LIGHTWEIGHT CONCRETE FOR LONG-SPAN BRIDGES – PAST, PRESENT AND FUTURE

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ABSTRACT

Lightweight concrete has been used in main spans of the three longest-span concrete box girder bridges in the world, including the Stolma Bridge in Norway with the current record span of 301 m. It has been used in suspension spans such as the upper deck of the San Francisco-Oakland Bay Bridge built in 1936 with 95 pcf concrete and still in service; pretensioned concrete girders, including 160 ft long girders for the emergency replacement of the Skagit River Bridge; spliced and post-tensioned precast girders with spans up to 240 ft when combined with a lightweight concrete deck slab; and the longest spliced girder span in the US at 325 ft with a 185 ft long lightweight concrete drop-in segment. In spite of these successful projects, some owners, designers and contractors remain unconvinced that this material should be used for long-span structures.

This paper discusses manufactured lightweight aggregates and structural properties of lightweight concrete. Conclusions of studies on lightweight concrete indicating its applicability to long-span concrete structures are reported, including results of creep and shrinkage tests. The enhanced durability of lightweight concrete will be discussed. Examples are given of long-span bridges that have used lightweight concrete in the US and Norway.

Keywords: Lightweight concrete, long spans, pretensioned girders, spliced girders, segmental box girders

INTRODUCTION

Structural lightweight concrete has been used in long-span bridges, including the segmental concrete box girder bridge with the current world record main span of 987 ft and major suspension spans such as the San Francisco-Oakland Bay Bridge. Even with its use in such bridges, some owners, design engineers and contractors are reluctant to use this material for long-span structures.

This paper introduces the process and types of raw materials used to manufacture structural lightweight aggregates in the US. Material properties of lightweight concrete made with these aggregates that are of interest to long-span bridge designers are discussed. An historical perspective is provided by reviewing several documents about structural lightweight concrete for bridges and buildings that were written by prominent engineers of the last century. Examples of long-span bridges that have used lightweight concrete are discussed for a number of categories of long-span bridges. The future of lightweight concrete for long-span bridges is also discussed.

This paper is an abridged version of a paper submitted by the author for presentation This paper is an abridged version of a paper submitted by the author for presentation at the 2015 Multi-Span Large Bridge Conference in Porto, Portugal[1] and eventual publication in the conference proceedings. This paper focuses more on concrete bridges and has been revised and expanded in some areas.

STRUCTURAL LIGHTWEIGHT AGGREGATES MANUFACTURED IN THE US

Many engineers consider structural lightweight aggregate to be a new material. However, it has been manufactured in the US since 1918 when a patent was granted to the developer of the rotary kiln process for manufacturing lightweight aggregate.[2] All of the structural lightweight aggregate currently manufactured in the US is made using this process.

In the US and in other parts of the world, structural lightweight aggregates manufactured from shale, clay and slate are used for lightweight concrete for bridges rather than using naturally occurring lightweight aggregates such as pumice and scoria. After crushing and grading, the raw material is fed into a rotary kiln, which is similar to kilns used to manufacture portland cement. In the kiln, the raw material is heated to 1800 to 2200°F. At these high temperatures, the raw material softens and expands as gases are released. The released gas forms many small, mostly discontinuous, pores. These pores remain as the expanded material exits the kiln and hardens as it cools. The result is a vitrified, inert aggregate that is significantly lighter than conventional aggregates (approximately half the relative density), yet still has strength required for structural aggregates. Expanded aggregate may be crushed to obtain the desired particle size and shape for use as aggregate in concrete.

Expanded structural lightweight aggregates manufactured using different types and sources of raw materials and processed using different techniques will have somewhat different properties. However, with proper attention to qualification of aggregates, quality control and mixture proportions, many structural grade lightweight aggregates have been successfully used for concrete bridge decks and several have been successfully used in the construction of long-span prestressed concrete bridges, including pretensioned and post-tensioned precast concrete girders and segmental concrete box girders.

For production of structural lightweight concrete, lightweight aggregate should be considered as simply a lighter type of aggregate. The lightweight aggregate is proportioned, handled and batched in the same way as normal weight aggregate. The same admixtures can be used for lightweight concrete. Lightweight aggregate has a greater absorption than normal weight aggregate, generally in the range of 6 to 30% depending on the aggregate source, so it is typically prewetted prior to batching, especially if the concrete is to be delivered by pumping. Prewetting the aggregate provides water for curing from within the concrete, a beneficial phenomenon that is referred to as “internal curing”.[3]

PROPERTIES OF LIGHTWEIGHT CONCRETE

When lightweight aggregates are used to make structural lightweight concrete, its properties will differ from conventional concrete. The properties of greatest interest for long-span bridges are discussed in this section, including density, design compressive strength, modulus of elasticity, tensile strength, creep, shrinkage, coefficient of thermal expansion, and durability.

In the *AASHTO LRFD Bridge Design Specifications*[4], two types of lightweight concrete are defined:

- “sand lightweight concrete”, which has lightweight coarse aggregate but normal weight fine aggregate
- “all lightweight concrete”, which contains only lightweight aggregate.

Sand lightweight concrete, which is used most frequently for structural lightweight concrete in the US, has typical densities for bridge construction ranging from 110 to 125 pcf. For all lightweight concrete, the typical density range used for bridges is 95 to 105 pcf. The density of lightweight concrete varies depending on the aggregate type and the compressive strength required. As with normal strength concrete, the density of lightweight concrete increases with compressive strength, although at an increased rate. In some situations, lightweight and normal weight aggregates may be blended to achieve the density needed to satisfy handling and shipping or structural design requirements.

Structural lightweight concrete mixtures have been developed that have a statistically established design minimum compressive strength of over 10 ksi. Such mixtures have been used successfully in the production of precast prestressed concrete girders. A lightweight concrete mixture with a design minimum compressive strength of 10 ksi was used in a recent bridge project (Liles and Holland 2010).[5] These lightweight concrete mixtures have early age strength gain characteristics very similar to normal weight concrete mixtures so they are appropriate for use for pretensioned girder fabrication.

The largest change in properties for lightweight concrete is the modulus of elasticity where the reduced stiffness of the lightweight aggregate results in a significant reduction in the modulus of the concrete, generally in the range of 30% to as much as 50%. This change is accounted for by including the concrete density in the equation for computing the modulus of elasticity that is found in the AASHTO LRFD [4] (AASHTO 2014). A revised equation for modulus of elasticity has been approved for the code. It will appear in the next interim to the code that will be released by mid-2015. The new equation, which still includes concrete density, provides a better estimate of the modulus of elasticity for high strength and lightweight concretes (Greene and Graybeal 2013).[6]

It has long been thought that the tensile strength of lightweight concrete is reduced compared to normal weight concrete with the same compressive strength. However, recent test data reported by Byard and Schindler[7] (2010) and by Cousins, et al.[8] (2013) show that the splitting tensile strength of lightweight concrete bridge deck and girder mixtures was close to or exceeded the expected splitting tensile strength for normal weight concrete with the same compressive strength. Based on this finding, a designer could specify the splitting tensile strength of lightweight concrete to be equal to or greater than the expected tensile strength for normal weight concrete with the same compressive strength. According to the AASHTO LRFD,[4] this would allow the design of a lightweight concrete member to be completed with no reduction factors for shear or other quantities related to concrete tensile strength.

For long-span bridges, creep and shrinkage of concrete are generally critical properties for design. Again, it has been long thought that creep and shrinkage of lightweight concrete is greater than for a similar normal weight concrete. However, recent test data reported by Cousins, et al.[8] (2013) and Lopez, et al.[9] (2004) show that creep and shrinkage behavior of lightweight concrete is very similar to the behavior of normal weight concrete.

The coefficient of thermal expansion for structural lightweight concrete is less than for a similar normal weight concrete. Tests of typical deck concrete mixtures using lightweight aggregate from three sources by Byard and Schindler[7] (2010) indicate that the coefficients of thermal expansion for sand lightweight concrete and all lightweight concrete mixtures were about 80% and 65%, respectively, of the coefficient for the normal weight concrete mixture. In addition to a reduced coefficient of thermal expansion, lightweight concrete responds to changes in ambient temperature more slowly than normal weight concrete. The combination of these factors would lead to a significant reduction in the thermal expansion and contraction of the deck in a long-span bridge. Additionally, the combination of a reduced coefficient of thermal expansion and the reduced modulus of elasticity for lightweight concrete can be expected to provide greater tolerance to thermal differentials that occur within mass concrete placements. The larger difference between the coefficients of thermal expansion for lightweight concrete and steel could be a potential concern, but there are no known instances of distress caused by this difference. It is possible that the insulating qualities of the lightweight concrete play a part in this.

For bridges, durability is always a concern because of the extreme exposure conditions to which bridges are exposed. Some of the factors mentioned above, such as the reduced modulus of elasticity and reduced coefficient of thermal expansion, can contribute significantly to enhanced durability. Furthermore, the internal curing effect when prewetted lightweight aggregate is used in lightweight concrete provides improved hydration of cement and the more complete reaction of supplementary cementitious materials for more effective use of cementitious materials and reduced permeability. The reduced stiffness of lightweight aggregate results in a concrete composite with a more homogeneous stiffness. This more uniform stiffness reduces microcracking around the perimeter of aggregate particles, which is a major source of increased permeability. The durability of lightweight concrete is discussed at length by Castrodale and Harmon (2008b).[10]

RESEARCH REPORTS ON LIGHTWEIGHT CONCRETE

More information on the material properties of lightweight concrete can be found in reports and papers from several research projects that have recently been completed in the US, such as Cousins et al.[8], Lopez et al.[9], Ozyildirim[11], Byard and Schindler[7], and Greene and Graybeal.[6]

HISTORICAL PERSPECTIVES ON STRUCTURAL LIGHTWEIGHT CONCRETE

In this section, observations by several prominent engineers regarding the use of structural lightweight concrete are presented. These reports and papers, which were published from 30 to 50 years ago, demonstrate that the beneficial use of lightweight concrete for bridges and other major structures has been recognized for many years.

REPORT OF THE FIP COMMISSION ON PRESTRESSED LIGHTWEIGHT CONCRETE

The FIP Commission on Prestressed Lightweight Concrete presented a report on their work in 1966. This report was reprinted in the Journal of the Prestressed Concrete Institute in 1967.[12] Ben Gerwick, Jr., served as chair of the Commission, and presented the report.

The report is very comprehensive, discussing all aspects of material properties, plant use and reported behavior of lightweight prestressed concrete. Two excerpts are presented that summarize the positive conclusions of the FIP Commission from nearly 50 years ago regarding the suitability of lightweight concrete for use in prestressed concrete elements. The data and reasoning upon which their conclusions are based are still compelling today.

The Synopsis of the report contains the following statement:

> The report discusses prestressed lightweight concrete, made with high-quality structural lightweight aggregates such as expanded shales, clays and slates, and capable of developing cube strengths from 280 to 500 kg/cm^2 (4000 to 7000 psi) at unit weights of 1400 to 2000 kg/m^3 (85 to 120 pcf). Satisfactory values of shrinkage and creep are obtainable. Modulus of elasticity is approximately half that of normal concrete at the same strength. Fire resistance and thermal insulation are significantly better than for normal weight concrete.

The conclusion of the Commission report states:

> It is believed that this report will have shown adequately the great potential for expanding the manufacture and use of prestressed lightweight concrete. In a recent article, Engineer I. G. Ivanov-Dyatlov states: "From studies of the technology of manufacture, the structural-mechanical properties, shrinkage, creep, water impermeability, heat resistance, and fatigue, it has been shown that high-quality expanded-clay-aggregate concretes are suitable for building the most demanding structures." Much work remains ahead in further research, development and application, but sufficient knowledge and experience exists to justify the assertion that prestressed lightweight concrete is already of major significance as a new and reliable material for wide structural use.

THE ONE SHELL PLAZA BUILDING, HOUSTON, TEXAS

While the One Shell Plaza Building in Houston, Texas, is not a long-span bridge, the 52-story tall building, which was designed by the outstanding engineer Fazlur Khan, is an important example of using a material in a new application to achieve an economical structural solution. The building, which was completed in 1971 and was the world’s tallest concrete building at that time, was constructed using high-strength lightweight concrete for all parts of the structure. Fazlur Khan wrote one paper and co-authored another on the design of the building, including the investigations of the material properties for the lightweight concrete,[13] and the rigorous quality control program required for successful implementation of lightweight concrete in all parts of the structure.[14]

The building was originally conceived as a 35-story structure, limited in height by the foundation conditions in the region. Fazlur Khan’s preliminary calculations indicated that using an optimized building layout with lightweight concrete having a density of 115 pcf for the entire structure including the heavy mat foundation would allow construction of a 52-story building. His estimates indicated that this taller structure constructed of lightweight concrete could be built for the original unit price of the 35 story structure.[13]

In his paper on design, Khan[13] documented his studies to determine the feasibility of using high strength lightweight concrete for the project. He was especially concerned about shrinkage of lightweight concrete. However, after completing a comprehensive testing program, he concluded that “the proper mix design and selection of materials for lightweight concrete can effectively reduce the shrinkage strain very close to that for normal weight concrete.”

In a later paper, Colaco,[15] who worked with Fazlur Khan on the design of the One Shell Plaza building, reports that the building was still the tallest lightweight concrete building in the world. He mentioned no problems regarding the performance of the building after more than 30 years in service.

CRITERIA FOR DESIGNING LIGHTWEIGHT CONCRETE BRIDGES

In 1985, the Federal Highway Administration published a report Criteria for Designing Lightweight Concrete Bridges that had been prepared by the consulting firm T.Y. Lin

International.[16] The report gave a comprehensive assessment of lightweight concrete for bridge construction, including a discussion of material properties, reports on performance of lightweight concrete bridges in the US, an economical evaluation of benefits of lightweight concrete for several structure types, a discussion of advantages and disadvantages of using lightweight concrete, and specifications and field control procedures for using lightweight concrete. Although the report is 30 years old, it still contains useful information that demonstrates that lightweight concrete can be effectively and economically used for bridges.

LONG-SPAN BRIDGES USING LIGHTWEIGHT CONCRETE

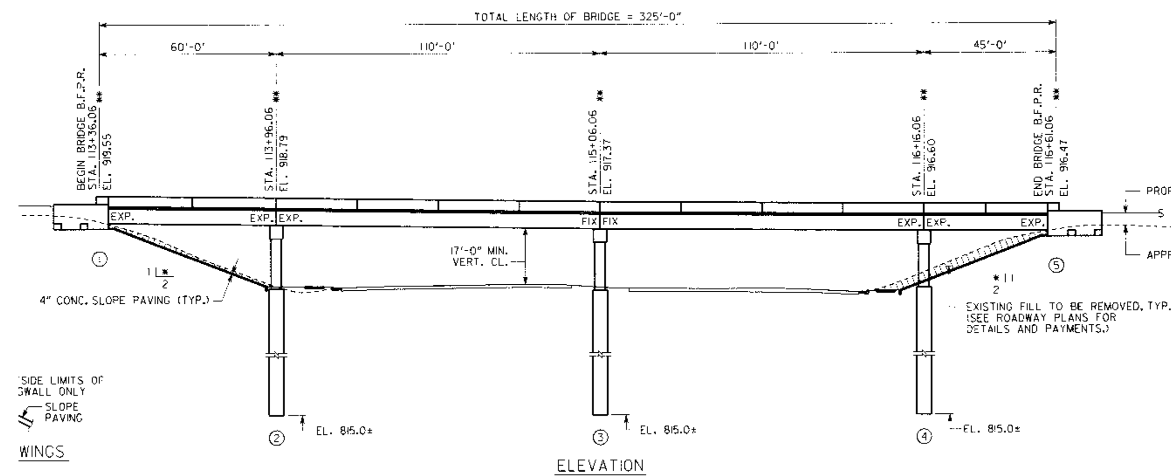
This section provides basic information on long-span bridges of several different types that have used lightweight concrete in the past and in recent years. The bridges are located in the US unless noted otherwise. A previous paper by the author gives more information for many of the long-span bridges discussed below.[17] While not discussed in this paper, lightweight concrete decks have also been used on long-span steel girder and truss bridges in the US.

PRETENSIONED CONCRETE GIRDER BRIDGES

Lightweight concrete has been used for pretensioned precast concrete girders for a number of bridges in the US. Several are described here.

A prominent bridge span replacement that used lightweight concrete was the emergency replacement of one span of the bridge carrying I-5 over the Skagit River in Washington State,[18] where an existing truss span had collapsed after being struck by an over-height vehicle in 2013. Structural lightweight concrete was used for the deck girders (the deck structure was part of the pretensioned girder) in the permanent replacement span to keep the total weight of the new span below 915 tons. This allowed the designers to use the existing foundations without reanalysis or strengthening. Girders were 160 ft long. Specifications for the lightweight concrete required a fresh density of 123 pcf (maximum of 128 pcf) and a minimum compressive strength of 9000 psi. The photographs below show erection of one of the lightweight concrete deck girders and the nearly completed span on temporary supports. These photos are from WSDOT's Flickr site.

The Georgia Department of Transportation (GDOT) completed construction in 2009 of a four span bridge using lightweight concrete. The project demonstrated that the material could be used to reduce the weight of long bridge girders to avoid special hauling permits. The project used girders that were 54 in. deep and had maximum spans of 110 ft and is described by Liles and Holland[5] and Holland and Kahn.[19] Specifications for the lightweight concrete required a maximum fresh density of 120 pcf and a minimum compressive strength of 10 ksi for the 110 ft girders. The shorter end spans (45 and 60 ft) were designed using the same density, but were only required to reach a compressive strength of 5 ksi. An elevation view of the bridge is shown below.



The Virginia Department of Transportation (VDOT) has used lightweight concrete girders on several projects. The first was a three span bridge with lightweight concrete deck and girders that was completed in 2001.[20] Specifications for the lightweight concrete required a maximum fresh density of 120 pcf for both the girders and deck and minimum compressive strengths of 8000 psi and 4000 psi for the girder and deck, respectively. The lightweight concrete was also required to have maximum rapid chloride permeability values of 1500 coulombs for the girders and 2500 coulombs for the deck. Several spans of the two Route 33 bridges that span rivers on either side of West Point, Virginia, also had lightweight concrete girders and decks.[11] All units with spans longer than 120 ft were constructed with lightweight concrete girders and lightweight concrete decks. One of the bridges also had a bascule span which utilized lightweight concrete fill in the grid deck. The bridges were completed in 2006 and 2007. The post-tensioned spliced girder units for these bridges are discussed in the next section.

SPLICED CONCRETE GIRDER BRIDGES

Spliced girder bridges are being used more frequently in the US. These bridges combine pretensioned girders with post-tensioning to connect girder segments together to achieve longer spans.[21] In a number of spliced girder bridges, lightweight concrete has been used for the deck to extend the span length. However, bridges mentioned below only use lightweight concrete for the girders unless otherwise noted.

One of the first long-span spliced girder bridges was the Shelby Creek Bridge in Kentucky, which was completed in 1991.[22] The spliced girder concept was proposed by the contractor as an alternate to a steel bridge. Reduced density concrete was used for the girders because of the difficult handling and erection conditions at the bridge site. The multi-span bridge has maximum spans of 218 ft using girders that had a constant depth of 8.5 ft. The designers called the reduced density concrete "semi-lightweight concrete," which had a density of 125 to 130 pcf with a design compressive concrete strength of 7000 psi. Actual concrete strengths approached 8000 psi. The specified density was achieved using a blend of lightweight and normal weight coarse aggregates, so the concrete did not meet the strict definition of "sand lightweight" concrete that was used in the AASHTO specifications. Photographs of the bridge during construction and when completed are from the referenced *PCI Journal* article.

The spliced girder bridge currently holding the record in the US for the longest main span is Route 22 over the Kentucky River.[23] As with the Shelby Creek Bridge, the spliced girder concept was proposed by the contractor as an alternate to a steel bridge. The four-span bridge has a main span over the river of 325 ft. Constant depth girders are 9 ft deep and the haunched pier segments vary in depth from 9 ft to 16 ft. Semi-lightweight concrete with a density of 125 pcf, which used a blend of normal and lightweight coarse aggregates, was specified for the 185-ft-long drop-in segment. The use of reduced density concrete facilitated handling and erection of the girders. The bridge was completed in 2010.

The Virginia Department of Transportation (VDOT) has used lightweight concrete for several spliced girder bridges. The Route 33 project at West Point, Virginia, used lightweight concrete for the deck and post-tensioned spliced girders on the four main units, all of which had span configurations of 200-240-240-200 ft.[11] Specifications for the lightweight concrete required a maximum fresh concrete density of 123 pcf for the girders and 120 pcf for the deck and minimum compressive strengths of 8000 psi for the girders and 5000 psi for the deck. The lightweight concrete was also required to have a maximum rapid chloride permeability value of 1500 coulombs for the girders and 2500 coulombs for the deck. The bridges opened to traffic in 2006 and 2007. The photographs below are of the Route 33 Bridge over the Mattaponi River on the east side of West Point and show erection of the spliced girder spans and the completed bridge.

SUSPENSION BRIDGES

Suspension bridges are obvious candidates for the use of lightweight concrete because a reduction in the dead load of the deck leads directly to a reduction in the quantity of material required for the main cables and hangers. A number of major suspension spans in the US have used lightweight concrete decks.

A notable use of lightweight concrete for a deck on a suspension bridge in the US is the San Francisco-Oakland Bay Bridge with main spans of 2310 ft. The upper deck on the bridge was constructed in 1936 using all lightweight concrete with an "air dry" density of 95 pcf. The original deck is still in service. Since installation, the lightweight concrete deck has been protected by a normal weight concrete wearing surface. Using all lightweight concrete for the deck was credited with saving $3,000,000 out of the original $77,000,000 total original project cost.[17]

Several major suspension bridges have used lightweight concrete when their deck was replaced. These bridges include the Brooklyn Bridge in New York City and the Walt Whitman Bridge near Philadelphia, Pennsylvania.

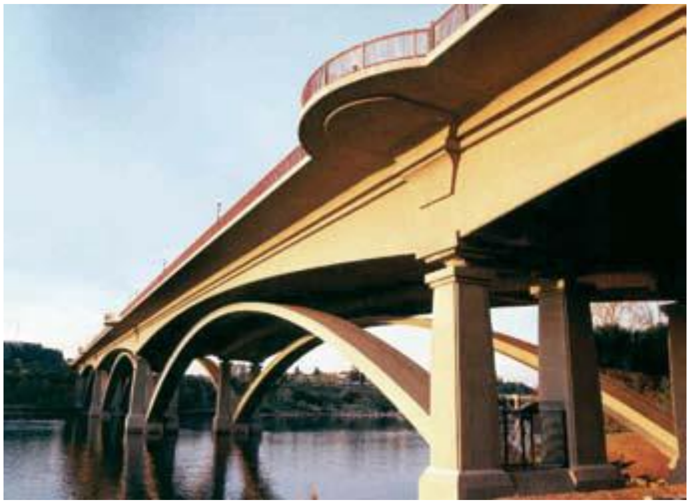
SEGMENTAL CONCRETE BOX GIRDER BRIDGES

Several of the first segmental concrete box girder bridges built in the US used sand light-weight concrete. Two more segmental concrete box girder bridges were recently constructed using lightweight concrete. All have been located in California.

The first concrete box girder bridge built in US was completed in Texas in 1972; the second was the Pine Valley Bridge in California that had a main span of 450 ft and was completed in 1974. Both of these bridges used normal weight concrete.

The next two box girder bridges were constructed in California using lightweight concrete. These were the Napa River Bridge (250 ft maximum spans) and the Parrots Ferry Bridge (640 ft main span), which were completed in 1977 and 1979, respectively. The Napa River Bridge has performed well, but the Parrots Ferry Bridge experienced excessive deflection at midspan and had to be retrofitted. It has been suggested that the deflection problems were related to design, material testing, and construction issues rather than problems with lightweight aggregate or lightweight concrete.

Recently, two segmental concrete box girder bridges have been successfully constructed in California using lightweight concrete. These are the Lake Natoma Bridge[25] and the Benicia-Martinez Bridge,[26] which have main spans of 328 ft and 659 ft, respectively. For both bridges, lightweight concrete was used to reduce the mass of the superstructure to decrease the seismic demands on the structure and foundations. The photographs of these two structures shown below are from the referenced articles in *ASPIRE* Magazine. The first photo is the Natoma Bridge with arches below the main structure; the Benicia-Martinez Bridge is the second photo with the longer spans.



SEGMENTAL CONCRETE BOX GIRDER BRIDGES AND OTHER SPECIAL TYPES OUTSIDE THE US

The three longest segmental concrete box girder bridges in the world are located in Norway. All three use lightweight concrete in the central portion of the main span to increase the possible span length. The three bridges are: the Stolma Bridge, completed in 1998 with a main span of 987 ft of which 604 ft is lightweight concrete; the Raftsundet Bridge, completed in 1998 with a main span of 978 ft of which 735 ft is lightweight concrete; and the Sundøy Bridge, completed in 2003 with a main span of 978 ft of which 735 ft is lightweight concrete.[27] Expanded slate lightweight aggregate from the US was used in the Sundøy and Raftsundet bridges to enable the lightweight concrete to be pumped. The photograph below is of the Raftsundet bridge, which held the world record for the longest span concrete segmental box girder bridge for a short time – photograph taken by Jan-Eirik Nilsskog.

Lightweight concrete was used for special purposes in two other bridges in Norway: the Nordhordland Bridge, completed in 1994, for which the deck on the main span of the cable stayed portion of the bridge and the pontoons for the floating bridge portion of the bridge are lightweight concrete; and the Sandhornøya Bridge, completed in 1989, for which the 361 ft back spans were constructed with lightweight concrete because they were longer than required for an efficient span layout with a main span of 505 ft.[27]

THE FUTURE OF LIGHTWEIGHT CONCRETE FOR LONG-SPAN BRIDGES

It is obvious that reducing the weight of construction materials for long-span bridges provides a great structural advantage, and even more so when the structure must be designed to resist seismic events. The past use and performance of lightweight concrete has also clearly demonstrated that it is an appropriate material for use in long-span bridges. Recent studies by Cousins, et al.[8] and Greene and Graybeal[6] have provided additional support for the use of lightweight concrete for long-span bridges by better defining properties of lightweight concrete for use in decks and prestressed concrete girders. Changes in the AASHTO LRFD related to lightweight concrete that were approved at the AASHTO Subcommittee on Bridges and Structures (SCOBS) meeting in 2015 (and will be published in mid-2016) have simplified and clarified design for lightweight concrete, and have removed some provisions that reduced the effectiveness of lightweight concrete in bridge design[28]. All of these factors combine to provide a strong case for the future use of lightweight concrete for long-span bridges.

CONCLUSIONS

The information presented in this paper clearly demonstrates from research, historical statements, and actual project experience that structural lightweight concrete is a material that has provided, and will continue to provide, an effective, economical, durable, and safe solution for the design and construction of long-span bridges.

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