Portland Cement Association

ENGINEERED CONCRETE STRUCTURES

December 1997
Vol. 10, No. 3

5420 Old Orchard Road

Skokie, Illinois 60077-1083

Phone: (847) 966-6200

FAX: (847) 966-9781

Contents

Lightweight Concrete for California's Highway Bridges

by James E. Roberts, Director, Engineering Service Center, Chief Structures Engineer, California Department of Transportation

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 on the California State Highway System for the past forty five years. A 1986 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 has 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, bents, 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 piling. The 11,000 cu yd (8410 m^3) 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.

Figure 1 Napa River Bridge during construction.

The design drawings and bid documents were based on the assumption that the balanced cantilever method of construction would be used. All final camber and prestressing diagrams as well as assumed form traveler loads were indicated on contract drawings based on this assumption. Optional details for precast girder segments were also provided on the contract drawings to provide as many alternatives to the bidders as possible. The design assumptions for structural lightweight concrete creep and modulus of elasticity were obtained from historical data maintained by the manufacturer.

Figure 2 Napa River Bridge

The successful bidder, Guy F. Atkinson Company of South San Francisco, California proposed an alternative construction method from that assumed by the designer. The Caltrans Standard Specifications for construction contracts provide this option to bidders. Atkinson chose to construct the bridge as a modified form of segmental construction by building segments up to 100 ft (30.5 m) in length on steel falsework towers (see Figure 1). The long segments were partially post-tensioned and the falsework removed and relocated as construction progressed across the valley. Figure 2 shows a general view of the completed bridge.

Benicia-Martinez Bridge Widening

The Benicia-Martinez Bridge is a 7200-ft (2195-m) deck truss carrying four lanes of Interstate 680 over the Carquinez Straits approximately 30 miles (48 km) Northeast of San Francisco. The bridge was completed and opened to traffic in 1962 and utilized a structural lightweight concrete deck with normal weight concrete topping. In 1988 plans were completed to widen the bridge deck from four to six lanes to handle increasing traffic. In order to minimize the additional reinforcement of the existing deck truss, the deck widening was also designed and constructed of expanded shale structural lightweight concrete with a polyester concrete overlay. The deck widening project was completed in June 1991. A total of 2600 cu yd (1990 m^3) of structural lightweight concrete was used in the deck widening. A parallel five lane bridge is currently being designed with a structural lightweight concrete superstructure.

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 concrete aggregate and the Caltrans designers prepared two alternative designs for the final bidding. It had been assumed after the study that the five column bent 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 widened. This 7200-ft (2195-m) bridge will carry five lanes of northbound traffic and the older, widened bridge will carry the southbound lanes. Design alternative studies were completed by four separate consulting firms to determine the two most competitive. Studies were conducted for a structural steel truss, similar to the existing bridge, a structural steel box girder, a concrete and steel cable stayed bridge, and a structural lightweight concrete segmental box girder bridge. The structural steel truss and the structural lightweight concrete segmental box girder bridge were the two most competitive designs. Confirming cost estimates were conducted by a fifth, cost estimating specialty consulting firm to remove any doubt from the comparisons.

Caltrans had planned to have two alternatives designed and bids taken for both, with the lowest bid accepted. Each bridge is composed of a series of 528 spans supported on normal weight piers ranging up to 250 ft (76.2 m) from bedrock to deck. Structural lightweight concrete will be used for the decks and superstructure on both alternatives, with polyester concrete overlay wearing surfaces. In 1996 the decision was made to complete design of only the structural lightweight concrete alternative, after bids on some nearby structural steel bridges showed that material not to be competitive with concrete in this region.

Structural Lightweight Concrete Research

Concerns over the shear strength and ductile performance of structural lightweight concrete in a seismic event prompted the Department to initiate a research project at the University of California at San Diego. The project is being conducted at the Charles Lee Powell Structures Laboratory under the supervision of Professor Nigel M. J. Priestley, who has conducted much of the Caltrans' seismic research for concrete members. This lightweight concrete testing program is being conducted in three phases; first to determine the shear strength of structural lightweight concrete, second to investigate the flexural strength and ductility, and third to investigate the dynamic behavior of structural lightweight concrete. Only the results of the fist two phases are available now.

The importance of assessing the shear strength of structural lightweight concrete lies in the undesirable characteristics of a shear failure. Since structural engineers try to provide adequate protection against shear failure in the design of any reinforced concrete member, it is important to accurately evaluate the shear strength of the material. Two structural lightweight concrete bridge column test specimens were built and tested.

While Caltrans has not used structural lightweight concrete in bridge columns or other supporting elements it was important to determine the flexural strength and ductility of columns designed with the concrete. This second series of tests was completed in late 1996. Three columns were constructed and tested, two with lightweight concrete and one with normal weight concrete for comparison.

Based on this work it is suggested that the initial cracked section stiffness of a lightweight concrete member can be conservatively reduced by 15% from the stiffness of a normal weight concrete column. This would result in an increase in elastic displacements in a moderate earthquake. For design for the ultimate limit state the reduced stiffness would not play a role. However, the use of force-based design would likely result in an inaccurate estimate of displacement. Therefore, the use of direct displacement-based design is recommended.

Based on these tests it can be concluded that the hysteretic damping of structural lightweight concrete is essentially the same as for normal weight concrete. For direct displacement-based design, damping relations for normal weight concrete can be applied without modification for lightweight concrete. Analysis of these test results indicate that the ultimate concrete compression strain is not affected by the type of concrete, and that estimates of displacement capacity with the same degree of conservatism as for normal weight concrete can be obtained for lightweight concrete.

Closing Remarks

The results to date indicate that structural lightweight concrete using expanded shale aggregate is a viable alternative, especially where dead load is a design consideration. It can be used in columns with dependable, predictable behavior in seismic zones.

Caltrans intends to continue the use of structural lightweight concrete in whatever applications prove to be cost effective. Research will continue on material performance in high seismic zones. Current policy will be updated to encourage the expanded use of the aggregate.

Tests performed at UCSD on structural lightweight concrete bridge columns indicate that the non-ductile shear strength of the concrete is not significantly altered. However, ductile shear strength appears to be lower based on strain levels in the transverse steel as well as observations on aggregate cracking. More detailed analyses are underway to develop design recommendations for structural lightweight concrete. Until this work is completed Caltrans will continue to use structural lightweight concrete only in the superstructures, and normal weight concrete in the substructures because of the need to design for ductile performance in the columns during a seismic event.

Reinforcing Bar Specifications — 1911 through 1968

by Gustav G. Erlemann, Consultant, Jeffersonville, NY

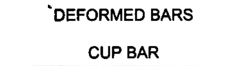
Investigating the feasibility of rehabilitating a reinforced concrete building constructed 60, 70 or more years ago requires a complete structural analysis in order to determine the present day load capacity of the structure. That capacity is determined by the strength of two materials, concrete and 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.

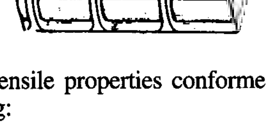
The first *Standard Specification for Billet Steel Concrete Reinforcement Bars* was adopted by ASTM in 1911, revised in 1914, designated A 15. The A 15 specification had three classes of bars: plain, deformed, and cold-twisted. The plain and deformed bars were specified in three grades: structural, intermediate 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."

COLD TWISTED SQUARE BARS



DEFORMED BARS

CUP BAR



The tensile properties conformed to the following:

	Structural	Intermediate	Hard	Cold-twisted
Yield min., psi (MPa)	33,000 (228)	40,000 (276)	50,000 (345)	55,000 (379)
Tensile, psi (MPa)	55,000 (379) to 70,000 (483)	70,000 (483) to 85,000 (586)	55,000 (379) min.	n/a

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 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 1/2 in. (13 mm) sq size was eliminated in 1942 as a war emergency measure.

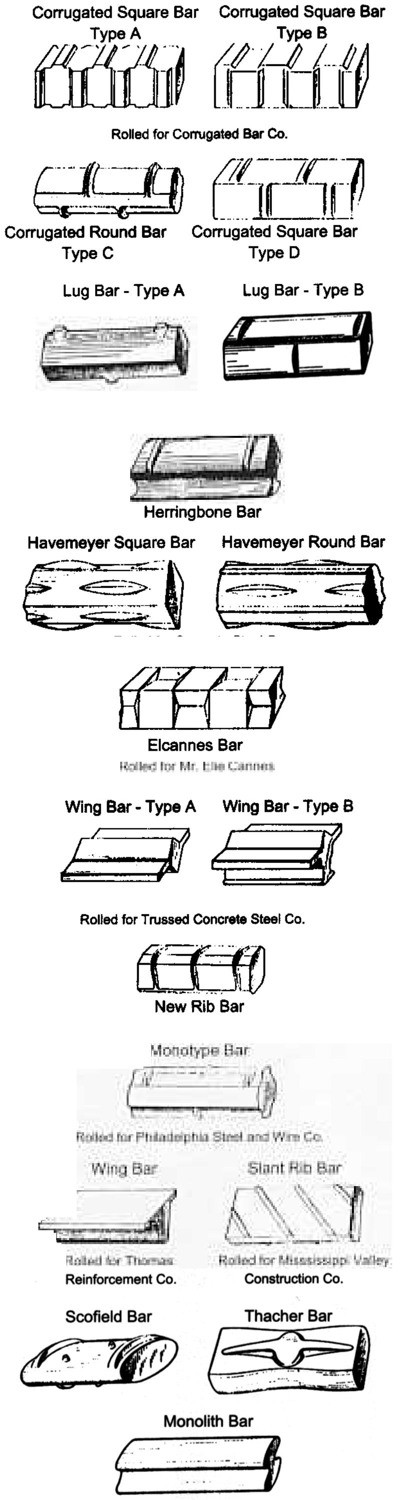
In 1950, ASTM revised the specifications pertaining to new billet reinforcing bars. ASTM A 15-50T changed all reinforcing bars to round, designated #3 (10 mm diameter) through #11 (35 mm diameter), replacing 3/8 in. (10 mm) rd through 1-1/4 in. (32 mm) sq. #2 or 1/4 in. (6 mm) rd was not classified as 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: Gr 40 (276 MPa yield strength) and Gr 60 (414 MPa yield strength) in sizes #3 (10 mm diameter) through #18 (57 mm diameter) and Gr 75 (517 MPa yield strength) in sizes #11 (35 mm diameter), #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.

DEFORMED BARS — cont'd



Publisher's Note

Intended for decision makers associated with design, management, and construction of buildings, bridges, and special structures such as convention centers and stadiums, Engineered Concrete Structures is published triannually by the Engineered Structures Program of the Portland Cement Association.

Our purpose is to disseminate information related to the uses of concrete in engineered structures. If there are topics or ideas you would like to have discussed in future issues, please let us know. Items from this newsletter may be reprinted without prior permission.

Direct all correspondence to:
S. K. Ghosh, Editor
Engineered Concrete Structures
Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077-1083
Telephone: 847/966-6200