrinkage strain of lightweight SCC reported by Bymaster et al. [9] was adopted in this study, due to the similarities in the mix proportion, concrete properties, and relative humidity. In Fig. 8, the fitting line represents the trend of shrinkage strains for the first 112 days of age. The interpolated strains at 26 day and 83 days were -41.27×10^{-6} and -111.31×10^{-6} that

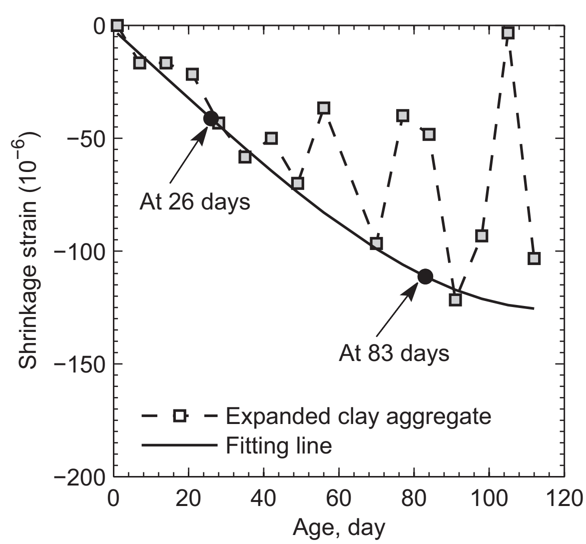

Fig. 8. Concrete shrinkage [9]. The equation of the fitting line is $y = 4.633 \times 10^{-5} \times x^3 - 1.672 \times 10^{-3} \times x^2 - 1.497 \times x - 2.031$; where y is the shrinkage strain (10^{-6}), and x is the age of concrete (day). The shrinkage strains at 26 days and 83 days are -41.27×10^{-6} and -111.31×10^{-6}, respectively.

resulted in shrinkage losses of 8.1 MPa and 21.9 MPa, respectively, as illustrated in Fig. 7. For girder DT-A, prestress loss due to concrete creep is a dominant contributor that is 53.6% of the time-dependent losses at 83 days, while the loss due to concrete shrinkage and steel relaxation is 39.5% and 6.9%, respectively. Girder DT-B shows a different trend in which prestress loss due to concrete shrinkage is a dominant contributor to the time-dependent losses. The contribution of concrete creep, concrete shrinkage, and steel relaxation were 30.1%, 59.8%, and 10.1%, respectively. The difference in creep loss was the most likely reason attributing to the variability in the contribution of concrete creep and shrinkage to the time-dependent losses.

The contribution of concrete and shrinkage to the time-dependent losses also varies between the existing methods as shown in Fig. 7. Zia et al. [46] study predicts the creep loss is70.3–71.7% of the time-dependent losses, while the shrinkage and steel-relaxation losses varied from 22.2% to 23.2% and 6.1 to 6.5%, respectively. The predicted prestress losses using the AASHTO-Approximate method [26] present a different trend in which shrinkage loss is significant for the time-dependent losses. The predicted prestress losses using the AASHTO-Refined method [26], in turn, show a similar trend to that of Zia et al. study. The creep and shrinkage losses at 26 days and 83 days are approximate 70% and 28% of the time-dependent losses. The steel-relaxation loss is small for low-relaxation prestressing strands that are about 2% of the time-dependent losses. In summary, these methods are inconsistent in estimating the contribution of concrete creep and shrinkage to the time-dependent losses; therefore, a special consideration should be given when using existing methods to predict time-dependent losses of pretensioned concrete girders cast with lightweight SCC, which is further discussed in the recommendation section.

5.5. Total losses

Fig. 9 shows the ratios of the total measured prestress losses to the predicted losses. On average, the Zia et al. study [46], AASHTO-Approximate method [26], and AASHTO-Refined method [26] over-estimated the measured prestress losses at 26 days of age by 153%, 116%, and 111%, respectively. At 83 days of age, the over-estimation of Zia et al. study, AASHTO-Approximate method, and AASHTO-Refined method was 117%, 86%, and 144%, respectively. The degree of over-estimation was attributed to the time-dependent losses since the existing methods provide an acceptable accuracy in predicting the elastic-shortening loss.

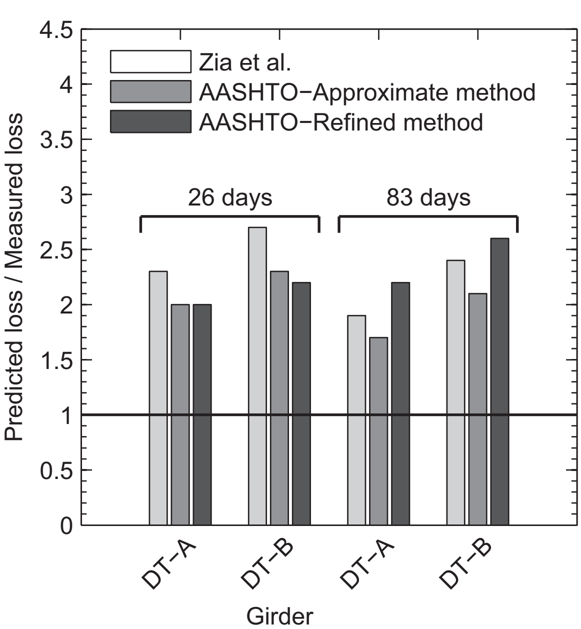

Fig. 9. Ratios of total predicted prestress loss to total measured losses at 26 days and 83 days.

In practice, AASHTO specifications [26] are widely used in the design of pretensioned concrete members. The effect of over-estimating prestress losses when using the AASHTO specifications should be considered when the members are designed with lightweight SCC. This over-estimation results in a high tensile stress in the prestressing strands that is greater than predicted, which causes cracking in the top fiber of the members. While these cracks may close or be sealed when the deck or topping slab is placed, the greater prestress force increases girder camber, which requires adjustments to the haunch height when the girder is erected; where haunch is the distance from the top fiber of the pretensioned concrete member to the bottom of the deck. If precast panels are used for the deck, the reduction of haunch height may result in inadequate concrete bearing thickness. If the deck is cast-in-place, to maintain the roadway profile requirements, the girder may project into the deck. For long-term effects, a greater prestress force results in girder deflections that are less than predicted. This effect causes an excessive amount of camber between bents. While the excessive camber affects the riding quality of the bridge, it has minimal influence on the girders' structural performance.

6. Conclusions

This study monitored prestress losses of two full-scale double-tee girders. The girders were cast with sand-lightweight SCC and 12.7-mm, Grade 1860, low-relaxation prestressing strands. Based on the investigations, several conclusions were made as follow:

1. The AASHTO equation is suitable for predicting the MOE of sand-lightweight concrete. The predicted MOE values using a correction factor K_1 of 0.99 provided a good agreement with the experimental results with an error of $\pm$10%.
2. The measured elastic-shortening loss when the girders were removed from the prestressing bed was similar to the predicted values. It was observed that the measured elastic-shortening loss immediately after release of the prestressing strands was less than the predicted values. This was due to the presence of a large friction force that existed between the girders and the prestressing bed.
3. The elastic-shortening loss can be predicted using the Zia et al. study, AASHTO iterative procedure, or AASHTO alternative procedure. For the first two techniques, the use of transformed-section properties provides better results than using the gross-section properties. Assuming the prestress after transfer of 90% of the prestress prior to transfer provided reasonable results in estimating elastic-shortening loss.
4. The Zia et al. study, AASHTO-Approximate method, and AASHTO-Refined method over-estimated the measured prestress losses at 26 days of age. Concrete creep and shrinkage are the two dominant factors contributing to the time-dependent losses, while the contribution of each component varied between the girders and the existing methods.
5. When compared to the total measured prestress losses at 26 and 83 days of age, the Zia et al. study, AASHTO-Approximate method, and AASHTO-Refined method over-estimated the measured prestress losses for both girders. On average, the over-estimation ranged from 86% to 153%.

7. Recommendation

The experimental results of this study confirm the over-estimation of current AASHTO specifications for the time-dependent losses of pretensioned members using sand-lightweight concrete. In addition, the predicted prestress losses are almost two times greater than the measured values. In this study, the experimental results are not adequate to propose new coefficients for enhancing the accuracy of existing methods. Therefore, more research is needed to evaluate prestress losses for pretensioned concrete girders cast with lightweight concrete.

1. The measurement of prestress losses for full-scale pretensioned concrete girders, which are cast with normal-strength and high-strength lightweight SCC, would provide useful experimental results for evaluating the adequacy of current AASHTO specifications. The experimental data can be additionally employed to revise the existing coefficients used in estimating time-dependent losses to enhance the accuracy in predicting the total losses.
2. Lightweight aggregates significantly affect the concrete properties and consequently influence the prestress losses of pretensioned concrete girders. Future research should develop concrete mixtures that contain various types of lightweight coarse aggregates, which may include expanded shales, clays, or slates. It is necessary to develop particular models to predict creep and shrinkage of lightweight SCC. The proposed models can be calibrated and validated that based on the prestress losses measured on pretensioned concrete girders.
3. A statistical study, which synthesizes experimental results collected in the literature, would be a useful tool to develop an extended specification for estimating prestress losses of pretensioned concrete girders cast with lightweight SCC.

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