Bridge Views

HIGH PERFORMANCE CONCRETE Academia States Industry FHWA HPC

Issue 64 November/December 2010

Inside This Issue...

SPONSORED BY

U.S. Department of Transportation
Federal Highway Administration

CO-SPONSORED BY
NATIONAL CONCRETE BRIDGE COUNCIL

PORTLAND CEMENT ASSOCIATION

PRECAST PRESTRESSED CONCRETE INSTITUTE

NATIONAL READY MIXED CONCRETE ASSOCIATION

AMERICAN SEGMENTAL BRIDGE INSTITUTE

EXPANDED SHALE CLAY AND SLATE INSTITUTE

CONCRETE REINFORCING STEEL INSTITUTE

POST-TENSIONING INSTITUTE

WIRE REINFORCEMENT INSTITUTE

SILICA FUME ASSOCIATION

Implementing Self-Consolidating Concrete Technology in Washington State

Bijan Khaleghi, Washington State Department of Transportation

Tieton River Bridge.

The Tieton River Bridge was the first use of self-consolidating concrete (SCC) for a precast, prestressed girder superstructure by the Washington State Department of Transportation (WSDOT). The project involved replacing two 77-year old bridges and widening lanes and shoulders along and over the Tieton River, about 14 miles (22.5 km) west of Naches, WA. Built in 1933, the original bridges were only 24 ft (7.3 m) wide and classified as structurally deficient. Design of the replacement bridge began in 2004, with construction completed in 2009.

The replacement Tieton River Bridge consists of a two-span continuous structure with span lengths of 80 and 167 ft (24.4 and 50.9 m) for a total length of 247 ft (75.3 m). The bridge is 32 ft (9.8 m) wide and carries two lanes of traffic. The bridge was designed per the 4th Edition of the AASHTO LRFD Bridge Design Specifications.[1] The bridge superstructure is composed of five WF74G wide-flange, precast, prestressed concrete girders spaced at 6 ft 9 in. (2.1 m) on center. The nominal depth of the precast girders is 74 in. (1.88 m) for both spans. The superstructure is composite with a 7.5-in. (190-mm) thick cast-in-place concrete deck.

SCC was used only for the prestressed concrete girders of the shorter span. The specified concrete compressive strengths for the SCC precast girders were 4500 psi (31 MPa) at release of the prestressing strands and 5700 psi (39 MPa) at 28 days. The specifications required a slump flow of 25 to 28 in. (635 to 710 mm) and an air content of 1.5%. The girders were lightly precompressed with twelve 0.6-in. (15.2-mm) diameter straight and three 0.6-in. (15.2-mm) diameter harped strands because WSDOT requires the use of the same type and number of girders in all spans of continuous bridges.

Self-Consolidating Concrete

WDSOT received Innovative Bridge Research and Deployment (IBRD) funding from the Federal Highway Administration for the Tieton River Bridge. The main objectives of the IBRD program are to promote, demonstrate, evaluate, and document the application of innovative designs, materials, and construction methods in the construction, repair, and rehabilitation of bridges and other highway structures. The use of SCC reduced production costs through faster placement and allowed for placement with fewer skilled workers. The SCC created a smooth surface to the girders without signs of bleeding or discoloration. On the other hand, the moisture content of the aggregate and variations in aggregate gradations have a greater impact on the properties of SCC than for conventional concrete.[2]

Concrete Mix Proportions

Material	Quantities (per yd^3)	Quantities (per m^3)
Cement, Type III	658 lb	390 kg
Fly Ash, Class C	150 lb	89 kg
Fine Aggregate	1412 lb	838 kg
Coarse Aggregate 1 AASHTO #67	781 lb	463 kg
Coarse Aggregate 2 AASHTO #8	781 lb	463 kg
Water	275 lb	163 kg
Entrained Air	1.5%	1.5%
High-Range Water-Reducing Admixture	5.5 fl oz	213 mL
Water-Cementitious Materials Ratio	0.34	0.34

Structural Design

The requirement for high flowability of SCC dictates the use of higher cementitious materials content, a high-range water-reducing admixture, and less coarse aggregate content. These materials result in concrete properties that could be different from those of conventional concrete. This created a lack of confidence among WSDOT bridge designers in the use of SCC for structural applications. The structural design concerns related to the use of SCC for constructing precast, prestressed girders include the likely lower modulus of elasticity,[3,4] greater shrinkage,[3,4] possible larger prestress losses,[3] and the reduced shear resistance resulting from the use of a smaller maximum aggregate size or a smaller volume of coarse aggregate. As a result, WSDOT requires the following design modification factors for use with SCC in precast, prestressed concrete girders:

Property	Modification Factors
Modulus of Elasticity	$k_{scc} = 0.9$
Creep	$k_{scc} = 1.5$
Shear (applies to V_c only)	$\varphi_{scc} = 0.7$
Shrinkage	$k_{scc} = 1.0$

Lessons Learned

This project did not tell us much about the structural properties of the SCC because the girders were deep, only 80-ft (24.4 m) long, and lightly prestressed with about 3/4 in. (19 mm) of camber. From the production perspective, WSDOT was concerned that SCC placed into a deep girder might segregate, but that did not happen. The placement went smoothly with fewer workers required than for a conventional concrete girder, and the finishing work was significantly reduced because of the high quality finish right out of the form. The concrete strengths at 28 days were comparable to those of the regular mixes. Although the material is more expensive, the reduction in labor more than compensates for the added cost. Our experience tells us that once we get a good handle on the design concrete properties, SCC is the way to go in the future. It will be more economical and the product will have a higher quality finish.

References

1. AASHTO LRFD Bridge Design Specifications, 4th Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2007.
2. Carr, M. K. and Strickland, B., "Self-Consolidating Concrete for Beams Speeds Biloxi Bay Bridge Construction, HPC Bridge Views, Issue No. 50,

July/August 2008.

3. Khayat, K. H. and Mitchell, D., "Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements," Transportation Research Board, NCHRP Report 628, Washington, DC, 2009.
4. Zia, P., Nunez, R. A., and Mata, L. A., "Implementation of Self-Consolidating Concrete for Prestressed Concrete Girders," Technical Report, North Carolina Department of Transportation, Research and Analysis Group, 2005.
5. Brewe, J. E. and Myers, J. J. "Shear Behavior of Reduced Modulus Prestressed High-Strength Self Consolidating Concrete Members Subjected to Elevated Concrete Fiber Stresses," PCI National Bridge Conference, 2009.

Further Information

For further information about this article, contact the author at khalegb@wsdot.wa.gov or 360-705-7181.

HPC for the Spliced Girders of Kealakaha Stream Bridge, Hawaii

Chuck Prussack, Central Pre-Mix Prestress Co.

Concrete with a specified compressive strength of 9000 psi (62 MPa) was used in the spliced girders.

In 2006, KSF Engineers Inc. (KSF) of Honolulu, HI, contacted Central Pre-Mix Prestress Co. (CPPC) located in Spokane, WA, to discuss spliced girder concepts. KSF had been retained by the general contractor, Hawaiian Dredging Construction Co. (HDCC), who was low bidder on the originally designed Kealakaha Stream Bridge—a cast-in-place, three span, single cell, curved segmental box girder structure. KSF's role was to examine options that would make construction of this bridge easier. Due to site constraints, the bridge needed to be built from the top down because access into the ravine below the bridge was very difficult. The bridge is also close to an active volcano and subject to high seismic activity. KSF had seen an article in the July/August, 1997, issue of the PCI Journal about a similar project that involved CPPC. From discussions between CPPC and KSF, the concept was developed to use a longitudinally spliced, post-tensioned girder bridge that would be easier to construct given the site constraints.

Value-Engineered Solution

The original design called for span lengths of 180, 360, and 180 ft (54.9, 109.7, and 54.9 m) using a horizontally curved, cast-in-place box girder. The value-engineered superstructure retained the same span lengths but used 150-ft (45.5-m) long straight cast-in-place box girders above each pier with 100-ft (30.5-m) long straight spliced girders between the ends of the box girders and the abutments and 205-ft (62.5-m) long straight spliced girders to complete the main span. This framing plan created five chords to provide for the curved horizontal alignment.

Due to tight road geometry leading to the site, the maximum girder segment length that could be hauled was limited to less than 50 ft (15.2 m). So, the end span spliced girders were made with two girder segments, and the main span was made with four girder segments. The girder segments were spliced together at the site, and then launched into place. The average segment length for all prefabricated segments was approximately 47 ft (14 m). Cast-in-place closures were used between the precast segments and between the spliced girders and the cast-in-place box girders.

Spliced Girder Cross Section

The spliced girder selected was the Washington State Department of Transportation (WSDOT) Standard WF95 PTG girder. This girder cross section, with a depth of 95 in. (2.41 m), had been jointly developed by industry and WSDOT to be able to span in excess of 200 ft (61 m) using splicing techniques. It is one of several depths of "supergirders" used by the WSDOT. When these "supergirders" are used in a post-tensioned scenario, the overall girder width is increased by 2 in. (51 mm) to give a 7⅞-in. (200-mm) wide stem, and 2-in. (51-mm) wider top and bottom flanges. Specified concrete compressive strengths for the precast girders were 8000 psi (55 MPa) at 28 days and 9000 psi (62 MPa) at 56 days. CPPC viewed these strengths as "business as usual" type strengths that would use a standard girder mix design.

High Strength Concrete Development

In 1996, CPPC was low bidder on the first WSDOT high performance concrete (HPC) bridge girder project called Covington Way Bridge. That project required 10,000 psi (69 MPa) for the 28-day strength and 7000 psi for strength at transfer. Until that point, a typical 28-day strength requirement for girders in Washington State had been in the 7000 psi (48 MPa) range, with release strengths in the 5000 psi (34 MPa) range. As CPPC began working on mix designs for the Covington Way Bridge, it quickly became clear that CPPC would not get 10,000 psi (69 MPa) strength, nor the required release strengths using their current mixes and approach to making concrete.

When CPPC began talking to other companies and material engineers about how to achieve these strengths, it quickly became apparent that there were many alternatives to achieving high strength concrete. Some materials engineers advocated large fly ash content, some advocated large silica fume content, some used metakaolins, some advocated "aggregate packing," and some just used a very low water-cementitious materials ratio. It was very confusing for a while trying to reconcile all these opinions! All aspects of concrete production from optimizing mix designs, curing, moisture control, admixtures, and testing were looked at. Finally, CPPC took the approach to use a combined gradation for aggregate selections, 5% silica fume, and 20% Class C fly ash for the mix itself. A high-range water-reducing admixture was used to increase workability, the preset period was determined by the use of a hydration chamber to optimize curing, the compressive strength testing machine was upgraded to a digital readout, and cylinder capping was switched to a high strength capping compound. New moisture sensors were installed in the aggregate bins that enabled a more accurate determination of the water-cementitious materials ratio, and a match-curing system was implemented.

Since that first HPC project, CPPC has continued to improve concrete mixes such as that used for the Kealakaha Stream Bridge. By the time Kealakaha Stream Bridge girders were cast, admixtures had been switched from the original HPC mixes to the new series of high-range water-reducing admixtures, and a small amount of slag cement was used. Fly ash and silica fume were not used, and because of the newer generation of admixtures, a lower water-cementitious materials ratio was possible. CPPC also switched to the use of neoprene pads for the cylinder testing.

Measured concrete compressive strengths ranged from 5500 to 6000 psi (37.9 to 41.4 MPa) at prestress transfer, 10,500 to 11,300 psi (72.4 to 77.9 MPa) at 28 days, and 10,600 to 12,600 psi (73.1 to 86.9 MPa) at 56 days.

Since Kealakaha Stream Bridge, CPPC now uses the latest version of polycarboxylate high-range water-reducing admixtures, with the remainder of the mix design for HPC girders remaining the same as shown above. Strengths at transfer are well into the 7000 psi (48 MPa) range and 28-day strengths well into the 12,000 psi (83 MPa) range. The strengths that are commonplace today would have seemed impossible to CPPC in 1996, but advances in technology and a new understanding have led to significant advances.

Further Information

Further information about the design and construction of Kealakaha Stream Bridge is provided in ASPIRE™ Summer 2010.

Concrete Mix Proportions

Material	Quantities (per yd^3)	Quantities (per m^3)
Cement, Type III	685 lb	406 kg
Slag Cement	65 lb	39 kg
Fine Aggregate 1	449 lb	266 kg
Fine Aggregate 2	800 lb	475 kg
Coarse Aggregate 1 AASHTO #67	548 lb	325 kg
Coarse Aggregate 2 AASHTO #8	1210 lb	718 kg
Water	260 lb	154 kg
Air Entrainer	As required	As required
High-Range Water-Reducing Admixture	As required	As required
Water-Cementitious Materials Ratio	0.35	0.35

Transfer and Development Length of 0.7-in. (17.8-mm) Diameter Strands in Pretensioned Concrete Bridge Girders

George Morcous, Kromel Hanna, and Maher K. Tadros, University of Nebraska-Lincoln

The Pacific Street Bridge, Omaha, NE, used 0.7-in. (17.8-mm) diameter strands in the precast, prestressed concrete beams.

For several years, 0.7-in. (17.8-mm) diameter strands have been used in cable-stayed bridges and mining applications in the United States, and for post-tensioning tendons in Europe and Japan. To the author's knowledge, the Pacific Street Bridge over I-680 in Omaha, NE, is the first bridge in the world to use 0.7-in. (17.8-mm) diameter prestressing strands in pretensioned concrete girders.[1] This strand has a cross-sectional area of 0.294 in.^{2} (190 mm^2) and a weight of 1 lb/ft (1.5 kg/m). Tensioning one 0.7-in. (17.8-mm) diameter strand up to 75% of its ultimate strength requires a prestressing force of 59.5 kips (265 kN), which is 35% greater than that of 0.6-in. (15.2-mm) diameter strand and 92% greater than that of 0.5-in. (12.7-mm) diameter strand. Using 0.7-in. (17.8-mm) diameter strands results in less strands to jack and release, requiring fewer chucks, and producing a higher flexural capacity due to the lower center of gravity of the strands.

A detailed study on optimized sections for high strength concrete bridge girders was carried out in 1996 by Russell et al.[2] Despite the unavailability of 0.7-in. (17.8-mm) diameter strand in the U.S. market at the time of the study, its cost-effectiveness compared to other strand sizes was evaluated. This study indicated that using 0.7-in. (17.8-mm) diameter strands at 2 in. (50 mm) centers in a 10,000 psi (69 MPa) BT-72 bulb-tee girder resulted in the longest girder span and most cost-effective superstructure compared to 0.5-in. (12.7-mm) and 0.6-in. (15.2-mm) diameter strands.

The Fifth Edition of the AASHTO LRFD Bridge Design Specifications[3] has transfer length and development length equations, as well as strand spacing requirements based on strands up to 0.6 in. (15.2 mm) in diameter. Transfer length is the length of the strand measured from the end of the prestressed concrete member over which the effective prestress is transferred to the concrete. Transfer length is important for shear design and concrete stresses at the girder ends following strand release. The development length of prestressing strands is defined as the minimum strand embedment in concrete required to achieve the ultimate capacity of the section without strand slippage. The development length is necessary for identifying the critical sections in flexure and shear and calculating their ultimate capacities.

Test Program

For 0.7-in. (17.8-mm) diameter strands to be used in prestressed concrete bridge girders at 2x2-in. (50x50-mm) spacing, an extensive experimental investigation was carried out at the University of Nebraska-Lincoln. The objective of this investigation was to determine whether the provisions of the AASHTO LRFD Bridge Design Specifications for transfer and development length are valid for 0.7-in. (17.8-mm) diameter strands tensioned to 75% of the ultimate strength and placed at the same 2-in. (50-mm) spacing as 0.6-in. (15.2-mm) diameter strands to avoid the costly retooling of existing prestressing beds. This investigation consisted of designing, fabricating, and testing eight 24-in. (610-mm) deep tee-girders and three NU1100 girders for transfer length and development length. The tee girders were 28 ft (8.5 m) long, prestressed with six 0.7-in. (17.8-mm) diameter strands, and made using 8000 to 14,000 psi (55 to 97 MPa) compressive strength concrete. Measured strengths at transfer ranged from 6500 to 8000 psi (45 to 55 MPa). Different spacings and lengths of confinement of the confinement reinforcement were used at the girder ends. The three NU1100 girders were 40 ft (12.2 m) long, prestressed using thirty-four 0.7-in. (17.8-mm) diameter strands, and made of high strength concrete. Different spacings and lengths of confinement of bottom flange confinement reinforcement were used.

Transfer Length

Transfer length was measured using a detachable mechanical (DEMEC) gage. Points were attached to the concrete surface at the girder ends at the elevation of the centroid of the prestressing strands before release. The change in the measured distance between the DEMEC points before and after release was used to calculate the strain in the concrete due to prestressing at different ages using the 95% average maximum strain method. According to the measured strains, the transfer length from all tests of 0.7-in. (17.8-mm) diameter strands after 28 days ranged from 24 to 31 in. (610 to 788 mm), which is well below the 42 in. (1.07 m) predicted using Article 5.11.4.1 of the Fifth Edition of the AASHTO LRFD Bridge Design Specifications.

Development Length

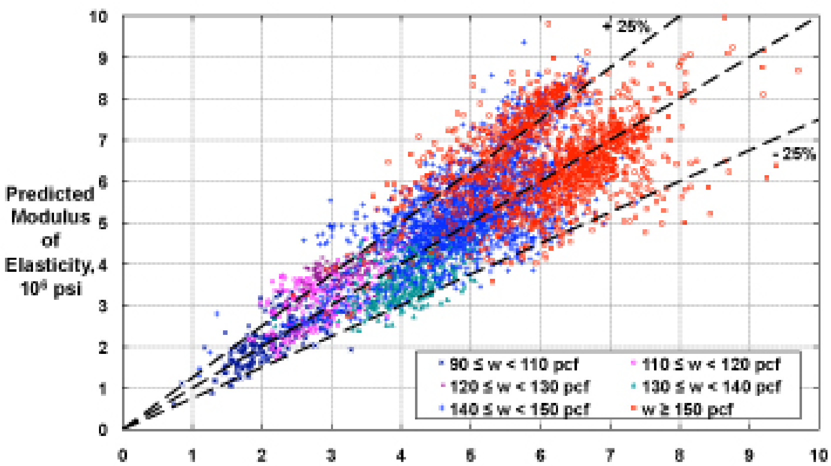
Development length was calculated using Equation 5.11.4.2-1 of the Fifth Edition of the AASHTO LRFD Bridge Design Specifications to be approximately 14 ft (4.3 m) for 0.7-in. (17.8-mm) diameter strands. Therefore, all the girders were tested using a point load located at 14 ft (4.3 m) from the girder end, while monitoring girder deflection at the loading point and strand slip at the girder end using linear potentiometers. The load-deflection and load-slip diagrams indicated that, even with the lowest concrete strength of 8000 psi (55 MPa) and minimum confinement reinforcement of No. 3 bars @ 6 in. (152 mm) centers for a distance of 1.5d from the end of the beam, the nominal flexural capacity was achieved without slip of any strands exceeding 0.01 in. (0.25 mm). Therefore, it can be concluded that the development length calculated using the Fifth Edition of the AASHTO LRFD Bridge Design Specification for 0.7-in. (17.8-mm) diameter strands tensioned to 75% of the ultimate strength and located at 2 in. (50 mm) centers is satisfactory.

References

1. Schuler, G., "Producer's Experience with 10,000 psi Concrete and 0.7-in. Diameter Strands," HPC Bridge Views, Issue No. 54, March/April 2009.
2. Russell, H. G., Volz, J. S., and Bruce, R. N., "Optimized Sections for High-Strength Concrete Bridge Girders," FHWA, U.S. Department of Transportation, Report No. FHWA-RD-95-180, 1997, 156 pp.
3. AASHTO LRFD Bridge Design Specifications, Fifth Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2010.

Testing and Predicting the Modulus of Elasticity of Concrete

Henry G. Russell, Henry G. Russell, Inc



Measured Modulus of Elastictiy

The accuracy of predicting camber and prestress losses in long-span bridges can be improved when measured values of concrete material properties are used. This article describes the ASTM test for modulus of elasticity and compares measured values with the design equation predictions.

Test Procedure

The procedure for measuring the static modulus of elasticity in compression is described in ASTM C469.(2) In this procedure, molded concrete cylinders or diamond-drilled concrete cores are subjected to a slowly increasing longitudinal compressive stress. Longitudinal strains are determined using either a bonded or unbonded sensing device that measures the average deformation of two diametrically opposite locations to the nearest 5 millionths of strain. ASTM C469 does not specify the diameter of the test specimens. However, molded concrete cylinders are usually the same size as those used for compressive strength measurements i.e. 6x12-in. or 4x8-in. (152x312-mm or 102x203-mm) cylinders. Concrete cores must have a length-to-diameter ratio greater than 1.50.

The applied load and longitudinal strain are recorded when the longitudinal strain is 50 millionths and when the applied load is equal to 40% of the cylinder compressive strength. Note that it is necessary to determine the compressive strength on companion specimens prior to testing for modulus of elasticity. The modulus of elasticity is calculated as the slope of the straight line between the 40% compressive stress point and the 50 millionths strain point. The same procedure may be used to obtain a stress-strain curve by taking more frequent readings either manually or automatically. ASTM C469 cautions that the modulus of elasticity values will usually be less than the modulus derived under rapid load application and usually greater than values obtained under slow load application, when all other test conditions remain the same.

Specifications

When specifying tests in accordance with ASTM C469, it is important to define the specimen size, test ages, and curing conditions prior to testing. It should also be stated whether a stress-strain curve is needed or only the chord modulus. The specifier should also check that local testing laboratories have the equipment available to perform the test on the specified cylinder size. Otherwise, it may be necessary to ship the cylinders to a specialized testing laboratory.

The test procedure does not prohibit the use of the same cylinders for modulus of elasticity and concrete compressive strength provided the loading can be applied continuously. This means that the measuring device must be expendable or adequately protected. For high strength concrete cylinders, which fail in an explosive manner, it is highly desirable to use separate cylinders. Because ASTM C469 is a test procedure, it may be used for normal strength concrete, high strength concrete, lightweight concrete, self-consolidating concrete, and ultra-high performance concrete.

Predicting the Modulus of Elasticity

Article 5.4.2.4 of the AASHTO LRFD Bridge Design Specifications contains the following equation for predicting the modulus of elasticity, E_c:

$E_c = 33{,}000 K_1 w_c^{1.5} \sqrt{f'_c}$ (ksi units)

where

K_1 = correction factor for source of aggregate to be taken as 1.0 unless determined by physical test

w_c = unit weight of concrete, kcf

f'_c = specified compressive strength of concrete, ksi

This equation represents average values and the actual modulus of elasticity can vary by ±25% as shown in the graph at the beginning of this article.[1] Many variables affect the modulus of elasticity in addition to those included in the equation. Consequently, when the modulus of elasticity is an important factor in design, more precise values can be obtained by testing with local materials than can be obtained from the equation.

References

1. Rizkalla, S., Mirmiran, A., Zia, P., Russell, H., and Mast, R., "Application of the LRFD Bridge Design Specifications to High-Strength Structural Concrete: Flexure and Compression Provisions," Transportation Research Board, NCHRP Report 595, Washington, DC, 2007, 28 pp.
2. Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM C469, ASTM International, Volume 04.02, West Conshohocken, PA, 2002.