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Lightweight Concrete and the New Benicia-Martinez

Ganapathy Murugesh, California Department of Transportation

Lightweight high performance concrete was used for the cast-in-place superstructure segments.

The new Benicia-Martinez Bridge across the Carquinez Strait on I-680 is an engineering marvel with the incorporation of several unique design and construction features. This 1.4-mile (2.3-km) long crossing is an important addition that meets the California Department of Transportation's (Caltrans) mission—"Caltrans Improves Mobility across California."

Unlike most of the San Francisco Bay area crossings, which are seismic upgrade projects, the new Benicia-Martinez Bridge is a congestion relief project. Despite corridor expansions, the existing bridge created a severe bottleneck for traffic, which the new bridge relieves. The new bridge carries five lanes of northbound I-680 traffic across the Carquinez Strait between the cities of Martinez and Benicia, California. In addition, the new bridge is designed to carry one future lane of light rail, mass transit traffic.

Choice of Lightweight Concrete

Feasibility studies conducted during the late 1980s evaluated the use of four types of bridges: a steel-truss bridge; a steel box-girder bridge; a concrete cable-stayed bridge; and a lightweight concrete bridge built using the cast-in-place balanced cantilever technique. Cost was an important factor in these studies. Even excluding the 150-year life-cycle aspect, the initial cost of the lightweight concrete, cast-in-place segmental structure was lowest. It should be noted that a span of 525 ft (160 m) was used for these preliminary evaluations.

Significant Changes during Design

Interstate Route 680 was included on the California's Lifeline route, which means, “the bridge needs to remain open to traffic after a major seismic event.” This resulted in the use of stringent design criteria. The proximity to the Green Valley Fault and the San Andreas Fault, together with the unique topography, created additional challenges to the design team. The U.S. Coast Guard required an increase to the original span lengths across the navigational channel from 525 to 663 ft (160 to 201 m). This change, combined with the seismic challenges, resulted in pushing the limits for this type of construction in a high seismic risk zone.

Design Summary

Span lengths on the cantilever portion of the new Benicia-Martinez Bridge range from 418 to 659 ft (127 to 201 m), which pushes the limit for this type of construction. Including the Caltrans-designed northern approach spans, the bridge comprises 22 spans, with 16 over water. The segment cross section consists of a single cell box girder with a total depth that ranges from 37.4 ft (11.4 m) over the piers to 14.9 ft (4.54 m) at midspan. The top flange excluding the barriers has a width of 78.7 ft (24.0 m), while the bottom-flange thickness varies from 5.9 ft (1.80 m) at the pier segment to 9.8 in. (250 mm) at midspan.

The superstructure was constructed using 15.8-ft (4.8-m) long segments with as many as 20 segments cantilevered on each side of a pier. Considering the fact that these long spans were designed for a high seismic risk zone, the bridge becomes the first of its kind—and a world-class structure.

Lightweight Concrete Adds Length

The key to achieving the span lengths was the choice of lightweight high performance concrete. The lighter the structure, the less massive is the structure that pushes the piers in a seismic event. But finding the right mix design required countless tests and evaluations of more than 30 concrete mix designs. Caltrans, the designers, and the contractor researched a variety of aggregates, admixtures, cement contents, and water-cementitious materials ratios, to achieve a concrete mix that met the engineering properties and the construction needs.

Sand-lightweight concrete is used for the entire superstructure except for the pier table segments. The sand-lightweight concrete uses normal weight sand and lightweight coarse aggregate to produce concrete that is lower in density. The anticipated higher creep and shrinkage and lower modulus of elasticity characteristics expected with the lightweight concrete, resulted in stringent material properties being specified for construction.

As finally designed, the segmental concrete specified has a density of 125 lb/cu ft (2000 kg/cu m), or about 16 percent less than conventional structural concrete. the designers considered using lightweight sand, which could have produced a concrete density of 110 lb/cu ft (1760 kg/cu m), but it would not meet all the necessary material property requirements. Lightweight concrete with normal weight sand and a density in the range of 120 to 125 lb/cu ft (1920 to 2000 kg/cu m) was specified to achieve higher compressive strength, higher modulus of elasticity, and less creep and shrinkage.

Segmental Concrete Properties

Property	Specified Value	Average Measured Values*
Density, lb/cu ft	125±2	125.2
Compressive Strength, psi	6500 at 28 days	10,500 at 35 days
Modulus of Elasticity at 28 days, ksi	3400 min.	3800
Shrinkage after 180 days, %	0.05 max.	0.042
Specific Creep after 365 days, millionths/psi	0.48 max.	0.22
Splitting Tensile Strength at 28 days, psi	450 min.	-

*From production concrete.
The above table lists the specified values and average measured values from production concrete for density, compressive strength, modulus of elasticity, shrinkage, creep, and splitting tensile strength.

Concrete Mix Proportions

Material	lb/yd³	kg/m³
Cement, Type II-IV	833	494
Fly Ash, Class F	49	29
Metakaolin	98	58
Sand	1233	509
Lightweight Aggregate	858	431
Water	304	180
w/cm ration	0.31	0.31

The above table lists the concrete mix proportions as 833 lb of cement, 49 lb of fly ash, 98 lb of metakaolin, 1233 lb of sand, 858 lb of lightweight aggregate, and 304 lb of water for a total water-cementitious materials ratio of 0.31.

In addition, a shrinkage-reducing admixture, hydration-stabilizing admixture, and high-range water-reducing admixture were included.

Challenges Faced during Construction

In all of the elaborate testing efforts, the design and construction team discovered that the lightweight concrete needed a high cementitious materials content to meet the modulus of elasticity requirements. The design mixes resulted in compressive strengths between 10,000 and 11,000 psi (69 and 76 MPa), while only 6500 psi (45 MPa) was needed by design. Special aggregates were used to achieve the desired properties. The fine sand was imported from Canada and the lightweight coarse aggregate came from North Carolina. Because of the high cementitious materials content, the lightweight concrete had a high heat of hydration. The specifications limited the maximum concrete temperature during curing to 160°F (71°C). To achieve this, the contractor used ice in the concrete instead of water and cooled the concrete with liquid nitrogen. A long wand with a nozzle was used to inject liquid nitrogen for a few minutes into the concrete in the trucks. The combination of ice and nitrogen lowered the concrete temperature to 40° to 50°F (4 to 10°C).

A system of PVC tubes in the segments carried water to cool the concrete during early hydration. Radiator-like tubes ran through the bottom slab, webs, top slab, and the flared connection of the web to the top slab. Thermocouples to measure internal concrete temperatures were spaced where the maximum heat would be generated. These methods controlled the heat of hydration well, even during hot summer months. Further discussion of the heat of hydration is provided in HPC Bridge Views, Issue No. 47.

Marine placement of lightweight concrete posed additional challenges. The contractor provided an on-site batching plant on the south shore of Carquinez Strait. Mixing trucks traveled from the batch plant to a barge and drove on board. The barge, which could carry four loaded mixing trucks at one time, transported the concrete to the desired pier cantilever location, where each segment was cast in one lift.

For some placements, the barges were secured to the side of a barge with a concrete pump that could pump the material vertically to a height of more than 181.5 ft (55 m). On board the pump barge, the concrete was remixed before being pumped vertically to the placement location. For other placements, the barges were secured to the side of a footing, where a tower crane lifted buckets of concrete to a remixer on the bridge deck from which the concrete was then pumped horizontally up to 330 ft (100 m) to the intended segment.

Through elaborate quality control measures by the contractor, quality and consistency of the lightweight concrete was achieved for over 60,000 cu yd (46,000 cu m) of placed concrete and over 2 years of production.

Conclusion

In spite of all the challenges encountered during the design and construction of this bridge, the choice of lightweight concrete was the right one that helped Caltrans build this important Bay crossing. A great partnering effort between the dedicated Caltrans staff, design team of TYLin/CH2M Hill Joint Venture, and the contractor, Kiewit Pacific, helped successfully complete this project.

(Articles continued on next page)

Lightweight Concrete for the Route 33 Bridge over the Mattaponi River

Rex Gilley, PB

Lightweight concrete was used for the superstructure to achieve longer span lengths while reducing foundation loads.

Lightweight concrete was specified for use in three units of the Route 33 bridge over the Mattaponi River in Virginia. One unit consists of three spans of 145 ft (44.2 m) each that utilize prestressed concrete bulb-tee beams made continuous for live load. The two others are twin units and consist of four spans of 200, 240, 240, and 200 ft (61, 73, 73, and 61 m) that utilize spliced post-tensioned haunched pier segments with drop-in midspan segments. Each unit utilizes bulb-tee beams that are 93.5 in (2.37 m) deep with a top flange width of 60 in. (1.52 m), web thickness of 8 in. (200 mm), and a bottom flange depth of 9 in. (230 mm). This section was one of many developed by the Mid-Atlantic States Prestressed Concrete Committee for Economic Fabrication. Lightweight high performance concrete was specified for the precast, prestressed beams as well as the cast-in-place deck slabs to achieve longer span lengths while reducing foundation loads.

Selection of Material Properties

During the design phase of this project, review of available lightweight concrete material properties was undertaken to determine appropriate design values. Test data from other projects using similar materials was provided by the Virginia Department of Transportation (VDOT). Material properties that were investigated were density, modulus of elasticity, shrinkage, and ultimate creep strain. The design values from this review were then used in the material specifications to provide the following target values for the lightweight concrete material for both the deck and beam concretes.

Also, the lightweight concrete for the decks and beams was specified to have a maximum chloride permeability of 1500 coulombs at 28 days to provide a durable structure. In addition to the literature review, a sensitivity analysis was made to determine the effect that the variability of each of these parameters would have on the completed structure. This analysis resulted in acceptance criteria for the contractor's concrete mix. In the case of compressive strength and modulus of elasticity, minimum acceptable values were given. For density, shrinkage strain, and creep strain, maximum acceptable limits were specified.

Target Values for the Lightweight Aggregate Hydraulic Cement Concrete

Member	28-day Strength, psi	Creep Notational Coeffiecient(1)	Shrinkage Notional Coeffiecient,(2) millionths	Density,(3) lb/ft^3	Air Content, %	Modulus of Elastictiy, ksi
Prestressed Beams	8000	4.2	450	125	4 ½ ± 1 ½	3400
Desks	5000	3.5	550	120	5½ ± 1 ½	2700

1. Based on a concrete age of 93 days with loading at 3 days.
2. Based on 93 days of drying.
3. Includes the weight of the reinforcing and prestressing steel.

The above table lists separate target values for compressive strength, creep, shrinkage, density, air content, and modulus of elasticity for the concrete used in the beams and decks.

Specification Requirements for Acceptance of Lightweight Aggregate Hydraulic Cement Concrete

Member	Maximum Value of Creep Strain, (1) millionth/psi	Maximum Value of Shrinkage Strain,(2) millionth	Maximum Density, lb/ft³	Minimum Modulus of Elasticity, ksi
Prestressed Beams	0.69	450	115	3000
Desks	0.75	530	110	2400

1. Based on a concrete age of 93 days with loading at 3 days.
2. Based on 93 days of drying.
1 millionth = 10-6 in/in.

The above table lists separate values for creep, shrinkage, density, and modulus of elasticity for the concrete used in the beams and decks.

The sensitivity analysis showed that the variation allowed in the acceptance criteria for modulus of elasticity, creep, and shrinkage resulted in changes in stress at the outer fibers of the beams of about 100 psi (700 kPa). Thus, a contingency was included in the design, while maintaining a reasonable range for the requirements of the materials.

Testing Requirements

The specifications required the following testing during construction:

- Prior to production, test mix designs for the beam concrete and the deck concrete were submitted for approval. From each test mix design, two samples were tested, and the results were used to determine values for the modulus of elasticity, creep, and shrinkage.
- During production of the beam and deck concretes, five samples from the beam mix and three samples from the deck mix were tested to determine the modulus of elasticity, creep, shrinkage, and density.
- During production, one compressive strength cylinder for each concrete type was required on each sublot, defined as 1 day's placement up to a maximum of 100 cu yd (76 cu m). For each compressive strength cylinder, two cylinders were required for the permeability test.
- During production, air content and temperature were monitored on the first two loads per sublot and every five loads thereafter.

For the deck concrete, additional discussion was held during construction by the VDOT's construction administration and materials division staff. While the specifications had testing requirements, further clarification was needed to assure that the concrete being placed met the intent of the specifications. This resulted in sampling and testing for air content, temperature, plastic density, and slump at the concrete plant on the first three trucks and every third truck thereafter, for each placement.

Testing during construction indicated that all parameters except the drying shrinkage for the deck concrete were within the acceptable limits as stated in the tables. The drying shrinkage of 560 millionths for the deck concrete was not considered to be enough outside the limit to warrant concern in the final product.

Lessons Learned

One issue addressed during construction was the definition of density. As shown in the tables, a specified density was given. This seemed straightforward enough as it was intended to be the oven dry density. For hydraulic cement concrete, however, there are several other "densities" to consider. The primary densities are equilibrium density and plastic or fresh density.(1) The issue was twofold: to ensure that the density of the concrete does not exceed the value used in determining the structure's dead load during design; to provide a rational means of acceptance for the concrete prior to placement. The fresh or plastic density was used as the means of acceptance. The fresh density of the concrete for the beams was allowed to vary from 117 to 123 lb/cu ft (1875 to 1970 kg/cu m) compared to an oven dry density of 115 lb/cu ft (1840 kg/cu m). The fresh density of the concrete for the deck was 116 lb/cu ft (1860 kg/cu m) compared to an oven dry density of 110 lb/cu ft (1760 kg/cu m). So clarification and coordination of the specified density is critical.

Limitations on pumping the deck concrete also required discussion. Due to the nature of the lightweight concrete mix, the distance over which the concrete mix could be pumped was limited to 500 ft (152 m). There were no requirements in the specifications pertaining to this issue. So it would be prudent to add a restriction in the specifications to preclude the contractor from potentially placing concrete that may be adversely affected during the pumping operation. Materials such as the ones used on this project will continue to be used on the bridges of the future as owners strive to make more durable bridges in order to stretch their funding. When the envelope is pushed, it requires good leadership and a team effort. Ultimately, that was the key to the success of this project.

Reference

1. Castrodale, R.W. and Harmon, K.S., "Specifying Lightweight Concrete for Long Span Bridges," Proceedings, First International Conference on Recent Advances in Concrete Technology, Washington, D.C., September 19-21, 2007.

Jeff Danzer Bridge, Ohio

Sand-lightweight concrete was used to reduce the shipping and handling weight of the precast, prestressed concrete beams.

The Jeff Danzer Bridge, formerly known as the Dixon Mill Road bridge, is located over the Little Scioto River in Scioto County, Southern Ohio. The bridge is a 201-ft 6-in. (61.4-m) long, two-lane, single span, precast, prestressed concrete structure. It replaced a steel truss bridge that was functionally obsolete, posted for reduced loads, and in critical need of replacement. A simple span structure was chosen to span the River in order to apply for and receive a U.S. Corps of Engineers nationwide permit rather than endure the lengthy individual permit process. The profile grade was raised approximately 10 ft (3 m) above the existing grade to accommodate the deeper superstructure of a simple span. The owner was able to acquire property for right-of-way and relocate utilities prior to awarding a design-build contract. The specified options for the bridge type were limited to galvanized steel, cast-in-place concrete, and precast, prestressed concrete. Two bids were submitted. One utilized three lines of 96-in. (2.44-m) deep steel plate girders, while the winning bid utilized four lines of precast, prestressed concrete beams.

Superstructure

The bridge design load was HS20-44 with alternate military loading. The allowable tensile stress in the precompressed tensile zone was taken as 3 psi (0.25 MPa). The superstructure consists of four lines of 103-in. (2.62-m) deep precast, prestressed concrete spliced bulb-tee beams with a 61-in. (1.55-m) wide top flange and an 8-in. (203-mm) thick web. The beams are spaced at 8 ft 0 in. (2.44 m) on centers and support an 8-1/2-in. (215-mm) thick cast-in-place normal weight concrete deck. Section lengths for the beams were 75 ft and 125 ft 6 in. (22.9 and 38.3 m) with a 1-ft (305-mm) long closure pour. The individual sections were pretensioned for shipping and erection. The individual lengths were selected so that they could be transported and erected without difficulty. To reduce the beam weight for shipping, a sand-lightweight concrete was specified.

Sand-Lightweight Concrete

The sand-lightweight concrete was specified to have a unit weight of 125 pcf (2000 kg/m3) and compressive strengths of 6000 and 7000 psi (41 and 48 MPa) at strand release and 28 days, respectively. Actual strengths ranged from 6050 to 7790 psi (41.7 to 53.7 MPa) at release and 8820 to 10,320 psi (60.8 to 71.2 MPa) at shipping

Material	Quantities (per yd^3)	Quantities (per m^3)
Cement	750 lb	445 kg
Fine Aggregate	1132 lb	672 kg
Coarse Aggregate	912 lb	541 kg
Lightweight Aggregate	458 lb	272 kg
Water	270 lb	160 kg
Air Entrainment	5.0 fl oz	195 mL
Retarder	6.0 fl oz	230 mL
Water Reducer	52.5 fl oz	2.03 L
Corrosion Inhibitor	256 fl oz	9.9 L
Water-Cementitious Materials Ratio	0.36	0.36

The above table lists the concrete mix proportions as 750 lb of cement, 1132 lb of fine aggregate, 912 lb of coarse aggregate, 458 lb of lightweight aggregate, 270 lb of water, 5 fl oz of air entrainment, 6 fl oz of retarder, 52.5 fl oz of water reducer, and 256 fl oz of corrosion inhibitor.

ages of 25 to 39 days. The concrete mix proportions for the sand-lightweight concrete are given in the table above.

Bridge Construction

A cast-in-place spread footing and abutment were used at one end of the bridge. At the other end, the abutment was supported on cast-in-place drilled shafts. A temporary concrete slab and steel bent were erected at the splice location. A semi-integral connection was provided between the beams and the abutments.

Post-tensioning of the beams was applied in two stages. The first stage was applied after the beams were erected and the splices cast. The second stage was applied after the deck was cast. The post-tensioning tendons consisted of two tendons with seventeen 0.6-in. (15-mm) diameter strands and two tendons with sixteen 0.6-in. (15-mm) diameter strands. The specified jacking forces were 750 and 710 kips (3.34 and 3.16 MN) for the larger and smaller tendons, respectively.

Construction of the bridge took only 120 days, which fulfilled the contract requirement for road closure. The bridge is named in honor of an outstanding Scioto County Engineer and serves as a monument to innovation. It is the longest single-span bridge in Ohio using precast, prestressed concrete girders. It is hoped that the bridge will serve as a prototype for single-span bridges in the future.

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Creep and Shrinkage of Structural Lightweight Concretes

Rodney T. Davis, Formerly with Virginia Transportation Research Council

Virginia has recently built several bridges with lightweight concrete beams and decks including the Route 33 bridge over the Mattaponi River. The measurement programs for these structures indicated that the high creep and shrinkage values assumed in the designs were not accurate for the concretes in the precast, prestressed concrete beams. In fact, the creep coefficients and shrinkage strains measured in the lightweight concretes were the same as, or only slightly higher than, those measured in typical normal weight concrete superstructures.

The most important differences between the properties of the lightweight and normal weight concrete used in the precast, prestressed beams were the reduction in modulus of elasticity and tensile strength of the lightweight concrete. The modulus of elasticity of the lightweight concrete used in Virginia's beams was about 60 percent of that for normal weight concrete. Typical lightweight concrete had a modulus at prestress transfer of about 3100 ksi (21 GPa), and a modulus in service of about 3400 ksi (23 GPa). Tensile strength of the lightweight concrete was about 7/8 that of the equivalent beam or deck normal weight concrete.

Typical mix designs for beam and deck concretes used in modern Virginia bridges are shown in the table on the next page.

Typical Normal Weight and Lightweight Concrete Mix Proportions

Material	Normal Weight	Lightweight
8000 psi Beam Concrete		
Density, lb/ft³	153	120
Portland Cement,lb/yd³	450	480
Slag, lb/yd³	300	320
Fine Aggregate, lb/yd³	1050	1150
Coarse Aggregate, lb/yd³	2100	1050
Water, lb/yd³	232	248
w/cm ratio	0.31	0.31
4000 psi Deck Concrete		
Density, lb/ft³	138	110
Cementitious Material, lb/yd³	635	650
Slag or Fly Ash, %	60/40 or 80/20	60/40 or 80/20
Fine Aggregate, lb/yd³	975	1050
Coarse Aggregate, lb/yd	1850	1150
Water, lb/yd³	280	260
w/cm ratio	0.44	0.40

The above table contains the concrete mix proportions for both normal weight and lightweight concretes used in precast, prestressed concrete beams and cast-in-place concrete decks.

The desired densities and strengths of the lightweight beam and deck concretes were achieved by doing little more than swapping lightweight aggregates for the normal weight coarse aggregates. Also, lightweight aggregate allowed the use of a lower water-cementitious materials (w/cm) ratio in deck concretes without plastic shrinkage cracking or other early age cracking. Ratios of 0.40 to 0.45 are used in Virginia deck mixes, with cementitious materials content in the range of 585 to 650 lb/cu yd (347 to 386 kg/cu m).

The creep of beam concretes under the application of prestressing force plus self-weight was found to be greatly influenced by the curing method, and not the presence of the lightweight aggregate. Virginia beam concretes contain slag cement in which the reactivity is dependent on temperature. Higher curing temperatures, such as a concrete temperature above 160°F (71°C) produced a creep coefficient of 0.25 to 0.50, with all the creep strain occurring by a concrete age of 7 days. Lower curing temperatures such as a concrete temperature of 135°F (157°C) produced a creep coefficient of 1.0 to 1.2, with all the creep strain occurring by a concrete age of 60 days. Lightweight prestressed concrete beams can be cured at the higher temperature to limit camber. Measured creep in all the precast beam concretes after deck placement has been found to be minimal.

Measured shrinkage was slightly higher for the lightweight beam concretes. Normal weight beam concretes shrunk about 350 to 400 millionths over two years, with about 250 millionths of that occurring before the beams are removed from the formwork. Lightweight beam concretes shrunk about 400 to 450 millionths. Unrestrained deck concrete specimens, both lightweight and normal weight, were found to shrink in excess of 450 millionths in Virginia weather. But measured beam strains indicate that little of this shrinkage strain is actually occurring in the bridge decks.

Many bridge decks, and especially the lightweight concrete decks, exhibit very little or no cracking after several years of service. This indicates that a good deck mix design, expert concreting, and proper moist curing can produce a deck that is capable of high creep or relaxation at early ages. Virginia's experience with lightweight concrete to date has given us confidence to design beams and spliced girders using lightweight concrete, and to expect higher quality decks when using lightweight aggregates.