SAND LIGHTWEIGHT CONCRETE FOR PRESTRESSED CONCRETE GIRDERS IN THREE WASHINGTON STATE BRIDGES

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ABSTRACT

Lightweight concrete is being used for more bridge structures as prestressed concrete girders and precast elements become larger and weight reduction becomes an important factor for shipping, handling, and improved structural efficiency. This paper reports on the recent successful use of high-strength sand lightweight concrete for precast, prestressed concrete girders for three projects constructed in Washington State. These projects are described briefly including the reason for using lightweight concrete. The main focus of the paper is to present the material property data collected for these projects which all used the same high-strength sand lightweight concrete mixture design. Data presented includes fresh unit weight, compressive strength, splitting tensile strength, modulus of elasticity, creep, and shrinkage. Test data are compared to project requirements, code estimates, and properties of a normal weight concrete mixture that the girder producer would have used had the design not required lightweight concrete. The relative cost of the sand lightweight concrete is also discussed.

Keywords: Lightweight concrete, bridge girders, creep, shrinkage, modulus of elasticity, tensile strength, compressive strength, fresh unit weight.

INTRODUCTION

Lightweight concrete has been used for bridge decks since at least the 1930s[1]. However, owners and designers have been reluctant to specify lightweight concrete for prestressed concrete bridge girders primarily because of the lack of understanding of long-term effects on prestress loss and camber. The development of NCHRP Report 733, *High-Performance/High-Strength Lightweight Concrete for Bridge Girders and Decks*[2], combined with experience gained and data collected on three recent bridge girder projects, has helped to provide an increased level of confidence in the specification, design, manufacturing and construction using lightweight concrete in Washington State.

This paper addresses the evolution of a sand lightweight concrete mixture design from lab trials to production from a precast concrete manufacturer's perspective. A cost comparison of the sand lightweight concrete mixture with a similar normal weight concrete mixture is also given. Material properties measured during production of the girders are presented including fresh unit weight, compressive strength, modulus of elasticity, creep, shrinkage and splitting tensile strength. The measured values are compared with specified values for most quantities.

PROJECTS

Three recent bridge projects in western Washington State used various precast/prestressed concrete bridge members for the primary superstructure supporting elements. All three projects used the same sand lightweight concrete mixture design to reduce the dead load supported by the substructure.

The Airport Way South Viaduct Replacement, owned by the City of Seattle, was the first of the three projects that specified the use of sand lightweight concrete for prestressed elements. The project consisted of replacing the existing superstructure of an approximately 800 foot long bridge that was originally built circa 1928 over an active rail yard. The existing superstructure consisted of lightweight concrete double tee members in the span range of 18 to 25 feet supported by steel floor beams, steel thru-girders, and concrete columns. In order to avoid significant retrofit work on the existing steel and concrete substructure, sand lightweight concrete was specified for the 226 replacement double tees to maintain the approximate equivalent superstructure dead load. The double tees were 20 in. deep with a top flange width of nearly 7'-11". The replacement double tees were manufactured in the spring and summer of 2012.

A replacement span for the Skagit River Bridge[3] on Interstate 5 was the second project to specify the use of sand lightweight concrete. In this case, sand lightweight concrete was used for decked bulb tee girders. The existing steel portal frame truss span collapsed after it was struck by a permitted over-size load on May 23rd, 2013. The design-build team selected by the Washington State Department of Transportation (WSDOT) for the permanent replacement span utilized a strategy similar to the Airport Way South project by limiting the replacement superstructure dead load to be approximately the same as the collapsed span to avoid substructure mitigation. The replacement span consisted of eight 65 in. deep decked bulb tee (DBT) girders that were 160 ft long with a nominal top flange width of 6'-6". The girders were manufactured in the summer of 2013.

Fig. 1 Double Tee Members for Airport Way South in Storage

Fig. 2 Decked Bulb Tee Girder for Skagit River Bridge in Storage

The third project to use sand lightweight concrete in prestressed girders is a two-span bridge designed by WSDOT to replace the existing crossing of State Route 162 over the Puyallup River. This project was intended as a demonstration project for the use of sand lightweight concrete for girders, but had been delayed for several years. The girders for this project are WSDOT WF74G girders. There are six girder lines on each of the two spans. Spans 1 and 2 are approximately 110 feet and 160 feet long, respectively. The girders for this project were manufactured and erected in the spring of 2015.

Fig. 3 WF74G Girder for SR162 Puyallup River Bridge in Storage

SAND LIGHTWEIGHT CONCRETE MIXTURE

MIXTURE DEVELOPMENT

The mixture used for all three projects described above was originally designed to satisfy the requirements specified for the Airport Way South project. The project required a "sand lightweight" concrete mixture, which is a type of reduced density concrete made using lightweight coarse aggregate and normal weight fine aggregate. A summary of the plastic and hardened concrete property requirements for the project is provided in Table 1.

Table 1 Airport Way South Concrete Mixture Design Requirements

Compressive Strength at Transfer (min.)	7,500	psi (achieve in 14-hour cycle)
28-Day Compressive Strength (min.)	9,000	psi
Slump (max.)	9.00	inches
Plastic Unit Weight (max.)	128.0	pcf
Modulus of Elasticity (min.)	3,200	ksi
Specific Creep (max.)	0.483	microstrain/psi
Shrinkage (max.)	0.05	% at 28 days
Splitting Tensile Strength (min.)	428	psi

The precast concrete manufacturer consulted with a lightweight aggregate manufacturer and performed a literature review to determine the state-of-the-art of high performance lightweight concrete. These activities led to the development of a lab batch trial program that tested various combinations of constituent ingredients. The final sand lightweight concrete mixture design is summarized in Table 2 which includes for comparison a normal weight concrete mixture that the precast concrete manufacturer would use to achieve similar concrete compressive strengths at transfer and at 28 days.

Table 2 Concrete Mixture Design Comparison

	Lightweight	Normal Weight
Type III Cement	800	752
Class F Fly Ash	135	N/A
Fine Aggregate (Natural)	1,125	1,215
Coarse Aggregate (Natural) – AASHTO #67	N/A	1,975
Coarse Aggregate (Lightweight) – ½” max.	965	N/A
Water	265	225
w/c Ratio	0.283	0.300
Calculated Fresh Density (pcf)	122.2	154.4
All values in pounds per cubic yard unless noted otherwise.		

The angular particle shape of the manufactured lightweight aggregate resulted in workability and placeability challenges during lab trials. The addition of Class F fly ash improved the workability and placeability of the sand lightweight mixture to an acceptable level.

The same sand lightweight concrete mixture was used for all three projects. The specified compressive strengths for the Skagit River Bridge were the same as the Airport Way South project which are shown in Table 1. The specified compressive strengths for the Puyallup River Bridge were 5.0 ksi and 6.0 ksi for transfer and 28-day strengths, respectively, for Span 1 girders and 7.1 ksi and 8.2 ksi for transfer and 28-day strengths for Span 2 girders except for one girder which required 7.8 ksi and 9.2 ksi for transfer and 28-day strengths.

Lightweight aggregate has a higher absorption than normal weight aggregates. In this case, the 24-hr absorption of the lightweight aggregate was approximately 6%. Lightweight aggregate is typically prewetted to a level approaching its 24-hr absorption to achieve predictable results when batching. The lightweight aggregate used for these projects was supplied in a prewetted condition so the girder manufacturer did not have to provide additional moisture.

PERFORMANCE IN PRODUCTION

Most activities associated with batching, delivering, placing, and finishing the sand lightweight concrete were very similar to conventional concrete. The one notable difference is in the finish of the unformed top surface of the member. The typical top surface finish of a bridge member that will receive a cast-in-place composite deck is a transverse rake which roughens the interface to approximately ¼” amplitude. Figure 4(a) represents a sample of a transverse rake of a normal weight prestressed girder. Numerous efforts were made to duplicate the transverse rake finish in the prestressed sand lightweight concrete members to no avail. Figure 4(b) represents a sample of the top flange finish that was achieved for the sand lightweight concrete mixture after screeding only. Note the absence of transverse rake marks, but more importantly, note the presence of an extremely rough surface.

(a) (b)

Fig. 4 Conventionally roughened (raked) surface for normal weight concrete (a) and surface of sand lightweight concrete after screeding (b).

COST COMPARISON

Understanding the costs associated with lightweight concrete is beneficial to all parties associated with bridge construction but can be confusing depending upon the specific element under consideration. For example, the precast concrete manufacturer uses a locally available natural coarse aggregate that is delivered in bulk via barge to a waterfront unloading facility. The cost premium of the lightweight coarse aggregate alone, on a per ton basis, is on the order of five times more expensive than the local coarse aggregate. Additionally, the precaster chose to use a source of aggregate on the opposite side of the country. Therefore, the freight cost for the lightweight aggregate is on the order of 25 times more than that for the locally available natural coarse aggregate delivered via barge.

However, with the exception of water, aggregate is the least expensive ingredient in a batch of concrete. Therefore, it seems reasonable to compare the cost of one cubic yard of sand lightweight concrete to one cubic yard of normal weight concrete to get a more complete cost comparison. In this case, the premium associated with this particular mix design is on the order of 2.0. In other words, a cubic yard of sand lightweight concrete is twice as expensive as a cubic yard of normal weight concrete.

Continuing with the comparison, the cost of concrete is a relatively small portion of the cost of a prestressed concrete girder. The authors studied two separate bridge projects using WSDOT WF50G and WF83G girders. The projects were designed and constructed with normal weight prestressed concrete girders. If the precaster had used sand lightweight concrete the overall cost of the girders to the owner would increase by 13% to 14%. This analysis does not take advantage of the potential cost savings associated with hauling and erecting lighter members, nor does it recognize the additional cost savings that may be available by reducing the dead load of the structure. The reduced structure weight would reduce the demand on the substructure and foundations, especially in seismic areas.

Table 3 summarizes the relative costs of lightweight aggregate and sand lightweight concrete compared to normal weight aggregate and concrete used by the precast concrete manufacturer, expressed as a ratio of [cost of lightweight]/[cost of normal weight].

Table 3 Concrete Mixture Relative Cost Comparison

	LW/NW
Aggregate	5
Aggregate Freight	25
Fresh Concrete	2.0
WF50G Girder Cost	1.14
WF83G Girder Cost	1.13
Trucking	No Cost Data
Erection	No Cost Data
Substructure	No Cost Data

This cost comparison represents what may be an upper bound for the cost of sand lightweight concrete since the aggregate was shipped all the way across the US. For producers in other areas of the country, the cost premium for LWC may be substantially less than what was computed for this project because the source of LWA would be closer, reducing the transportation cost.

MEASURED PROPERTIES OF SAND LIGHTWEIGHT CONCRETE

Test data for properties of the sand lightweight concrete mixture are discussed in this section. Since all projects used the same mix design, the sand lightweight concrete data from all projects are combined in this discussion, unless otherwise noted. Additionally, data from a normal weight concrete mix design that the precaster would use to attain similar compressive strengths are presented for comparison purposes.

FRESH CONCRETE UNIT WEIGHT

Fresh concrete unit weight measurements from the production concrete of the Airport Way South project are summarized in Figure 5. Testing was performed in accordance with ASTM C138. The specifications required that every batch of concrete must be sampled and tested for unit weight prior to placement in the forms. This established a level of confidence in the precast concrete manufacturer's abilities to produce uniform concrete and ensure that every batch of concrete was within the specification limits. It should be noted that future jobs did not require that every batch of concrete be tested for unit weight prior to placement. The projects subsequent to Airport Way South specified acceptance testing for unit weight at the same frequency as conventional testing such as slump and temperature. Table 4 summarizes the data represented in the histogram shown in Figure 5.

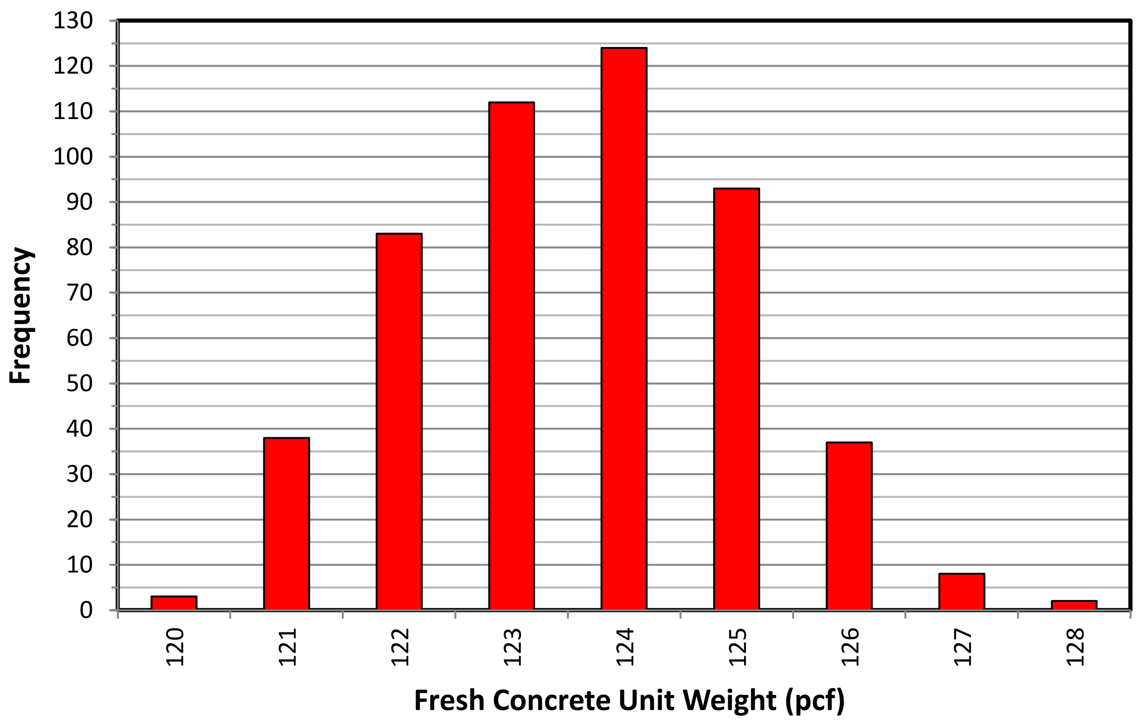

Fig. 5 Fresh Concrete Unit Weight Histogram (Airport Way South)

COMPRESSIVE STRENGTH

Figures 6 through 8 present plots of compressive strength data versus age of the concrete for the production concrete for each project. Testing was performed in accordance with ASTM C39. Trend lines for the data are shown in the figures. Note that the sand lightweight concrete has a similar magnitude of compressive strength and rate of strength gain when compared to a normal weight concrete mix cast and cured under similar conditions. The initial strength gain prior to transfer was also very similar for the two types of concrete. A summary of the data used to plot the 28-day compressive strengths is presented in Tables 5 through 7. The quantity in the tables designated "ACI Design Strength" has been calculated in accordance with ACI 301-05[4], Section 4.2.3.3.a for $f'_c > 5{,}000$ psi. It should be noted that the k-factor per Section 4.2.3.3.b for increasing standard deviation for number of tests less than 30 has not been applied to the Skagit River Bridge and Puyallup River Bridge data sets.

Table 4 Fresh concrete unit weight (Airport Way South)

Count:	501	each
Average:	123.1	pcf
Minimum:	119.6	pcf
Maximum:	128.2	pcf
Range:	8.6	pcf
Std. Dev.:	1.5	pcf

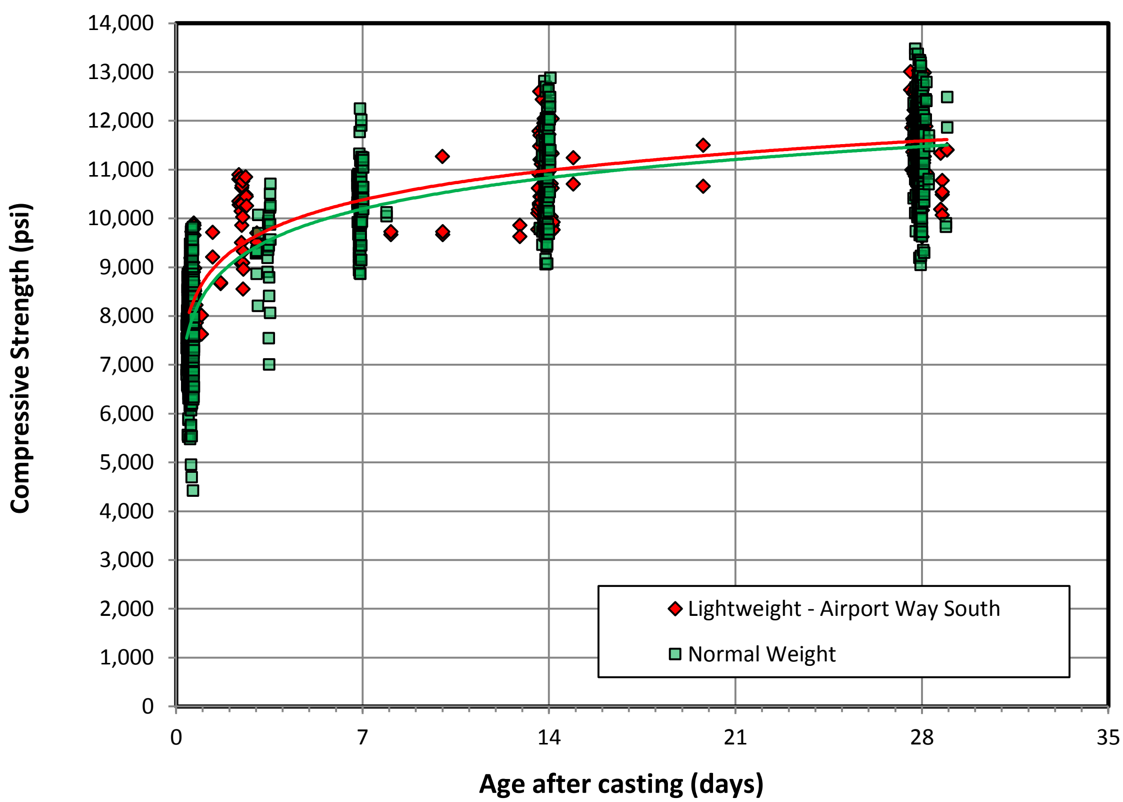

Fig. 6 Compressive strength versus age of concrete (Airport Way South)

Table 5 28-day compressive strength data (Airport Way South)

	Lightweight	Normal Weight
Count	138	324
Average	11,578	11,446
Minimum	9,620	9,045
Maximum	13,025	13,475
Range	3,405	4,430
Standard Deviation	698	880
Coefficient of Variation	6.0	7.7
ACI Design Strength	10,600	10,300

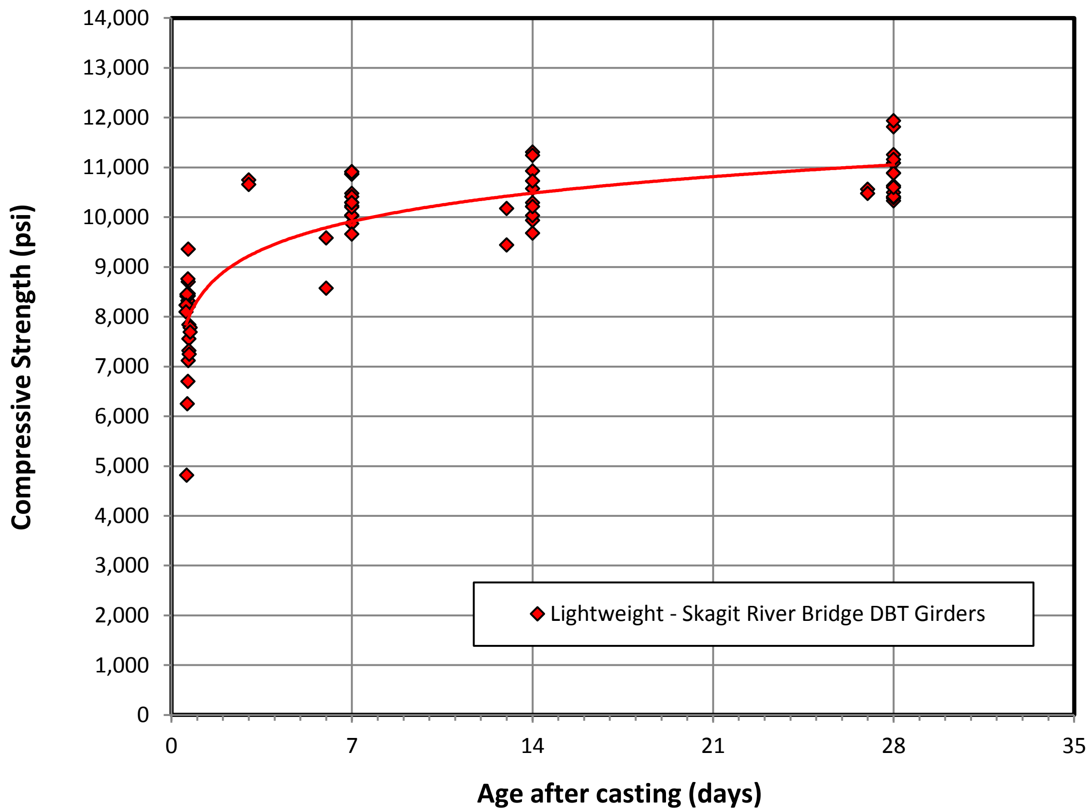

Fig. 7 Compressive strength versus age of concrete (Skagit River Bridge)

Table 6 28-day compressive strength data (Skagit River Bridge DBT Girders)

Count	16
Average	10,832
Minimum	10,330
Maximum	11,940
Range	1,610
Standard Deviation	503
Coefficient of Variation	4.6
ACI Design Strength	10,158

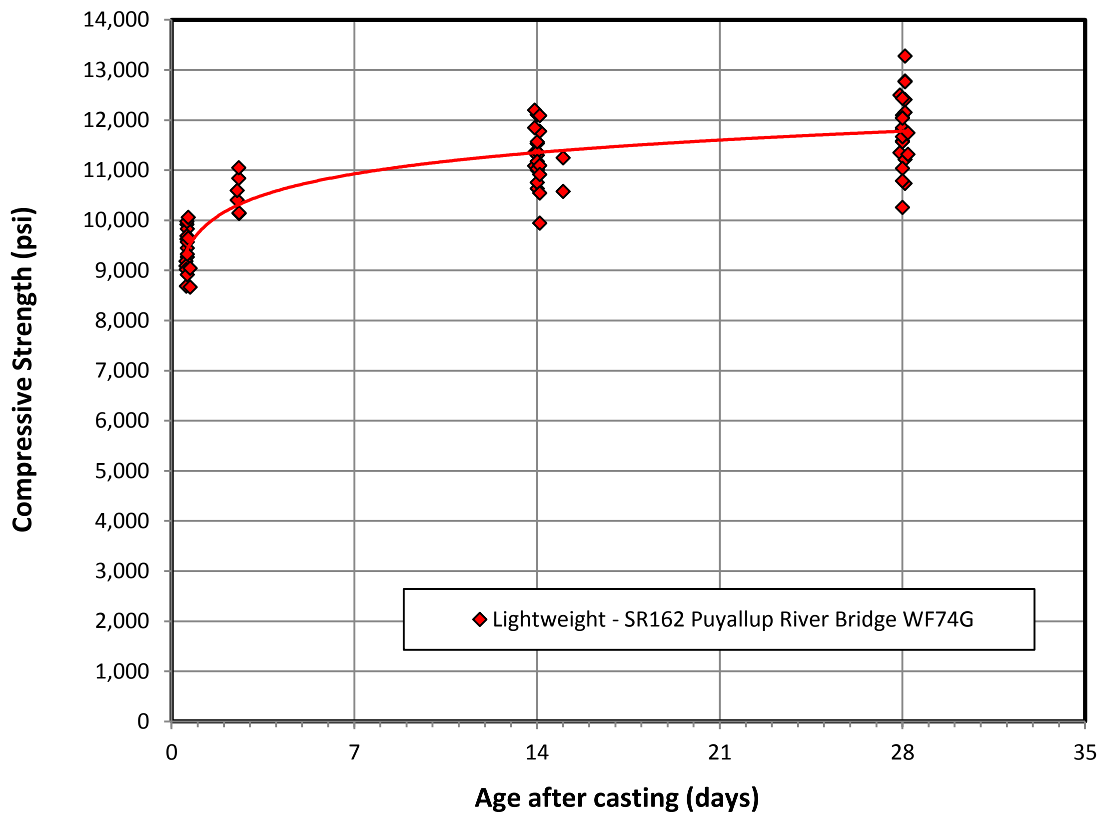

Fig. 8 Compressive strength versus age of concrete (SR162 Puyallup River Bridge)

Table 7 28-day compressive strength data (SR162 Puyallup River Bridge WF74G)

Count	24
Average	11,845
Minimum	10,260
Maximum	13,280
Range	3,020
Standard Deviation	740
Coefficient of Variation	6.2
ACI Design Strength	10,854

MODULUS OF ELASTICITY

Figure 9 represents a normalized plot of modulus of elasticity (MOE) for the sand lightweight concrete for lab batch trial program, all three projects and the normal weight comparison concrete. The predicted MOE, using the actual unit weight and compressive strength of companion specimens, is plotted on the x-axis. The measured MOE, which was determined in accordance with ASTM C469, is plotted on the y-axis. Data that plots along the solid black line represents measured values that exactly agree with predicted values (unity). Data that plot below the solid black line indicate data with a measured MOE less than that predicted by ACI and AASHTO. The lightweight data is clustered around a line drawn 10% lower than unity. The normal weight data is clustered around the line of unity or just above it. It is important to note that the AASHTO LRFD K_1 factor has been set to 1.0 for this data set.

Figure10 represents a plot of measured modulus of elasticity versus age of concrete for all three projects. Using 9 ksi design compressive strength and a unit weight of 123 pcf, the modulus of elasticity for the sand lightweight concrete computed using Eq. 5.4.2.4-1 of the AASHTO LRFD Bridge Design Specifications was 4,270 ksi. The values shown in Figure 10 are close to this value for later ages.

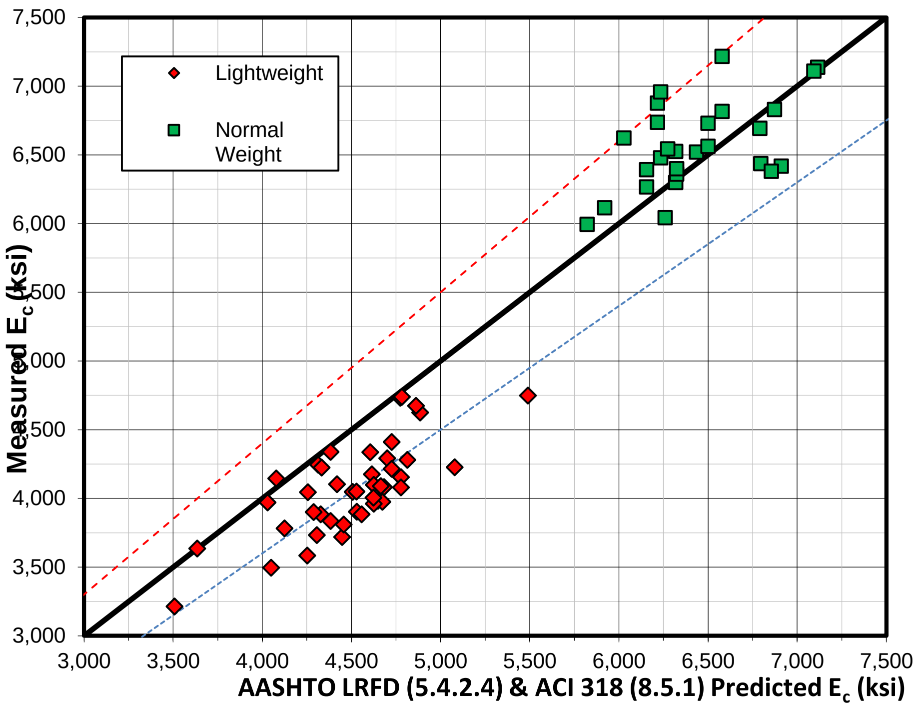

Fig. 9 Measured versus predicted modulus of elasticity for lightweight concrete and normal weight concrete (all three projects, K_1 = 1.0 for all predictions)

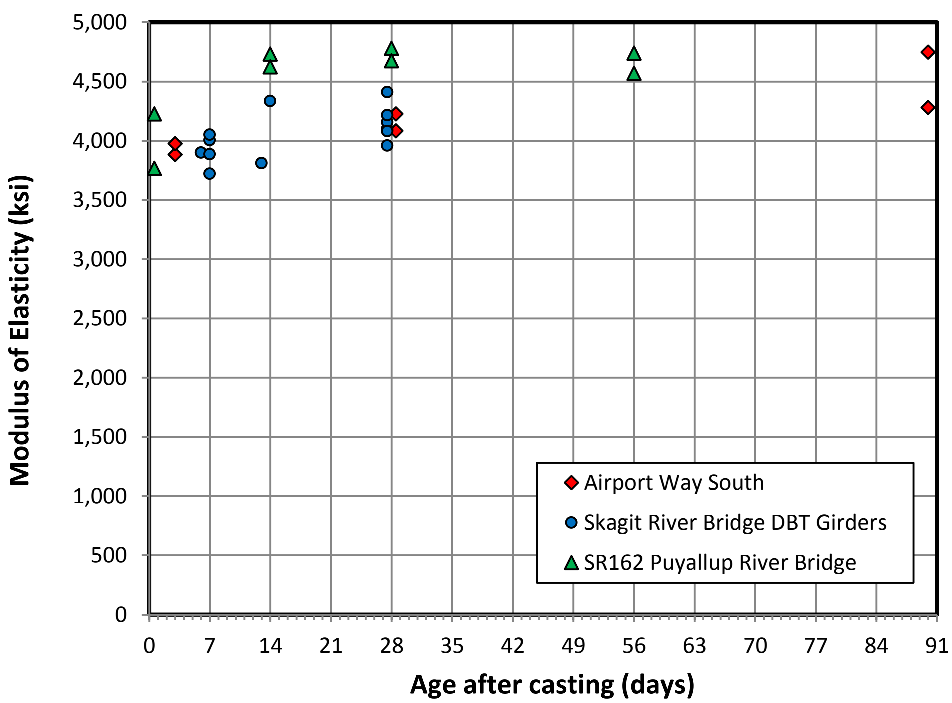

Fig. 10 Measured modulus of elasticity for sand lightweight concrete (all three projects)

CREEP

Project specifications for the Airport Way South project required creep testing for the lightweight concrete in accordance with ASTM C512. The measured creep coefficient and specific creep for the sand lightweight concrete and the normal weight comparison concrete are shown in Figure 11. The predicted creep coefficient per AASHTO LRFD 5.4.2.3.2 is also included for comparison.

SHRINKAGE

Figure 12 represents shrinkage data that was collected for the Airport Way South sand lightweight concrete and the normal weight comparison concrete in the summer of 2012. Shrinkage testing was performed in accordance with ASTM C157. It should be noted that the data is rather scattered, especially for the normal weight concrete specimens. In response to the scattered data the precast concrete manufacturer tested shrinkage for the sand lightweight concrete and for the normal weight comparison concrete again during the production of the SR162 Puyallup River Bridge girders in the spring of 2015. The data collected for the 2015 shrinkage specimens is much more uniform. Refer to Figure13 for a plot of the spring of 2015 shrinkage specimens.

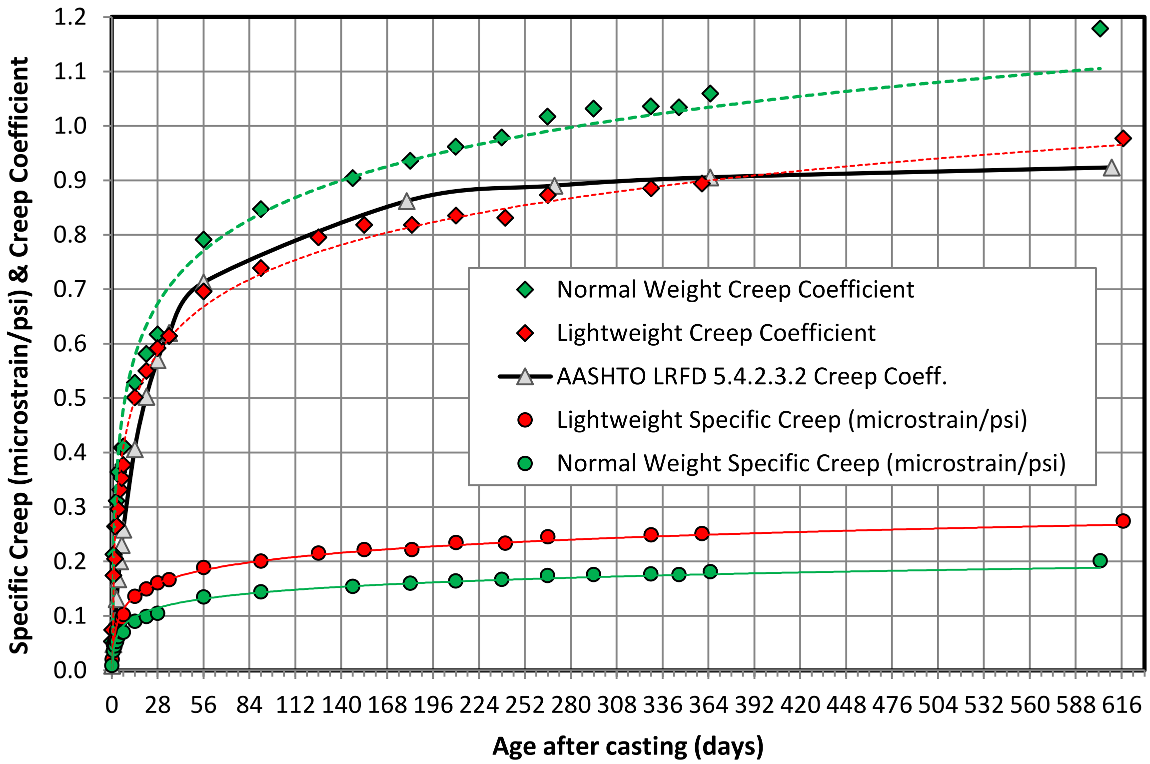

Fig. 11 Measured and predicted creep (Airport Way South)

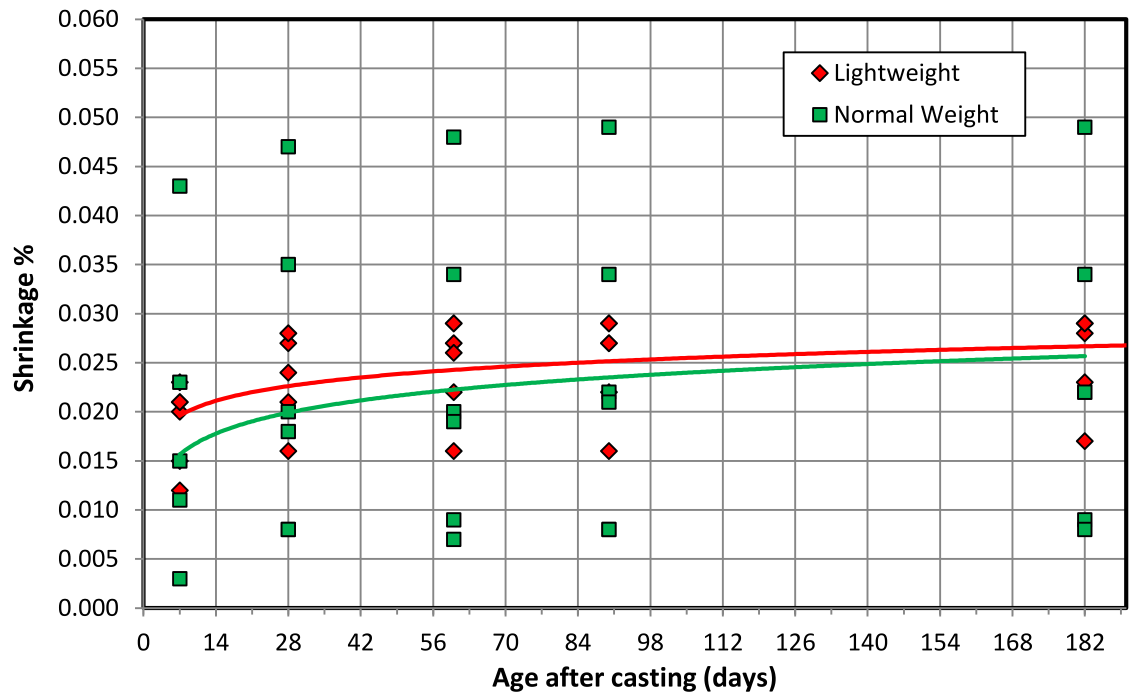

Fig. 12 Measured shrinkage (summer 2012, Airport Way South & Normal Weight)

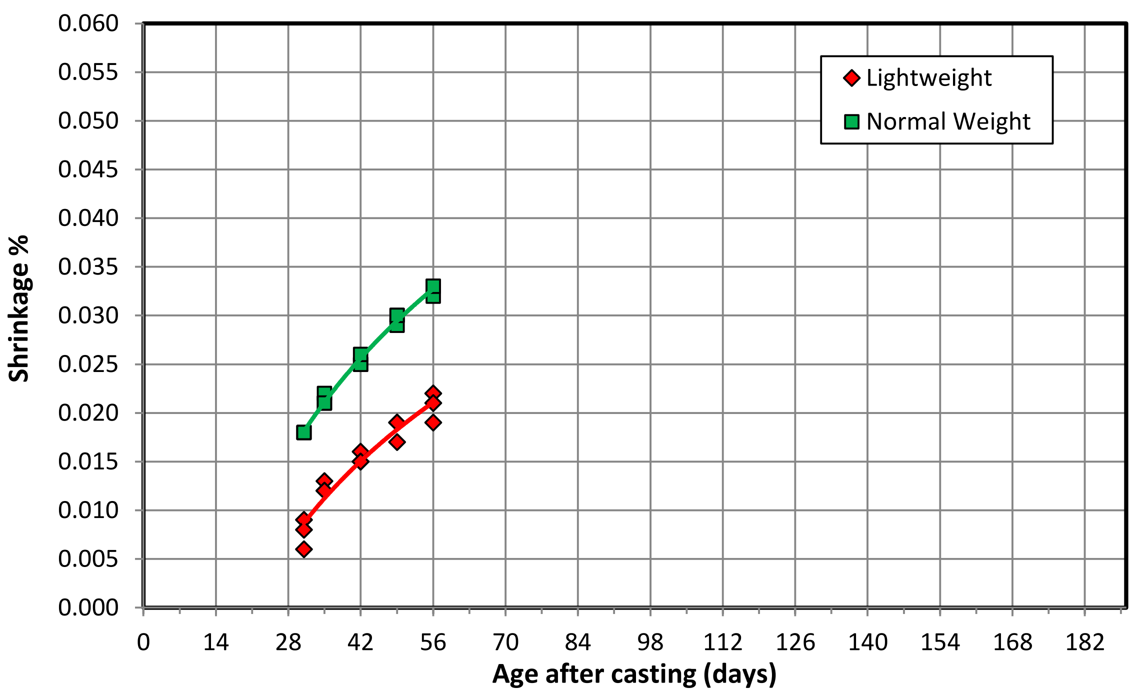

Fig. 13 Measured shrinkage (spring 2015, Puyallup River Bridge & Normal Weight)

SPLITTING TENSILE STRENGTH

Splitting tensile strength specimens were tested for all three projects in accordance with ASTM C 496. The results are presented in Figure 14 and Table 8. The table includes the predicted tensile strength based on the average compressive strength for the project. The splitting tensile strength expected for normal weight concrete can be computed by the relationship in LRFD Article 5.8.2.2. Using this expression and the design compressive strength of 9,000 psi, the expected splitting tensile strength for normal weight concrete is 638 psi. Almost all data for splitting tensile strengths at 28 days for the sand lightweight concrete exceed this value, and the averages for each project well exceed this value. This indicates that a designer could specify the splitting tensile strength of the sand lightweight concrete to be equal to the splitting tensile strength of normal weight concrete and thereby avoid the use of the shear reduction factor of 0.85 that the specifications require if f_{ct} is not specified.

It should be noted that the splitting tensile strength specimens were cast in 6x12 plastic cylinder molds and received a standard "ambient" ASTM C31 cure. All of the compressive strength data reported in this paper is representative of 4x8 cylinders produced in temperature controlled match-cast cylinders. The compressive strength cylinder time versus temperature profiles matched that of the beams and girders they represented which are accelerated cured and reached a maximum temperature of 160 degrees F in approximately 12 hours.

Photographs of lightweight and normal weight concrete splitting tensile test specimens after testing are shown in Figure 15.

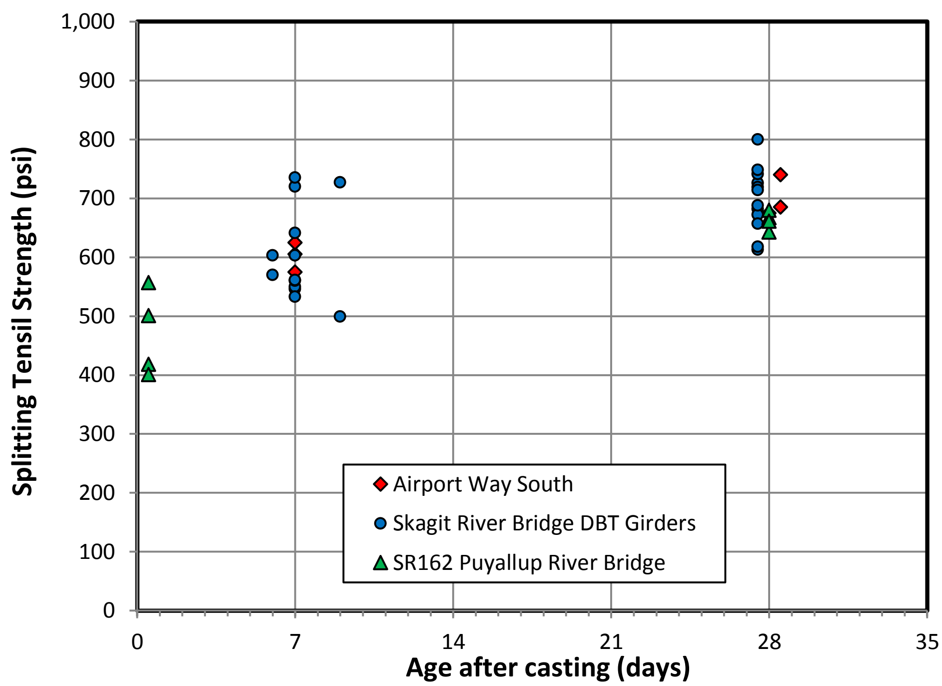

Fig. 14 Measured Splitting Tensile Strength versus Time (All Projects)

Table 8 28-day splitting tensile strength (all projects)

Project	AWS	Skagit	SR162
Count	3	10	4
Average	700	696	663
Minimum	675	613	643
Maximum	740	800	680
Range	65	187	37
Standard Deviation	35	58	15
Average 28-day f'_c	11,578	10,832	11,845
Predicted f_{ct}	721	697	729
AWS = Airport Way South			
Skagit = Skagit River Bridge DBT Girders			
SR162 = SR162 Puyallup River Bridge WF74G			

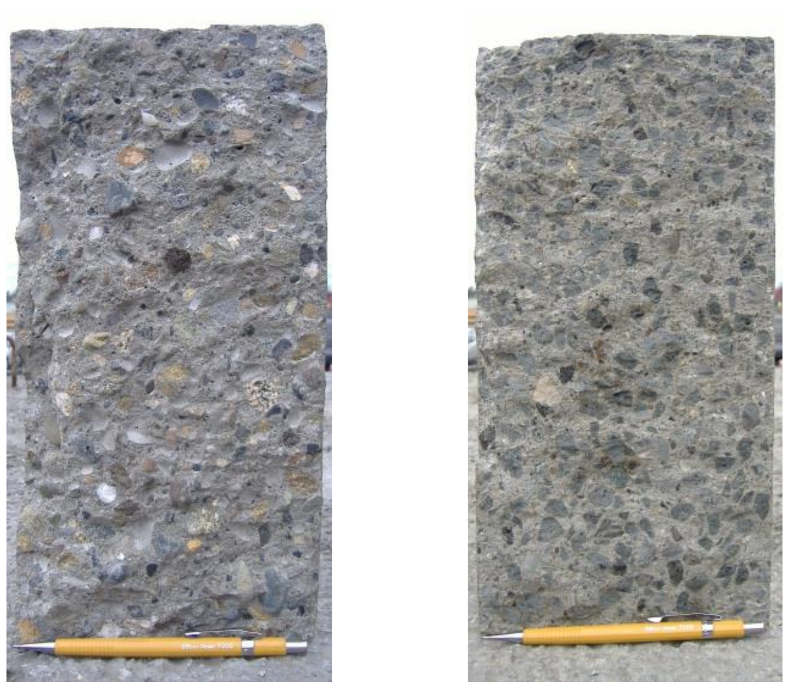

Fig. 15 Splitting tensile strength specimens after testing (NWC - left, LWC - right)

CAMBER

The prestressed double tee members for the Airport Way South project were relatively short for a bridge member. The average length of the members was on the order of 23 feet. Accordingly, the camber associated with the members was relatively small, on the order of ¾" to one inch. However, since the double tee members were the full width of the bridge deck, excess camber had the potential to add a significant volume of cast-in-place overlay and corresponding dead load that the 1928 substructure was not designed to support. The forms for the prestressed members were deflected downward approximately ¾" in an effort to balance the upward camber growth and provide a flat top surface. This effort was a success with most pieces arriving at the job site with a slight upwards camber and within the tolerance established by the owner.

The camber of the Skagit River decked bulb tee girders had an impact on dead load similar to the Airport Way South project. The DBTs for this project were essentially adjacent members whose width covered the majority of the bridge width. The design-build team worked with the precast concrete manufacturer to predict the camber growth and deflect the girder forms approximately 4½" at midspan to accommodate the upward camber growth. Figure16 represents predicted and measured camber values for all eight of the Skagit River DBTs.

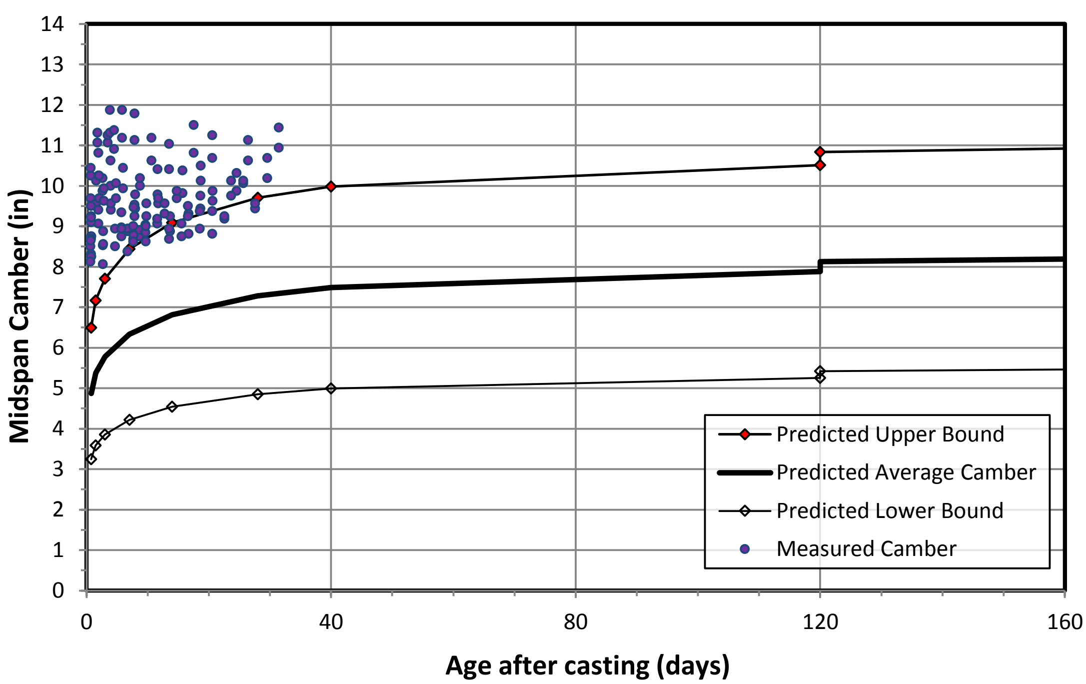

Fig. 16 Measured camber versus age after casting, Skagit River Bridge DBTs

Figure17 represents camber growth of three of the 160-ft-long Span 2 WF74G girders for the SR162 Puyallup River Bridge project. The girders were measured periodically while in storage in the precast concrete manufacturer's storage yard. The G5.4.1 and G5.5.1 plots represent girders that were cast and subjected to accelerated curing under a normal "weekday" cure cycle. The G6.6.1 data series represents a girder that was cast on a Friday and left in the form to cure at lower temperatures until the following Monday, at which point the prestress force was transferred to the girder. All three girders are identical with respect to design (length, strand quantities, specified concrete strengths, etc.)

It should be noted that the measured camber generally falls within the predicted upper and lower bounds. The only exceptions are data points where the camber was measured in the afternoon on sunny days. The effect of differential temperature over the depth of the girder caused these data points to plot slightly above the predicted upper bound. Another camber trend that should be pointed out is that the girders behaved similar to normal weight girders with respect to growth rate.

The last data points for the Span 2 girders shown in Figure 17 were measured after the temporary top strands had been detensioned in the field. After detensioning, the camber increased instantaneously due to elastic rebound .

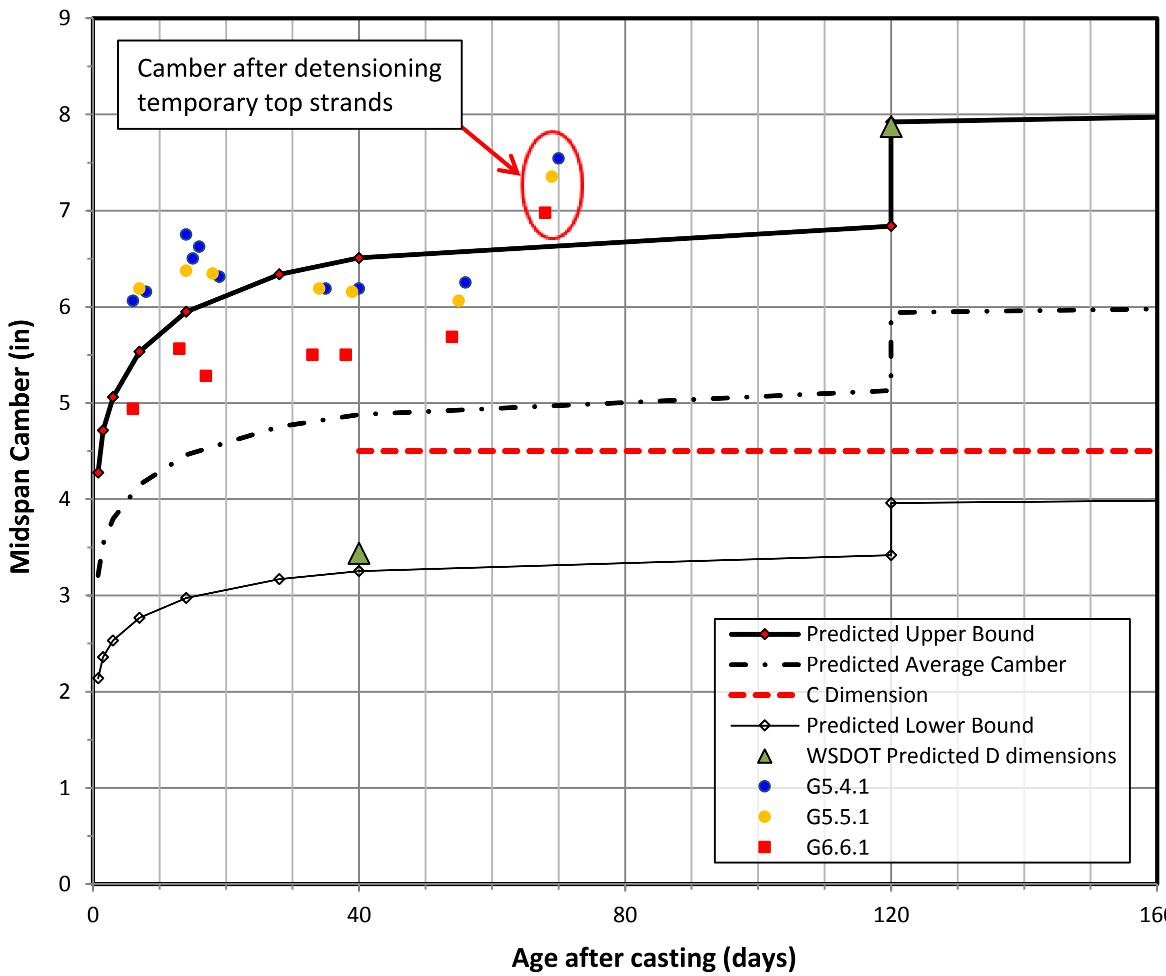

Fig. 17 Measured camber versus age after casting, SR162 Puyallup River Bridge WF74Gs

RECOMMENDATIONS

The following recommendations are proposed by the precast concrete manufacturer for the specific sand lightweight concrete mixture that has been used on these three projects. The concepts can be applied to lightweight concrete mixtures with other properties.

UNIT WEIGHT, w_c

There is a potential for miscommunication regarding the various definitions of concrete unit weight. It is important that design and construction documents clearly state which numerical value applies to the relevant property of interest. The authors recommend the following values which apply specifically to the mix used in these projects, but the concepts can be applied to other lightweight concrete mixtures:

- Use 123 pcf for material property calculations. This represents an average density for design, assuming little or no reduction in density due to drying. Specifically, this applies to the calculation of modulus of elasticity.
- Use 128 pcf for acceptance of maximum plastic (fresh) concrete density. This value allows for some tolerance in the batching, mixing, sampling and testing processes.
- Use 138 pcf for reinforced concrete unit weight to calculate girder self-weight. This value includes an effective increase in density of 10 pcf that is caused by strand, rebar, and other embedded steel items.

COMPRESSIVE STRENGTH, f'_{ci}, f'_c

- Limit the release strength, f'_{ci}, to 7,500 psi. This is achievable in a 12 to 14 hour accelerated cure cycle.
- Limit the specified 28-day compressive strength, f'_c, to 10,000 psi.

MODULUS OF ELASTICITY, E_c

Use AASHTO LRFD Eq. 5.4.2.4-1 as-is with the following input variables:

- $K_1 = 0.9$
- $w_c = 123$ pcf

CREEP, CR

Use AASHTO LRFD Eq. 5.4.2.3.2-1 as-is. No modification of the equation is required.

SHRINKAGE, SH

Use AASHTO LRFD Eq. 5.4.2.3.3-1 as-is. No modification of the equation is required.

SPLITTING TENSILE STRENGTH, f_{ct}

Use the expression in AASHTO LRFD Article 5.8.2.2 as-is. No modification is required.

LESSONS LEARNED

The lightweight aggregate used by the precast concrete manufacturer is not available locally. This presented logistical challenges with delivery of the aggregate. An additional week or two should be allowed for delivery if the material is delivered by truck, which is economical for small projects. Material delivery by rail becomes more economical as the volume of aggregate required increases, but an allowance of three to four weeks should be considered for delivery via rail.

Batching, placing, workability, and finishing efforts are similar to those of normal weight concrete. The formed finish surfaces were identical to normal weight concrete surfaces. The only noticeable difference is the finish of the up-face (unformed) surface.

CONCLUSIONS

The use of sand lightweight concrete has been successfully used in three prestressed concrete bridge beam and girder projects in Washington State. The material properties of the fresh and hardened concrete are just as predictable as normal weight concrete and, with the exception of unit weight and modulus of elasticity, are very similar in magnitude to those of normal weight concrete. Even with the cost of lightweight concrete for this project being about twice as much as a similar normal weight concrete, the cost premium for lightweight concrete girders is on the order of 10% to 15% compared to normal weight concrete girders. The potential for additional cost savings exists because of reduced hauling equipment requirements, lower permitting costs, smaller capacity cranes for erection, and reduced substructure demand. The magnitude of the potential cost savings are project-dependent and have not been addressed in this paper.

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