DESIGN OF PRESTRESSED CONCRETE BRIDGE MEMBERS USING LIGHTWEIGHT CONCRETE

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ABSTRACT

Lightweight concrete, with a typical density of 115 to 125 pcf, is an important design tool with many applications for precast and prestressed concrete bridge construction where reduced structure weight is beneficial.

Some designers are reluctant to use lightweight aggregate concrete because they are not familiar with the structural properties and historical performance of the material. Therefore, this paper briefly mentions the benefits of using lightweight concrete for bridges. It then discusses how the properties of lightweight concrete differ from normalweight concrete. It concludes by discussing how these differences are addressed in the AASHTO LRFD Specifications, using limited design comparisons for some quantities. Design using specified density concrete, which is not addressed in the AASHTO specifications but which can have great benefit for large precast concrete elements, is introduced and briefly discussed.

KEYWORDS: Prestressed Concrete, Lightweight Concrete, Bridges, Girders, Design, Material Properties, Specified Density Concrete, LRFD

INTRODUCTION

Lightweight concrete has been used for bridges constructed using prestressed concrete girders since prestressing was introduced in the US in the 1950s. In general, the use of lightweight concrete for bridges has been satisfactory, with some bridges providing service for over 40 years.

Some designers, when presented with the properties and advantages of using lightweight concrete for bridges, ask why lightweight concrete has not been used more frequently. There is no single answer for this question.

The objective of this paper is to supply information that will allow designers to consider using lightweight concrete to improve the structural performance of a prestressed concrete bridge while maintaining or improving its economy and enhancing its durability.

To accomplish this objective, three questions are considered that need to be answered before a designer should attempt to use lightweight concrete in a bridge. These questions are:

- Why use lightweight concrete?
- How do the properties of lightweight concrete differ from normalweight concrete?
- How are the properties of lightweight concrete addressed in the LRFD Specifications?

Each of these questions is addressed in this paper, with the main focus on the second and third questions, where details of bridge design with lightweight concrete are discussed.

This paper addresses the design of bridges, so the AASHTO LRFD Specifications[1] are the main focus of discussion. However, this paper will also refer to the design provisions found in ACI 318-05[2], the "Building Code Requirements for Structural Concrete and Commentary." The design requirements found in the ACI Building Code have been closely scrutinized by a committee of design practitioners and researchers and any changes are subject to the rigorous rules for consensus documents. Therefore, the ACI Building Code is generally taken as representing the industry consensus for design requirements for concrete structures.

OTHER RESOURCES

This paper provides a brief overview of the material properties and design issues related to using lightweight concrete for bridge design. Additional information on properties and design parameters of lightweight concrete can be found in the following references.

A major publication that provides guidance for the design of structures using lightweight concrete is the "Guide for Structural Lightweight-Aggregate Concrete" developed by ACI Committee 213[3]. 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."

ASTM has recently published Special Technical Publication 169D[4], entitled "Significance of Tests and Properties of Concrete and Concrete-Making Materials." Chapter 46 of this document addresses the properties of lightweight aggregates and lightweight concrete. It gives an excellent up-to-date overview of material properties for lightweight aggregates and concrete. The single chapter is available as a reprint from the Expanded Shale, Clay and Slate Institute (ESCSI)[5].

Another major document on lightweight concrete 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[6]. This document provides a wide array of detailed information on lightweight concrete material properties that are very useful in design.

Several other 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

Lightweight concrete is used in bridge construction for several reasons, including:

- Improved structural efficiency of superstructure
- Reduced bearing, substructure and foundation loads, where there are poor soil conditions or where seismic loads must be considered
- Reduced weight for handling of precast elements, including deck panels, girders, pier caps, columns, piles and other elements
- Enhanced durability

The authors of this paper have written another paper[7] in which the range of benefits of lightweight concrete are presented. The reader is directed to that paper for more information on benefits of using lightweight concrete in bridges, including a design comparison between lightweight and normalweight concrete used for bulb-tee girder bridges and examples of improved structural efficiency, reduced foundation loads and reduced girder weights through the use of lightweight concrete.

CHARACTERISTICS OF LIGHTWEIGHT CONCRETE

While lightweight concrete shares most of the characteristics and properties of normalweight concrete, there are some significant differences that need to be understood as a designer uses lightweight concrete in a bridge. The properties of lightweight concrete that differ from normalweight concrete are discussed in this section. The ways in which these differences are addressed in the design of bridges, including specific recommendations for design parameters, are discussed in the next section.

REDUCED DENSITY

The most obvious characteristic of lightweight concrete in which it differs from normalweight concrete is density. The reduced density is achieved by using lightweight aggregate for some or all of the aggregate in the concrete. For the great majority of bridge construction, a “sand-lightweight” mix is used which uses lightweight aggregate for the coarse aggregate and normalweight sand for the fine aggregate. For the remainder of this paper, lightweight concrete will be taken as sand-lightweight concrete, except where noted otherwise.

Lightweight aggregate is manufactured by heating shale, clay or slate in a rotary kiln where it expands by forming pores of gas within the softened aggregate. After cooling, the pores remain, creating a much lighter aggregate particle. Because lightweight aggregates are manufactured using different raw materials and processes, the properties of the aggregate and concrete produced with the aggregate may differ. The reader is referred to ACI 213[3] and other documents for more information on the materials and processes used to manufacture structural lightweight aggregates.

The density of lightweight concrete is generally specified using the equilibrium density, which can be computed or measured for a given mix design as specified in ASTM C 567[8]. As the name implies, the equilibrium density is the density of the concrete after it has come to equilibrium with the environment by losing the moisture absorbed in the aggregate. The equilibrium density is generally reached in about 90 days, although for mixes with higher cementitious contents, the loss of internal moisture will be slower. The fresh or plastic density is required for quality control when the concrete is placed and may also be specified in the contract documents. The difference between the fresh and equilibrium densities depends on the mix design and the absorption of the aggregate. Generally, the higher the absorption of the lightweight aggregate, the greater the difference between the fresh and equilibrium density.

The equilibrium density for lightweight concrete alone typically ranges from 110 to 125 pcf. Sand-lightweight concrete for bridge decks can have a density of 110 to 115 pcf, while the density for prestressed girders is generally higher, or about 120 to 125 pcf, which reflects the fact that the density of lightweight concrete usually increases with strength.

In some cases, a specified density concrete may be beneficial for addressing design or construction issues. This concrete has a density between sand-lightweight and normalweight concrete and is typically obtained by using a blend of lightweight and normalweight coarse aggregates. Using this technique, the density can be set to any value in the range. Concrete of this type has been used widely in some areas to reduce weight of large pretensioned girders to facilitate handling, shipping and erection. For concrete with 50 percent or less replacement of normalweight coarse aggregates with lightweight aggregates, it has been found that many material properties (except modulus of elasticity) are minimally or not reduced by the addition of lightweight aggregate[9]. See Bremner, et al.[10] and Holm and Ries[11] for more information on specified density concrete.

COMPRESSIVE STRENGTH

Since lightweight aggregate particles contain many small pores, the compressive strength of the aggregate, and consequently the compressive strength of the concrete, is reduced compared to a normalweight concrete with the same cement content. However, lightweight concrete with design compressive strengths up to 10 ksi can be produced with proper mix design for several of the types of lightweight aggregate available. Researchers at Georgia Tech have demonstrated that 10 ksi concrete with an equilibrium density of approximately 120 pcf can be produced using expanded slate aggregate[12].

The relationship between density and strength is not unique, so some variation in combinations of density and strength is possible. However, some combinations will be easier to achieve on a production basis than others. As with all types of aggregate, each lightweight aggregate has a “strength ceiling” which means that there is a limit to the compressive strength that can be achieved with a reasonable quantity of cementitious material.

TENSILE STRENGTH

The tensile strength of lightweight concrete is typically less than the tensile strength of normalweight concrete. The potentially reduced tensile strength of lightweight concrete affects structural properties that are related to tensile strength, such as cracking, shear and development of reinforcement.

The modulus of rupture, f_r, is generally taken as the measure of the tensile strength of normalweight concrete with the same compressive strength. However, the splitting tensile strength, f_{ct}, is used to characterize the tensile strength of lightweight concrete. The splitting tensile strength is generally recognized as providing a more realistic and reliable indication of the tensile strength of concrete. If a minimum splitting tensile strength is specified in the contract documents, it can be used as the basis for the modification of design parameters (e.g., shear and torsion) for use with lightweight concrete. The modification factor is discussed in the next section.

AGGREGATE BOND STRENGTH

Although individual lightweight aggregate particle are not as strong as typical normalweight aggregate particles, the strength of the bond between the aggregate and the paste is improved in lightweight concrete. The improvement in bond strength is attributed to the coarse texture and somewhat pozzolanic nature of the surface of the aggregate particles. In some cases, this characteristic may result in the tensile strength of lightweight concrete approaching the tensile strength of normalweight concrete with the same compressive strength.

The improved bond strength between lightweight aggregate and the paste combined with the reduced tensile strength of lightweight aggregate tends to cause cracks in lightweight concrete to be smooth. The cracks are typically smooth because they propagate through the aggregate particles rather than around them. In normalweight concrete, where the aggregate particles are stronger than the paste and the bond between the paste and aggregate are relatively weak, cracks tend to be rougher because they generally propagate around the aggregates, except in high-strength concrete.

STIFFNESS

Since lightweight aggregate particles contain internal pores, the aggregate is typically less stiff than normalweight aggregates. The stiffness of the lightweight aggregate is therefore closer to the stiffness of the paste. The more uniform stiffness of the components of lightweight concrete, which has been called "elastic compatibility"[13], reduces stress concentrations that occur at the surface of normalweight aggregate particles, which can lead to microcracking, increased permeability, and decreased durability.

The reduced stiffness of lightweight aggregate results in a reduced modulus of elasticity for lightweight concrete. ACI 213[3] indicates that the modulus of elasticity of lightweight concrete generally varies between 50 and 75 percent of the modulus of a normalweight concrete of the same compressive strength. The lower end of this range represents all-lightweight mixes which are not usually used for bridge construction. It should be noted that in some areas normalweight concrete may have only slightly greater modulus of elasticity than lightweight concrete with the same strength because of the low stiffness of the normalweight aggregate.

CREEP

Creep of lightweight concrete is generally somewhat greater than the creep in a similar normalweight concrete. ACI 213[3] indicates that creep is reduced for sand-lightweight concrete compared to all-lightweight concrete, and that creep is significantly reduced for lightweight concrete as compressive strength increases. The second statement was corroborated in a recent study by Lopez, et al.[14], which found that high strength lightweight concrete (10 ksi) had significantly less creep than a lower strength lightweight concrete (8 ksi) mixed using essentially the same materials. Since the variability of creep is significant for both lightweight and normalweight concrete, creep tests should be performed where creep will be important in the design of an element[6].

SHRINKAGE

Since lightweight aggregate is less stiff than normalweight aggregate, it has been generally assumed that it offers less resistance to shrinkage of the cement paste, resulting in greater shrinkage for lightweight concrete. For normal strength concrete, this has generally been the case. Shrinkage also typically takes longer to develop for lightweight concrete than for normalweight concrete. The maximum shrinkage strain may be about 15 percent greater than normalweight concrete with a similar cement paste content[6].

However, it has also been found that higher strength lightweight concrete may have less shrinkage than normalweight concrete with the same compressive strength[3,14]. This surprising finding is apparently the result of reducing autogenous shrinkage by the release of absorbed moisture from the lightweight aggregate to the concrete, which maintains the internal relative humidity at a sufficiently high level to prevent self-desiccation, the source of autogenous shrinkage. This beneficial effect of lightweight aggregate on shrinkage is related to internal curing which is discussed further below.

INTERNAL CURING

Water absorbed into the near surface pores of lightweight aggregate provides a source of moisture within the concrete which allows the continued hydration of cementitious materials within concrete. This phenomenon is called “internal curing” and is especially significant for high performance concrete which has low permeability that for all practical purposes prevents externally applied curing moisture from reaching the interior of a concrete section. In high performance concrete, the cementitious materials in the interior of an element may not fully hydrate, which can limit the strength and other properties of the concrete. Internal curing provided by lightweight concrete is very beneficial for deck concrete where proper curing in field conditions may be difficult to achieve consistently. See Bremner, et al. [10] and the recently published ESCSI publication[15] for more information on internal curing.

Internal curing occurs in lightweight concrete and in normalweight concrete mixtures in which a small portion of the coarse or fine normalweight aggregate has been replaced with lightweight aggregate. It has been found that the use of a relatively small quantity of lightweight aggregate will not appreciably change the mechanical properties of the concrete other than the modulus of elasticity[9]. In some cases, the introduction of a limited quantity of lightweight aggregate can also improve the combined aggregate grading, enhancing the fresh as well as hardened properties of the concrete.

DURABILITY

The improved bond between lightweight aggregate particles and the paste, the lower stiffness of the lightweight aggregate (which reduces stress concentrations), and the more uniform stiffness of lightweight concrete (elastic compatibility) tend to reduce micro-cracking of concrete. This enhances the durability of lightweight concrete by providing greater resistance to the penetration into the concrete of the materials required to initiate corrosion.

While some think that the increased porosity of lightweight aggregate would result in less durable concrete, the excellent performance of properly proportioned and installed lightweight concrete has been demonstrated on many bridges and other structures. Examples include the lightweight concrete upper deck on the San Francisco-Oakland Bay Bridge which was installed when the bridge was built in 1936, the precast concrete girders in the Coronado Bridge in San Diego which was completed in 1969, as well as surviving concrete ships constructed in both World War I and II[16,17].

COST

Lightweight aggregate costs more than normalweight aggregate because of the additional processing required to manufacture the aggregate. Because of the limited number of plants manufacturing lightweight aggregate, there is also generally a significant cost because of the greater distance that it must be shipped. The cost premium depends on the increased cost of the lightweight aggregate, transportation costs, and the delivered cost of normalweight aggregates. If a concrete supplier or contractor is not familiar with using lightweight concrete, additional costs may be introduced. In most cases, the total cost premium for a cubic yard of lightweight concrete ranges from around $20 to more than $30.

ADDRESSING THE CHARACTERISTICS OF LIGHTWEIGHT CONCRETE IN DESIGN

The ways in which the different characteristics of lightweight concrete are addressed in the design of prestressed concrete bridge girders are discussed in this section. The following issues, which represent the most significant issues that must be considered in the design of prestressed lightweight concrete girders, are discussed:

- Compressive strength
- Density
- Modulus of elasticity
- Tensile strength
- Shear
- Development of reinforcement
- Strength limit state
- Prestress losses
- Cost
- Specifying lightweight concrete

Several of the issues listed have subheadings where specific details of design are discussed.

COMPARATIVE DESIGNS

A series of preliminary girder designs were performed for several simple span Type II and PCI BT-72 prestressed lightweight concrete girders with lightweight concrete decks to obtain a limited number of design results for this paper. Where appropriate, results from these designs are included in the discussion of the following issues.

To demonstrate the effects of using lightweight concrete in bridges with prestressed concrete girders, a series of simple span designs were performed using AASHTO Type II and PCI BT-72 girders. An 8 in. thick deck with a compressive strength of 4.5 ksi is used for both lightweight and normalweight concrete designs. The compressive strength of the girder concrete was varied as required for the design. For the normalweight concrete designs, the density was taken as 145 pcf for both the girder and deck. For the lightweight concrete designs, the density of the deck concrete was taken as 115 pcf and the density of the girder concrete was taken as 120 pcf. Design was performed according to the AASHTO Standard Specifications, 17th edition[18], using a spreadsheet.

Designs were obtained for normalweight concrete (NWC) and lightweight concrete (LWC) using the same span and girder spacing. The girder spacings were selected to give a practical range for the PCI BT-72 designs, and the span was selected to be near the maximum span for the normalweight concrete design. The concrete strength and number of strands were selected by design requirements, which generally resulted in lower compressive strengths and a decreased number of strands for the lightweight concrete designs. A second lightweight concrete design for the PCI BT-72 with a girder spacing of 10.5 ft (indicated by shaded cells in the tables) was performed using the same concrete strengths and number of strands that were used for the normalweight concrete design.

Basic parameters of the designs are presented in Table 1.

Table 1 Basic Parameters for Comparative Designs

	Girder Spacing (ft)	Span (ft)	Girder				Strands		
			f'_{ci} (ksi)		f'_c (ksi)		Size (in.)	No. of Strands	
			NWC	LWC	NWC	LWC		NWC	LWC
AASHTO Type II	7.5	58	5.5	5.0	6.5	6.5	0.5	24	22
PCI BT-72	5.5	135	5.0	4.5	7.0	7.0	0.6	32	28
PCI BT-72	8.5	122	6.0	6.0	7.0	7.0	0.6	36	32
PCI BT-72	10.5	118	7.5	6.5	8.5	7.5	0.6	44	38
PCI BT-72	10.5	118	7.5	7.5	8.5	8.5	0.6	44	44
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design									

Other results from this group of designs are discussed in sections that follow.

COMPRESSIVE STRENGTH

Design compressive strengths for lightweight concrete in the “normal” range, from 4 to 6 ksi, are generally achievable with any structural lightweight aggregate. Lightweight aggregates from a number of sources are capable of achieving a design compressive strength of 8 ksi. However, the number of lightweight aggregates capable of producing a design compressive strength of 10 ksi is limited. Therefore, where higher compressive strengths are necessary, prestress fabricators and lightweight aggregate suppliers should be consulted to obtain an achievable compressive strength and the associated cost. In situations where the required compressive strength may not be achievable using the closest source of aggregate, a higher strength source may be used, but at an increased cost.

DENSITY

Designers of lightweight concrete bridge structures generally specify a sand-lightweight mixture with an equilibrium density of 115 pcf for decks (4 to 5 ksi), 120 pcf for 6 and 8 ksi concrete, and 125 pcf for 10 ksi concrete. Table 3.5.1-1 in the AASHTO LRFD Specifications gives a density of 110 pcf for lightweight concrete, 120 pcf for sand-lightweight concrete, 145 pcf for normalweight concrete up to 5 ksi, and an expression for computing the density for compressive strengths exceeding 5 ksi. It is recommended that the designer check with lightweight aggregate suppliers to obtain an estimate of the density corresponding to the specified compressive strength. In some cases, a density lower than those listed above can be achieved while maintaining the specified compressive strength. The equilibrium densities listed above are used for computing the dead load of the structure in its final condition, after adding an allowance for the weight of reinforcement (usually taken as 5 pcf).

The designer should also specify the fresh density for lightweight concrete, which will be used for quality control during concrete placement and for computing handling loads before the concrete has lost its excess moisture. For normal strength lightweight concrete mixes, the difference between fresh and equilibrium densities is roughly 5 pcf, but for higher strength lightweight concrete made with low absorption aggregate, the difference may be smaller. The lightweight aggregate supplier should be consulted to obtain a fresh concrete density that corresponds to the equilibrium concrete densities. A simplified and conservative approach is to specify the fresh density and use it for computing the dead loads at all construction stages, neglecting the reduction in weight that occurs as the lightweight concrete dries.

Where concrete with an intermediate density is desired, i.e., a specified density concrete, any density can be specified between sand-lightweight and normalweight densities. A blend of equal volumes of lightweight and normalweight coarse aggregates will typically yield a density around 135 pcf.

Several issues regarding specifying the density of lightweight concrete are discussed in a later section.

MODULUS OF ELASTICITY

The modulus of elasticity of lightweight concrete is typically lower than a normalweight concrete mix with the same compressive strength. This reduction is included in the equation for modulus of elasticity, E_c, given in the AASHTO LRFD Specifications:

$$E_c = 33{,}000\ K_1\ w_c^{1.5}\ \sqrt{f'_c} \quad \text{[ksi]} \qquad \text{(LRFD Eq. 5.4.2.4-1)}$$

where:

K_1 = correction factor for source of aggregate to be taken as 1.0 unless determined by physical test, and as approved by the authority of jurisdiction

w_c = unit weight of concrete (kcf)

f'_c = specified compressive strength of concrete (ksi)

ACI 213[3] recommends the use of this equation (as it appears in ACI 318[2] with $K_1 = 1.0$) for densities of concrete between 90 and 155 pcf and for strength levels up to 5,000 psi.

The above equation tends to overestimate the modulus for lightweight concrete, especially for higher compressive strengths. It is possible to adjust this equation for lightweight concrete by using an experimentally determined value for the coefficient K_1. However, such coefficients are not generally available. Therefore, it is suggested that the following equation, found in the ACI Committee 363 Report[19] and modified for use with lightweight concrete, be used:

$$E_c = (40{,}000\ \sqrt{f'_c} + 1{,}000{,}000)(w_c/145)^{1.5} \quad \text{[psi]}$$

where:

w_c = unit weight of concrete (pcf)

f'_c = specified compressive strength of concrete (psi)

Using either of the above equations for a given concrete strength, the ratio between the computed modulus for lightweight concrete and normalweight concrete is independent of the concrete strength, f'_c, varying only with the density of the concrete (w_c). The reduction in E_c, computed using either of the above equations for a given concrete strength as the density changes, is shown in Figure 1. The data in this figure indicate that lightweight concrete (110 to 120 pcf) can be expected to have a modulus of elasticity of 70 to 80% of the value for normalweight concrete with the same compressive strength. It is important to note that the modulus of elasticity for normalweight concrete is in fact widely variable and may not conform to the values computed by equations.

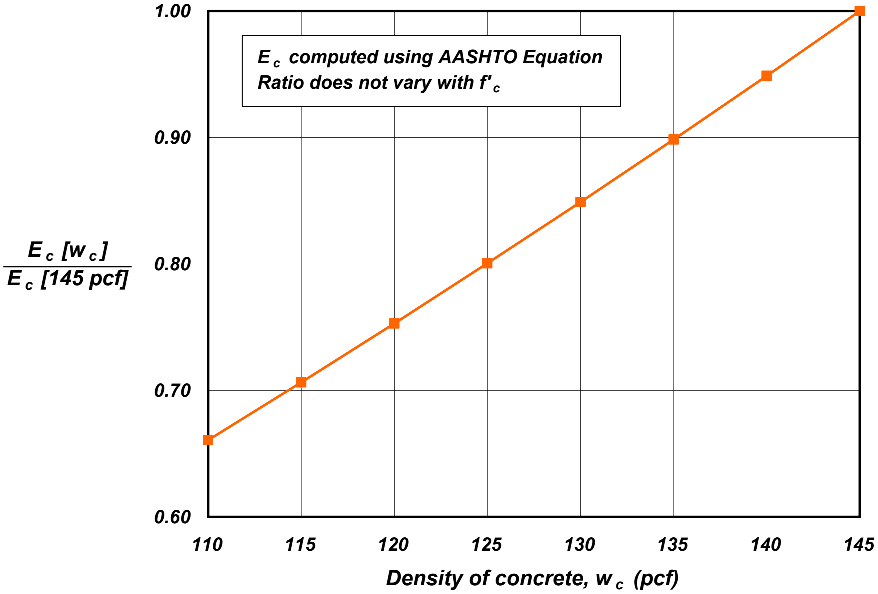

Figure 1 Variation in Modulus of Elasticity with Density of Concrete

To get a feel for the expected variation in modulus of elasticity values for lightweight and normalweight concrete, values computed using both the AASHTO LRFD and modified ACI 363 equations are shown in Figure 2 for 6 and 10 ksi concrete. This figure shows that the difference between the equations increases with increasing concrete strength.

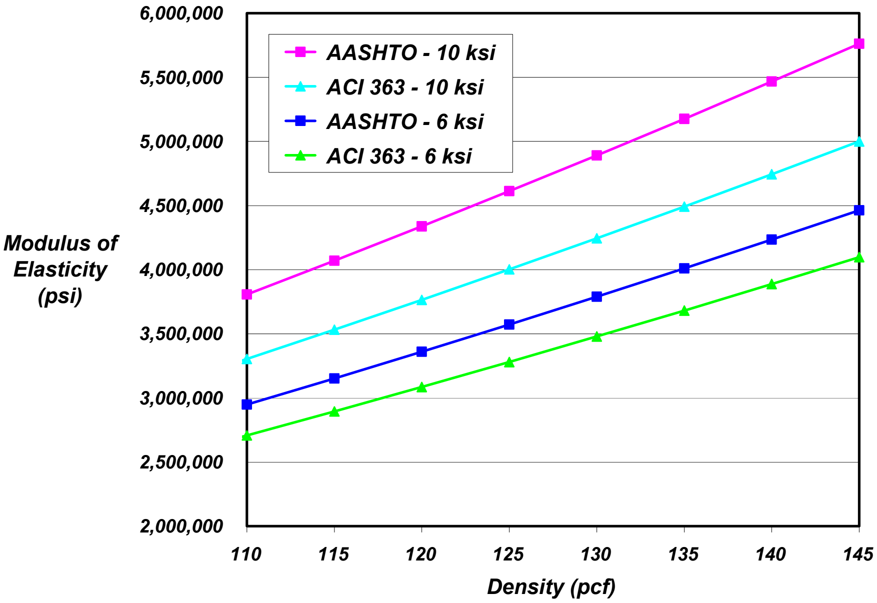

Figure 2 Variation in Modulus of Elasticity with Density of Concrete and Concrete Strength – AASHTO and ACI 363 Equations

The ratio between modulus of elasticity values computed by the two equations for any given density and a range of concrete strengths is shown in Figure 3. This indicates that for higher strength concrete, the reduction in modulus of elasticity using the ACI 363 equation instead of the AASHTO equation will be significant (over 15% at $f'_c = 12$ ksi), while for normal strength concrete, the difference is minor.

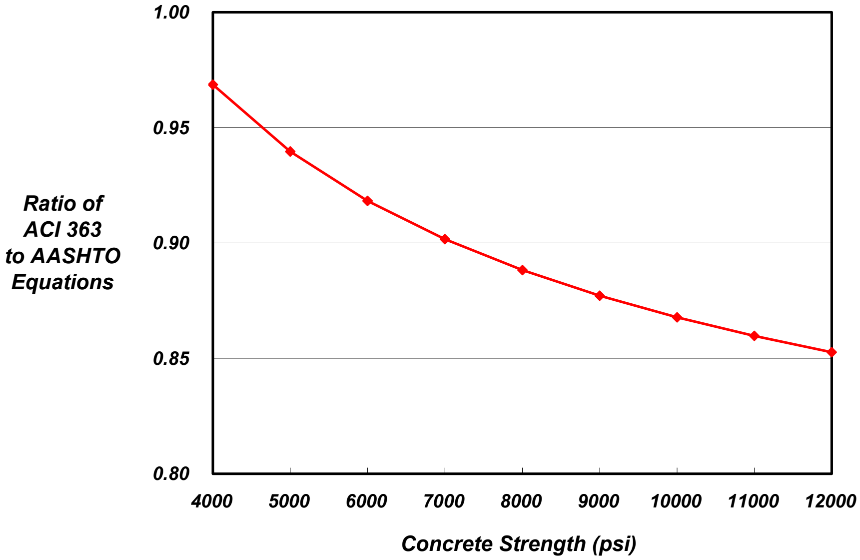

Figure 3 **Ratio of Modulus of Elasticity Computed with AASHTO and ACI 363 Equations**

New approaches to obtain more accurate estimates of the modulus of elasticity for lightweight and normalweight concrete at all levels of compressive strength are currently being considered by several researchers, but the issue does not appear to have an easy solution. Therefore, if an accurate estimate of modulus of elasticity is critical for the performance or construction of the structure, measurements of modulus of elasticity should be taken using concrete with the same materials that will be used in production. Where critical, the modulus of elasticity can be specified. It has been found that the modulus of elasticity is sensitive to mix components. For example, changing the source of sand used in the mixture may make a significant difference in the modulus.

The reduced modulus of elasticity for lightweight concrete has a significant impact on three major design parameters: the elastic shortening component of prestress loss; the modular ratio between the girder and deck; and the camber and deflection of prestressed girders. Each of these parameters is discussed below.

Elastic Shortening

It is recommended that the modulus of elasticity for lightweight concrete be computed using the modified ACI 363 equation for use in the equation for elastic shortening loss.

The reduced modulus of elasticity of lightweight concrete will increase the prestress loss from elastic shortening. While the prestress loss will be greater for lightweight concrete (about 33% for 120 pcf concrete, neglecting the possible reduction in loss because fewer strands may be required), the change in effective prestress will not be as great because the loss is subtracted from the initial prestress. For example, if the elastic shortening loss is 15% for normalweight concrete, the loss may be increased by a third to 20% for 120 pcf lightweight concrete. However, for the normalweight design, the remaining prestress would be 85% of the initial prestress, while the remaining prestress would be 80% for the lightweight concrete design, or a reduction in effective prestress of 5/85 or about 6%. While this is a noticeable change, it will be offset to some degree by the reduced dead load of the structure which will require less prestress force.

See the discussion of prestress losses later in this section for comparisons of prestress losses, including elastic shortening, for the group of comparative designs.

Modular Ratio between Girder and Deck

The modular ratio between the girder and deck will be affected by the use of lightweight concrete. Where a lightweight concrete deck is used on a lightweight girder, the effect will be small. In any case, the design should be modified to use the modulus of elasticity for lightweight concrete as appropriate.

Camber and Deflection

It is difficult to make a general statement regarding the effect of the reduced modulus of elasticity of lightweight concrete on cambers and deflections because of the complex interaction of several factors.

Cambers and deflections computed for the comparative designs are shown in Tables 2 and 3 for normalweight and lightweight concrete designs for four conditions: net camber at release (girder only); net camber at erection (girder only, using the PCI multipliers[20] at erection); final condition with all dead loads (using the PCI multipliers at erection only); and estimated live load deflection. For each quantity, the percent change in the quantity for the lightweight concrete design is indicated relative to the normalweight concrete design. Positive deflection values indicate upward camber.

From the information presented in these tables, it is clear that lightweight concrete designs will have greater cambers and deflections. This should be accommodated in the design by using a deeper build-up or haunch. No clear trends in the cambers or deflections are evident which is probably due to the limited number of designs and the complex interaction of a number of variables.

Table 2 Net Camber at Release and Erection for NWC and LWC Designs

	Girder	Net Camber at Release (in.)			Net Camber at Erection (in.)		
	Spcg (ft)	NWC	LWC	% Chng.	NWC	LWC	% Chng.
AASHTO Type II	7.5	1.190	1.767	+48%	2.213	3.302	+49%
PCI BT-72	5.5	2.078	2.689	+29%	3.672	4.787	+30%
PCI BT-72	8.5	2.594	3.407	+31%	4.760	6.286	+32%
PCI BT-72	10.5	2.559	3.739	+46%	4.730	6.947	+47%
PCI BT-72	10.5	2.559	3.495	+37%	4.730	6.494	+37%
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

Table 3 Full Dead Load and Live Load Deflections for NWC and LWC Designs

	Girder	Final, with all Dead Loads (in.)			Live Load Deflection (in.)		
	Spcg (ft)	NWC	LWC	% Chng.	NWC	LWC	% Chng.
AASHTO Type II	7.5	1.285	2.297	+79%	-0.632	-0.843	+33%
PCI BT-72	5.5	1.574	2.482	+58%	-0.988	-1.327	+34%
PCI BT-72	8.5	2.714	4.052	+49%	-0.992	-1.331	+34%
PCI BT-72	10.5	2.738	4.634	+69%	-0.972	-1.375	+41%
PCI BT-72	10.5	2.738	4.318	+58%	-0.972	-1.304	+34%
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

The comparison between the two PCI BT-72 designs for a girder spacing of 10.5 ft yielded some interesting results. The girder design that was optimized for lightweight concrete by using a decreased concrete strength and number of strands (see Table 1 for basic details of the designs) had greater camber and deflection than the lightweight concrete design that used the same concrete strength and number of strands as the normalweight concrete design. Initially, it would appear reasonable that the design with more strands would have greater camber. However, the opposite was true, apparently because the modulus of elasticity was lower because the concrete strength at transfer was lower for the first design (with fewer strands).

TENSILE STRENGTH

The tensile strength of concrete is generally not a significant issue in the design of pretensioned bridge girders. The related of issues of shear and development length are considered separately in later sections. Design issues directly related to tensile strength will be considered briefly in this section.

Splitting Tensile Strength

The splitting tensile strength, f_{ct}, may be specified in the contract documents so that it can be used as the basis for computing the resistance modification factor for lightweight concrete for the concrete contribution to shear (see LRFD Article 5.8.2.2) and other quantities, which are discussed later in this section. If the lightweight aggregate source is known, a value for f_{ct} can be obtained from the lightweight aggregate supplier and used in design to compute the resistance modification factor. However, since the source of lightweight aggregate is not generally known during design, the splitting tensile strength is not usually specified and the modification factors based on the type of lightweight concrete mix (sand-lightweight or all-lightweight) are used instead. The use of a specified value for the splitting tensile strength of lightweight concrete will generally result in a larger resistance modification factor compared to the factors based on the type of lightweight concrete mix.

If the splitting tensile strength is specified in the contract documents, it should only be used for design purposes and not for field acceptance of the lightweight concrete. This requirement does not appear in the LRFD Specifications. However, the commentary to Article 5.1.5 of ACI 318-05 clearly states "tests for splitting tensile strength of concrete … are not intended for control of, or acceptance of, the strength of concrete in the field."

Modulus of Rupture

The AASHTO LRFD Specifications give expressions for the modulus of rupture for normalweight concrete and for sand- and all-lightweight concrete in Article 5.4.2.6. The expressions for sand- and all-lightweight concrete reflect a reduction of 83% and 71%, respectively, from the lower bound normalweight concrete expression.

The Specifications give an upper bound modulus of rupture for normalweight concrete, which is slightly more than 1.5 times the lower bound value. This increased tensile strength is to be used for computing the cracking moment for minimum reinforcement requirements. Upper bound values are not given for lightweight concrete, but a factor of 1.5 could reasonably be applied to the expressions given for lightweight concrete to obtain upper bound values.

Limiting Tensile Stresses

Limiting tensile stresses for service limit state design are given in Article 5.9.4 of the LRFD Specifications. No modification of these stresses is required for lightweight concrete.

Anchorage Zones of Pretensioned Members

LRFD Article 5.10.10 does not require any adjustment for the design of bursting reinforcement at the ends (anchorage zones) of lightweight concrete pretensioned girders. The designer should consider the possible effect of the reduced tensile strength of lightweight concrete on the potential splitting at the ends of pretensioned girders.

Anchorage Zones of Post-Tensioned Members

The use of lightweight concrete in post-tensioned anchorage zones is indirectly addressed by the introduction of a capacity reduction factor for lightweight concrete in LRFD Article 5.5.4.2.1. However, in the authors' opinion, the correction for lightweight concrete can be made more directly and consistently by using the resistance modification factor, λ, that is used for shear, when computing the anchorage zone capacity in LRFD Article 5.10.9.3.1 (third paragraph). This approach is taken in ACI 318 Article 18.13.4, where no separate capacity reduction factor is given for anchorages in lightweight concrete, but the same λ factor is applied to the limiting compressive stress behind the anchorage that is used for the reduction of the $\sqrt{f'_c}$ terms for shear. The commentary to ACI 318 Article 18.13.4 states that "the inclusion of the λ factor for lightweight concrete reflects its lower tensile strength, which is an indirect factor in limiting compressive stresses, as well as the wide scatter and brittleness exhibited in some lightweight concrete anchorage zone tests."

SHEAR

Shear Resistance

Since the strength of lightweight aggregate is closer to the strength of the paste, shear cracks tend to be smooth, lacking the aggregate interlock contribution to shear transfer across the crack. This type of smooth crack is similar to the shear cracks observed for high strength normalweight concrete. Therefore, the concrete contribution to shear, V_c, has been reduced for lightweight concrete members.

The reduction is accomplished by modifying the $\sqrt{f'_c}$ terms that appear in equations for V_c, using factors specified in LRFD Article 5.8.2.2. If the splitting tensile strength, f_{ct}, is specified, then the shear resistance equations are modified by replacing $\sqrt{f'_c}$ with the factor $4.7f_{ct}$, where $4.7f_{ct} \leq \sqrt{f'_c}$. If f_{ct} is not specified, the $\sqrt{f'_c}$ term is multiplied by 0.75 for all-lightweight concrete and 0.85 for sand-lightweight concrete, with linear interpolation permitted between these values for partial sand replacement. The reduction factor is taken as 1.0 for normalweight concrete. This approach of using resistance modification factors for shear design of lightweight concrete has been in the AASHTO specifications for many years. For design, where the source of lightweight aggregate may not be known and hence, f_{ct} is not specified, the reduction factors are generally used. Sand-lightweight concrete will almost always be used for bridge construction, so a reduction factor of 0.85 is typically used.

The LRFD Specifications give no guidance for a reduction factor to be used with specified density concrete. It appears reasonable to use linear interpolation between sand-lightweight and normalweight concrete. However, since the Specifications give no guidance, it is suggested that the resistance modification factor for sand-lightweight concrete may be used conservatively. ACI Committee 318 is currently reviewing proposals to revise provisions related to lightweight concrete in the Building Code[2]. These proposals include an allowed interpolation for the resistance modification factor for specified density concrete. It is expected that any changes approved by ACI will be proposed to AASHTO for inclusion in the LRFD Specifications.

While V_c is reduced by the resistance modification factors described above for bridge girders constructed with lightweight concrete, it should be remembered that the dead load portion of the factored shear V_u will also be significantly reduced so the required shear capacity is smaller. Because of the many factors involved, a general statement cannot be made regarding the combined effect of the reduced shear capacity and reduced load.

The effect of using lightweight concrete on shear design is demonstrated in Tables 4 through 6 for the group of comparative designs mentioned earlier in this paper. The reduction in dead load shear and the corresponding reduction in total factored shear, V_u, are shown in Table 4 for the different designs. The reductions in the dead load shear and factored shear, V_u, for the lightweight concrete designs is significant, compared to the normalweight concrete designs. There is no effect of concrete density on the live load shear, as expected.

Table 4 Total Unfactored and Factored Design Shears using Standard Specifications

	Girder Spcg (ft)	$V_{Dead\ Load}$ (kips)		$V_{Live\ Load}$ (kips)		V_u (kips)	
		NWC	LWC	NWC	LWC	NWC	LWC
AASHTO Type II	7.5	37.5	31.4	50.5	50.5	158.1	150.2
PCI BT-72	5.5	102.3	85.6	39.6	39.6	218.8	197.1
PCI BT-72	8.5	113.3	94.7	60.0	60.0	277.3	253.0
PCI BT-72	10.5	124.7	104.3	74.0	74.0	322.4	295.9
PCI BT-72	10.5	124.7	104.3	74.0	74.0	322.4	295.9
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

Several of the design parameters used in shear design are compared in Table 5. Differences in the effective depth, d_p, and the vertical component of the prestress force, V_p, between normalweight and lightweight concrete designs are due to changes in the number and pattern of the strands. Differences between the normalweight and lightweight concrete designs for the quantity f_{pc}, which is a function of the self-weight of the girder, the effective prestress force immediately after transfer and its eccentricity, are surprisingly large.

These results are carried to their conclusion in Table 6, where the required nominal shear strength, the concrete contribution and the required area of shear reinforcement are given. For this comparison, the shear design was only considered at the critical section, where V_{cw} governs. Therefore, only V_{cw} is listed in the table. The reduction in shear capacity V_{cw} for the lightweight concrete designs is significant, with a difference of nearly 40% indicated in one case (the Type II girder design). The required steel contribution to shear, $V_{s\ req'd}$, varies significantly, with the requirement doubled for one case, but nearly the same for another case. Therefore, it is not possible to make any general statement about the effect of using lightweight concrete on the design of pretensioned girders for shear from this limited sample of designs.

Table 5 Selected Parameters for Shear Design using Standard Specifications

	Girder Spcg (ft)	d_p (in.)		f_{pc} (ksi)		V_p (kips)	
		NWC	LWC	NWC	LWC	NWC	LWC
AASHTO Type II	7.5	35.0	37.4	1.021	0.378	13.0	4.6
PCI BT-72	5.5	63.8	63.8	1.048	0.880	22.3	17.3
PCI BT-72	8.5	64.9	71.0	0.851	0.589	18.6	7.8
PCI BT-72	10.5	63.8	67.3	1.240	0.695	35.5	14.3
PCI BT-72	10.5	63.8	63.8	1.240	1.163	35.5	33.4
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

Table 6 Shear Design Results – $\phi = 0.9$ for Both NWC and LWC using Std. Specs.

	Girder Spcg (ft)	$V_{n\ req'd}$ (kips)		V_{cw} (kips)		$V_{s\ req'd}$ (kips)	
		NWC	LWC	NWC	LWC	NWC	LWC
AASHTO Type II	7.5	175.7	166.9	136.6	83.9	39.0	83.0
PCI BT-72	5.5	243.2	219.0	254.8	213.6	-11.6	5.4
PCI BT-72	8.5	308.1	281.1	231.9	189.0	76.2	92.1
PCI BT-72	10.5	358.2	328.8	301.4	202.6	56.9	126.2
PCI BT-72	10.5	358.2	328.8	301.4	272.0	56.9	56.8
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

The values in Table 6 were computed using the same capacity reduction factor, ϕ, for lightweight and normalweight concrete, as specified in the Standard Specifications. The effect of using a reduced capacity reduction factor for lightweight concrete, as is specified in the LRFD Specifications, is discussed later in this section.

It should be noted that these shear comparisons were performed using the Standard Specifications, rather than the LRFD Specifications. As a result, the reduction in the shear capacity, V_{cw}, can be larger than the reduction expected from the resistance modification factor alone, because the quantity f_{pc} is also involved in the computation of V_{cw},. As shown in Table 5, the differences in f_{pc} were large, leading to a compounded reduction in the shear capacity. For designs using the LRFD Specifications, the resistance modification factor alone will apply, so the reduction in shear resistance is expected to be on the order of 15% for sand-lightweight concrete.

Horizontal Shear Resistance

For interface (horizontal) shear where lightweight concrete is used, LRFD Article 5.8.4.2 requires that the coefficient of friction be reduced by the resistance modification factor, λ, which is taken as 0.75 and 0.85 for all lightweight and sand-lightweight concrete, respectively. The factor is taken as 1.0 for normalweight concrete. No provision is given for computing a reduction factor if f_{ct} is specified, as is allowed in the shear design provisions.

Resistance Factor

LRFD Article 5.5.4.2.1 specifies a reduced capacity reduction factor, ϕ, of 0.7 for use with lightweight concrete in shear, compared to a factor of 0.9 for normalweight concrete. This reduced factor for lightweight concrete has not appeared in the AASHTO Standard Specifications or the ACI Building Code. The use of a different capacity reduction factor for lightweight concrete appears to be unwarranted since the reduction in shear capacity is addressed directly by modifications in the computation of V_c discussed above. With the addition of a different ϕ factor for shear for lightweight concrete, it is possible that the required shear reinforcement may be significantly higher for some lightweight concrete designs.

Table 7 shows results of designs where capacity reduction factors, ϕ, of 0.9 and 0.7, given in the LRFD Specifications, are used for normalweight and lightweight concrete, respectively. The design computations are still performed using the shear design equations of the Standard Specifications, so the comparison cannot be used as a direct evaluation of the results obtained if the LRFD Specifications were used. The use of the different ϕ factors affect $V_{n\ req'd}$ and $V_{s\ req'd}$, but do not affect the concrete contribution, V_{cw}. It is clear when comparing these results with those found in Table 6, where the same resistance factor (ϕ=0.9) is used for normalweight concrete and lightweight concrete designs, that the required nominal shear capacity and the required shear reinforcement increase significantly for the lightweight concrete designs.

Table 7 Shear Design Results – ϕ = 0.9 for NWC and ϕ = 0.7 for LWC – LRFD Specs

	Girder Spcg (ft)	$V_{n\ req'd}$ (kips)		V_{cw} (kips)		$V_{s\ req'd}$ (kips)	
		NWC	LWC	NWC	LWC	NWC	LWC
AASHTO Type II	7.5	175.7	214.6	136.6	83.9	39.0	130.7
PCI BT-72	5.5	243.2	281.6	254.8	213.6	-11.6	68.0
PCI BT-72	8.5	308.1	361.5	231.9	189.0	76.2	172.4
PCI BT-72	10.5	358.2	422.8	301.4	202.6	56.9	220.2
PCI BT-72	10.5	358.2	422.8	301.4	272.0	56.9	150.8
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

DEVELOPMENT OF REINFORCEMENT

Transfer and Development Length for Pretensioned Strand

LRFD Article 5.11.4 does not require that the transfer and development length of strand be modified for use 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[21] and can be conservatively predicted using current AASHTO expressions[22].

Development Length for Mild Reinforcement

The LRFD Specifications provide modification factors in Articles 5.11.2.1.2 and 5.1.2.5.2 that increase the tension and hook development lengths of mild and wire reinforcement, respectively, when lightweight concrete is used. The factors, which are greater than unity, are approximately equal to the reciprocal of the factors used to modify the shear resistance for lightweight concrete.

STRENGTH LIMIT STATE

Capacity Reduction Factors

The AASHTO LRFD Specifications have capacity reduction factors specific to lightweight concrete for shear and anchorage zones. Issues related to these factors have been discussed earlier in this paper.

Stress Block Factors and Ultimate Concrete Strain in Compression

While the stress-strain characteristics of lightweight concrete differ somewhat from normalweight concrete, it has been found that the assumptions used to compute the strength of a concrete section by the equivalent rectangular stress block can be used for lightweight concrete.

PRESTRESS LOSSES

Research has shown that the refined method for estimating prestress losses that appeared in the LRFD Specifications prior to 2005 was conservative when predicting prestress losses for girders made of high performance lightweight concrete[21]. It is expected that the new loss estimation methods will also prove to be conservative for lightweight concrete members.

The "instantaneous" elastic shortening loss was discussed earlier in the paper, since it is affected by the modulus of elasticity, which is a function of the density of the concrete. This loss will be added to the estimated time-dependent loss (using either the approximate or refined methods discussed below), so the effects of lightweight concrete are considered in the total loss estimate.

Approximate Estimate of Time-Dependent Losses

The AASHTO LRFD Specifications have a new approximate method for estimating time-dependent losses. It is presented in Article 5.9.5.3 as Equation 5.9.5.3-1. The article clearly states that this equation is only intended for use with normalweight concrete.

The same article also contains a table with approximate time-dependent loss expressions for several types of prestressed concrete structures other than girders with composite decks. The article states that the expressions in Table 5.9.5.3-1 can be used for lightweight concrete members by increasing the losses 5 ksi. It would seem reasonable to apply the same increase to Equation 5.9.5.3-1 for use with lightweight concrete.

Refined Estimates of Time-Dependent Losses

The refined method for computing time-dependent prestress losses in Article 5.9.5.4 of the LRFD Specifications does not require any modifications for the use of lightweight concrete.

The effect of using lightweight concrete on refined estimates of prestress loss using the methods of the AASHTO Standard Specifications is demonstrated in Tables 8 and 9 for the group of comparative designs mentioned earlier in this paper.

Table 8 Components and Total Prestress Losses using Standard Specifications

	Girder Spcg (ft)		Prestress Loss Components (ksi)				Total Loss (ksi)	
			ES	SH	CRc	CRs	Initial	Final
AASHTO Type II	7.5	NWC	18.77	6.50	26.74	1.46	19.50	53.47
		LWC	23.56	6.50	24.57	1.09	24.11	55.72
PCI BT-72	5.5	NWC	17.42	6.50	21.33	1.87	18.35	47.12
		LWC	20.89	6.50	18.46	1.66	21.73	47.51
PCI BT-72	8.5	NWC	20.48	6.50	28.15	1.22	21.09	56.34
		LWC	23.95	6.50	25.26	1.02	24.46	56.73
PCI BT-72	10.5	NWC	23.11	6.50	37.04	0.51	23.37	67.17
		LWC	28.30	6.50	31.83	0.25	28.43	66.89
		LWC	30.30	6.50	38.35	-0.27	30.17	74.88
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design								

Table 8 shows the components of loss and the initial and final total losses. These data show that while the elastic shortening loss increases for lightweight concrete designs, the creep loss decreases by about the same amount, so the final total losses are nearly the same for the normalweight and lightweight concrete designs. Therefore, it appears from this limited comparison that the use of an assumed 5 ksi increase in time-dependent losses from normalweight to lightweight concrete designs would be reasonable and conservative for the approximate estimate.

Table 9 lists the initial and final effective prestress based on the losses in Table 8. These data demonstrate that the difference in final prestress loss is minor between the normalweight and lightweight concrete designs. The difference between initial losses for the two types of concrete is somewhat more significant. The data in the bottom two rows of the table indicate that, with respect to prestress losses, it is best to redesign a girder for lightweight concrete rather than use the same concrete strength and number of strands determined for a normalweight concrete design.

Table 9 Initial and Final Effective Prestress

	Girder	Initial Effective Prestress, f_{pi} (ksi)			Final Effective Prestress, f_{pe} (ksi)		
	Spcg (ft)	NWC	LWC	% Chng.	NWC	LWC	% Chng.
AASHTO Type II	7.5	183.0	178.4	-3%	149.0	146.8	-2%
PCI BT-72	5.5	184.2	180.8	-2%	155.4	155.0	-0%
PCI BT-72	8.5	181.4	178.0	-2%	146.2	145.8	-0%
PCI BT-72	10.5	179.1	174.1	-3%	135.3	135.6	+0%
PCI BT-72	10.5	179.1	▨ 172.3	-4%	135.3	▨ 127.6	-6%
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design							

COST

While the material cost of lightweight concrete may be significantly greater than normalweight concrete, the advantages of using lightweight concrete for a bridge design can offset the additional cost. Therefore, to obtain a clear understanding of the difference in cost between a normalweight and lightweight concrete design, it is important to consider the impact of the use of lightweight concrete on all parts of the bridge, including bearings, substructure units and foundations. The potential for reducing project costs for bridges has been demonstrated in a number of projects where the use of lightweight concrete has provided significant advantages. An example is the Rugsund Bridge in Norway where use of lightweight concrete, for which the aggregate was shipped from the US, resulted in a 15% lower bid price for the lightweight concrete design alternate than for the original normalweight concrete bridge alternate[23]. A design comparison using normal- and lightweight concrete performed by Bender[24] for a precast segmental box girder bridge demonstrated a nearly 15% overall cost reduction when using lightweight concrete. See Castrodale and Harmon[7] for more discussion and comparisons regarding the cost of lightweight concrete bridges.

SPECIFYING LIGHTWEIGHT CONCRETE

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 clearly state the density requirements.

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 generally be the density specified in the contract documents. According to ASTM C 567[8], 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[2]. More information on equilibrium density is available in Holm and Ries[5] and ACI 213[3].

The equilibrium density is usually specified in the contract documents and is used as the basis for computing loads for structural design after adding an allowance for reinforcement. However, it cannot be used for acceptance of concrete at the time of placement. Instead, it is used to qualify a mix design, and the fresh density of concrete is used as the acceptance criteria when the concrete is placed. Therefore, a relationship must be established by the concrete supplier between the fresh and equilibrium densities, so compliance with the specified equilibrium density can be assured if the fresh density is within specifications.

Since the fresh and equilibrium densities only represent the weight of the concrete, the contract documents should state the assumed allowance for reinforcement used for computing dead loads. For heavily reinforced members, the designer should compute the actual weight of reinforcement because the usual assumption of 5 pcf may not be adequate.

Other material properties may also be specified as required for the design, such as modulus of elasticity or splitting tensile strength. However, the designer should consult a lightweight aggregate supplier to ensure that any quantities specified beyond density and compressive strength can be achieved economically using reasonable mixtures with available materials.

CONCLUDING REMARKS

Prestressed concrete bridges have been designed using lightweight concrete since they were introduced in the 1950s. Many of these bridges, which used lightweight concrete to economically satisfy design requirements, are still in service. While the structural properties of lightweight concrete differ in some aspects from the properties of normalweight concrete, the AASHTO specifications account for these differences. This paper has presented and discussed the differences in material properties and the corresponding design provisions to supply the information needed by engineers to design bridges using lightweight concrete.

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