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.

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. 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.

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
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). 

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>
<thead>
<tr>
<th>Table 1. Selected concrete mix designs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Date</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Design 28-day strength (ksi)</td>
</tr>
<tr>
<td>Design release strength (ksi)</td>
</tr>
<tr>
<td>Target $w_c$ (kcf)</td>
</tr>
<tr>
<td>Water/cementitious materials ratio</td>
</tr>
</tbody>
</table>

— 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.

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

*Release strength not necessary for nonprestressed elements.
— Indicates no value was recorded.
1 ksi = 6.89 MPa
0.001 kcf = 16.01 kg/m³
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. 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 design 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 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>
<thead>
<tr>
<th>Data Source</th>
<th>AASHTO LRFD(^{(2)})</th>
<th>NCHRP 12-64(^{(8)})</th>
<th>ACI 363(^{(9)})</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFHRC LWC and NCHRP NWC</td>
<td>0.957</td>
<td>1.087</td>
<td>1.056</td>
<td>1.000</td>
</tr>
<tr>
<td>TFHRC LWC</td>
<td>0.936</td>
<td>1.206</td>
<td>1.001</td>
<td>1.019</td>
</tr>
<tr>
<td>NCHRP NWC</td>
<td>0.972</td>
<td>1.007</td>
<td>1.094</td>
<td>0.987</td>
</tr>
</tbody>
</table>
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.\(^{(14,10)}\) 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.
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*. 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 \times 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 \( \lambda \)-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.\(^{(3)}\) 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.

<table>
<thead>
<tr>
<th>LWC</th>
<th>( F_{sp} ) Expression</th>
<th>Total ( w_c \leq 0.090 ) kcf</th>
<th>0.090 ( &lt; w_c \leq 0.100 ) kcf</th>
<th>0.100 ( &lt; w_c \leq 0.110 ) kcf</th>
<th>0.110 ( &lt; w_c \leq 0.120 ) kcf</th>
<th>0.120 ( &lt; w_c \leq 0.135 ) kcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-lightweight</td>
<td>AASHTO LRFD</td>
<td>1.222</td>
<td>1.011</td>
<td>0.920</td>
<td>0.992</td>
<td>1.181</td>
</tr>
<tr>
<td></td>
<td>Proposed</td>
<td>1.150</td>
<td>1.138</td>
<td>1.036</td>
<td>1.061</td>
<td>1.137</td>
</tr>
<tr>
<td>All-lightweight</td>
<td>AASHTO LRFD</td>
<td>1.129</td>
<td>0.991</td>
<td>1.143</td>
<td>1.094</td>
<td>1.190</td>
</tr>
<tr>
<td></td>
<td>Proposed</td>
<td>1.078</td>
<td>0.984</td>
<td>1.135</td>
<td>1.034</td>
<td>1.050</td>
</tr>
</tbody>
</table>

\( 0.001 \) kcf = 16.01 kg/m\(^3\)
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 $\lambda$-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 ($\lambda$-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 ($\lambda$-factor), and $f_r$. The new expressions are not based on the proportions of constituent materials and include tests from types of
mix designs that are not explicitly permitted by the current edition of the AASHTO LRFD Bridge Design Specifications. 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 \(wc\) and as a result the definitions of sand-lightweight 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. 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

<table>
<thead>
<tr>
<th>LWC</th>
<th>(f_r) Expression</th>
<th>Total</th>
<th>0.090 (&lt; w_c \leq 0.100) kcf</th>
<th>0.100 (&lt; w_c \leq 0.110) kcf</th>
<th>0.110 (&lt; w_c \leq 0.120) kcf</th>
<th>0.120 (&lt; w_c \leq 0.135) kcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-lightweight</td>
<td>AASHTO LRFD</td>
<td>1.394</td>
<td>1.277</td>
<td>1.222</td>
<td>1.344</td>
<td>1.415</td>
</tr>
<tr>
<td></td>
<td>Proposed</td>
<td>1.299</td>
<td>1.419</td>
<td>1.357</td>
<td>1.412</td>
<td>1.351</td>
</tr>
<tr>
<td>All-lightweight</td>
<td>AASHTO LRFD</td>
<td>1.571</td>
<td>1.328</td>
<td>1.664</td>
<td>1.538</td>
<td>1.498</td>
</tr>
<tr>
<td></td>
<td>Proposed</td>
<td>1.409</td>
<td>1.254</td>
<td>1.571</td>
<td>1.387</td>
<td>1.253</td>
</tr>
</tbody>
</table>

0.001 kcf = 16.01 kg/m\(^3\)
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. 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:

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

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. However, a single unified expression or LWC modification factor is not specified. This section proposes a term, the $\lambda$-factor, to quantify the modification in nominal resistance that could be included in any expression for nominal resistance. The $\lambda$-factor relates to the material properties of structural LWC so the new article for the definition for the $\lambda$-factor could be located in Article 5.4.2.

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

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

Figure 7. Expression for $\lambda$-factor with $f_{ct}$ specified.

Figure 5. Expression for $E_c$.

Figure 6 for proposed expression.

Compressive Strength (ksi) to Modulus of Elasticity (ksi)
Where $f_{ct}$ is not specified, $\lambda$ shall be determined using the equation in figure 8.

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

Figure 8. Expression for $\lambda$-factor with $f_{ct}$ not specified.

An illustration of the proposed expression for the $\lambda$-factor is shown in figure 9, and the predicted splitting ratios ($\lambda$-factor $\times$ 0.212) are shown in figure 10. The $\lambda$-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 $\lambda$-factor in expressions for nominal resistance needs to be evaluated. The proposed $\lambda$-factor could then be included in the expression for nominal resistance in the AASHTO LRFD Bridge Design Specifications.\(^2\) For example, the $\lambda$-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.\(^2\)
Proposed Expression for \( f_r \)

The expression for \( f_r \) in the AASHTO LRFD Bridge Design Specifications is in Article 5.4.2.6. The proposed expression for \( f_r \) is as follows for NWC and LWC:

\[
fr = 0.24 \lambda \sqrt{f'_c}
\]

Figure 11. Expression for \( f_r \) except when used in Article 5.8.3.4.3.

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

\[
fr = 0.20 \lambda \sqrt{f'_c}
\]

Figure 12. Expression for \( f_r \) when used in Article 5.8.3.4.3.

The proposed expressions for \( f_r \) include the proposed \( \lambda \)-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 \( \lambda \)-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.

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.

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. 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. 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.
References


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


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