

Design Related Issues with Lightweight Concrete

Reid W. Castrodale, PhD, PE
Castrodale Engineering Consultants, PC

2018 Virginia Concrete Conference

BRIDGE BREAKOUT SESSION

March 2, 2018

Introduction

Lightweight concrete (LWC) has a number of beneficial features including:

- **Improved design efficiency**
- **Reduced handling, hauling and erection costs**
- **Increased service life – less cracking, less permeable**

You should consider LWC for your next bridge design

But what do you need to know to use LWC?

Overview

Design requirements

- **AASHTO LRFD – 7th and 8th Editions**
- **VDOT**

Material properties

Specifications

Cost

Design Specifications

ACI 318 first mentioned LWC in 1947, but fully addressed design using LWC in 1963

AASHTO bridge design specifications have addressed LWC since at least 1973

Major revisions to the AASHTO LRFD regarding LWC were recently adopted

- **Revised equation for E_c better reflects behavior of LWC and high strength concrete (2014)**
- **Broad package of revisions related to LWC (2015)**

Changes should be incorporated in design programs, but designer should verify

Recent Revisions to LRFD regarding LWC

- Modulus of elasticity
- Definition of LWC
- Concrete density modification factor, λ
- Resistance factor, ϕ

Definition of LWC

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.

Definition of LWC

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.

- **Simplified: LWC contains LWA (AASHTO M 195)**
- **“Equilibrium density” not “air-dry unit weight”**
- **No gap between LWC & NWC ($LWC \leq 0.135$ kcf)**

Definition of LWC

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.”~~

- Simplified: Definitions of types of LWC are removed

Definition of NWC

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 (NWC > 0.135 kcf)**

Definition of NWC

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 (NWC > 0.135 kcf)
- Term “equilibrium density” added for lower value

Definition of LWC

Changes carried throughout specifications

- **Unit weights for computing dead load (Table 3.5.1-1)**
 - Removed entry for “sand lightweight”
 - Revised entry for “Lightweight” to 0.110 to 0.135 (kcf)
- **Compressive strength (5.4.2.1)**
 - Changed term “air-dry unit weight” to “equilibrium density”
- **Interface shear transfer (C5.8.4.1, C5.8.4.3)**
 - Removed terms “sand-lightweight” and “all-lightweight”
- **Brackets and corbels (5.13.2.4.2)**
 - Removed terms “sand-lightweight” and “all-lightweight”

Concrete Density Modification Factor, λ

Modification factor is provided to account for the assumed reduced tensile strength of LWC

- **In ACI 318 – λ factor**
- **In LRFD, factor was defined, but no variable assigned**
 - **Definition was repeated in each article where needed**
- **Factor was based on two types of LWC**
 - **0.85 for “sand LWC” (coarse LWA & NW sand)**
 - **0.75 for “all LWC” (coarse & fine LWA)**
 - **Interpolation was permitted between the two types**
 - **Other types not included**

But designers are only concerned with the concrete density, not the types of aggregate in the LWC mixture

Concrete Density Modification Factor, λ

Definition for λ was added in 2015 revisions

- **Definition is only in Article 5.4.2.8**
 - Previously defined in (most) sections where required
 - Eliminates duplication
- **Definition is based on density, w_c**
 - Not on type of concrete – sand or all LWC
- **The λ factor has been inserted in all equations where appropriate**
 - Removes concerns about proper application of factor

Simplifies and clarifies use of LWC

- **Easier for designers to use, and is clearly applied**

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:

$$\lambda = 4.7 f_{ct} / \sqrt{f_c'} \leq 1.0 \quad (5.4.2.8-1)$$

- Where f_{ct} is not specified:

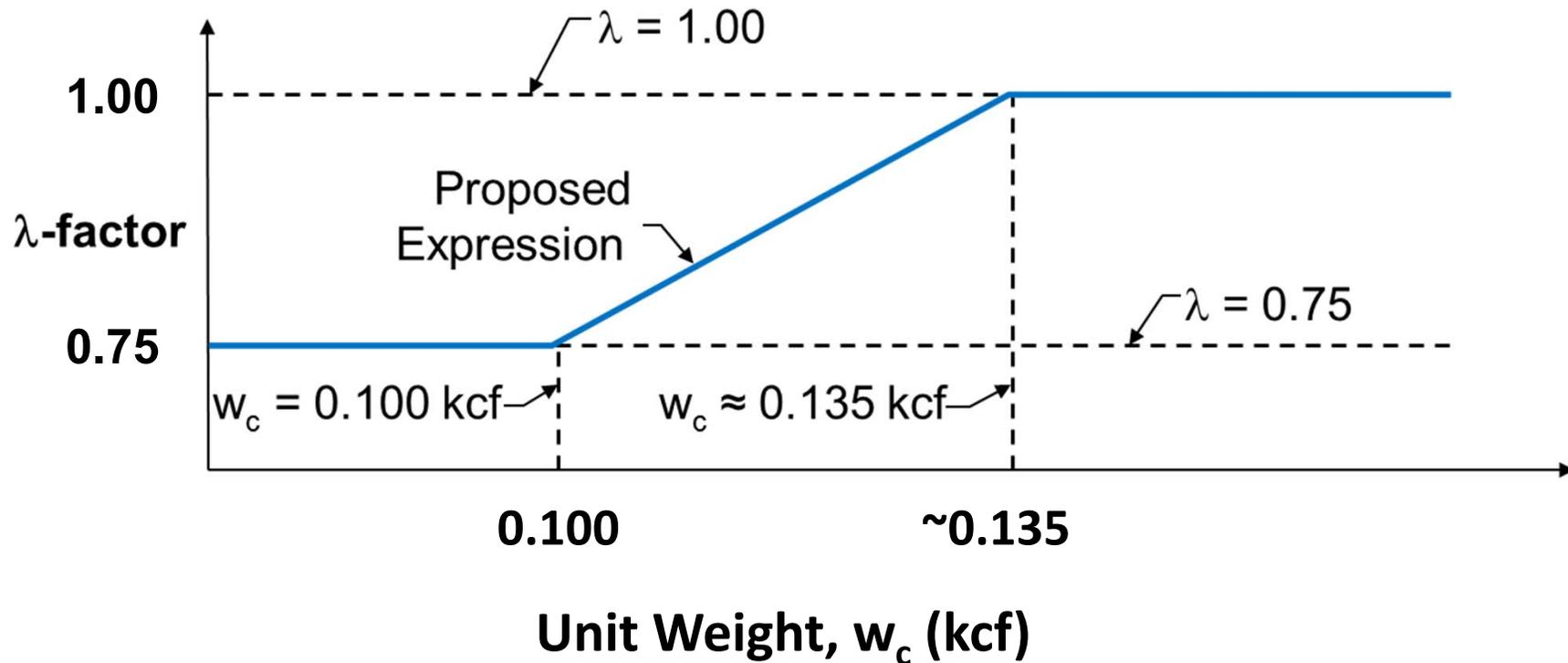
$$0.75 \leq \lambda = 7.5 w_c \leq 1.0 \quad (5.4.2.8-2)$$

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

Concrete Density Modification Factor, λ

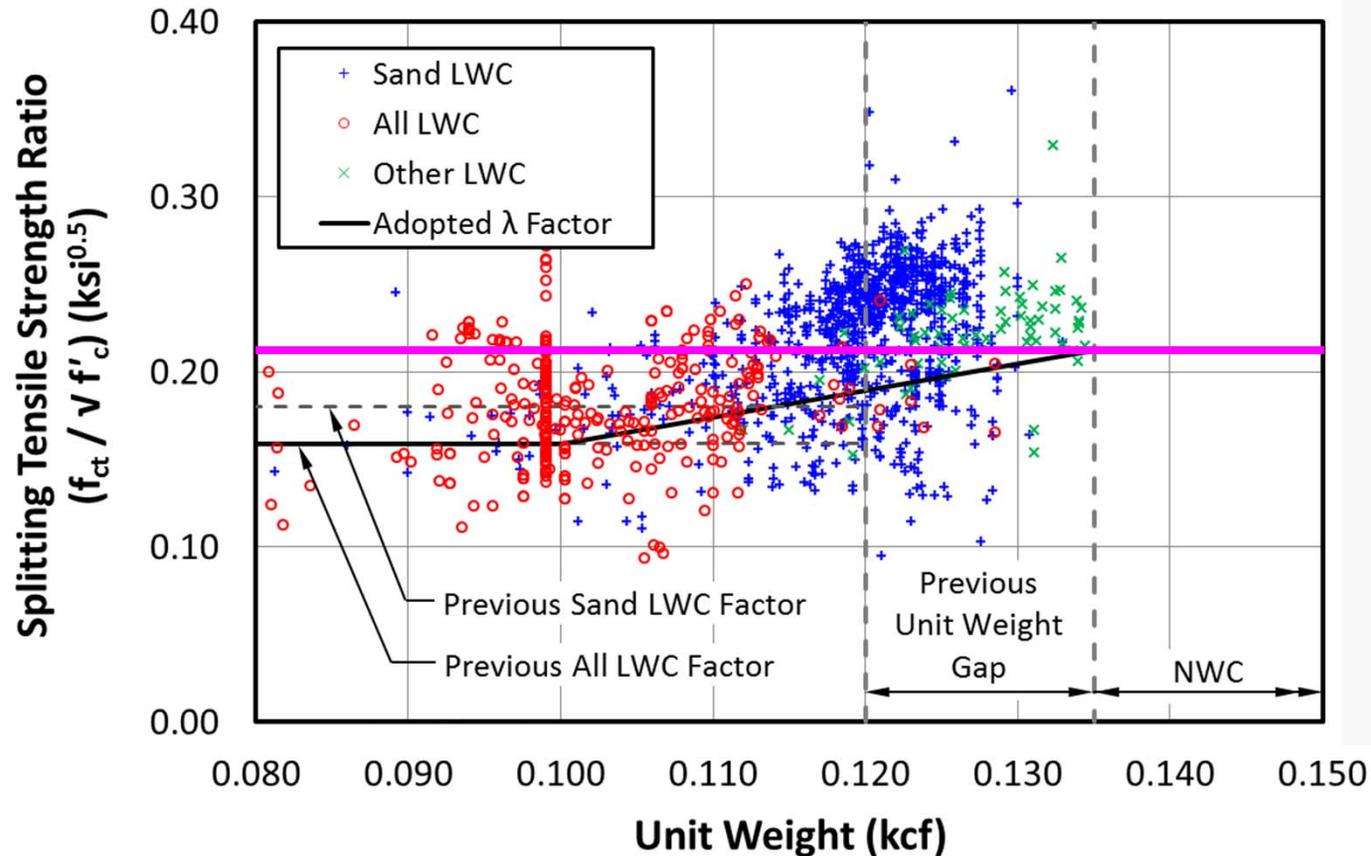
- Where f_{ct} is not specified:

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



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 $\lambda = 1.0$ line for NWC

Concrete Density Modification Factor, λ

Factor has been added to equations where needed

- Components of nominal shear resistance

$$V_c = 0.0316\beta\lambda\sqrt{f_c'}b_vd_v \quad (\text{LRFD Article 5.7.3.3 – 8}^{\text{th}} \text{ Ed.})$$

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

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

(LRFD Article 5.8.3.4.3 – 7th Ed.)

Concrete Density Modification Factor, λ

Factor has been added to equations where needed

- Minimum transverse reinforcement (LRFD Article 5.7.2.5 – 8th Ed.)

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

Concrete Density Modification Factor, λ

Factor has been added to equations where needed

- Development length of mild reinforcement (from LRFD Article 5.10.8.2.1a – 8th Ed.)

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

Factor for LWC moved
from numerator to
denominator

Concrete Density Modification Factor, λ

Factor has been added in some new locations

- Modulus of rupture, f_r (LRFD Article 5.4.2.6)

- 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: $0.20\lambda\sqrt{f'_c}$
(this expression is only in 7th Ed.)

Concrete Density Modification Factor, λ

Factor has been added in some new locations

Table 5.9.4.1.2-1 Tensile Stress Limits ... before Losses
(7th Ed.)

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

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

- In areas with bonded... $0.24 \lambda \sqrt{f_{ci}'} \text{ (ksi)}$

- For handling stresses... $0.158 \lambda \sqrt{f_{ci}'} \text{ (ksi)}$

Concrete Density Modification Factor, λ

Factor has been added in some new locations

Table 5.9.4.2.2-1 Tensile Stress Limits ... after Losses
(7th Ed.)

- **Other Than Segmentally Constructed Bridges**

- **Tension in Precompressed Tensile Zone,
Assuming Uncracked Sections**

- **For components with bonded...**

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

- **For components with bonded...**

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

Resistance Factor, ϕ

The LRFD Specifications introduced a different shear resistance factor for LWC when released in 1994

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

In 2011, shear resistance factor for LWC was increased

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

In 2015, shear resistance factor for LWC was set = NWC (LRFD Article 5.5.4.2 – 8th Ed.)

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

Resistance Factor, ϕ

Section 5.5.4.2.2 Segmental Construction (7th Ed.)

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 resistance factors are also now used for both NWC and LWC for segmental construction

Material Properties

Density, w_c

Compressive strength, f'_c

Tensile strength

Modulus of elasticity, E_c

Coefficient of thermal expansion

Creep and shrinkage

Concrete Density, w_c

Full range of potential design densities for LWC:

- **95 - 135 pcf**

Typically, the best balance of cost & performance:

- **110 - 125 pcf**
- **“Sand LWC” – LW coarse + NW fine (sand)**

Specifying Density of LWC

"Equilibrium density"

- **Density after moisture loss has occurred**
 - Used for long-term design dead load
- **Defined in ASTM C567**
 - Usually computed from mix design
- **“air-dry unit weight” is similar, but no longer used**

"Fresh density" or “plastic density"

- **Required as QC check during placement**
- **May be specified or provided by concrete supplier**
- **Density for handling loads at early age**

Specifying Density of LWC

In VDOT's *2016 Road and Bridge Specifications*

217.12—Low Shrinkage Class A4 Modified Concrete

Option (b)

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.

Specifying Density of LWC

In VDOT's *2016 Road and Bridge Specifications*

217.12—Low Shrinkage Class A4 Modified Concrete

Option (b)

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.

- **Maximum density is specified; no minimum needed**

Specifying Density of LWC

In VDOT's *2016 Road and Bridge Specifications*

217.12—Low Shrinkage Class A4 Modified Concrete

Option (b)

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.

- **Maximum density is specified; no minimum needed**
- **Fresh density is used – not equilibrium**
 - **Density loss with time may be minor, so is neglected**

Specifying Density of LWC

Route 198 over Harpers Creek Bridge

General Notes:

Concrete in prestressed concrete bulb-T's shall be Class A5 lightweight concrete with a maximum density of 115 lb/ft³ in accordance with the Special Provision for Lightweight Concrete for Beams. Concrete in superstructure including deck, rails and terminal walls; and substructure shall be Class A4 lightweight concrete with a maximum density of 105 lb/ft³ in accordance with the Special Provision for Lightweight Concrete.

Special Provisions (Deck):

The maximum concrete density shall be 105 lb/ft³ or as specified in the plans. Lightweight coarse aggregates shall be in conformance with AASHTO M195 (ASTM C330). Lightweight fine aggregate (LWFA) meeting the requirements of ASTM C1761 shall be used for achieving the density.

- **Recommend clarifying the type of density intended**
- **Good that just maximum value was specified**

Specifying Density of LWC

Density for computing dead load for reinforced concrete

- **Must add an increment to the concrete density that reflects the weight of the reinforcement**
- **Usually use 5 pcf, but may not be sufficient in some situations**
- **Recommend indicating in the contract documents the density of reinforced concrete used for dead loads**

Design Compressive Strength, f'_c

LWC compressive strengths available for design

- 5 ksi – possible with most LWAs
- 7 to 10 ksi – possible with some LWAs
- Local projects have used 8.5 ksi
- VDOT IIM-S&B-80.5 limits strength of LWC to 8 ksi; strengths up to 10 ksi require a design waiver
- GDOT and WSDOT projects have used up to 10 ksi

Densities generally increase as strength increases

- Contact LWA and/or concrete suppliers to confirm desired strength and density

Tensile Strength

Design specifications have assumed that the tensile strength for LWC is lower than for NWC for same f'_c

- Indicated by using λ to reduce tensile strength

Modulus of rupture, f_r – often used for tensile strength

- $0.24 \lambda \sqrt{f'_{ci}}$ (LRFD Article 5.4.2.3)
- Related to bending rather than direct tension

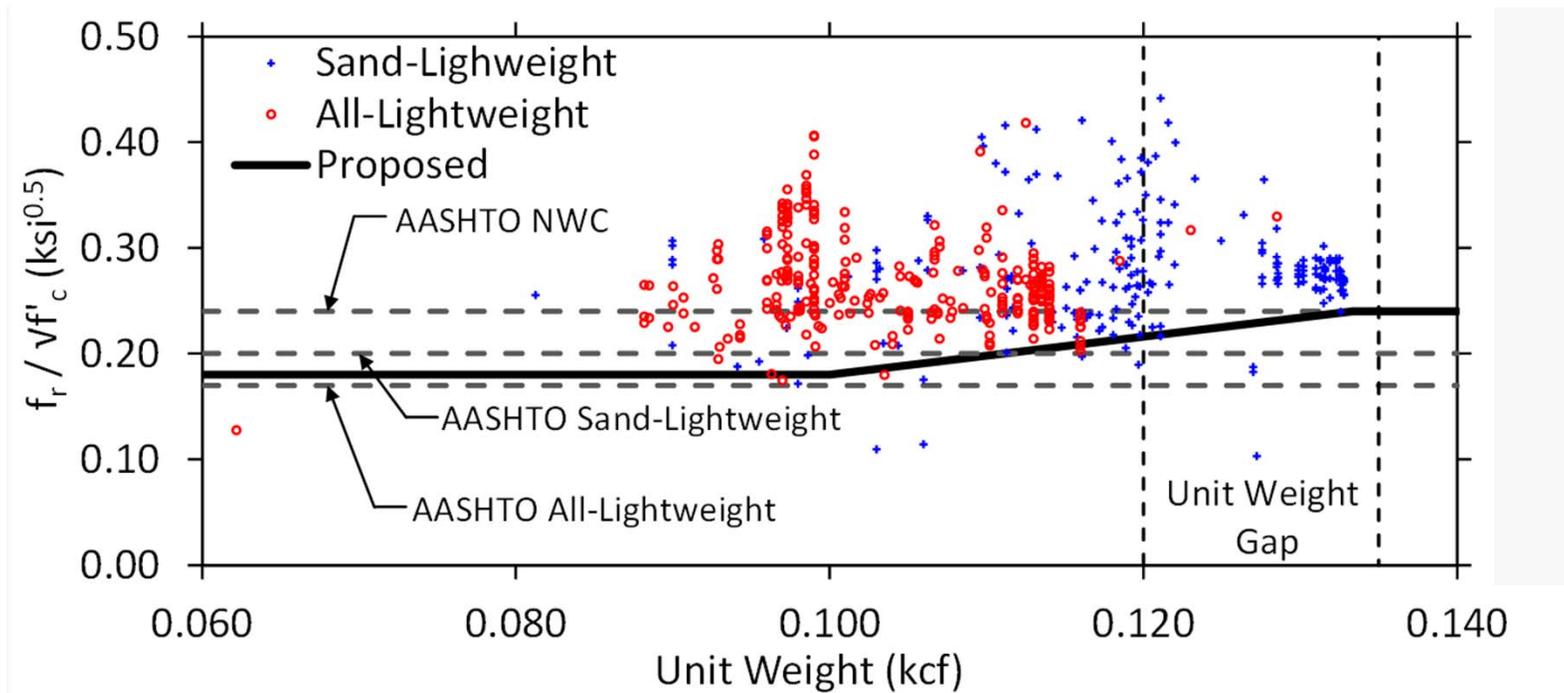
Splitting tensile strength, f_{ct} , is used to evaluate tensile strength of LWC

- $(1/4.7) \lambda \sqrt{f'_{ci}} \approx 0.21 \lambda \sqrt{f'_{ci}}$ (LRFD Article 5.4.2.8 – 8th Ed.)
- Can be used to determine λ as discussed earlier

Modulus of rupture, f_r

For NWC and LWC (LRFD Article 5.4.2.6):

- 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 (7th Ed.): $0.20\lambda\sqrt{f'_c}$



Modulus of rupture, f_r

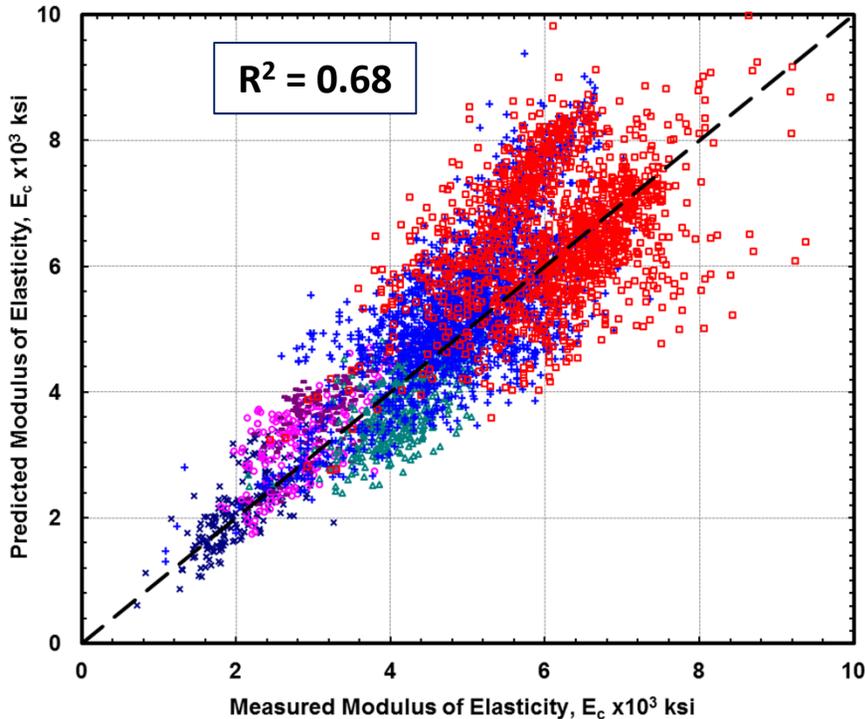
Predicted v. measured modulus of elasticity, E_c

Previous equation

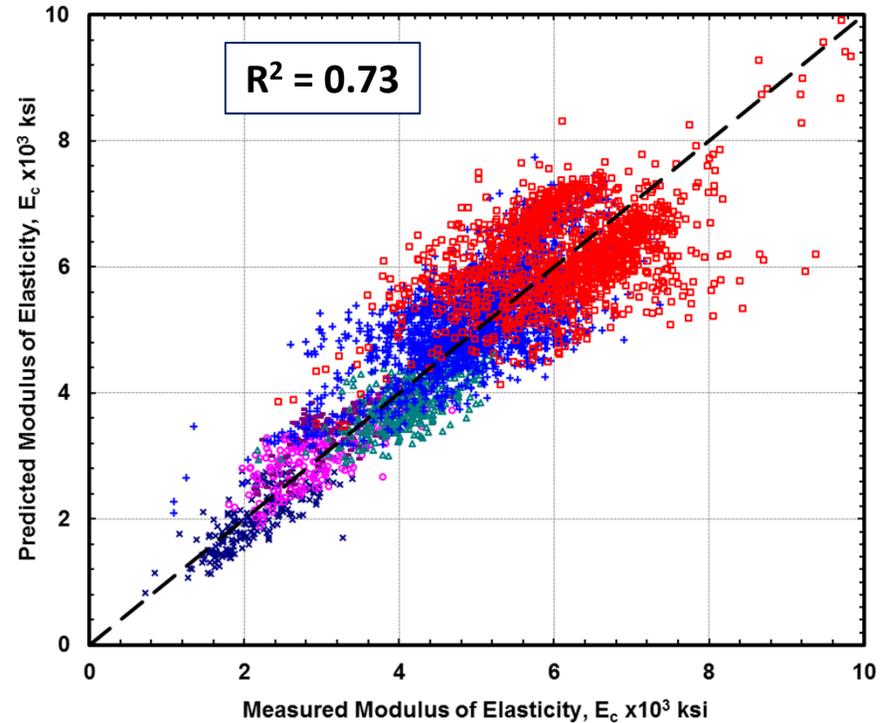
$$E_c = 33,000 K_1 w_c^{1.5} f'_c{}^{0.5}$$

New equation

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



- \times $0.090 \leq w_c < 0.110$ kcf
- \circ $0.110 \leq w_c < 0.120$ kcf
- $-$ $0.120 \leq w_c < 0.130$ kcf
- \triangle $0.130 \leq w_c < 0.140$ kcf
- $+$ $0.140 \leq w_c < 0.150$ kcf
- \square $w_c \geq 0.150$ kcf



- \times $0.090 \leq w_c < 0.110$ kcf
- \circ $0.110 \leq w_c < 0.120$ kcf
- $-$ $0.120 \leq w_c < 0.130$ kcf
- \triangle $0.130 \leq w_c < 0.140$ kcf
- $+$ $0.140 \leq w_c < 0.150$ kcf
- \square $w_c \geq 0.150$ kcf

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

Splitting Tensile Strength, f_{ct}

Tests show that LWC has splitting tensile strength close to or exceeding tensile strength assumed for NWC

- NCHRP Report 733 found the average f_{ct} for LWC girders & decks was $0.25 \sqrt{f_{ci}'} > \sqrt{f_{ci}'} / 4.7 \approx 0.21 \sqrt{f_{ci}'}$

When data shows that the tensile strength for LWC is not less than expected for NWC

- Designers should consider specifying f_{ct} for LWC = f_{ct} expected for NWC

$$f_{ct} \geq \sqrt{f_{ci}'} / 4.7 \text{ (ksi) or } 6.7 \sqrt{f_{ci}'} \text{ (psi)} \Rightarrow \lambda = 1.0$$

- Especially useful for elements where shear governs
- Should work for a range of LWA sources

Modulus of Elasticity, E_c

Modulus is lower for LWC because LWA is porous and less stiff

New LRFD equation to estimate E_c (2014):

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

- Includes density of concrete, w_c
- Aggregate modification factor, K_1 , can be taken as 1.0 unless other information is available
 - $K_1 = 1.0$ is a reasonable value for local LWA

New equation reduces modulus of LWC more than old equation

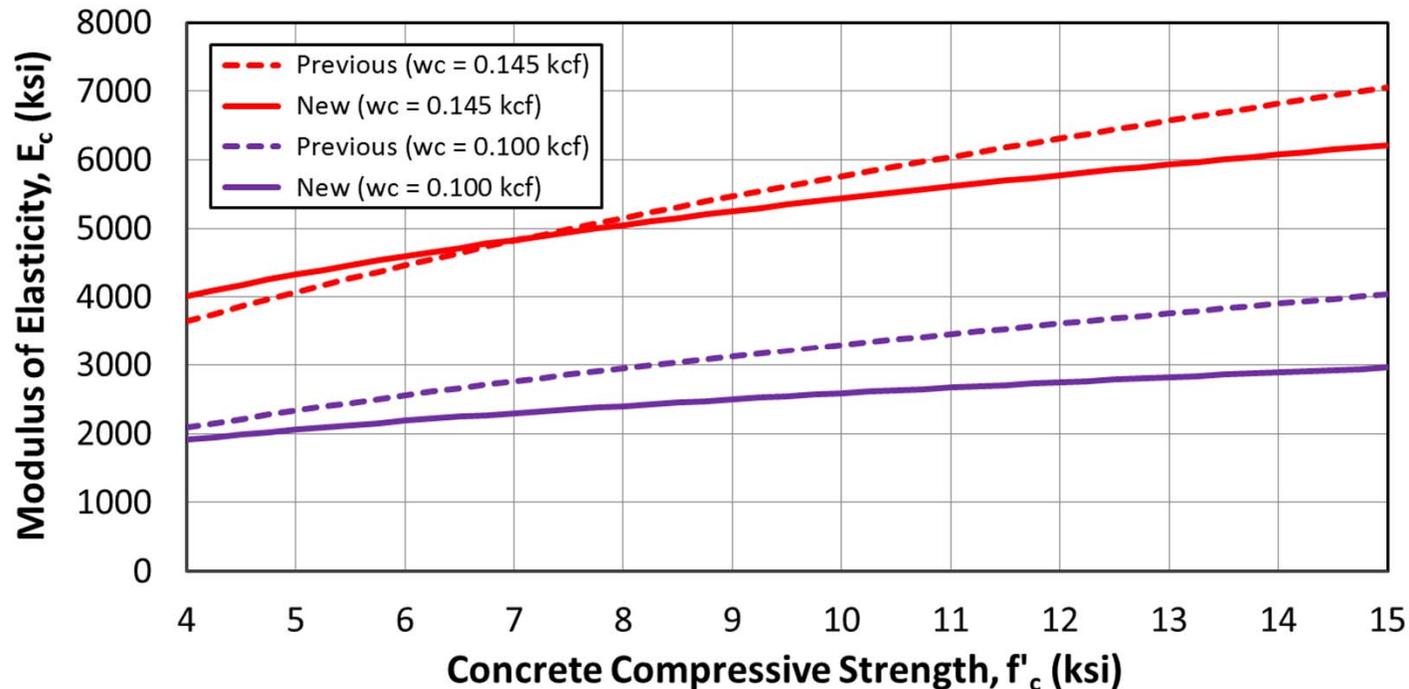
Modulus of Elasticity, E_c

Revised equation adopted in 2014

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

Previous equation:

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



Coefficient of Thermal Expansion

LWC has lower coefficient of thermal expansion

- Coefficient of thermal expansion for LWC and NWC ($\mu\epsilon/^\circ\text{F}$) (from Byard & Schindler 2010)

Aggregate Type	NWC	Sand LWC	All LWC
NWA	6.2	--	--
Slate LWA	--	5.1	4.3
Clay LWA	--	5.1 83%	4.0 66% - Average
Shale LWA	--	5.2	4.0

- Not in specifications – can use test results
- Other thermal properties are also modified

Creep & Shrinkage

Several research projects have evaluated creep and shrinkage, as well as prestress losses, for LWC prestressed concrete girders

They have found

- Total creep and shrinkage deformations for LWC are not significantly different from NWC of the same compressive strength and quality
- Equations in the AASHTO LRFD for estimating creep and shrinkage effects can be used for LWC without modification

LWA Specifications

LWA aggregate properties for structural concrete are governed by AASHTO M 195 or ASTM C330

“Standard Specification for Lightweight Aggregates for Structural Concrete”

- Covers manufactured and natural LWAs



LWA Specifications

LWA should be required to meet requirements for NWA – except for grading

- **Most LWAs should be able to meet the other physical requirements for NWA**

Using LWA to make LWC

LWA is a just a lighter rock!

When LWA is used to make LWC

- **Same batch plants and mixing procedures**
- **Same admixtures**
- **Can use same mix design procedures**
- **“Roll-o-meter” for measuring air content**

LWA has higher absorption than NWA

- **Prewet aggregate, especially for pumping**

Density is specified & checked, so more QC attention

LWC Specifications

Generally, the only structural properties that need to be specified are density and compressive strength

Durability properties can also be specified

Other structural properties may be specified if required for the design, such as modulus of elasticity or splitting tensile strength, f_{ct}

- Specifying f_{ct} can avoid use of concrete density reduction factor, λ

Specify only material properties actually required for the particular design

Beware of copied special provisions!

Specifications related to Construction

Moisture conditioning (prewetting) LWA

- Especially important for concrete placed by pumping

Method for prewetting LWA is not critical

- Some LWA is vacuum saturated or requires soaking
- Other LWA can be prewetted just by sprinkling
- Depends on absorption of the LWA

Specifications should require that the minimum absorption recommended by LWA supplier be consistently achieved prior to batching

- Methods and duration of prewetting are left to concrete supplier

Typical Testing Issues for Special Provisions

Density testing

- Standard Specs may not include density testing and consequences of lack of conformance

LA abrasion

Freezing and thawing

Typical Testing Issues for Special Provisions

LA Abrasion Test Modification

- Recommend modifying procedure to charge cylinder with volume of LWA = typ. volume of NWA
- Using standard weight of LWA to charge cylinder results in over-filling
- Results may not be a realistic indication of LWA performance

Freezing and Thawing Requirements

AASHTO M 195 / ASTM C330 specifications include revised testing procedures for ASTM C666 tests of LWC

- **Allow specimens to dry before testing**
- **Neglecting these procedures can lead to poor test results that do not reflect field performance**

Since modifications to testing methods are not in ASTM C666, they can be missed by testing labs not familiar with LWC

- **Recommend including reference to modifications in special provisions**

Batching

Procedure for making free moisture corrections for LWA is identical to NWA

- Absorbed water does **NOT** affect batch water, so is not included in adjustment
- Absorbed water does not come out of LWA until after set
- Towel dry method is an effective way to achieve WSD condition for coarse LWA

Delivering & Placing

Air content is key to achieving specified density

- **Care must be taken to ensure target air content is reached and maintained**
- **Good concrete placement techniques must be used so air not driven out**

The quantity of mix water affects the density

- **Concrete supplier should not hold back water when batching**

QC in Field – Air Content

Roll-o-meter is specified

- **Pressure meter is not allowed**

With good control of batching, can get good indication of air content with unit weight

In some cases, using both roll-o-meter and pressure meter has been successful

- **Use both initially to obtain a calibration**
- **Use pressure meter for periodic checks**
- **If pressure meter gives questionable result, then run roll-o-meter**

Pumping

LWC has been pumped successfully for many bridges and buildings

- **Can be pumped vertically to top of tall buildings**

Some states disallow pumping of LWC

- **Not necessary and limits the application of LWC**

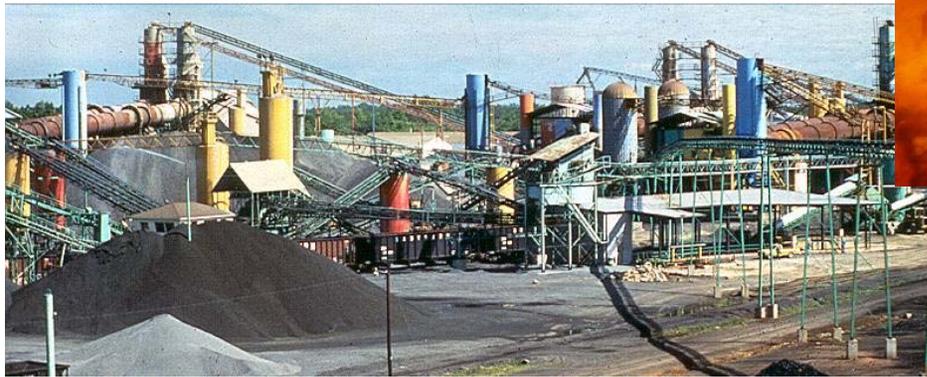
Key is proper prewetting of LWA

- **LWA does not have to be vacuum or thermally saturated for successful pumping as mentioned in FHWA report (1985)**

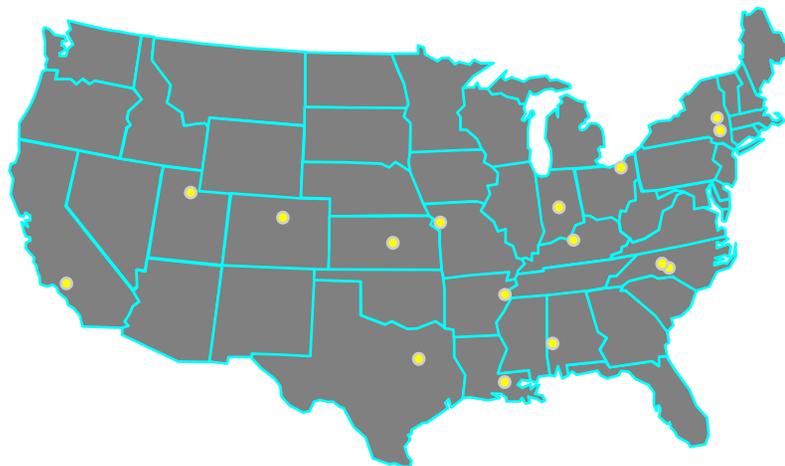
Cost of LWA and LWC

Increased cost of LWA

- High temperature processing



- Shipping from the manufacturing plant



Cost of LWA and LWC

LWA costs more than NWA; LWC cost more than NWC

But, as with any construction material, it is difficult to provide any firm idea of cost

- **Many variables affect cost**
- **Bid tabs are not much help**

02/25/2015, 2 bidders for a quantity of 170.2 CY.

Bids: \$1,450 & \$1,310 per CY.

12/18/2013, 3 bidders for a quantity of 2586.2 CY.

Bids: \$540, \$730 & \$750 per CY.

02/27/2013, 3 bidders for a quantity of 157 CY.

Bids: \$700, \$450 & \$820 per CY.

05/25/2011, 3 bidders for a quantity of 306 CY.

Bids: \$700, \$681 & \$812 per CY.

Cost of LWA and LWC

Cost premium for LWC over NWC

- **Ranges from 25% to 40% depending on the market in Virginia**
- **Cost of LWC may be affected by how familiar the concrete supplier is with LWC**
 - **In metropolitan areas, most suppliers have a lot of experience with LWC for buildings**
 - **For rural projects, suppliers may not be familiar with LWC. However, it is not rocket science**
- **Cost of LWC may be affected by perceived risk**
 - **More QC is required**
 - **Density is another factor that could lead to rejection**

Thank you!

Reid W. Castrodale, PhD, PE

Castrodale Engineering Consultants, PC

reid.castrodale@castrodaleengineering.com

704-904-7999

Supported by

All Rocks Are NOT Created Equal...

STALITE
STRUCTURAL
Lightweight Aggregate