Lightweight Concrete Bridge Design Primer

U.S. Department of Transportation
Federal Highway Administration

Office of Infrastructure
FHWA-HIF-19-067

November 2021

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HIF-19-067	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Lightweight Concrete Bridge Design Primer	5. Report Date November 2021 6. Performing Organization Code:

7. Author(s) Castrodale, Reid	8. Performing Organization Report No.
9. Performing Organization Name and Address WSP USA One Penn Plaza, 2nd floor, 250 W 34th Street New York, NY 10119 Castrodale Engineering Consultants, PC 419 Winfield Blvd SE Concord, NC 28025	10. Work Unit No. 11. Contract or Grant No. DTFH61-14-D-00048

12. Sponsoring Agency Name and Address Federal Highway Administration Office of Infrastructure – Bridges and Structures 1200 New Jersey Ave., SE Washington, DC 20590	13. Type of Report and Period 14. Sponsoring Agency Code

15. Supplementary Notes

Work funded by task order "Advance Concrete Bridge Technology to Improve Infrastructure Performance" between FHWA and WSP.

16. Abstract

Lightweight concrete has been used successfully for the construction of bridges since soon after commercial production of lightweight aggregate began in the United States in 1920. Design provisions for lightweight concrete have been provided in AASHTO specifications for over 35 years. However, the material is not commonly used for bridge construction.

This document presents basic information about lightweight concrete to equip owners, designers, specifiers, and contractors to design and evaluate the potential benefits, using the provisions of the *AASHTO LRFD Bridge Design Specifications, 8th Edition, 2017,* which are incorporated by reference at 23 CFR 625.4(d)(1)(v). Information presented includes laboratory data, field experience, and project descriptions which demonstrate that lightweight concrete can be used as a durable and cost-effective material for bridges.

17. Key Words Lightweight concrete, lightweight aggregate, bridge, material properties, durability, design, internal curing, cost, deck, girder, projects, specifications, construction	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. https://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 129	22. Price

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
BT	bulb tee (precast, prestressed concrete girder shape)
CFR	Code of Federal Regulations
CTE	coefficient of thermal expansion
DOT	Department of Transportation
ENR	*Engineering News Record*
ESCSI	Expanded Shale, Clay and Slate Institute
FHWA	Federal Highway Administration
fib	International Federation for Structural Concrete / Fédération Internationale du béton
FIB	Florida I-Beam (girder shape)
FIP	Federation Internationale de la Precontrainte
IC	Internal curing, or internally cured
kcf	kip per cubic foot
kip	1000 lb
ksf	kip per square foot
LRFD	Load and Resistance Factor Design
LWC	lightweight concrete
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NRMCA	National Ready Mixed Concrete Association
NWC	normal-weight concrete
PCA	Portland Cement Association
PCI	Precast/Prestressed Concrete Association
RH	relative humidity (%)
SDC	specified density concrete
SSD	saturated surface dry
TFHRC	Turner-Fairbank Highway Research Center
UHPC	Ultra-high-performance concrete
w/cm	water/cementitious materials ratio

w/c	water/cement ratio
WSD	wetted surface dry
$\mu\varepsilon$	micro-strain ($\times 10^{-6}$ in./in.)

LIST OF NOTATIONS

This section provides a list of notations used in this report.

A	absorption of lightweight aggregate, expressed as a percentage of the oven-dry mass (%) (2.3.3)
A_{sc}	cross-sectional area of a stud shear connector (in.^{2}) (4.17.3)
C_f	cement factor (content) for concrete mixture (lb/yd^3) (2.3.3)
CS	chemical shrinkage of cement; usually taken as 7 lb/100 lb cement or 7 percent (2.3.3)
D	desorption of lightweight aggregate, which is the quantity of absorbed water that is released by the aggregate in drying conditions, expressed as a percentage of the mass of absorbed water (%) (2.3.3)
E_c	modulus of elasticity of concrete (ksi) (2.2.4.5)
f'_c	compressive strength of concrete for use in design (ksi) [psi for ACI 318 provisions in section 4.15.1] (2.2.4.5)
$f'_{c\,NWC}$	compressive strength of normal-weight concrete for use in design (ksi) (3.5.2.2)
f'_{ci}	design concrete compressive strength at the time of prestressing in reference to material test values and specified compressive strength at the time of prestressing (ksi) (3.5.3.1)
f_{ct}	average splitting tensile strength of concrete (ksi) (3.3.4)
$f_{ct\,LWC}$	average splitting strength of lightweight concrete (ksi) (3.5.2.2)
$f_{ct\,NWC}$	average splitting strength of normal-weight concrete (ksi) (3.5.2.2)
f_r	modulus of rupture of concrete (ksi) (3.3.4)
f_t	direct tensile strength of concrete (ksi) (2.2.4.3)
F_u	specified minimum tensile strength of a stud shear connector determined as specified in [LRFD Specifications] Article 6.4.4 (ksi) (4.17.3)
f_y	specified minimum yield strength of reinforcement (ksi) (4.11.1.1)
h_{ef}	effective embedment depth of anchor, in. (4.15.1)
k_c	coefficient for basic concrete breakout strength in tension (4.15.1)
K_{IC}	coefficient for internal curing for given type of cement and lightweight aggregate (2.3.3)
K_1	correction factor for source of aggregate taken as 1.0 unless determined by physical test, and as approved by the Owner (2.2.4.5)
L_c	length of channel shear connector (in.) (4.17.3)
ℓ_d	development length (in.) (4.12.3.2)
M_{PLWA}	mass of prewetted fine LWA per unit volume of concrete (lb/yd^3) (2.3.3)

N_b	basic concrete breakout strength in tension of a single anchor in cracked concrete, lb (4.15.1)
Q_n	nominal shear resistance of a single shear connector (kip) (4.17.3)
t_f	flange thickness of channel shear connector (in.) (4.17.3)
t_w	web thickness of channel shear connector (in.) (4.17.3)
w_c	unit weight of concrete (kcf) (2.2.4.5)
w/c	water/cement ratio (2.3.2)
w/cm	water/cementitious materials ratio designated in earlier practice as water–cement ratio (5.2)
α_1	stress block factor taken as the ratio of equivalent rectangular concrete compressive stress block intensity to the compressive strength of concrete used in design (2.2.5.1)
β_1	stress block factor taken as the ratio of the depth of the equivalent uniformly stressed compression zone assumed in the strength limit state to the depth of the actual compression zone (2.2.5.1)
ε_{cu}	failure strain of concrete in compression (in./in.) (2.2.5.1)
λ	concrete density modification factor (3.3.4)
λ_a	modification factor to reflect the reduced mechanical properties of lightweight concrete in certain concrete anchorage applications (4.15.1)

1 INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) publishes multiple standard specifications that are referenced in this report. Those incorporated by reference in CFR Title 23 include:

- *AASHTO LRFD Bridge Design Specifications, 8th Edition* (2017) are incorporated by reference at 23 CFR 625.4(d)(1)(v) and referred in this report as the AASHTO LRFD-8 Design Specifications.

- *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Parts 1-3*, *2017 Edition* are incorporated by reference at 23 CFR 625.4(d)(1)(x) and referred in this report as the AASHTO Materials and Testing Specifications.

- *AASHTO LRFD Bridge Construction Specifications, 4th Edition* (2017) are incorporated by reference at 23 CFR 625.4(d)(1)(iv) and referred in this report as the AASHTO LRFD Construction Specifications.

The above AASHTO standard specifications reference multiple industry standards for the design and construction of bridges, some of which are not incorporated by reference in the CFR Title 23. Where such industry standard is referenced in this report, a footnote is used to provide additional information.

AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) provide the following definition for lightweight concrete:

> *Concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567.*

There are two key points in the definition of lightweight concrete: the material uses structural lightweight aggregate as specified in AASHTO M 195[1], and it has a reduced density compared to normal-weight concrete.

The purpose of this document is to present basic information about lightweight concrete meeting this definition, and to provide information about the design of bridge elements with lightweight concrete using the provisions of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Lightweight concrete it is not a new material, although many engineers may not be familiar with it. It has been used successfully for the construction of bridges since soon after commercial

[1] AASHTO M 195, Standard Specification for Lightweight Aggregates for Structural Concrete, is not incorporated in the CFR Title 23. However, AASHTO M 195 is referenced in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) and in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

production of lightweight aggregate began in the United States in 1920 (ESCSI 1971). The previous and outdated versions of AASHTO bridge design specifications have included some mention of lightweight concrete since at least 1969 and provisions similar to those in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) have been present since at least 1983. A comprehensive report on the use of lightweight concrete for prestressed concrete products was developed in 1966 by the Federation Internationale de la Precontrainte (FIP) Commission on Prestressed Lightweight Concrete (1967). In 1985, the Federal Highway Administration (FHWA) published *Criteria for Designing Lightweight Concrete Bridges*. That 1985 FHWA report stated that lightweight concrete has a "sufficient record of successful applications to make it a suitable construction material … for bridges" and that "sufficient information is available on all aspects of its performance for design and construction purposes."

While lightweight concrete has been successfully used for bridge projects for over 80 years, and design provisions for lightweight concrete have been provided in previous and outdated versions of AASHTO specifications and the AASHTO LRFD-8 Design Specifications (AASHTO 2007) (23 CFR 625.4(d)(1)(v)) for over 35 years, the material is not commonly used for bridge construction. Owners, designers, contractors, and others might assume that lightweight concrete is not a reasonable option for bridges. After all, who would specify concrete using a porous aggregate that may have a lower tensile strength in a structure exposed to the elements and traffic that should provide service for at least 75 years? Another potential obstacle to the use of lightweight concrete is the perceived higher cost of the material. Finally, designers may be unsure about how to select properties of lightweight concrete for design, and how to perform design calculations.

This document is intended to inform owners, designers, specifiers, and contractors about basic information relating to lightweight concrete so they can be equipped to properly evaluate the potential benefits of using lightweight concrete. Information presented will include laboratory data and field experience that demonstrate that lightweight concrete can be durable and cost effective for bridge designs.

1.1 BENEFITS OF LIGHTWEIGHT CONCRETE FOR BRIDGES

A reason for using lightweight concrete in bridges is the reduced density of the concrete, which leads to a reduction in dead loads that are supported by a structure. This can be used to improve design efficiency in several ways (Castrodale et al. 2009) including:

- Extended span ranges, wider girder spacings, or shallower girder sections.
- Reduced design loads on bearings, substructure elements, and foundations.
- Reduced weight of precast elements for handling, transportation, and erection.

A second benefit is less obvious or even counter-intuitive—enhanced durability. While it would seem likely that using a porous aggregate would reduce the durability, and therefore the expected service life, of a bridge, field and laboratory experience have shown that lightweight concrete has equal or improved durability compared to normal-weight concrete with the same compressive strength (Holm et al. 1984, Vaysburd 1996, Castrodale and Harmon 2008, Castrodale 2018a). Reasons for the enhanced durability of lightweight concrete include:

- Internal curing from prewetted lightweight aggregate, which reduces shrinkage, cracking, and permeability.
- Elastic compatibility where similar stiffness of aggregate and paste reduces internal microcracking, which also reduces permeability.
- Lower modulus of elasticity, which tends to reduce cracking.
- Lower coefficient of thermal expansion, which also tends to reduce cracking.

These and other benefits will be more fully discussed later in the document.

In recent years, the concept of internal curing, in which prewetted lightweight aggregate is substituted for a portion of the conventional sand in an otherwise conventional concrete mixture, has become increasingly recognized as an effective approach to improve durability of concrete (Weiss et al. 2012, ESCSI 2012a, Castrodale 2016a). In this way, internal curing uses prewetted lightweight aggregate to deliver curing water to the interior of concrete rather than using the aggregate to reduce density. Some information on the concept of internal curing will be provided, but this topic is not a major focus of this document.

1.2 DISADVANTAGES OF LIGHTWEIGHT CONCRETE FOR BRIDGES

Common concerns raised about using lightweight concrete for bridges include:

- Increased cost.
- Reduced durability.
- Reduced structural capacity.
- Availability of lightweight aggregate.
- Lack of familiarity of contractors with lightweight concrete.

Lightweight aggregate is more expensive on a per ton basis than normal-weight aggregate because of its heat treatment and usually greater transportation costs. However, each ton of lightweight aggregate provides nearly twice as much volume as a ton of normal-weight aggregate. Therefore, the weight of lightweight aggregate used to produce a given volume of concrete is typically about half the weight of the normal weight aggregate, so the difference in cost is immediately reduced. Information presented in this document will also show that the other concerns listed above may be based on misconceptions or can be addressed in design. The many bridge projects that have been constructed using lightweight concrete demonstrate the listed concerns do not prevent the use of lightweight concrete as an economical long-term solution for bridge construction. These concerns will be discussed in greater length later in the document.

1.3 EXAMPLES OF THE EFFECTIVE USE OF LIGHTWEIGHT CONCRETE FOR BRIDGES

To demonstrate that lightweight concrete can be used to provide economical bridge designs, brief descriptions of three bridge projects are presented. These examples show that, though lightweight concrete has a higher cost than normal-weight concrete, savings in other aspects of the project can more than offset the additional cost. Information on more bridge projects for which lightweight concrete was used are presented later in the document.

1.3.1 San Francisco-Oakland Bay Bridge – California

The San Francisco-Oakland Bay Bridge was completed in 1936. Designers decided to use lightweight concrete with a unit weight of 0.095 kcf to construct the upper deck of the suspension spans. Woodruff (1938) credits the use of lightweight concrete with saving $3 million out of the original $40 million total construction cost for the two suspension-span units crossing the bay. The lightweight concrete provided a 25 lb/ft^2 reduction in dead load (a total of 31.6 million lbs for both suspension-span units) that reduced 1) the quantity of steel used for the suspension cables, 2) foundation loads, and 3) seismic design forces on the superstructure and foundations. That deck, which has been protected by a thin conventional concrete mortar wearing surface throughout its life, is still in service. It is remarkable that the designers used a relatively new material in such a significant structure, but the savings were compelling. In 1979, the lightweight concrete deck was found to have a chloride content at the level of the reinforcement that was generally below the corrosion threshold. The normal-weight concrete in the approach spans for the bridge were tested in 1984 and found to have chloride concentrations at the level of the reinforcement that were above the corrosion threshold, and at some locations were very high. Repairs were necessary for the normal-weight concrete approach spans (Vaysburd 1996).

1.3.2 I-5 Bridge over the Skagit River – Washington State

Lightweight concrete deck bulb tee girders were used for the permanent replacement of a steel portal frame truss span on the I-5 bridge over the Skagit River that collapsed after being struck by a truck in May 2013 (Vanek et al. 2015). By selecting structural lightweight concrete deck-girders (a full-depth deck was cast monolithically with the pretensioned girders) for the permanent replacement span, the design/build team was able to keep the total weight of the new span below 918 tons. This allowed the designers to use existing foundations without reanalysis or strengthening, saving significant cost and time. Table 1 shows the relative costs of lightweight aggregate, lightweight concrete, and lightweight concrete girders compared to conventional materials and concrete using cost data from the Skagit River Bridge and two similar projects (Chapman and Castrodale 2016). While the costs of lightweight aggregate (which was shipped across the country from the aggregate supplier in North Carolina to the prestress plant in Tacoma, Washington) and lightweight concrete are significantly greater than for the comparable normal-weight concrete mix, the cost of the lightweight concrete girders is only slightly higher (13 or 14 percent) than the cost of normal-weight concrete girders. As explained by Chapman, this relatively small difference in girder cost is because the cost of aggregate is a relatively small part of the total cost for a girder. Furthermore, the relative girder costs shown in the table below do not reflect significant savings expected in trucking, erection, and substructure, as well as in design effort, material costs, and schedule.

Table 1. Relative cost comparison of materials and prestressed girders using lightweight and normal-weight concrete (Chapman and Castrodale 2016).

Cost item	Relative cost of lightweight / normal-weight ($/$)
Aggregate	5
Aggregate freight	25
Fresh concrete	2.0
WF50G girder cost	1.14
WF83G girder cost	1.13

Note: WF50G and WF83G are designations for Washington State DOT wide flange precast, prestressed concrete girders that are 50 in. and 83 in. deep, respectively.

1.3.3 Rugsund Bridge – Norway

The Rugsund Bridge is a cast-in-place segmental box-girder bridge that crosses a fjord in Norway initially designed with a main span of 564 ft using normal-weight concrete (Harmon 2002). A peer review stated that a design using lightweight concrete for a major portion of the main span should also be developed. The alternate design used lightweight concrete for 604 ft of the 623 ft main span. The new design used the same quantity of prestressing steel as the original normal-weight concrete design, even though the main span was 10 percent longer. The increased main span length allowed piers to be moved out of deep water, thereby saving significant costs in foundation construction. Both designs were sent to bid; the low bid used the lightweight concrete design. It was 15 percent lower than the normal-weight concrete bid, even though it included costs for shipping lightweight aggregate from the United States to allow the contractor to deliver the concrete by pumping.

1.4 SCOPE AND ORGANIZATION

The purpose of the document is to provide owners, designers, contractors, and others basic information on how to use lightweight concrete to obtain the structural, durability, and cost benefits available when the material is appropriately used in bridge projects.

An introduction to lightweight aggregate and lightweight concrete is provided, followed by a discussion of initial design considerations, including benefits and typical concerns related to the use of lightweight concrete for bridges. Provisions in the AASHTO LRFD-8 Design Specifications (AASHTO 2007) (23 CFR 625.4(d)(1)(v) relevant to the design of lightweight concrete bridges are then discussed. The document then presents practical information on construction using lightweight concrete and issues to consider when specifying lightweight concrete. The document concludes with a discussion of a wide variety of bridge projects where lightweight concrete was successfully used to address different design and construction issues. References are provided as sources for additional information.

1.5 SPECIFICATIONS, NOTATION, AND ABBREVIATIONS

This document is primarily based on the AASHTO LRFD-8 Design Specifications (AASHTO 2007)(23 CFR 625.4(d)(1)(v). Notation conforms to the AASHTO LRFD-8 Design Specifications unless indicated otherwise. Any reference to a section is an internal reference to locations within this document, unless it is specifically used to refer to a section (chapter) in the AASHTO LRFD-8 Design Specifications (AASHTO 2007) (23 CFR 625.4(d)(1)(v).

In addition to the abbreviations listed above, the following abbreviations are used in this document:

LW	Lightweight.
LWA	Lightweight aggregate.
LWC	Lightweight concrete.
ALWC	All-lightweight concrete.
SLWC	Sand-lightweight concrete.
IC	Internal curing, or internally cured, using prewetted lightweight aggregate.
NW	Normal-weight.
NWA	Normal-weight aggregate.
NWC	Normal-weight concrete.

Other abbreviations conform to the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v) or List of Abbreviations.

Finally, when comparisons are discussed between lightweight and normal-weight concrete mixtures, it should be assumed that the mixtures are designed for the same compressive strength; have the same constituents (except aggregate); are mixed, placed, finished, and cured using the same methods with the same attention to quality; and are exposed to the same conditions.

2 PROPERTIES OF LIGHTWEIGHT AGGREGATE AND LIGHTWEIGHT CONCRETE

This chapter discusses the mechanical and durability properties of lightweight aggregate and lightweight concrete that are relevant for bridge design. This information is provided for background and is intended to support the design assumptions made in chapter 3 where suggestions are provided for the selection of design parameters for lightweight concrete bridges. The properties of internally cured concrete are also discussed. More information can be obtained from the reports of the American Concrete Institute (ACI) Committee 213 (2014)[2], by Holm and Bremner (2000), the Expanded Shale, Clay and Slate Institute (ESCSI) Reference Ma*nual* (Holm and Ries 2007), and other sources.

2.1 LIGHTWEIGHT AGGREGATE

Structural lightweight aggregate has been produced in the United States by using rotary kilns to expand shale, clay and slate since 1920, shortly after the technology for the process was patented (ESCSI 1971). The raw materials are expanded at temperatures as high as 2200 °F. At this temperature, gases are evolved within the raw material particles causing them to approximately double in volume by forming internal bubbles that range in size from 5 to 300 μm (Holm and Bremner 2000). Upon cooling, the bubbles become the pores that give the aggregate its lighter weight (visible in Figure 1). The relative density of the particles is reduced from about 2.65 for the raw material to less than 1.55 for the expanded aggregate. The term "relative density" is now the preferred term that is equivalent to the previously used term "specific gravity." It is used in AASHTO M 195[1] (ASTM C330) for lightweight aggregates for structural concrete.

Source: FHWA

Figure 1. Photo. Lightweight aggregate particle showing pore structure. Surface of particle is approximately 2 in. square.

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[2] ACI 213, Guide for Structural Lightweight-Aggregate Concrete, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

The thermal processing produces a vitrified porous aggregate in which the solid material has a hardness similar to quartz (Holm and Bremner 2000). Properties of lightweight aggregate vary between sources, but structural lightweight concrete can be produced using aggregate from all current lightweight aggregate sources in the United States While naturally occurring lightweight aggregates and lightweight aggregates manufactured from other raw materials or processes may also be available in the United States, this document focuses on aggregates manufactured from shale, clay, and slate that generally have more consistent properties, are more widely available and used, and for which structural test data are available.

2.1.1 Specifications and Gradation

The governing material specification for lightweight aggregate for structural concrete is AASHTO M 195[1] (2011), which is designated as ASTM C330 in the AASHTO M 195[1]. This standard specification provides requirements for addresses the chemical composition and physical properties of lightweight aggregate intended for use in structural concrete. Lightweight concrete that is used for non-structural purposes, such as insulating concrete, are not covered by AASHTO M 195[1] will not be discussed in this document. Both manufactured and natural lightweight aggregates are covered by the specification. As mentioned above, this document focuses on the most widely used types of lightweight aggregate in the United States, which are expanded shales, clays and slates produced using a rotary kiln.

Typical lightweight aggregates are shown in Figure 2 and Figure 3. For most sources of lightweight aggregate in the United States, clinker is produced by the kilns, which is then crushed to produce the final gradation. For some sources, lightweight aggregate is produced in pellets that are not crushed (Figure 2). Structural lightweight concrete can be made with lightweight aggregate manufactured from any of the types of raw materials. Therefore, the type of raw material should not be used as a primary criterion to determine suitability of an aggregate source for use in lightweight concrete.

Figure 2. Photo. Lightweight aggregates from two different sources: uncrushed and crushed.

© 2013 NAS

Figure 3. Photo. Different types of lightweight aggregates tested by Cousins et al. (2013). From left to right: Clay1, Shale1, Shale2, Clay2, Shale3, and Slate1. All of these lightweight aggregates are crushed.

In the AASHTO M 195[1], standard specifications for lightweight aggregates have been available for many years. Some agency standard specifications for construction of bridges also address lightweight aggregate.

Standard gradings for coarse lightweight aggregate from AASHTO M 195[1] are shown in Table 2; gradings for fine lightweight aggregate and for combined coarse and fine lightweight aggregate are also given in AASHTO M 195. Nominal size designations are simply the largest sieve opening size on which some material may be retained rather than the designations that are used in AASHTO M 6[3] and M 80[4] (ASTM C33, which addresses both AASHTO specifications) for normal-weight aggregate (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)). The largest lightweight aggregate grading typically available in the United States is ¾ inches (19 mm). The fine aggregate grading has broad limits, wider than most agency specifications for manufactured fine aggregate.

[3] AASHTO M 6, Standard Specification for Fine Aggregates for Hydraulic Cement Concrete, is not incorporated in the CFR Title 23. However, AASHTO M 6 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

[4] AASHTO M 80, Standard Specification for Lightweight Aggregates for Structural Concrete, is not incorporated in the CFR Title 23. However, AASHTO M 80 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

Table 2. Grading requirements for coarse lightweight aggregates for structural concrete from AASHTO M 195[1] (2011).

Nominal Size Designation	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (3/8 in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	0.075 mm (No. 200)
25.0 to 4.75 mm	95-100	--	25-60	--	0-10	--	--	0-10
19.0 to 4.75 mm	100	90-100	--	10-50	0-15	--	--	0-10
12.5 to 4.75 mm	--	100	90-100	40-80	0-20	0-10	--	0-10
9.5 to 2.36 mm	--	--	100	80-100	5-40	0-20	0-10	0-10

AASHTO grading requirements for lightweight aggregate to be used in concrete differ from those for normal-weight aggregate because the relative density of lightweight aggregate particles increases for the smaller size fractions as the larger pores are lost as particle size is reduced (AASHTO 2017b) (23 CFR 625.4(d)(1)(x)). Therefore, to obtain the desired volumetric distribution of aggregate particle sizes to provide comparable workability for lightweight concrete, the grading is different for lightweight and normal-weight aggregates, with a greater percentage of mass retained on the smaller screens for lightweight aggregate (ACI 213 2014).

2.1.2 Mechanical Properties

Summaries of mechanical properties of lightweight aggregate are found in Holm and Bremner (2000) and ACI 213[2] (2014). Several items are discussed here to provide basic information.

The particle shapes of lightweight aggregate can vary by source and processing, and can range from rounded and fairly smooth (when the raw material is extruded or pelletized and is not crushed after firing) to angular and irregular (when the aggregate is crushed after firing). The surface textures can also vary from fairly smooth with few exposed pores to very irregular and angular with many pores exposed. The aggregate characteristics should be considered when proportioning a concrete mixture for use on a project because the shape and texture of the aggregate will affect workability, pumpability, fine-to-coarse aggregate ratio, binder content, and water content(ACI 213 2014). This is also the case for normal-weight aggregate, where the same range of shapes and textures are possible, other than the presence of pores.

The *bulk density* of coarse lightweight aggregate ranges from about 0.045 to 0.055 kcf, and from about 0.060 to 0.070 kcf for fine lightweight aggregate (maximum values are given in AASHTO M 195[1]), while the bulk density of normal-weight aggregate ranges from about 0.075 to 0.110 kcf (Kosmatka and Wilson 2016). The *relative density* of lightweight aggregate particles varies with particle size, with greater relative values for smaller aggregate particles. In general, the relative density of lightweight aggregate ranges from 1/3 to 2/3 of that for normal-weight aggregate, depending on particle size and source (ACI 213 2014).

Absorption of lightweight aggregate may range from 5 percent to more than 25 percent by mass of dry aggregate after soaking for 24 hours, depending on the lightweight aggregate source and size. This absorption is higher than normal-weight aggregates, which typically absorb less than 2 percent moisture by mass (Holm and Bremner 2000). Lightweight aggregate particles that have not been crushed after firing appear to have a sealed surface and may have less absorption than crushed aggregates. Some owner agency specifications in the past required lightweight aggregate to not be crushed after firing. This may not be necessary because the absorption should not be considered as the single determinant of whether the properties or performance of a lightweight aggregate should be acceptable.

The absorption with time for fine gradations of lightweight aggregates from most sources in the United States are shown in Figure 4 (Castro 2011). Lines in this and the next figure are not identified but are only provided to indicate the comparative behavior between the various sources of lightweight aggregate in the United States The same data for fine gradations of lightweight aggregates are shown in Figure 5 normalized by the 24-hour absorption (Castro 2011). Data in this figure indicate that the absorption behavior of the different lightweight, fine aggregates is similar when normalized by the 24-hour absorption. This figure also gives an indication of the rate at which water is absorbed by the aggregates from an oven dry condition. The study by Castro (2011) also reports absorptions for each of the lightweight, fine aggregates tested.

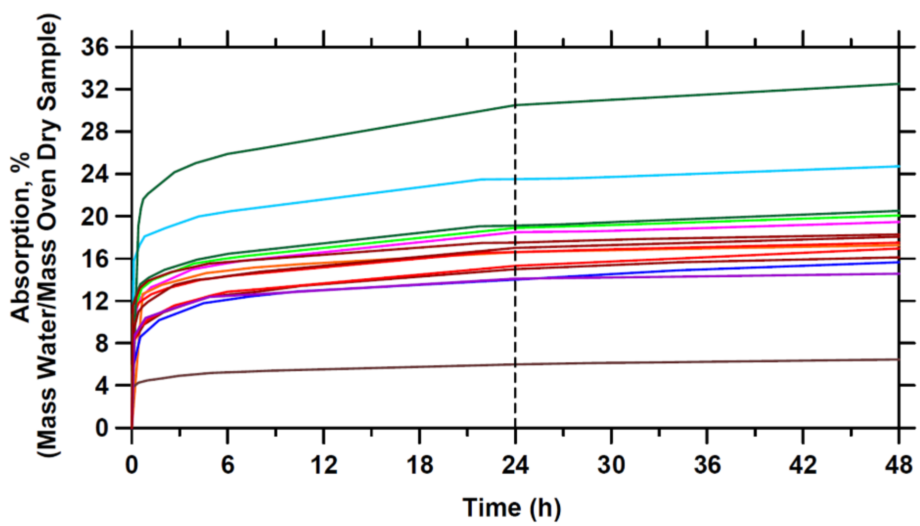


Figure 4. Graph. Water absorption of initially oven-dry lightweight aggregate during first 48 hours of soaking .

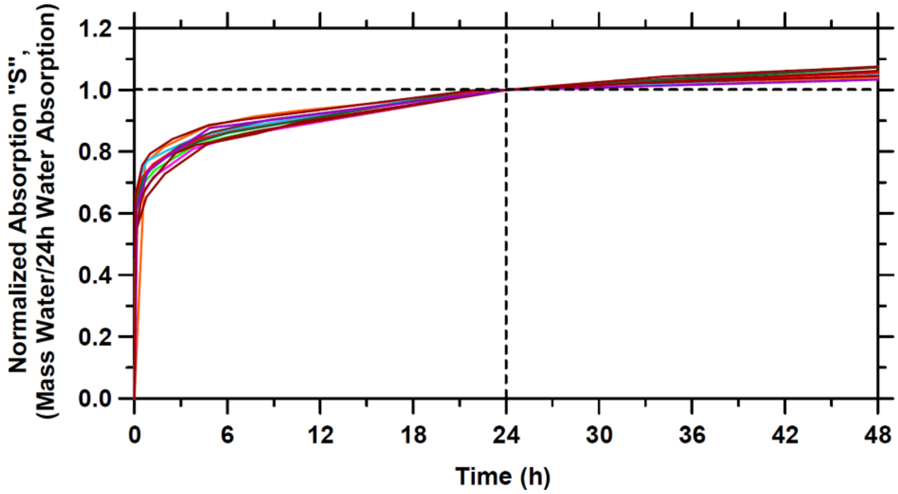
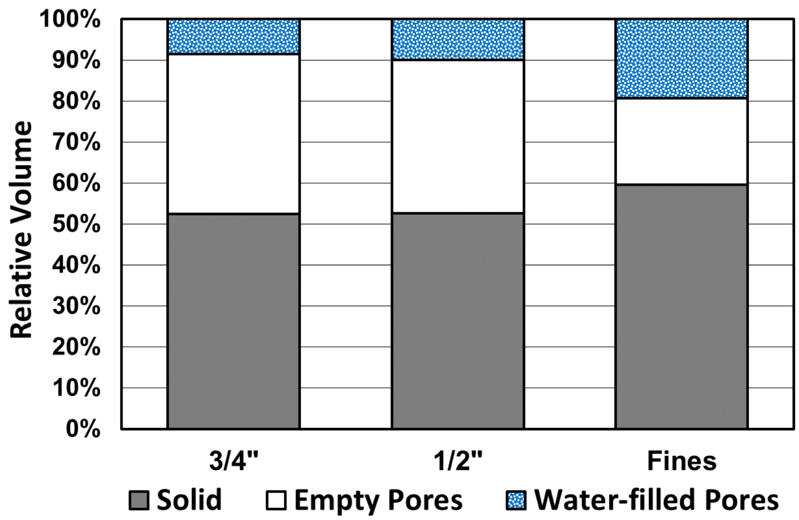


Figure 5. Graph. Water absorption of initially oven-dry lightweight aggregate during first 48 hours of soaking normalized by the 24-hour absorption.

While lightweight aggregate appears to be porous, most of the pores in an aggregate particle are not connected, which results in relatively low absorption for such a porous material. An approach for computing the relative volumes of connected pores that fill with water and disconnected pores that do not fill with water is given in Castrodale (2018b). Using this approach, Figure 6 shows a schematic representation of relative volumes of solid material and pores for three gradations of an expanded slate lightweight aggregate, along with the relative volume of pores that are accessible to water. This demonstrates that while approximately half of the volume of aggregate particles is comprised of pores, only a relatively small portion of the pores fill with water to reach the 24-hour absorption. Other types of lightweight aggregate have similar behavior.



Source: FHWA

Figure 6. Graph. Schematic representation of the relative volume of solid material, empty pores, and water-filled pores for three sizes of a lightweight aggregate.

2.1.3 Durability Properties

Most lightweight aggregates will meet the same material performance criteria specified for normal-weight aggregates, such as abrasion resistance, resistance to freezing and thawing, and soundness. Modifications to the test method for soundness should be used to address issues presented by the porosity of the aggregate.

To show that lightweight aggregate can meet typical criteria specified for normal-weight aggregate, the following example is provided. A study by Wall and Castrodale (2013) showed that the soundness loss (AASHTO T 104) and abrasion loss using the Los Angeles (LA) machine (AASHTO T 96) of lightweight aggregate were similar to the average of these quantities for all aggregates on the North Carolina Department of Transportation (NCDOT) Approved Coarse Aggregate (Stone) List. Table 3 provides an analysis of test results in the current NCDOT list (NCDOT 2020) that satisfy the NCDOT requirements (NCDOT 2018), which are shown in Table 4. The number of quarries used to compute each of the average values shown in Table 3 is also included in the table.

Table 3. Average test results for soundness loss and LA abrasion loss for ¾ in. Gradations for NCDOT aggregate sources meeting standard property specifications compared to lightweight aggregate test results (Data from NCDOT (2020)).

Test Results for ¾ in. Gradations (A)	Soundness Test Loss	LA Abrasion Test Loss
Average all sources	0.73%	31.0%
Lightweight Aggregate – Quarry A	0.4%	32%
Lightweight Aggregate – Quarry B	0.1%	31%
Number of sources included in average	*166*	*149*

Table 4. NCDOT maximum test limits for soundness loss and LA abrasion loss.

NCDOT Maximum Test Limit	Soundness Test Loss	LA Abrasion Test Loss
General test limit	15%	55%
For $f'_c > 6$ ksi	8%	40%
For lightweight aggregate	10%	*See Note 2*

Notes:

1. *Maximum test result limits are from NCDOT Standard Specifications (NCDOT 2018): Article 1014-2(B) for soundness test loss requirements; Article 1014-2(D) for LA abrasion test loss requirements.*
2. *Requirements for lightweight aggregate are given in NCDOT Project Special Provision (PSP) PSP017 (2011) which does not specify a limit for LA abrasion test loss.*

2.2 LIGHTWEIGHT CONCRETE

Lightweight concrete uses a lighter aggregate to reduce concrete density. Otherwise, the constituent material and processes for batching, transporting, placing, and finishing are the same as for normal-weight concrete. Admixtures, fibers, and supplementary cementitious materials can be used with lightweight aggregate and can be expected to perform in lightweight concrete as they do for normal-weight concrete. Therefore, there is no further discussion of the effect of these additional materials when used with lightweight concrete. The porous nature of lightweight aggregate affects some properties of lightweight concrete. Descriptions for commonly used types of lightweight concrete and terms used to describe the density of lightweight concrete under different conditions are discussed in sections 2.2.1 and 2.2.2, respectively.

This section presents data and discussion about material properties of lightweight concrete to demonstrate the expected performance of the material. Because lightweight concrete made with manufactured lightweight aggregate has been in use in the United States for nearly 100 years, a significant body of test data is available on the properties of the material. Design provisions related to material properties are presented in chapter 4.

Several fresh and hardened properties are specified for lightweight concrete just as they are for normal-weight concrete. However, for lightweight concrete, the density is also specified in order to achieve the design objective of reducing the weight of the structure or element. Because conformance with the specified density is one of the criteria for acceptance of lightweight concrete, the material typically receives closer attention during production in an attempt to maintain consistency in meeting the specified density. Possibly because of this closer attention, it has been found that the compressive strength of lightweight concrete mixtures is more consistent than normal-weight concrete mixtures (Nowak and Rakoczy 2010).

Properties of lightweight concrete can vary depending on variation in constituent properties and batch tolerances, which is also the case for normal-weight concrete. The field performance of lightweight concrete is also affected by the environment in which it is placed and will serve and the consistency and quality of activities that affect each load of concrete as it is batched, mixed, transported, placed, finished, and cured. All of these influences also apply to performance of normal-weight concrete. Therefore, equations found in the design specifications that provide estimates of material properties should only be taken as providing a reasonable estimate of expected material behavior . Variation from the expected properties is possible for all types of concrete, that is, both lightweight and normal-weight concrete.

2.2.1 Types of Lightweight Concrete

In the past, types of lightweight concrete were described by the composition of the concrete. Although these descriptions no longer appear in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(iv)), they may be useful.

- ***All-lightweight concrete***: All of the aggregate in this type of concrete is lightweight aggregate; that is, both coarse and fine aggregates are lightweight. This is the lightest type of structural concrete, with density possibly as low as 0.090 kcf, which is nearly a 40 percent reduction from the typical normal-weight concrete density of 0.145 kcf. In the early years of using lightweight concrete, this was the default meaning when lightweight concrete was used. Now this type of concrete is usually used only when the greatest possible reduction in density is needed to meet design objectives.
- ***Sand-lightweight concrete***: Coarse aggregate in this type of concrete is lightweight aggregate, but the fine aggregate (sand) is normal weight. This produces an intermediate density of concrete. The name was derived from the transition from lightweight concrete (which originally meant "all-lightweight concrete") to "sanded" lightweight concrete by using normal-weight sand in place of lightweight sand when it was found that this type of mixture provided most of the weight reduction but at a lower cost. Eventually the name was shortened to "sand-lightweight concrete." This type of lightweight concrete is currently the most widely used.

While the terms above can be useful, the ranges of densities of lightweight concrete achieved using them vary depending on the type of lightweight aggregate used and other mixture properties. When the term "sand-lightweight concrete" was used, confusion was sometimes introduced. For example, a project specification may specify "sand-lightweight concrete" with a density of 0.115 kcf. If the concrete supplier used lightweight aggregate "A" with a low relative density, a mix with a density of 0.115 kcf would be achieved most economically with a blend of normal-weight and lightweight coarse aggregates. However, if the concrete supplier used lightweight aggregate "B" with a higher relative density, the 0.115 kcf mix may be achieved with a sand-lightweight concrete mix or the addition of lightweight fines may be used to achieve the target. Therefore, if the concrete supplier or designer strictly conformed to the descriptions above, a less economical mix may have been used.

It should be recognized that lightweight aggregate is simply a lighter type of aggregate, and there is no reason that it cannot be combined with normal-weight aggregate to achieve any desired density in the range between "all-lightweight concrete" and normal-weight concrete. That was the reason the concrete industry moved from all-lightweight concrete to sand-lightweight concrete, where the lightweight sand was totally replaced by normal-weight sand. Therefore, a third term is occasionally used:

- ***Specified-density concrete***: This type of concrete consists of any blend of conventional and lightweight aggregates to obtain a specified density, which can range from all-lightweight concrete to normal-weight concrete.

Effectively, this is the type of concrete now specified using the AASHTO LRFD-8 Design Specifications Section 5.2 because the definition of lightweight concrete no longer includes any reference to constituent materials (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Since the AASHTO LRFD-8 Design Specifications requires the grades or properties of all materials to be specified in the contract document as shown in Section 5.4.1 (23 CFR 625.4(d)(1)(v)), the concrete supplier can use a blend of lightweight and normal-weight aggregates that conform to the standards for the grades of construction materials as specified in AASHTO LRFD Construction Specifications (23 CFR 625.4(d)(1)(iv)) to design the concrete mix that provides the best combination of economy and performance to meet the specified project objectives for density and other properties (such as workability, pumpability, strength, and durability).

2.2.2 Types of Density for Lightweight Concrete

For bridge applications, the range in density for lightweight concrete typically varies from 0.110 to 0.125 kcf. For comparison, normal-weight concrete typically has a density in the range of 0.140 kcf to 0.155 kcf (Kosmatka and Wilson 2016). However, if necessary, a density as low as 0.090 kcf may be achieved. Additional information on density is given in section 3.3.2, where the selection of densities for design is discussed.

Whenever the density of lightweight concrete has been mentioned up to this point, a type of density has not been specified. This section describes the types of density for lightweight concrete that are necessary to successfully specify and use lightweight concrete. Because they involve both fresh and hardened conditions, the discussion precedes the discussions of other fresh and hardened properties of lightweight concrete that follow in section 2.2.3 and 2.2.4.

2.2.2.1 Fresh Density

Fresh density is the density of fresh concrete in its plastic state, which is measured at delivery and placement, or when the concrete is still workable or plastic.

This density is used for acceptance when concrete is delivered. It may be specified by the designer. If the equilibrium density (see below) is specified instead, the concrete supplier should determine the fresh density corresponding to the equilibrium density which will be used as the limit for acceptance.

2.2.2.2 Equilibrium Density

Lightweight aggregate is generally prewetted prior to batching. Therefore, there is more water within lightweight concrete than there is in normal-weight concrete with similar mix proportions. As the concrete cures, absorbed moisture is released that contributes to continued hydration of cement and reaction of supplemental cementitious materials. However, moisture that is not bound in reaction products may migrate out of the concrete with time, resulting in a small reduction in density. The reduced density that occurs with time is referred to as the "equilibrium density." This type of density appears in the definitions of lightweight and normal-weight concrete in section 5.2 of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(iv)). The AASHTO LRFD Construction Specifications states *"the equilibrium density of lightweight concrete shall be determined by ASTM C567"* (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)), which provides the description for the term equilibrium density and three methods for determining the equilibrium density:

- ***Equilibrium density***: The density … reached by structural lightweight concrete after exposure to relative humidity of 50 ± 5 % and a temperature of 23 ± 2 °C [73.5 ± 3.5 °F] for a period of time sufficient to reach constant mass.

Therefore, equilibrium density is simply the density of concrete reached after excess moisture from the lightweight aggregate has escaped from the concrete. ASTM C567[5] provides three methods for determining the equilibrium density for lightweight concrete:

1. By calculating the oven dry density from mix proportions and adding 0.003 kcf.
2. By determining the oven dry density of concrete cylinders and adding 0.003 kcf.
3. By measuring the density of concrete cylinders placed in a specified drying environment.

The calculated value (first method) is most widely used (NRMCA 2016). Current specification limits for oven drying of concrete may not adequately capture the true oven dry condition due to the slow rate at which moisture may be driven off from relatively impermeable mixtures. Therefore, if the second method is used, it is suggested that concrete samples be dried for an extended period to achieve an accurate oven dry condition.

While the great majority of applications of lightweight concrete for bridge construction will allow the concrete to dry, some applications, especially those in marine situations where the lightweight concrete is fully or partially submerged or may be constantly rewetted, may not allow drying to occur. In such cases, the reduction in density below the fresh density, which is computed as the equilibrium density, will not be achieved because the concrete cannot dry. If lightweight concrete is used in mass concrete applications, it may also be prudent to use the fresh density or some partial reduction in density, because it may be unlikely that the moisture at the center of a large mass of lightweight concrete will be able to migrate out and result in a loss of density.

The term "air-dry unit weight" was commonly used in the past to recognize the loss of density with time for lightweight concrete, so it is similar to the equilibrium density. However, the term is no longer used in current specifications.

2.2.2.3 Density for Acceptance at Delivery

The fresh density is used as the basis for acceptance of the concrete at delivery. When only the equilibrium density is specified, a corresponding fresh density can be computed using mixture proportions, which can then be used for acceptance at delivery. When the fresh density is not

[5] ASTM C567, Standard Test Method for Determining Density of Structural Lightweight Concrete, is not incorporated in the CFR Title 23. However, ASTM C567 is referenced in the AASHTO LRFD Construction Specifications (23 CFR 625.4(d)(1)(iv)).

specified, the fresh density corresponding to the equilibrium density, which will be used for acceptance should be agreed upon prior to delivery of concrete (NRMCA 2016).

In some cases, the designer may choose to specify only the fresh density, especially when the computed difference between the fresh and equilibrium density is small, on the order of 0.005 kcf or less. This approach may be used with mixtures that use a low absorption lightweight aggregate, or for which a low *w/cm* is used, such as for prestressed concrete girders.

2.2.2.4 Density Allowance for Reinforcement in Reinforced Concrete

Densities of lightweight concrete used to determine material properties for design, such as estimating the modulus of elasticity or determining the concrete density modification factor (discussed later), and in specifications for construction, are intended to be plain concrete, i.e., without reinforcement. However, for computing dead loads, the density of reinforced concrete should be used. Typically, as noted in the AASHTO LRFD-8 Design Specifications article C3.5.1, the density of reinforced concrete is taken as 0.005 kcf greater than the density for plain concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). While this may be adequate for many cases, it is suggested that this increment of density be evaluated when elements are heavily reinforced. This is especially important for precast elements where weights are important for transportation (including permitting) and safe handling. It is also especially significant for lightweight concrete where the density of the concrete is generally an important factor in the design. In some cases, it has been found that the reinforcement may add as much as 0.010 kcf (Chapman and Castrodale 2016) or more to the density of plain concrete.

2.2.2.5 Density and Unit Weight

When describing lightweight and normal-weight concrete, the AASHTO LRFD-8 Design Specifications use the term "density" (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). However, "unit weight" has been used in the specifications for many years and is still used in the definition of terms such as w_c, the unit weight of concrete. The terms "unit weight" and "density" appear to be used interchangeably in the specifications. This document will also use both terms.

2.2.3 Fresh Concrete Mechanical Properties

The fresh properties of lightweight concrete, such as slump and air content, are similar to those for normal-weight concrete. Some test methods are different, as discussed in chapters 5 and 6.

Because of its reduced density, a lightweight concrete mixture with the same workability as a normal-weight concrete mixture will slump slightly less because there is less weight to drive the slumping of the concrete. See discussion in section 5.5.

Entrained air is generally specified in concrete to achieve freeze-thaw resistance. It can also be used to improve workability and to reduce bleeding and segregation (Kosmatka and Wilson 2016). However, for lightweight concrete, air entrainment is an important component in the reduction of concrete density. Therefore, proper concrete delivery and placement techniques should be used to preserve the air content. As noted in chapters 5 and 6, to determine the entrained air content for concrete, the AASHTO LRFD Construction Specifications require standard testing method of AASHTO T 152[6] which suggests the volumetric method of AASHTO T 196[7] to determine the entrained air content for lightweight concrete (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

Lightweight concrete can be proportioned to provide self-consolidating concrete. As with normal-weight concrete, the mixture should be properly proportioned to prevent segregation. Ozyildirim (2014) reports on the fabrication, material properties, and performance of bridge girders fabricated with lightweight self-consolidating concrete.

2.2.4 Hardened Concrete Mechanical Properties

Data on the mechanical properties of lightweight concrete from both research studies and field production are presented in this section to demonstrate actual performance of the material. Section 2.2.5 discusses design parameters that are affected by the use of lightweight concrete but are not material properties, such as flexure and shear, prestress losses, camber, and transfer and development lengths.

Data presented here provide only a small sample of relevant data; additional data are available in the cited references and many other sources including Kahn et al. (2004), Russell (2007), Byard and Schindler (2010), Cousins et al. (2013), Greene and Graybeal (2013), and Chapman and Castrodale (2016), as well as some thorough discussions in older references by FIP (1967), Freedman (1985) and T. Y. Lin International (1985). Information is also presented in Holm and Bremner (2000) and ACI 213[2] (2014). It may be useful for a designer to review test results, such as those presented in this section, to obtain a better perspective of the variability of the data and the accuracy of the prediction for each of the material properties used in design.

Some test results in the past have shown a reduction in tensile and shear strengths and an increase in creep and shrinkage for lightweight concrete relative to normal-weight concrete. This may have made some designers reluctant to use lightweight concrete because they perceived it as having inferior properties. However, other past and recent test results indicate that the properties of lightweight concrete can be close to the properties expected for conventional normal-weight concrete, and may, in some cases, provide better properties. The modulus of elasticity and coefficient of thermal expansion for lightweight concrete are consistently less than for normal-weight concrete, but these reduced properties can be beneficial in some design situations. The bridges described in chapter 7 for which lightweight concrete has been used demonstrate that differences in material properties may not present a barrier to its successful use. Tests also show that lightweight concrete has essentially the same or even improved durability compared to normal-weight concrete with the same quality and compressive strength (see section 2.2.7).

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[6] AASHTO T 152, Standard Method of Test for Air Content of Freshly Mixed Concrete by Pressure Method, is not incorporated in the CFR Title 23. However, AASHTO T 152 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

[7] AASHTO T 196, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

2.2.4.1 Density

Lightweight concrete density descriptions were discussed in Section 2.2.2. The density of lightweight concrete is related to the compressive strength of the concrete and the type of lightweight aggregate that is used, which is also the case for normal-weight concrete. The relationship between density and compressive strength, and the densities suggested for use in design, are discussed in chapter 3.

The density of hardened concrete cylinders will typically be greater than the density of fresh concrete measured in a unit weight bucket because of the greater consolidation achieved in cylinder molds.

2.2.4.2 Compressive Strength

Conventional concrete compressive strengths specified for design are easily achieved with lightweight concrete. Bridge projects in the United States have used lightweight concrete in pretensioned girders with design compressive strengths from 8.5 to 10 ksi (Ozyildirim 2009, Ozyildirim 2014, Liles and Holland 2010, Holland and Kahn 2010, Chapman and Castrodale 2016, West 2019). Some research projects have reported that design compressive strengths for lightweight concrete greater than 8 ksi could not be achieved with some lightweight aggregates; however, field experience shows that high compressive strengths can be achieved using several aggregate sources (Greene and Graybeal 2013).

Experience with laboratory and field production of lightweight concrete has shown strength gain with time is similar to normal-weight concrete for both decks (Byard and Schindler 2010) and girders (Chapman and Castrodale 2016).

2.2.4.3 Modulus of Rupture and Direct Tensile Strength

The AASHTO LRFD-8 Design Specifications refer to three types of tensile strengths: modulus of rupture, direct tensile strength, and splitting tensile strength, which are addressed in the AASHTO LRFD-8 Design Specifications articles 5.4.2.6, 5.4.2.7, and 5.4.2.8, respectively (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). This section will discuss the modulus of rupture and the direct tensile strength. The next section will discuss the splitting tensile strength, which is most relevant for design using lightweight concrete, and the related concrete density modification factor, λ.

The modulus of rupture, f_r, (AASHTO LRFD-8 Design Specifications article 5.4.2.6 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) is often used as an indication of the flexural tensile strength of concrete, but it is best suited for elements that are not thick, such as deck slabs, pavements, and slabs on grade (Kosmatka and Wilson 2016). Freedman (1985) states that the modulus of rupture gives a considerably higher tensile strength than either the splitting tensile or direct tensile strengths. Modulus of rupture values vary with the depth of the test specimen, because the measured tensile strength is affected by the strain gradient (Freedman 1985) and is also sensitive to curing conditions (Russell 2007).

Direct tensile strength is mentioned in the AASHTO LRFD-8 Design Specifications article 5.4.2.7 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). However, there is no standard test for determining this quantity, so it is not practical for use in design. Article C5.4.2.7 provides an expression that can be used to estimate the direct tensile strength of normal-weight concrete: $f_t = 0.23 \sqrt{f'_c}$. However, the expression has not been modified for use with lightweight concrete by introducing λ.

2.2.4.4 Concrete Density Modification Factor and Splitting Tensile Strength

The AASHTO LRFD-8 Design Specification article 5.4.2.8 is titled "Concrete Density Modification Factor" (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The splitting tensile strength is included in the definition of the factor but an expression for the quantity is not given in the specifications. Therefore, both terms are discussed in this section.

The most widely accepted measure of the tensile strength of lightweight concrete is the splitting tensile strength, f_{ct}, which is determined using AASHTO T 198[8] (ASTM C496) as required in the AASHTO LRFD-8 Design Specifications, section 5.4.2.7 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). It is a more reliable measure of tensile strength than the modulus of rupture; it has less variability in test results and gives a reasonably accurate indication of the tensile strength of concrete, although it slightly overestimates the true axial tensile strength (Freedman 1985). Therefore, it is suggested that the splitting tensile strength be used for calculations where an accurate representation of the tensile strength of concrete is necessary.

While not explicitly stated in the AASHTO LRFD-8 Design Specifications, the expected value of the splitting tensile strength of normal-weight concrete can be computed as $f_{ct} = 0.213 \sqrt{f'_c}$ by solving AASHTO LRFD-8 Design Specifications equation 5.4.2.8-2 for f_{ct} with $\lambda = 1.0$, the value of λ for normal-weight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The AASHTO LRFD-8 Design Specifications have provided reduction factors that account for the potential that the tensile strength of lightweight concrete is less than the tensile strength of normal-weight concrete with the same compressive strength (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). As a result, design properties of lightweight concrete related to tensile strength, such as shear and development length, have been reduced in design specifications. With a major revision to the LRFD Design Specifications that was adopted in 2015, the reduction factor was assigned a name, the concrete density modification factor, and a variable, λ, as shown in section 5.4.2.8 of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). With the assignment of a variable as part of the revision, the factor was also inserted into equations where appropriate.

While the tensile strength of lightweight concrete may be less than normal-weight concrete, this is not always the case. Freedman (1985) reported that test data indicate splitting tensile strengths of lightweight concrete ranges from about 70 to 100 percent of values for normal-weight concrete. Data from Cousins et al. (2013) and others as discussed below show that, for a range of lightweight aggregate types and compressive strengths, the splitting tensile strength of lightweight concrete can be equal to or greater than the splitting tensile strength computed for

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[8] AASHTO T 198, Standard Testing of Testing for Splitting Tensile Strength of Cylindrical Concrete Specimens, is not incorporated in the CFR Title 23. However, AASHTO T 198 is referenced in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

normal-weight concrete with the same compressive strength using the AASHTO LRFD-8 Design Specifications expression mentioned above (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Test data on lightweight concrete bridge deck mixes reported by Byard and Schindler (2010) illustrate this point. The researchers used three sources of lightweight aggregate, which represented three types of raw materials. Splitting tensile strength and compressive strength test results for the normal-weight concrete control mixture and the three sand-lightweight concrete mixtures are summarized in Table 5. The data show that the splitting tensile strength of lightweight concrete bridge deck mixes for all three lightweight aggregate sources exceeded the splitting tensile strength for the normal-weight concrete control mix. The last column of the table presents the ratio of the splitting tensile strength test results to the expected splitting tensile strength for normal-weight concrete, which is taken as $0.213\sqrt{f'_c}$, computed using the measured compressive strength for each concrete. Data in the table indicate that all of the sand-lightweight concrete mixtures had tensile strengths exceeding the expected tensile strength computed using the measured compressive strength of the concrete, that is, the ratio is greater than unity, while the tensile strength test result for the normal-weight concrete control mixture was 12 percent below the expected tensile strength. All of the tensile strength test results for the sand-lightweight concrete mixtures shown in Table 5 also exceed the expected splitting tensile strength of 0.426 ksi computed using an assumed design compressive strength of 4 ksi. Similar behavior was observed for all-lightweight concrete mixtures with all of the all-lightweight mixtures also having values for the ratio in the last column that were greater than unity (Castrodale 2019). These data indicate that the splitting tensile strength for all three types of lightweight aggregate were equal to or exceeded the tensile strength expected for normal-weight concrete, which means that no reduction for reduced tensile strength would be necessary in designs using these mixtures.

Table 5. Splitting tensile and compressive strength test results and comparison of test results to predicted splitting tensile strength for sand-lightweight and normal-weight bridge deck concrete mixtures (data from Byard and Schindler 2010).

Type of Concrete	f_{ct} (ksi)	f'_c (ksi)	$f_{ct} / (0.213\sqrt{f'_c})$
NWC	0.438	5.505	0.880
LWC with Slate LWA	0.490	5.135	1.02
LWC with Clay LWA	0.520	5.200	1.08
LWC with Shale LWA	0.510	4.980	1.08

Splitting tensile test results from production of prestressed lightweight concrete girders (Chapman and Castrodale 2016) were discussed by Castrodale (2019). Data for three projects that used the same lightweight concrete mix proportions and type of lightweight aggregate had measured splitting tensile strengths greater than the expected tensile strength computed using the specified compressive strength. Data presented in Greene and Graybeal (2013) also demonstrate that measured mean splitting tensile strengths for lightweight concrete for girders made with three different types of lightweight aggregate exceed the computed splitting tensile strengths computed using the design 28-day compressive strength.

2.2.4.5 Modulus of Elasticity

The porous nature of lightweight aggregate reduces its stiffness, which results in the reduction of the modulus of elasticity of lightweight concrete compared to normal-weight concrete of the same compressive strength and other mix design parameters. This reduction has been accounted for in the equation for modulus of elasticity in previous and outdated versions of AASHTO bridge design specifications since the 1960s by including the concrete unit weight (density) term. In 2014, a revised equation for the modulus of elasticity, E_c, was adopted as shown in the LRFD Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$E_c = 120{,}000\, K_1\, w_c^{2.0}\, f'_c{}^{0.33}$$

Where

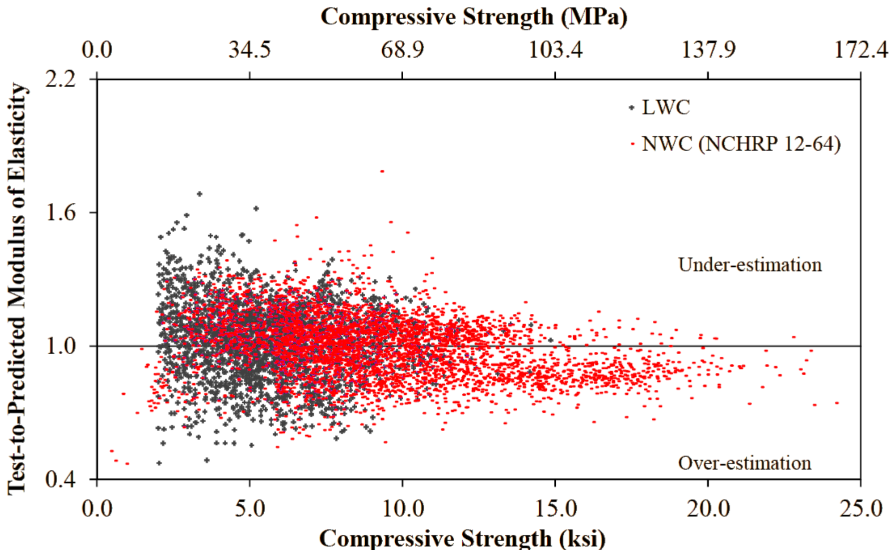
K_1 = correction factor for source of aggregate taken as 1.0 unless determined by physical test, and as approved by the Owner.

w_c = unit weight of concrete (kcf).

f'_c = compressive strength of concrete for use in design (ksi).

The aggregate correction factor, K_1, can be used to adjust the equation for lightweight aggregates. However, it was shown for one project that using the default value of $K_1 = 1.0$ gave a result close to the measured value (Castrodale and Hanks 2016). The unit weight of concrete, w_c, used in this equation should be for unreinforced (plain) concrete.

The equation adopted in 2014 gives a better estimate for lightweight concrete and for high strength concrete (Greene et al. 2015) compared to the prior equation. The 2014 equation still includes a term for the density of concrete; however, the effect of a change in density is greater for the 2014 equation when compared to the prior equation because the exponent on the density has been increased from 1.5 to 2. To demonstrate the expected reduction in modulus of elasticity for lightweight concrete as computed by the 2014 equation, lightweight concrete with a density of 0.115 kcf is computed to have a modulus that is 63 percent of the value for normal-weight concrete (0.145 kcf) with the same compressive strength; for an all-lightweight concrete mix with a density of 0.100 kcf, the modulus is predicted to be 48 percent of the value for normal-weight concrete with the same compressive strength. However, while the equation provides improved prediction of the modulus of elasticity, there is still wide scatter associated with the prediction the modulus of elasticity of concrete for both lightweight and normal-weight concrete as is evident in Figure 7 (Greene and Graybeal 2013). For this figure, the prediction equation differs slightly from the equation adopted in 2014 because a different coefficient (121,400 rather than 120,000) was used. However, trends in the data are still close to what would be presented if the equation adopted in 2014 had been used.

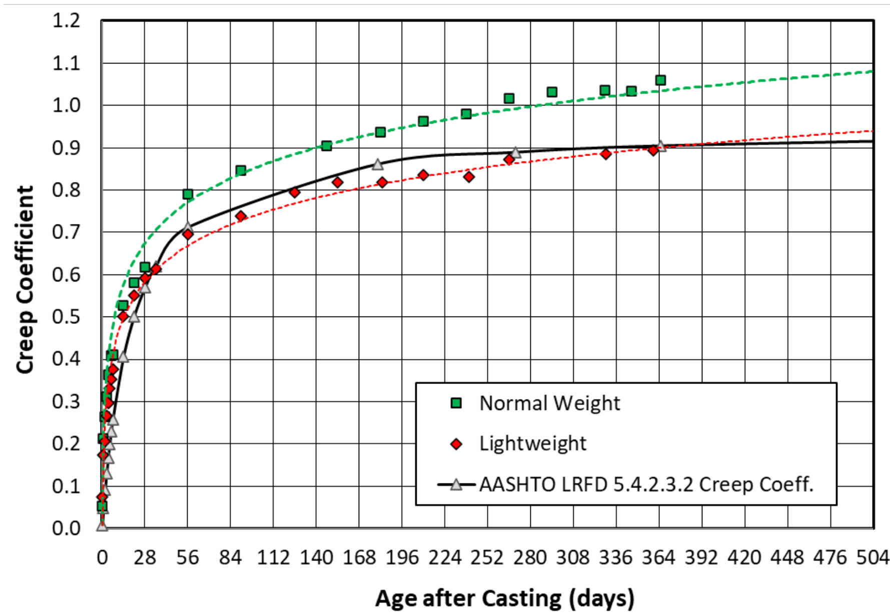


Source: FHWA

Figure 7. Graph. Modulus of elasticity test-to-prediction ratio compared to compressive strength.

2.2.4.6 Creep

Many designers assume that creep of lightweight concrete is greater than for a comparable normal-weight concrete. However, it has been shown that creep of higher strength lightweight concrete is similar to the creep expected for normal-weight concrete (Cousins et al. 2013, Lopez et al. 2004). Test results for a lightweight concrete production mix with a design compressive strength of 9 ksi for a prestressed girder shown in Figure 8 demonstrate that creep can even be less than for a comparable normal-weight concrete mix (Chapman and Castrodale 2016). This is not a new discovery, as Freedman (1985) reports that "high-strength lightweight concrete has about the same shrinkage and creep as comparable normal-weight concrete." The 1985 FHWA report has a similar statement regarding creep and shrinkage of lightweight concrete being similar to those of normal-weight concrete.

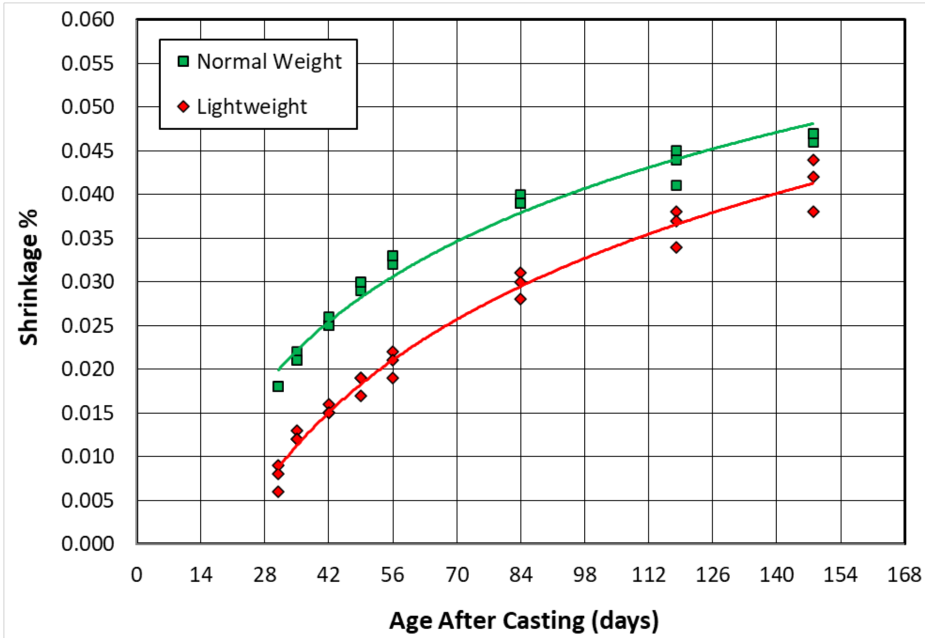


Original Graph: © 2016 PCI

Figure 8. Graph. Creep of high strength lightweight and normal-weight concretes.

2.2.4.7 Shrinkage

It is commonly assumed that shrinkage of lightweight concrete is greater than for normal-weight concrete because the less stiff lightweight aggregate offers less resistance to shrinkage strains. However, shrinkage of high strength lightweight concrete can be similar to values for normal-weight concrete as noted above in the discussion of creep (Freedman 1985, T. Y. Lin International 1985). It is also reported that shrinkage of lightweight concrete can range from slightly less to 30 percent more than normal-weight concrete (Freedman 1985). Additional data for the project reported by Chapman and Castrodale (2016) are shown in Figure 9. The data show that the lightweight concrete girder concrete had less shrinkage than the comparable normal-weight concrete mix. This behavior was unexpected because the lightweight concrete mixture had a total cementitious materials content of 935 lb/yd^3 while the normal-weight concrete mixture had only 752 lb/yd^3, which would typically result in the lightweight concrete mixture having significantly greater shrinkage. Test results for shrinkage for both lightweight concrete and normal-weight concrete can vary considerably between mixtures and aggregate types (Lopez et al. 2004, Chapman and Castrodale 2016, Ozyildirim 2009), so it is not possible to state a relationship that applies in all cases. Lightweight concrete typically exhibits less early-age shrinkage than normal-weight concrete because of the effect of internal curing.



Original Graph: © 2016 PCI

Figure 9. Graph. Shrinkage of high strength lightweight and normal-weight concrete.

2.2.4.8 Stress-strain Curve in Compression

Lightweight concrete has been shown to have linear stress-strain behavior to higher stress level than is typical of normal-weight concrete, even up to 90 percent of the ultimate strength (Neville 2011). This is an indication that there is less microcracking between the aggregate and paste in lightweight concrete; when microcracks are present, they soften the behavior of the concrete as the microcracks open when load is applied. The lack of microcracking in lightweight concrete is the result of the stiffness of the paste being closer to the stiffness of the aggregates, so lightweight concrete behaves more like a homogeneous material (Neville 1997). Evidence of the lack of microcracking has been demonstrated in the gas permeability of lightweight concrete, which is discussed in section 2.2.7.1. A consequence of this more homogeneous behavior of lightweight concrete, which is similar to the behavior observed for high strength normal-weight concrete, is that cracking generally occurs through aggregate particles leaving a smooth crack surface.

2.2.4.9 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) is generally assumed to be less than for normal-weight concrete. Test data for the coefficient of thermal expansion for lightweight concretes are presented in Russell (2007), Byard and Schindler (2010), Holland and Kahn (2010), and Cavalline et al. (2017). Values for the coefficient of thermal expansion for normal-weight concrete vary considerably depending on aggregate type as demonstrated by data in Freedman (1985), where values for normal-weight concrete range from 3.4 to 8.7 × 10^{-6} / °F for a range of aggregate types; for lightweight concrete, Freedman shows data ranging from 3.6 to 4.5 × 10^{-6} / °F. This information indicates that lightweight aggregate is in the low end of the range of values for normal-weight concrete. Therefore, the coefficient of thermal expansion for lightweight concrete will be comparable for concrete made with aggregate with a low quartz content, like limestone, but the coefficient will be significantly lower than concrete made with high quartz content aggregate, such as quartzite and sandstone, and somewhat lower than normal-weight concrete made with aggregate with an intermediate quantity of quartz, including igneous rocks such as basalt and granite (Freedman 1985).

Byard and Schindler (2010) report data for the coefficient of thermal expansion for the bridge deck mixtures shown in Table 6. These mixtures, which satisfied typical State Department of Transportation (DOT) specifications, included three types of lightweight aggregate, each with three types of mixes as shown, and a normal-weight concrete control using river gravel for the coarse aggregate. These data indicate that coefficients of thermal expansion for sand-lightweight concrete and all-lightweight concrete mixtures were about 80 percent and 65 percent, respectively, of the coefficient for the normal-weight concrete control mixture.

Table 6. Coefficient of thermal expansion for lightweight and normal-weight concretes (με/°F) (data from Byard and Schindler 2010).

Type of Concrete	Control	Internal Curing	Sand-LWC	All-LWC
NWC	6.2	--	--	--
LWC with Slate LWA	--	5.9	5.1	4.3
LWC with Clay LWA	--	5.8	5.1	4.0
LWC with Shale LWA	--	6.0	5.2	4.0

Note: "Internal Curing" mixture has partial replacement of fine NWA with prewetted fine LWA.

2.2.4.10 Other Thermal Properties

The pores in lightweight aggregate give lightweight concrete thermal insulating properties. Therefore, lightweight concrete responds more slowly to changes in temperature than normal-weight concrete. However, the condition of the pores, which can be empty, partially saturated, or fully saturated with water, can vary, which can cause the effective heat mass and thermal conductivity to vary widely (ACI 213 2014), especially at early ages. More information on thermal properties of lightweight concrete are found in ACI 213[2] (2014), Holm and Bremner (2000), Tatro (2006), and Cavalline et al. (2017).

2.2.4.11 Variation in Properties with Time

Data presented in studies by Byard and Schindler (2010) and Chapman and Castrodale (2016), as well as other studies listed in section 2.2.4, indicate that the variation in material properties, such as compressive strength, tensile strength, modulus of elasticity, creep, and shrinkage, with time for lightweight concrete is generally similar to the increase with time for normal-weight concrete.

2.2.4.12 Fatigue

Fatigue of concrete is not generally a concern for bridges. Holm and Bremner (2000) provide a good review of data on this topic. In general, fatigue properties of lightweight concrete are not significantly different from normal-weight concrete (ACI 213 2014). However, Gerwick (1985) states that high strength lightweight concrete has “far fewer microcracks between paste and aggregate resulting in better high cycle fatigue endurance,” which is a significant concern for the design of offshore structures. Hoff (1994), who was also concerned with the design of offshore structures, also concluded that “under fatigue loading, high-strength lightweight concrete performs as well as high-strength normal-weight concrete and, in many instances, provides longer fatigue life.” Testing by Brown et al. (1995) of the U.S. 19 Bridge over the Suwanee River at Fanning Springs after more than 28 years in service revealed no degradation in behavior from fatigue or other effects.

2.2.5 Design Parameters

This section discusses design parameters, which are not material properties, for which the effects of using lightweight concrete should be considered.

2.2.5.1 Equivalent Rectangular Stress Block Parameters

The simplified approach for computing the flexural resistance of concrete sections uses the principles of the equivalent rectangular stress block to approximate the effect of the actual stress-strain behavior of concrete. There are three parameters that are used to describe the stress block: the maximum usable concrete strain, ε_{cu}, the uniform stress factor, α_1, and the stress block factor, β_1. The default values of these quantities given in the AASHTO LRFD-8 Design Specifications are used for lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Use of these values is supported by data presented by Russell (2007) as discussed below.

Limited data are available for the failure strain of concrete in compression, ε_{cu}, which is also called the maximum useable concrete compressive strain. Based on the evaluation of available data, Russell (2007) found that the strain used for normal-weight concrete, 0.003 in./in., was conservative for most of the reported lightweight concrete tests.

Data from several sources presented by Russell (2007) demonstrate that the default values of the factors α_1 and β_1, as given in the AASHTO LRFD-8 Design Specifications, are reasonable for use with lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The appropriateness of the default values of these factors can also be evaluated by considering whether the flexural resistance computed using the factors is conservative in predicting test results for lightweight concrete flexural elements. Russell (2007) presents such a comparison, which demonstrates that the measured flexural resistance exceeds the predicted capacity, and is therefore conservative, for almost all available tests for lightweight concrete members. For the few tests where results were not conservative, the difference appeared to be less than 10 percent.

2.2.5.2 Prestress Losses

Tests have demonstrated that the prestress loss equations in the AASHTO LRFD-8 Design Specifications (AASHTO 2007) (23 CFR 625.4(d)(1)(v)) may be used without modification for prestressed lightweight concrete elements (Russell 2007, Liles and Holland 2010, Cousins et al. 2013). Use of the prestress loss equations without modification for lightweight concrete is possible because creep and shrinkage for prestressed lightweight concrete are within the range of expected behavior of normal-weight concrete as discussed earlier in this chapter.

2.2.5.3 Camber

Cambers and long-term deflections of lightweight concrete girders have been reported by Cousins et al. (2013) and Holland et al. (2011). Both studies found that initial cambers and long-term cambers could be estimated using conventional methods. Because of the reduced modulus of elasticity and reduced weight of lightweight concrete, cambers will typically be greater for lightweight prestressed concrete girders (Castrodale and Harmon 2006, Castrodale et al. 2009).

2.2.5.4 Transfer and Development of Pretensioned Strands

Cousins et al. (2013) report that data collected in their study and data from previous studies confirm that provisions in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) for both transfer and development lengths can be used for lightweight concrete prestressed girders. Holland and Kahn (2010) report that transfer lengths for five lightweight concrete girders were less than the predicted transfer length using provisions in the LRFD Specifications. Russell (2007) presents results from tests that also support the use of current transfer and development provisions for lightweight concrete.

2.2.5.5 Vertical Shear

Using available shear test results for lightweight concrete girders, Russell (2007) reports that the shear design provisions of the previous and outdated versions of LRFD Design Specifications provided conservative estimates of shear capacity, although one of the researchers had concluded that the results for lightweight concrete were less conservative than for similar normal-weight concrete tests. Cousins et al. (2013) and Greene and Graybeal (2019) report results of tests of lightweight concrete girders in shear. Cousins et al. (2013) found that the shear calculations in the previous and outdated versions LRFD Design Specifications gave a conservative estimate of the shear test results even when the concrete density modification factor was not used. Greene and Graybeal (2019) compared computed shear resistance using the previous and outdated versions of LRFD Specifications to their own tests and a database of other shear test data and found that the current procedures work well. They proposed several improvements to the specifications which have been adopted.

2.2.5.6 Horizontal Shear

Russell (2007) reported a lack of data for horizontal shear with lightweight concrete but concluded that current provisions are probably conservative. Cousins et al. (2013) tested several specimens in horizontal shear and found the results to be conservative.

2.2.5.7 Resistance Factors

When the first edition of the LRFD Design Specifications was published in 1994, the same resistance factors were used for lightweight concrete as for normal-weight concrete, except for shear. In that case, a resistance factor of 0.70 was introduced for lightweight concrete while a value of 0.90 was used for normal-weight concrete. The lower resistance factor was introduced because of a lack of data that could be evaluated by the team that developed the specifications. After evaluating their own shear test results Greene and Graybeal (2019) and a database of other shear test results, Greene and Graybeal (2015) proposed the same resistance factor be used for both lightweight concrete and normal-weight concrete. This proposal was adopted by AASHTO in 2015.

2.2.6 Seismic Performance

Lightweight concrete has great potential for use in bridges designed for seismic loadings because its use would reduce the seismic demand on the structure. However, the more brittle nature of lightweight concrete may discourage designers from using lightweight concrete in structures where ductile behavior is needed during a seismic or other extreme loading event. Holm and Bremner (2000) cite several studies that indicate that lightweight concrete can be detailed to perform with the same ductility as normal-weight concrete, although some additional confinement reinforcement may be necessary for columns.

Tests by Kowalsky et al. (2000) of seismically loaded lightweight concrete bridge piers demonstrated "that lightweight concrete, when properly detailed, will perform as well as normal-weight concrete …" A later series of tests reported by Hendrix and Kowalsky (2010) showed that "the strength of the lightweight concrete shear-resisting mechanism appears to be lower than the normal-strength mechanism when subjected to reversed cyclic loads" and strength reduction factors were proposed for use in design. While the concrete strength reductions suggested by the authors were significant, the reduced mass of a lightweight concrete structure would significantly reduce the seismic lateral forces to which a structure would be subjected during a seismic event. Therefore, the researchers concluded that the "reduction in shear demand will more than compensate for the reduced strength of the concrete shear-resisting mechanism." The findings of these studies provide data that support the use of lightweight concrete for bridge superstructure and substructure elements that are designed to resist seismic events.

2.2.7 Durability Properties

Some of the differences in the mechanical properties of lightweight concrete discussed above (such as the modulus of elasticity, shrinkage, and coefficient of thermal expansion) contribute to the observed equal or improved durability of lightweight concrete compared to normal-weight concrete. Other improvements in durability are related to the improved quality of the paste and the more complete reaction of cementitious materials resulting from internal curing. These different types of improvements combine to contribute to a reduction in both permeability and cracking.

In this section, a selection of durability topics is discussed briefly. Comprehensive discussions of the durability of lightweight concrete can be found in Holm and Ries (2007), Castrodale and

Harmon (2008), Ozyildirim (2008), and ACI 213[2] (2014). The potential extension in service life resulting from the improvements in durability for lightweight concrete bridges is discussed in section 2.2.8.

2.2.7.1 Permeability

Permeability has an important influence on concrete durability. Lightweight concrete has improved (reduced) permeability compared to normal-weight concrete as the result of more impermeable paste (from internal curing and elastic compatibility) and reduced cracking. The reduced cracking that lightweight concrete provides as discussed above is also an important factor in reducing the permeability of concrete and providing improved protection against corrosion of embedded reinforcing steel.

ACI Committee 213 (2014) lists seven references that give results of tests comparing the permeability of lightweight and normal-weight concrete. The tests, which used different approaches and material properties, all found that the permeability of lightweight concrete was equal to or lower than the permeability of the comparable normal-weight concrete.

It is often assumed that lightweight concrete made with porous lightweight aggregate cannot achieve specified limits for the rapid chloride permeability test (AASHTO T 277 or ASTM C1202), a common measure of permeability. However, data indicate otherwise. An example of concrete permeability test results from production a sand-lightweight concrete bridge deck for a Virginia DOT (VDOT) project is given in Castrodale and Robinson (2008). VDOT's specifications for deck concrete mixtures at the time required a maximum permeability of 2,500 coulombs (VDOT 2016) determined using elevated temperature curing for the rapid chloride permeability test to provide results more representative of later ages which would include the effect of supplementary cementitious materials (VDOT 2020). Using 17 samples collected over the 6-month construction schedule, the average measured permeability was 989 coulombs, with maximum and minimum test results of 1,467 and 593 coulombs, respectively, all of which were well below the specified limit.

A unique test procedure by Bremner et al. (1992) demonstrated the reduced permeability of lightweight concrete by using gas to pressurize hollow concrete cylinders under different levels of stress and gas pressure. The testing revealed a relationship between gas permeability and the extent of microcracking within the concrete. The initial gas permeability of lightweight concrete was noticeably less than normal-weight concrete. When the applied axial stress exceeded a threshold value, the permeability began to increase rapidly as the stress continued to increase, which indicated the increasing growth and connectivity of microcracks that allowed the gas to pass more readily through the concrete. The report states that "rapid increases in permeability occurred at approximately 54 to 62 percent of the ultimate strength for normal-weight concrete and 72 to 83 percent of the ultimate strength for structural lightweight concrete." Further discussion of this testing can be found in Castrodale and Harmon (2008).

2.2.7.2 Cracking Tendency

Dimensional changes in concrete caused by shrinkage, temperature changes, or other effects may lead to cracking if the movement is restrained. Therefore, the reduced shrinkage, modulus of elasticity, and coefficient of thermal expansion, all of which are features of lightweight concrete that have been presented, result in reduced and/or delayed cracking. Nair et al. (2016) reported that lightweight concrete decks can be constructed that have no cracking or less cracking than normal-weight concrete decks based on the evaluation of field performance for several bridges in Virginia. Based on the experience in Virginia of little or no cracking for lightweight concrete decks, section 217.12 of the Virginia DOT *Road and Bridge Specifications* (2016) includes a lightweight concrete mixture as one of the three options to achieve deck concrete with low shrinkage cracking tendency. The specifications do not require shrinkage testing for lightweight concrete mixtures while testing is required for conventional mixes and those using shrinkage-reducing admixtures. Barrett et al. (2015), Carpenter (2019), and others report that internally cured concrete decks also have a reduced tendency for cracking.

Figure 10 is a typical figure from a study by Byard and Schindler (2010) that shows the development of stresses from restrained shrinkage of normal-weight concrete and three types of lightweight concrete mixtures for one type of lightweight aggregate used in their study. In Figure 10, the following abbreviations are used: CTRL = normal-weight concrete control mixture; SLW = sand-lightweight concrete; ALW = all-lightweight concrete; and Sum = summer.

In Figure 10, age versus concrete stress data are plotted for each mixture until the concrete specimen cracked, which is represented by the end of the data line. Data indicate that normal-weight concrete cracked at less than two days in the fall scenario and at about 1 day in the summer scenario, while the sand lightweight (SLW) and all lightweight (ALW) concrete mixtures did not crack at 4 days for either condition; after 4 days, the researchers reduced the temperature to force the specimens to crack and end the test. These plots show a significant improvement in cracking behaviour for lightweight concrete mixtures compared to the normal-weight concrete control. The behaviour of lightweight concrete made with the two other types of lightweight aggregate (shale and clay) was similar.

2.2.7.1 Corrosion Resistance

While corrosion resistance is not usually considered a property of concrete, it is determined by characteristics of the concrete, such as permeability and the cracking tendency. With the reductions in permeability and cracking tendency that accompany the use of lightweight concrete, it is clear that the corrosion resistance of lightweight concrete would be improved accordingly. ACI 213[2] (2014) discusses the factors that contribute to corrosion resistance of lightweight concrete.

2.2.7.1 Freeze and Thaw Resistance

Lightweight concrete has good resistance to freezing and thawing cycles when properly proportioned, batched and placed. This seems counter-intuitive because lightweight aggregate is more porous. However, the pores are not all connected, so water cannot penetrate deeply into the aggregate. Other features of enhanced durability mentioned above also contribute to the freeze-thaw durability of lightweight concrete. It has performed well on bridge decks in northern climates (Wolfe 2008).

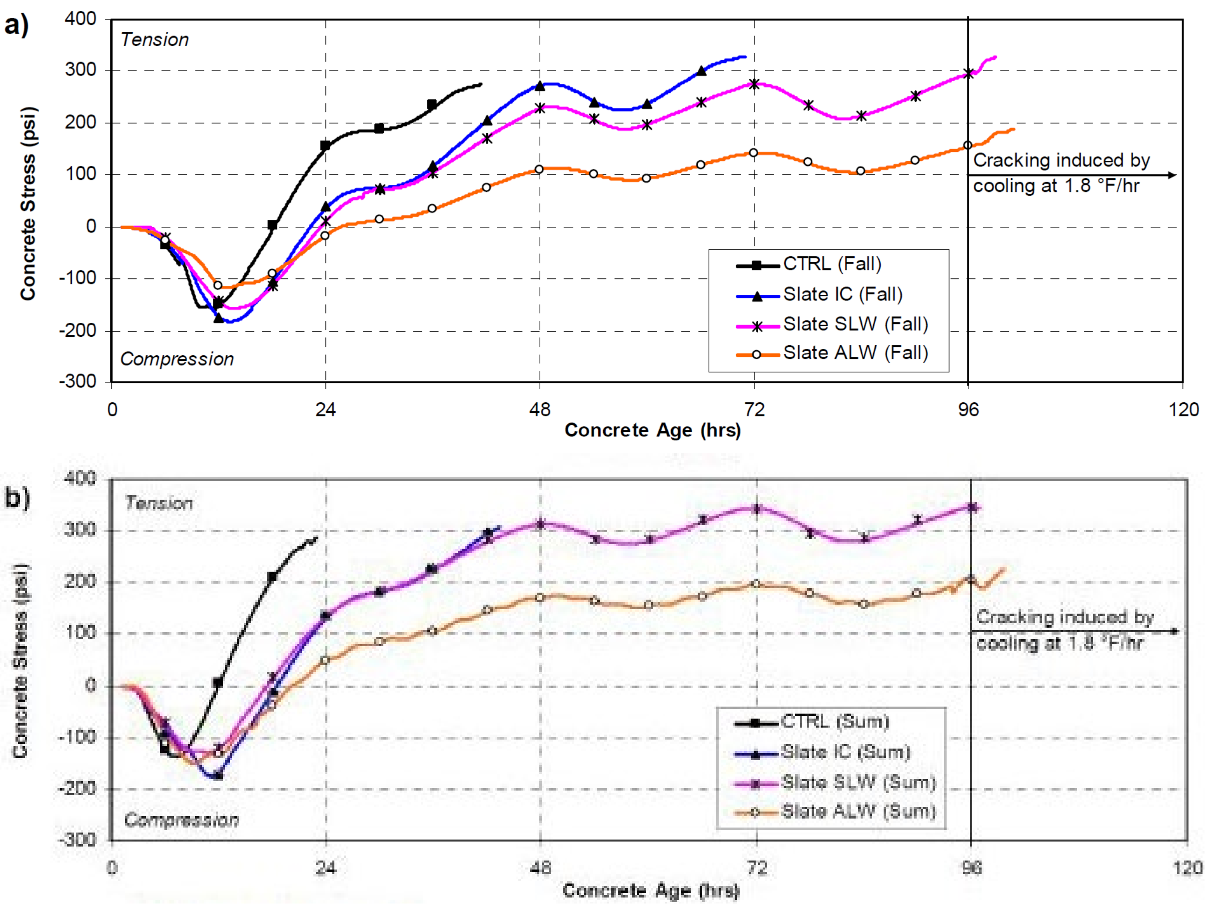


Figure 10. Graph. Initial restrained stress development for lightweight concrete mixtures with slate lightweight aggregate and normal-weight concrete for a) Fall and b) Summer placement conditions

Early laboratory tests of lightweight concrete reported inadequate resistance to freezing and thawing when tested using standard procedures (Klieger and Hanson 1961). It was then found that allowing lightweight concrete to dry prior to exposure to a freeze-thaw environment significantly improved its durability (Kosmatka and Wilson 2016). Therefore, the standard procedure for freeze-thaw testing given in AASHTO T 161[9] was modified for lightweight concrete by provisions in AASHTO M 195[1] ,which call for a drying period before testing. A number of studies have found that lightweight concrete has generally demonstrated resistance to freezing and thawing cycles: Walsh (1967), Holm (1980), ESCSI (1988), and Ramirez et al. (2000). A study by Ozyildirim and Gomez (2005) found unsatisfactory freeze-thaw performance of lightweight concrete, but recognized that a period of drying before testing, as specified in AASHTO M 195, would have improved the results.

It is typical practice to grind bridge decks to achieve proper rideability and profile, and to groove them for skid resistance. To address concerns of whether lightweight concrete bridge decks that

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[9] AASHTO T 161, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

have been ground or grooved will be durable when exposed to freezing and thawing, one lightweight aggregate supplier engaged an independent testing laboratory to conduct freeze-thaw tests for a typical DOT sand-lightweight concrete mixture. Tests on four specimens were conducted according to AASHTO T 161[9] (ASTM C666) as modified by AASHTO M 195[1] (ASTM C330): two specimens had all faces except the ends cut with a saw to expose the interior of the lightweight aggregate particles to freeze-thaw cycling, while the other two specimens were left as cast (see Figure 11 (TEC Services 2009)). After 308 cycles of freezing and thawing, both of the standard (uncut) specimens had a relative dynamic modulus of 102, while the cut-face specimens had relative dynamic modulus values of 100 and 98, showing good performance that was nearly identical to the standard specimens. The NCDOT specification project special provision for sand-lightweight concrete (2011) required a relative dynamic modulus of at least 80 after 300 cycles of freezing and thawing. These test results indicate that lightweight aggregate could be used on bridge decks that are ground and grooved, even if the location is subject to freeze-thaw cycles.

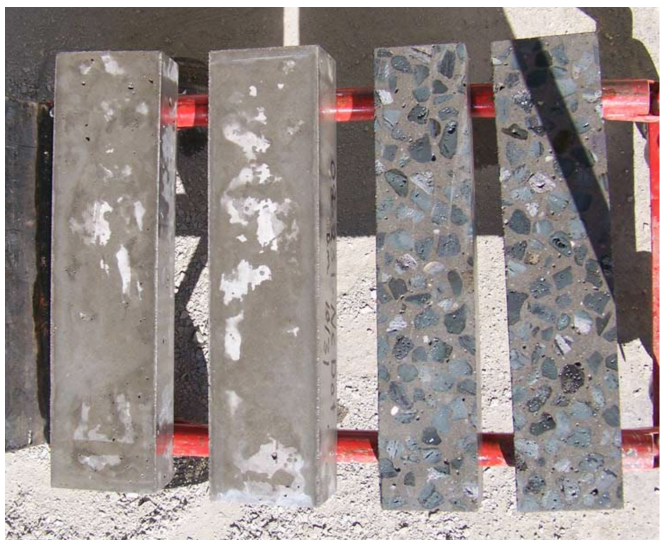

Figure 11. Photo. Freeze-thaw specimens for a typical DOT sand-lightweight concrete deck mixture prior to testing – typical (uncut) specimens are on the left; specimens on the right have all side faces cut to expose the lightweight aggregate .

2.2.7.2 Alkali-Aggregate Reactivity

ACI 213[2] (2014) reports that there are no documented instances of damage to structures in the field caused by alkali reactions with lightweight aggregate. The pores within lightweight aggregate particles are also thought to provide space into which detrimental reaction products can form without damaging the concrete. The reduced permeability of lightweight concrete may also contribute to this performance, because without the presence of water, detrimental reactions cannot proceed. It has also been suggested that the firing of manufactured lightweight aggregate to high temperatures activates the surface of the aggregate so that it can "act as a source of silica to react with the alkalis from the cement at an early age to counteract any potential long-term disruptive expansion" (Holm and Ries 2007). This may be the reason that combining lightweight aggregate with reactive aggregates tends to reduce the detrimental expansion of concrete (Holm and Ries 2007). A study by Ideker et al. (2016) concluded that the substitution of lightweight aggregate in concrete mixtures with reactive normal-weight aggregate was effective in reducing the expansion caused by alkali-silica reaction in both concrete and mortar.

2.2.7.3 Abrasion

Field experience has shown that the wear characteristics of lightweight concrete bridge decks subjected to auto and truck traffic are similar to normal-weight concrete (Holm and Bremner 2000). There does not appear to be a direct correlation between the results of aggregate abrasion tests with the abrasion resistance of concrete made with the same aggregate. Therefore, the abrasion resistance of concrete should be determined by abrasion tests of the concrete itself (Kosmatka and Wilson 2016). This would indicate that it may be possible, as indicated by field experience, that lightweight concrete could have good abrasion resistance.

Comparative data from measurements of wear on bridge decks are limited. One set of data are presented in Castrodale and Harmon (2008). Lightweight concrete batched with expanded clay coarse aggregate and quartz sand was used for all elements of a drop-in span, including prestressed girders, for the Sebastian Inlet Bridge in Florida which was completed in 1964 (ESCSI 2001b). The design density of the lightweight concrete deck was 0.115 kcf. Normal-weight concrete with a fossiliferous limestone coarse aggregate and quartz sand was used for the remainder of the structure. Florida DOT (2007) investigated the wear of the normal-weight and lightweight concrete decks on the bridge in 1997 and again in 2006. Results from depth of wear measurements on the two-lane deck showed that the wear of the lightweight concrete deck was less than the wear of the adjacent normal-weight concrete deck (data are presented in Castrodale and Harmon (2008)).

2.2.7.4 Thermal Effects

Holm and Bremner (2000) have a significant discussion of thermal properties of lightweight concrete, including thermal expansion, specific heat, thermal diffusivity, and thermal conductivity. Cavalline et al. (2017) present data on several thermal properties of expanded slate lightweight aggregate. These properties can all affect the durability of a structure. A thorough study of the effects of the thermal properties of lightweight concrete on the durability of a bridge, such as the magnitude of deformations during daily and seasonal temperature changes and the resulting effect on stresses, bearings, joints, and connections within the structure, has not been performed. It is anticipated that such a study may reveal further benefits to the use of lightweight concrete that are not currently being considered.

Because lightweight concrete has insulating properties, lightweight concrete may reach a higher initial peak temperature during hydration and may reach it more rapidly than normal-weight concrete with the same quantity of cementitious materials, and therefore, the same potential total heat of hydration (ACI 213 2014). This could result in durability concerns. Maggenti (2007) discusses this effect, which was experienced in the construction of the Benicia-Martinez Bridge, a major segmental box girder structure that used lightweight concrete with a high cementitious content. However, Tankasala et al. (2017) have found that the lower modulus of elasticity and coefficient of thermal expansion of lightweight concrete combine to significantly reduce the effects of the increased temperature that would typically be experienced if normal-weight concrete were used.

2.2.8 Service Life

Based on the improved durability-related properties of lightweight concrete, the service life of structures constructed using the material is expected to be extended. However, few such analyses for lightweight concrete have been conducted. Results of some studies of extended service life for internally cured concrete bridges are presented in section 2.3.

2.2.9 Safety Properties

2.2.9.1 Skid Resistance

As concrete decks are exposed to traffic and environmental conditions, the concrete will wear, exposing the lightweight aggregate. When lightweight concrete decks wear, the internal pores of the lightweight aggregate particles are exposed. The exposed pores of the lightweight aggregate provide excellent skid resistance which continues to be refreshed as wear continues, rather than polishing and experiencing a reduction in skid resistance that occurs with some normal-weight aggregates (T. Y. Lin 1985). This good skid resistance also applies for decks that are ground to achieve the final profile.

2.2.9.2 Fire and Blast Resistance

The insulating properties of lightweight concrete give it greater fire resistance than normal-weight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion, and high temperature stability (ACI 213 2014). While fire resistance is not generally considered as a durability concern for bridges, the recent greater focus on resiliency and hardening infrastructure in the United States should make this aspect of lightweight concrete performance worthy of further investigation for bridges. For building construction, the improved fire resistance of lightweight concrete is widely accepted and is commonly used to reduce the thickness of a floor needed for a certain fire rating. Because lightweight aggregate is exposed to high temperatures during manufacturing, it remains stable to elevated temperatures that may occur in a fire, while some types of conventional aggregate become unstable at high temperatures. However, because lightweight concrete initially has more water content than normal-weight concrete, any remaining moisture in the concrete may cause more spalling during a fire event than would be expected for a normal-weight concrete (Holm and Bremner 2000, ACI 213 2014).

While data are limited, low density lightweight concrete has been shown to have improved resistance to blast and to firearm projectiles (Speck and Burg 2000).

2.3 INTERNAL CURING

Introductions to the concept of internal curing of conventional concrete mixtures by using prewetted lightweight fines have been published by ACI 308-213[10] (2013), Weiss et al. (2012), ESCSI (2012a, 2014), Byard and Ries (2012), Castrodale (2016a), and Rupnow et al. (2016). A comprehensive state-of-the-art report on the subject was prepared by Bentz and Weiss (2011)

[10] ACI 308-213, Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate, is not incorporated in the CFR Title 23. Therefore, this industry publication is not a federal requirement.

and a compilation of papers on a range of topics related to internal curing was edited by Schindler et al. (2012). Brief summaries of relevant topics are given in this section.

2.3.1 Concept of Internal Curing

Lightweight concrete for which the lightweight aggregate is prewetted prior to batching releases water into the concrete as it hardens. This effect was recognized as "internal curing" in lightweight concrete by the 1950s, and possibly earlier. It contributes to improved concrete quality by facilitating continued hydration of cement and more complete reaction of supplementary cementitious materials.

In the last two decades, the concept of replacing a portion of the sand in a conventional normal-weight concrete mixture with prewetted lightweight fines (sand) to provide internal curing that can improve durability of conventional concrete has been explored and refined. ESCSI published specifications (2012b) for internally cured concrete that includes a description for internal curing. ASTM C1761[11] specifies minimum physical properties for lightweight aggregate to be used for internal curing, test methods for absorption and desorption, and a procedure for calculating the quantity of lightweight aggregate.

The goal of this approach is to modify a conventional concrete mixture with prewetted lightweight aggregate to provide internal curing, not reduce its density. Because lightweight aggregates have a relatively high capacity for absorbing water, they offer a convenient means to deliver curing water to the interior of a concrete element using a structural material that does not compromise the strength of the concrete. In many cases, the resulting concrete still meets the LRFD Specifications description of normal-weight concrete as having a density greater than 0.135 kcf and not exceeding 0.155 kcf, so the concrete does not have to be considered lightweight concrete and the design does not have to be modified. Therefore, a discussion of internal curing does not appear in chapter 4 on design. However, if the density of an internally cured mixture is less than 0.135 kcf, the design should be modified as discussed in chapter 4.

The concept is illustrated by Figure 12 (Castrodale 2016a) which gives a graphical representation of the constituents of a conventional concrete mixture and a concrete mixture that has been modified to provide internal curing. From the figure, it is clear that the mix proportions for the conventional and internally cured mixtures are the same, except for the replacement of a volume of conventional sand with prewetted lightweight sand that carries curing water into the concrete.

2.3.2 Benefits of Internal Curing

The fundamental benefit of internal curing is that the relative humidity within the concrete is maintained at a higher level than in conventional concrete, which allows continued curing of the concrete. This benefit is illustrated in Figure 13, which is a photo from a trial concrete placement for a 10-million-gallon water storage tank (Bates et al. 2012). The two slabs were placed at the same time in the hot and dry environment (92 °F and 20 percent RH) near Denver, CO. No curing compound was placed on either slab. The photo shows the condition of the slabs the morning after the concrete was placed. The internally cured concrete appears to still be moist,

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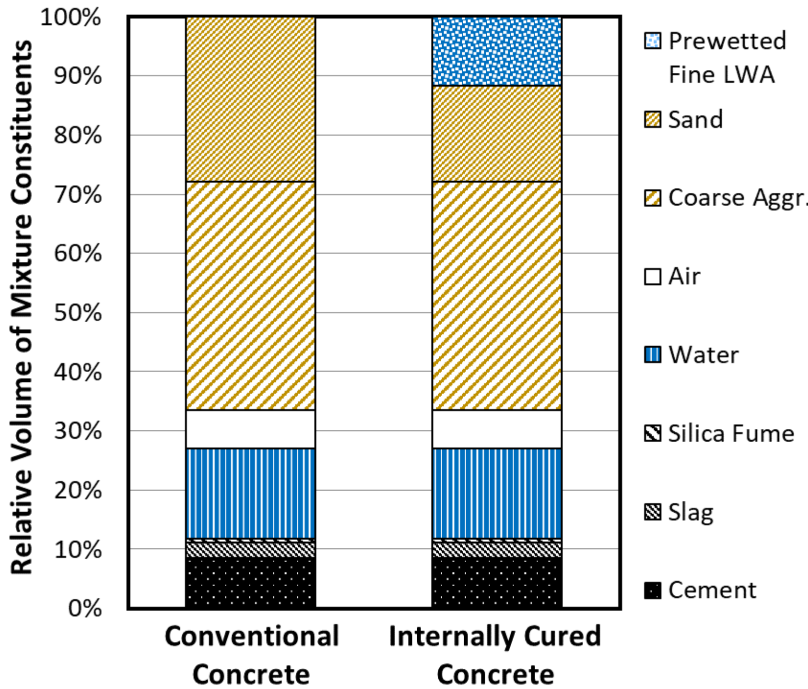
[11] ASTM C1761, Standard Specification for Lightweight Aggregate for Internal Curing of Concrete, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

while the conventional concrete appears to have dried out, which demonstrates the benefit of providing curing from within the concrete.



Source: FHWA

Figure 12. Graph. Comparison of constituents for conventional and internally cured concrete mixtures.

© 2012 Arcosa Lightweight

Figure 13. Photo. Trial slabs the morning after placement showing difference in condition between concrete with and without internal curing.

The main benefits of internal curing that result from the continued curing from within the concrete are 1) reduced shrinkage, which leads to a reduced cracking tendency, and 2) reduced permeability. These factors, which are briefly discussed below and are discussed in greater length in the other references cited in section 2.3, are important in preventing or delaying reinforcement corrosion and other processes leading to deterioration of concrete.

A list of the potential benefits of internal curing that contribute to improved long-term performance of concrete include:

- Maintained elevated moisture content within the concrete.
- Reduced plastic, autogenous, and drying shrinkage.
- Reduced cracking tendency.
- Reduced permeability.
- Reduced modulus of elasticity.
- Reduced coefficient of thermal expansion.
- More efficient use of portland cement and especially other cementitious materials through more complete hydration and reaction.
- Improved interfacial transition zone around aggregate particles.
- Reduced curling and warping.
- Increased concrete strength.
- Reduced density.

One example is provided to demonstrate the reduced permeability of internally cured concrete, which is a result of the improved hydration of cement and an improved interfacial transition zone at the surface of lightweight aggregate particles. The better-hydrated cement provides a denser and less porous paste and the improved interfacial transition zone restricts movement of fluids along the surface of aggregate particles, which is usually a major pathway for water penetration into conventional concrete mixtures. This is demonstrated by resistivity data from a pair of bridge decks constructed in 2010 in Indiana with and without internal curing as shown in Figure 14 (Di Bella et al. 2012).

Increased surface resistivity of concrete indicates lower permeability. The data show the internally cured bridge deck concrete (blue line) has significantly greater resistivity (lower permeability) than the conventional concrete mixture (red line). After one year, the internally cured concrete had 75 percent higher resistivity than the conventional concrete mixture. This large of an increase in surface resistivity should not be expected in all cases.

A report by Barrett et al. (2015) documents the improvements in material properties that were observed for four bridge decks constructed using internal curing in Indiana in 2013. The study concluded that the internally cured concrete mixtures demonstrated the potential "to more than triple the service life of the typical bridge deck in Indiana while reducing the early age autogenous shrinkage by more than 80 percent compared to non-internally cured concretes."

Because of the improved durability of internally cured concrete, the structure can be expected to have an increased service life (Schlitter et al. 2010, Taylor et al. 2016, D'Ambrosia et al. 2017, Wang et al. 2019). Any added costs associated with improvements in durability can then be distributed over the increased life of the structure, reducing the impact of the costs. Cusson et al. (2010) conducted both a deterministic and reliability-based analysis of the service life of a bridge deck using three types of concrete mixtures, one of which used internal curing with prewetted lightweight concrete. The expected improvement in service life for the reliability-based analysis is presented in Figure 15, which shows that the use of high-performance concrete with internal curing could be expected to significantly increase the service life of a bridge deck. To understand Figure 15, the following abbreviations and information are useful: NC = normal concrete with *w/c* = 0.40; HPC = high performance concrete with *w/c* = 0.35; and HPC-IC = high performance concrete with internal curing using prewetted lightweight aggregate with *w/c* = 0.35.

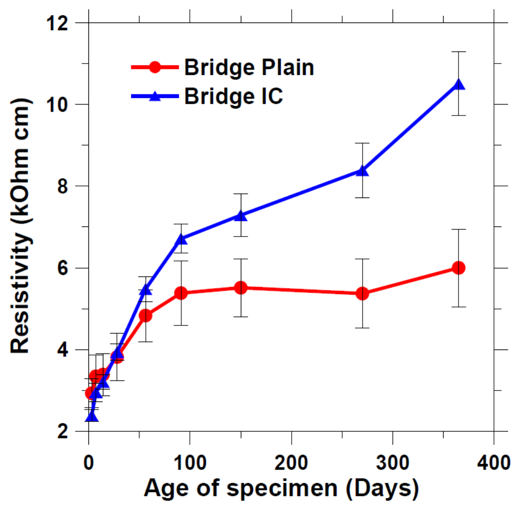


Figure 14. Graph. Surface resistivity of concrete mixtures with age.

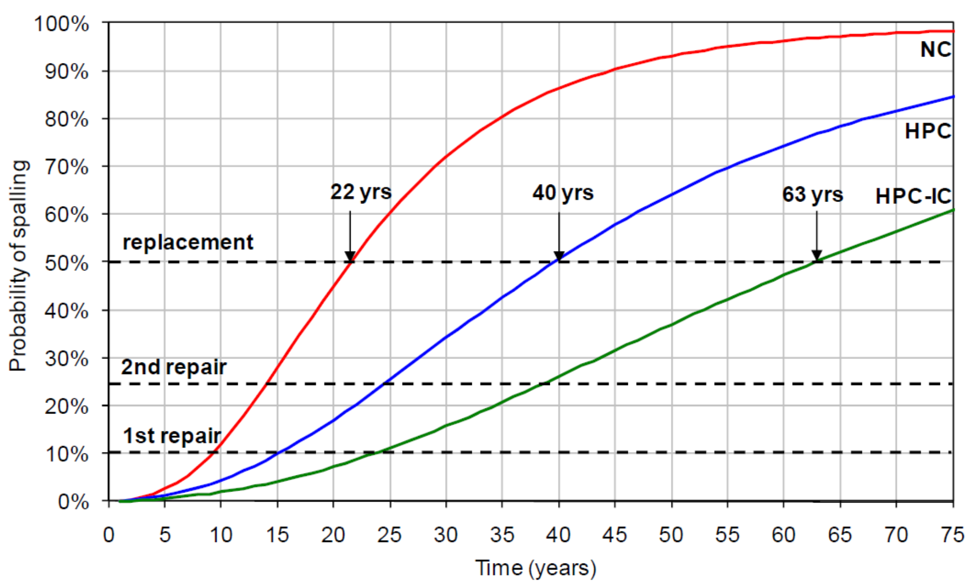


Figure 15. Graph. Expected service life using a reliability-based method for three types of concrete bridge deck mixtures.

As another example of increased expected service life, key assumptions and results of a life-cycle cost analysis for a bridge in Iowa are presented in Table 7 (Wang et al. 2019). The data show that the life-cycle cost of the bridge with internal curing is 29 percent less than for the bridge with the control concrete, even though the initial construction cost is 14 percent greater than for the control concrete. Note that the change to internal curing concrete was not the only modification between the two bridges; the slag replacement was also increased for the internally cured bridge.

Table 7. Life-cycle cost of alternatives per unit area of bridge deck (Wang et al. 2019).

Aggregate Type	Concrete unit volume cost ($/yd^3)	Initial construction cost ($/ft^2)	Repair cost ($/ft^2)	Life-cycle cost ($/ft^2)
Control concrete with 30% slag	470	153,266	151,868	305,134
Internally cured concrete with 50% slag	550	174,994	43,158	218,152

2.3.3 Proportioning Concrete Mixtures for Internal Curing

The basic approach to determine the amount of prewetted lightweight aggregate to provide internal curing in a concrete mixture is given by Bentz et al. (2005). This approach is based on offsetting the chemical shrinkage that occurs as cement hydrates (the demand) with water supplied internally from absorbed water in prewetted lightweight aggregate (the supply). The quantity of prewetted lightweight aggregate is therefore determined by setting the supply equal to the demand and solving for the mass of lightweight aggregate, which may be stated as oven-dry or prewetted. The application of this method is relatively simple, using only the cement content of the mix and the absorption and desorption of the lightweight aggregate, which can be determined using ASTM C1761[11]. A calculator for computing the quantity of lightweight aggregate for internal curing is provided on the ESCSI website (www.escsi.org).

The following simplified approach to proportioning an internally cured mixture is given in Castrodale (2016a) which, for a given type of cement and lightweight aggregate, provides a constant coefficient that is multiplied by the cement factor for a particular mix to obtain the quantity of prewetted lightweight aggregate:

$$M_{PLWA} = C_f K_{IC}$$

where:

M_{PLWA} = mass of prewetted fine LWA per unit volume of concrete (lb/yd^3).

C_f = cement factor (content) for concrete mixture (lb/yd^3).

$K_{IC} = CS\ (1 + A) / (A \times D)$

= coefficient for internal curing for given type of cement and lightweight aggregate.

CS = chemical shrinkage of cement; usually taken as 7 lb/100 lb cement or 7 percent.

A = absorption of lightweight aggregate, expressed as a percentage of the oven-dry mass (%).

D = desorption of lightweight aggregate, which is the quantity of absorbed water that is released by the aggregate in drying conditions, expressed as a percentage of the mass of absorbed water (%).

Methods for determining the absorption and desorption of the lightweight aggregate are presented in ASTM C1761[11].

Several State DOT have used internal curing by specifying that a fixed percentage (by volume) of conventional sand be replaced with prewetted lightweight, fine aggregate. The New York State DOT has now made this a requirement for all multi-span bridges (Carpenter 2019). This approach may be successful when available lightweight aggregate sources have similar absorption properties and the cement factor of mixtures do not vary. A more general approach presented in the references mentioned above allows use of a wider selection of aggregate sources. To provide the intended quantity of internal curing water in a mix, the needed replacement quantity for lightweight aggregate with a higher absorption is less than for a lightweight aggregate with a lower absorption.

Water absorbed in the lightweight aggregate (of any type, coarse or fine) should not be counted as part of the mix water and should not be included in mix water adjustments during batching. The absorbed water remains in the aggregate until after the concrete paste is hardened. As the pore structure of the paste develops and the pores become smaller than the pores in the aggregate particles, the water is then physically pulled out of the aggregate by capillary action.

2.3.4 Mechanical Properties of Concrete with Internal Curing

The density of internally cured concrete mixtures, for which a portion of the fines have been replaced by an equal volume of prewetted lightweight aggregate, typically is only slightly reduced compared to the concrete mixture without internal curing. Therefore, the concrete can usually be designed as conventional normal-weight concrete. If the density is reduced below 0.135 kcf, which is the minimum density in the definition of normal-weight concrete in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)), structural properties should be computed using design provisions for lightweight concrete, although the properties will only be slightly modified from conventional concrete. While the modulus of elasticity and coefficient of thermal expansion are both reduced slightly, they can still provide a noticeable improvement in the long-term durability of concrete.

3 INITIAL DESIGN CONSIDERATIONS

This chapter begins by providing a more detailed discussion of reasons for using lightweight concrete. Some potential concerns expressed by designers about the use of lightweight concrete are then discussed A process for the selection of reasonable basic design parameters related to lightweight concrete is then discussed to provide designers with an understanding of practical material properties that can be used for preliminary or final designs. Recognizing that there are increased material costs associated with the use of lightweight concrete for a project, information on the cost of lightweight aggregate and lightweight concrete are presented. The necessity for designers to consider overall project costs rather than only the increased cost of lightweight aggregate and lightweight concrete is then discussed. The chapter closes with a discussion of other features of design for which lightweight concrete may be used, but which are not addressed in the design specifications.

3.1 REASONS TO USE LIGHTWEIGHT CONCRETE IN BRIDGES

There are many reasons lightweight concrete has been used in bridges; most are related to the reduction in the weight of the structure, which results in improved efficiency in many areas. However, durability and extended service life are also recognized as significant benefits of lightweight concrete (Holm et al. 1984, Gerwick 1985).

This section discusses the main benefits of using lightweight concrete for bridges. More detailed discussions of these and other benefits are found in FIP (1967), T. Y. Lin International (1985), and ACI 213[2] (2014).

Several bridges are mentioned in this section as examples of the benefits of using lightweight concrete. More information is provided on these and other projects in chapter 7.

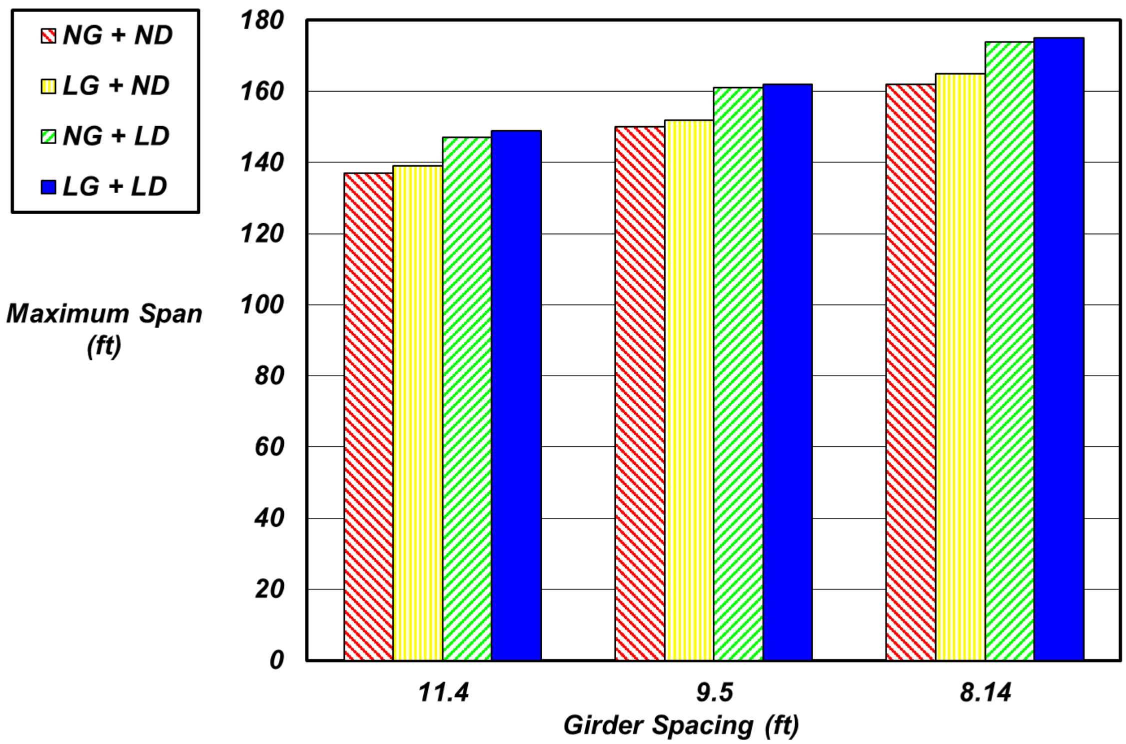
3.1.1 Reduced Weight/Load

Typically, the main benefit of using lightweight concrete is the reduction of the weight of the structure or an element that results in improved design efficiencies and reduced costs for girders, substructures, and foundations. While this discussion is divided into separate topics, the topics are often interrelated.

3.1.1.1 Improved Design Efficiency

Increasing the span length for a bridge is often thought to be the goal of increasing design efficiency. However, other effects should also be evaluated when considering the use of lightweight concrete in a bridge superstructure.

Bridges with lightweight concrete decks and girders typically have greater span length capabilities compared to the same girders with a normal-weight concrete decks and girders, as is demonstrated in Figure 16, which shows maximum span ranges for a given typical section using prestressed concrete bulb-tee girders (Castrodale et al. 2009). In Figure 16, the following abbreviations are used: NG = NWC girder; LG = LWC girder; ND = NWC deck; LD = LWC deck. Data in the figure indicate that using a sand-lightweight concrete deck rather than a normal-weight concrete deck increases the possible span length by about 7 percent; using a sand-lightweight concrete girder with a sand-lightweight concrete deck increases the span by about 8 percent for this comparison. This shows that changing the deck to lightweight concrete typically provides a greater increase in maximum span for a given bridge cross-section than using lightweight concrete for girders. Using an all-lightweight concrete deck provides an additional increase in possible span length. The study also shows that fewer strands may be necessary when using lightweight concrete for decks or girders, which can partially offset the increased cost. Steel girders will also typically have an increased span capability with a lightweight concrete deck, unless deflections govern the design.



Source: FHWA

Figure 16. Graph. Results for maximum span designs for a bulb tee girder bridge with different combinations of lightweight and normal-weight concrete for girders and deck.

3.1.1.2 Long-Span Bridges

As span length increases, dead load becomes the most dominant component of the design loads for bridges. Therefore, any reduction in the weight of a long span bridge can lead to efficiencies in design. This benefit is reflected in the number of long-span bridges for which lightweight concrete has been used (Castrodale 2016b). This was illustrated by the example given in chapter 1 of the San Francisco-Oakland Bay Bridge where lightweight concrete was used for the upper deck in the suspension spans. Several other suspension spans, such as the Mackinac Bridge and Brooklyn Bridge, have used lightweight concrete for the deck. Lightweight concrete has been used for the superstructure of at least one cable-stayed bridge in Norway as well as a number of segmental box girder bridges for which lightweight concrete was used in portions of spans to reduce the effect of unbalanced span arrangements for continuous structures (Helland 2000, Melby 2003).

3.1.1.3 Seismic Designs

Seismic loads on bridges are computed based on the mass of the structure. Therefore, reducing the mass of the structure by using lightweight concrete will reduce the seismic loads for which the bridge is designed. Lightweight concrete was used for the segmental box girder in the design of the Benicia-Martinez Bridge, which is a major segmental concrete box girder bridge in California (Murillo et al. 1994, Murugesh and Cormier 2007). The final design for the 1.5-mile-long bridge has multiple 659 ft main spans. Lightweight concrete was used for the entire cross-section of the box girder superstructure (except for the pier segments) to reduce the superstructure mass and therefore reduce seismic demands on the substructure and foundations.

In a conversation with one of the lead designers of the bridge several years after its completion, the author was told that if the results of the research on ductility of lightweight concrete discussed in section 2.2.6 had been available earlier, the columns and pier segments would also have been designed with lightweight concrete to achieve a further reduction in the structure mass and foundation design loads.

In a review of lightweight concrete bridges in California, Thompson and Wu (2008) presented a design comparison for a typical two-span overpass when the box girder superstructure uses normal-weight concrete versus lightweight concrete. Results showed that the footing size of lightweight concrete bridge was smaller with fewer piles, resulting in a 20 percent savings in overall foundation cost for the lightweight concrete bridge, including the column, footing and piles.

3.1.1.4 Accelerated Bridge Construction

Accelerated bridge construction frequently uses prefabricated elements or systems. Therefore, the use of lightweight concrete to reduce the mass of elements has clear advantages (Castrodale 2014b). Lightweight concrete has also been employed to accelerate project delivery in other ways, such as to allow reuse of existing substructure elements, avoiding additional piling, widening bridges without modifying the substructure or superstructure, reduced handling or shipping loads and costs, and the use of larger elements to avoid or reduce the number of joints in a structure. An example of potential weight savings from using lightweight concrete for a project moved by self-propelled modular transporters (SPMTs) is given in Castrodale (2015). Reducing the weight of the structure may reduce the quantity of equipment used to move the bridge. Several examples of projects that highlight some of these approaches are mentioned in chapter 7.

3.1.1.5 Reduced Bearing, Substructure, and Foundation Loads

The use of lightweight concrete in a structure will reduce bearing, substructure, and foundation loads. This reason for using lightweight concrete has been employed for bridges such as the Coleman Bridge near Yorktown, VA (Abrahams 1996); the I-5 Bridge over the Skagit River in WA (Vanek et al. 2015); the Route 198 Bridge over Harper Creek in VA (Schlussel et al. 2017); and the I-895 Bridge over the Patapsco River Flats near Baltimore, MD (Kodkani et al. 2019).

3.1.1.6 Reuse of Existing Substructure Elements

The use of lightweight concrete can allow the reuse of existing substructure elements, which can provide significant cost savings and a reduced construction schedule. This was accomplished in each of the four projects mentioned in the previous item.

3.1.1.7 Rehabilitation of Structures without Superstructure or Substructure Modification

For rehabilitation projects, use of lightweight concrete can allow widening or load rating improvements, or both, without modifying the existing superstructure and/or substructure. Examples of this approach include the widening of the Woodrow Wilson Bridge in the 1980s (Lutz and Scalia 1984), the Whitehurst Freeway (Stolldorf and Holm 2002), and the deck replacement for the Patapsco River Flats Bridge (Kodkani et al. 2019).

3.1.1.8 Handling and Transportation Loads and Hauling Permits

Loads and permits for handling and transporting large precast concrete elements can become significant issues for a project. Several examples where lightweight concrete (including reduced density concrete where blended mixtures were used) are discussed in Castrodale and Harmon (2007), including girders for the Mark Clark Expressway in Charleston, SC, where a permit for moving a large girder to another State could not be obtained without a weight reduction, and the CONRAC project at the Atlanta airport, where large tub girders as initially designed were heavier than could be safely lifted by the equipment in the plant. In both of these cases, the density of the concrete was reduced to meet handling limitations. For other projects mentioned in the same paper, the density of the concrete was reduced to make it easier to handle and erect precast elements.

3.1.1.9 Use of Larger Precast Elements

If the lifting equipment for a project has been selected, lightweight concrete can be used to allow larger pieces to be handled without exceeding the capacity of the lifting equipment. This can result in fewer pieces being fabricated for a project, which can accelerate project delivery and minimize joints in the structure. This approach also results in fewer loads of precast elements delivered to a site, which can also improve safety for construction personnel and traveling public and reduce costs associated with traffic control. Bender (1980) developed a comparison for using lightweight concrete instead of normal-weight concrete for a hypothetical precast segmental box girder bridge. His analysis demonstrated that the segment length could be increased, which would reduce the number of segments, which shortened the project duration.

3.1.1.10 Addressing Issues During Construction

Occasionally, an issue during construction is encountered that is encountered where a design modification is needed before the project can be completed. One example is the Bowman Road over Shem Creek Bridge where the driven piles did not reach capacity. Instead of splicing the piles, it was determined that use of lightweight concrete for the structure, which was a three-span cast-in-place flat slab bridge, would allow use of the under-capacity piles (Lansing 2015).

For another bridge, a limitation in the analysis software used to design a bridge did not allow consideration of a very wide sidewalk. The design proceeded without considering the full width of the sidewalk. When the issue was found during construction, it was determined that using lightweight concrete for the deck and sidewalk allowed the superstructure to satisfy design criteria with the wide sidewalk.

A final example was encountered during construction of a spliced girder bridge where the girder segments were erected so that the buildups over the girders were much larger than anticipated in the design. The added load from the deck concrete resulted in an overstress on the girders. The deck was changed to lightweight concrete to allow the superstructure to satisfy design criteria with the larger buildups.

An unusual example of a construction issue that could drive the use of lightweight concrete is that streets in some urban areas are load rated because of the facilities located below the street. This can also be an issue for a project where a load rated bridge is on the delivery route to a project. Such load restrictions require concrete suppliers to reduce the volume of normal-weight concrete in each truck to comply with load rating requirements under 23 CFR 650.313(c). However, with lightweight concrete, a greater volume of concrete can be transported in each load, which speeds construction, reduces the cost of transporting concrete, and reduces traffic congestion.

3.1.2 Enhanced Durability and Extended Service Life

Using a porous lightweight aggregate in concrete for a bridge can lead to improved durability. The durability of lightweight concrete may be comparable or even improved over normal-weight concrete with the same compressive strength and similar mix proportions. This may have been recognized by some designers and is reflected in a quote by engineer Ben Gerwick, Jr. in 1984. (Gerwick 1985):

> *This … new material … has a number of concomitant properties of potentially great value. When confined, it has greater ductility, due to the progressive crushing of the aggregate. There are far fewer microcracks between paste and aggregate resulting in better high cycle fatigue endurance. The lower modulus accommodates thermal and other deformation strains with less cracking. Finally the protection of the reinforcing steel from corrosion under severe environmental exposure appears to be enhanced.*
> *Thus we have a superior material available, originally chosen for its lighter density, which now appears justified for use in sophisticated structures for many other reasons as well.*

The properties of lightweight aggregate and lightweight concrete related to durability are discussed in chapter 2, and include reduced permeability, reduced cracking, and good freezing and thawing resistance. It is also anticipated that using lightweight concrete for mass concrete applications would reduce the cracking potential (Tankasala and Schindler 2017, Tankasala et al. 2017).

The reduced coefficient of thermal expansion is expected to reduce joint movement in bridges, which can extend the life of these elements that are often maintenance problems. In some cases, the reduced stiffness of lightweight concrete can be beneficial, such as reduced deck restraint from girders that can lead to early age cracking and reduced restraint from short columns on the superstructure, if the columns were constructed using lightweight concrete.

3.1.3 Other Benefits

It is anticipated that a lightweight concrete deck will generate less noise associated with tires because of its lower stiffness. If the pavement is ground or grooved, exposing the interior pores of the lightweight aggregate particles, noise should be further reduced because "negative texture" has been shown to be a major contributor to reduced tire noise because air can be pushed into the pores as a tire passes (Rasmussen et al. 2007). It is not known if this has been verified in the field.

The improved resistance of lightweight concrete to fire is well known. This can be useful for bridges where resilience is a special concern, or where the potential for fire is elevated. Speck and Burg (2000) also discuss the greater resistance to blast and projectile impact of lightweight concrete.

3.1.4 Types of Elements for which Lightweight Concrete May Be Used

Lightweight concrete has most frequently been used for decks on bridges. It has also been used for pretensioned and post-tensioned girders, including segmental box girders.

Other applications where lightweight concrete has been or can be used include railings, substructure elements (such as pier caps, columns, and abutment walls), piles, culverts, and mass concrete. The use of lightweight concrete for mass concrete and culverts is for reduced cracking due to thermal effects (Tankasala and Schindler 2017, Tankasala et al. 2017) and cracking due to restraint, respectively.

3.2 CONCERNS ABOUT USING LIGHTWEIGHT CONCRETE IN BRIDGES

Some concerns heard when owners, designers, and contractors are asked to consider use of lightweight concrete for bridges are related to cost, durability, material properties, and constructability, and how to specify and design using lightweight concrete the material. Many concerns are discussed in Castrodale and Harmon (2008) which provides a lengthy discussion of durability of lightweight aggregate and lightweight concrete. The 1985 FHWA report (T. Y. Lin International 1985) makes the following statements:

> *The performance of the lightweight concrete in bridges has generally been satisfactory, but there have been problems. Most of the problems have to do with the specifications of the concrete, its placement in the field, and the familiarity with its behavior. There have also been conflicting opinions regarding the occasional poor performance of the material.*
>
> *Although there is no consensus of opinion concerning the suitability of lightweight concrete for bridge structures, nor concerning experiences with its performance, it should be noted that the material does have sufficient record of successful applications to make it a suitable construction material for buildings and ships, as well as for bridges. Sufficient information is available on all aspects of its performance for design and construction purposes.*

This document addresses the concerns and provides information relating to wider use of lightweight concrete. Section 3.3 provides information on properties that can be used for design; the issue of cost is addressed in section 3.4. Details of design provisions are discussed in chapter 4. Examples of projects are given in chapter 7 and in other sections to provide information on how lightweight concrete has been successfully used.

3.2.1 Availability of Lightweight Aggregate

The number of facilities producing lightweight aggregate in the United States is limited. See ESCSI website at http://www.escsi.org for a listing of facilities for the member companies. Lightweight aggregate suppliers produce large quantities and typically can provide the quantity of aggregate required for a bridge project. While it is generally preferred to obtain materials locally, lightweight aggregate can be shipped long distances and still provide an economical solution. Producers often provide terminals in major cities where the aggregate can be obtained. Otherwise, aggregate is shipped directly to the concrete supplier.

3.3 SELECTION OF MATERIAL PROPERTIES FOR DESIGN

Information from research projects and data presented in chapter 2 demonstrated that material properties of lightweight concrete can generally be assumed using the provisions found in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Properties should be specified only as necessary for the project to perform as intended; over-specifying properties should be avoided as discussed in section 6.2. Lightweight concrete shall conform to requirements in the contract documents as shown in section 8.2.3 of the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)) including the minimum compressive strength and density as shown in section 3.5.1 of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Other material properties used in design can then be obtained by using equations in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

This section provides information to assist the designer in the selection of design parameters for lightweight concrete elements. It is suggested that concrete suppliers or prestressed concrete fabricators be consulted when determining the design concrete compressive strength and density to be used to make sure that the values assumed are achievable with the lightweight aggregate types available.

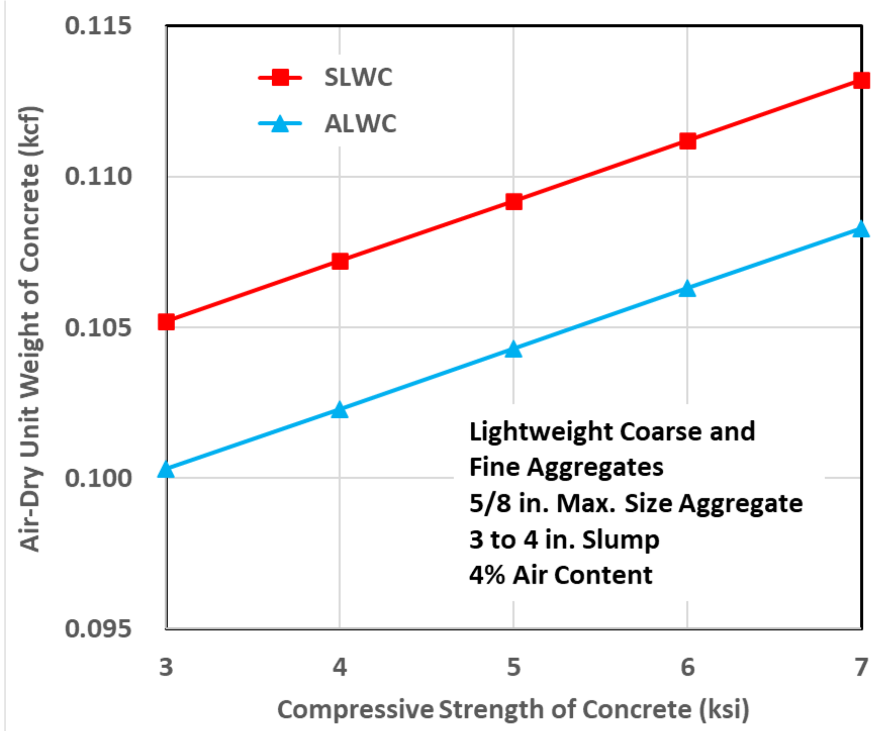
3.3.1 Compressive Strength

For most designs, the same design compressive concrete strength can be used as would be used for the design of a comparable normal-weight concrete element. All structural lightweight aggregates are capable of producing concrete with design compressive strengths in excess of 5.0 ksi; design compressive strengths of 6.0 ksi are widely available; and several lightweight aggregates have been used in concrete with design compressive strengths of 7.0 to 10.0 ksi (ACI 213 2014). The practical current maximum design compressive strength for lightweight concrete is 10 ksi (Russell 2007), which is also the limit given in AASHTO LRFD-8 Design Specifications article 5.1 for the design of lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). A 10 ksi design compressive strength has been shown to be attainable using at least one source of lightweight aggregate available in the United States (Liles and Holland 2010, Chapman and Castrodale 2016). Lightweight aggregate from several suppliers can be used for design compressive strengths of up to 8 ksi. Before using design compressive strengths greater than 8 ksi for lightweight concrete, it is suggested that concrete suppliers and lightweight aggregate suppliers be consulted.

3.3.2 Density

As the design compressive strength of any type of concrete increases, the density will also increase. This is recognized for normal-weight concrete by the expression in the AASHTO LRFD-8 Design Specifications table 3.5.1-1 that expresses density in terms of the compressive strength with an increase of 0.001 kcf per 1.0 ksi compressive strength (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Figure 17, which is based on results of a study presented in a figure in the 1985 FHWA report, shows the increase in air-dry unit weight (roughly equivalent to equilibrium density) with increasing compressive strength, but at a rate of 0.002 kcf per 1.0 ksi in compressive strength for both all-lightweight and sand-lightweight concrete mixtures (T. Y. Lin International 1985). The relationships shown in Figure 17 should not be taken as a general rule, but only as an indication of the increase in density with increased compressive strength as the relationship will vary depending on the type of lightweight aggregate and other mix parameters. For lightweight concrete used for pretensioned girders with a design compressive strength of 8 to 10 ksi, a fresh density of 0.120 to 0.125 kcf has been used (Liles and Holland 2010, Chapman and Castrodale 2016, Ozyildirim et al. 2017).

An equilibrium density of 0.100 kcf should be possible for an all-lightweight concrete deck mixture with a typical design compressive strength of 4 to 5 ksi using any structural lightweight aggregate available in the United States; lower densities may only be achieved by some of the available lightweight aggregates. As noted in section 2.2.2.1, only the fresh density may be specified in cases where the loss of density with time is not expected to be significant, which typically occurs when the absorption is low.



Source: FHWA

Figure 17. Graph. Air-dry unit weight of lightweight concrete versus compressive strength.

The value and type of density (fresh and/or equilibrium) should be clearly stated on the plans and in the specifications. Approaches for specifying the density in contract documents are discussed in chapter 6.

The design density discussed here is for plain (unreinforced) concrete and should be used in design when computing the modulus of elasticity.

3.3.2.1 Concrete Density for Dead Load

For computing concrete dead loads for design, the density of reinforced concrete should be used. As noted in the AASHTO LRFD-8 Design Specifications article C3.5.1, the density of reinforced concrete is typically taken as 0.005 kcf greater than the density for plain concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). While this may be adequate for many cases, this increment of density should be re-evaluated when elements are heavily reinforced. For example, in Chapman and Castrodale (2016), the density used to compute dead loads was 0.138 kcf, which was 0.010 kcf greater than the maximum fresh density and 0.015 kcf greater than the target density to properly reflect the effect of strand, rebar and other embedded steel items. This is especially important for precast elements where handling weights are important for safe handling.

3.3.3 Concrete Modulus of Elasticity

The modulus of elasticity of concrete should be computed using AASHTO LRFD-8 Design Specifications equation 5.4.2.4-1 with the default value of $K_1 = 1.0$ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Cousins et al. (2013) found that using the default value of K_1 provided a good correlation with test results for lightweight concrete. The same study also found that predicted modulus of elasticity values can be improved for a particular lightweight aggregate or mixture by calibrating the K_1 value (Cousins et al. 2013). The density (unit weight, w_c) for plain concrete should be used in the equation.

3.3.4 Tensile Strength

The modulus of rupture, f_r, can be computed using the expression in AASHTO LRFD-8 Design Specifications article 5.4.2.6 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$f_r = 0.24\lambda\sqrt{f'_c}$$

where:

λ = concrete density modification factor.

f'_c = compressive strength of concrete for use in design (ksi).

The average splitting tensile strength of concrete, f_{ct}, can be computed using the following expression, which is derived from AASHTO LRFD-8 Design Specifications article 5.4.2.8 as discussed in section 4.6.8 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$f_{ct} = (\lambda/4.7)\sqrt{f'_c} \approx 0.21\lambda\sqrt{f'_c}$$

For normal-weight concrete, λ = 1.0; for lightweight concrete, λ is determined using AASHTO LRFD-8 Design Specifications equation 5.4.2.8-2 based on the unit weight of the lightweight concrete, w_c (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.3.5 Concrete Density Modification Factor, λ

The AASHTO LRFD-8 Design Specifications give designers the option to compute the concrete density modification factor, λ, for lightweight concrete based on a specified splitting tensile strength (see section 2.2.4.4, later discussion on AASHTO LRFD-8 Design Specifications article 5.4.2.8 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)), and Castrodale (2019)). If the splitting tensile strength is specified to be equal to the computed splitting tensile strength for normal-weight concrete (see equation above with λ = 1.0), a lightweight concrete member can be designed with λ = 1.0, which eliminates any reduction and makes design for shear and other quantities related to concrete tensile strength the same as if the concrete were normal-weight concrete. The designer can also specify an intermediate value of f_{ct} to adjust the value of λ to satisfy some design objective. Data that support use of the approach to specify f_{ct} equal to the splitting tensile strength of normal-weight concrete are presented in section 2.2.4.4. If a designer is considering specifying f_{ct} to set the value of λ, lightweight aggregate suppliers should be consulted.

Some designers have counteracted the effect of λ on various design quantities by increasing the design compressive strength of the lightweight concrete. Since the use of λ is associated with the $\sqrt{f'_c}$ term, an increase in f'_c only results in a small increase in the quantity considered since the square root of the compressive strength is taken. However, this approach can provide a relatively effective means to address the situation and reduce or remove differences between designs using normal-weight and lightweight concrete.

3.3.6 Other Material Properties

Other material properties, such as creep, shrinkage, and the coefficient of thermal expansion, should be determined using the standard provisions of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.3.7 Increase in Mechanical Properties of Lightweight Concrete with Time

Time functions provided for properties in the AASHTO LRFD-8 Design Specifications should be used for lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.3.8 Internally Cured Concrete

Concrete with internal curing typically has a density that remains above the minimum density for normal-weight concrete in the AASHTO LRFD-8 Design Specifications, which is 0.135 kcf (AASHTO 2017) (23 CFR 625.4(d)(1)(v)),. As a result, design calculations are not affected. If the concrete density is reduced below 0.135 kcf, structural properties should be computed using design provisions for lightweight concrete, although the properties will only be slightly modified from conventional concrete.

3.4 ESTIMATING THE COST OF USING LIGHTWEIGHT CONCRETE

Lightweight concrete is generally more expensive than normal-weight concrete because the cost of the lightweight aggregate is greater. The main reasons for the increased cost for lightweight aggregate are the high temperature processing used to expand the aggregate and the typically greater transportation costs because a lightweight aggregate manufacturing plant may not be near the project. Further, concrete suppliers usually have other costs to consider when producing lightweight concrete. Such costs may include the effect of devoting one or more bins to lightweight aggregate and the impact that will have on their production of other concrete. Concrete suppliers may also have some added quality control costs in producing lightweight concrete that has an additional specified property (density) upon which acceptance is based, which may expose them to an increased risk for rejection of loads. Lightweight concrete mixtures often use a slightly higher cement content than a corresponding normal-weight concrete mixture to achieve the same strength and workability, which adds another small increment to the cost.

It is not possible to give a simple answer to the question of "how much more does lightweight concrete cost than normal-weight concrete?" Many factors are involved in estimating the difference in cost, including the cost of the lightweight aggregate, the cost of transportation of the aggregate, the cost of the normal-weight aggregates that are being replaced, and the familiarity of the concrete supplier and contractor with using lightweight concrete. Most of the difference in cost is a result of the increased material costs; concrete suppliers also typically add an increment of cost related to their familiarity and experience with lightweight concrete production and the increased quality control effort and potential risks related to use of lightweight concrete.

When evaluating the cost of using lightweight concrete for a project, it is suggested that long-term costs related to durability and service life should be considered, as well as initial costs. In many cases, the greater initial cost of lightweight concrete can be offset by design or durability improvements that may lead to significant reductions in the overall project cost or construction schedule as reflected by the use of lightweight concrete in many bridges (see list in chapter 7).

In preliminary design stages, a designer should obtain cost estimates from local concrete suppliers. The background given in the following sections include factors that may affect the cost of lightweight concrete. The information provided can prepare the designer with questions to get a better understanding whether the supplier is familiar with production of lightweight concrete and can give a reasonable estimate. The designer can also talk to lightweight aggregate suppliers and possibly to contractors to see if they have any information on the relative cost of lightweight concrete in the project area.

In States where lightweight concrete has been used, bid tabulation data for lightweight concrete may be available. However, such data should be used with care because of the wide variations in bid tabulation data even for the same project.

3.4.1 Aggregate and Concrete Cost

While normal-weight aggregate is typically obtained locally, lightweight aggregate can be shipped long distances and still provide an economical solution. The construction of the replacement span for the I-5 Bridge over the Skagit River, which was presented in chapter 1, is an example. For that project, lightweight aggregate was shipped from a supplier in North Carolina to Tacoma, WA, with significant additional cost when compared to the local normal-weight aggregate (see Table 1). However, it was still possible to provide an economical solution for the project because the use of lightweight concrete allowed other costs to be avoided. While the cost of the lightweight aggregate was significantly more than normal-weight aggregate, the in-place cost of lightweight concrete girders is relatively small.

It is also not possible to provide a generally applicable "cost premium" for the use of lightweight concrete compared to normal-weight concrete because the difference in cost varies with location and other conditions. Therefore, a range of cost premiums is given in the following section.

The example demonstrates that designers should not look at only the additional cost of the lightweight aggregate and use that alone as the basis of whether to consider lightweight concrete for a project. The impact of using lightweight aggregate should instead be based on the total impact on the project cost which depends on many variables. Therefore, designers are encouraged to consult with local concrete suppliers or prestressed concrete manufacturers and lightweight aggregate suppliers when trying to determine whether lightweight concrete is a viable solution.

3.4.1.1 Concrete Suppliers

Several factors may cause a lightweight concrete supplier to increase the cost of lightweight concrete above the cost of a similar normal-weight concrete. These factors include the following:

- Lightweight concrete uses an additional type of aggregate that may not be regularly used by the concrete supplier. If this is the case, the concrete supplier may have to empty and clean out aggregate bins that will be used for lightweight aggregate prior to production of lightweight concrete. This is especially true for "all-lightweight concrete", which uses two types of lightweight aggregate, and therefore two bins. For some plants, the use of one or two bins for lightweight aggregate will restrict the ability of the plant to produce other types of concrete.
- The use of another type of aggregate also involves additional aggregate storage space, which may be difficult to accommodate for some plants.
- Lightweight concrete mixtures often use a slightly larger quantity of cement to provide the same compressive strength.
- Concrete suppliers may also consider adding cost associated with the risk of rejected loads because density is an additional factor upon which acceptance of a load of lightweight concrete is based.
- Typically, lightweight aggregate is prewetted and its absorbed and surface water content is monitored. In contrast, prewetting of normal-weight aggregate is generally only used to cool the aggregate.
- Challenges may also be encountered if lightweight aggregate is delivered to the plant by a mode of transportation that is not usual for a plant. Such issues can typically be overcome, although usually at an additional increment of cost.

All of these factors contribute to an increased cost beyond just the greater cost of the lightweight aggregate. Where production of other types of concrete may be restricted when supplying lightweight concrete, producers may be reluctant to supply lightweight concrete projects, especially for "all-lightweight concrete" projects. However, it should be noted that lightweight concrete is often used in metropolitan areas for medium- and high-rise buildings, so concrete suppliers may already be familiar with production of lightweight concrete. The lightweight aggregate supplier may provide support to concrete suppliers as they prepare for the project.

3.4.1.2 Contractors

Contractors may add another increment of cost to a lightweight concrete project because of perceived risks. Some contractors have the impression that lightweight concrete is more difficult to place and finish, but this has been demonstrated not to be the case. They may also be concerned about the equipment used to place the concrete, because some believe that lightweight concrete cannot be pumped. However, with proper mix design and proper attention to pump line configurations, lightweight concrete can be pumped successfully.

Contractors and concrete suppliers in many metropolitan areas will have experience with using lightweight concrete, so they may be familiar with the material when a designer may not be.

3.4.2 Perspective on Increased Cost of Lightweight Concrete

Table 8 shows a range of values for the potential material cost premium for sand-lightweight concrete over normal weight concrete for bridge deck concrete (Castrodale 2012). The top of the range would apply where the lightweight aggregate is shipped a long distance for use in a project. The computed cost per square foot shown in the table assumes an average deck thickness of 9 inches. The premium cost for sand-lightweight concrete for pretensioned girders would be expected to be slightly higher than the values shown in the table because of higher concrete compressive strength typically used for girders.

Table 9 shows range of values for the potential material cost premium for all-lightweight concrete for a bridge deck concrete, using the same assumptions as Table 8. The premium costs shown correspond to the three cost premiums for sand-lightweight concrete shown in Table 8.

The cost premium for both types of lightweight concrete depends on the cost of the lightweight aggregate, including shipping, and the cost of the normal-weight aggregate that is being replaced. Costs for all-lightweight concrete shown in Table 9 are based on the relative cost between coarse and fine aggregate from one supplier, which may vary for other lightweight aggregate suppliers.

Table 8. Estimated material cost premium for sand-lightweight concrete (SLWC) compared to normal-weight concrete for a 9-in. thick bridge deck.

Premium for SLWC / yd^3	Cost Premium / ft^2
\$20 / yd^3	\$ 0.56 / ft^2
\$40 / yd^3	\$1.11 / ft^2
\$60 / yd^3	\$1.67 / ft^2

Table 9. Estimated material cost premium for all-lightweight concrete (ALWC) compared to normal-weight concrete for a 9-in. thick bridge deck.

Premium for ALWC / yd^3	Cost Premium / ft^2
\$35 / yd^3	\$ 0.97 / ft^2
\$75 / yd^3	\$2.08 / ft^2
\$115 / yd^3	\$3.19 / ft^2

A similar comparison can be made with girders. Assuming a cost premium for sand-lightweight concrete for a girder of \$40/yd^3, the cost per lineal foot of girder has been computed for the girders shown in Table 10. Assuming a girder spacing of 10 ft, the girder cost can be converted to the cost per unit area.

Table 10. Estimated material cost premium for sand-lightweight concrete (SLWC) bridge girders on a per ft and per ft^2 basis assuming a cost premium for sand-lightweight concrete of \$40/yd^3 and a girder spacing of 10 ft.

Girder Type	Cost Premium / ft	Cost Premium / ft^2
PCI BT-54	\$ 6.78 / ft	\$ 0.68 / ft^2
PCI BT-72	\$7.89 / ft	\$ 0.79 / ft^2
FIB 54	\$9.60 / ft	\$ 0.96 / ft^2
FIB 72	\$10.90 / ft	\$ 1.09 / ft^2
FIB 96	\$12.62 / ft	\$ 1.26 / ft^2

Note: PCI = Precast/Prestressed Concrete Institute; BT = bulb-tee; FIB = Florida I-beam. These are types of precast, prestressed concrete girders. Numbers in girder designations indicate girder depths in inches.

The cost premium values presented in the tables look relatively large when considered alone. Compared to the 20-city average price for ready-mix concrete from *Engineering News Record* (ENR) for June 2019 (ENR 2019), which was \$133 for 4 ksi concrete, the premiums range from 15 to 86 percent of the cost of normal-weight concrete. The ENR price for concrete is for commercial work, which would likely be somewhat less than the price for DOT work. When cost premiums are considered as an equivalent cost per square foot of deck area, the cost appears to be relatively minor, especially for sand-lightweight concrete. Using data reported on the FHWA National Bridge Inventory (NBI) website (FHWA 2018), the average of the unit cost for bridge construction in 2018 was \$223/ft^2 for bridges on the Federal-aid system and \$252/ft^2 for bridges not on the Federal-aid system. This means that the additional cost for a sand-lightweight concrete bridge deck would generally be less than 1 percent of the average cost of a bridge, with the cost for an all-lightweight concrete bridge deck equal to no more than 1.5 percent of the average cost of a bridge. The additional cost for the sand-lightweight concrete girders is also well below 1 percent of the cost of a bridge. These estimates of the cost premium do not consider offsetting savings that may result from the use of lightweight concrete, such as explored in the following examples. The results of comparing lightweight to normal-weight concrete are similar to the ACI 213[2] (2014) estimate that the in-place cost of using lightweight concrete is about 1 percent more than normal-weight concrete.

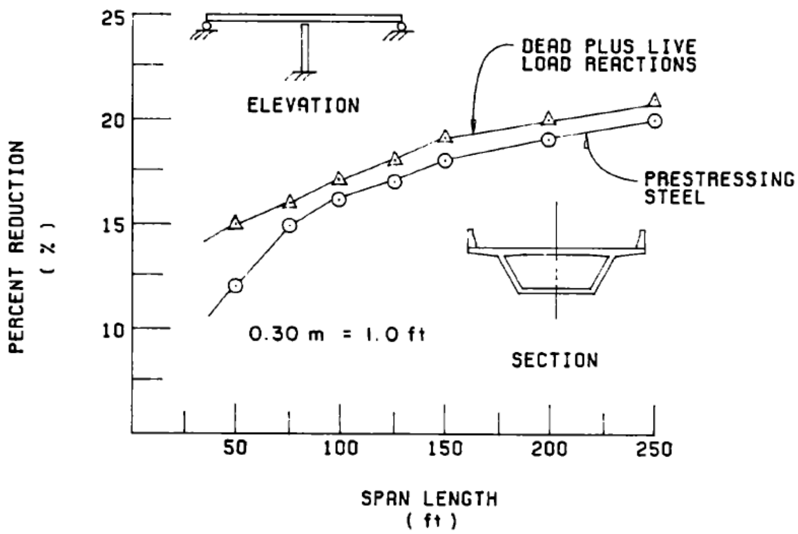
3.4.3 Examples of Cost Savings with Lightweight Concrete

Limited data on cost comparisons between lightweight and normal-weight concrete for bridges are found in the literature in addition to those mentioned in chapter 1. The FIP Commission on Prestressed Lightweight Concrete (1967) provides a discussion of the economics of using lightweight concrete. Bender (1980) estimated the effect of using lightweight or normal-weight concrete on the cost of a precast segmental box girder bridge and found savings in both schedule and cost by using lightweight concrete. Holm and Bremner (2000) present a cost comparison for a project that indicated only a 4 percent increase in the in-place cost of lightweight concrete compared to normal-weight concrete, and that was without considering any cost savings from using lightweight concrete such as reduced foundation loads, reduced seismic loads, or reduced cost to transport precast elements. Using a simple example of a foundation for a typical bridge subjected to seismic loads, Thompson and Wu (2008) found that using lightweight concrete for a bridge superstructure reduced the foundation cost, including column, footing, and piles, by about 20 percent when compared to a design using normal-weight concrete. This study neglected any additional potential savings in the superstructure. The Wabash River Bridge was an early project in Indiana that used precast lightweight concrete girders with both pretensioning and post-tensioning to extend the span length to 175 ft. Using lightweight concrete resulted in savings of $1.7 million on the $9.4 million project (ESCSI 2001a).

Castrodale (2012) presented the following comparison of the cost of lightweight concrete for dual bridges that were about 3000 ft long and 78 ft wide. Lightweight concrete was not used by the team that was awarded the project; however, the second-place team did include a sand-lightweight concrete deck in its design concept. The superstructure was assumed to be comprised of 150-ft-long, 74-inch-deep modified PCI bulb-tee girders. Using a cost premium of $\$30/yd^3$ for sand-lightweight concrete, the additional cost of the lightweight concrete was computed to be $1,024 per girder. A prestressed girder manufacturer obtained an estimate from his hauling subcontractor for shipping the 150 ft girder about 300 miles to the project location. The estimated cost to ship each sand-lightweight concrete girder (0.125 kcf) through three States was $811 less than the cost to ship a normal-weight concrete girder (0.150 kcf). The lightweight concrete girder was 23 kip lighter than the normal-weight concrete girder, which could be a significant benefit to the fabricator for handling and to the contractor for erection. A further cost reduction was realized because the sand-lightweight concrete girder design needed four fewer strands for this design comparison of an all-lightweight concrete deck on sand-lightweight concrete girders to a normal-weight concrete deck on normal-weight concrete girders. The cost of an installed prestressing strand was assumed to be $0.65/ft. The elimination of the four strands resulted in an additional cost reduction of $390 for the sand-lightweight concrete girder. Therefore, the total savings for the lightweight concrete girder compared to the normal-weight concrete design was $1,201, for $177 per girder net savings ($1,024 - $1,201 = -$177). Therefore, the additional cost of the sand-lightweight concrete was completely offset with savings.

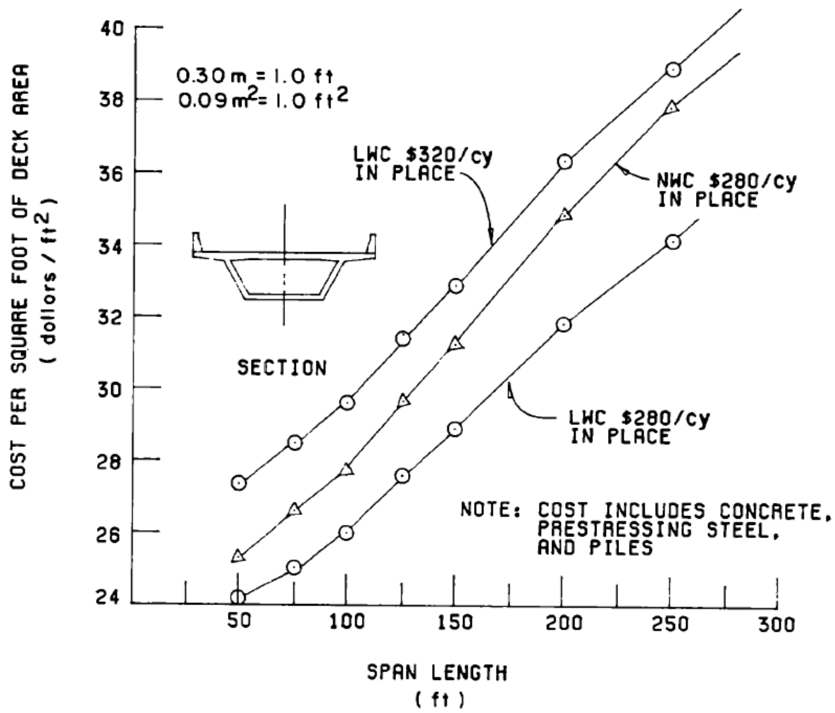
To complete the comparison, use of a sand-lightweight concrete girder with an all-lightweight concrete deck allowed elimination of a girder line. Taking this into account as well as the premium cost for the all-lightweight concrete deck, the overall savings in the superstructure was estimated at over $700,000, without considering any other potential cost savings in the bearings, substructure or foundations, or for the contractor in erection. The total superstructure reaction at each interior bent was reduced about 770 kip or 25 percent, so it is reasonable to assume that additional savings in foundation or substructure costs may have been possible.

The 1985 FHWA report presents several detailed comparisons of cost and material savings when using lightweight concrete for a two-span single box girder, two-span steel plate girder, two-span pretensioned girder, three-span haunched segmental cantilever box girder, and a three-span cable stayed bridge (T. Y. Lin International 1985). While costs are significantly different today from those used in the report, the relative comparisons are still useful. Several figures showing results of the comparisons are presented here. Figure 18 shows the reduction in dead and live load reactions and quantity of prestressing steel for a single cell box girder. As expected, lightweight concrete provides greater benefit for longer span where dead load is a greater part of the design moment. For the same bridge, Figure 19 shows the unit cost of the bridge assuming the lightweight and normal-weight concrete have the same in-place cost, and also for a lightweight concrete with a greater in-place cost. Based on this comparison, the study suggests that the in-place cost of lightweight concrete would have to be no more than $305/yd^3 to be competitive. However, this approximately 10 percent increase from the cost of normal-weight concrete would result in about a 50 percent increase in the delivered cost of lightweight concrete over normal-weight concrete because the delivered cost of concrete is typically about 15 to 20 percent of the in-place cost. Figure 20 compares the weight of cable stays needed for lightweight and normal-weight concrete designs, with about a 15 percent increase for the longer spans. Table 11 summarizes the approximate reductions in steel weight for each of the designs considered.



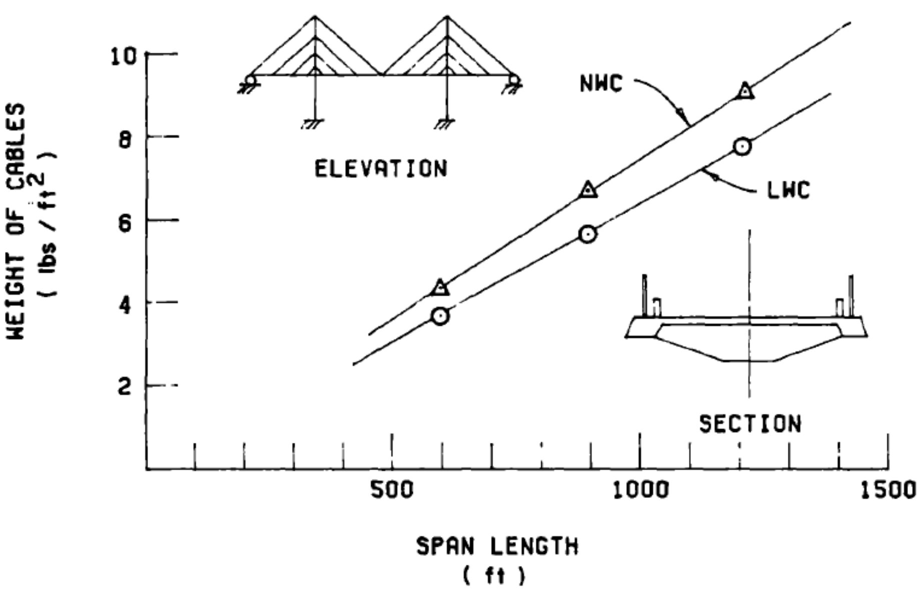
Source: FHWA

Figure 18. Graph. Percent reduction in load reactions and prestressing steel when using lightweight concrete instead of normal-weight concrete for single cell box girder bridge.



Source: FHWA

Figure 19. Graph. Cost comparison between lightweight concrete and normal-weight concrete with variable unit concrete cost for single cell box girder bridge.



Source: FHWA

Figure 20. Graph. Weight of longitudinal cable stays for cable-stayed bridge using lightweight concrete and normal-weight concrete superstructure.

Table 11. Approximate reduction in structural steel or prestressing steel from normal-weight to lightweight concrete design (FHWA1985).

Bridge Type	Structural Steel	Prestressing Steel
Single-cell box girder	--	16.6%
Steel plate girder	13.7%	--
AASHTO I-girder	--	18.6%
Segmental box girder	--	21.4%
Cable-stayed girder	--	13.5%

3.5 DESIGN CONSIDERATIONS FOR ELEMENTS AND STRUCTURE TYPES

In this section, considerations for specific types of structural elements and structure types will be discussed briefly. Design provisions are discussed in the next chapter.

3.5.1 Reinforced Concrete Structural Elements

This section discusses considerations for the design of reinforced concrete elements using lightweight concrete, such as slab spans, pier caps, columns, and footings.

3.5.1.1 Material Properties

For these members, typically only basic properties should be specified: $f'c$ and w_c. In a few cases, the splitting tensile strength, f_{ct}, may be specified for situations where shear governs the design, like pier caps, and the designer would like to remove the reduction of the concrete density modification factor, λ.

3.5.1.1.1 Modulus of Elasticity

Equation 5.4.2.4-1 in the AASHTO LRFD-8 Design Specifications can be used to provide a reasonable estimate of E_c using the default value of 1.0 for K_1 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The equation can be calibrated to specific mixtures containing locally available aggregate by adjusting the K_1 factor.

3.5.1.1.2 Creep and Shrinkage

Default expressions for creep and shrinkage found in the AASHTO LRFD-8 Design Specifications article 5.4.2.3 can be used (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.5.1.1.3 Coefficient of Thermal Expansion

Default expressions for creep and shrinkage found in the AASHTO LRFD-8 Design Specifications article 5.4.2.2 can be used (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.5.1.2 Design

Design is conducted using the provisions of the AASHTO LRFD-8 Design Specifications currently state that use of the strut-and-tie model is limited to normal-weight concrete because of a lack of data (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). However, the method is conceptual rather than empirical, so it appears reasonable to use the strut-and-tie model for lightweight concrete.

A reduced resistance factor for shear for lightweight concrete was introduced in the initial edition of the LRFD Design Specifications. However, the revisions adopted in 2015 set the resistance factor for shear for lightweight concrete equal to the resistance factor for normal-weight concrete as shown in the AASHTO LRFD-8 Design Specifications article 5.5.4.3, removing what has been a significant hindrance to the use of lightweight concrete for elements with significant shear, such as pier caps (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.5.1.2.1 Deflections

Deflections of reinforced concrete elements are computed using E_c which will be reduced when using lightweight concrete.

3.5.1.3 Detailing

Proper detailing of structures is an important factor in obtaining good performance and durability from bridge structures. Several detailing issues addressed in the AASHTO LRFD-8 Design Specifications are discussed in this section.

3.5.1.3.1 Cover

Concrete cover is important for protecting reinforcement from corrosion and for providing anchorage for reinforcement. The provisions addressing cover in the AASHTO LRFD-8 Design Specifications article 5.10.1 do not include any provisions that differentiate between normal-weight and lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Therefore, the minimum cover depth is unaffected by use of lightweight concrete.

3.5.1.3.2 Mild Reinforcement Development Lengths

The AASHTO LRFD-8 Design Specifications account for the potential reduction in the development length of mild reinforcement by including the concrete density modification factor, λ, in the determination of the development length in article 5.10.8 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). In these provisions, the development length of reinforcement is increased by $1/\lambda$. The increase in development length can be eliminated by specifying f_{ct} of lightweight concrete equal to the value expected for normal-weight concrete as discussed in section 3.3.5 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.5.1.3.3 Deformation Limits

The AASHTO LRFD-8 Design Specifications article 2.5.2.6 addresses bridge deformations and provides optional limits (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Article 2.5.2.6.2 provides optional deflection limits for the types of elements considered in this section. Table 2.5.2.6.3-1 provides optional traditional minimum depth limits (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The limits in both articles, if the owner decides to invoke them, do not differentiate between normal-weight and lightweight concrete, so they are applied without modification to the design of lightweight concrete elements. The reduced modulus of elasticity of lightweight concrete will result in increased deformations in a bridge, so the deformation limits of article 2.5.2.6.2 may be more likely to affect a design (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). However, the minimum depth limitations in table 2.5.2.6.3-1 do not account for the stiffness of the concrete, so the designer may want to consider this when evaluating deflections of bridges with lightweight concrete.

3.5.2 Reinforced Concrete Decks

3.5.2.1 Material Properties

Default values for material properties should be used as discussed in section 3.5.1.1.

Although the coefficient of thermal expansion for lightweight is usually less than for normal-weight concrete, it is compatible with both concrete and steel girders.

3.5.2.2 Design

Some State DOTs use design tables for design of reinforced concrete decks, which are based on strength limit state design. These tables would not change because flexural strength is not affected by lightweight concrete and the weight of the deck is not a significant factor. However, shear is not considered for deck design. Shear should be evaluated for all-lightweight concrete deck designs to verify that the reduced capacity will still be adequate. Results of such an evaluation for one deck configuration performed by Castrodale and Hanks (2016) indicated that the capacity of the deck was adequate even with a reduced shear capacity using $\lambda = 0.75$ and a reduced resistance factor, which is no longer included in the design provisions.

The concrete density modification factor will affect development and splice lengths of mild reinforcement in lightweight concrete decks. Increasing the development and splice lengths of mild reinforcement can be avoided by setting $\lambda = 1.0$ by specifying $f_{ct\,LWC} = f_{ct\,NWC}$ as discussed in section 3.3.5.

Some DOTs use a second approach to avoid any modification of deck designs and details. In this approach, the compressive strength of lightweight concrete has been increased to offset the effect of the concrete density modification factor. For lightweight concrete with a density modification factor of 0.85 ($w_c = 0.113$ kcf), the increased compressive strength for lightweight concrete can be determined by the expression $f'_{c\,NWC} / \lambda^2$. For this case, the increase would be $f'_{c\,NWC} / 0.7225 = 1.384 f'_{c\,NWC}$, or, for a 4 ksi conventional deck concrete, the f'_c for lightweight concrete would be 5.54 ksi. For an all-lightweight concrete deck, with $w_c = 0.100$ kcf and $\lambda = 0.75$, the compressive strength for lightweight concrete would be $1.778 f'_{c\,NWC}$, or for a 4 ksi conventional deck concrete, the f'_c for lightweight concrete would be 7.11 ksi.

Lightweight concrete decks have been constructed as composite slabs on prestressed concrete and steel girders for many years. With a lower modulus of elasticity for the lightweight concrete deck compared to a normal-weight concrete deck, the modular ratio used to compute transformed section properties will differ, causing a reduction in composite section properties. However, this can be compensated for in the design. Castrodale (2014a) evaluated the results of changing the deck to lightweight concrete for prestressed concrete girders designed for normal-weight concrete decks and found only minor differences in the results of the design.

3.5.2.3 Exposed Lightweight Concrete Decks

It is not necessary to provide a wearing surface to protect lightweight concrete decks from freezing and thawing or from traffic wear. Furthermore, as discussed in section 2.2.9.1, lightweight concrete decks continue to provide good skid resistance even with wear.

Examples of bridges in freezing environments where decks have been left exposed and have performed well include the I-95 bridge across the James River in Richmond, VA, which has been in service since 2001, and the Coleman Bridge over the York River at Yorktown, VA, which has been in service since 1996 (Castrodale and Robinson 2008).

Field performance has demonstrated that exposed lightweight concrete decks can be ground and grooved with no detrimental effects related to wear or freezing and thawing resistance (Castrodale and Robinson 2008). The deck of Virginia Dare Bridge in NC was diamond ground for rideability for the full length of the 5.2-mile-long bridge. A resident engineer reported that after 5 years of service, the bare deck had not suffered surface popouts from freezing (Castrodale and Harmon 2008). The decks on the Route 33 bridges in West Point, VA, were ground where needed for rideability, then were grooved for their full length. These decks have also performed well.

3.5.2.4 Grid Deck Filled with Lightweight Concrete

Lightweight concrete has been successfully used as fill concrete in both cast-in-place and precast grid deck installations (see several project reports on the website of the Bridge Grid Flooring Manufacturers Association – http://www.bgfma.org). The reduced density of the fill concrete gives the lowest possible weight for the deck system; the lower modulus of elasticity and coefficient of thermal expansion are expected to reduce potential cracking in the fill concrete because of the high degree of restraint offered by the grid deck system. Several truss and moveable bridges have used grid deck with lightweight concrete fill, including the Matthews Bridge in Jacksonville, FL; the swing span for the Ben Sawyer Bridge in Mount Pleasant, SC (Castrodale 2014b); and many other moveable bridges in Florida. Grid deck partially filled with all-lightweight concrete was also used recently for the I-895 Bridge over the Patapsco River Flats in Baltimore, MD (Kodkani et al. 2019).

3.5.2.5 Use of Overlays on Lightweight Concrete Decks

Overlays can be applied to a lightweight concrete deck in the same manner as they are applied to a normal-weight concrete deck. For some types of overlays, it may be appropriate to allow the deck to dry before the overlay is applied.

3.5.3 Prestressed Concrete Girders

Lightweight concrete has been used for pretensioned bridge girders since the mid-1950s (Erickson 1957). Initially, there appeared to be great promise in using the material for bridge girders as mentioned in Erickson (1957). However, while lightweight concrete was used for a number of girder bridges, its use did not become as widespread as initially expected. Use of lightweight concrete girders is once again gaining wider acceptance. Several projects have been constructed in Virginia, including two spliced girder bridges (Ozyildirim 2009) and girders using self-consolidating lightweight concrete (Ozyildirim 2014).

3.5.3.1 Material Properties

For pretensioned girders, typically only basic properties should be specified: f'_{ci}, f'_c, and w_c. In a few cases, the splitting tensile strength, f_{ct}, may be specified for situations where shear governs the design and the designer would like to remove the reduction of the concrete density modification factor, λ. In rare cases, E_c may also be specified. If the design is sensitive to other properties, an initial investigation of the properties of a lightweight concrete mixture produced for the project could be conducted. This is generally not necessary.

Default values for E_c, creep, shrinkage and the coefficient of thermal expansion can be used for design as discussed in section 3.5.1.1, unless more refined values are necessary.

The reduced value for E_c for lightweight concrete will affect transformed section properties of composite sections, as well deflections and the elastic shortening component of prestress loss.

3.5.3.2 Design

Design progresses as it would for a normal-weight concrete girder. A few items specific to the design of prestressed concrete girders are discussed below.

3.5.3.2.1 Prestress Losses

Standard equations are used to estimate prestress losses for prestressed concrete girders. No modifications are made for lightweight concrete, other than including density in the modulus of elasticity equation.

The modulus of elasticity for typical lightweight concrete mixtures will be less than the modulus for normal-weight concrete mixtures of the same compressive strength. This results in an increased elastic shortening loss. However, other components of prestress losses are computed with no modification for lightweight concrete. Designs for lightweight concrete girders will typically use fewer strands, so the losses may not be significantly different.

3.5.3.2.2 Transfer and Development for Strands

Standard equations for transfer and development of strands have been found to apply to lightweight concrete.

3.5.3.2.3 Splitting Resistance at Ends of Girder

provisions in the AASHTO LRFD-8 Design Specifications article 5.9.4.4.1 are intended to prevent web splitting cracking at the ends of pretensioned girders by providing web reinforcement operating at a reduced working stress to control the crack widths (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). These provisions do not mention lightweight concrete and do not include parameters affected by using lightweight concrete, such as tensile strength or modulus of elasticity. Because lightweight concrete has a potentially reduced tensile strength, it is appropriate to modify the calculated splitting resistance to reflect this effect. However, while a potentially lower tensile strength can make end splitting more likely in lightweight concrete, the reduced stiffness of lightweight concrete may tend to mitigate the splitting force. Therefore, it is not clear that the force provided by the reinforcement should be greater. Additional analysis and research may be useful to better understand the effect of using lightweight concrete on end splitting. However, a reasonable design approach could use current provisions with a slightly reduced working stress in the reinforcement.

3.5.3.2.4 Flexure – Service Limit State

Section properties are transformed in the usual manner using appropriate values for E_c.

Limiting stresses are modified by the concrete density modification factor, λ, as indicated in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

3.5.3.2.5 Flexure – Strength Limit State

For the strength limit state, no modifications to the equivalent rectangular stress block or resistance factors are necessary when using lightweight concrete.

If moment curvature is used, the stress-strain curve for lightweight concrete should be similar to a curve for high-strength normal-weight concrete, which remains linear to a higher fraction of the strength and decreases steeply for the descending branch.

3.5.3.2.6 Camber and Deflections

Camber and deflections are computed in the same way as for normal-weight concrete designs. The initial camber will typically be greater than for normal-weight concrete designs because of reduced dead load and reduced modulus of elasticity. The deflection due to the dead load of the deck will be greater for a lightweight concrete girder compared to a normal-weight concrete girder, for the same deck load.

The camber is typically increased for a lightweight concrete girder compared to a normal-weight concrete girder, even with the reduced number of strands that is typically used for a lightweight concrete design.

3.5.3.2.7 Lateral Stability

The use of lightweight concrete will affect the lateral stability of girders by the reduction of girder weight, modulus of elasticity, and related quantities such as camber. With the complex interaction of parameters, it is not possible to make a general statement regarding the effect of lightweight concrete on lateral stability without additional study.

3.5.4 Spliced Prestressed Concrete Girders and Segmental Concrete Box Girders

The provisions discussed for prestressed concrete girders will also apply for spliced prestressed concrete girders and segmental concrete box girders. Additional topics are addressed here.

3.5.4.1 Design

3.5.4.1.1 Post-Tensioning Anchorage Design

Provisions in the AASHTO LRFD-8 Design Specifications article 5.9.5.6 regarding post-tensioning anchorage design do not mention lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Anchorage design is based on providing sufficient reinforcement to control cracking in the anchorage zone. Because lightweight concrete has a potentially reduced tensile strength, it would seem reasonable to modify the computed splitting resistance to reflect this effect. However, while a potentially lower tensile strength may make cracking more likely for lightweight concrete, it is not clear that the force provided by the reinforcement should be greater. See related discussion on end splitting in pretensioned girders in section 3.5.3.2.3 for further discussion on this topic.

3.5.4.1.2 Detailed Time-Dependent Analysis

Time-dependent analysis for the design of spliced girders and segmental box girders should include consideration of creep, shrinkage, and strength gain with time. For lightweight concrete, these properties have been shown to be similar to normal-weight concrete, so typical design methods should be used.

3.5.5 Steel Girders

The issues of the coefficient of thermal expansion and transforming the deck have been discussed in the section on decks (section 3.5.2). The only issue related to the use of lightweight concrete for decks on steel girders is discussed below.

3.5.5.1 Steel Stud Design for Composite Girders

The AASHTO LRFD-8 Design Specifications provide equations 6.10.10.4.3-1 and -2 for the shear resistance of composite shear connectors (studs and channels) in concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The equation includes both E_c and f'_c under the radical which appears to reasonably account for the potentially reduced composite shear connector capacity when lightweight concrete is used. See additional discussion in section 4.17.3.

3.5.6 Mass Concrete

Recently, the use of lightweight concrete has been proposed for mass placements to improve the tolerance of the concrete to thermal gradients and cracking. The compounding effect of reduced modulus of elasticity and coefficient of thermal expansion is expected to reduce the cracking tendency of mass concrete elements. Initial work was performed by Tankasala and Schindler

(2017) and Tankasala et al. (2017), but additional analysis and field trials should be used to demonstrate the effectiveness of this approach.

3.5.7 Lightweight Concrete Bridge Railings

Bridge railings have been constructed from lightweight concrete in some States for quite a few years. There is no clear consensus regarding whether lightweight concrete can be used for railings.

Lightweight concrete could be used for railings using the same details as for normal-weight concrete for the following reasons:

1) lightweight concrete can be proportioned to have the same compressive strength as the conventional concrete used for a crash-tested railing,

2) development of mild reinforcement is similar or can be adjusted to account for lightweight concrete, or

3) the compressive strength can be adjusted as discussed above to avoid adjusting reinforcement development and splice lengths.

However, this should be confirmed with agencies responsible for a project.

4 DESIGN FOR LIGHTWEIGHT CONCRETE USING LRFD SPECIFICATIONS

After a designer selects the compressive strength, density, and other properties of lightweight concrete to be used for a project, design proceeds using the provisions of the AASHTO LRFD-8 Design Specifications (23 CFR 650.4(d)(1)(v)) in the same way that a design would proceed with normal-weight concrete (AASHTO 2017)Unless otherwise noted, all references to the binding LRFD Specifications will be to the 8th Edition just cited.

This chapter begins with section 4.1, which discusses an overview of revisions related to lightweight concrete that have been adopted and incorporated into the AASHTO LRFD-8 Design Specifications (23 CFR 650.4(d)(1)(v)). Sections 4.2 through 4.17 discuss articles directly from the AASHTO LRFD Design Specifications (AASHTO 2017) (23 CFR 650.4(d)(1)(v)).

Design using the AASHTO LRFD-8 Design Specifications for lightweight concrete elements proceeds in the same way as for normal-weight concrete (AASHTO 2017) (23 CFR 650.4(d)(1)(v)). Therefore, articles from AASHTO LRFD-8 Design Specifications that have particular application to lightweight concrete are listed and discussed including Section 5-Concrete Structures and a few articles from Section 6-Steel Structures and Section 9-Decks and Deck Systems. The relevant articles are presented in the order they appear in the AASHTO LRFD-8 Design Specifications (23 CFR 650.4(d)(1)(v)). Where some background for the design provisions is helpful, it is presented with the appropriate article.

4.1 OVERVIEW OF RECENT CHANGES RELATED TO LIGHTWEIGHT CONCRETE

Researchers at the FHWA Turner-Fairbank Highway Research Center (TFHRC) conducted an extensive study of the properties and performance of lightweight concrete. . The research efforts are presented in several research reports by Greene and Graybeal (2013, 2014, 2015, 2019) and are summarized in a paper by Greene et al. (2015). This section highlights most of the changes that are incorporated to the AASHTO LRFD-8 Design Specifications based on FHWA TFHRC research results including a new equation for the modulus of elasticity, E_c, and a major revision that affects many aspects of design using lightweight concrete in 2015 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.1.1 Types of Lightweight Concrete

Prior to 2015, lightweight concrete was defined in the previous and outdated versions of LRFD Design Specifications as having a unit weight of 0.120 kcf or less, while normal-weight concrete was defined as having a unit weight between 0.135 and 0.155 kcf, so there was a range of unit weights (0.120 to 0.135 kcf) for which the type of concrete was undefined. Refer to discussion in section 2.2.1 concerning related definitions of sand-lightweight concrete, all-lightweight concrete, and specified-density concrete.

Prior to 2015, previous and outdated versions of the LRFD Design Specifications defined lightweight concrete mixtures in terms of the combinations of types of aggregate used. Two types of lightweight concrete were defined: "all-lightweight" concrete, which had both lightweight coarse and lightweight fine aggregate and had the lowest density of about 0.100 kcf, and "sand-lightweight" concrete, which had lightweight coarse aggregate combined with normal-weight fine aggregate, that had an intermediate density of 0.110 to 0.125 kcf. The full range of densities from "all-lightweight" concrete to normal-weight concrete could be achieved by blending lightweight and normal-weight aggregates, in what is often called "specified density" concrete, but these concretes using other blends of aggregates were not addressed in the specifications. Furthermore, a designer specifying a concrete density could not be sure whether the mixture would be a "sand-lightweight" concrete or would contain a blend of aggregates, because the mix proportions to achieve a specified density will vary depending on the properties of the source(s) of lightweight aggregate. Quotations

This was addressed by the new definition for lightweight concrete adopted in 2015 and appears in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *Lightweight Concrete – Concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567.*

This definition expanded on the previous definition to include any concrete that contained lightweight aggregate that had a density less than normal-weight concrete (0.135 kcf). The definition no longer included types of concrete based on the types of aggregate, i.e., sand- or all-lightweight concrete. The terms referring to types of lightweight concrete may still be used informally for convenience but are not used in the specifications.

4.1.2 Concrete Density Modification Factor

The concept of the concrete density modification factor has been present in previous and outdated versions of LRFD bridge design specifications since at least 1983, but a variable was not assigned to the factor. With the revisions of 2015, the factor was given the notation, λ, and was given in only one section of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

In addition to a new definition of lightweight concrete, the definition of the concrete density modification factor, λ, has also been revised by removing its previous dependence on the type of concrete, i.e., sand- or all-lightweight concrete. Now, the value of λ is simply a function of the unit weight, w_c, with the value varying linearly between 0.75 at a density of 0.100 kcf or less to a value of 1.00 at a density of about 0.135 kcf. This relationship is expressed in AASHTO LRFD-8 Design Specifications as (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$0.75 \leq \lambda = 7.5\, w_c \leq 1.0$$

This equation is used when the splitting tensile strength, f_{ct}, of the mix is not specified, which has usually been the approach taken by designers when using lightweight concrete. However, if the splitting tensile strength is specified, then the concrete modification factor can be determined based on the ratio of the specified splitting tensile strength to the expected splitting tensile strength for normal-weight concrete, which can be determined by solving AASHTO LRFD-8 Design Specifications equation 5.4.2.8-2 for λ, resulting in this expression (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$\lambda = 4.7\, f_{ct} \leq 1.0$$

where:

f_{ct} = splitting tensile strength of normal-weight concrete, which is generally taken as = $0.21\sqrt{f'_c}$

Recent tests indicate that the splitting tensile strength of lightweight concrete mixtures can often meet this limit. Therefore, in situations where using a lower value of λ may have a detrimental effect on the design, designers should consider specifying the splitting tensile strength of the lightweight concrete so the value of λ will be greater than the value computed based on unit weight, or even use a value of 1.0, which will lead to no difference between the design for lightweight concrete or normal-weight concrete for quantities where λ is involved.

Prior to the revisions in 2015, the previous and outdated versions of LRFD Design Specifications included the concrete modification factor without assigning a variable. As a result, it could not be inserted into equations where it should be used. As part of the revisions adopted in 2015, all equations where the factor should be used were identified and were revised to include the factor in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Provisions in the AASHTO LRFD-8 Design Specifications that now use the concrete modification factor include allowable tensile stress limits for prestressed concrete, modulus of rupture, shear resistance, and development of mild reinforcement (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). See Greene et al. (2015) for further details.

4.1.3 Concrete Modulus of Elasticity

The equation used prior to 2015 for the concrete modulus of elasticity, E_c, in LRFD bridge design specifications, including the AASHTO LRFD-8 Design Specifications (23 CFR 625.4(d)(1)(v)), was proposed by Pauw (1960). As part of a study by FHWA, Greene and Graybeal (2013) evaluated a database of elastic modulus test results that included over 2,500 measurements for lightweight concrete and 3,800 measurements for normal-weight concrete (Rizkalla et al. 2007). Based on this evaluation, the following new equation was developed and adopted by AASHTO (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

$$E_c = 120{,}000\, K_1\, (w_c)^{2.0}\, (f'_c)^{0.33}$$

where:

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

w_c = unit weight of concrete (kcf)

f'_c = compressive strength of concrete for use in design (ksi)

While there is considerable scatter in test values for the modulus of elasticity for concrete, it was demonstrated that the new equation provided better estimates for both lightweight concrete and high-strength normal-weight concrete, while providing results similar to those from the previous equation for normal-weight concrete with compressive strengths up to 10 ksi.

4.1.4 Resistance Factor for Shear for Lightweight Concrete

When the first and outdated LRFD Design Specifications were introduced in 1994, a shear resistance factor of 0.7 was provided for lightweight concrete, rather than the shear resistance factor of 0.9 for normal-weight concrete. This lower factor was used because of a lack of shear test data for lightweight concrete. For the evaluation of shear resistance at the strength limit state, the combination of this factor with the concrete density modification factor resulted in a compounding in the reduction of shear resistance that eliminated the use of lightweight concrete from consideration from several structures where shear was critical. With data from the lightweight aggregate industry, Paczkowski and Nowak (2010) reevaluated the shear resistance factor for lightweight concrete, resulting in an increase in the factor to 0.8 in 2011. New lightweight concrete shear test results became available from a National Cooperative Highway Research Program (NCHRP) study (Cousins et al. 2013) and from FHWA TFHRC testing (Greene and Graybeal 2015, Greene and Graybeal 2019). These test results support the revision of the shear resistance factor to be equal to the factor for normal weight concrete (Greene and Graybeal 2015, Greene and Graybeal 2019). The increased shear resistance factor for lightweight concrete was adopted as part of the 2015 revisions as shown in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.2 ARTICLE 3.5—PERMANENT LOADS

As previously mentioned at the beginning of this chapter, sections 4.2 through 4.17 provide discussions on articles directly from the AASHTO LRFD-8 Specification (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The first mention of lightweight concrete in the AASHTO LRFD-8 Design Specifications is in table 3.5.1-1 that provides traditional values for unit weights of construction materials, including lightweight concrete, that can be used in the absence of more precise information (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Provision of a single unit weight for lightweight concrete is a simplification, since values ranging from 0.095 to 0.135 kcf are possible. The portion of the table with concrete unit weights is replicated in Table 12.

Table 12. Unit weights for concrete from AASHTO LRFD-8 Design Specifications table 3.5.1-1. (AASHTO 2017) (23 CFR 625.4(d)(1)(v))

Concrete Material Type:	Unit Weight (kcf)
Lightweight	0.110 to 0.135
Normal Weight with $f'_c \leq 5.0$ ksi	0.145
Normal Weight with $5.0 < f'_c \leq 15.0$ ksi	$0.140 + 0.001 f'_c$

The concrete unit weights shown in Table 12 are for unreinforced concrete. The commentary indicates that the unit weight of reinforced concrete is generally taken as 0.005 kcf more than the unit weight of plain (unreinforced) concrete. This assumed increment of dead load should be evaluated, especially for heavily reinforced concrete of any type, because it may be inadequate. Excess weight for an element can be an important factor for its handling and transportation as well as its performance in service.

4.3 ARTICLE 5.1—SCOPE

The first paragraph of article 5.1 of the AASHTO LRFD-8 Design Specifications includes the following, which indicates that, unless otherwise stated, the specifications are applicable for the design of lightweight concrete members (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The provisions in this Section apply to the design of bridge and ancillary structures constructed of normal weight or lightweight concrete… The provisions are based on design concrete compressive strengths varying from 2.4 ksi to 10 .0 ksi for normal weight and lightweight concrete, except where higher strengths not exceeding 15.0 ksi are allowed for normal weight concrete.*

4.4 ARTICLE 5.2—DEFINITIONS

Definitions for lightweight concrete and normal-weight concrete include (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *Lightweight Concrete—Concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined by ASTM C567.*
>
> *Normal Weight Concrete—Plain concrete having an equilibrium density greater than 0.135 kcf and a density not exceeding 0.155 kcf.*

These definitions use the same term "density" as in ASTM C567. However, in other parts of the AASHTO LRFD-8 Design Specifications (see the next section, for example), the terms "unit weight" and "density" are used interchangeably. This document will also use both terms interchangeably.

4.5 ARTICLE 5.3—NOTATION

Notations that appear in the AASHTO LRFD-8 Design Specifications section 5 that are related to lightweight concrete are shown below (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> f_{ct} = average splitting tensile strength of lightweight concrete (ksi) (5.4.2.8)
>
> w_c = unit weight of concrete (kcf) (5.4.2.4)
>
> λ = concrete density modification factor (5.4.2.8)

These quantities are discussed elsewhere in this document.

4.6 ARTICLE 5.4—MATERIAL PROPERTIES

Each subarticle of article 5.4.2—Normal Weight and Lightweight Concrete of the AASHTO LRFD-8 Design Specifications that has a specific reference to lightweight concrete, or about which a comment regarding lightweight concrete could be made, is discussed in this section. Information on test data for the material properties discussed in this section were discussed in chapter 2.

4.6.1 Article 5.4.2.1—Compressive Strength

The fourth paragraph in this article states (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *For lightweight concrete, physical properties in addition to compressive strength shall be specified in the contract documents.*

In most cases, the only additional physical property that should be specified is the density. If other properties would be specified for a design using normal-weight concrete, those properties should also be specified for lightweight concrete.

It should be noted that article 5.1 limits the use of the specifications to lightweight concrete with compressive strengths that do not exceed 10 ksi.

The following statement appears in the commentary:

> *Lightweight concrete is generally used only under conditions where weight is critical.*

This statement does not limit the use of lightweight concrete because other applications are possible such as internal curing (Carpenter 2019).

4.6.2 Article 5.4.2.2—Coefficient of Thermal Expansion

This article provides the following values for the coefficient of thermal expansion for use when more precise data are not available (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

- *For normal weight concrete:* $6.0 \times 10^{-6}/°F$*, and*
- *For lightweight concrete:* $5.0 \times 10^{-6}/°F$

The commentary to this article provides additional information and several references (not repeated) on the topic (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The thermal coefficient depends primarily on the types and proportions of aggregates used and on the degree of saturation of the concrete.*
>
> *The thermal coefficient of normal weight concrete can vary between 3.0 to* $8.0 \times 10^{-6}/°F$*, with limestone and marble aggregates producing the lower values, and chert and quartzite the higher. Only limited determinations of these coefficients have been made for lightweight concrete. They are in the range of 4.0 to* $6.0 \times 10^{-6}/°F$ *and depend on the amount of natural sand used.*

Test data for the coefficient of thermal expansion reported by Byard and Schindler (2010) and Castrodale and Cavalline (2017) are in reasonable agreement with the values shown

4.6.3 Article 5.4.2.3—Creep and Shrinkage

Article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Therefore, the equations in this article 5.4.2.3 can be applied directly for use with lightweight concrete with compressive strength not to exceed 10 ksi. This is supported by research cited in sections 2.2.4.6 and 2.2.4.7.

4.6.4 Article 5.4.2.4—Modulus of Elasticity

A new equation for the modulus of elasticity of concrete was adopted by AASHTO in 2014 as shown in the LRFD Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The equation retains the form of the earlier equation but uses a different coefficient and exponents to provide a better estimate for lightweight concrete and high-strength concrete (Greene and Graybeal 2013, Greene et al. 2015). The equation is repeated here:

$$E_c = 120{,}000\, K_1\, w_c^{2.0} f'^{0.33}_c$$

The commentary includes two forms of the prior equation, but indicates that these prior equations:

> *… do not fully reflect lightweight concrete and higher compressive strengths.*

The value for w_c used in the equation should be for plain (unreinforced) concrete.

4.6.5 Article 5.4.2.5—Poisson's Ratio

This article provides a single value of Poisson's ratio that applies for both lightweight concrete and normal-weight concrete which is consistent with article 5.1 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *Unless determined by physical tests, Poisson's ratio may be assumed to be 0.2 for lightweight concrete with design compressive strengths up to 10.0 ksi and for normal weight concrete with design compressive strengths up to 15.0 ksi.*

4.6.6 Article 5.4.2.6—Modulus of Rupture

This article provides an expression for the modulus of rupture, which includes λ to allow its use for both lightweight concrete and normal-weight concrete and is consistent with article 5.1:

> *Unless determined by physical tests, the modulus of rupture, fr, for lightweight concrete with specified compressive strengths up to 10.0 ksi and normal weight concrete with specified compressive strengths up to 15.0 ksi may be taken as 0.24 λ□√f'c where λ is the concrete density modification factor as specified in Article 5.4.2.8.*

See discussion in section 2.2.4.3, which suggests use of the splitting tensile strength rather than the modulus of rupture for general tensile strength considerations.

4.6.7 Article 5.4.2.7—Tensile Strength

This article refers to both the direct tensile strength and splitting tensile strength of concrete. See discussion in section 2.2.4.4 that suggests the use of splitting tensile strength.

4.6.8 Article 5.4.2.8—Concrete Density Modification Factor

This article describes the concrete density modification factor, λ.

The concrete density modification factor is used in the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)) to address the potential reduction in tensile strength of lightweight concrete compared to normal-weight concrete with the same compressive strength. If the tensile strength is reduced, design properties of lightweight concrete related to tensile strength, such as shear and development length, should be reduced. In the AASHTO LRFD-8 Design Specifications the reduction factor was assigned a name, the concrete density modification factor, and a variable, λ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). With the assignment of a variable, the factor was also inserted into appropriate equations as part of the revision. However, it is important to note that the tensile strength of lightweight concrete is not always less than a comparable normal-weight concrete, as discussed in section 2.2.4.4. The AASHTO LRFD-8 Design Specifications provide a means to account for this in the provisions that follow by allowing the splitting tensile strength, f_{ct}, of lightweight concrete to be specified (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The following is the text from the article:

> *The concrete density modification factor, λ, shall be determined as:*
>
> - *Where the splitting tensile strength, f_{ct}, is specified:*
>
> $$\lambda = 4.7\, f_{ct} / \sqrt{f'_c} \leq 1.0 \qquad (5.4.2.8\text{-}1)$$
>
> - *Where f_{ct} is not specified:*
>
> $$0.75 \leq \lambda = 7.5\, w_c \leq 1.0 \qquad (5.4.2.8\text{-}2)$$
>
> - *Where normal weight concrete is used, λ shall be taken as 1.0.*

While the AASHTO LRFD-8 Design Specifications do not provide an equation for the expected splitting tensile strength of normal-weight concrete, an expression can be obtained from equation 5.4.2.8-1 by solving for f_{ct} when $\lambda = 1.0$, which results in the expression: $f_{ct} = (1/4.7)\sqrt{f'_c} = 0.213\sqrt{f'_c}$. Solving equation 5.4.2.8-1 without inserting $\lambda = 1.0$ results in a general form of the equation that can be used to compute f_{ct} for situations where λ is not specified: $f_{ct} = (\lambda/4.7)\sqrt{f'_c}$ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The expression in equation 5.4.2.8-2 provides results that give the same range of variation in λ as was used in the previous versions of the specifications.

In most cases, the simplified approach in the 2nd and 3rd bullets (rather than specifying f_{ct}) can be used without significant negative impact on the design of an element. However, for elements in which shear or development length is an important design parameter, designers should consider specifying the splitting tensile strength with a value that will allow an increased λ above the value computed in the 2nd bullet, or to specify $f_{ct} = 0.213\sqrt{f'_c}$ as determined above so λ = 1.0 and there will be no difference in shear or development length between a lightweight concrete and normal-weight concrete design.

The commentary text for this article is repeated here (the figure and associated text are not repeated):

> *The concrete density modification factor was developed based on available test data. There is a lack of data for concrete mix design wherein a large majority of the fine aggregate is lightweight and a large majority of the coarse aggregate is normal weight. The concrete density modification factor, λ, is based on work on mechanical properties, development of reinforcement, and shear by Greene and Graybeal (2013), (2014) and (2015), respectively.*

The combination of lightweight fine aggregate and normal-weight coarse aggregate is commonly referred to as an "inverted mix" and has not been widely used for structural concrete so data are lacking for the performance of this type of mix.

4.7 ARTICLE 5.5—LIMIT STATES AND DESIGN METHODOLOGIES

4.7.1 Article 5.5.3—Fatigue Limit State

The AASHTO LRFD-8 Design Specifications article 5.5.3 states in the last sentence of the article as shown below when the section properties for fatigue investigations should be based on cracked sections when the computed tensile stress exceeds the limit shown (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The section properties for fatigue investigations shall be based on cracked sections where the sum of stresses, due to unfactored permanent loads and prestress, and the Fatigue I load combination is tensile and exceeds $0.095\sqrt{f'_c}$.*

The stress limit at the end of the sentence is equal to the limiting tensile stress in table 5.9.2.3.2b-1. In the AASHTO LRFD-8 Design Specifications, stresses in that table appear without the concrete density modification factor, λ. However, in the AASHTO LRFD Design Specifications, 9th Edition (2020)[12], the factor has been added to the stresses in that table.

4.7.2 Article 5.5.4—Strength Limit State

Resistance factors for the strength limit state are presented in article 5.5.4.2. The introductory statements to the article explicitly state the applicability to lightweight concrete:

[12] AASHTO LRFD Bridge Design Specifications, 9th Edition (2020), is not incorporated in the CFR Title 23.

Where no distinction is made for density the values given shall be taken to apply to normal weight and lightweight concrete.

In all cases in article 5.5.4.2 where resistance factors are specifically listed for lightweight concrete, the values for lightweight concrete and normal-weight concrete are equal. Where lightweight concrete is not specifically listed, the resistance factor value given applies to both lightweight concrete and normal-weight concrete.

4.8 ARTICLE 5.6—DESIGN FOR FLEXURAL AND AXIAL FORCE EFFECTS – B-REGIONS

4.8.1 Article 5.6.2—Assumptions for Strength and Extreme Event Limit States

This article gives assumptions used for the equivalent rectangular stress block, which is the simplified approach used for computing the concrete contribution to the flexural resistance of members and begins by stating the following:

The following assumptions may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.

The explicit identification of normal-weight concrete and lack of reference to lightweight concrete in this article appears to indicate that the provisions of these articles only apply to normal-weight concrete. Similar statements appear in several other articles. However, article 5.1 of the AASHTO LRFD Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.8.2 Article 5.6.3—Flexural Members

This article gives assumptions used for flexural design at the strength limit state and begins by stating:

The following assumptions may be used for normal weight concrete with design compressive strengths up to 15.0 ksi and lightweight concrete up to 10.0 ksi.

This article is consistent with article 5.1, Scope, of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.8.3 Article 5.6.4—Compression Members

4.8.3.1 Article 5.6.4.2—Limits for Reinforcement

The first paragraph of this article states the following:

The following reinforcement limits may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.

This text is the same as appears in article 5.6.2 (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The following the text appears before equation 5.6.4.2-4:

> *For design compressive strengths of normal weight concrete up to 15.0 ksi where …, the reinforcement ratio calculated by Eq. 5.6.4.2-3 need not be greater than: …*

This appears to provide a limit that is intended to apply only when high-strength normal-weight concrete is used and does not apply for lightweight concrete.

4.8.3.2 Article 5.6.4.3—Approximate Evaluation of Slenderness Effects

Using lightweight concrete reduces modulus of elasticity of lightweight concrete, which will affect the results of calculations related to slenderness of compression members.

4.8.3.3 Article 5.6.4.4—Factored Axial Resistance

This article begins by stating the following:

> *The following assumptions may be used for normal weight concrete with design compressive strengths up to 15.0 ksi and lightweight concrete up to 10.0 ksi.*

4.8.3.4 Article 5.6.4.5—Biaxial Flexure

The first paragraph of this article states the following:

> *The following assumptions may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.*

This text is the same as appears in article 5.6.2. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.8.3.5 Article 5.6.4.6—Spirals, Hoops and Ties

The first paragraph of this article states the following:

> *The following assumptions may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.*

This text is the same as appears in article 5.6.2. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.9 ARTICLE 5.7—DESIGN FOR SHEAR AND TORSION – B-REGIONS

Several provisions in article 5.7 of the AASHTO LRFD-8 Design Specifications account for the effect of lightweight concrete by including the concrete density modification factor, λ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Therefore, design can proceed for lightweight concrete as for normal-weight concrete, but with the use of λ as indicated in the equations, such as in 5.7.2.1—General and 5.7.2.5—Minimum Transverse Reinforcement.

4.9.1 Article 5.7.3—Sectional Design Model

The first paragraph of article 5.7.3.1 states:

> *The sectional design model may be used for shear design where permitted in accordance with the provisions of Article 5.7.1. The provisions herein may be used for normal weight concrete with compressive strength of concrete used for design up to 15.0 ksi and lightweight concrete up to 10.0 ksi.*

This article clearly states that the provisions in this article apply for lightweight concrete with compressive strengths up to 10 ksi, as stated in article 5.1. Therefore, design can proceed for lightweight concrete as for normal-weight concrete, but with the use of λ as indicated in the equations, such as in article 5.7.3.3—Nominal Shear Resistance.

4.9.2 Article 5.7.4—Interface Shear Transfer

Article C5.7.4.3 states that the development of equations 5.7.4.3-3 through 5 included data from tests of lightweight concrete compressive strengths from 2 to 6 ksi, and a wider range of strengths for normal-weight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Article 5.7.4.4 provides parameters to be used to compute the interface shear resistance of various types and conditions of interfaces. The first and third bullets include direct references to lightweight concrete. Commentary is provided for the third bullet that indicates that the parameters listed are conservative because of a lack of data. The fifth and sixth bullets do not specify concrete type, so they can be assumed to apply to both normal-weight concrete and lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.10 ARTICLE 5.8—DESIGN OF D-REGIONS

4.10.1 Article 5.8.2—Strut-and-Tie Method (STM)

Article 5.8.2.1 provides introductory information for the use of provisions for the strut-and-tie model (STM). The third paragraph states (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The provisions of these articles apply to components with reinforcement yield strengths not exceeding 75.0 ksi and normal weight concrete compressive strength for use in design up to 15.0 ksi.*

This limitation to normal-weight concrete appears to be similar to other articles already discussed where the mention of normal-weight concrete was only intended to indicate the applicability of the provisions to the higher compressive strength range up to 15 ksi. However, commentary article C5.8.2.1 clearly states that this is not intended (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The limitation on the use of the STM for only normal weight concrete components is based solely on a lack of suitable experimental verification.*

The strut-and-tie method is a conceptual design approach that simplifies behavior of concrete elements using a truss analogy in which tension forces are resisted by ties (reinforcement) and compression forces are resisted by struts (concrete). This approach conservatively neglects the contribution of the concrete tensile strength to shear resistance. Since it is conceptual rather than empirical, the basic concept can be applied without specific information about the properties of the concrete. In late 2021, AASHTO was considering revising this statement for the next edition of the AASHTO LRFD Design Specifications to allow use of the strut-and-tie method with lightweight concrete.

4.10.2 Article 5.8.4—Approximate Stress Analysis and Design

The legacy design approaches in this article have been modified for use with lightweight concrete by including the concrete density modification factor, λ, in equations in Articles 5.8.4.2.2—Alternative to Strut-and-Tie Model, 5.8.4.3.4—Design for Punching Shear, and 5.8.4.3.5—Design of Hanger Reinforcement (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.11 ARTICLE 5.9—PRESTRESSING

4.11.1 Article 5.9.2—Stress Limitations

4.11.1.1 Article 5.9.2.3.1—For Temporary Stresses before Losses

The type of concrete is not mentioned for the temporary compressive stress limits before losses in article 5.9.2.3.1a.

The expressions for temporary tensile stress limits before losses are listed in table 5.9.2.3.1b-1 and have been modified for use with lightweight concrete by including the concrete density modification factor, λ. It appears that the compressive strength limits for lightweight concrete and normal-weight concrete that are listed in the Bridge Type column in the AASHTO LRFD-8 Design Specifications table 5.9.2.3.2b-1 should also appear in this table (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). A portion of table 5.9.2.3.1b-1 is replicated in Table 13. Note that λ appears in the expressions for the stress limits.

Table 13. Temporary tensile stress limits in prestressed concrete before losses for "Other Than Segmentally Constructed Bridges" (from AASHTO LRFD-8 Design Specifications table 5.9.2.3.1b-1) (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Location	Stress Limit
In precompressed tensile zone without bonded reinforcement	N/A
In areas other than the precompressed tensile zone and without bonded reinforcement	$0.0948\lambda\sqrt{f'_{ci}} \leq 0.2$ (ksi)
In areas with bonded reinforcement (reinforcing bars or prestressing steel) sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$, not to exceed 30.0 ksi	$0.24\lambda\sqrt{f'_{ci}}$ (ksi)
For handling stresses in prestressed piles	$0.158\lambda\sqrt{f'_{ci}}$ (ksi)

4.11.1.2 Article 5.9.2.3.2—For Stresses at Service Limit State after Losses

The first paragraph of article 5.9.2.3.2 is repeated here.

> *Compression shall be investigated using the Service Limit State Load Combination I specified in Table 3.4.1-1. The limits in Table 5.9.2.3.2a-1 shall apply. These limits may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.*

The last sentence is essentially the same as the text that appears in article 5.6.2. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). A portion of table 5.9.2.3.2b-1 is replicated in Table 14. Note that λ appears in the expressions for the stress limits and that the following note that appears in the Bridge Type column of the original table applies to these stress limits: "These limits may be used for normal weight concrete with concrete compressive strengths for use in design up to 15.0 ksi and lightweight concrete up to 10.0 ksi."

Table 14. Tensile stress limits in prestressed concrete at service limit state after losses in the Precompressed Tensile Zone, assuming uncracked sections, for "Other Than Segmentally Constructed Bridges" (from AASHTO LRFD-8 Design Specifications table 5.9.2.3.2b-1) (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

Location and Other Conditions	Stress Limit
For components with bonded prestressing tendons or reinforcement that are subjected to not worse than moderate corrosion conditions	$0.19\lambda\sqrt{f'_c} \leq 0.6$ (ksi)
For components with bonded prestressing tendons or reinforcement that are subjected to severe corrosive conditions	$0.0948\lambda\sqrt{f'_c} \leq 0.3$ (ksi)
For components with unbonded prestressing tendons	No tension

4.11.1.3 Article 5.9.2.3.3— Principal Tensile Stresses in Webs

The third paragraph of this article specifies the principal tensile stress limit of $0.110\lambda\sqrt{f'_c}$, which can be used for lightweight concrete because λ is included in the expression. This limit applies for all post-tensioned superstructures. However, the limit only applies to pretensioned concrete girders with design compressive strengths greater than 10 ksi, so it does not apply for lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.11.2 Article 5.9.3—Prestress Losses

4.11.2.1 Article 5.9.3.1—Total Prestress Losses

The first paragraph of this article states the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *Values of prestress losses specified herein shall be applicable to normal weight concrete only and may be used for concrete compressive strengths for use in design up to 15.0 ksi, unless stated otherwise.*

This text appears to state that the provisions in this article can only be used for normal-weight concrete. However, the commentary in C5.9.3.1 states the following:

> *The extension of the provisions to 15.0 ksi was based on Tadros (2003), which only included normal weight concrete. Consequently, the extension to 15.0 ksi is only valid for members made with normal weight concrete.*

The commentary clarifies that the intent of this article is consistent with the rest of the specifications, that is, the limitation of the application to normal-weight concrete is only for the extension of compressive strength to 15.0 ksi. This indicates that the provision was not intended to exclude lightweight concrete. The study of lightweight concrete girders and decks by Cousins et al. (2013) confirmed this by concluding that the existing design provisions for prestress losses in the AASHTO LRFD-8 Design Specifications "yield reasonable results when used to calculate prestress loss in members made with sand-lightweight concrete." (AASHTO 2017) (23 CFR 625.4(d)(1)(v))

4.11.2.2 Article 5.9.3.2.3—Elastic Shortening

This article does not mention lightweight concrete; however, a comment is provided. The equation for modulus of elasticity in the AASHTO LRFD-8 Design Specifications includes the density term to account for the reduced density of lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The lower modulus of elasticity for lightweight concrete results in greater elastic shortening losses. However, the increased elastic shortening loss is typically a minor fraction of the effective prestress, so the detrimental effect on designs is not significant.

4.11.2.3 Article 5.9.3.3—Approximate Estimate of Time-Dependent Losses

This article applies only to the approximate estimate of the time-dependent losses, that is creep, shrinkage, and relaxation. This simplified loss computation method, which is equivalent to lump sum methods of the past and is not frequently used, was developed using only normal-weight concrete data. Therefore, as the first bullet states, it only applies to normal-weight concrete. This simply means that prestress losses for lightweight concrete members should be computed using the refined or time-step methods for computing losses, which are used for the great majority of designs.

4.11.2.4 Article 5.9.3.3—Refined Estimates of Time-Dependent Losses

As discussed in section 4.11.2.1, the provisions for estimating time-dependent losses using the refined method have been found to apply to lightweight concrete without modification.

4.11.3 Article 5.9.4—Details of Pretensioning

4.11.3.1 Article 5.9.4.3.1—General

The last paragraph of this article states the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The provisions of Article 5.9.4.3 may be used for normal weight concrete with design concrete compressive strengths up to 10.0 ksi at transfer (f'_{ci}) and up to 15.0 ksi for design (f'_c).*

C5.9.4.3.1 states the following:

> *The extension of the transfer and development length provisions to normal weight concrete with design concrete compressive strength up to 10.0 and 15.0 ksi for f'_{ci} and f'_c respectively, is based on the work presented in NCHRP Report 603 (Ramirez and Russell, 2008).*

Research by Cousins et al. (2013) demonstrated "these provisions yield reasonable results when used to calculate transfer and development length in members made with sand-lightweight concrete.

4.11.3.2 Article 5.9.4.4—Splitting Resistance

This article appears under 5.9.4.4—Pretensioned Anchorage Zones and does not mention lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The provisions are intended to prevent web-splitting cracking by providing web reinforcement operating at a reduced working stress to control the crack widths. However, while a potentially lower tensile strength may make end-splitting cracking more likely for lightweight concrete, it is not clear that the force provided by the reinforcement should be increased. Furthermore, the reduced stiffness of lightweight concrete may also tend to reduce the splitting force. Additional research and analysis of this item is suggested.

4.11.4 Article 5.9.5—Details of Post-Tensioning

Only one article in this section is modified for lightweight concrete, which is Article 5.9.5.4.4b—Shear Resistance to Pull-Out, where the concrete density modification factor λ is included in equations to account for the effect of lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.12 ARTICLE 5.10—REINFORCEMENT

4.12.1 Article 5.10.4—Transverse Reinforcement for Compression Members

4.12.1.1 5.10.4.3—Ties

The first paragraph of this article states the following:

> *The following requirements for transverse reinforcement may be used for normal weight concrete with design compressive strengths up to 15.0 ksi.*

This text is like the text that appears in article 5.6.2. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.12.2 Article 5.10.6—Shrinkage and Temperature Reinforcement

Lightweight concrete is not mentioned in this article. However, because of the reduced shrinkage and CTE that are expected for lightweight concrete, there may be potential to reduce shrinkage and temperature reinforcement. However, no research has been conducted in this area to support such a reduction.

4.12.3 Article 5.10.8—Development and Splices of Reinforcement

4.12.3.1 Article 5.10.8.1—General, and others as noted

This article gives design provisions for development and splices of reinforcement and begins with stating the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The provisions of Articles 5.10.8.2.1, 5.10.8.2.4, and 5.10.8.4.3a are valid for No. 11 bars or smaller, in normal weight concrete with design concrete compressive strength (f'_c) of*

up to 15.0 ksi and lightweight concrete up to 10.0 ksi, subject to the limitations as specified in each of these articles.

This statement indicates that these provisions apply to both lightweight and normal-weight concrete with a limiting design concrete compressive strength of 10.0 ksi for lightweight concrete. A similar statement recognizing application to both lightweight and normal-weight concrete appears in Article 5.10.8.2.1—Deformed Bars and Deformed Wire in Tension and 5.10.8.2.4—Standard Hooks in Tension, both of which also repeat the maximum compressive strength limit for lightweight concrete.

4.12.3.2 Article 5.10.8.2.1a—Tension Development Length, and others as noted

Several articles in this section are modified for lightweight concrete by adding the concrete density modification factor, λ, to equations to account for the effect of lightweight concrete, including Articles 5.10.8.2.1a—Tension Development Length, 5.10.8.2.1b—Modification Factors which Increase ℓ_d, 5.10.8.2.4a—Basic Hook Development Length, 5.10.8.2.5a—Welded Deformed Wire Reinforcement, 5.10.8.2.5b—Welded Plain Wire Reinforcement, and 5.10.8.2.6b—Anchorage of Deformed Reinforcement. Several of these articles mention the limitation of compressive strength for lightweight concrete in the definition of f'_c and include a definition for λ.

It should be noted that in articles where a modified development length ℓ_d is determined using two equations, such as Article 5.10.8.2.1a, the term λ does not appear in the same equation with $\sqrt{f'_c}$ but the combination of the two equations properly accounts for its effect on the tension development length.

4.12.3.3 Article 5.10.8.2.2a—Compressive Development Length

Equation 5.10.8.2.2a-1 does not include λ in the denominator, while the quantity is included in similar equations in articles 5.10.8.2.1a—Tension Development Length and 5.10.8.2.4a—Basic Hook Development Length.

ACI 318-19 includes the λ factor in one of the two equations that are to be evaluated to determine the development length of deformed bars in compression in article 25.4.9.1; the second equation is related to steel properties so λ is not relevant. The commentary to this section states the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

The term λ is provided in the expression for development in 25.4.9.2 recognizing that there are no known test data on compression development in lightweight concrete but that splitting is more likely in lightweight concrete.

Based on the inclusion of the factor in the ACI equation, designers could add the λ factor to the denominator of equation 5.10.8.2.2a-1 to be conservative.

4.12.3.4 Article 5.10.8.2.4b—Modification Factors

This article lists the concrete density modification factor, λ, as one of the modification factors applied to the basic development length of a standard hook in tension. The reference also lists the maximum design compressive strength limit of 10 ksi for lightweight concrete (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.12.3.5 Article 5.10.8.4.3—Splices of Reinforcement

This article does not include the concrete density modification factor, λ. However, the commentary for this article indicates the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *The tension development length, ℓ_d, used as a basis for calculating splice lengths should include all of the modification factors specified in Article 5.10.8.2.*

Because modification factors including λ are included in the provisions of Article 5.10.8.2, the factor is included indirectly in the calculations of Article 5.10.8.4.3.

4.12.3.6 Article 5.10.8.5—Splices of Welded Wire Reinforcement

The equations in this article do not include the concrete density modification factor, λ. However, its effect is included because these provisions are based on ℓ_d, which is calculated considering factors to increase the development length, including λ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.13 ARTICLE 5.11—SEISMIC DESIGN AND DETAILS

There is no mention of lightweight concrete in this article except for articles 5.11.4.2—Requirements for Wall-Type Piers and 5.11.4.3—Column Connections, where the concrete density modification factor, λ, is inserted into equations for computing the nominal or factored shear resistance (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

However, the lack of mention of lightweight concrete does not exclude its use for seismic design because of the statement in AASHTO LRFD-8 Design Specifications article 5.1. Furthermore, research described in section 2.2.6 of this document found that the ductility of lightweight concrete is adequate for use in structural elements where seismic design is necessary.

4.14 ARTICLE 5.12—PROVISIONS FOR STRUCTURE COMPONENTS AND TYPES

Lightweight concrete is only mentioned for two of the structure components or types in this article. Other sections are discussed where modifications for lightweight concrete may be considered

4.14.1 Article 5.12.2—Slab Superstructures

4.14.1.1 Article 5.12.2.3—Precast Deck Bridges

Shear keys are important components in construction of this type of bridge. However, there are no design provisions for shear keys. If shear capacity of lightweight concrete is reduced when λ < 1.0, then the shear capacity of keys should be reviewed with the reduced concrete resistance. The concrete design compressive strength of the lightweight concrete could be increased to compensate for the computed reduction in shear capacity.

4.14.2 Article 5.12.3—Beams and Girders

4.14.2.1 Article 5.12.3.2.5—Concrete Strength

This article is part of Article 5.12.3.2—Precast Beams. The second paragraph in this article states the following (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *For normal weight concrete, the 90-day strength of slow curing concretes may be estimated as 115 percent of the 28-day concrete strength.*

Lightweight concrete typically has similar strength gain characteristics as normal-weight concrete, and in some cases, the strength gain may be improved because of the effect of internal curing with prewetted lightweight aggregate.

4.14.3 Article 5.12.5—Segmental Concrete Bridges

The two articles discussed here are part of Article 5.12.5.3—Design.

4.14.3.1 Article 5.12.5.3.3—Construction Load Combinations at the Service Limit State

The first sentence in the last paragraph in this article states:

> *Tensile stresses in concrete due to construction loads shall not exceed the values specified in Table 5.12.5.3.3-1, except for structures with less than 60 percent of their tendon capacity provided by internal tendons, in which case the tensile stresses shall not exceed* $0.095\sqrt{f'_c}$.

Table 5.12.5.3.3-1 provides tensile stress limits for construction load combinations. The tensile stress limits are expressed in terms of $\sqrt{f'_c}$. Article 5.12.5.3.8c—Nominal shear resistance

The nominal shear resistance equations in this article have been modified for use with lightweight concrete by including the concrete density modification factor, λ.

4.14.4 Article 5.12.7—Culverts

4.14.4.1 Article 5.12.7.3—Design for Shear in Slabs of Box Culverts

The nominal shear resistance equations in this article have been modified for use with lightweight concrete by including the concrete density modification factor, λ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.14.5 Article 5.12.8—Footings

4.14.5.1 Article 5.12.8.6.3—Two-Way Action

The nominal shear resistance equations in this article have been modified for use with lightweight concrete by including the concrete density modification factor, λ (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.15 ARTICLE 5.13—ANCHORS

4.15.1 Article 5.13.1—General

The sixth paragraph in this article states (AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

> *Lightweight concrete factors for anchor design shall comply with ACI 318-14, Chapter 17.*

Note that the AASHTO reference to the ACI document cites the 2014 edition of the document, ACI 318-14[13].

The AASHTO LRFD-8 Design Specifications article 5.4.2.8 shows how the concrete density modification factor, λ, is determined, which is based on unit weight (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The lightweight concrete modification factor, λ, in ACI 318-14[13], Article 19.2.4, is determined differently and depends upon aggregate type combinations. The determination of λ was revised in the ACI 318-19[12] to also be based on unit weight, similar to the AASHTO LRFD-8 Design Specifications, although some significant differences remain. These differences should be considered when using the anchor design provisions of ACI 318-14[13] for bridge designs.

ACI 318-14[13] Article 17.2.6 also provides a modification factor, λ_a, which includes a further reduction of the λ factor determined in Article 19.2.4 for some concrete anchorage applications. The ACI 17.2.6 provisions are repeated here:

> *17.2.6 Modification factor λ_a for lightweight concrete shall be taken as:*
>
> *Cast-in and undercut anchor concrete failure 1.0 λ*
> *Expansion and adhesive concrete anchor failure 0.8 λ*
> *Adhesive anchor bond failure per Eq. (17.4.5.2) 0.6 λ*
>
> *where λ is determined in accordance with 19.2.4. It shall be permitted to use an alternative value of λ_a where tests have been performed and evaluated in accordance with ACI 355.2 or ACI 355.4.*

The additional modification coefficients for different types of anchors given in ACI 17.2.6 are applied to λ to obtain λ_a for use in computing the strength of an anchor. The commentary to article 17.2.6 in ACI 318-14 (article 17.2.4 in ACI 318-19) provides useful discussion that should be considered for anchors in lightweight concrete.

The factor λ_a is incorporated into anchor strength equations in ACI 318-14[13] in a similar manner to the use of λ elsewhere in ACI 318-14[13] and the AASHTO LRFD-8 Design Specifications. The following is an example for the basic concrete breakout strength of a single anchor in tension in cracked concrete, N_b, given in ACI 318-14 equation 17.4.2.2a:

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[13] ACI 318-14 and 318-19, Building Code Requirements for Structural Concrete, is not incorporated in the CFR Title 23. However, ACI 318-14 is referenced in the AASHTO LRFD Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

$N_b = k_c \lambda_a \sqrt{f'_c} h_{ef}^{1.5}$

Where as defined in ACI 318-14[13]):

N_b = basic concrete breakout strength in tension of a single anchor in cracked concrete (lb)

k_c = coefficient for basic concrete breakout strength in tension

λ_a = modification factor to reflect the reduced mechanical properties of lightweight concrete in certain concrete anchorage applications

f'_c = compressive strength of concrete for use in design (psi)

h_{ef} = effective embedment depth of anchor (in.)

When using provisions in ACI 318-14[13], designers should note that the unit used for concrete and steel stress is psi rather than ksi, and the unit used for force is lb rather than kip (1000 lb).

4.16 ARTICLE 5.14—DURABILITY

There is no reference to lightweight concrete in this section or equations that are modified for use with lightweight concrete. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). Discussion is provided for a few topics that could possibly be affected by using lightweight concrete.

4.16.1 Article 5.14.2.5—Delayed Ettringite Formation

When using lightweight concrete, there is potential for the concrete to experience higher temperatures compared to a similar conventional concrete mixture because of the porous, and therefore insulating, nature of lightweight aggregate. However, as for normal-weight concrete, such potential should be identified during mixture development and provision should be made to maintain the temperature of the concrete below the specified limit to avoid detrimental effects.

4.16.2 Articles 5.14.2.6 and 7—Alkali-Silica Reactive Aggregates and Alkali-Carbonate Reactive Aggregates

As mentioned in section 2.2.7.2, lightweight aggregate is not known to have ever been documented as a cause of damage from alkali-silica reactivity . Holm and Ries (2007) provide a brief discussion and several references on this topic.

4.17 SECTION 6—STEEL

4.17.1 Article 6.10.1.1.1b—Stresses for Sections in Positive Flexure

This article addresses transforming a concrete deck for computing stresses in a composite steel girder bridge. Lightweight concrete is not mentioned, but the effect of lightweight concrete is included by the modulus of elasticity of concrete in the modular ratio. Creep in the concrete is also discussed in this article as it relates to long-term deformations. As discussed in section 2.2.4.6, creep of lightweight concrete is similar to creep of normal-weight concrete.

4.17.2 6.10.1.7—Minimum Negative Flexural Concrete Deck Reinforcement

In this article, the modulus of rupture of lightweight concrete and normal-weight concrete are addressed in separate bullets. However, article 5.4.2.6 now includes the effect of lightweight concrete by the insertion of λ in the single expression $0.24\lambda\sqrt{f'_c}$. This article can still be used because it refers to article 5.4.2.6, which has the current expression (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

4.17.3 6.10.10.4.3—Nominal Shear Resistance

This article provides equations to compute the nominal shear resistance of two types of shear connectors. The equations and associated text are presented here (AASHTO 2017) (23 CFR 625.4(d)(1)(v)).

The nominal shear resistance of one stud shear connector embedded in a concrete deck shall be taken as:

$$Q_n = 0.5A_{sc}\sqrt{(f'_c E_c)} \leq A_{sc} F_u$$

Where (as defined in section 6 of the LRFD Specifications) (AASHTO 2017) (23 CFR 625.4(d)(1)(v))

Q_n = nominal shear resistance of a single shear connector (kip)

A_{sc} = cross-sectional area of a stud shear connector (in.^{2})

f'_c = specified minim 28-day compressive strength of concrete (ksi)

E_c = modulus of elasticity of the deck concrete determined as specified in Article 5.4.2.4 (ksi)

F_u = specified minimum tensile strength of a stud shear connector determined as specified in Article 6.4.4 (ksi)

The nominal shear resistance of one channel shear connector embedded in a concrete deck shall be taken as:

$$Q_n = 0.3(t_f + 0.5t_w)\, L_c\sqrt{(f'_c E_c)}$$

Where (as defined in section 6 of the AASHTOLRFD-8 Design Specifications; variables listed for the previous equation are not repeated) (AASHTO 2017) (23 CFR 625.4(d)(1)(v))

t_f = flange thickness of channel shear connector (in.)

t_w = web thickness of channel shear connector (in.)

L_c = length of channel shear connector (in.)

There is no mention of lightweight concrete in the provisions, but lightweight concrete is mentioned in the commentary(AASHTO 2017) (23 CFR 625.4(d)(1)(v)):

Studies have defined stud shear connector strength as a function of both the concrete modulus of elasticity and concrete strength (Ollgaard et al., 1971). Note that an upper bound on stud shear strength is the product of the cross-sectional area of the stud times its ultimate tensile strength. Equation 6.10.10.4.3-2 is a modified form of the formula for the resistance of channel shear connectors developed in Slutter and Driscoll (1965) that extended its use to lightweight as well as normal weight concrete.

Because equations 1 and 2 include the term $\sqrt{f'_c}$, it would at first appear that the concrete density modification factor, λ, should be inserted prior to the $\sqrt{f'_c}$ term to account for the effect of lightweight concrete and to be consistent with the remainder of the specifications. However, an examination of Ollgaard et al. (1971) reveals that equation 6.10.10.4.3-1 was developed using both lightweight concrete and normal-weight concrete and that including the modulus of elasticity of the concrete under the radical provided the necessary adjustment to account for the difference in performance of lightweight concrete. Therefore, no modification of the equations appears necessary for use with lightweight concrete.

4.18 SECTION 9—DECKS

There is no reference to lightweight concrete for decks in this section or equations that are modified for use with lightweight concrete. However, article 5.1 of the AASHTO LRFD-8 Design Specifications states that the provisions of the specifications apply to lightweight concrete with strengths up to 10 ksi (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). There is one occurrence of the word "lightweight" in this section, but it appears to refer to lightweight deck systems, rather than lightweight concrete.

5 CONSTRUCTION CONSIDERATIONS

Construction of bridges using lightweight concrete is little different from construction using normal-weight concrete, because lightweight concrete is simply concrete that uses lighter aggregate. However, the increased absorption and some related properties do affect some aspects of construction. This chapter discusses such differences in all phases of the production and use of lightweight concrete and approaches that can be used to achieve the desired results in the field.

While writing specifications (chapter 6) precedes construction in the timeline of a project, it is placed after the discussion of construction issues in this document because many of the issues to be addressed in specifications are related to the construction-related issues discussed in this section.

While internally cured concrete does contain lightweight aggregate, its fresh properties, testing methods, and other construction related considerations are consistent with normal-weight concrete rather than lightweight concrete. This is because the lightweight aggregate is only added in relatively small quantities, more like an admixture, rather than in quantities sufficient to significantly reduce the density as is the case for lightweight concrete. Therefore, construction considerations for internally cured concrete are discussed in a separate section at the end of this chapter.

5.1 QUALITY CONTROL

As is true for any construction project, quality control should be considered for a successful project outcome. This section discusses several topics related to the quality control of lightweight concrete as they differ from normal-weight concrete. Issues related to batching will be discussed in section 5.4.

5.1.1 Testing of Fresh Concrete

In general, the same test procedures are used for fresh concrete as are used for normal-weight concrete, with the exception of testing for entrained air content. As discussed in section 6.2.8, tests for entrained air content for lightweight concrete generally use the volumetric method of AASHTO T 196[7] (ASTM C173). The pressure method of AASHTO T 152[6] (ASTM C231) is based on observed change in volume of the concrete under known change in pressure and the pores in the lightweight aggregate will contribute to the air content being measured by this method. By contrast, the volumetric method of AASHTO T 196[7] (ASTM C173) is based on the removal of air in the mortar fraction through agitation and, thus, can be used for lightweight concrete (Kosmatka and Wilson 2016).

The unit weight for lightweight concrete is checked in the field as one of the criteria that will determine whether a load of concrete will be accepted. Therefore, attention to sampling and testing procedures should be paid, including providing adequate precision in calibration factors for the unit weight bucket (Castrodale and Harmon 2017).

5.1.2 Testing of Hardened Concrete

In general, the same test procedures are used for hardened concrete as are used for normal-weight concrete. However, there are several exceptions, which include modified freezing-and-thawing procedures of AASHTO M 195[1] (ASTM C330) and a suggested modification to the aggregate abrasion test of AASHTO T 96[14] (ASTM C131), both of which are discussed in section 6.3.

It should be noted that the initial density of cylinders when removed from the mold after hardening will typically be slightly greater than the fresh density of the concrete measured using a unit weight bucket in the field. This difference is caused by the greater compaction energy that is applied to the concrete in the cylinders compared to the concrete in the unit weight bucket.

While the splitting tensile strength of a lightweight concrete may be specified to address design considerations, the strength is intended for mix development and qualification and is not intended for control or acceptance of the strength of concrete in the field (ACI 213 2014).

5.2 PROPORTIONING LIGHTWEIGHT CONCRETE MIXTURES

The proportioning of lightweight concrete is discussed at length in a standard practice by ACI Committee 211[15] (211.2-98). However, responsibility for the ACI Committee 211 document was recently transferred to ACI 213[2] – Lightweight Aggregate and Concrete. During the transition, it was not updated and therefore no longer appears as an active ACI document. A new document is being prepared by ACI Committee 213.. The information on proportioning provided in the most recent version of the Committee 211 document is still valid, however, so it is still a resource. Hoff (2002) also provides a discussion on proportioning lightweight concrete mixtures.

Two methods are used to proportion lightweight concrete mixtures (ACI 213 2014). The two methods are the absolute volume method, which is typically used to proportion normal-weight concrete mixtures, and the volumetric method. Details of the methods are presented in ACI 211.2[15] (1998). Either method can be used to successfully proportion lightweight concrete mixtures.

Lightweight concrete mixtures are designed for a specified compressive strength using the same approach that is used for normal-weight concrete, while still having a reduced density. Some design specifications have assumed that typical proportioning approaches based on *w/cm* cannot be used with lightweight concrete. However, if lightweight aggregates are adequately prewetted prior to batching, little additional water will be absorbed by the lightweight aggregate during mixing and placing, which allows the *w/cm* to be determined with an accuracy comparable to normal-weight concrete mixtures (ACI 213 2014). Therefore, adequate prewetting of the

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[14] AASHTO T 96, Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in Los Angeles Machine, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

[15] ACI 211.2-98, Selecting Proportion for Structural Lightweight Concrete, is not incorporated in the CFR Title 23. However, this industry standard is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

aggregate is important. It should also be noted that maximum limits on *w/cm* for durability that are used for normal-weight concrete should also be used for lightweight concrete.

High-strength, lightweight concrete mixtures have been achieved by using various pozzolans combined with water-reducing admixtures. Air content may also be limited to 4 to 5 percent. To address durability concerns for bridges and marine structures, the *w/cm* has, in many cases, been specified to be 0.45 or less. Such mixtures will generally result in equilibrium densities that are higher than 0.120 kcf (ACI 213 2014).

Levels of air entrainment consistent with normal-weight concrete mix designs are usually used in lightweight concrete to assist in reducing the density of the mixture. Entrained air can also be an important tool to improve workability and reduce the necessary mixing water, bleeding, and segregation (ACI 213 2014). On the other hand, for higher strength mixes, it may be beneficial to reduce the entrained air content to maximize the compressive strength.

When developing a high-strength, lightweight concrete mixture, it is suggested that a smaller maximum coarse aggregate size be used (ACI 213 2014). As discussed in section 2.2.1, a blend of lightweight and normal-weight aggregates that conform to the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)) can be used to design concrete mixes. Admixtures and other additives used in normal-weight concrete mixtures, such as supplementary cementitious materials and fibers, may be used in lightweight concrete (Hoff 2002).

Trial batches should be used to develop lightweight concrete mixtures, especially if there is no prior experience with a mixture that meets the same specified properties (ACI 213 2014). Lightweight concrete mixtures generally use slightly more cementitious material to reach the same compressive strength as a normal-weight concrete mix. If the equilibrium density is specified, the maximum fresh density of the lightweight concrete mix that produces the specified equilibrium density should be determined as the mix design is developed so it will be available prior to beginning construction on a project (ACI 213 2014).

Workability, finishability, and general appearance are also important features of a concrete mixture. Lightweight concrete can be proportioned to have the same features as a properly proportioned normal-weight concrete mixture. It is important to have adequate cement paste in the mix to coat each particle, so that coarse aggregate particles will not separate from the mortar. The mix should contain enough fine aggregate to allow the fresh concrete to be cohesive (Kosmatka and Wilson 2016). A properly proportioned lightweight concrete mixture should meet typical mix performance criteria. In some cases, lightweight concrete mixtures may even improve the workability and finishability of conventional mixtures, as has been observed for some internally cured concrete mixes (Rupnow et al. 2016). It has been noted that excessive amounts of water or slump will cause lightweight aggregate to segregate from the mortar (NRMCA 2016).

When developing a lightweight concrete mix design, it should be recognized that lightweight concrete will have less slump for the same workability because there is less mass to cause the concrete to slump. Therefore, a lightweight concrete mixture will have about the same workability with 1 to 2 inch less slump. Kosmatka and Wilson (2016) report that a lightweight, air-entrained mixture with 2 to 3 inches of slump can be placed under conditions where a slump of 3 to 5 inches should be used for a comparable normal-weight concrete. They also note that it is seldom necessary to use a slump greater than 5 inches when using lightweight concrete for normal applications. If higher slump is used, larger aggregate particles may rise to the surface and make finishing difficult. Such behavior was reported in Chapman and Castrodale (2016).

While it might appear unlikely that lightweight aggregate could be successfully used to produce self-consolidating concrete (SCC), such mixtures have been used in precasting plants for several years with great success. Information on applications for and proportioning of lightweight SCC mixtures are given in ACI 213[2] (2014).

5.3 PREWETTING LIGHTWEIGHT AGGREGATE

Prewetting (or presoaking) of lightweight aggregate is a simple and effective precaution that avoids the absorption of mix water by lightweight aggregate that has not reached its full absorptive capacity. Prewetting is not intended to completely saturate lightweight aggregate particles. Rather, prewetting allows lightweight aggregate particles to absorb as much of their total absorptive capacity as is practical. The 24-hour absorption test, specified by AASHTO T 84[16] (ASTM C128) and AASHTO T 85[17] (ASTM C127) for fine and coarse aggregates, respectively, provides an indication that can be used for comparison against the total absorptive capacity. Lightweight aggregate particles immersed for 24 hours will generally not be fully saturated, although the rate of additional moisture absorption is expected to be low enough that weight measurements will remain unchanged (Holm and Ries 2006).

Lightweight aggregate is generally prewetted prior to batching to satisfy its higher absorption as discussed in section 5.2. Prewetting lightweight aggregate affects the specific gravity of the lightweight aggregate, and therefore the batch weights, so wetting should be complete and consistent throughout the lightweight aggregate stockpile. This will make it possible to maintain consistent mix proportions and fresh properties such as workability, pumpability, and the ability to finish the concrete. Adequate prewetting of lightweight aggregate is essential for internal curing and for lightweight concrete that will be pumped.

5.3.1 Prewetting

The typical criteria for prewetting lightweight aggregate is that the absorbed water content measured according to AASHTO T 84[16] (ASTM C128) and AASHTO T 85[17] (ASTM C127) should be no less than the 24-hour absorption. When the absorbed water content equals or exceeds the 24-hour absorption, the rate of further absorption will be slow and the effect of additional absorption will be small. This allows batching and subsequent activities related to delivery, placement, and finishing to progress consistently and as expected. It also allows the *w/cm* to be established with greater precision (Bohan and Ries 2008). If the absorption has not

[16] AASHTO T 84, Standard Testing of Testing for Specific Gravity and Absorption of Fine Aggregate, is not incorporated in the CFR Title 23. However, AASHTO T 84 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

[17] AASHTO T 85, Standard Testing of Testing for Specific Gravity and Absorption of Coarse Aggregate, is not incorporated in the CFR Title 23. However, AASHTO T 85 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

reached the 24-hour value, mixing water can be absorbed by the lightweight aggregate particles during the mixing process, or it can be forced into the pores of the lightweight aggregate particles during concrete pumping (Bohan and Ries 2008). It is also important for the moisture content to be uniform throughout a stockpile to ensure consistent concrete properties.

5.3.2 Methods of Prewetting

The most important factor in prewetting lightweight aggregate is that the aggregate has the desired absorbed moisture content when batched. Methods for prewetting lightweight aggregate include sprinkling, soaking, inundation, thermal saturation, and vacuum saturation. These methods are discussed in ACI 213[2] (2014). When sprinkling or soaking are used, the lightweight aggregate stockpile should be handled properly to achieve uniform moisture conditions throughout the pile. The concrete supplier should be assigned the responsibility for determining the method of prewetting because selection of the prewetting method depends on the type of lightweight aggregate and the facilities available to the concrete supplier.

5.3.3 Cold Weather

In freezing weather, prewetting lightweight aggregate can be a challenge unless the aggregate is stored in enclosed and heated bins. Where such protection is not available, some concrete suppliers have been successful in supplying lightweight concrete by maintaining the aggregate in drier than optimal condition, so the stockpile does not freeze into a solid block. Additional mix water is then added to provide the quantity of water that is expected to be absorbed by the lightweight aggregate during the period from batching to placement.

5.3.4 Effect of Absorbed Water on *w/cm*

It is not uncommon for those involved with batching lightweight concrete for the first time to assume that absorbed water should be included in the batch water corrections for surface moisture. However, water absorbed in lightweight aggregate remains in the aggregate until the concrete has begun to harden, so it is not included in moisture adjustments. Furthermore, it also does not affect *w/cm*.

5.4 BATCHING

Kosmatka and Wilson (2016) report that mixing procedures for lightweight concrete are generally like those for normal-weight concrete other than the typical prewetting of lightweight aggregate prior to batching. Several topics that should be considered to ensure successful batching of lightweight concrete are discussed in this section.

When a concrete supplier is preparing to batch lightweight concrete, bins should be made available to receive the lightweight aggregate. Normal-weight aggregate should be completely removed from bins to be used for lightweight aggregate to prevent contamination of the lightweight aggregate with normal-weight aggregate.

As was noted in the previous section, absorbed water should not be considered when adjusting mixing water to account for surface moisture on the aggregate or in the *w/cm* calculations (ACI 213 2014). Absorbed water remains in the aggregate until after the concrete has hardened.

Some practices commonly used in projects with conventional concrete mixes can have an unexpected effect on lightweight concrete. For example, a common practice is the holding back of mix water by the concrete supplier during batching to allow for the addition of water at the job site to adjust slump. ACI 304 (2000) recommends holding back 2 to 3 gallons of water per cubic yard of concrete to make sure that the concrete will not be too wet when it arrives at the job. The document also notes that adding water at the job is often necessary and permissible if slump has been lost because mix water was absorbed by the lightweight aggregate during transit. However, the concrete supplier should recognize that reducing the mix water will increase the concrete density, because after entrained air, water is the least dense component of the mixture. For a conventional lightweight concrete deck mix with a fresh density of 0.116 kcf, holding back 2 gallons of water will increase the density by nearly 0.001 kcf. Therefore, this practice should be used cautiously for lightweight concrete.

Resistance to the use of lightweight concrete has been encountered for some projects where concrete suppliers do not have enough aggregate bins to allow them to batch both lightweight concrete and normal-weight concrete at the same time. However, such situations may be overcome by using temporary aggregate bins or other means.

5.5 PLACING

Delivery and placement of lightweight concrete should follow the same standard industry practices that are used for normal-weight concrete, such as ACI 304 (2000 and 2017)[18] and ACI 309 (2005)[19]. ACI 213[2] (2014) reports that a well-proportioned lightweight concrete mixture can generally be placed, screeded, and floated with less effort than a comparable normal-weight concrete because less effort is needed to move the lighter concrete. The report cautions against over-vibration or overworking lightweight concrete because over-manipulation tends to drive the heavier mortar away from the surface where it is useful for finishing and to bring the lightweight, coarse aggregate to the surface. ACI 309 (2005) reports that the tendency for lightweight coarse aggregate particles to appear on the top surface is reduced for all-lightweight concrete because the difference in density between the coarse aggregate and the mortar is reduced. A similar beneficial effect is noted when air entrainment is used for lightweight concrete because of improved cohesiveness in the mortar (ACI 309 2005). Coarse, lightweight aggregate may also appear on the top surface if the suggested slump is exceeded (NRMCA 2016).

Hoff (2002) provides practical suggestions for placing lightweight concrete. He begins by stating that lightweight concrete can be placed using any of the means used for normal-weight concrete. Lightweight concrete should be placed close to its final location because it is more prone to segregation when moved using vibration. Lightweight concrete should not be allowed to fall more than about 5 ft from the end of the discharge device. When concrete is being placed in lifts, the thickness of a layer of lightweight concrete is typically about 20 percent less than the thickness of a layer of normal-weight concrete, and the layer thickness should typically be

[18] ACI 304, Guide to Placing Concrete by Pumping Methods, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

[19] ACI 309, Guide for Consolidation of Concrete, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

limited to 16 inches When self-consolidating lightweight concrete is used, these limits should be reevaluated since this type of concrete was not common when Hoff compiled his report.

A lightweight concrete mixture with a 3-inch slump is usually more workable than a comparable normal-weight concrete mix because the slump test is affected by the density of the concrete (ACI 213 2014). This slump typically provides sufficient workability, but also maintains the cohesiveness of the mix, so the lower-density coarse particles are not allowed to move to the surface (ACI 213 2014). If the top surface of the lightweight concrete element should have a smooth finish, the slump should be limited to 5 inches at the point of placement. If additional concrete is to be placed on the top surface of a precast element, such as a deck on a girder flange, then the rough top surface that occurs with higher slump lightweight concrete, such as reported in Chapman and Castrodale (2016), can be an acceptable roughened finish for composite structural action.

Typical industry placement techniques should be employed to preserve entrained air, like those used for placement of normal-weight concrete mixtures. This is important for lightweight concrete because entrained air is often a significant part of the strategy used to reduce the density of the concrete. In some cases, concrete has been placed using a conveyor system rather than a pump to avoid potential difficulties in managing air content or other properties of lightweight concrete.

Vibration can be used to consolidate lightweight concrete (Kosmatka and Wilson 2016). The same vibration frequencies and amplitudes commonly used for normal-weight concrete should also be used for lightweight concrete. The length of time for consolidation varies, depending on mixture characteristics. Excessive vibration should be avoided because it can cause segregation by forcing the larger lightweight aggregate particles to the surface.

Hoff (2002) notes that if slump is lost by absorption of mix water into the lightweight aggregate during transit, the slump can be restored by adding water without affecting the strength of the lightweight concrete. This is because the mix water was absorbed and is no longer available to influence w/cm; added water will restore the mixture to its intended properties.

5.5.1 Pumping

Lightweight concrete may be delivered by pumping; the material has been successfully pumped to heights of more than 800 ft in high-rise buildings (Holm and Bremner 2000). Murugesh and Cormier (2007) report pumping lightweight concrete for box girder segments of the Benicia-Martinez Bridge to heights of more than 180 ft or over horizontal distances of more than 330 ft. ACI 213[2] (2014), ACI 304 (2017)[20], and ESCSI (1996) provide information for mix proportioning and pumping equipment. Hoff (2002) also provides a thorough discussion of pumping lightweight concrete, although the report was prepared for the U.S. Army Corps of Engineers and focuses on the Corps' specifications and applications. ACI 213[2] (2014) suggests that the mix be proportioned to provide slump of 4 to 6 inches at the point of placement; Bohan and Ries (2008) indicate that current practices for pumping lightweight concrete suggest a

[20] ACI 304, Guide to Placing Concrete by Pumping Methods, is not incorporated in the CFR Title 23. Therefore, it is not a federal requirement.

minimum slump of 3 inches be attained before any addition of water reducing admixtures; and Hoff (2002) suggests slump of 2 to 6 inches, although higher slumps achieved through the use of superplasticizers can usually be pumped without difficulty.

During pumping, concrete is subjected to significantly higher pressures than during mixing, transport or non-pumped conveyance. This increased pressure can force mix water into the pores of lightweight aggregate, which can lead to slump loss and decreased pumpability (ACI 304 2017). Proper prewetting of the lightweight aggregate prior to batching is therefore important for successful pumping of lightweight concrete.

Using the proper configuration for the boom on a pump truck can be important for preserving the air content in both lightweight and normal-weight concrete. A National Ready Mixed Concrete Association (NRMCA) publication (2005) discusses how to prevent loss of air content while pumping.

When pumping is being considered for the placement of lightweight concrete, field trials using the pump and mixture planned for the project was recommended by ACI 213[2] (2014). The relationship between the slump at the point of delivery (truck) and the point of placement (pump) should be correlated (Kosmatka and Wilson 2016).

5.6 FINISHING

Lightweight concrete can be finished using the same equipment and procedures that are used for normal-weight concrete. Some contractors report difficulties when finishing lightweight concrete, but such issues can usually be addressed by proper mix proportioning, adequate prewetting of the lightweight aggregate, and familiarity with the mix (Castrodale and Harmon 2017). A well-proportioned lightweight concrete mixture can generally be placed, screeded, and floated with less effort than a normal-weight concrete (ACI 213 2014). Carpenter (2019) reports a contractor's comment that an internally cured deck finished a bit better than a conventional deck because it was not as sticky. The concern that finishing a lightweight concrete deck will be more difficult is addressed in Castrodale and Harmon (2008).

A slump of 2 to 4 inches typically produces the best results if the top surface is to receive a smooth finish. Greater slumps may cause coarse lightweight aggregate to rise to the surface (Kosmatka and Wilson 2016). Lightweight aggregates may tend to be pushed to the surface of a lightweight concrete slab as the heavier materials settle. This can be avoided by presoaking the lightweight aggregate and carefully monitoring mixture adjustments (NRMCA 2016). Hoff (2002) notes that if a smooth finish is intended but the coarse lightweight aggregate has risen to the surface, a hand-operated grid tamper or mesh roller may be used to push the aggregate back beneath the surface to allow finishing.

5.7 CURING

In general, curing practices used for normal-weight concrete should also be used for lightweight concrete, including hot and cold weather practices. However, all types of lightweight concrete mixtures for which the lightweight aggregate is prewetted prior to batching will also benefit from internal curing that occurs by the release of water that was absorbed in the pores of the lightweight aggregate. The New York State DOT has recognized the benefits of this additional curing by reducing the duration of wet curing of internally cured concrete from the standard 14 days to 7 days in Section 557-3.11 A of its *Standard Specifications* (NYSDOT 2019).

5.8 GRINDING AND GROOVING

Lightweight concrete bridge decks have been successfully ground and grooved. The freezing and thawing performance of lightweight concrete specimens that had been cut to expose the interior of the lightweight aggregate particles was discussed in section 2.2.7.4. Castrodale and Robinson (2008) report on the good performance of lightweight concrete decks on several bridges that had been ground and/or grooved. The concern that a lightweight concrete deck that has been ground and grooved will not be durable is addressed in Castrodale and Harmon (2008).

5.9 HEAT OF HYDRATION

As discussed in other sections, lightweight concrete has insulating properties because of the pores in the lightweight aggregate. As a result, somewhat higher temperatures can be expected during hydration of cement (ACI 213 2014). However, this is not usually a significant concern unless the cementitious materials content of the mixture is high and the minimum dimension of the concrete element is thick enough for mass concrete effects to be considered (Maggenti and Brignano 2008). For such project conditions, the thermal characteristics of the lightweight concrete mixture should be investigated during mix development and practices, such as those found in ACI 207.1 (2006), should be implemented to keep temperatures below specified limits.

5.10 INTERNAL CURING

Concrete with internal curing using prewetted lightweight aggregate, as discussed in section 2.3, is concrete that contains lightweight aggregate which is typically a fine or intermediate gradation. The addition of lightweight aggregate is not for the purpose of reducing the density of the concrete, but rather to deliver curing water to the interior of the concrete element. Therefore, the quantity of lightweight aggregate in the mixture is relatively small so the concrete behaves more like conventional concrete for placing and finishing. Therefore, internally cured concrete should be batched, placed, and finished using practices for conventional concrete. Fresh and hardened properties of internally cured concrete should be tested using conventional test methods. One notable exception is that NYSDOT has recognized the effectiveness of internal curing in providing water for curing, and has reduced the duration of water curing for decks with internal curing as discussed in section 6.4.

6 SPECIFYING LIGHTWEIGHT CONCRETE

To procure the construction of a bridge, designers prepare specifications that present expectations for that construction. When preparing specifications for a project using lightweight concrete, it is common to find that some necessary topics may not be addressed in the owner agency's current standard construction specifications. Therefore, special provisions are often prepared for projects using lightweight concrete. While this approach can be effective for occasional use of lightweight concrete for bridges, uniformity of construction is achieved when provisions are added to owner agency's standard specifications that address lightweight concrete, or to have agency-approved standard special provisions. As an example, the Virginia DOT has incorporated its requirements for lightweight aggregate and lightweight concrete into its standard construction specifications.

This chapter provides suggestions for agencies to consider when drafting specifications related to lightweight aggregate, lightweight concrete, and internal curing using prewetted lightweight aggregate. Transportation agencies normally write special provisions for any project using lightweight concrete. The information in this chapter can be used to develop special provisions or revisions to standard specifications. Topics that are typically addressed by specifications, special provisions, or contract documents are discussed, such as density, additional or modified test methods, and provisions related to proportioning, batching, and placement. General information on specifying lightweight concrete is provided in ACI 213[2] (2014) and Castrodale and Harmon (2017). Although written for marine structures, sample specifications in Holm and Bremner (2000) may be adapted for use with bridges. It should be noted that topics are only discussed for which specifications for lightweight concrete differ from, or need some explanation compared to, normal-weight concrete .

6.1 DENSITY

The AASHTO T 121[21] (ASTM C138) test method for determining the density of fresh concrete should be added by special provision. When specified, it is suggested that the equilibrium density of hardened concrete should be determined in accordance with ASTM C567[5], using the method that calculates the equilibrium density based on the mix proportions.

Specifications and other contract documents should clearly indicate the type of density being specified: equilibrium and/or fresh. See discussion of types of density in section 2.2.2. It should be noted that the term "air-dry density" is no longer used as is also discussed in section 2.2.2. Contract documents should also indicate the concrete density used for dead load calculations, which should include an allowance for the weight of embedded reinforcement, which is typically taken as 0.005 kcf as suggested in article C3.5.1 of the AASHTO LRFD-8 Design Specifications (AASHTO 2017) (23 CFR 625.4(d)(1)(v). However, this allowance may not be adequate for heavily reinforced sections.

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[21] AASHTO T 121, Standard Testing of Testing for Weight per Cubic Foot, Yield, and Air Content (Gravimetric) of Concrete, is not incorporated in the CFR Title 23. However, AASHTO T 121 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

If only an equilibrium density is specified, the contract documents should direct the contractor or concrete supplier to determine a fresh density that can be expected to provide the specified equilibrium density (see AASHTO M 157[22] (ASTM C94)). The fresh density is computed from mix proportions and is usually 0.003 to 0.008 kcf less than the equilibrium density. Prior to delivery of concrete for production, the parties should agree upon a fresh density corresponding to the equilibrium density, which will then be used for acceptance when concrete is delivered (NRMCA 2016).

The equilibrium density is typically computed from the mix proportions during mix development and approval rather than by determining the density by drying cylinders. If the owner specifies that the concrete should be dried to determine the equilibrium density, testing can take a long time, and the drying of the test specimen may not reflect the drying of the actual element because of differences in dimensions (volume-to–surface area ratio) between the test specimen and the structural element.

If tolerances for concrete density are specified, any variability (+/–) limit should realistically account for variation in other constituents like entrained air and water. A maximum density limit with no minimum value could be used in standard specifications or special provisions by State DOTs. For example, Virginia DOT only specifies a maximum density limit without minimum value required in the standard specifications (Virginia DOT 2020):

> *Maximum density of freshly mixed lightweight concrete, when tested according to ASTM C138, shall be 120 lbs./cu.yd., or as specified on the plans.*

ACI 213[2] (2014) suggests only specifying a maximum fresh and equilibrium density while NRMCA (2016) suggests using a tolerance on the densities of +/– 0.004 kcf. An approach is discussed in Chapman and Castrodale (2016) where a target fresh density of 0.123 kcf was specified along with a maximum fresh density of 0.128 kcf. The target fresh density was used as the density for design. Data from production of the concrete indicated that this this approach was functionally equivalent to using a target density of 0.123 kcf with a + 0.005 / – 0.003 kcf tolerance.

6.2 MATERIAL PROPERTIES

Material properties that will be used for design should be known when the project begins. The purpose of this section is to give such information for lightweight concrete. Background information on the performance of lightweight concrete has been given in chapter 2 and should be consulted if the designer has little or no experience with lightweight concrete.

Specifications for lightweight aggregate or lightweight concrete should generally use the same criteria as for normal-weight aggregate or normal concrete, except for the design density. In some cases, where there has been no prior use of lightweight aggregate or lightweight concrete, the owner may approach a project as a demonstration project and require some additional data to be collected. Such an approach may be useful for the initial exploration of mix designs and

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[22] AASHTO M 157, Standard Specification for Ready-Mixed Concrete, is not incorporated in the CFR Title 23. However, AASHTO M 157 is referenced in the AASHTO LRFD Construction Specifications (AASHTO 2017b) (23 CFR 625.4(d)(1)(iv)).

material properties, to allow the parties involved to become familiar with lightweight aggregate and concrete. However, this may not be necessary with respect to the performance of structural elements because data are available and have been reported about the performance of lightweight concrete in bridges earlier in this report.

Lightweight concrete should not be held to a higher standard of conformance to material properties than is used for normal-weight concrete unless the reason is explained. Because designers may consider lightweight concrete a new material, they may want to have a better idea of the material properties, which is understandable as discussed above.

For normal-weight concrete, material properties are assumed during the design of a bridge using the AASHTO LRFD Design Specifications (23 CFR 650.4(d)(1)(v)) and the AASHTO LRFD Construction Specifications (23 CFR 650.4(d)(1)(iv)). However, the actual values of these material properties are not measured until sampling and testing of concrete mix can be carried out during construction. Proper design and construction of bridges can still be achieved if the design is performed using the material property assumptions from the AASHTO specifications.

As presented in the earlier chapters of this report, the AASHTO LRFD Design Specifications (23 CFR 650.4(d)(1)(v)) and the AASHTO LRFD Construction Specifications (23 CFR 650.4(d)(1)(iv)) provide adequate information upon which lightweight concrete designs can be reasonably based.

6.2.1 Lightweight Aggregate

Lightweight aggregate should conform to the same material properties and performance criteria used for conventional aggregate except for the aggregate grading as shown in the AASHTO LRFD Construction Specifications (23 CFR 650.4(d)(1)(iv)). The gradings for lightweight aggregate specified in AASHTO M 195[1] (ASTM C330) are slightly different than typical gradings for normal-weight coarse aggregate in AASHTO M 80[4] and fine aggregate in AASHTO M 6[3] (ASTM C33). The distribution of particle sizes is also different between the standards, which is the result of the smaller sized lightweight aggregate particles having a higher specific gravity than the larger particles because the larger voids have generally been lost during crushing. Therefore, the gradings for lightweight aggregate have been adjusted to provide the same relative volume of each fraction as is specified for normal-weight aggregate.

The size designations for lightweight aggregate in AASHTO M 195[1] (ASTM C330) are simply the maximum particle size, such as ¾ inch or ½ inch If concrete mixtures in specifications include aggregate gradings, the gradings should be converted to equivalent sizes for lightweight aggregate.

Structural properties of lightweight concrete are not directly related to the absorption of lightweight aggregate; therefore, limiting absorption of lightweight aggregate should not be considered in lightweight concrete specifications unless other factors are involved (Castrodale 2020). Proper preparation of lightweight aggregate can generally allow the use of any type of lightweight aggregate for bridge construction, including delivery by pumping.

The AASHTO LRFD-8 Design Specifications (23 CFR 650.4(d)(1)(v)) and the AASHTO LRFD Construction Specifications (23 CFR 650.4(d)(1)(iv)) specify requirements for all concrete structures which are constructed using either normal or lightweight concrete, therefore, lightweight aggregate should be subject to the same performance limits under different testing as normal-weight aggregate such as soundness. However, testing for soundness using AASHTO T 104 (ASTM C88) may be challenging for lightweight aggregate because the testing solution may be absorbed into the aggregate.

6.2.1.1 Prewetting

The specified level of absorption to be achieved by prewetting should be stated in terms of the 24-hour absorption because the absorption may vary between sources of lightweight aggregate. Therefore, special provisions suggest lightweight aggregate should have an absorbed moisture content not less than the 24-hour absorption as determined by AASHTO T 85[17] (ASTM C127) or AASHTO T 84[16] (ASTM C128) when it is incorporated into a mix. This is especially important for concrete to be placed by pumping.

It is not usually necessary to specify the method used to achieve the desired moisture content in the lightweight aggregate. The concrete supplier should select the method depending on plant facilities and the type of lightweight aggregate being used. Lightweight aggregate suppliers should be consulted regarding the minimum absorption needed for proper performance of aggregate in concrete mixtures.

The absorbed moisture content should also be consistent throughout the stockpile by following proper methods of stockpile management as suggested in ACI 304 (2000), which apply to normal-weight aggregate but may also be used for lightweight aggregate.

6.2.2 Fresh Properties of Lightweight Concrete

One approach for proportioning concrete mixtures is to use *w/cm* (water-cementitious materials ratio) limits. It has been shown that lightweight concrete mixtures can be successfully proportioned by specifying the *w/cm* to achieve desired hardened concrete properties. It should also be noted that the reduced density of lightweight concrete results in a lower slump for the same workability (Kosmatka and Wilson 2016).

Air entrainment is specified to achieve durability in some, but not all, types of concrete elements for which lightweight concrete may be used. However, air entrainment is generally specified in lightweight concrete to provide an additional reduction in density beyond that which can be achieved by the use of lightweight aggregate alone and to provide other needed properties for the fresh concrete.

6.2.3 Hardened Properties of Lightweight Concrete

Article 5.4.2.1 of the AASHTO LRFD-8 Design Specifications states "for lightweight concrete, physical properties in addition to compressive strength shall be specified in the contract document" (AASHTO 2017) (23 CFR 625.4(d)(1)(v)). The physical property that differentiates lightweight concrete from normal concrete is density. Therefore, the hardened properties specified for lightweight concrete are the compressive strength and density. A designer may choose to specify the minimum splitting tensile strength to reduce or eliminate the reduction factor for shear capacity or development length (Castrodale 2019). In a very few cases, the designer may choose to specify the creep, shrinkage, or modulus of elasticity of lightweight concrete when these additional properties are needed for the design. However, if these quantities are not specified for normal-weight concrete designs for the same type of elements, then specifying them for lightweight concrete should be carefully evaluated. The Research Team suggests that specifying more physical properties than necessary will increase costs and potentially delay delivery of the project, as the contractor and concrete supplier may have to wait for testing to be completed before the project can proceed. Furthermore, the use of design compressive strengths at 56 days rather than 28 days will generally allow the use of higher design compressive strengths for lightweight concrete, just as it does with normal-weight concrete.

Several standard test methods are modified, or should be modified, for lightweight aggregate and lightweight concrete. Test methods are discussed in this section so that appropriate provisions can be included in the specifications.

6.2.4 Abrasion Resistance of Lightweight Aggregate

Lightweight aggregate should meet abrasion test limits for normal-weight aggregate by AASHTO T 96[14] (ASTM C131), although test results for lightweight aggregate may be lower than normal-weight aggregate as discussed in section 2.1.3.

The standard aggregate abrasion test of AASHTO T 96[14] (ASTM C131) specifies a mass of aggregate to be introduced into the testing drum. However, if the specified mass of aggregate is used when testing lightweight aggregate, a larger volume of aggregate would be placed in the drum. The larger volume of lightweight aggregate would restrict the motion of the balls in the drum and give an inaccurate indication of the abrasion resistance. Some DOTs have developed revised test methods to address this, which can be handled by specifying that an equivalent volume of aggregate be placed in the drum rather than the specified mass (see Florida DOT FM 1-T 096 (2015)).

6.2.5 Soundness of Lightweight Aggregate

Lightweight aggregate should meet soundness tests limits for normal-weight aggregate using AASHTO T 104[23] (ASTM C88). See discussion in section 2.1.3.

6.2.6 Absorbed Water and Aggregate Moisture Corrections

When batching lightweight aggregate, a correction should be made for surface water, as should be done for any aggregate. Conventional aggregates are soaked to achieve a saturated condition. After soaking and drying, conventional aggregate is taken to be in its "saturated surface dry" condition (SSD). However, lightweight aggregate can have both absorbed and surface water. In addition, because of its higher absorption and discontinuous internal pore structure, lightweight aggregate does not reach a true saturated condition in which all pores are filled with water. Therefore, when lightweight aggregate is in what would usually be called a "saturated surface

[23] AASHTO T 104, Standard Method for Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

dry" condition (SSD), it is more accurately said to be in the "wetted surface dry" condition (WSD).

For coarse lightweight aggregate, the surface of aggregate particles in a sample can be dried using a towel as is done for normal-weight aggregates. For fine lightweight aggregate fractions, a paper towel drying method has been developed by the New York State DOT (2008). However, towel drying is typically not as effective and repeatable for fine aggregate. A method has been developed in which the wet fine lightweight aggregate is brought to the WSD condition using a centrifuge (Miller et al. 2014). Indiana DOT has implemented a test method for the centrifuge (Indiana DOT 2015), the Louisiana Department of Transportation and Development has evaluated it (Rupnow et al. 2016), and AASHTO is currently considering the test method.

Some specifications for use of lightweight concrete, such as those included in an appendix to T. Y. Lin International (1985), suggested that lightweight aggregate be vacuum or thermally saturated if the lightweight concrete is to be pumped. However, this level of prewetting may not be necessary, depending on the type of aggregate. Instead, aggregate should be prewetted using appropriate means to consistently achieve the level of absorption discussed in section 6.2.1.1 or as otherwise specified.

It is important for contractors and concrete suppliers to understand that the absorbed water does not affect the mix water – it is not released from the aggregate until after the cement has begun to hydrate and the pore size in the cement paste becomes smaller than the pores in the aggregate, which means capillary forces increase causing the extra water inside the lightweight aggregate to be drawn to the paste to continue the hydration process (Holm and Ries 2007). Therefore, batch water is not adjusted for absorbed moisture, but only for surface moisture, which is the same procedure that is used for normal-weight aggregate.

6.2.7 Unit Weight

The acceptance test for lightweight concrete should be performed when the concrete is delivered or placed. Therefore, special provisions for projects using lightweight concrete should include reference to AASHTO T 121[21] (ASTM C138) for measuring unit weight for acceptance in the field.

Because the unit weight of lightweight concrete is checked for acceptance, special attention should be given to the calibration factors established for testing equipment, i.e., the unit weight bucket. The density of water is given in AASHTO T 19[24] (ASTM C29) to five significant digits for use in calibrating the bucket, so the calibration should reflect this precision. If insufficient digits are included in the calibration factors, concrete can appear to exceed the specified limit when it actually meets the specification.

6.2.8 Entrained Air Content

The AASHTO LRFD Construction Specifications (23 CFR 625.4(d)(1)(iv)), section 8.5.6 lists standard methods for sampling and testing of concrete regarding air content including AASHTO

[24] AASHTO T 19, Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

T 152[6] (Air Content of Freshly Mixed Concrete by the Pressure Method) and AASHTO T 121[21] (Weight per Cubic Foot, Yield, and Air Content (Gravimetric) of Concrete). As stated in the scope of AASHTO T 152[6], it is only applicable to normal-weight concrete. It also states that AASHTO T 196[7] should be used for lightweight concrete. Therefore, for lightweight concrete, the volumetric method of determining entrained air content of AASHTO T 196[7] (ASTM C173) should be specified rather than the usual pressure method of AASHTO T 152[6] (ASTM C231) used for normal-weight concrete. The gravimetric method of AASHTO T 121[21] (ASTM C138) may also be used for lightweight concrete because this method gives formulas for calculating the air content of both types of freshly mixed concrete as stated in its scope. A discussion of the reasons for using different test methods for determining the air content of lightweight concrete is given in Kosmatka and Wilson (2016).

For some projects, a calibration has been established between the pressure and volumetric test method results. This allows use of the pressure method, which may take less time to perform than the volumetric method, if results are within the acceptable range. If a test falls outside the acceptable range, then the volumetric method should be used to determine whether the load is acceptable or should be rejected.

6.2.9 Freezing and Thawing Resistance of Concrete

When testing lightweight concrete, the provisions of AASHTO T 161[9] (ASTM C666) are modified by provisions in AASHTO M 195[1] (ASTM C330). The typical method for testing normal-weight concrete calls for specimens to be moist cured for 28 days prior to testing; for lightweight concrete, specimens are moist cured for 14 days, allowed to dry in a 50 percent RH environment for 14 days, then submerged for 24 hrs. prior to the beginning of the freezing and thawing test. The modification to the testing method is not mentioned in AASHTO T 161[9] (ASTM C666), so it can be overlooked by testing labs. Therefore, the difference should be mentioned in the special provisions.

6.2.10 Splitting Tensile Strength

The standard test for splitting tensile strength of concrete AASHTO T 198[8] (ASTM C496) is not used for all projects using lightweight concrete but should be used during mix qualification if the splitting tensile strength is specified for use in determining the value of the concrete density modification factor, λ. The splitting tensile strength is not intended to be used for control or acceptance of concrete in the field (ACI 213 2014).

6.2.11 Rapid Chloride Permeability

The rapid chloride permeability test of AASHTO T 277[25] (ASTM C1202) may be used for lightweight concrete. However, as is the case with normal-weight concrete, it may be useful to use either an accelerated cure or to perform the test at a later age to allow more complete reaction of supplementary cementitious materials that would give a better indication of the behavior of the concrete. Some DOTs specify the use of an accelerated version of this test method. See additional discussion in section 2.2.7.1.

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[25] AASHTO T 277, Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, is not incorporated in the CFR Title 23. Therefore, this industry standard is not a federal requirement.

6.3 CONSTRUCTION SPECIFICATIONS

Specifications for lightweight concrete typically state a minimum compressive strength, a maximum density, a maximum slump, and an acceptable range of air content (Kosmatka and Wilson 2016). This is the same as for normal-weight concrete with the addition of the maximum density. As discussed in section 2.2.2, the equilibrium and/or fresh density should be specified; the equilibrium density will generally be specified unless the difference between the fresh and equilibrium densities is small (section 2.2.2.3). The fresh density can be specified or the responsibility to obtain a fresh density that corresponds to the equilibrium density should be assigned to the contractor or concrete supplier. A tolerance on the density may also be given, although it is preferred to specify a maximum value.

ACI 213[2] (2014) also mentions that a minimum tensile strength is typically specified. The AASHTO LRFD-8 Design Specifications allow the tensile strength to be specified to determine the concrete density modification factor, but this option has not been frequently used.

Due to lower aggregate density, structural lightweight aggregate concrete does not slump as much as normal-weight concrete with the same workability. Kosmatka and Wilson (2016) report that an air entrained lightweight concrete mixture with a slump of 2 to 3 inches can be placed under conditions for which a slump of 3 to 5 inches would be necessary for a comparable normal-weight concrete. However, because the difference is not great, slump limits specified for normal-weight concrete are often used for lightweight concrete. It is seldom necessary to exceed slumps of 5 inches for normal placement of structural lightweight aggregate concrete. With higher slumps, the large aggregate particles tend to rise to the surface making finishing more difficult (Kosmatka and Wilson 2016).

Prewetting of lightweight aggregate prior to batching should be discussed. As discussed in section 5.3.2, determination of the method of prewetting should be left to the concrete supplier because selection of the prewetting method depends on the type of lightweight aggregate and the facilities available to the concrete supplier.

6.3.1 Involvement of Lightweight Aggregate Supplier

Involving the lightweight aggregate supplier before concrete placement begins provides an opportunity for the entire construction team to discuss construction considerations. It allows the construction team the opportunity to discuss the use of lightweight concrete.

In some cases, it may be prudent to conduct a field trial or mock-up to demonstrate placement of the concrete. This should include all personnel and equipment to be used in the actual placement so that any issues encountered can be worked out prior to actual production placements.

6.4 INTERNAL CURING

A standard specification for lightweight aggregates used for internal curing in concrete has been developed (ASTM C1761[11] 2017). No equivalent AASHTO specification exists. The ASTM specification provides minimum physical properties for lightweight aggregate to be used to provide internal curing, test methods for absorption and desorption, and a procedure for computing the quantity of lightweight aggregate to provide internal curing based on the Bentz equation (Bentz et al. 2005).

State agencies that have used internal curing have employed several approaches for their project special provisions. States have used a prescriptive specification involving a minimum absorption for the lightweight aggregate and a minimum replacement fraction of the sand by lightweight aggregate. The New York State DOT (NYSDOT) has recently added provisions for high-performance internal curing (HPIC) concrete to Section 557 of their Standard Specifications (2019) that specify 30 percent replacement of conventional fine aggregate with prewetted lightweight, fine aggregate (Carpenter 2019). Where the characteristics of the available lightweight aggregate vary and where the cement content of the mixture may differ from what is used in deck concrete, this approach should be revised to provide the desired quantity of internal curing moisture. A general approach to specifying the quantity of lightweight aggregate for internal curing appears in ASTM C1761[11] and ESCSI (2012b). A comprehensive general specification for internally cured concrete was recently published by Weiss and Montanari in the *Guide Specifications for Internally Curing Concrete* (2017). Lightweight aggregate suppliers can provide additional information regarding specifications.

7 PROJECT EXAMPLES

This chapter provides a limited list of bridges for which lightweight concrete has been successfully used. It includes a range of bridge projects, large and small, new and old, from decks to pretensioned girders to segmental box girders to suspension bridges. Most projects are in the United States, along with two from Norway. The projects are listed in groups that reflect the primary reason that lightweight concrete was used for the bridge. Many bridges have several reasons for using lightweight concrete, so the grouping is not precise. The overarching reason for using lightweight concrete is to provide a more economical, and often a more quickly constructed, solution. The groups used are:

- Projects where lightweight concrete was used to allow reuse of existing structural elements.
- Projects where lightweight concrete was used to improve structural efficiency.
- Projects where lightweight concrete was used to reduce element weight for shipping and handling.

Basic details are presented for each project including its location, a description of the project, the reasons for using lightweight concrete, the types of elements for which lightweight concrete was used, and references from which additional information can be obtained about the project. References that only discuss the specific project are shown in **bold typeface**; more general references which provide some information on the project are shown in standard typeface. In each category, the most recent projects are presented first.

Sources of information about other lightweight concrete bridges include, but are not limited to: T. Y. Lin International (1985), Philleo (1986), Vaysburd (1996), ESCSI (2001a,b), Wolfe (2008), Castrodale and Robinson (2008), Castrodale (2012, 2014b, 2018c), Castrodale and Harmon (2006, 2007, 2009), and Ozyildirim et al. (2017).

The use of prewetted lightweight aggregate fines to replace a volume of conventional fines to provide internal curing for concrete is a relatively new concept. It is used more like an admixture or a refinement of a mix, so it does is not usually provide a topic about which project articles are written. Therefore, projects with internal curing are not presented in this chapter. A discussion of one demonstration project that compares the performance of a conventional deck and an internally cured deck is presented by Di Bella et al. (2012). Carpenter (2019) has reported on changes to the NYSDOT specifications that will be used for internal curing for many bridge decks in the State.

7.1 PROJECTS WHERE LIGHTWEIGHT CONCRETE WAS USED TO ALLOW REUSE OF EXISTING STRUCTURAL ELEMENTS

7.1.1 I-895 Bridge over the Patapsco River Flats – Baltimore, MD

Description: These dual 2380-ft-long bridges have 42 simple spans in each direction. It was determined that the deck and superstructure should be replaced. The substructure could be reused, but its capacity was limited.

Reasons for LWC: To allow reuse of substructure units, which accelerates the construction schedule, and maintain superstructure stresses at or near allowable limits.

Uses of LWC: Filled grid deck panels–w_c = 0.100 kcf (air-dry); f'_c = 4.5 ksi

Construction completed: 2019

References: **Kodkani et al. (2019)**

7.1.2 Shasta Arch Bridge on Southbound I-5 – Shasta County, CA

Description: This unique new box girder bridge supported by an arch was designed to use normal-weight concrete for the entire structure. After completion of the arch ribs and columns the bridge was reanalyzed; it was found that the weight of the superstructure had to be reduced to provide the desired performance.

Reasons for LWC: Lightweight concrete was used for the entire post-tensioned superstructure box girder and the bent caps to reduce the load on the arch.

Uses of LWC: Box girder and bent caps–w_c = 0.120 kcf (equilibrium); f'_c = 5.5 ksi

Construction completed: 2018

References: **Maggenti and Fereira (2019)**

7.1.3 Route 198 (Dutton Road) Bridge over Harper Creek – Gloucester County, VA

Description: A deteriorated single-span T-beam bridge was replaced with prestressed concrete girders and a cast-in-place deck. Abutments could be reused, but the capacity of the timber piling supporting them was not known. Abutment modifications were needed to accommodate the new structure.

Reasons for LWC: The weight of the new structure was limited to the weight of the existing structure.

Uses of LWC: Pretensioned girders–w_c = 0.115 kcf (fresh); f'_c = 5.0 ksi
Deck and railings–w_c = 0.105 kcf (equilibrium); f'_c = 4.0 ksi
Abutment modifications–w_c = 0.105 kcf (equilibrium); f'_c = 4.0 ksi

Construction completed: 2016

References: **Schlussel et al. (2017)**, Ozyildirim et al. (2017)

7.1.4 I-5 Bridge over the Skagit River – Skagit County, WA

Description: One truss span of the I-5 bridge over the Skagit River collapsed when struck by an over-height load. To accelerate construction of a permanent replacement span, design/build teams were allowed to reuse existing foundations without reanalysis or strengthening if the weight of the new structure did not exceed 915 tons. The bridge was constructed off-line and was slid into place during a weekend closure.

Reasons for LWC: Lightweight concrete deck girders (a full-depth deck was cast as part of the pretensioned girder) was used for the permanent span replacement, along with lightweight concrete diaphragms and barriers, to achieve the weight limit.

Uses of LWC: Pretensioned girders–w_c = 0.122 kcf (fresh); f'_c = 9.0 ksi
Diaphragms and railings–f'_c = 4.0 ksi

Construction completed: 2013

References: **Vanek et al. (2015)**, **Vanek et al. (2014)**, **Khaleghi (2014)**, **Baker et al. (2014)**

7.1.5 Beach Bridge – North Haven, ME

Description: Precast, pretensioned NEXT beams (double-tee sections) replaced a deteriorated steel girder bridge located on an island off the coast of Maine at a site that was exposed to tidal conditions. The two-span bridge has spans of 17 and 12 m, and it is the only land access to part of the island, warranting faster construction.

Reasons for LWC: Lightweight concrete was used to allow reuse of the existing pier, avoiding reconstruction of the pier on difficult soil conditions. Reusing the existing pier allowed more rapid construction of the bridge. The use of lightweight concrete decreased transportation costs because the girders had to be shipped by boat from the mainland to the island.

Uses of LWC: Pretensioned girders–w_c = 0.120 kcf (fresh); f'_c = 6.0 ksi

Construction completed: 2013

References: **Castrodale and Seraderian (2014)**

7.1.6 Ben Sawyer Bridge – Sullivan's Island, SC

Description: This project replaced a deteriorated existing 247-ft-long swing span and its approaches to improve the roadway function and address seismic capacity. The approach spans were constructed off-line and slid into their final location. The new swing span was constructed off-site and floated into place. Piers were in good condition.

Reasons for LWC: Lightweight concrete was used for the deck on the approach spans to allow reuse of existing piers without the need for seismic retrofits. For the swing span, lightweight concrete was used to fill a grid deck that minimized the weight of the movable span and capacity of the machinery.

Uses of LWC: Deck–w_c = 0.115 kcf; f'_c = 5.0 ksi

Construction completed: 2010

References: **Gilley et al. (2011)**, Castrodale (2014b)

7.1.7 Massaponax Church Road Bridge over Interstate 95 - Spotsylvania County, VA

Description: The original four-span bridge opened in 1964 and the normal-weight concrete deck was in poor condition. Increased traffic needed a wider structure with an improved load rating. The bridge was widened from 20 ft to 40 ft. Existing steel beams would be overstressed and an increased service load rating could not be achieved with a normal-weight concrete deck.

Reasons for LWC: Using lightweight concrete for the deck and railings enabled reuse of the existing steel beams and efficient widening of the bridge.

Uses of LWC: Deck and railings–w_c = 0.120 kcf (fresh); f'_c = 4.0 ksi

Construction completed: 2009

References: **Castrodale and Kerr (2011)**, Ozyildirim et al. (2017)

7.1.8 Brooklyn Bridge over the East River – New York City, NY

Description: The Brooklyn Bridge is the oldest bridge spanning the East River. The suspension bridge connects Manhattan and Brooklyn. A deck replacement was needed.

Reasons for LWC: The entire deck was replaced in an emergency contract using prefabricated panels of grid deck filled with lightweight concrete. The new floor system was designed to have the same weight as the existing floor system. Panels were installed at night to avoid affecting rush hour traffic.

Uses of LWC: Deck panels (filled grid)–w_c = 0.118 kcf (fresh); f'_c = 3.6 ksi

Construction completed: 1999

References: **Kulczycki et al. (2000)**, Castrodale and Harmon (2009).

7.1.9 Coleman Bridge over the York River – Yorktown, VA

Description: Improvements were needed for a large river bridge with dual 500-ft-long swing spans. Because of lengthy detours when the bridge was out of service, the swing spans and long-span truss approaches were constructed off-site and were then barged to the site and replaced during a 9 day closure. The replacement span was widened for increased traffic flow.

Reasons for LWC: Lightweight concrete was used for the deck on the swing spans and approaches to reduce the loads imposed on the new bridge trusses, but to also allow reuse of the existing piers, including the major piers supporting the swing spans.

Uses of LWC: Pretensioned deck panels–$_c$ = 0.115 kcf (air-dry); f'_c = 5 ksi

Construction completed: 1983

References: **Abrahams (1996)**, AASHTO TIG (2002), Castrodale and Robinson (2008), Castrodale and Harmon (2009).

7.1.10 Woodrow Wilson Bridge over the Potomac River – Washington, D.C.

Description: About 15 years after opening, the normal-weight concrete deck on this bridge began to deteriorate. The deck was replaced and widened using precast lightweight concrete panels that were post-tensioned in the transverse and longitudinal directions.

Reasons for LWC: Lightweight concrete was used for the panels to allow a thicker deck to provide longer service life (the normal-weight concrete deck was too thin, which led to its early failure); to allow an increased roadway width without needing to strengthen the existing structure; to reduce shipping costs from the precast plant that was 75 miles from the site; and to reduce the weight of the panels for installation.

Uses of LWC: Pretensioned deck panels–w_c = 0.115 kcf (air-dry); f'_c = 5 ksi

Construction completed: 1983

References: **Lutz and Scalia (1984)**, **Kassner et al. (2007)**

7.2 PROJECTS WHERE LIGHTWEIGHT CONCRETE WAS USED TO IMPROVE STRUCTURAL EFFICIENCY

7.2.1 Marc Basnight Bridge over the Oregon Inlet – Outer Banks, NC

Description: This 14,800 ft-long new bridge spans a treacherous inlet along the Outer Banks of North Carolina. The lifeline structure replaces a bridge that had outlasted its service life and was also subject to scour. The solution was to combine a 3,550-ft long series of precast segmental box girder spans with approaches of pretensioned girders with a cast-in-place deck. The project was designed for a 100-year service life.

Reasons for LWC: A lightweight concrete deck was used on the approaches to increase girder span lengths, which decreased the number of spans, bents, and foundations.

Uses of LWC: Deck–w_c = 0.120 kcf (fresh); f'_c = 4.5 ksi

Construction completed: 2019

References: **Coletti et al. (2019), Coletti et al. (2018)**

7.2.2 Pulaski Skyway Bridge Rehabilitation – Between Newark and Jersey City, NJ

Description: This major viaduct between Newark and Jersey City in northeast New Jersey is a heavily travelled link to the Holland Tunnel to New York City. After being in service for over 80 years, the structure was rehabilitated by replacing the deck and making other improvements. To accelerate the work, the deck was replaced using full-depth precast concrete panels connected with ultra-high-performance concrete (UHPC) joints or unfilled steel grid deck panels with a composite precast concrete deck.

Reasons for LWC: Lightweight concrete was used for the conventionally reinforced precast concrete decks to increase the load rating by significantly reducing dead load on the bridge.

Uses of LWC: Precast deck panels–w_c = 0.120 kcf (equilibrium); f'_c = 6 ksi

Construction completed: 2018

References: **Foden et al. (2014)**, **McDonagh and Foden (2019)**

7.2.3 Benicia-Martinez Bridge – Benicia, CA

Description: This 1.5-mile, 22-span cast-in-place segmental concrete box girder bridge was constructed using lightweight concrete for the entire cross-section of all box girder segments, except for the pier segments. It has main spans of 659 ft.

Reasons for LWC: Lightweight concrete was used for the superstructure to reduce its mass, decreasing the seismic demands on the foundations in this high seismic zone.

Uses of LWC: Cast-in-place box girders–w_c = 0.125 kcf (fresh); f'_c = 6.5 ksi

Construction completed: 2007

References: **Murugesh and Cormier (2007)**, Castrodale and Harmon (2009)

7.2.4 Route 33 Bridges over the Mattaponi and Pamunkey Rivers – West Point, VA

Description: Lightweight concrete was used for the post-tensioned spliced girders and deck for the two main units on each of these two bridges. Each of the four units had span configurations of 200-240-240-200 ft. Lightweight concrete was also used for decks and girders made continuous for live load in units with spans of more than 120 ft.

Reasons for LWC: Lightweight concrete was used to reduce foundation loads on the poor soils, which reduced the number of footings and piles.

Uses of LWC: Deck–w_c = 0.120 kcf (fresh); f'_c = 5.0 ksi
Pretensioned girders–w_c = 0.125 kcf (fresh); f'_c = 8.0 ksi

Construction completed: 2006 and 2007

References: **Nasser (2008)**, **Ozyildirim (2009)**

7.2.5 Stolma Bridge – Hordaland, Norway

Description: This bridge is representative of several long-span cast-in-place segmental concrete box girder bridges that have been constructed in Norway. The three-span bridge was constructed using the balanced cantilever technique with a main span of 988 ft and side spans of 308 ft and 236 ft. When completed, the bridge held the world record span for segmental concrete box girder bridges.

Reasons for LWC: Lightweight concrete was used in the center 604 ft of the main span to allow designers to achieve a better dead load balance between the main and side spans.

Uses of LWC: Box girder–w_c = 0.122 kcf; f'_c = 8.7 ksi

Construction completed: 1998

References: **Rosseland and Thorsen (2000)**, Melby (2000), Castrodale and Harmon (2009)

7.2.6 Nordhordaland Bridge – Hordaland, Norway

Description: This long-span concrete bridge combines a floating structure with a 369-m long concrete cable-stayed terminal structure.

Reasons for LWC: Lightweight concrete was used in the deck of the main span of the cable-stayed structure and the pontoons of the floating portion of the structure. Jakobsen (2000) estimates that using lightweight concrete for the pontoons saved between 3.3 and 7.5 percent of the cost of the floating portion of the bridge: the smaller lightweight concrete pontoons reduced wave forces, which reduced the quantity of reinforcement in the superstructure. Fergestad and Jordet (2000) report that using lightweight concrete for the cable-stayed structure saved about 0.83 percent of the total contract cost. They noted that most of the savings came from the reduced cost of the stays and hold-down structure.

Uses of LWC: Deck on main span–w_c = 0.119 kcf; f'_c = 8.0 ksi
Pontoons–w_c = 0.119 kcf; f'_c = 8.0 ksi

Construction completed: 1994

References: **Jakobsen (2000)**, Fergestad and Jordet (2000), Helland (2000), Melby (2003), Castrodale and Harmon (2009)

7.2.7 Francis Scott Key Bridge - Baltimore, MD

Description: The Francis Scott Key Bridge is an 8,636-ft-long structure that carries the Baltimore Beltway (I- 695) over the Baltimore Harbor at its easternmost crossing. The main span is a continuous truss structure with a 1,200-foot (366 m) main span and two 722-foot (220 m) back spans.

Reasons for LWC: The bridge deck on the main structure was constructed with structural lightweight concrete to allow for a longer span.

Uses of LWC: Deck–w_c = 0.112 kcf (fresh); f'_c = 4.0 ksi

Construction completed: 1977

References: Wolfe (2008)

7.2.8 San Francisco-Oakland Bay Bridge, CA

Description: Lightweight concrete was used for the upper roadway deck for the suspension spans on the West Bay Crossing of the San Francisco-Oakland Bay Bridge, which has main spans of 2,310 ft. The 5 3/8-inch-thick deck was initially protected by a ½-inch topping of mortar. Although the overlay has been replaced several times over the years, the deck is still in service today. When reconfigured for two-way traffic in 1961, all-lightweight concrete was also used for the lower deck.

Reasons for LWC: Using all-lightweight concrete for the upper deck in this bridge, which was completed in 1936, reduced the dead load by 25 lbs. per square foot for a total weight reduction of 31.6 million pounds for the entire structure. This decreased dead load made possible a reduction in area and cost of members in the superstructure, as well as reducing foundations loads and stresses on foundations and superstructure due to seismic forces. Overall cost savings from using lightweight concrete were estimated at $3 million for the $40 million-dollar total original construction cost for the two bay crossing bridges.

Uses of LWC: Deck–w_c = 0.095 kcf (air-dry); f'_c = unspecified

Construction completed: 1936 (new lower deck: 1961)

References: **Woodruff (1938)**, Vaysburd (1996), ESCSI (1971)

7.3 PROJECTS WHERE LIGHTWEIGHT CONCRETE WAS USED TO REDUCE ELEMENT WEIGHT FOR SHIPPING AND HANDLING

7.3.1 I-5 Portland Avenue to Port of Tacoma Southbound ramp – Tacoma, WA

Description: This bridge over the Puyallup River and multiple rail lines has long span lengths and extreme skews. The longest girder is 223 ft long and spans five existing and future rail lines and has a skew of approximately 55 degrees. It holds the record for the longest single piece prestressed concrete girder made in the United States

Reasons for LWC: Lightweight concrete was used to make the handling and shipping of this very long girder possible.

Uses of LWC: Girder–w_c = 0.125 kcf (fresh); f'_c = 10.0 ksi

Construction completed: 2020

References: **West (2019)**

7.3.2 I-95 Bridge over James River and Bridges North of Downtown – Richmond, VA

Description: The replacement of the 4,185-ft-long dual bridges carrying I-95 over the James River in downtown Richmond was completed in 2002 using full-span preconstructed composite units to allow rapid installation of the replacement structure. A second project just north of the first project was completed in 2014, replacing 11 bridges using the same techniques.

Reasons for LWC: Lightweight concrete decks were placed on the steel superstructure in a precasting yard for both projects. Lightweight concrete was used to reduce the weight of the full-span units for handling and erection.

Uses of LWC: Deck–w_c = 0.115 kcf (not specified); f'_c = 5.0 ksi

Construction completed: 2002 and 2014

References: **Fisher et al. (2014)**, AASHTO TIG (2002), Castrodale and Robinson (2008), Castrodale (2012), Ozyildirim et al. (2017).

7.3.3 Route 22 Bridge over the Kentucky River – Gratz, KY

Description: This four-span spliced-girder bridge includes the longest main span for a bridge of this type in the United States at 325 ft. The design was a contractor submitted alternate to a steel girder bridge. The contractor had significant challenges regarding erection of the girders because of site restrictions and was not able to use cranes to erect the main span.

Reasons for LWC: Lightweight concrete was used to reduce the weight of the 185-ft-long drop-in span girders, which simplified handling during loading the barges and erection.

Uses of LWC: Girder–w_c = 0.125 kcf; f'_c = 7.5 ksi

Construction completed: 2010

References: **Slagle (2011)**, **Schweitzer (2011)**

7.3.4 I-85 Ramp over State Route 34 – Newnan, GA

Description: This bridge was a demonstration project for the use of lightweight concrete in long-span pretensioned bridge girders.

Reasons for LWC: Lightweight concrete was used to allow the use of longer girders while avoiding the complications and expense of obtaining a super load permit.

Uses of LWC: Girders–w_c = 0.120 kcf (air-dry); f'_c = 10 ksi (56 d)

Construction completed: 2010

References: **Liles and Holland (2010)**, **Holland and Kahn (2010)**, **Holland et al. (2011)**.

7.3.5 Automated People Mover (APM) Project – Atlanta, GA

Description: This design build project had large pretensioned box girders, each cast with a deck slab already attached, that carried a light-rail system connecting a new remote auto rental facility to Atlanta's Hartsfield-Jackson International Airport terminal.

Reasons for LWC: The girder fabricator's equipment could only lift a girder that weighed no more than 255 kip. However, the fabricator discovered that, when using the actual concrete density and reinforcement quantities, the largest girders would weigh 291 kip. The situation was solved by using a specified-density concrete mixture for each of two groups of the heavier girders so the entire cross-section could be cast with the same concrete, reducing the girder weight to less than the lifting capacity of the available equipment.

Uses of LWC: Pretensioned box girders–w_c = 0.127 and 0.139 kcf (fresh); f'_c = 8.5 ksi

Construction completed: 2009

References: **Castrodale and Harmon (2007)**

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