New Design Provisions for Lightweight Concrete in Bridges

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Rotary Kiln Structural Lightweight Aggregate

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

Recent 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

- **Compressive strength (5.4.2.1)**
  - Change term “air dry unit weight” to “equilibrium density”
- **Interface shear transfer (C5.8.4.1, C5.8.4.3)**
  - Remove terms “sand-lightweight” and “all-lightweight”
- **Brackets and corbels (5.13.2.4.2)**
  - 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 2011 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:**

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

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

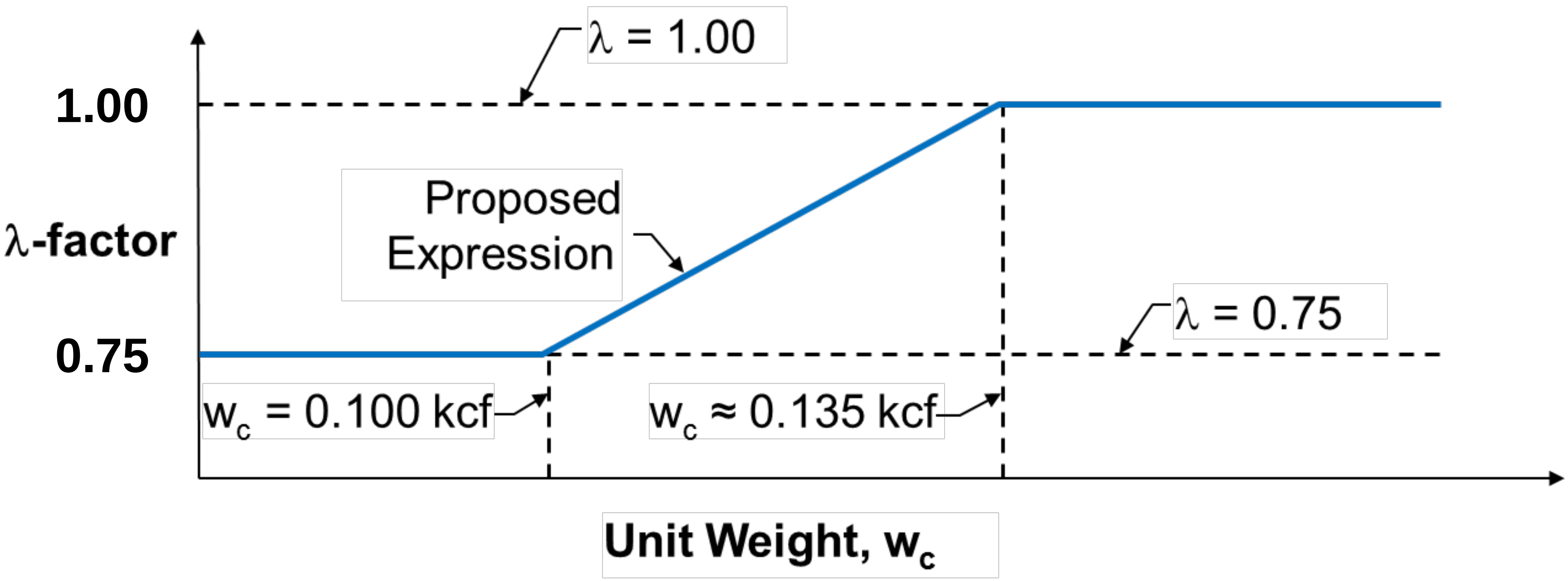
  $$0.75 \leq \lambda = 7.5\, w_c \leq 1.0 \qquad (5.4.2.8\text{-}2)$$

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

Concrete Density Modification Factor, λ

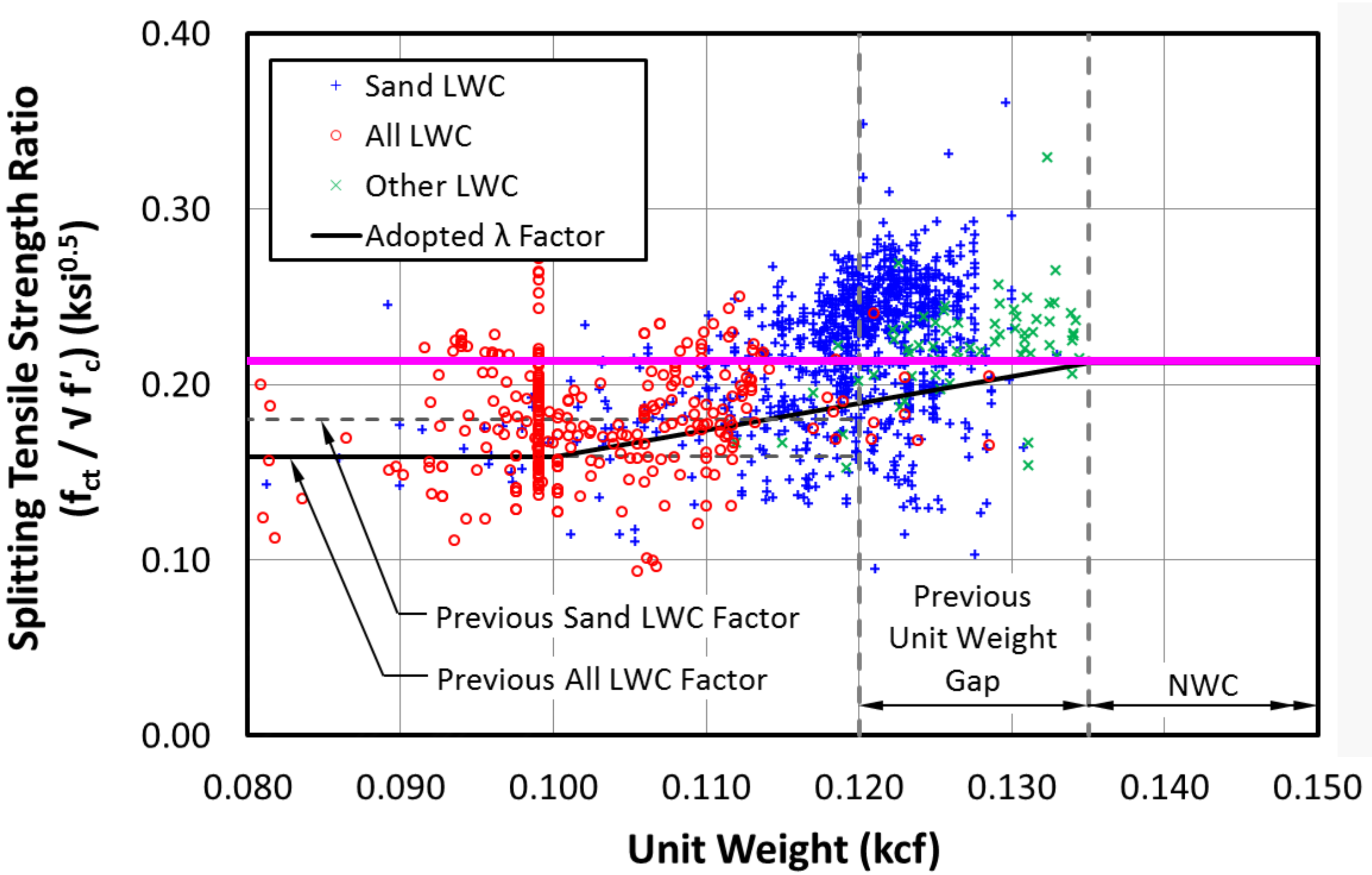
- **Where f_{ct} is not specified:**

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



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

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

$$V_{ci} = 0.02\lambda\sqrt{f_c{}'}b_v d_v + V_d + \frac{V_i M_{cre}}{M_{max}} \geq 0.06\lambda\sqrt{f_c{}'}b_v d_v$$

$$V_{cw} = \left(0.06\lambda\sqrt{f_c{}'} + 0.30f_{pc}\right)b_v d_v + V_p$$

Minimum transverse reinforcement

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

Development length of mild reinforcement

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

Factor for LWC moved from numerator to denominator

Concrete Density Modification Factor, λ

The λ factor has been added in some new locations

Table 5.9.4.1.2-1 Tensile Stress Limits … before Losses

- **Other Than Segmentally Constructed Bridges**
  - **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…** $0.24\lambda\sqrt{f'_{ci}}$ (ksi)
  - **For handling stresses…** $0.158\lambda\sqrt{f'_{ci}}$ (ksi)

Concrete Density Modification Factor, λ

The λ factor has been added in some new locations

Table 5.9.4.2.2-1 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**

The changes adopted in 2015 set both factors to 0.90

Resistance Factors

Changes also made to Section 5.5.4.2.2 – Segmental Construction

Table 5.5.4.2.2-1—Resistance Factor for Joints in Segmental Construction

	ϕ_f Flexure	ϕ_v Shear
~~Normal Weight Concrete~~		
Fully Bonded Tendons	0.95	0.90
Unbonded or Partially Bonded Tendons	0.90	0.85
Sand-Lightweight Concrete		
Fully Bonded Tendons	0.90	0.70
Unbonded or Partially Bonded Tendons	0.85	0.65

- **Same factors are now used for both NWC and LWC**

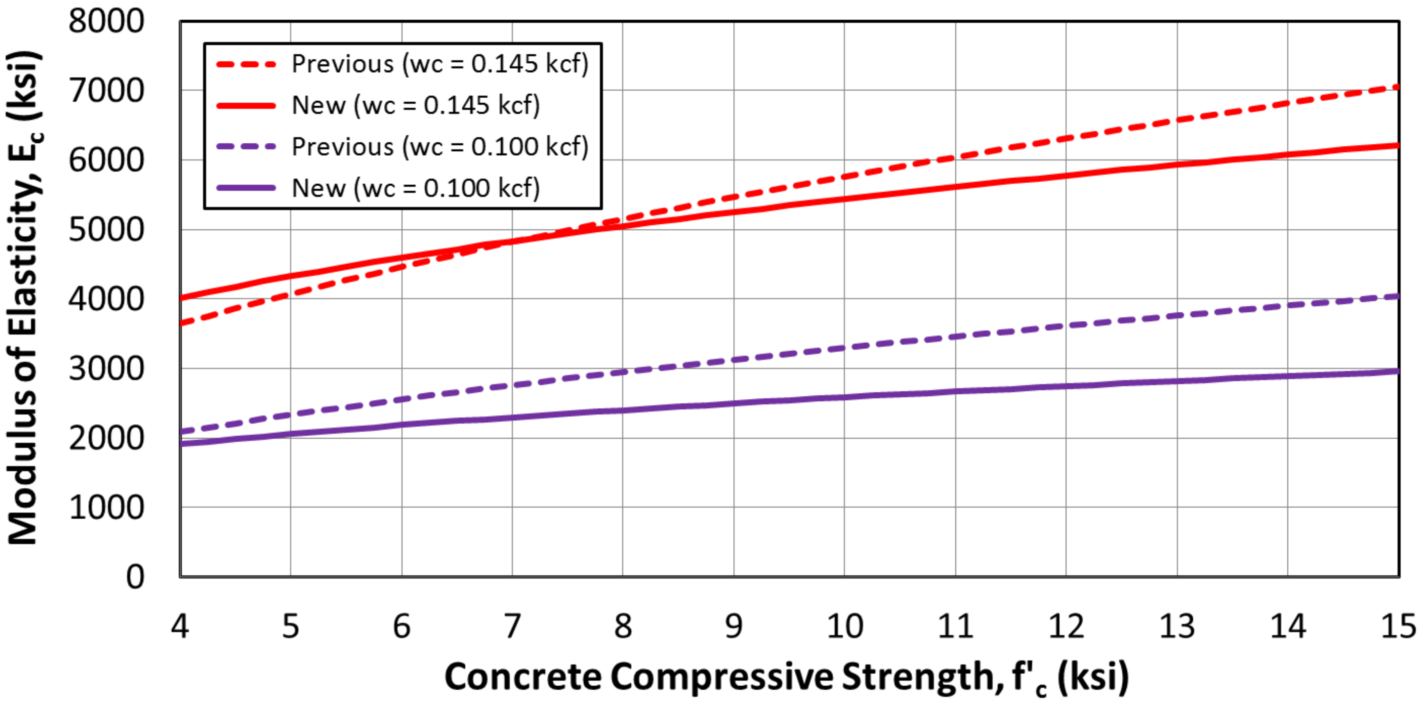
Material Properties

Modulus of elasticity, E_c – revision 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

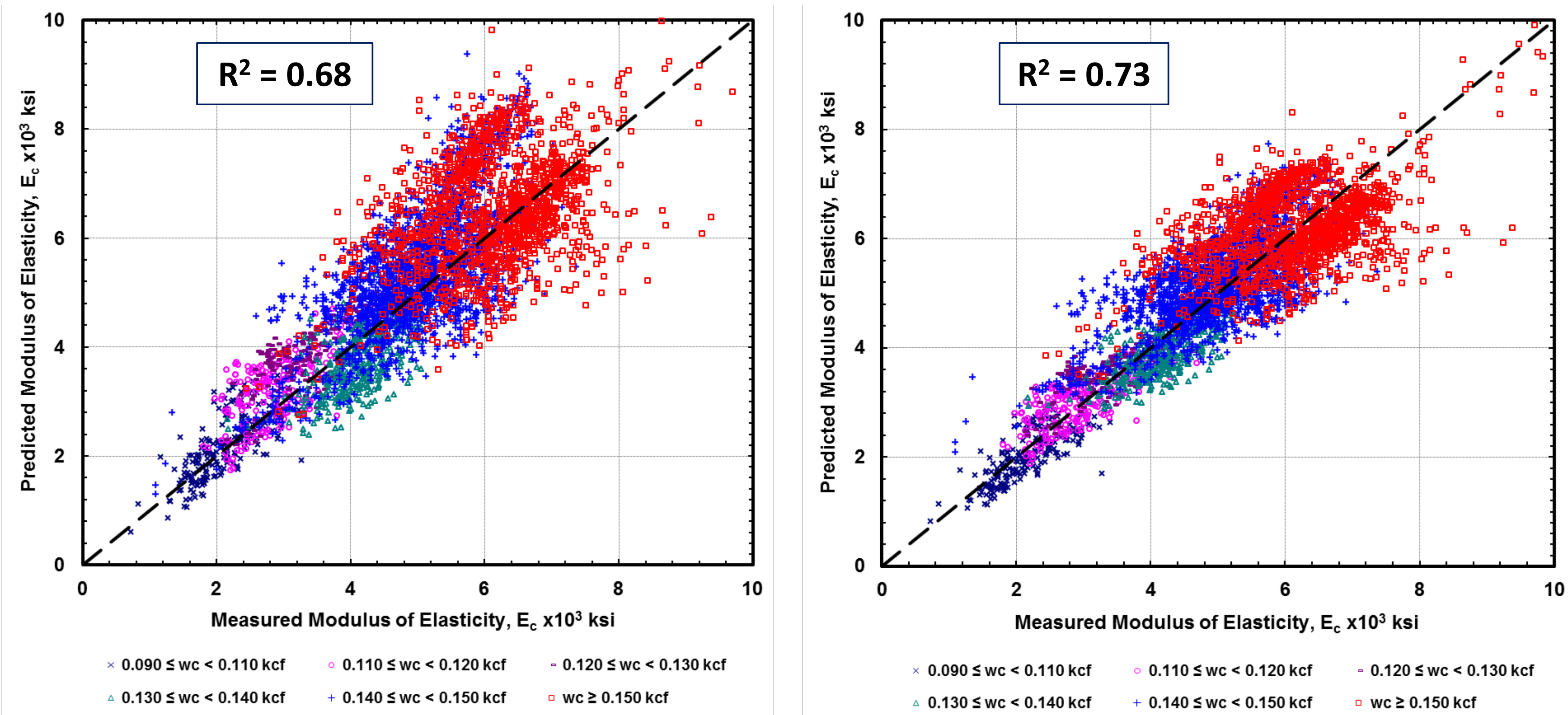
Predicted v. measured modulus of elasticity, E_c

Previous equation

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

New equation

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



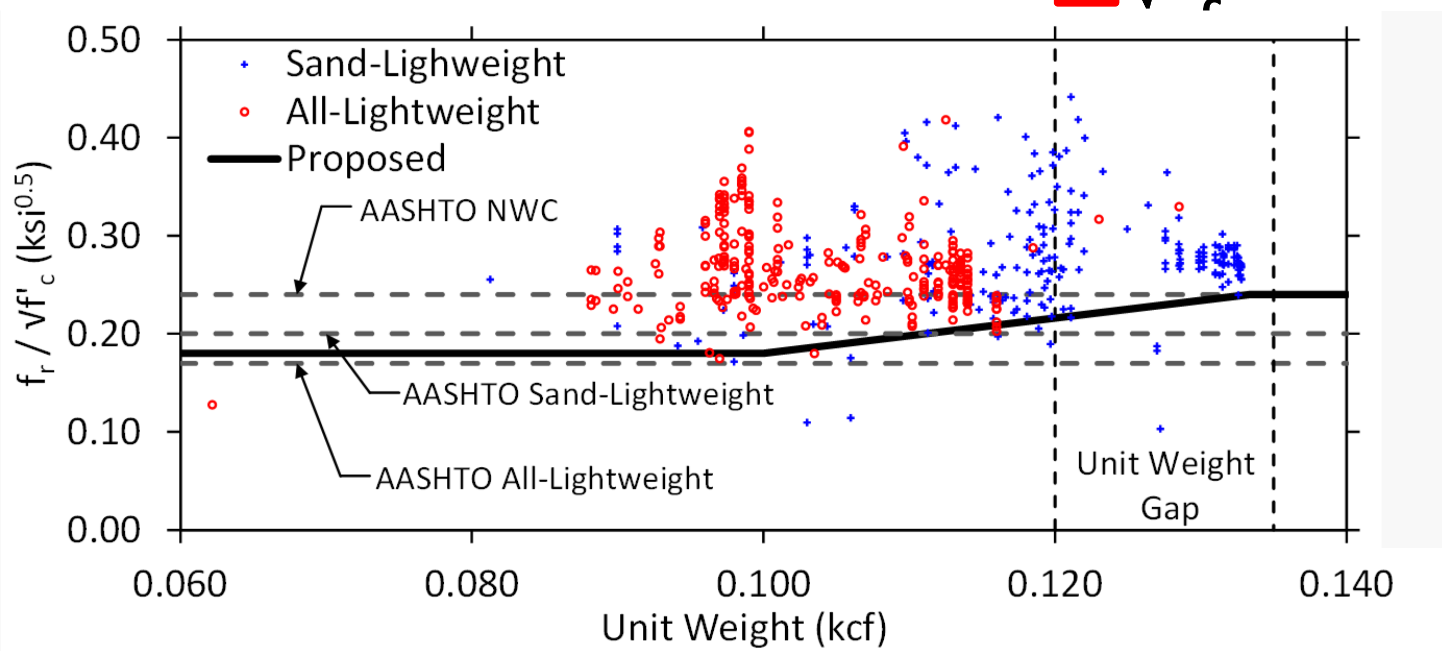
Measured data and figure for previous data are based on work of NCHRP 12-64 (Report 595)

Material Properties

Modulus of rupture, f_r

For normal-weight and lightweight concrete:

- **Except as specified below: $0.24\lambda\sqrt{f_c'}$**
- **When used to calculate the cracking moment of a member in Article 5.8.3.4.3: $0.20\lambda\sqrt{f_c'}$**



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Thank you!

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