Lightweight Concrete for California's Highway Bridges
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Introduction
The California Department of Transportation (Caltrans) has used expanded shale structural lightweight concrete for bridge construction as a substitute for normal weight concrete for both replacement of older bridge decks and widening, and new bridge construction of the California State Highway System for the past forty-five years. A 1966 Design Policy Memo suggests the use of structural lightweight concrete in deck replacement and rehabilitation at locations where local aggregates are unsuitable, as a cost-effective material for long span structures, and in seismic regions where superstructure dead load needs to be reduced. Examples of four major projects illustrate the durability and reliability of a properly designed and constructed structural lightweight aggregate concrete bridge. Cost comparisons of structural lightweight aggregate structures bid in competition with structural steel and normal weight concrete alternative structures demonstrate the economic viability of this material.

The outstanding performance of Caltrans' lightweight concrete bridges under heavy traffic, and the close competition in bidding suggests that lightweight aggregate is a material which should be considered in future bridge designs, especially in earthquake country where dead load is such an important factor in seismic design. The known consistent creep, shrinkage and modulus of elasticity properties of lightweight aggregate concrete remove any doubts about performance as Caltrans' structures have shown. The industry advances in controlling lightweight aggregate moisture content have considerably reduced the handling and finishing problems of earlier years.

Preliminary plans to bridge two large bodies of water in the San Francisco Bay Area with long span structures over 1.5 miles (2.4 km) in length have prompted Caltrans to review and update the overall policy on use of structural lightweight concrete, incorporating the latest technological developments. Questions regarding the shear strength and ductile performance of structural lightweight concrete have prompted research at the University of California at San Diego, funded by Caltrans.

Background
Caltrans bridge engineers have designed and constructed expanded shale structural lightweight concrete bridges or bridge components since the mid 1950's. The use was primarily for deck elements to reduce the dead load imposed on supporting superstructures, bent, abutments and foundations. The additional weight imposes severe problems on foundation design in a highly active seismic zone. A total of 15 major bridges have been designed with structural lightweight concrete decks. There have been several bridges designed using structural lightweight aggregate concrete for the entire superstructure to further reduce substructure design requirements in poor foundation materials. Two of those have been in service for several years.

Structural lightweight concrete has been used for decks with the typical normal weight concrete topping or polyester concrete overlays but several have been constructed without topping. Eight of these bridges have been in place in excess of 30 years with no apparent deterioration of the deck concrete. In 1957 structural lightweight concrete was used in portions of the conventionally reinforced concrete box girders on the Terminal Separation Interchange at the west end of the San Francisco-Oakland Bay Bridge. Lightweight aggregate was used to bring the concrete stresses within reasonable limits while simultaneously satisfying the aesthetic requirements of the site. In the mid 1960's, the San Francisco-Oakland Bay Bridge was converted to one-way traffic on each level, requiring continued on next page...
strengthening of the upper deck to carry modern truck traffic. Since it had previously carried only automobile traffic, substantial strengthening of the deck support system was required and lightweight aggregate concrete decks were used to reduce those requirements.

**Napa River Bridge**

The Napa River Bridge was designed in 1973-74 and constructed in 1975-77. It is a thirteen-span continuous post-tensioned cast-in-place structural lightweight concrete box girder with a total length of 2230 ft (680 m). It carries four lanes of State Highway 12 over the Napa River, immediately south of the city of Napa and about 35 miles (56 km) northeast of San Francisco. It was designed as an alternative to a structural steel girder system. Both alternatives were advertised. Seven bids were received. Six bids were for the prestressed concrete box girder, including the lowest bid of $10.96 million. The seventh bid was for the structural steel girder; it was the highest bid at $16.66 million.

The bridge superstructure is constructed entirely of expanded shale structural lightweight aggregate and has shown no significant problems during its 20-year life. Spans range from 150 to 250 ft (45.7 to 76.2 m) over the main river navigation channel and are supported on 100 ft (30.5 m) normal weight concrete piers and prestressed concrete pilings. The 11,000 cu yd (8410 m³) of structural lightweight concrete utilized expanded shale aggregate produced by Port Costa Materials at their Port Costa, California plant, located approximately 20 miles (32 km) from the bridge site. This bridge is not only an economical alternative in direct competition with structural steel but is an aesthetic award winner in national competition. It has been inspected annually since 1977 and there are no apparent problems with the structural lightweight concrete.

**Alameda Street Viaduct**

This bridge is a ten-lane 3500-ft (1067-m) viaduct carrying Interstate 105, the Century Freeway, over an industrial area with complex foundation problems. At the request of the Port Costa expanded shale lightweight concrete aggregate producer, the Department allowed a consultant to prepare conceptual designs to show that a structural lightweight concrete alternative would be competitive. When the study was completed it concluded that the savings in substructure would offset the additional cost of lightweight aggregate concrete and the Caltrans designers prepared two alternative designs for the final bidding. It had been assumed after the study that the five columns best required for the normal weight concrete alternative could be reduced to three columns for the lightweight alternative. Unfortunately, during final design some difficult foundation problems caused by underground utilities were encountered and the total savings anticipated in foundations were not achieved. The normal weight concrete alternative was estimated at $29.78 million and the lightweight concrete alternative was estimated at $30.56 million. The normal weight concrete alternative was low bid at $26.35 million, a savings of $3.43 million below the lowest Engineer's Estimate for either alternative. With the proper site conditions, the lightweight alternative would have been extremely competitive and may have been the lowest bid. The competitive position of lightweight aggregate concrete is close enough to warrant further designs. From the perspective of the owner agency, the competition generally results in a lower bid, regardless of the successful alternative.

**San Juan Creek Bridge**

This bridge is on State Route 74 east of San Juan Capistrano in Orange County. It is designed as a 267-ft (81.4 m) two-span prestressed structural lightweight concrete box-girder structure as an alternative to a hard rock concrete structure. Structural lightweight concrete is being used to generate some competition in bidding in Southern California. The bridge provides a 42 ft (12.8 m) roadway and is replacing a deficient older bridge. The project is scheduled for completion and advertising in late 1997.

**Future Plans for Structural Lightweight Concrete**

Two major crossings of the Carquinez Straits at the northeast end of San Francisco Bay are being planned and the use of structural lightweight concrete superstructures is being considered at both sites. The Carquinez Bridge site is on Interstate 80 at Vallejo where two bridges carry the east and west bound lanes. The west bound bridge was erected in 1927 and is severely overloaded by the current truck loads. A new westbound bridge has been financed and design studies are underway. Several alternatives were studied, including a structural lightweight concrete segmental bridge superstructure. In any bridge constructed at this site the decks will be constructed of structural lightweight concrete.

The Benicia-Martinez site is on Interstate 680, upstream of the Carquinez site, and parallel to the bridge which was recently wid-
Reinforcing Bar Specifications — 1911 through 1968

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Investigating the feasibility of rehabilitating a reinforced concrete building constructed 60, 70 or more years ago requires a complete structural analysis in order to determine the present day load capacity of the structure. That capacity is determined by the strength of two materials, concrete and steel. Random drilled cores taken from the old building will give the present strength of the concrete with a great deal of accuracy, but how to determine the strength of the imbedded reinforcing bars?

It would be extremely expensive and destructive to obtain sufficient samples of different bar sizes in order to test the bars. The original architectural and engineering plans, if available, could provide data pertaining to bar sizes, spacings, cover and typical details, but would not necessarily specify the grade of steel. The question thus is what type and grade of steel was typically manufactured and furnished during the period the building was constructed.

During the period 1900 to 1930, steel was produced mainly by the open hearth furnace process, using a combination of pig iron, iron ore and steel scrap as the raw material. Some steel was produced using the Bessemer process, and a small percentage by electric furnace. In comparison, today's reinforcing bars are produced almost exclusively by electric furnace with steel scrap as the raw material.

The first Standard Specification for Billet Steel Concrete Reinforcement Bars was adopted by ASTM in 1911, revised in 1914, designated A 15. The A 15 specification had three classes of bars: plain, deformed, and cold-twisted. The plain and deformed bars were specified in three grades: structural, intermediate and hard. Cold-twisted bars conformed to structural grade only. Section 2 (a) of A 15 stated "the basis of purchase shall be structural grade unless otherwise noted."

The tensile properties conformed to the following:

COLD TWISTED SQUARE BARS

DEFORMED BARS

CUP BAR

The Portland cement Association
Deformations were not standard, and in fact very dissimilar compared to present markings. Most were patented and particular to the producing mill, and were labeled cup, corrugated, lug, herringbone, or by the name of the producing mill, and were labeled cup, corrugated, lug, herringbone, or by the name of the inventor, such as Havemeyer, Elcannes, Scofield, or Thacher. Bar sizes were also not standard, with each manufacturer publishing a list of sizes available from that mill. Shapes were round, square, oval, flat with either raised lugs or depressed dimples. A conservative estimate of the steel grade of the reinforcing bars furnished for a concrete structure built between 1910 and the mid 1920's would be structural grade.

Effective January 1, 1928, the U.S. Department of Commerce recommended that the "Standard" for new billet reinforcing bars be intermediate grade. In effect, this suggested not specifying structural grade reinforcing bar. It is interesting to note that in 1928, A 15-14 was still in effect. During the decade of the 1920's, the producing mills standardized reinforcing bar to: 1/4 in. (6 mm) rd; 1/2 in. (13 mm) rd; 1/2 in. (13 mm) sq; 5/8 in. (16 mm) rd; 3/4 in. (19 mm) rd; 7/8 in. (22 mm) rd; 1 in. (25 mm) sq; 1-1/8 in. (29 mm) sq; 1-1/4 in. (32 mm) sq; 1-1/2 in. (38 mm) sq; and 2 in. (51 mm) sq. During the same decade, each mill developed its own deformation or brand pattern with a quality mark "N" for new billet, plus a letter or symbol designating the producing mill. Thus, intermediate grade new billet reinforcing bar became typical into the 1930's through the 1940's. As a historical note, the 2 in. (13 mm) sq size was eliminated in 1942 as a war emergency measure.

In 1950, ASTM revised the specifications pertaining to new billet reinforcing bars. ASTM A 15-50T changed all reinforcing bars to round, designed #3 (10 mm diameter) through #11 (35 mm diameter), replacing 3/8 in. (10 mm) rd through 1-1/4 in. (32 mm) sq. #2 or 1/4 in. (6 mm) rd was not classified as deformed, and was available only as plain round. However, A 15-50T still listed plain and deformed reinforcing bar with the same three grades: structural, intermediate and hard. At the same time, ASTM issued Tentative Specifications for the Deformations of Deformed Steel Bars for Concrete Reinforcement, designated A 305-50T. A 305 required minimum deformation heights, a maximum angle of the deformations with respect to the bar axis, deformation spacings per foot, and the overall length of the deformations.

It was not until 1964 that ASTM A 408, Special Deformed Round Bars, namely #14S (44 mm diameter) and #18S (57 mm diameter), originally 1-1/2 in. (38 mm) sq and 2 in. (51 mm) sq, now round with the same cross-sectional area, became available in the same grades as A 15. In the same year (1964), ASTM adopted two higher strength grades of reinforcing steel: A 432-64, yield 60,000 psi (414 MPa) min., tensile 90,000 psi (621 MPa) min., and A 431-64, yield 75,000 psi (517 MPa) min., tensile 100,000 psi (690 MPa) min., for sizes #3 (10 mm diameter) through #18S (57 mm diameter).

Finally, in 1968, ASTM adopted A 615-68 titled Standard Specifications for Deformed Billet Steel Bars for Concrete Reinforcement. A 615 incorporated previous A 15, A 305, A 408, A 431, and A 432 into one specification, and also eliminated structural grade steel and plain round reinforcing bar, listing three grades: Max 40 (276 MPa yield strength) and Max 60 (414 MPa; yield strength) in sizes #3 (10 mm diameter) through #18 (57 mm diameter) and #14 (44 mm diameter), and #18 (57 mm diameter) only.

In conclusion, it is reasonable to assume that a reinforced concrete structure built in the period 1910 through 1927 was reinforced with structural grade (Gr 33 or 228 MPa yield strength) deformed reinforcing bars, and from 1928 through 1963 with intermediate grade (Gr 40 or 276 MPa yield strength) deformed reinforcing bars. Of course, during these same periods higher strength steel reinforcing bars were available and may have been used or specified for a particular project; however, unless specific data are available regarding the grade of the material supplied to that project, conservative judgment would use the foregoing values of the grade of steel when evaluating an "elderly" structure.