INCREASING DESIGN EFFICIENCY USING LIGHTWEIGHT CONCRETE FOR PRESTRESSED GIRDER BRIDGES

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ABSTRACT

Lightweight concrete has many applications for bridge construction, ranging from use of lightweight concrete to reduce the weight of prefabricated elements for handling and transportation to the use of lightweight concrete for decks and prestressed concrete beams to reduce the weight of the structure for improved structural efficiency and seismic performance. However, there are other significant advantages, especially for bridge decks, that support the increased use of lightweight concrete for bridge components.

The benefits of using lightweight concrete for bridges related to material properties will be reviewed, which include improved durability and reduced transportation costs. Design modifications and definitions that appear in the design specifications for lightweight concrete will be discussed briefly.

The main focus of the presentation will be to evaluate the structural benefits of the use of lightweight concrete (with a density of 115 to 125 pcf) in both bridge decks and prestressed concrete girders. Increased structural efficiency will be demonstrated by comparing the maximum span lengths achievable for different combinations of design parameters. The benefits of using reduced density concrete (125 to 145 pcf) in prestressed concrete girders to reduce shipping weights and foundation loads will also be considered. The relative cost of lightweight concrete will be briefly discussed.

Projects where lightweight and reduced density concrete have been used will be highlighted to illustrate the practical use of lightweight concrete.

KEYWORDS: Prestressed Concrete, Lightweight Concrete, Bridges, Girders, Decks, Durability, Shipping, Handling, Cost, Material Properties

INTRODUCTION

Lightweight concrete has many applications for bridge construction, ranging from use of lightweight concrete to reduce the weight of prefabricated elements for handling and transportation to the use of lightweight concrete for decks and prestressed concrete beams to reduce the weight of the structure for improved structural efficiency and seismic performance. However, there are other significant advantages, especially for bridge decks, that support the increased use of lightweight concrete for bridge components.

The benefits of using lightweight concrete for bridges related to material properties will be reviewed, which include improved durability and reduced transportation costs. Design modifications and definitions that appear in the design specifications for lightweight concrete will be discussed briefly.

The main focus of the presentation will be to evaluate the structural benefits of the use of lightweight concrete (with a density of 115 to 125 pcf) in both bridge decks and prestressed concrete girders. The effect of using lightweight concrete will be demonstrated through two groups of preliminary design computations.

Increased structural efficiency will be demonstrated by comparing the maximum span lengths achievable for the following pairs of element densities:

- Normalweight concrete girder and deck (NG + ND)
- Normalweight concrete girder and lightweight concrete deck (NG + LD)
- Lightweight concrete girder and deck (LG + LD)

Three girder spacings are used to represent the range of practical girder spacings: 6, 8 and 10 ft. Designs will also be conducted using normal (7 ksi) and high strength (10 ksi) concrete for the girders for each of the combinations.

A second set of design computations will be performed using the same spans for all of the combinations of density and other parameters. The spans selected are slightly below the maximum spans computed in the previously mentioned designs.

The benefits of using reduced density concrete in prestressed concrete girders and other elements to reduce shipping weights and foundation loads will also be considered. The relative cost of lightweight concrete will be briefly discussed.

The paper will conclude with a discussion of several projects where lightweight and reduced density concrete have been used to illustrate applications of lightweight concrete.

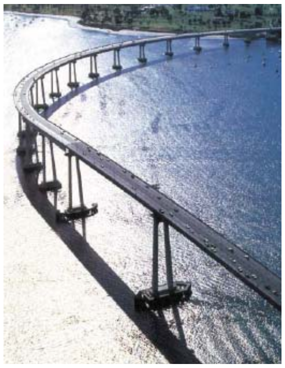
USE OF LIGHTWEIGHT CONCRETE IN BRIDGES

The FHWA Report "Criteria for Designing Lightweight Concrete Bridges", published in 1985, gives a good, although dated, perspective on the use of lightweight concrete for bridge construction. This report indicates that, at that time, more than 400 bridges had been constructed in the US using lightweight concrete.

The earliest use of structural lightweight concrete in a bridge was in 1922 (FHWA, 1985). A notable early use of lightweight concrete was the upper roadway deck of the San Francisco-Oakland Bay Bridge, which was constructed in 1936 and is still in service today (Harmon, 2005). The use of lightweight concrete for bridges continued, reaching a maximum in the mid 1950s, and major projects throughout the world continue to be constructed with the material today, including the Benecia-Martinez Bridge, a cast-in-place segmental box girder bridge in California with spans up to 655 ft (Murillo, et al, 1994), and two spliced girder bridges on Route 33 in Virginia.

Several projects which have used lightweight concrete in precast, prestressed concrete bridge girders are briefly discussed in this section.

CORONADO BRIDGE, SAN DIEGO, CALIFORNIA



This bridge over San Diego Bay was built in 1969 using over 300 precast, prestressed structural lightweight concrete girders (ESCSI, 2001b). The use of lightweight concrete in the pretensioned beams made possible the benefits of plant fabrication and overland transportation to the bridge site from a plant located over 100 miles from the bridge site. The lightweight concrete had a specified air-dry density of 115 pcf and a compressive strength of 5,500 to 6,000 psi. The deck was normalweight concrete.

US ROUTE 19 OVER THE SUWANNEE RIVER, FANNING SPRINGS, FLORIDA

This four span bridge was constructed in 1964 using precast prestressed lightweight concrete girders spanning 121 ft (Brown, et al, 1995). This span, which was relatively long for AASHTO Type IV girders at the time, was required to match the spans of the existing bridge, which would remain in service. The original bridge has since been replaced with a lightweight concrete bridge essentially identical to the one constructed in 1964. To achieve this long span length, the prestressed concrete girders were fabricated using lightweight concrete with a specified compressive strength of 5,000 psi that had a maximum fresh density of 120 pcf. The deck slab was also constructed using lightweight concrete with a maximum fresh density of 120 pcf, but with a specified compressive strength of 4,000 psi.

Since this was the first bridge in Florida to use lightweight concrete, the bridge was instrumented and observed for several years after completion. In 1992, after 28 years in service, researchers returned to the bridge to determine its condition and to measure its response to loads (Brown, et al, 1995). At that time, it was found that the bridge response to loads was essentially identical to the measurements taken in 1968, four years after construction was completed. The two lightweight concrete bridges remain in service today, and appear to be in excellent condition. The bridge constructed in 1964 is shown in the photograph taken by one of the authors in 2005.

SEBASTIAN INLET BRIDGE, FLORIDA

In 1964, the Florida DOT also constructed an innovative long-span bridge crossing the Indian River at Sebastian Inlet on Route A1A (ESCSI, 2001b). The main unit of the bridge consisted of three spans of 100-180-100 ft. In order to achieve the center span, which was very long for concrete at the time, the designers used anchor spans cantilevered over the pier to provide 20 ft overhangs, which reduced the length of the drop-in span to 120 ft. To make the concept work, the designers used lightweight concrete for all concrete in the drop in span. The minimum specified compressive strength for the lightweight concrete girders was 5,000 psi with a density of 115 pcf. A minimum compressive strength of 4,000 psi was specified for the lightweight deck concrete, also with a density of 115 pcf. The Sebastian Inlet Bridge won the Prestressed Concrete Institute Special Award in 1964. The bridge remains in service today, and appears to be in excellent condition, as shown in the photograph taken by one of the authors in 2005.

SHELBY CREEK BRIDGE, PIKEVILLE, KENTUCKY

The 987 ft long bridge carrying US Route 23-119 Bridge over Shelby Creek near Pikeville, Kentucky, was completed in 1991. The bridge utilizes precast I-girder segments that are spliced together to achieve maximum spans of 218’-6” (Caroland, et al, 1992). To reduce the weight and facilitate handling of the precast concrete girders, the largest of which weighed 145,000 lbs, the designers specified a semi-lightweight concrete with a density of 125 to 130 pcf. The specified minimum compressive strength for the prestressed girders was 7,000 psi, with actual strengths approaching 8,000 psi. The girders were pretensioned in a prestress plant and then post-tensioned on the site to create a five-span continuous bridge. This innovative bridge was recognized as an award winning design by PCI, PCA and ACEC.

RTE. 106 OVER CHICKAHOMINY RIVER, EAST OF RICHMOND, VIRGINIA

Lightweight high performance concrete was used for the beams and deck for the Route 106 Bridge over the Chickahominy River east of Richmond, Virginia (Harmon, 2005). The bridge, constructed in 2001, has three spans of 85 ft and a 7.9 in. thick deck that is continuous over the two intermediate piers. This demonstration project was accompanied by research into the material properties and fabrication of the high performance lightweight concrete.

The specified 28-day compressive strength and 28-day permeability were 8,000 psi and 1500 coulombs, respectively, for the beams and 4,000 psi and 2500 coulombs, respectively, for the deck. The target density for the lightweight concrete for both the beams and deck was 120 pcf.

Research results indicated that measured transfer and development lengths of prestressed strand in the pretensioned beams were conservatively predicted by current AASHTO provisions (Ozyildirim, et al, 2004). Condition surveys were performed after the placement of the deck and two years later. The condition survey of the deck after two years of exposure indicated only limited cracking. The research, construction and performance of this bridge demonstrated that high performance lightweight concrete can be produced that is workable, strong, volumetrically stable, and resistant to cycles of freezing and thawing, thus leading to a long service life with minimal maintenance for both prestressed concrete beams and bridge decks. The current condition of the bridge is shown in the photograph taken by one of the authors in 2005.

ROUTE 33 BRIDGES AT WEST POINT, VIRGINIA

Based on the successful use of high performance lightweight concrete for the Chickahominy Bridge, two more much larger structures in Virginia have been designed using high performance lightweight concrete in both beams and decks. The bridges, which carry Route 33 across the Mattaponi and Pamunkey Rivers on either side of the town of West Point, are currently under construction. Lightweight concrete is being used for the deck and bulb-tee girders for the longer approach spans and channel units of the bridges. The channel spans are spliced post-tensioned long span units with haunched pier segments with a maximum span of 240 ft. The specified concrete compressive strength for the beams is 6,000 psi at transfer and 8,000 psi at 28 days with density of 125 pcf. The specified compressive strength for the deck is 5,000 psi with a density of 120 lb/cu ft. The photograph shown appears in a progress report on the VDOT project website (Browder, 2005).

BASIC CONCEPTS

DEFINITIONS OF LIGHTWEIGHT CONCRETE

Lightweight concrete is a structural concrete in which some or all of the coarse and fine aggregate has been replaced with aggregate that is lighter than normalweight aggregates. Structural lightweight concrete in the US uses lightweight aggregates that are manufactured using a rotary kiln process (see next section). Several definitions for lightweight concrete are presented in this section to introduce the concept of lightweight concrete.

ACI Committee 213 (Lightweight Aggregate and Concrete) has defined structural lightweight-aggregate concrete (SLC) as concrete which:

- is made with structural lightweight aggregate as defined in ASTM C 330
- has a minimum 28-day compressive strength of 2,500 psi
- has an equilibrium density between 70 and 120 pcf
- consists entirely of lightweight aggregate or a combination of lightweight and normal-density aggregate

The committee emphasizes that this is a definition, not a specification. It also indicates that most lightweight concrete has an equilibrium density in the range of 105 to 120 pcf, with densities below 105 pcf used infrequently.

The ACI *Building Code Requirements for Structural Concrete* (ACI 318) provides the following definition in Section 2.2:

> **Structural Lightweight Concrete -** Concrete containing lightweight aggregate that conforms to [Section] 3.3 and has an equilibrium density as determined by "Test Method for Determining Density of Structural Lightweight Concrete" (ASTM C 567), not exceeding 115 lb/ft^3. In this code, a lightweight concrete without natural sand is termed "all-lightweight concrete" and lightweight concrete in which all of the fine aggregate consists of normalweight sand is termed "sand-lightweight concrete".

This definition includes two other definitions: "all-lightweight concrete" and "sand-lightweight concrete". These sub-definitions are used to determine modification factors for lightweight concrete for several design parameters. Commentary to this definition indicates that interpolation can be used where the fine aggregate may be a combination of lightweight and normalweight sand. Sand-lightweight concrete is typically used to achieve equilibrium densities as low as 110 pcf. If there is a compelling reason to require a lower density, all-lightweight concrete may be used. Designers should contact lightweight aggregate suppliers when deciding on the type of mix to use.

The definition of structural lightweight concrete in the AASHTO *Standard Specifications for Highway Bridges* (2002) is essentially the same as the definition in ACI 318, containing all of the points of the ACI definition, with only minor changes in wording.

The *AASHTO LRFD Bridge Design Specifications* (2004) give the following definitions in Section 5.2:

> **Lightweight Concrete -** Concrete containing lightweight aggregate and having an air-dry density not exceeding 0.120 kcf, as determined by ASTM C 567.
>
> **Normalweight Concrete -** Concrete having a weight between 0.135 and 0.155 kcf.
>
> **Sand-Lightweight Concrete –** A class of lightweight concrete containing lightweight coarse aggregate and natural sand fine aggregate.

These definitions leave an obvious gap for concrete mixtures with densities between 0.120 and 0.135 ksi. The specifications give no direction for use of concrete with a density in this range, which may be called specified density concrete (see below). The Specifications also do not provide a definition for “all-lightweight concrete”, although the term is used in the Specifications.

Concrete mixtures with a density that falls between the limits for lightweight and normalweight concrete are now defined by ACI Committee 213 as:

> **Specified Density Concrete (SDC)** – Structural concrete having a specified equilibrium density between 50 to 140 lb/ft^3 or greater than 155 lb/ft^3.

Specified density concrete is frequently used when the weight of a concrete precast element needs to be reduced for shipping and handling (Holm and Ries, 2000). For specified density concrete, the coarse aggregate fraction in the concrete is typically a blend of normalweight and lightweight aggregates. ACI Committee 213 recommends that a detailed mixture testing program involving the aggregate supplier should be conducted when using SDC. During one such program, where a broad range of material properties were tested for a high performance application, it was found that, for concrete in which up to half of the volume of coarse aggregate is replaced with lightweight aggregate, the physical properties of the specified density concrete (except the modulus of elasticity) may not change significantly from normalweight concrete (Walum, et al, 1995; Hoff and Elimov, 1995).

SPECIFYING LIGHTWEIGHT CONCRETE

Contract documents must clearly define the intended requirements for lightweight concrete. Frequently this involves the specification of material properties that are not normally specified for normalweight concrete.

The designer should consult material suppliers and fabricators early in the design process so that reasonable requirements for material properties may be developed and used for the design of the structure. The requirements should generally include adequate tolerances to reflect the variability inherent in production of any concrete.

For many design situations, the specification of equilibrium density and compressive strength will be adequate. If prestressing is employed, the designer may consider specifying other properties such as the modulus of elasticity. Issues that should be considered when specifying properties of lightweight concrete are discussed in this section.

Density

The contract documents must clearly indicate the intent of the designer regarding the density of lightweight concrete. Since the density of the concrete can be measured at different times and in several ways, this can be a source of confusion if the contract documents do not properly specify the density requirements. The proper approach to specifying density for lightweight concrete is discussed in this section.

Equilibrium density has been adopted by ACI and others as the measure for determining compliance with specified in-service density requirements for lightweight concrete. Therefore, it should be the density specified in the contract documents. Air-dry and oven-dry densities have been specified for lightweight concrete in the past, but these quantities should no longer be specified.

ACI Committee 213 provides the following definition:

> **Equilibrium Density –** As defined in ASTM 567, it is the density reached by structural lightweight concrete (low density) after exposure to relative humidity of 50 ± 5% and a temperature of 73.5 ± 3.5 °F for a period of time sufficient to reach a density that changes less than 0.5% in a period of 28 days.

According to ASTM C 567, equilibrium density may be determined by measurement or approximated by calculation using either the measured oven-dry density or the oven-dry density calculated from the mixture proportions. Unless specified otherwise, ASTM C 567 requires that equilibrium density be approximated by calculation (ACI 318R, 2005).

While the equilibrium density should be specified in the contract documents and is used as the basis for computing loads for structural design (after the allowance for reinforcement is added – see below), the fresh density of concrete is used for quality control when the concrete is placed. The two densities are different because the concrete loses moisture with time. All concrete loses moisture and therefore weight with time, but lightweight concrete typically loses more than normalweight concrete. The fabricator should be made responsible to determine the fresh density that corresponds to the specified equilibrium density for the mix proportions being used.

Typically, the fresh density for lightweight concrete will be greater than the equilibrium density by from 5 to 10 pcf, depending on mixture proportions and the degree of saturation of the lightweight aggregate. The air-dry density at 28 days will be slightly higher than the equilibrium density, and the oven-dry density will be slightly lower than the equilibrium density. The approximate calculated equilibrium density is taken as 3 pcf greater than the density for a computed oven-dry condition.

Additionally, it takes a period of time for the moisture to leave lightweight concrete and obtain the equilibrium density, as illustrated in Figure 1. The length of time required and the amount of weight reduction as the moisture leaves vary depending on the mixture proportions and other factors. Therefore, when lightweight concrete is used to reduce the weight of an element for handling or shipping, the variation in density with time should be considered when computing member weights at critical events. For handling of precast members immediately after form removal, the density should be taken as the fresh density of the concrete.

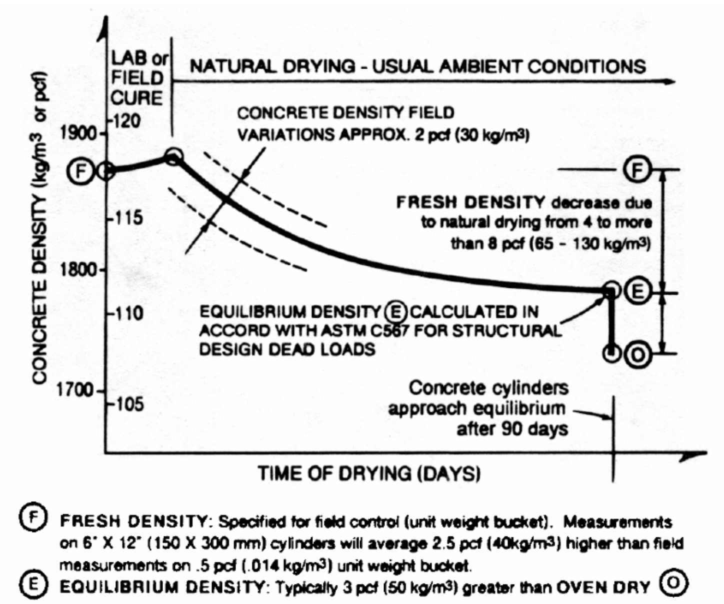


Figure 1 Concrete Density versus Time of Drying for Structural Lightweight Concrete (Holm 2001)

Density requirements for lightweight concrete are frequently accompanied with a tolerance, or are stated as a maximum value. Air content has a significant effect on both the fresh and equilibrium densities of the concrete. Since the air content is specified with a tolerance, the density of the concrete should be expected to have some variability.

Designers should be aware that the concrete densities mentioned throughout this section are for the concrete only and do not include the weight of reinforcement. It has been traditional to add 5 lb/ft^3 to the concrete density as an allowance for the weight of steel in reinforced concrete. However, the allowance may need to be increased for special cases. Therefore, the equilibrium density specified for lightweight concrete in the contract documents must be adjusted by the reinforcement allowance to compute the dead load of the structure.

Compressive Strength

Structural lightweight concrete is defined by some specifications as having a minimum compressive strength of 2,500 psi (ACI 213R-03). This is a lower limit the compressive strength of structural lightweight concrete, with most structural-grade lightweight aggregates capable of being used to produce compressive strengths up to 5,000 psi. Higher strengths are routinely achieved with many aggregates. Recent research has demonstrated that a design concrete compressive strength of 10,000 psi can be obtained at a fresh density of approximately 120 pcf using a high performance lightweight aggregate (Kahn, et al, 2004). Higher compressive strengths have also been achieved in production for specified density concretes (Walum, et al, 1995).

As with any type of aggregate, lightweight aggregates have a strength ceiling which limits the compressive strength of the concrete regardless of how much cementitious material is added. This ceiling varies depending on the type, source and processing of the lightweight aggregate.

In general, the design compressive strength will decrease as the density of the concrete is reduced. Therefore, a designer should consult prestress fabricators and lightweight aggregate suppliers to obtain a reasonable combination of compressive strength and density. The relationship between density and strength is not unique, so there is considerable latitude in reaching a solution, but some combinations will be easier to achieve on a production basis than others.

Other Properties or Characteristics

For some projects with complex structure types or erection procedures, designers have specified the modulus of elasticity, creep and shrinkage characteristics of lightweight concrete. However, for many projects, this level of detail is not required unless there is a significant prestress being applied to the member. Usual structural design requirements call for a tensile splitting strength factor of 85% of that for normalweight concrete, however for some projects, the tensile splitting strength may be specified. Whenever additional properties are specified, the lightweight aggregate suppliers must be consulted and a test program may be required to ensure that the specified properties can be achieved economically in a production environment.

In some cases, the absorption of lightweight aggregate may be an important factor related to the placement of the concrete or the long-term performance of the concrete. However, for most situations, the absorption of the lightweight aggregate can be accommodated in mixture proportions and quality control procedures.

TYPES OF MANUFACTURED LIGHTWEIGHT AGGREGATE

Lightweight aggregates are manufactured using shale, clay and slate as the raw material. After crushing and grading, the raw material is fed into a rotary kiln, where the raw feed is heated to 1,800 to 2,300 deg. F. At these temperatures, the material expands as gases are released in the softened material. This results in the formation of many small, mostly discontinuous, pores which remain as the material cools and hardens. The result is a vitrified, inert material that is significantly lighter than the raw material, yet has retained much of its strength. Depending on the type of raw material and processing, the aggregate may or may not be crushed after cooling to obtain the desired particle shape and size for use as aggregate in concrete.

Expanded aggregates manufactured using different types and sources of raw materials and processed using different methods will have different properties. However, with proper attention to qualification of aggregates, quality control and mixture proportions, most structural grade lightweight aggregates have been successfully used for concrete bridge deck construction.

Designers need to be aware of differences in material properties and should specify properties that will be important for the desired performance of the bridge element. Material properties can be obtained from the lightweight aggregate supplier or from testing for the type or types of aggregate that may be available for use on any project.

It is recommended that designers consult prestressed concrete fabricators that may produce lightweight concrete elements for a project to learn the available sources for lightweight aggregate. The prestressed concrete fabricators may have information on material properties for lightweight concrete they have used, or they may be able to refer the designer to an aggregate supplier who should be able to provide additional information on material properties of lightweight concrete produced using their aggregate.

LIGHTWEIGHT AGGREGATE PROPERTIES

The relative density (previously referred to as the specific gravity) of rotary kiln expanded lightweight aggregates typically ranges from 1.3 to 1.6, where the relative density for normalweight aggregates typically ranges from 2.6 to 3.0.

For structural lightweight aggregates, the maximum dry loose density is 70 pcf for fine aggregates, 55 pcf for coarse aggregates and 65 pcf for the loose density for the combination of coarse and fine aggregates, as specified in ASTM C 330.

Because of their cellular structure, lightweight aggregate absorbs more water than normalweight aggregates. Based on 24 hour tests, lightweight aggregates typically absorb from 5 to more than 25% by weight of dry aggregate (Holm, 2001). Absorption of normalweight aggregates is typically less than 2%. With proper consideration of absorption in mixture proportioning, batching and control, lightweight concrete can be consistently produced with the required workability and mechanical properties.

LIGHTWEIGHT CONCRETE PRODUCTION ISSUES

The fundamental concepts of handling aggregate and batching concrete apply to lightweight aggregate. However, because of the cellular nature of lightweight aggregates, the absorption is higher than most normalweight aggregates. Therefore, dry aggregates should not be used in the batching process. Usually, aggregates at a moisture content of at least their 24-hour absorption moisture content can be used with no significant slump loss in the lightweight concrete during mixing or placement using a conveyor or a bucket. This level of saturation can generally be accomplished by sprinkling the aggregate stockpile with water. If concrete is to be pumped, the lightweight aggregate should be prewetted to obtain a higher degree of saturation. The lightweight aggregate supplier should be consulted for guidance (Holm and Bremner, 2000).

Because lightweight aggregate properties, aggregate storage arrangements and water delivery and distribution systems are variable, it is difficult to give specific recommendations regarding the duration of aggregate conditioning by water sprinkling. However, in most cases, adequate aggregate conditioning by sprinkling with water can usually be achieved in 2 to 4 days. It is recommended that sprinkling be discontinued and that the stockpiles be allowed to drain prior to batching (usually overnight) to avoid excessive surface moisture and to provide more uniform moisture content. The absorbed moisture content is determined by oven drying after removing the visible film of water from the aggregate surface with an absorbent cloth.

When properly proportioned, lightweight concrete can be delivered and placed with the same equipment as normalweight concrete. Holm and Bremner (2000) provide the following basic principles required to obtain proper consolidation in the forms and to avoid separation of lightweight coarse aggregate from the mortar fraction during placement:

- Design of a well-proportioned, workable mixture that uses a minimum amount of water
- Equipment capable of expeditiously moving the concrete
- Quality workmanship in consolidating and finishing the concrete

Normalweight aggregates are generally of higher density than the cement paste matrix and, when subjected to vibration, they tend to sink. The opposite occurs with lightweight aggregates, which tend to rise if a concrete mixture lacking cohesion is subjected to improper handling, placement, and consolidation procedures. Usually lightweight concrete is cast with a lower slump than normalweight concrete (usually in proportion to the reduction in density because the lower-density concrete is generally easier to consolidate) and with a nominal amount of air entrainment, even for concrete not subjected to freezing and thawing. Although lightweight concrete does need vibration for proper consolidation, it normally will require a shorter period of vibration than used for normalweight concrete (Holm and Bremner, 2000).

Well-proportioned lightweight concrete can be placed and screeded with less physical effort than that required for normalweight concrete. Excessive vibration should be avoided to prevent driving the heavier mortar fraction down from the surface where it is required for finishing. On completion of final finishing, curing operations similar to those for normalweight concrete should begin as soon as possible; however, membrane-forming curing compounds should not be applied until bleeding has stopped. Lightweight concrete with aggregates having high absorptions carry their own internal water supply for curing, and as a result are more forgiving to poor curing practices or unfavorable ambient conditions (Holm and Bremner, 2000).

REFERENCES ON LIGHTWEIGHT CONCRETE

In addition to the FHWA report mentioned above, several other references are available to assist designers in the application of lightweight concrete to bridge structures.

A major publication is the "Guide for Structural Lightweight-Aggregate Concrete" developed by ACI Committee 213. This document provides information and guidelines for designing and using lightweight concrete, asserting that lightweight concrete "structures can be designed and performance predicted with the same confidence and reliability as normalweight concrete and other building materials."

A second major document is the "State of the Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments" which was prepared by Holm and Bremner for the US Army Corps of Engineers (2000). This document provides a wide array of detailed information on lightweight concrete properties that would be very useful in design.

Several useful publications on lightweight concrete are available from the Expanded Shale, Clay and Slate Institute (ESCSI). Some of these resources, including the US Army Corps of Engineers report by Holm and Bremner, can be downloaded from the ESCSI website, www.escsi.org.

BENEFITS OF LIGHTWEIGHT CONCRETE

High performance lightweight concrete has generally been used in bridge decks, prestressed concrete beams and segmental construction to reduce the weight of the structure for improved structural efficiency and seismic performance. However, there are other significant benefits to the use of lightweight concrete in bridges, including enhanced durability and reduced handling and transportation costs of precast components. Some of the specific characteristics of high performance lightweight concrete that enhance durability include improved bond between aggregate and paste, elastic compatibility between aggregate and paste, and internal curing. Several factors that make lightweight concrete especially well-suited for use in bridge decks will also be highlighted.

This section discusses these advantages and the properties of lightweight concrete that contribute to them.

REDUCED DEAD LOAD

A precast concrete element fabricated using lightweight concrete typically weighs 25 to 30% less than the same element fabricated using normalweight concrete. The reduced dead load of a lightweight concrete component compared to the same component fabricated with normalweight concrete can contribute to decreased overall project costs because of improved structural efficiency and to decreased costs related to handling and shipping.

Improved Structural Efficiency

When lightweight concrete is used for bridge girders and/or the deck slab, the total weight of the structure is reduced. This improves the efficiency of the overall structural design, allowing the following cost-saving design changes to be realized:

- Increased girder span lengths, with the potential for reducing the number of substructure elements
- Wider girder spacings, with the potential for reducing the number of girders required for a given span length
- Reduced structure mass for seismic designs, with the potential for reducing the substructure and foundation requirements
- Reduced substructure and foundation requirements, with the potential for reducing the size and/or number of foundation elements, including piles
- Reduced requirements for girder bearings
- Reduced reinforcement and prestressing in the deck panels, superstructure and substructure elements
- Increased deck width on the same superstructure
- Increased live load rating using the same superstructure

The final two bullet points are particularly significant for deck replacement projects where the superstructure may have to be strengthened or modified to accommodate a deck widening using normalweight concrete, where design changes must be accommodated late in the design process, or where the rating of an existing structure needs to be improved. A major factor in the use of lightweight concrete for the deck replacement on the Woodrow Wilson Memorial Bridge in the early 1980s (Lutz and Scalia, 1984; Jenkins, 1996) was the fact that the existing superstructure did not need to be modified if lightweight deck panels were used, even though the new roadway was widened.

The design comparisons for pretensioned girder bridges using lightweight and normalweight concrete reported later in this paper provide insight into the potential for improved structural efficiency that can be achieved in many of the area listed above.

Reduced Handling and Transportation Requirements

The use of lightweight concrete for girders can significantly reduce the weight of girders for handling and transportation. This may allow for reduced equipment sizes for handling or erecting the girders, which may result in reduced costs.

A research study has been conducted for GDOT at Georgia Tech to determine whether a 150 ft high performance lightweight concrete bulb-tee girder could be designed that could be transported without a "super load" permit, which is required for gross vehicle weights in excess of 150 kips. Researchers performed both analytical and experimental studies to determine the feasibility of such a design (Kahn, et al, 2004).

The researchers concluded that a bulb-tee girder designed using high performance lightweight concrete with a specified strength of 10 ksi and a density of 120 pcf could meet the project requirements. The physical testing revealed that the production of high performance lightweight concrete was feasible and the material had properties required for the design of pretensioned concrete girders.

The researchers performed a series of designs to demonstrate the reduction in weight of girders when using lightweight concrete. The results of a study by Meyer and Kahn (2000) are shown in Figure 2. The arrows have been added to highlight the reduction in girder weight for several design cases. The two highlighted designs for spans of about 140 ft and 150 ft have eliminated the need for a super load permit by using lightweight concrete for the girders.

While the difference in the direct costs of transporting a girder with a super load permit versus transporting the same length girder without a permit is significant, an even more significant benefit may be the elimination of the time required to obtain the permit, which can slow the progress of a bridge project, causing costs in many other areas.

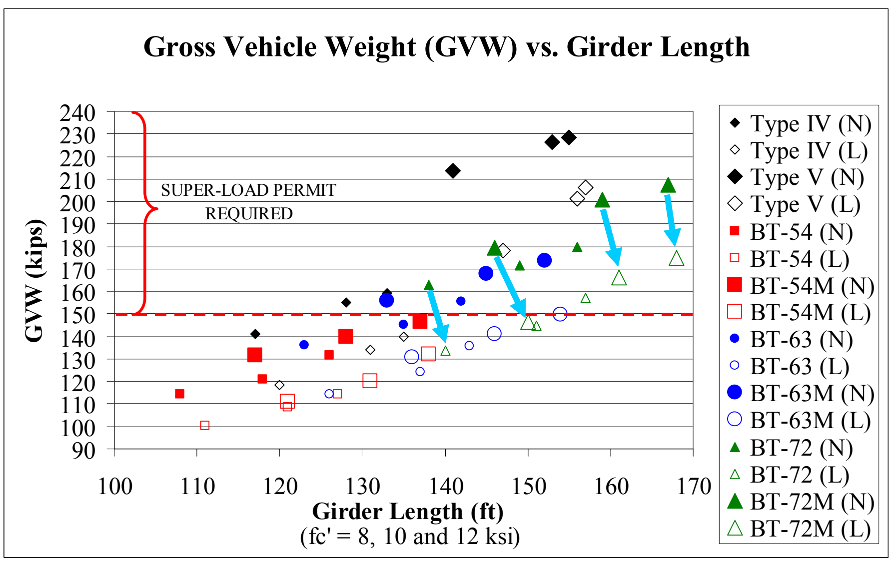


Figure 2 Gross vehicle weight vs. girder length

Other factors that can also lead to cost reductions from the reduced weight of lightweight concrete structures are discussed later in this paper.

ENHANCED DURABILITY

Some designers are concerned that elements constructed using lightweight concrete may not be as durable as the same type of element in the same environment constructed using normalweight concrete. However, observations of field performance of bridges often indicate that lightweight performs as well as or even better than normalweight concrete.

The FHWA report "Criteria for Designing Lightweight Concrete Bridges" (1985) mentions that while some have questioned the durability, wear resistance and long-term freeze-thaw qualities of lightweight concrete, "no evidence was found that these properties differ from those of normalweight concrete. In fact, there is evidence that these properties could be better for lightweight concrete, especially if the normal-weight concrete is of poor quality."

Some of the mechanisms to which the enhanced durability of lightweight concrete may be attributed are discussed below. Most are related to the permeability of concrete, which is strongly affected by the degree of microcracking that is present in the concrete.

Elastic Compatibility

The modulus of elasticity of lightweight aggregate particles is closer to the modulus of the cement paste because of the cellular nature of the aggregate. The more uniform stiffness of the elements in the concrete matrix reduces stress concentrations that form around stiffer aggregate particles in normalweight concrete. This results in reduced microcracking around aggregate particles, autogenous shrinkage, and shrinkage cracking in lightweight concrete. With reduced microcracking, the durability of the concrete is improved by reducing penetration into the concrete through the microcracks. A detailed discussion of this topic can be found in Bremner and Holm (1986).

Bond between Cement Paste and Lightweight Aggregates

The surface of lightweight aggregate particles is generally more porous and irregular than that of normalweight concrete. The firing process used to produce lightweight aggregate also causes the surface of the aggregate particles to become pozzolanic. Therefore, the bond between the lightweight aggregate particles and paste is typically superior to that between normalweight aggregate particles and paste because of the mechanical and chemical bonding that occurs between the aggregate and paste. In fact, it has been found that the boundary between lightweight aggregate particles and paste is not well defined after hydration of the cement because of the interaction between the aggregate, paste and hydrated cement. This interaction between constituents in lightweight concrete is called the "transition zone" because of its unique characteristics.

Because of the superior bond between aggregate and paste, microcracking is reduced. As mentioned above, reduced microcracking means that there are fewer paths for moisture, oxygen and chlorides to enter the concrete and initiate deterioration through corrosion of the reinforcement.

Internal Curing

An additional advantage for lightweight concrete is that water absorbed in the lightweight aggregate is available to be released over time into the concrete, which provides enhanced curing. This is especially beneficial for high performance concrete that is nearly impermeable to externally applied curing moisture. This enhanced curing from moisture initially contained within lightweight aggregate is called “internal curing”. The internal curing water is transferred from the lightweight aggregate to the mortar phase as hydration proceeds and evaporation takes place on the concrete surface. This action maintains a continuous moisture balance by replacing moisture essential for an extended continuous hydration period (Holm and Bremner, 2000).

Internal curing can improve the tolerance of concrete to improper curing and may increase strength of concrete. Improved curing will lead to more complete hydration of the cement, increasing the impermeability of concrete. Internal curing can be achieved by replacing a relatively small fraction of normalweight aggregate with saturated lightweight aggregate. The use of lightweight fine aggregate has been found to be especially effective. The replacement of a small fraction of normalweight aggregate with lightweight aggregate does not usually cause a noticeable change the engineering properties of the concrete.

SPECIAL CONSIDERATIONS FOR DECKS

Bridge decks are subject to severe exposure conditions in many locations. Conditions are especially severe where freezing and thawing occurs and the decks are subjected to applications of deicing chemicals. It has also been observed that bridge decks are prone to cracking at early ages, even before traffic has been placed on the bridge. This early cracking can also lead to premature deterioration of decks by allowing exposing the reinforcement to corrosion. Therefore, the reduced microcracking in lightweight concrete improves the impermeability of concrete, which is one of the most important factors in improving the long-term performance of bridge decks.

Krauss and Rogalla, authors of the NCHRP report titled "Transverse Cracking in Newly Constructed Bridge Decks" (1996), stated that “the project’s analytical studies showed that the concrete modulus of elasticity, adjusted for creep, affects both thermal and shrinkage stresses more than any other physical concrete property …". The authors continued: "Using low-elasticity aggregates should therefore reduce thermal and shrinkage stresses, and the risk or severity of transverse cracking." In response to these findings, the report recommends that concrete with a low cracking tendency should be used for bridge decks. To accomplish this objective, the authors present a list of recommendations, the first two of which are that concrete for bridge decks should have a low early modulus of elasticity and low early compressive strength. However, lightweight concrete can be used to satisfy the main requirement (low modulus of elasticity) without having to sacrifice strength, since the elastic modulus of lightweight concrete is less than that of normalweight concrete for the same strength.

As mentioned in the discussion of examples of durable lightweight concrete in the field, the freeze-thaw resistance and wear characteristics of lightweight concrete decks are excellent. One special feature of lightweight concrete decks is that as the concrete surface wears with time, as all bridge decks will, the aggregate particles also wear, exposing the internal cellular structure of the aggregate. This allows a lightweight concrete bridge deck to continue to have excellent skid resistance over the life of the bridge, rather than losing skid resistance with time as normalweight aggregates are exposed and polished.

Examples of Improved Durability for Lightweight Concrete Decks

An example of a direct comparison of lightweight and normalweight concrete performance is the Silver Creek Bridge over I-80 in Summit County, Utah (ESCSI, 2001a). The bridge was constructed in 1968. In 1991, after more than 23 years in service, cores were taken from the lightweight concrete deck and the normalweight concrete approach slab immediately adjacent to the bridge deck. The core samples were evaluated for chloride concentrations at different distances from the surface of the concrete. The results, which are presented in Table 1, indicate that the lightweight concrete deck appeared to be more effective in preventing infiltration of chloride to the depth of the concrete where reinforcement would be located than the normalweight concrete approach slab.

Table 1 Chloride Content Test Results – Silver Creek Overpass after 23 Years in Service (ESCSI, 2001b)

Depth	*Lightweight Concrete Bridge Deck*	*Normalweight Concrete Approach Slab*
0" to ½"	*36.7 lbs / CY*	*20.5 lbs / CY*
½" to 1"	*18.0 lbs / CY*	*18.0 lbs / CY*
1" to 1½"	*7.7 lbs / CY*	*15.7 lbs / CY*
1½" to 2"	*0.5 lbs / CY*	

Another example is the bridge crossing the Indian River at Sebastian Inlet on Route A1A in Florida. This bridge, which was constructed in 1964, utilized lightweight concrete prestressed precast girders and deck for the drop-in span of this innovative structure. The precast prestressed girders and the cast-in-place deck slabs, curbs, and parapets for the drop-in portion are structural lightweight concrete. An examination of the bridge deck after nearly 30 years in service revealed that the lightweight concrete had performed as well, if not better, than the normalweight concrete (Brown, et al, 1995).

The William Preston Lane, Jr., Memorial Bridge consists of two parallel structures that cross the upper reaches of the Chesapeake Bay in Maryland (ESCSI, 2001b). The first structure, constructed in 1952, had lightweight concrete decks on the steel girder, truss and suspension spans of the superstructure. After 23 years of service, it was found that the normalweight concrete decks, that were on precast concrete girders, had deteriorated. As a result of the good performance of the lightweight concrete decks, the normalweight concrete decks were replaced with lightweight concrete. After only 9 years in service, the new lightweight decks were found to have high chloride concentrations, but no signs of steel corrosion and deterioration. Therefore, it was suggested that the lightweight concrete may have a high tolerance for chloride (Vaysburd, 1996). An independent study of the bridge in 1975 concluded that "concrete containing porous lightweight aggregate is less susceptible to deterioration from freezing and thawing" than normalweight concrete (ESCSI, 2001a).

DESIGN ISSUES

When designing bridge members utilizing lightweight concrete, some procedures and computations must be modified to account for the different material properties of lightweight concrete. A thorough discussion of design issues for lightweight concrete can be found in several sources, including Holm and Bremner (2000). The most significant differences are related to the tensile strength and modulus of elasticity of lightweight concrete. Some of these design issues are discussed below.

CONCRETE MATERIAL PROPERTIES

Modulus of Elasticity

The modulus of elasticity of lightweight concrete is typically less than the modulus for normalweight concrete of the same strength. This parameter is an important factor in computing the composite section properties and for estimating prestress losses.

The *LRFD* and *Standard Specifications* provide an equation for estimating the modulus of elasticity which takes into account the density of concrete. While this equation accounts for the reduction in modulus for lightweight concrete, it may still over-estimate the modulus for lightweight concrete, especially for higher strengths. Other expressions have been proposed for estimating the modulus of high strength lightweight concrete (ACI 363; Kahn, et al, 2004). Consult lightweight aggregate suppliers for more information on this subject.

Tensile Strength

The tensile strength of lightweight concrete is typically less than the tensile strength of normalweight concrete. While the modulus of rupture, f_r, is generally taken as the measure of the tensile strength of normalweight concrete, the splitting tensile strength, f_{ct}, is used to characterize the tensile strength of lightweight concrete. The splitting tensile strength is also used in one of the approaches to modifying other design parameters (e.g., shear and torsion) for use with lightweight concrete. However, the commentary to Article 5.1.5 of ACI 318 (2005) clearly states that "tests for splitting tensile strength of concrete … are not intended for control of, or acceptance of, the strength of concrete in the field." For a lightweight aggregate from a given source, it is intended that appropriate values of f_{ct} be obtained in advance of design.

Shrinkage

Lightweight aggregate is less stiff than most normalweight aggregates, so it offers less resistance to shrinkage of concrete. Therefore, shrinkage of lightweight concrete is generally, but not always, slightly greater than that of normalweight concrete. The shrinkage also typically takes longer to develop for lightweight concrete. The maximum shrinkage strain may be about 15 percent greater than normalweight concrete containing a similar cement paste content (Holm and Bremner, 2000). A recent study by Lopez, et al (2005), indicated that high strength lightweight concrete (10 ksi) had significantly less shrinkage than a lower strength lightweight concrete (8 ksi) mixed using essentially the same materials.

Creep

Creep of lightweight concrete is generally equal to or slightly greater than the creep in a similar normalweight concrete. However, since the variability of creep is great for both lightweight and normalweight concrete, direct comparisons between materials should be performed where creep will be important in the design of an element (Holm and Bremner, 2000). A recent study by Lopez, et al (2005), indicated that high strength lightweight concrete (10 ksi) also had significantly less creep than a lower strength lightweight concrete (8 ksi) mixed using essentially the same materials.

The total strain (creep and shrinkage) of a high strength lightweight concrete has been compared to a normalweight concrete with similar strength and cement paste content (Lopez, et al, 2005). Results indicate that the total strains, after two years under load, in the high strength lightweight concrete were only about 75% of those in the similarly loaded normalweight high strength concrete.

BASIC DESIGN COMPUTATIONS

Flexure

Design of lightweight concrete for flexure is essentially unchanged from normalweight concrete. There are no changes in the parameters for flexural strength design or in allowable stresses for service loads. The reduced modulus of elasticity of lightweight concrete must be considered in computing transformed section properties, cambers and deflections.

Shear

The reduced tensile capacity of lightweight concrete results in reductions in the concrete contribution to shear capacity, V_c. In the AASHTO specifications, the $\sqrt{f'_c}$ term is replaced by a fraction of the splitting tensile strength, f_{ct}, or is factored by 0.75 to 0.85 for all lightweight and sand-lightweight concrete, respectively.

For interface (horizontal) shear where lightweight concrete is used, the coefficient of friction is reduced by the factor λ, which is taken as 0.75 and 0.85 for all lightweight and sand-lightweight concrete, respectively.

The *AASHTO LRFD Specifications* also provide reduced capacity reduction factors for shear and torsion for lightweight concrete. This compounds the reduction in shear strength of lightweight concrete members. It should be noted that capacity reduction factors for shear in the *Standard Specifications* and ACI 318 are not reduced for lightweight concrete.

REINFORCEMENT

The reduced tensile strength and stiffness of lightweight concrete may affect the development of reinforcement. Specification requirements related to development are discussed below.

Tension and Hook Development Lengths for Mild Reinforcement

The *LRFD Specifications* provide factors to increase the tension and hook development lengths of mild reinforcement when lightweight concrete is used.

Transfer and Development Lengths for Prestressing Strand

The *LRFD Specifications* do not provide factors to modify the transfer and development length of strand with lightweight concrete. Research has demonstrated that the transfer and development lengths for high strength lightweight concrete are essentially the same as for high strength normalweight concrete (Kahn, et al, 2004) and can be conservatively predicted using current AASHTO expressions (Ozyildirim, et al, 2004).

PRESTRESS LOSSES

The refined method for computing prestress losses in the *LRFD Specifications* does not include any specific modifications for lightweight concrete. The component of prestress loss from elastic shortening will be increased because of the reduced modulus of elasticity of lightweight concrete that will be used in the computation. When using the lump sum method for estimating time-dependent prestress losses in the *LRFD Specifications*, the tabulated losses are increased by 5 ksi for members constructed using lightweight concrete.

Recent research has shown that the refined method for estimating prestress losses in the *LRFD Specifications* was conservative when predicting prestress losses for girders made of high performance lightweight concrete (Kahn, et al, 2004).

ANCHORAGE ZONES

The *LRFD* and *Standard Specifications* require the use of a reduced capacity reduction factor for compression in anchorage zones of post-tensioned elements which are constructed using lightweight concrete.

DESIGN COMPARISONS

To demonstrate the structural benefits of using lightweight concrete, a series of preliminary designs were developed. Designs were performed using three combinations of concrete properties:

- normalweight girder and normalweight deck (NG + ND)
- normalweight girder and lightweight deck (NG + LD)
- lightweight girder and lightweight deck (LG + LD)

The procedures and assumptions used in the design computations and the results of the analyses are reported in the following.

DESIGN METHODS AND ASSUMPTIONS

The loads, limitations and procedures of the AASHTO *Standard Specifications* were used as the basis for the design computations. For this preliminary design investigation, stresses were only evaluated at midspan for transfer and service loads conditions.

The designs were performed using three depths in the PCEF family of girders: 31, 63 and 95 in., corresponding to section designations XB 3147, XB 6347 and XB 9547. The dimensions of the 63 in. girder are shown in Figure 3. All three girders have the same dimensions for the top and bottom flange and vary only in the height of the web.

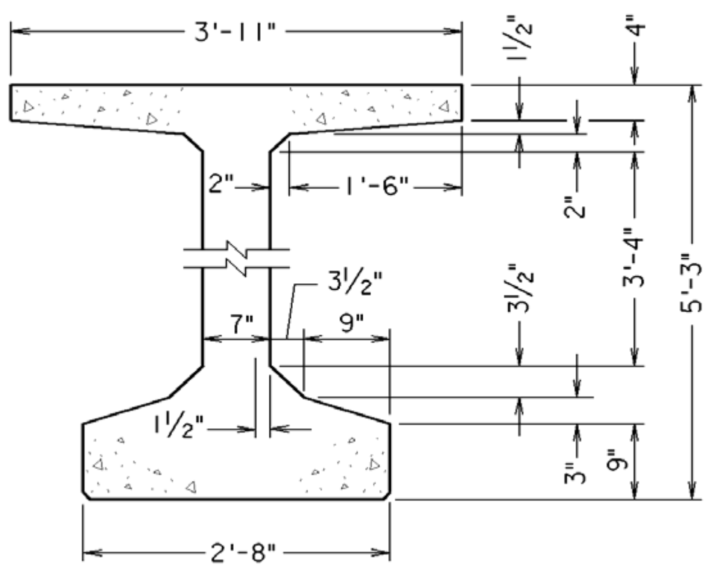


Figure 3 Section Dimensions

Designs were performed for three girder spacings: 6, 8 and 10 ft. The deck thickness was taken as 8 in. for all computations. A 1.5 in. buildup over the top flange was assumed for computing dead loads, but was neglected in computing section properties.

Preliminary design calculations were performed for the three combinations of concrete densities using two combinations of concrete strengths for the pretensioned girders:

- Normal strength design with f'_{ci} = 5.5 ksi and f'_c = 7 ksi
- High strength design with f'_{ci} = 8 ksi and f'_c = 10 ksi

Maximum spans were limited by the release strength when it governed the design.

The assumed properties of concrete and strand for the preliminary designs are summarized in Table 2. The densities shown in the table are for computing material properties and are intended to be conservative values for unreinforced concrete for the concrete strengths used. Dead loads were computed using a 5 pcf allowance for reinforcement for all types of concrete. It is possible that further reductions in density could be achieved depending upon design requirements and actual materials used.

Table 2 Assumed Concrete and Strand Properties for Preliminary Designs

Allowable tension at release	$7.5\sqrt{f'_{ci}}$
Allowable compression at release	$0.6 f'_{ci}$
Allowable tension at service load	$6\sqrt{f'_c}$
Allowable compression at service load	$0.6 f'_c$
Deck concrete strength	*4.5 ksi*
Girder concrete strength at release – Normal strength	*5.5 ksi*
Girder concrete strength at 28 days – Normal strength	*7.0 ksi*
Girder concrete strength at release – High strength	*8.0 ksi*
Girder concrete strength at 28 days – High strength	*10.0 ksi*
Deck concrete density – Normalweight	*145 pcf*
Deck concrete density – Lightweight (equilibrium)	*115 pcf*
Girder concrete density – Normalweight, Normal & High strength	*145 pcf*
Girder concrete density – Ltwt (equilibrium), Normal strength	*120 pcf*
Girder concrete density – Ltwt (equilibrium), High strength	*125 pcf*
Prestressing strand diameter	*0.6 in.*
Grade of prestressing strand	*270 ksi*

SUPERSTRUCTURE COMPARISONS USING MAXIMUM SPAN DESIGNS

Design computations were performed to determine the maximum span achievable for the design assumptions and combinations. The maximum spans achieved and the number of strands required to achieve these spans are shown in Table 3. The table is presented in two parts, one for each of the girder concrete strengths: normal and high.

Table 3 Results of Maximum Span Designs

f'_{cg} = 7 ksi		XB3147		XB6347		XB9547	
Grdr Spcg (ft)	Combination	Max Span (ft)	# Str	Max Span (ft)	# Str	Max Span (ft)	#Str
10	NG + ND	58	26	110	42	155	56
	NG + LD	59	26	114	42	160	56
	LG + LD	61	28	115	44	160	56
8	NG + ND	65	28	122	44	169	58
	NG + LD	67	28	127	46	175	60
	LG + LD	67	28	127	46	175	60
6	NG + ND	74	30	138	48	181	60
	NG + LD	76	30	144	50	186	56
	LG + LD	77	30	144	50	194	66

f'_{cg} = 10 ksi		XB3147		XB6347		XB9547	
Grdr Spcg (ft)	Combination	Max Span (ft)	# Str	Max Span (ft)	# Str	Max Span (ft)	#Str
10	NG + ND	67	40	126	66	168	72
	NG + LD	69	42	130	66	173	72
	LG + LD	69	44	128	64	172	70
8	NG + ND	75	44	139	70	181	72
	NG + LD	77	44	144	72	186	72
	LG + LD	77	46	141	68	186	72
6	NG + ND	85	46	153	70	197	72
	NG + LD	87	48	157	70	202	72
	LG + LD	87	50	156	70	203	72

The results of these maximum span designs are presented graphically in Figures 4 and 5.

The change in maximum span and number of strands for designs using the same section, girder spacing and girder concrete strength are tabulated in Table 4. The designs where both girder and deck are normalweight concrete (NG + ND) are used as the basis for computing the changes shown. The data presented in Table 4 are shown graphically in Figure 6.

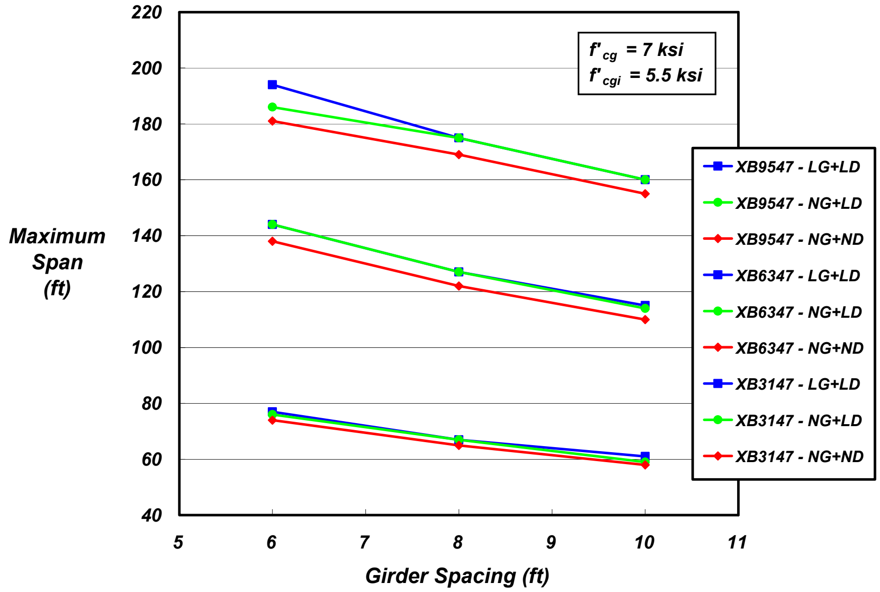


Figure 4 Results of Maximum Span Designs – f'_c = 7 ksi

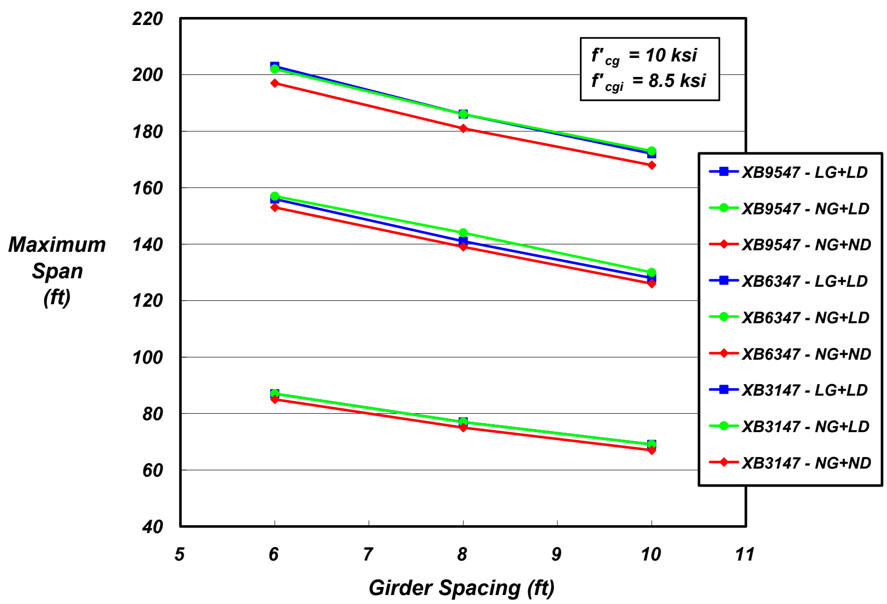


Figure 5 Results of Maximum Span Designs – f'_c = 10 ksi

From the figures and tables, it can be seen that the designs using lightweight concrete have increased maximum span lengths compared to normalweight concrete designs. The increase in maximum span is typically on the order of several feet. The tables also indicate that a slight increase in number of strands typically accompanies the increase in maximum span length with lightweight concrete girders. This is attributed to the increased prestress loss in lightweight concrete girders caused by the reduced modulus of elasticity of lightweight concrete.

Table 4 Change in Results of Maximum Span Designs from NG + ND

f'_{cg} = 7 ksi		XB3147		XB6347		XB9547	
Grdr Spcg (ft)	Combination	Max Span (ft)	# Str	Max Span (ft)	# Str	Max Span (ft)	#Str
10	NG + ND	0	0	0	0	0	0
	NG + LD	1	0	4	0	5	0
	LG + LD	3	2	5	2	5	0
8	NG + ND	0	0	0	0	0	0
	NG + LD	2	0	5	2	6	2
	LG + LD	2	0	5	2	6	2
6	NG + ND	0	0	0	0	0	0
	NG + LD	2	0	6	2	5	-4
	LG + LD	3	0	6	2	13	6

f'_{cg} = 10 ksi		XB3147		XB6347		XB9547	
Grdr Spcg (ft)	Combination	Max Span (ft)	# Str	Max Span (ft)	# Str	Max Span (ft)	#Str
10	NG + ND	0	0	0	0	0	0
	NG + LD	2	2	4	0	5	0
	LG + LD	2	4	2	-2	4	-2
8	NG + ND	0	0	0	0	0	0
	NG + LD	2	0	5	2	5	0
	LG + LD	2	2	2	-2	5	0
6	NG + ND	0	0	0	0	0	0
	NG + LD	2	2	4	0	5	0
	LG + LD	2	4	3	0	6	0

A final comparison is made between the normal and high strength concrete designs. The change in maximum span from the f'_c = 7 ksi designs to the 10 ksi designs are shown graphically in Figure 7 for each design combination in Table 4. This comparison indicates that the combination of normalweight girder and lightweight deck (NG + LD) generally benefits as much from increased concrete strength in the girder as the normalweight concrete designs. The combinations with lightweight concrete girder and deck (LG + LD) generally achieve the same or slightly less increase in span as the normalweight concrete combinations.

A similar design study using AASHTO girder shapes was performed to determine the benefits of using lightweight concrete for prestressed concrete girder bridges by Matorras (1995). The results of his study were very similar to those reported here, corroborating these conclusions.

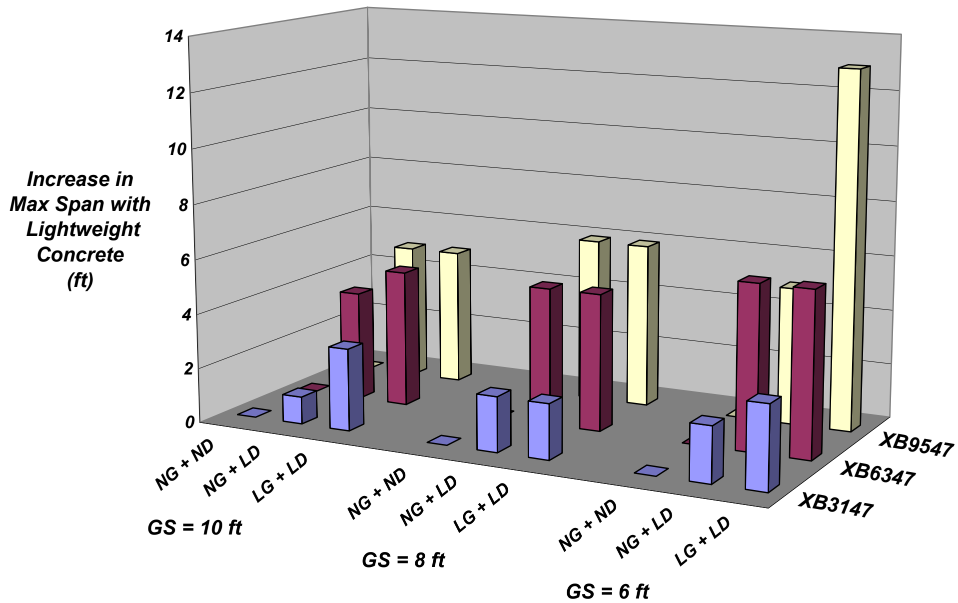


Figure 6 Change in Results of Maximum Span Designs from NG + ND

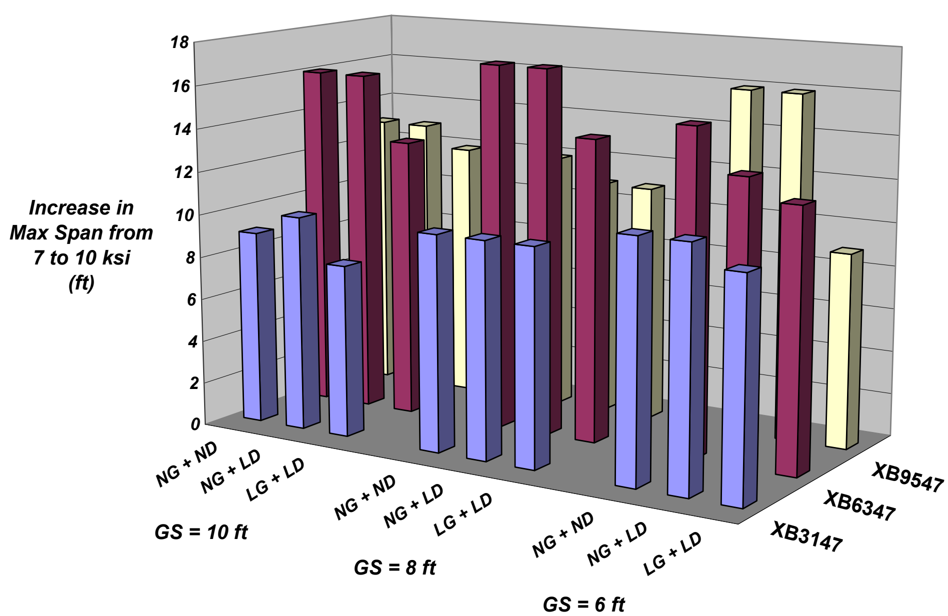


Figure 7 Change in Results of Maximum Span Designs from f'_c = 7 ksi to 10 ksi

SUPERSTRUCTURE COMPARISONS USING SAME SPAN DESIGNS

The second set of design comparisons was performed to examine the differences in the same design combinations used for the maximum span comparisons, but for a given span for each combination. The spans used were set at roughly 95% of the maximum span for the normalweight design found in the maximum span study.

For each design, the number of strands, required release strength (f'_{ci}), the girder weight and the total weight (deck and girder) were computed. The results are tabulated in Table 5. The change in tabulated items from the design using the normalweight concrete deck and girder (NG + ND) are tabulated in Table 6. The same information, but presented as a percent change from the (NG + ND) design is shown in Table 7.

From the values presented in these tables, several significant conclusions can be drawn:

- Designs with lightweight concrete decks on normalweight girders (NG + LD) allow for a reduction in the number of strands required for a design from 2 to 4. Designs with both lightweight concrete girders and deck (LG + LD) require even fewer strands for a given span. The maximum reduction for the lightweight girder and deck (LG + LD) designs is 8 strands, which represents a reduction of approximately 14% for those designs.
- Designs with lightweight concrete decks on normalweight girders (NG + LD) allow for a slight reduction in the required concrete strength at release in some cases, but no reduction in others. Designs with both lightweight concrete girders and deck (LG + LD) always allow for a reduction in the required concrete strength at release. The reduction for the lightweight girder and deck (LG + LD) designs ranges from 11 to 16%.
- As expected, there is no reduction in girder weight for the designs with lightweight concrete decks on normalweight girders (NG + LD). The weight of the girder is reduced for the lightweight girder and deck designs (LG + LD) by the ratio of the densities of the concrete, which is a 17% reduction for the 7 ksi girders and a 13% reduction for the 10 ksi girders, because of the difference in assumed densities.
- The total weight of the girder and deck are reduced for all of the designs using lightweight concrete in either deck or girders. The reduction for the designs with lightweight concrete decks on normalweight girders (NG + LD) ranges from 7 to 12% depending on girder spacing and girder size. The reduction for the lightweight girder and deck (LG + LD) designs ranges from 16 to 19%. (See the next section for additional discussion of total weights.)

While the increase in maximum spans when using lightweight concrete were not large, the reductions in numbers of strands, concrete strength at release and component weights when considering a specific design are more significant. Therefore, the evaluation of benefits of using lightweight concrete should not be limited by the results of maximum span design.

Table 5 Results of Designs Using Same Spans

f'_{cg} = 7 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)
	NG + ND		22	4.51	41.2	102.1		36	4.69	102.5	217.0		44	4.36	175.2	332.6
10	NG + LD	55	22	4.51	41.2	89.9	105	34	4.40	102.5	194.1	145	40	3.87	175.2	301.1
	LG + LD		20	4.09	34.4	83.0		32	4.16	85.4	177.0		38	3.76	146.0	271.9
	NG + ND		24	4.67	46.3	101.9		38	4.69	112.1	214.0		48	4.45	193.1	334.3
8	NG + LD	62	24	4.67	46.3	90.8	115	34	4.12	112.1	193.7	160	44	3.97	193.1	306.1
	LG + LD		22	4.28	38.6	83.1		32	3.94	93.4	175.0		42	3.91	160.9	273.9
	NG + ND		26	4.76	52.2	100.4		40	4.52	126.5	215.2		46	3.93	205.1	320.7
6	NG + LD	70	24	4.34	52.2	90.8	130	36	3.94	126.5	197.5	170	42	3.45	205.1	297.5
	LG + LD		22	4.02	43.5	82.1		34	3.84	105.5	176.4		40	3.46	170.9	263.4

f'_{cg} = 10 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)
	NG + ND		34	6.61	47.8	118.3		52	6.56	116.9	247.5		58	5.71	193.1	366.6
10	NG + LD	64	32	6.25	47.8	104.2	120	46	5.77	116.9	221.4	160	52	5.02	193.1	331.9
	LG + LD		30	5.85	41.4	97.8		46	5.78	101.3	205.8		50	4.90	167.4	306.2
	NG + ND		34	6.37	52.2	114.8		50	5.99	126.5	241.6		56	5.21	205.1	355.0
8	NG + LD	70	32	6.00	52.2	102.2	130	46	5.45	126.5	218.6	170	50	4.50	205.1	325.0
	LG + LD		30	5.64	45.2	95.3		44	5.27	109.7	201.7		48	4.44	177.7	297.7
	NG + ND		36	6.27	59.4	114.4		52	5.74	141.0	239.7		56	4.76	223.0	348.7
6	NG + LD	80	34	5.91	59.4	103.4	145	48	5.21	141.0	220.0	185	52	4.29	223.0	323.5
	LG + LD		32	5.60	51.5	95.5		46	5.09	122.2	201.2		48	4.06	193.2	293.8

Table 6 Change in Results of Designs Using Same Spans from NG + ND

f'_{cg} = 7 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
10	NG + LD	55	0	0.00	0.0	-12.2	105	-2	-0.29	0.0	-22.9	145	-4	-0.49	0.0	-31.5
	LG + LD		-2	-0.42	-6.8	-19.1		-4	-0.53	-17.1	-40.0		-6	-0.60	-29.2	-60.7
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
8	NG + LD	62	0	0.00	0.0	-11.1	115	-4	-0.57	0.0	-20.3	160	-4	-0.48	0.0	-28.2
	LG + LD		-2	-0.39	-7.7	-18.8		-6	-0.75	-18.7	-39.0		-6	-0.54	-32.2	-60.4
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
6	NG + LD	70	-2	-0.42	0.0	-9.6	130	-4	-0.58	0.0	-17.7	170	-4	-0.48	0.0	-23.2
	LG + LD		-4	-0.74	-8.7	-18.3		-6	-0.68	-21.0	-38.8		-6	-0.47	-34.2	-57.3

f'_{cg} = 10 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)	(ft)		(ksi)	(kips)	(kips)
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
10	NG + LD	64	-2	-0.36	0.0	-14.1	120	-6	-0.79	0.0	-26.1	160	-6	-0.69	0.0	-34.7
	LG + LD		-4	-0.76	-6.4	-20.5		-6	-0.78	-15.6	-41.7		-8	-0.81	-25.7	-60.4
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
8	NG + LD	70	-2	-0.37	0.0	-12.6	130	-4	-0.54	0.0	-23.0	170	-6	-0.71	0.0	-30.0
	LG + LD		-4	-0.73	-7.0	-19.5		-6	-0.72	-16.8	-39.9		-8	-0.77	-27.4	-57.3
	NG + ND		0	0.00	0	0		0	0.00	0	0		0	0.00	0	0
6	NG + LD	80	-2	-0.36	0.0	-11.0	145	-4	-0.53	0.0	-19.7	185	-4	-0.47	0.0	-25.2
	LG + LD		-4	-0.67	-7.9	-18.9		-6	-0.65	-18.8	-38.5		-8	-0.70	-29.8	-54.9

Table 7 Percent Change in Results of Designs Using Same Spans from NG + ND

f'_{cg} = 7 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)	%	%	%	%	(ft)	%	%	%	%	(ft)	%	%	%	%
10	NG + ND	55	0	0.00	0	0	105	0	0.00	0	0	145	0	0.00	0	0
	NG + LD		0%	0%	0%	-12%		-6%	-6%	0%	-11%		-9%	-11%	0%	-9%
	LG + LD		-9%	-9%	-17%	-19%		-11%	-11%	-17%	-18%		-14%	-14%	-17%	-18%
8	NG + ND	62	0	0.00	0	0	115	0	0.00	0	0	160	0	0.00	0	0
	NG + LD		0%	0%	0%	-11%		-11%	-12%	0%	-9%		-8%	-11%	0%	-8%
	LG + LD		-8%	-8%	-17%	-18%		-16%	-16%	-17%	-18%		-13%	-12%	-17%	-18%
6	NG + ND	70	0	0.00	0	0	130	0	0.00	0	0	170	0	0.00	0	0
	NG + LD		-8%	-9%	0%	-10%		-10%	-13%	0%	-8%		-9%	-12%	0%	-7%
	LG + LD		-15%	-16%	-17%	-18%		-15%	-15%	-17%	-18%		-13%	-12%	-17%	-18%

f'_{cg} = 10 ksi		XB3147					XB6347					XB9547				
Grdr Spcg	Combination	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt	Span	# Str	f'_{cgi}	Grdr Wt	Total Wt
(ft)		(ft)	%	%	%	%	(ft)	%	%	%	%	(ft)	%	%	%	%
10	NG + ND	64	0	0.00	0	0	120	0	0.00	0	0	160	0	0.00	0	0
	NG + LD		-6%	-5%	0%	-12%		-12%	-12%	0%	-11%		-10%	-12%	0%	-9%
	LG + LD		-12%	-11%	-13%	-17%		-12%	-12%	-13%	-17%		-14%	-14%	-13%	-16%
8	NG + ND	70	0	0.00	0	0	130	0	0.00	0	0	170	0	0.00	0	0
	NG + LD		-6%	-6%	0%	-11%		-8%	-9%	0%	-10%		-11%	-14%	0%	-8%
	LG + LD		-12%	-11%	-13%	-17%		-12%	-12%	-13%	-17%		-14%	-15%	-13%	-16%
6	NG + ND	80	0	0.00	0	0	145	0	0.00	0	0	185	0	0.00	0	0
	NG + LD		-6%	-6%	0%	-10%		-8%	-9%	0%	-8%		-7%	-10%	0%	-7%
	LG + LD		-11%	-11%	-13%	-16%		-12%	-11%	-13%	-16%		-14%	-15%	-13%	-16%

SUBSTRUCTURE AND BEARING COMPARISONS USING SAME SPAN DESIGNS

Frequently, comparisons between lightweight and normalweight concrete in bridges only consider the effect on the design of the superstructure. However, the reduced weight of the superstructure can have significant effects on the other elements of the bridge and should be considered when assessing the merits of the use of lightweight concrete in a bridge.

The use of lightweight concrete in the substructure and foundation elements, which is not considered here, may provide further savings, especially where precast elements are used, where substructure elements are very large or tall and therefore contribute significantly to the foundation loads, or where soil conditions are poor.

The discussion in this section demonstrates the potential for improved economy in bearings and substructures using lightweight concrete in the superstructure using the results from the superstructure comparisons for same span designs described in the preceding section.

Bearing Design

The reduced total superstructure weights for designs using lightweight concrete tabulated for the given span designs (Tables 5 through 7) indicate that the total girder reactions, and therefore the bearing loads, for designs utilizing lightweight concrete are significantly reduced from designs using normalweight concrete. Therefore, the size and cost of bearings may be reduced.

Substructure and Foundations

The use of lightweight concrete for deck and girders allows for a significant reduction in dead loads for substructure design. This is demonstrated in Table 8 for an interior bent which supports two equal simple spans of the span length used in the same span designs. A roughly 40 ft deck width was assumed, which requires the number of girders listed in the second column of the table. While the percentage reduction in foundation loads would be the same as presented in earlier tables, the absolute reduction is instructive because it provides a direct measure of the possible reduction in substructure elements, such as columns or piles.

The design of substructure elements, such as pier caps, columns and footings, would also be affected by the reduced superstructure loads by possible reductions in the size and quantity of reinforcement required. However, these reductions are less direct than the reductions in foundation elements.

As can be seen in Table 8, the greatest reduction in substructure loads is for the longest spans and the narrowest girder spacings, since these designs have the greatest quantity of superstructure to support. The maximum reduction in the total superstructure dead load when using lightweight concrete is over 400 kips for a 170 ft span. This would represent a potential reduction in several piles at each bent. Since piles supporting column footings are generally arranged in a rectangular array, the reduction in one or more piles may actually result in a larger reduction if the array can be reduced in size.

Table 8 Reduction in Reactions for Interior Bents

f'_{cg} = 7 ksi			XB3147		XB6347		XB9547	
Grdr Spcg (ft)	No. Grdrs	Combination	Span (ft)	Total Wt (kips)	Span (ft)	Total Wt (kips)	Span (ft)	Total Wt (kips)
10	4	NG + ND	55	-	105	-	145	-
		NG + LD		48.8		91.6		126.0
		LG + LD		76.4		160.0		242.8
8	5	NG + ND	62	-	115	-	160	-
		NG + LD		55.5		101.5		141.0
		LG + LD		94.0		195		302.0
6	7	NG + ND	70	-	130	-	170	-
		NG + LD		67.2		123.9		162.4
		LG + LD		128.1		271.6		401.1

f'_{cg} = 10 ksi			XB3147		XB6347		XB9547	
Grdr Spcg (ft)	No. Grdrs	Combination	Span (ft)	Total Wt (kips)	Span (ft)	Total Wt (kips)	Span (ft)	Total Wt (kips)
10	4	NG + ND	64	-	120	-	160	-
		NG + LD		56.4		104.4		138.8
		LG + LD		82.0		166.8		241.6
8	5	NG + ND	70	-	130	-	170	-
		NG + LD		63.0		115.0		150.0
		LG + LD		97.5		199.5		286.5
6	7	NG + ND	80	-	145	-	185	-
		NG + LD		77.0		137.9		176.4
		LG + LD		132.3		269.5		384.3

COST COMPARISONS

Lightweight concrete costs more than normalweight concrete because of the additional cost for processing and shipping the lightweight aggregate. There are only 20 plants producing structural lightweight aggregates in the US, as shown in Figure 8, so transportation costs can be a significant component of the cost of the lightweight aggregate. However, the benefits of using lightweight concrete can easily offset the additional cost in many cases, as demonstrated by the use of lightweight aggregate manufactured in North Carolina for long-span segmental bridges in Norway (ESCSI, 2001b).

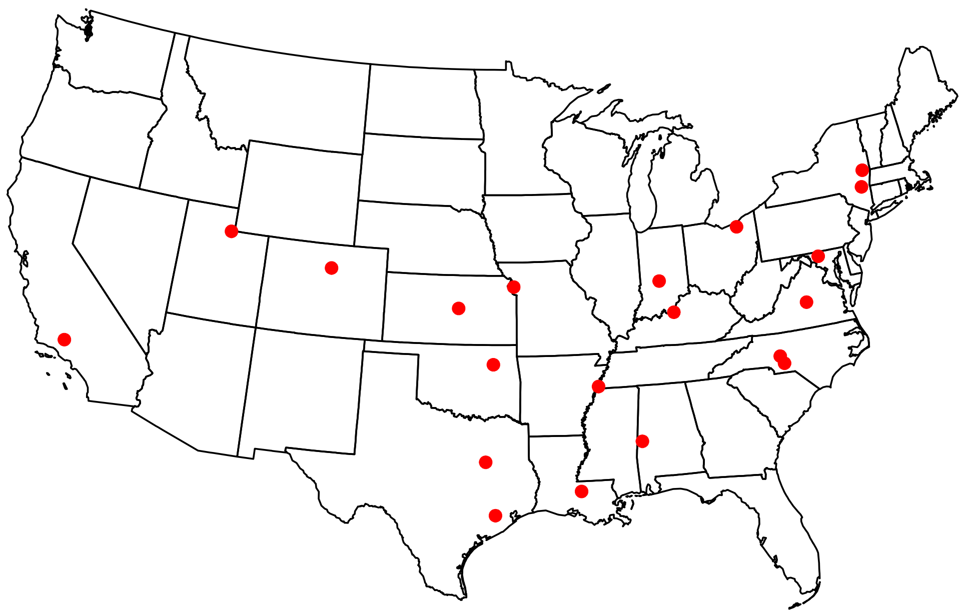


Figure 8 Lightweight Aggregate Manufacturing Plant Locations in the US

It is difficult to make a general statement regarding the cost premium for lightweight concrete compared to normalweight concrete because of the differences in the costs of lightweight and normalweight aggregates and factors related to shipping and handling of lightweight aggregate. A small group of lightweight concrete users in Texas (mostly prestressed concrete plants) were surveyed as part of a research project to obtain information on the premium cost for lightweight concrete (Silva, et al, 2002). The results of the survey indicated that the premium cost for lightweight concrete ranged from $6 to $30 per cubic yd, with an average premium cost of about $18.50 per cubic yd.

While the cost of lightweight aggregate is the major cause for the cost premium for lightweight concrete, there may be other factors that fabricators consider in determining the difference in cost. Therefore, it is suggested that both prestressed concrete fabricators and lightweight aggregate suppliers be consulted to get a more accurate estimate of the premium cost for producing lightweight concrete at a specific precast plant location and for specific project requirements.

A sample cost comparison for deck concrete is given in Table 9. This example clearly illustrates the fact that, while the cost per ton of lightweight aggregate may be several times the cost of normalweight aggregate, the increase in cost per cubic yard of concrete is much less. This reduction occurs because lightweight concrete requires approximately half the weight of lightweight aggregate per cubic yard compared to normalweight aggregate requirements for normalweight concrete, so the impact of the increased cost of aggregate is quickly reduced. The example also illustrates that the difference in cost between lightweight and normalweight concrete becomes insignificant when compared to the total cost of the project.

Table 9 Effect of Aggregate Cost on Cost of Deck Concrete (Holm and Bremner, 2000)

		LWA & LWC	NWA & NWC	Relative Cost
		A	B	A/B (%)
Cost of coarse aggregate	*\$/ton*	*45*	*10*	*450%*
Coarse aggregate for 1 yd^3 of concrete	*lb*	*900*	*1710*	*--*
Cost of coarse aggregate for 1 yd^3 of concrete	*\$/yd^3*	*20.25*	*8.50*	*238%*
Cost increase with lightweight aggregate	*\$/yd^3*	*11.75*	*--*	*--*
Typical cost of concrete delivered to project, including small increase for additional cement in lightweight concrete	*\$/yd^3*	*85*	*70*	*121%*
Cost of concrete in-place, including formwork, reinforcement, conveying, finishing and curing	*\$/yd^3*	*365*	*350*	*104%*

LWA – Lightweight aggregate; LWC – Lightweight concrete
NWA – Normalweight aggregate; NWC – Normalweight concrete

A second example of the impact of the increased cost of a lightweight concrete bridge deck on the overall cost of a project was developed by Holm and Ries (2001). They assumed a cost premium of \$30/cu yd for lightweight HPC on an 8-in. thick concrete bridge slab. One cubic yard of concrete yields approximately 40 sq ft of 8 in. thick deck, resulting in an increase in slab cost of \$30/40 sq ft = \$0.75/sq ft. For a bridge project with a total cost of \$75/sq ft, the increase in deck cost results in an increase of only one percent in the total project cost.

Both of the cost comparisons discussed above neglect any other cost reductions that may be realized in the project by using lightweight concrete in the deck. These additional cost reductions may include reduced handling and transportation costs, reduced slab reinforcement, and the reduced size and cost of girders, substructure elements and foundations because of the approximately 20% lower deck weight.

CONCLUDING REMARKS

This paper has demonstrated the many benefits of using lightweight concrete for bridges, including for prestressed concrete beams. Information is available for its use in the design of bridges and long-term performance of lightweight concrete bridges can be observed to demonstrate its excellent durability. With the current emphasis on more efficient designs and more rapid construction, designers should consider the use of lightweight concrete for bridge construction.

REFERENCES

AASHTO LRFD Bridge Design Specifications, 3rd Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2004.

ACI Committee 213, "Guide for Structural Lightweight-Aggregate Concrete (ACI 213R-03)", American Concrete Institute, Farmington Hills, MI, 2003, 38 pp. Also *ACI Manual of Concrete Practice.*

ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-03) and Commentary (ACI 318R-03)," American Concrete Institute, Farmington Hills, MI, 2003. Also *ACI Manual of Concrete Practice.*

ACI Committee 363, "State-of-the-Art Report on High-Strength Concrete (ACI 353R-92)," American Concrete Institute, Farmington Hills, MI, 1992 (Reapproved 1997), 55 pp. Also *ACI Manual of Concrete Practice.*

ASTM C 330, "Specification for Lightweight Aggregates for Structural Concrete," *Annual Book of ASTM Standards*, Vol. 04.02, American Society for Testing and Materials, West Conshohocken, PA, 2004.

ASTM C 567, "Test Method for Density of Structural Lightweight Concrete," *Annual Book of ASTM Standards*, Vol. 04.02, American Society for Testing and Materials, West Conshohocken, PA, 2004.

Bremner, T. W., and Holm, T. A., "Elastic Compatibility and the Behavior of Concrete," *ACI Journal*, V. 83, No. 2, March-April 1986, pp. 244-250.

Browder, Jamie, "Lord Delaware and Eltham Bridge Replacement Projects - Monthly Report - May 23, 2005,", http://www.virginiadot.org/quick/fredericksburg/resources/fr_current_WestPt_report.pdf, Virginia DOT, 2005

Brown, W. R., Larsen, T. J., and Holm, T. A., "Long-Term Service Performance of Lightweight Concrete Bridge Structures," International Symposium on Structural Lightweight Aggregate Concrete, Sandefjord, Norway, June 1995. *Reprint is available from ESCSI.*

Caroland, William B., Depp, David, Janssen, H. Hubert, and Spaans, Leo, "Spliced Segmental Prestressed Concrete I-Beams for Shelby Creek Bridge, PCI JOURNAL, V. 37, No. 5, September-October 1992, pp. 22-33.

Expanded Shale, Clay and Slate Institute (ESCSI), "Building Bridges and Marine Structures with Structural Lightweight Concrete," Information Sheet # 4700.3, Salt Lake City, UT, February 2001, 14 pp.

Expanded Shale, Clay and Slate Institute (ESCSI), "Back-up Statistics to Building Bridges and Marine Structures with Structural Lightweight Concrete," Information Sheet # 4700.4, Salt Lake City, UT, February 2001, 26 pp.

FHWA/RD-85/045, "Criteria for Designing Lightweight Concrete Bridges," T.Y. Lin International, August 1985, pp. 153.

Harmon, K. S., "High Performance Lightweight Concrete for Bridges – An Advanced Material," submitted for publication in the Proceedings, Advanced Materials for Construction of Bridges, Buildings and Other Structures-IV, Maui, Hawaii, 2005.

Hoff, G. C., and Elimov, R., "Concrete Production for the Hibernia Platform," Proceedings, 1995 Annual Meeting of the Canadian Society of Civil Engineers, Ottawa, Ontario, 1995.

Holm, Thomas A., "Lightweight Concrete and Aggregates," Standard Technical Publication 169C, ASTM International, 2001, pp. 522-532.

Holm, T. A., and Bremner, T. W., "State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments", ERDC/SL TR-00-3, US Army Corps of Engineers,. Engineer Research and Development Center, Structures Laboratory, Vicksburg, MS, August 2000, 103 pp. *Available on ESCSI website.*

Holm, Thomas A., and Ries, John P., "Specified Density Concrete – A Transition," Proceedings, Second International Symposium on Structural Lightweight Aggregate Concrete, " Kristiansand, Norway, June 18-22, 2000. *Reprint is available from ESCSI.*

Holm, T. A., and Ries, J. P., "Benefits of Lightweight HPC," *HPC Bridge Views*, Federal Highway Administration/National Concrete Bridge Council, Issue No. 17, September/October 2001, p.3

Jenkins, Thomas D., "Redecking and Widening of the Woodrow Wilson Bridge," Proceedings, International Symposium on Lightweight Concrete Bridges, September 10, 1996, sponsored by Caltrans and Pacific Custom Materials, Sacramento, CA, 16 pp.

Kahn, L. F., Kurtis, K. E., Lai, J. S., Meyer, K. F., Lopez, M, and Buchberg, B., "Lightweight Concrete for High Strength/High Performance Precast Prestressed Bridge Girders," Final Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, Revised November 2004, 155 pp.

Krauss, Paul D., and Rogalla, Ernest A., "Transverse Cracking in Newly Constructed Bridge Decks", NCHRP Report 380, Transportation Research Board, Washington, DC, 1996, 126 pp.

Lopez, M., Kahn, L., Kurtis, K., and Buchberg, B., "Long-Term Creep and Shrinkage in High-Strength Lightweight Concrete," ACI SP-227, American Concrete Institute, Detroit, 2005, pp. 317-336.

Lutz, James G., and Scalia, Dino J., "Deck Widening and Replacement of Woodrow Wilson Memorial Bridge," *PCI Journal*, V. 29, No. 3, May/June 1984, pp. 74-93.

Matorras, Juan Luis, "High Strength Lightweight Concrete for Prestressed Composite Bridge Girders," Masters Thesis, North Carolina State University, 1995, pp. 73.

Meyer, K. F. and Kahn, L. F., "Analytical Investigation of Lightweight Concrete for High Strength/High Performance Precast Prestressed Bridge Girders," Task 1 Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, January 2000, 27 pp.

Murillo, Juan A., Thoman, Steve, and Smith, Dennis, "Lightweight Concrete for a Segmental Bridge," *Civil Engineering-ASCE*, Vol. 64, No. 5, May 1994, pp. 68-70.

Ozyildirim, C., Cousins, T., and Gomez, J., "First Use of Lightweight High-Performance Concrete Beams in Virginia," ACI SP-218, American Concrete Institute, Detroit, 2004, pp. 1-8.

Standard Specifications for Highway Bridges, 17th Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2002.

Sylva, G.S., Breen, J. E., and Burns, N.H., "Feasibility of Utilizing High-Performance Lightweight Concrete in Pretensioned Bridge Girders and Panels," Research Report 1852-2, Center for Transportation Research, The University of Texas at Austin, January 2002, 74 pp.

Vaysburd, Alexander M., "Durability of Lightweight Concrete Bridges in Severe Environments," *Concrete International*, V. 18, No. 7, July 1996, pp. 33-38.

Walum, R., Weng, J. K., Hoff, G. C., and Nunez, R. A., "The Use of High-Strength Modified Normal Density Concrete in Offshore Structures," Proceedings, International Conference on Concrete Under Severe Conditions, Sapporo, Japan, 1995, 10 pp.