Showcase – Two LWC Bridges AASHTO LRFD 9th Edition – Design Updates for Lightweight Concrete

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Introduction

Lightweight concrete (LWC) has been included in bridge design specifications in the US since at least 1973, and in the ACI Building Code longer than that.

Design provisions for LWC in the *AASHTO LRFD Bridge Design Specifications* have been essentially the same as in the *Standard Specifications*

- **The major exception: a resistance factor for shear for LWC introduced with the LRFD**
  - **NWC: $\phi = 0.90$**
  - **LWC: $\phi = 0.70$ (until changed to 0.80 in 2011)**
- **Also, research data for LWC was limited to $f'_c \leq 6$ ksi**

Introduction

Modification factors are provided to account for the effect of the assumed reduced tensile strength of LWC

- **In ACI 318 – λ factor**
- **In LRFD, factor was defined, but no variable assigned**
- **Factor was based on the type of LWC**
  - **0.85 for “sand LWC” (coarse LWA + NW sand)**
  - **0.75 for “all LWC” (coarse & fine LWA)**
  - **Other types not included**
  - **Interpolation was permitted between the two types**
- **But designers are only concerned with the concrete density, not the types of aggregates in the LWC mix**

Introduction

Major revisions to the AASHTO LRFD were developed based on research on LWC for girders and decks

- NCHRP Project 18-15 (Report 733)
- A large research program at FHWA's lab
- Other available data

In 2014, a revised equation for E_c was adopted to better reflect behavior of LWC and high strength concrete

In 2015, broad revisions related to LWC were adopted

This presentation presents these changes and discusses their impact on bridge designs using LWC

Revisions to LRFD regarding LWC

- **Definition of LWC**
- **Concrete density modification factor, λ**
- **Resistance factors**
- **Material properties**

Definition of LWC

Significant revision

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. ~~**Lightweight Concrete without natural sand is termed "all-lightweight concrete" and lightweight concrete in which all of the fine aggregate consists of normal weight sand is termed "sand-lightweight concrete."**~~

- **Definitions of types of LWC are removed**
- **No gap between LWC and NWC**

Definition of NWC

Slightly modified

Normal Weight Concrete—Concrete having an equilibrium density greater than 0.135 kcf and a density not exceeding 0.155 kcf.

- **Density range remains the same**
- **Term “equilibrium density” added for lower value**

Definition of LWC

Changes carried throughout specifications

- **Interface shear transfer**
  - **Remove terms “sand-lightweight” and “all-lightweight”**
- **Brackets and corbels**
  - **Remove terms “sand-lightweight” and “all-lightweight”**

Definition of LWC

Table 3.5.1-1 Unit Weights

- **New table entry for LWC**
  - Lightweight 0.110 to 0.135 (kcf)
- **Old table entries for LWC**
  - Lightweight 0.110 (kcf)
  - Sand Lightweight 0.120 (kcf)

Definition of LWC

Add reference to ASTM C567 to Article 8.2.3 in the *AASHTO LRFD Bridge Construction Specifications*

The equilibrium density of lightweight concrete shall be determined by ASTM C567.

Concrete Density Modification Factor, λ

Density modification factor, λ, is now defined in only one section – Article 5.4.2.8

- **Definition is now based on density**
  - **Previously, the definition was based on type of concrete – sand or all LWC**
- **Eliminates duplication of definition**
- **Allows insertion of the λ factor where required**
  - **ACI 318 uses the λ factor and inserted it in all appropriate locations in the 2019 edition**
- **Simplifies and clarifies use of LWC**

Concrete Density Modification Factor, λ

5.4.2.8—Concrete Density Modification Factor

The concrete density modification factor, λ , shall be determined as:

- **Where the splitting tensile strength of lightweight concrete, f_{ct}, is specified:**

  $\lambda = 4.7\, f_{ct} / \sqrt{f'_c} \leq 1.0$ (5.4.2.8-1)

- **Where f_{ct} is not specified:**

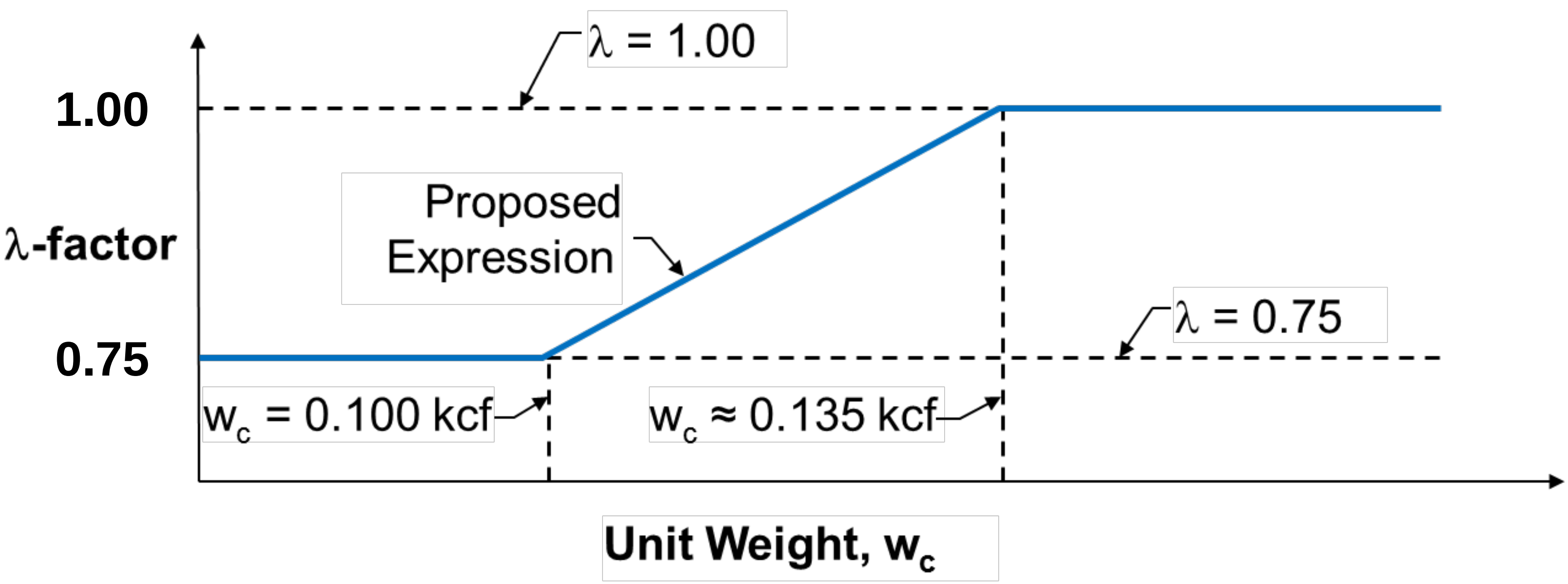
  $0.75 \leq \lambda = 7.5\, w_c \leq 1.0$ (5.4.2.8-2)

- **Where normal weight concrete is used, λ shall be taken as 1.0.**

Concrete Density Modification Factor, λ

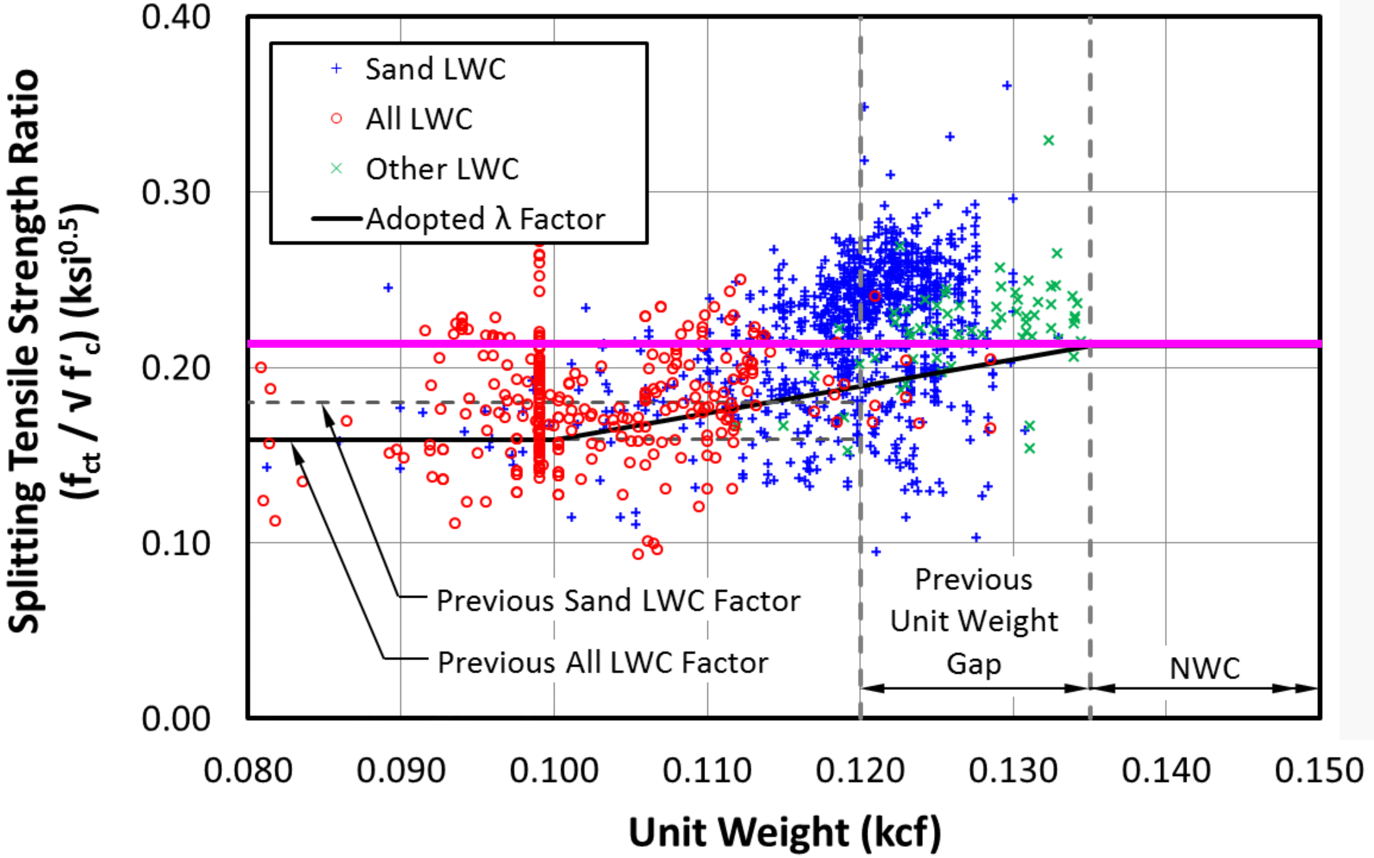
- **Where f_{ct} is not specified:**

$$0.75 \leq \lambda = 7.5\, w_c \leq 1.0 \qquad (5.4.2.8\text{-}2)$$



Concrete Density Modification Factor, λ

Comparison of Eq. 5.4.2.8-2 with tensile strength data



- **Most data falls above the line for Eq. 5.4.2.8-2**
- **Many points lie above the λ = 1.0 line for NWC**

Concrete Density Modification Factor, λ

The λ factor is inserted in all equations where appropriate

- **Previously the modification was stated generally and the engineer had to apply it where appropriate**
- **This simplifies application of design using LWC and eliminates opportunities for errors**

- **A few examples are given in next slide**
- **A number of other equations were also modified by adding the λ factor**

Concrete Density Modification Factor, λ

Components of nominal shear resistance

$$V_c = 0.0316\beta\lambda\sqrt{f_c{}'}b_v d_v$$

Minimum transverse reinforcement

$$A_v \geq 0.0316\lambda\sqrt{f_c{}'}\frac{b_v s}{f_y}$$

Development length of mild reinforcement

$$\ell_d = \frac{2.4 d_b f_y}{\sqrt{f'_c}}\left(\frac{\lambda_{rl}\lambda_{cf}\lambda_{rc}\lambda_{er}}{\lambda}\right)$$

Factor for LWC moved from numerator to denominator

Concrete Density Modification Factor, λ

The λ factor has been added in some new locations

Prestressed Concrete: Tensile Stress Limits before Losses

- Other Than Segmentally Constructed Bridges
  - In areas other than the precompressed tensile zone and without bonded reinforcement…

    $$0.0948\boxed{\lambda}\sqrt{f_{ci}'} \leq 0.2 \text{ (ksi)}$$

  - In areas with bonded… $0.24\boxed{\lambda}\sqrt{f_{ci}'}$ (ksi)
  - For handling stresses… $0.158\boxed{\lambda}\sqrt{f_{ci}'}$ (ksi)

Concrete Density Modification Factor, λ

The λ factor has been added in some new locations

Prestressed Concrete: Tensile Stress Limits after Losses

- **Other Than Segmentally Constructed Bridges**
  - **Tension in Precompressed Tensile Zone, Assuming Uncracked Sections**
    - **For components with bonded…**

$$0.19\,\boxed{\lambda}\sqrt{f_{ci}'} \leq 0.6 \text{ (ksi)}$$

    - **For components with bonded…**

$$0.0948\,\boxed{\lambda}\sqrt{f_{ci}'} \leq 0.3 \text{ (ksi)}$$

Resistance Factors

Since its introduction in 1994, the LRFD Specifications have had a resistance factor for shear for LWC

- **For shear and torsion (5.5.4.2.1):**
  - **Normal weight concrete…… 0.90**
  - **Lightweight concrete……….. 0.70**

In 2011, after data on LWC was analyzed, the resistance factor for shear for LWC was increased

- **Normal weight concrete…… 0.90**
- **Lightweight concrete……….. 0.80**

Resistance Factors

The changes adopted in 2015 set both factors to 0.90 for reinforced concrete

- **Based on evaluation of material & structural test results**

More recent changes set resistance factors for prestressed concrete of both normal weight and lightweight to the same values:

- **0.90 for bonded strands and tendons**
- **0.85 for unbonded or debonded strands or tendons**

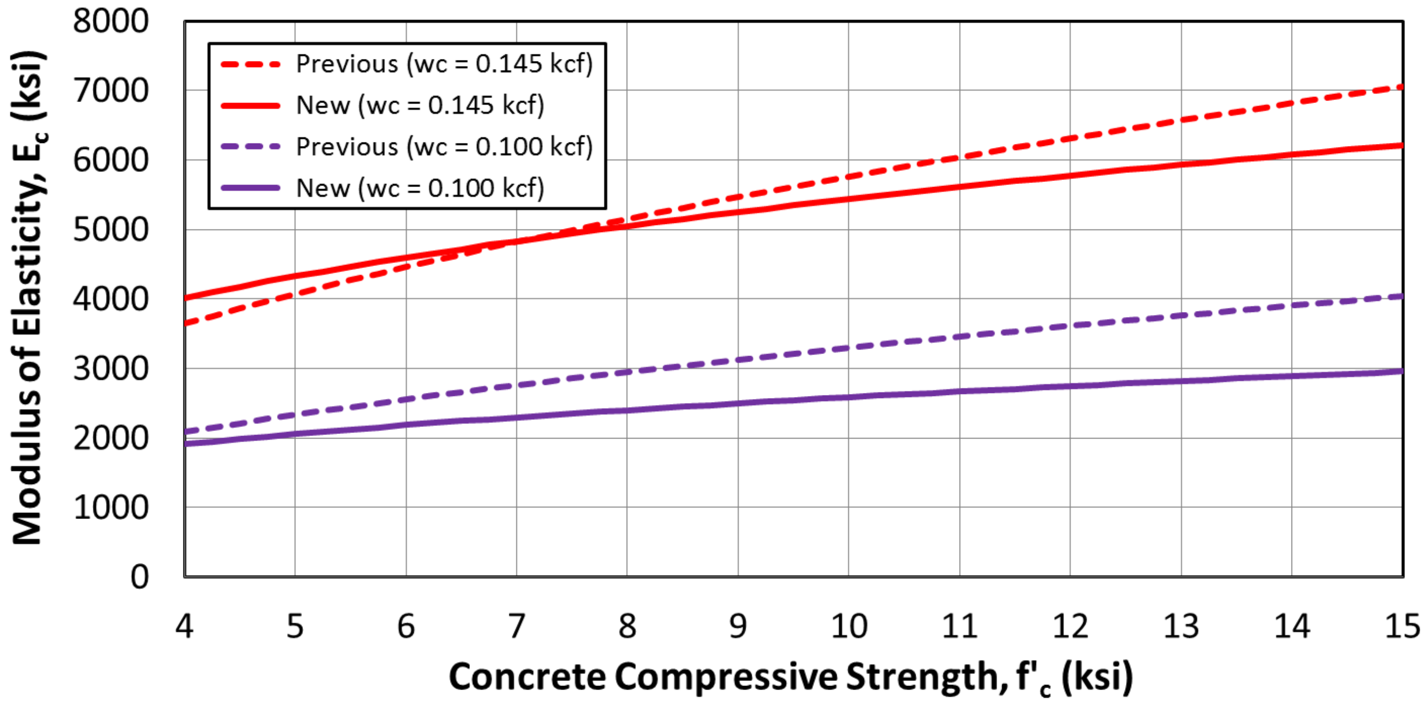
Material Properties

Modulus of elasticity, E_c – adopted in 2014:

$$E_c = 121{,}000\ K_1\ w_c^{2.0}\ f'_c{}^{0.33} \qquad (5.4.2.4\text{-}1)$$

Previous expression:

$$E_c = 33{,}000\ K_1\ w_c^{1.5}\ f'_c{}^{0.5}$$

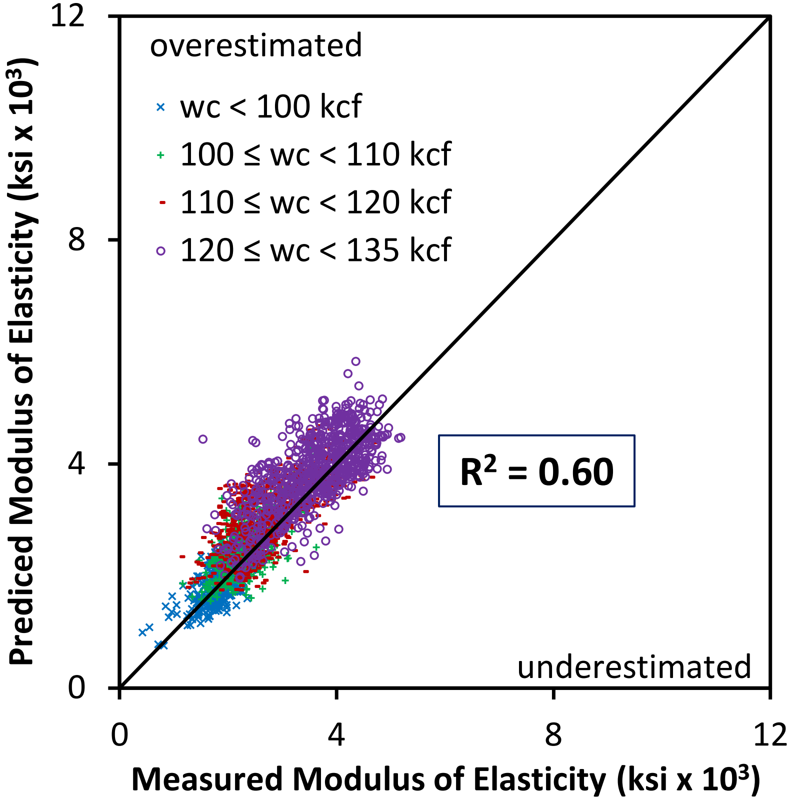


Material Properties

Predicted v. measured modulus of elasticity, E_c, LWC

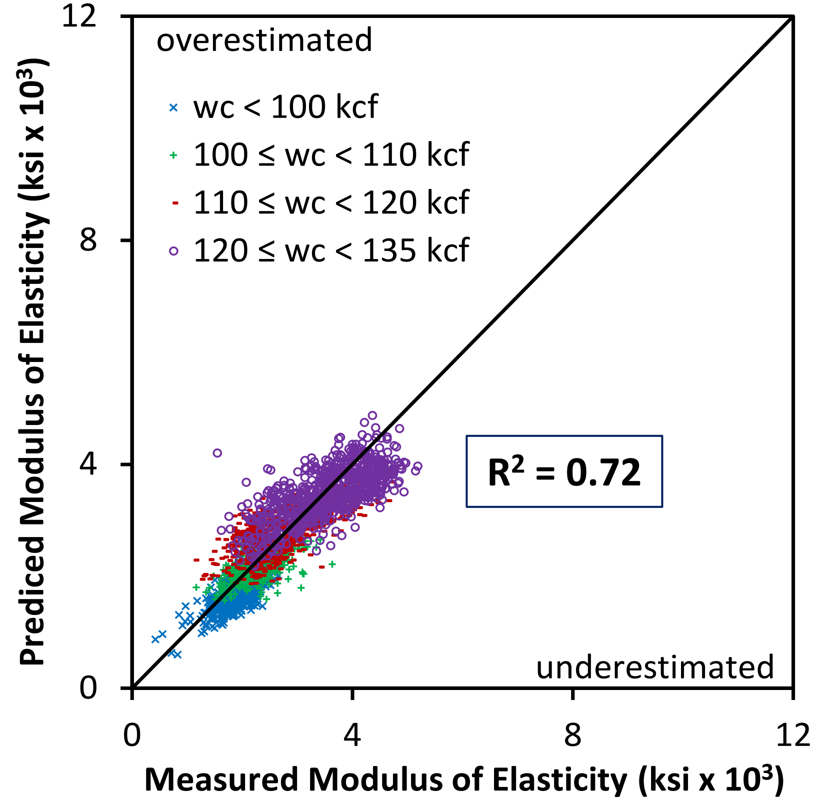
Previous equation

$$E_c = 33{,}000\ K_1\ w_c^{1.5}\ f'_c{}^{0.5}$$



New equation

$$E_c = 121{,}000\ K_1\ w_c^{2.0}\ f'_c{}^{0.33}$$



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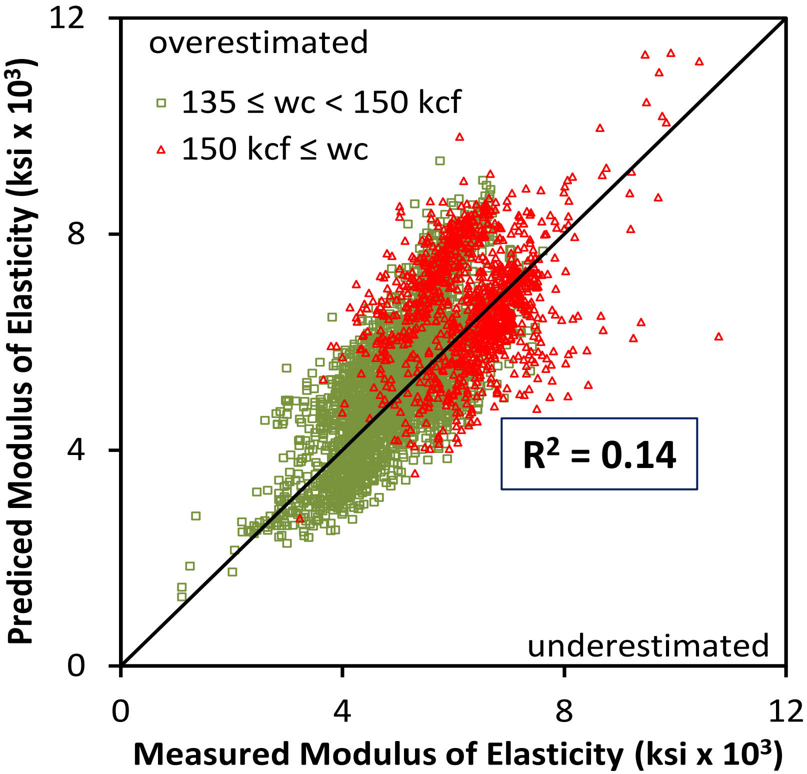
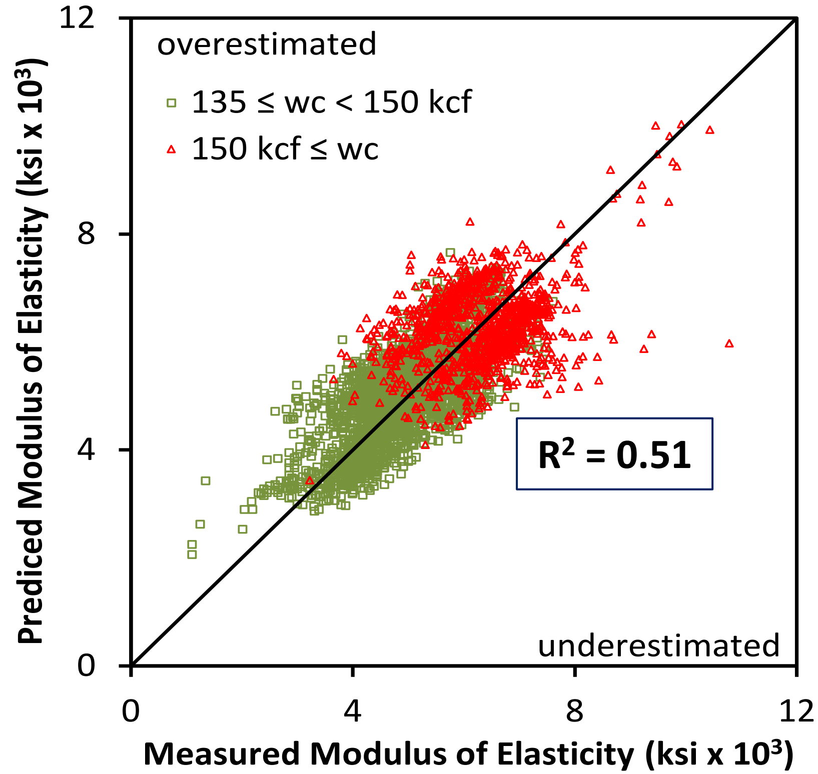


New equation

$$E_c = 121{,}000\ K_1\ w_c^{2.0}\ f'_c{}^{0.33}$$

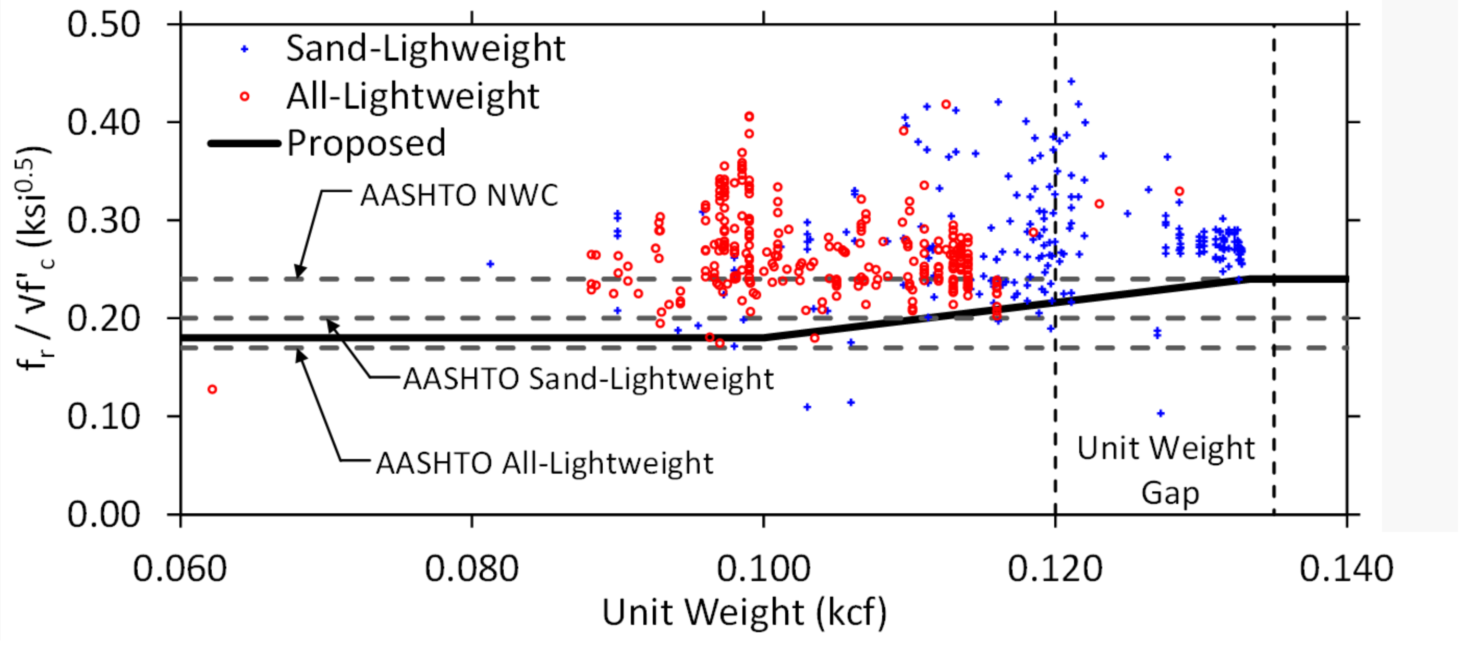


Material Properties

Modulus of rupture, f_r

For normal-weight and lightweight concrete:

- $0.24\lambda\sqrt{f_c'}$



Effect of Changes on Bridge Designs

Most of the changes to the *AASHTO LRFD Bridge Design Specifications* related to LWC will not result in significant changes to LWC bridge designs

New definition for LWC

- No noticeable effect on bridge designs
- It will provide designers with greater freedom in specifying concrete densities without considering the type of materials required

Modulus of Elasticity

- Reduced for all strength levels for LWC
- For PS members, will lead to slightly larger predicted losses and cambers

Effect of Changes on Bridge Designs

New definition for density modification factor, λ

- **No significant effect on bridge designs using LWC because factors were present in previous editions of the AASHTO Standard and LRFD specifications**
- **Basing definition on density is helpful, eliminating confusion from material-based definition**
- **With an assigned variable name, λ, the factor has been inserted in all equations and expressions where appropriate – simplifying and clarifying design using LWC**

Effect of Changes on Bridge Designs

New definition for density modification factor, λ (cont'd)

- **Introducing λ in equations where it has not previously been included will not have a large effect since the factor ranges from 0.75 to 1.00**
- **In the case of the limiting tensile stress in the precompressed tensile zone of prestressed concrete elements, the stress limit is already fairly low and the reduction is not significant**
- **Inserting λ into all equations and expressions where the assumed reduction in tensile strength could affect the computed quantity was appropriate and necessary to be consistent**

Effect of Changes on Bridge Designs

Elimination of different shear reduction factors (ϕ)

- **This change will have the most significant change on bridge designs using LWC**
- **With the new revisions, the shear resistance factors for NWC and LWC are both 0.9**
- **This eliminates the reduced shear capacity for LWC that in some cases has made LWC designs uneconomical when member dimensions had to be increased to counteract the reduced shear capacity**

Concluding Remarks

Significant changes have been made in the AASHTO LRFD Bridge Design Specifications related to LWC

- **Effects of the changes on bridge designs are not generally expected to be large**
- **But the changes make bridge design using LWC more rational and consistent**

This could make LWC more attractive to designers, allowing them to consider this material as an option for more economical bridge designs

Acknowledgements

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References

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Thank you!

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