TECHBRIEF

Lightweight Concrete: Mechanical Properties

FHWA Publication No.: FHWA-HRT-13-061

FHWA Contact: Ben Graybeal, HRDI-40, (202) 493-3122, benjamin.graybeal@dot.gov.

This document is a technical summary of the Federal Highway Administration report, *Lightweight Concrete: Mechanical Properties* (FHWA-HRT-13-062), available through the National Technical Information Service at www.ntis.gov.[1]

NTIS Accession No. of the report covered in this TechBrief: PB2013-107688

Objective

There is a limited amount of test data on the mechanical properties of high-strength lightweight concrete (LWC) with a concrete unit weight (w_c) between that of traditional LWC and normal weight concrete (NWC). Concrete with a w_c in this range is also not covered in the American Association of State Highway and Traffic Officials *(AASHTO) Load-and-Resistance Factor Design (LRFD) Bridge Design Specifications.*[2] This research program includes a significant number of mechanical property tests on this type of concrete. The results from this research project are included into a LWC database that covers a range of w_c to determine trends for LWC as a function of w_c. New design expressions for mechanical properties are proposed for LWC as a function of w_c as opposed to the more common method of using concrete constituent materials. The design expressions represent potential revisions to the *AASHTO LRFD Bridge Design Specifications* relating to the mechanical properties of LWC.[2]

Introduction

Much of the fundamental basis for the current LWC provisions in the *AASHTO LRFD Bridge Design Specifications* is built on research of LWC from the 1960s. (See references 2–6.) The LWC that was part of this research used traditional mixes of coarse aggregate, fine aggregate, portland cement, and water. Broad-based advancement in concrete technology over the past 50 years has led to significant advancements in concrete mechanical and durability performance. Research during the past 30 years, including the recent National Cooperative Highway Research Program (NCHRP) studies on different aspects of high-strength concrete, has resulted in revisions to the *AASHTO LRFD Bridge Design Specifications* to capitalize on the benefits

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology

Turner-Fairbank Highway Research Center

6300 Georgetown Pike

McLean, VA 22101-2296

www.fhwa.dot.gov/research

of high-strength NWC. However, as described by Russell, many of the design equations in the *AASHTO LRFD Bridge Design Specifications* are based on data that do not include tests of LWC specimens, particularly with regard to structural members with compressive strengths in excess of 6 ksi (41 MPa).[7]

The Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) has executed a research program investigating the performance of LWC with concrete compressive strengths in the range of 6 to 10 ksi (41 to 69 MPa) and equilibrium densities between 0.125 and 0.135 kcf (2,000 and 2,160 kg/m^3). The research program used LWC with three different lightweight aggregates that were intended to be representative of those available in North America. The program included tests from 27 precast/prestressed LWC girders to investigate topics including transfer length and development length of prestressing strand, time-dependent prestress losses, and shear strength of LWC. The development and splice length of mild steel reinforcement used in girders and decks made with LWC was also investigated using 40 reinforced concrete (RC) beams. While much of the research program focused on structural behavior, it also included a material characterization component wherein the compressive strength, elastic modulus (E_c), and splitting tensile strength (f_{ct}) of the concrete mixes used in the structural testing program were assessed. One key outcome of the research program is to recommend changes to the *AASHTO LRFD Bridge Design Specifications* relevant to LWC.[2]

This TechBrief summarizes the results of mechanical property testing that was conducted as part of the prestressed girder and RC beam testing. The mechanical properties of LWC tested in this study are included in a database of mechanical property tests on LWC that was collected from test results available in the literature. This TechBrief also summarizes the LWC database and the analysis of mechanical properties in the database. Design expressions in the current edition of the *AASHTO LRFD Bridge Design Specifications* are compared to the database.[2] Potential revisions to the *AASHTO LRFD Bridge Design Specifications* relating to LWC are also presented.

LWC Mix Designs

The Expanded Shale, Clay, and Slate Institute assisted FHWA in obtaining LWC mixes that had been used in production. One of the criteria for this research project was to use lightweight aggregate sources that were geographically distributed across the United States. Additional selection criteria included mixes using a large percentage of the coarse aggregate as lightweight coarse aggregate, mixes using natural sand as the fine aggregate, and mixes with a target equilibrium density between 0.125 and 0.135 kcf (2,000 and 2,160 kg/m^3). The concrete density needed to be in the range of densities not currently covered by the *AASHTO LRFD Bridge Design Specifications*.[2]

Three mix designs were selected with a design compressive strength greater than or equal to 6.0 ksi (41.4 MPa) to represent concrete that could be used for bridge girders. Another mix design was selected that had a design compressive strength less than 6.0 ksi (41.4 MPa) to represent concrete that could be used for a bridge deck. The selected mix designs are shown in table 1.

Table 1. Selected concrete mix designs.

Cast Date	Haydite Girder (HG)	Stalite Girder (SG)	Utelite Girder (UG)	Stalite Deck (SD)
Design 28-day strength (ksi)	6.0	10.0	7.0	4.0
Design release strength (ksi)	3.5	7.5	4.2	—
Target w_c (kcf)	0.130	0.126	0.126	0.125
Water/cementitious materials ratio	0.36	0.31	0.34	0.43

— Indicates release strength not necessary for nonprestressed elements.
1 ksi = 6.89 MPa
0.001 kcf = 16.01 kg/m^3

Each uses partial replacement of the coarse aggregate with lightweight aggregate to achieve their reduced w_c. The lightweight aggregates in the mixes were Haydite (an expanded shale from Ohio), Stalite (an expanded slate from North Carolina), and Utelite (an expanded shale from Utah). The normal weight coarse aggregate was No. 67 Nova Scotia granite. Natural river sand was used as the fine aggregate. Type III portland cement was used to obtain the high early strengths typically required in high-strength precast girders. Admixtures included a water reducer, an air entrainer, and a high-range water reducer.

Specimen Fabrication and Testing

The girders were fabricated at a concrete precasting plant in Mobile, AL. The fabricator was asked to prescriptively produce the concrete mixes without trying to adjust them for target strengths or w_c. This was intended to remove batch-to-batch variations as a variable in the study. The lightweight aggregates were stored in three piles at the plant and watered continuously using a sprinkler on each pile as shown in figure 1.

Figure 1. Lightweight aggregate stockpiles with continuous sprinklers.

Compression tests were performed on 4- by 8-inch (102- by 203-mm) and 6- by 12-inch (152- by 305-mm) cylinders to determine the compressive strength at release of prestressing, at 28 days, and at girder testing. E_c was determined using one of the 4- by 8-inch (102- by 203-mm) cylinders intended for compressive strength testing. The indirect tensile strength was measured on 4- by 8-inch (102- by 203-mm) cylinders using the f_{ct} test. Density measurements were made to determine the air-dry density of cylinders used for compression testing. They were also conducted on separate cylinders to determine the oven-dry density and equilibrium density. Average compressive strength, E_c, f_{ct}, and air-dry w_c for each concrete mix are provided in table 2.

Summary of Specimen Test Results

The LWC test results were compared to design expressions for a lightweight modification factor and for E_c. Nearly all f_{ct} tests on all three girder mixes gave splitting ratios that were greater

Table 2. Mean concrete properties from tests on 4- by 8-inch (102- by 203-mm) cylinders.

Concrete Mix	Specimen Age	Compressive Strength (ksi)	Air-Dry Density (kcf)	f_{ct} (ksi)	E_c (ksi)
HG	Release	7.07	0.133	0.607	3,840
	28 days	9.50	0.132	0.714	4,470
	Test day	10.45	0.130	0.771	4,320
SG	Release	7.32	0.125	0.604	3,770
	28 days	9.66	0.125	0.680	4,140
	Test day	10.56	0.123	0.717	4,360
UG	Release	6.04	0.131	0.569	3,500
	28 days	8.68	0.130	0.685	4,110
	Test day	10.10	0.127	0.757	4,150
SD*	28 days	5.67	0.138	—	—
	Test day	7.59	0.137	—	—

*Release strength not necessary for nonprestressed elements.
— Indicates no value was recorded.
1 ksi = 6.89 MPa
0.001 kcf = 16.01 kg/m^3

than the splitting ratio requiring modification of LWC for shear and development length of mild steel in tension in the *AASHTO LRFD Bridge Design Specifications*.[2] On average, E_c was overestimated by the AASHTO LRFD expression and underestimated by the NCHRP 12-64 expression and the ACI 363-10 expression.[2,8,9]

TFHRC LWC Database

A thorough literature review was performed to find published journal papers, conference papers, technical reports, and university dissertations that included tests, analyses, and discussions of LWC. Over 500 references were found that mentioned LWC. These documents were reviewed for LWC data consisting of a compressive strength value and data from at least one other mechanical test. The citations for the reviewed documents are provided in the full report.[1] The recorded mechanical tests included compressive strength, E_c, f_{ct} test, modulus of rupture (f_r), and Poisson's ratio. The concrete density was also recorded. Unpublished test data, data in graphs, and NWC test data were not included in the database.

The TFHRC LWC database consists of 3,835 data lines. These data were collected from 128 publications. Data lines were selected for evaluating material properties based on the presence of available data and on being within a range of material property values. A full list of references for the TFHRC LWC database and more information about the data selection criteria is included in the full report.[1]

Design Expressions for E_c

A total of 2,556 data lines are in the TFHRC subset database for E_c. To compare design expressions for E_c to both NWC and LWC data, the E_c database from NCHRP Project 12-64 was utilized.[8] The NWC and LWC data contain lines of compressive strength, E_c, and w_c.[8] For this evaluation, test data from concrete with a w_c greater than or equal to 0.135 kcf (2,160 kg/m^3) (i.e., NWC data) from the NCHRP 12-64 database was combined with test data from concrete with a w_c less than 0.135 kcf (2,160 kg/m^3) (i.e., LWC data) from the TFHRC database.

The E_c data were compared to three designs expressions: (1) the expression in the *AASHTO LRFD Bridge Design Specifications*, (2) the expression in the NCHRP Project 12-64 final report, and (3) the expression in the ACI Committee 363 report on high-strength concrete.[2,8,9] The ratio of the tested E_c to the predicted E_c by the three design expressions is provided in table 3. A test-to-prediction ratio greater than unity indicates an underestimation of E_c, while a ratio less than unity indicates an overestimation of E_c. The mean test-to-prediction ratios in table 3 show that the AASHTO LRFD expression overestimates E_c of LWC, and the NCHRP 12-64 expression underestimates E_c of LWC. The ACI 363-10 expression closely predicts E_c of LWC but underestimates E_c of NWC. The test-to-prediction ratios using the AASHTO LRFD expression is compared to compressive strength in figure 2. This figure shows that the AASHTO LRFD expression tends to overestimate E_c at higher compressive strength levels for both NWC and LWC.

Optimization of E_c Equation Variables

An analysis was performed to evaluate the effect of different exponents on the basic form of the expression for E_c. The analysis was performed on a database consisting of the TFHRC LWC subset database combined with the NCHRP 12-64 NWC database.[1,8] The analysis was divided into three parts. In the first part, the exponent applied to the w_c term was

Table 3. Mean test-to-prediction ratio of E_c for LWC data from the TFHRC database and NWC data from the NCHRP 12-64 database.

Data Source	AASHTO LRFD[2]	NCHRP 12-64[8]	ACI 363[9]	Proposed
TFHRC LWC and NCHRP NWC	0.957	1.087	1.056	1.000
TFHRC LWC	0.936	1.206	1.001	1.019
NCHRP NWC	0.972	1.007	1.094	0.987

varied and showed that an exponent of 1.5 or 2.0 applied to w_c resulted in the lowest coefficient of variation (COV) and a test-to-prediction ratio near unity for the LWC data. In the second part, the exponent applied to the compressive strength term was varied and showed that the exponent applied to compressive strength should be 0.33 or 0.5 for a low COV without considerable overestimation of E_c for LWC data. The third part was to vary the exponents applied to both w_c and compressive strength. A new proposed expression with an exponent of 2.0 for w_c and 0.33 for compressive strength was evaluated and had the lowest COV of the four expressions evaluated in the third part of the analysis. The proposed expression slightly underestimated the prediction of E_c for LWC and gave a close prediction of E_c for NWC.

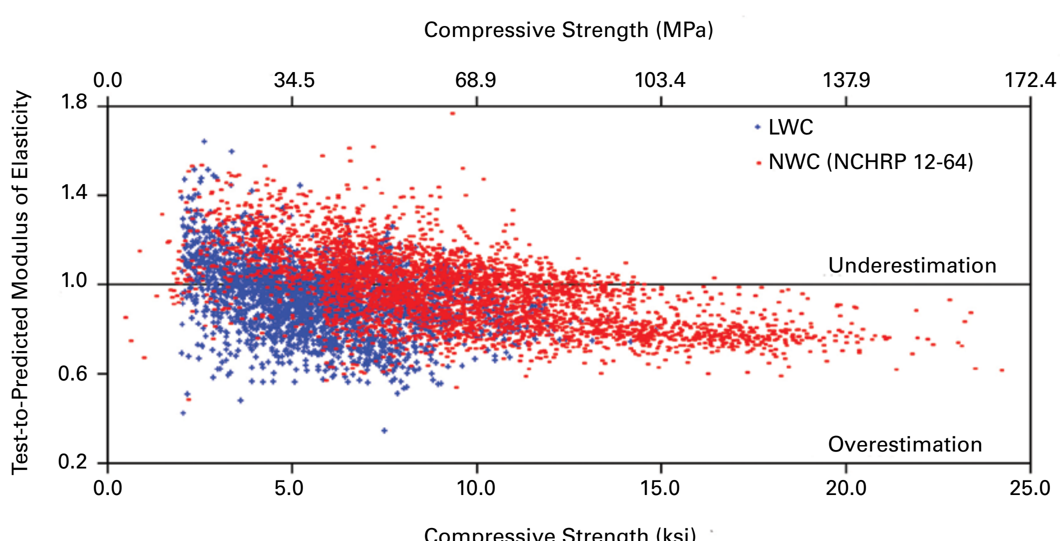
LWC Modification Factor

The *AASHTO LRFD Bridge Design Specifications* account for the reduced tensile strength of LWC in a variety of ways.[2] Article 5.8.2.2 of the report gives a modification for LWC that is applicable to the articles of the specifications involving sectional analysis of nominal shear resistance.[2] In this article, a 0.75 factor is used for all-lightweight concrete, and a 0.85 factor is used for sand-lightweight concrete. The article allows interpolation between the two factors for partial sand replacement. Article 5.11.2.1.2 describing the development length of mild reinforcement in tension also includes modification factors all-lightweight concrete and sand-lightweight concrete and allows for interpolation to be used with partial sand replacement.[2] Unfortunately, the amount of sand replacement is rarely known during the design phase of a project. Also, a definition based on the proportions of constituent materials becomes more cumbersome if partial replacement of normal weight coarse aggregate with lightweight coarse aggregate is also considered. A lightweight modification factor based on a specified mix property, such as concrete density, may be preferable.

Prediction of the Splitting Ratio

The ratio of f_{ct} to the square root of the compressive strength is known as the splitting ratio, F_{sp}. Early references to F_{sp} was made by Hanson and ACI Committee 318.[4,10] The term "splitting ratio" is no longer used in the *AASHTO LRFD Bridge Design Specifications*, but the definition is still a part of the modification factor for LWC in Articles 5.8.2.2 and 5.11.2.1.2.[2] Concrete with a F_{sp} greater than 0.212 does not require modification of the expressions in

Figure 2. E_c Test-to-prediction ratio compared to compressive strength for AASHTO LRFD equation.



1 ksi = 6.89 MPa

Articles 5.8.2 and 5.8.3 for LWC. F_{sp} implied by the *AASHTO LRFD Bridge Design Specifications* for sand-lightweight concrete and all-lightweight concrete are based on the 0.85 and 0.75 modification factors described in Article 5.8.2.

The f_{ct} subset of the TFHRC LWC database was used to evaluate the expression for F_{sp} implied by the *AASHTO LRFD Bridge Design Specifications*.[2] The database includes 954 lines of sand-lightweight and 311 lines of all-lightweight concrete. The test-to-prediction ratios for the sand-lightweight and all-lightweight AASHTO LRFD expressions for F_{sp} are given in table 4. A test-to-prediction ratio greater than unity is an overestimation of the splitting ratio and indicates a conservative prediction of concrete tensile strength when used for calculating nominal shear resistance or development length of mild reinforcement. The AASHTO LRFD expression gave conservative predictions of concrete tensile strength for most of the data.

Linear Expressions for F_{sp} Using w_c

An expression for predicting F_{sp} as a function of w_c was developed. This section describes this piecewise continuous function for predicting F_{sp}. Other types of expressions for F_{sp} are evaluated in the full report.[1] The expression consists of a constant predicted F_{sp} of 0.159 for $w_c \leq$ 0.100 kcf (1,600 kg/m^3). The prediction then assumes a linearly increasing F_{sp} with w_c to a limit on w_c of 0.135 kcf (2,160 kg/m^3). For $w_c \geq$ 0.135 kcf (2,160 kg/m^3), a constant predicted value of 0.212 for F_{sp} is used since this aligns with the existing provisions for NWC. A lower limit of 0.159 on F_{sp} is used because this value is specified in Article 5.8.2.2 as F_{sp} for all-lightweight concrete (0.75 × 0.212).[2] The test-to-prediction ratios for the proposed expression are shown in figure 3.

The proposed expression gave a larger predicted f_{ct} than the expression in the *AASHTO LRFD Bridge Design Specifications* for sand-lightweight concrete with a w_c up to 0.110 kcf (1,760 kg/m^3).[2] For larger unit weights, the AASHTO LRFD expression gave a very conservative prediction of f_{ct}.

The proposed expression for F_{sp} can be converted to LWC modification factor by dividing it by 0.212, the upper limit on F_{sp}. The term λ-factor is used to refer to a LWC modification factor.

Modulus of Rupture

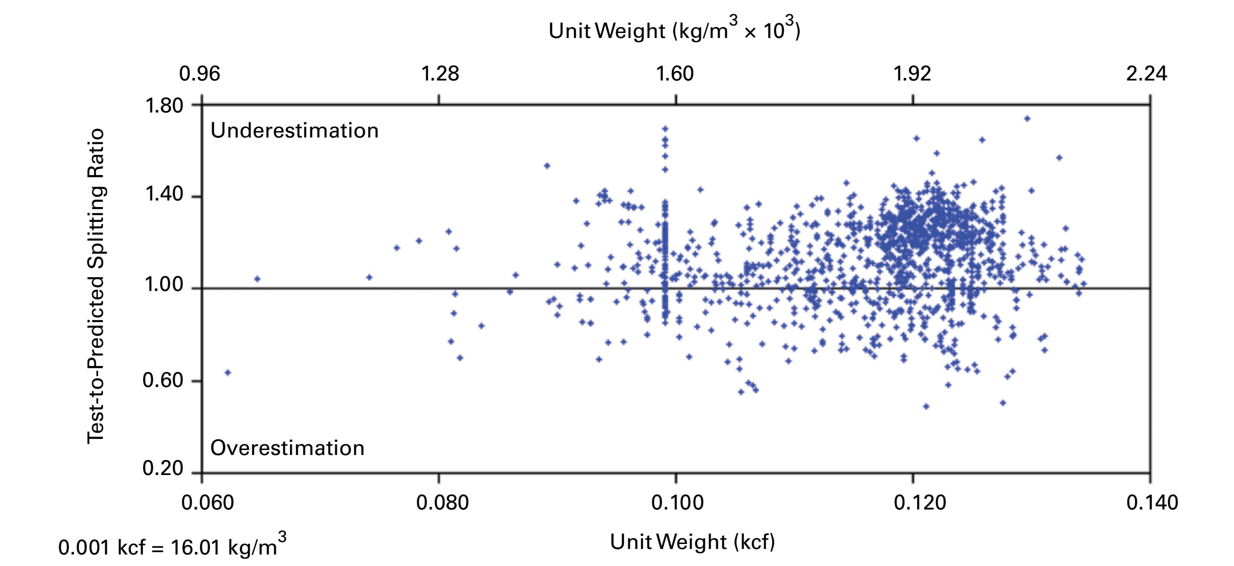
The accuracy of the f_r expression is important for the strength, serviceability, and ductility of structural concrete bridges. The *AASHTO LRFD Bridge Design Specifications* have different expressions for f_r depending on the use of the calculation and the type of concrete.[2] For normal weight concrete, one expression for f_r is used to calculate the nominal shear resistance provided by concrete when inclined cracking results from combined shear and moment (V_{ci}) (Article 5.8.3.4.3), and another expression for f_r is used for all other calculations such as effective moment of inertia, cracking control, and minimum flexural reinforcement.[2] For LWC, there are two different expressions for f_r depending on the use of sand-lightweight concrete or all-lightweight concrete. Unlike NWC, the *AASHTO LRFD Bridge Design Specifications* do not give different expressions for f_r of LWC depending on the use of the concrete.[2] This creates varying levels of conservatism in the calculations of cracking control, effective moment of inertia,

Table 4. Test-to-prediction ratios of F_{sp} using the AASHTO LRFD expression and proposed expression.

LWC	F_{sp} Expression	Total	$w_c \leq$ 0.090 kcf	0.090 < $w_c \leq$ 0.100 kcf	0.100 < $w_c \leq$ 0.110 kcf	0.110 < $w_c \leq$ 0.120 kcf	0.120 < $w_c \leq$ 0.135 kcf
Sand-lightweight	AASHTO LRFD	1.222	1.011	0.920	0.992	1.181	1.279
	Proposed	1.150	1.138	1.036	1.061	1.137	1.169
All-lightweight	AASHTO LRFD	1.129	0.991	1.143	1.094	1.190	1.188
	Proposed	1.078	0.984	1.135	1.034	1.050	0.956

0.001 kcf = 16.01 kg/m^3

Figure 3. Test-to-prediction ratios of F_{sp} predicted by the proposed expression.



and cracking moment for V_{ci} when used for members made from LWC.

Comparison of f_r to f_{ct}

In this section, f_r is compared to the f_{ct} in order to justify defining the material property f_r in terms of another material property f_{ct} (through the λ-factor).

For this comparison, a new subset database was created for concrete mixes with test results in both the f_{ct} subset database and a wet f_r subset database. An alternate wet f_r subset database was created to include only specimens that remained wet until tested due to the reduction in the tested f_r of specimens allowed to dry. A comparison of f_r and f_{ct} is shown in figure 4. The figure shows f_r increasing proportional to f_{ct}, which supports the observations of previous research on a limited number of data points.[4]

Proposed Design Expression for f_r

A new expression for f_r was proposed that includes the LWC modification factor (λ-factor). The proposed expression for f_r is applicable to the calculation of the effective moment of inertia, cracking control requirements, and minimum area of flexural reinforcement.

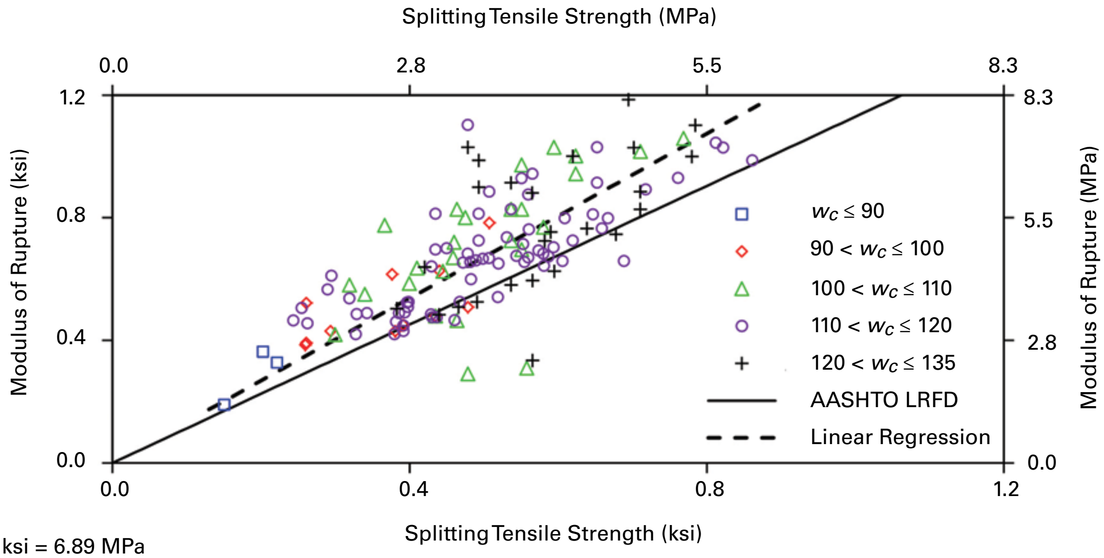
The ratio of the tested f_r from the wet f_r subset database to the f_r predicted by the AASHTO LRFD expressions and proposed expression is given in table 5. Both the proposed expression and the AASHTO LRFD expression gave predictions of f_r that were larger than the tested values.

Preliminary Recommendations

A set of preliminary recommended changes to the *AASHTO LRFD Bridge Design Specifications* were developed in this research effort.[2] This TechBrief has only considered the analysis of tests on the mechanical properties of LWC. Additional analysis on the structural performance of LWC members is needed before final recommendations can be made. The areas needing additional analysis include the development of mild reinforcement in tension, the transfer and development length of prestressing strands, and the shear resistance of reinforced and prestressed members. The effects of the preliminary recommendations will be included in those further analyses.

The analysis of the TFHRC LWC database using the subset database for E_c and the subset database for f_{ct} has resulted in several new expressions for E_c, an LWC modification factor (λ-factor), and f_r. The new expressions are not based on the proportions of constituent materials and include tests from types of

Figure 4. f_r compared to f_{ct} with AASHTO LRFD expression and linear regression.



1 ksi = 6.89 MPa

Table 5. Test-to-prediction ratios of f_r using the AASHTO LRFD expression and proposed expression.

LWC	f_r Expression	Total	$w_c \leq$ 0.090 kcf	0.090 $< w_c \leq$ 0.100 kcf	0.100 $< w_c \leq$ 0.110 kcf	0.110 $< w_c \leq$ 0.120 kcf	0.120 $< w_c \leq$ 0.135 kcf
Sand-lightweight	AASHTO LRFD	1.394	1.277	1.222	1.344	1.415	1.414
	Proposed	1.299	1.419	1.357	1.412	1.351	1.227
All-lightweight	AASHTO LRFD	1.571	1.328	1.664	1.538	1.498	1.901
	Proposed	1.409	1.254	1.571	1.387	1.253	1.428

0.001 kcf = 16.01 kg/m^3

mix designs that are not explicitly permitted by the current edition of the *AASHTO LRFD Bridge Design Specifications*.[2] These mix types include specified density LWC (typically a blend of lightweight and normal weight coarse aggregate) and inverted mixes (normal weight coarse and lightweight fine aggregate). The new expressions are instead based on w_c and as a result the definitions of sand-lightweight concrete and all-lightweight concrete would no longer be needed. This section proposes a revised definition of LWC that does not include the terms sand-lightweight concrete or all-lightweight concrete.

Proposed Definition for LWC

The definition for LWC in Article 5.2 of the *AASHTO LRFD Bridge Design Specifications* limits w_c for LWC to 0.120 kcf (1,920 kg/m^3) and includes definitions for sand-lightweight and all-lightweight concrete.[2] The proposed definition for LWC expands the range of w_c and eliminates the definitions for terms relating to the constituent materials in LWC. The proposed definition for LWC is as follows: concrete containing lightweight aggregate and having an equilibrium density not exceeding 0.135 kcf (2,160 kg/m^3), as determined by ASTM C567.[11]

The term "air-dry unit weight" is used in the current definitions; however, this term is not found in ASTM C567.[11] The *AASHTO LRFD Bridge Design Specifications* term "air-dry unit weight" is interpreted to be equivalent to the ASTM C567 term "equilibrium density."[2,11] A statement could be added to the commentary to clarify the term "air-dry unit weight" or the term “equilibrium density” could be used in the definition for LWC.

Proposed Expression for E_c

The proposed new expression for E_c would have the same limits on w_c and specified compressive strength as the current expression in Article 5.4.2.4.[2] The only proposed change is the expression for E_c itself. The proposed expression for E_c is shown in figure 5.

According to the *AASHTO LRFD Bridge Design Specifications*, in the absence of measured data, E_c for concrete with unit weights between 0.090 and 0.155 kcf (1,440 and 2,480 kg/m^3) and specified compressive strengths up to 15.0 ksi (103 MPa) may be taken as follows:[2]

Figure 5. Expression for E_c.

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

Where:

E_c = Modulus of elasticity in ksi.
K_1 = Correction factor for source of aggregate.
w_c = Concrete unit weight in kcf.
f'_c = Compressive strength in ksi.

Figure 6 shows the expression compared to the current AASHTO LRFD expression for an assumed w_c of 0.110 kcf (1760 kg/m^3) and K_1 equal to unity.

Proposed Expression for LWC Modification Factor

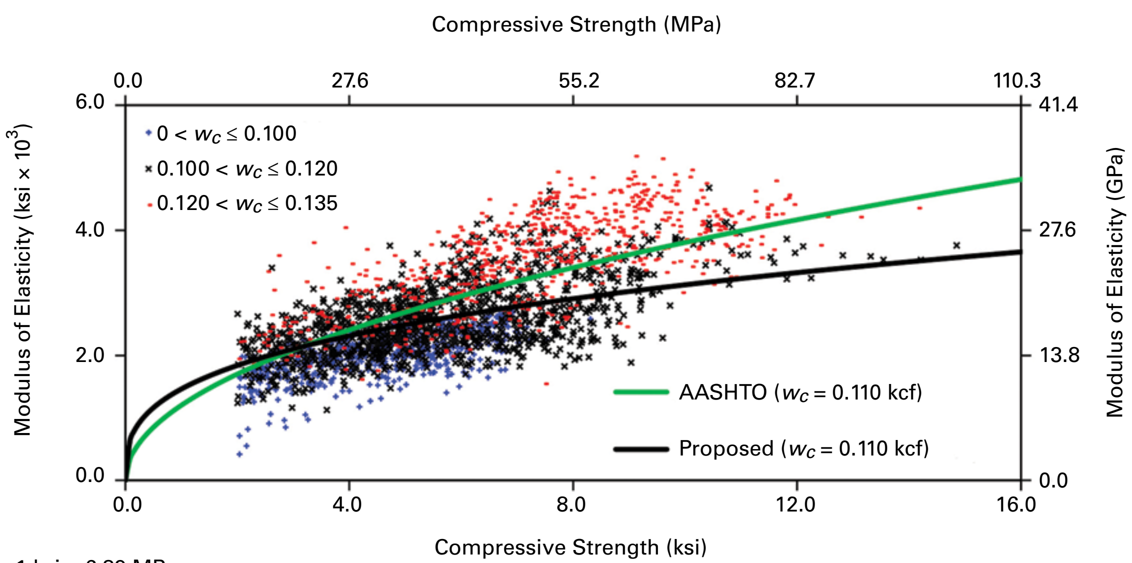
The concept of including a modification factor for LWC in expressions for predicting nominal resistance is included in many articles of the *AASHTO LRFD Bridge Design Specifications.*[2] However, a single unified expression or LWC modification factor is not specified. This section proposes a term, the λ-factor, to quantify the modification in nominal resistance that could be included in any expression for nominal resistance. The λ-factor relates to the material properties of structural LWC so the new article for the definition for the λ-factor could be located in Article 5.4.2.[2]

Where lightweight aggregate concretes are used, the LWC modification factor, λ, shall be determined using the equation in figure 7 where f_{ct} is specified.

Figure 7. Expression for λ-factor with f_{ct} specified.

$$\lambda = \frac{4.7 f_{ct}}{\sqrt{f'_c}} \leq 1.0$$

Figure 6. E_c for proposed expression.



1 ksi = 6.89 MPa

Where f_{ct} is not specified, λ shall be determined using the equation in figure 8.

Figure 8. Expression for λ-factor with f_{ct} not specified.

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

An illustration of the proposed expression for the λ-factor is shown in figure 9, and the predicted splitting ratios (λ-factor × 0.212) are shown in figure 10. The λ-factors implied in AASHTO LRFD for sand-lightweight concrete and all-lightweight concrete are also shown. Figure 10 shows that a considerable amount of sand-lightweight concrete data are not defined in the current *AASHTO LRFD Bridge Design Specifications.*[2]

As stated previously, the effect of using the λ-factor in expressions for nominal resistance needs to be evaluated. The proposed λ-factor could then be included in the expression for nominal resistance in the *AASHTO LRFD Bridge Design Specifications.*[2] For example, the λ-factor could be added directly to design expressions for nominal shear resistance in Articles 5.8.2 and 5.8.3 and would replace the existing modification factor for LWC.[2]

Figure 9. Proposed expression for λ-factor.

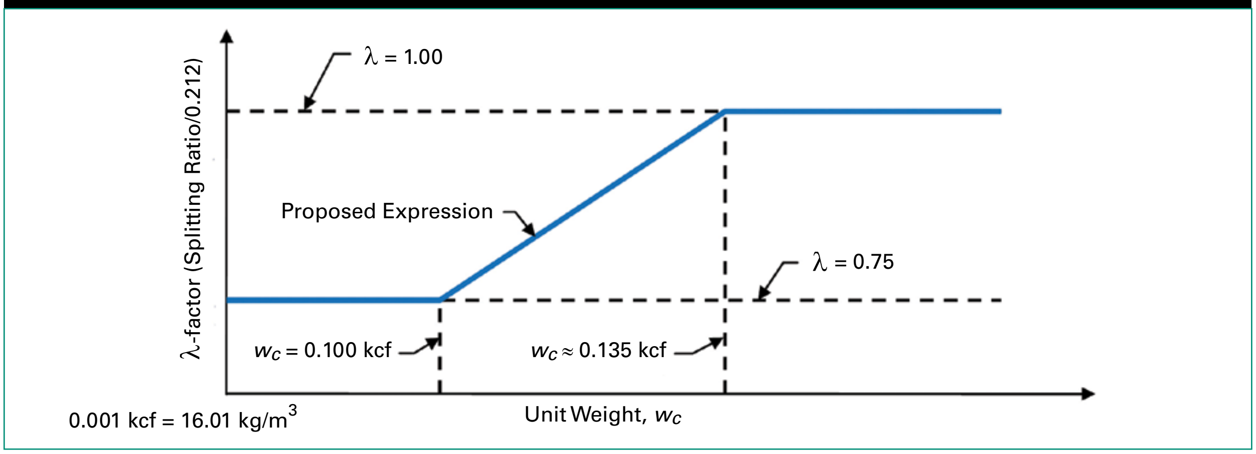
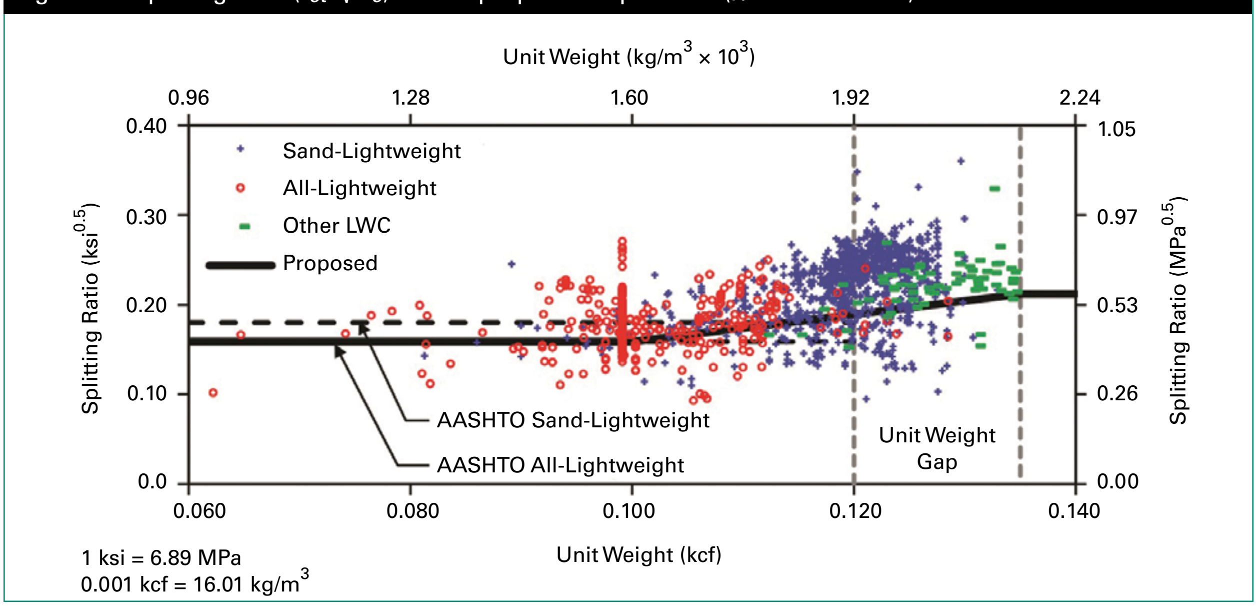


Figure 10. Splitting ratio ($f_{ct}/\sqrt{f'_c}$) for the proposed expression (λ-factor × 0.212).



Proposed Expression for f_r

The expression for f_r in the *AASHTO LRFD Bridge Design Specifications* is in Article 5.4.2.6.[2] The proposed expression for f_r is as follows for NWC and LWC:

Figure 11. Expression for f_r except when used in Article 5.8.3.4.3.[2]

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

The proposed expression is as follows when used to calculate the cracking moment of a member in Article 5.8.3.4.3:[2]

Figure 12. Expression for f_r when used in Article 5.8.3.4.3.[2]

$$f_r = 0.20\lambda\sqrt{f'_c}$$

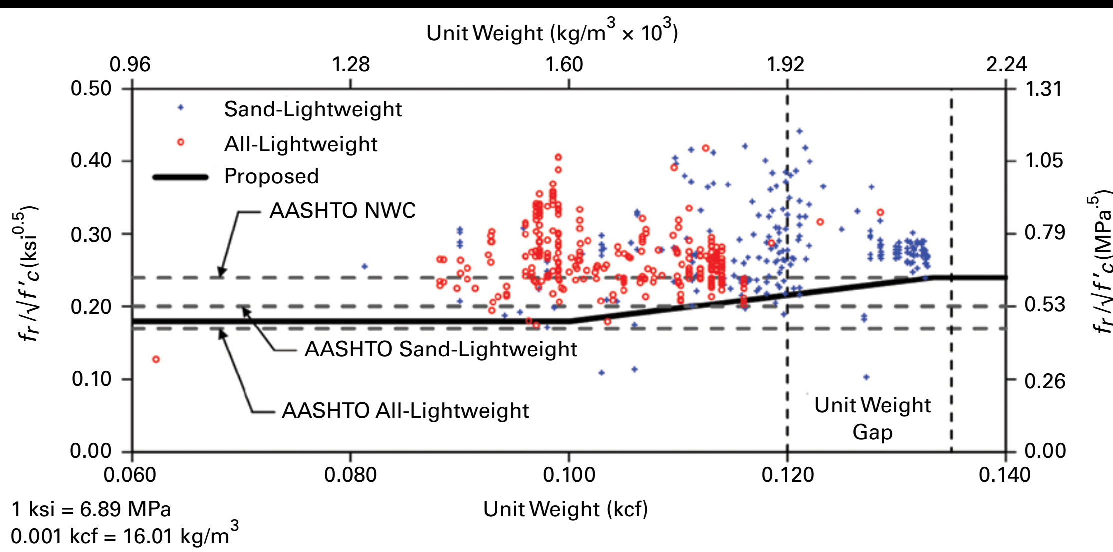
The proposed expressions for f_r include the proposed λ-factor and would be applicable to both NWC and LWC. The expression for f_r used to calculate the cracking moment of a member in Article 5.8.3.4.3 (V_{ci}) includes the proposed λ-factor for consistency. The f_r expression for use with Article 5.8.3.4.3 will need to be validated on shear test data from LWC members available in the literature before it is proposed for inclusion into the *AASHTO LRFD Bridge Design Specifications*.[2]

The ratio of the predicted f_r (see figure 11) to $\sqrt{f'_c}$ is shown in figure 13 with sand-lightweight and all-lightweight concrete data. Figure 13 shows that most of the test data are above the predicted f_r (i.e., underestimated) and that a considerable amount of the sand-lightweight concrete data are in the gap of w_c not defined in the current *AASHTO LRFD Bridge Design Specifications*.[2]

Conclusion

This TechBrief describes mechanical property tests on LWC, provides information about a LWC mechanical property database, and presents potential revisions to the *AASHTO LRFD Bridge Design Specifications* relating to the definition and mechanical properties of LWC.[2] The proposed design expressions for E_c, LWC modification factor, and f_r were compared to tested values in a LWC database collected as part of this research effort. A full description of the database and the development and evaluation of prediction expressions are included in the full report.[1] Future phases of this research compilation and analysis effort will include synthesis of past work on structural performance of LWC. The test results will be compared to the prediction expressions for nominal resistance in the *AASHTO LRFD Bridge Design Specifications* incorporating appropriate proposed revisions for LWC mechanical properties as presented in this TechBrief.

Figure 13. $f_r/\sqrt{f'_c}$ for the proposed expression ($0.24\lambda\sqrt{f'_c}$).



References

1. Greene, G. and Graybeal, B. (2013). *Lightweight Concrete: Mechanical Properties*, Report No. FHWA-HRT-13-062, Federal Highway Administration, Washington, DC.

2. AASHTO. (2012). *AASHTO LRFD Bridge Design Specifications*, Sixth Ed., American Association of State Highway and Transportation Officials, Washington, DC.

3. ACI Committee 213. (1967). "Guide for Structural Lightweight Aggregate Concrete," *ACI Journal*, *64*(8), 433–469, American Concrete Institute, Farmington Hills, MI.

4. Hanson, J.A. (1961). "Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete," *ACI Journal*, *58*(1), 1–40, American Concrete Institute, Farmington Hills, MI.

5. Ivey, D.L. and Buth, E. (1966). "Splitting Tension Test of Structural Lightweight Concrete," *ASTM Journal of Materials*, *1*(4), 859–871.

6. Pauw, A. (1960). "Static Modulus of Elasticity of Concrete as Affected by Density," *ACI Journal*, *57*(6), 679–687, American Concrete Institute, Farmington Hills, MI.

7. Russell, H. (2007). *Synthesis of Research and Provisions Regarding the Use of Lightweight Concrete in Highway Bridges*, Report No. FHWA-HRT-07-053, Federal Highway Administration, Washington, DC.

8. Rizkalla, S., Mirmiran, A., Zia, P., Russell, H., and Mast, R. (2007). *Application of the LRFD Bridge Design Specifications to High-Strength Structural Concrete: Flexure and Compression Provisions, NCHRP Report 595*, NCHRP Project 12-64, National Cooperative Highway Research Program, Washington, DC.

9. ACI Committee 363. (2010). *Report on High-Strength Concrete*, ACI 363R-10, American Concrete Institute Committee 363, Farmington Hills, MI.

10. ACI Committee 318. (1962). "Building Code Requirements for Reinforced Concrete (ACI 318-56)," *ACI Journal*, *59*(12), 1821–1848, American Concrete Institute, Farmington Hills, MI.

11. ASTM C567. (2005). "Standard Test Method for Determining Density of Structural Lightweight Concrete," *Book of Standards Volume 04.02*, ASTM International, Conshohocken, PA.

Researchers—This study was led by Ben Graybeal at FHWA's Turner-Fairbank Highway Research Center. It was conducted by Gary Greene of PSI, Inc. through laboratory support contract DTFH61 10 D 00017. For additional information, contact Ben at (202) 493-3122 or in the FHWA Office of Infrastructure Research and Development located at 6300 Georgetown Pike, McLean, VA, 22101-2296.

Distribution—The report (PB2013-107688) covered in this TechBrief is being distributed through the National Technical Information Service at www.ntis.gov.

Availability—This TechBrief may be obtained from the FHWA Product Distribution Center by email to report.center@dot.gov, fax to (814) 239-2156, phone to (814) 239-1160, or online at http://www.fhwa.dot.gov/research.

Key Words—LWC, lightweight concrete, bridge design, LRFD design specifications.

JUNE 2013

FHWA-HRT-13-061
HRDI-40/06-13(250)E