Material Properties of Lightweight Concrete for Bridge Design

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2015 Western Bridge Engineers' Seminar

Session 6C – BRIDGE MATERIALS AND DETAILS

September 10, 2015

ESCSI

Expanded Shale, Clay and Slate Institute

Rotary Kiln Structural Lightweight Aggregate

Introduction

Lightweight concrete (LWC) has been used in bridges in the US since the 1930s

But many designers are still reluctant to use it

One typical reason for reluctance:

- Uncertainty about the material properties of LWC to be used for bridge design

Recent field experience and testing have demonstrated that the mechanical properties of LWC are well-suited for design of bridges

Introduction

Presentation discusses material properties of LWC important for structural design of bridges

Properties discussed include:

- **compressive strength**
- **splitting tensile strength**
- **modulus of elasticity**
- **creep and shrinkage**

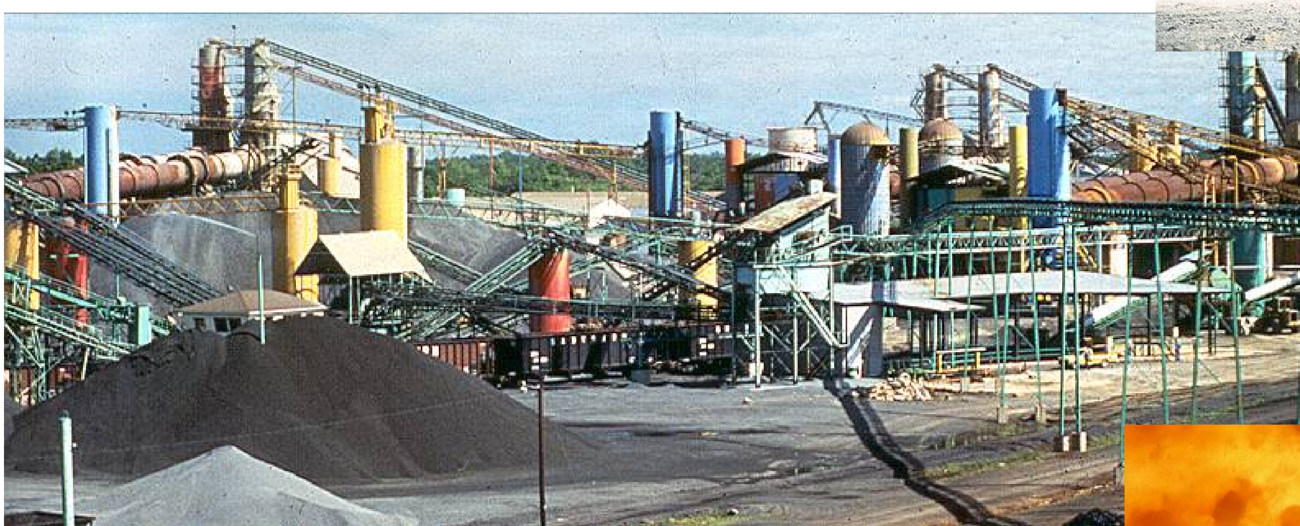
Recent changes to AASHTO LRFD for LWC are included

The impact of LWC properties on bridge design and performance is also presented

LWA is a manufactured product

Raw material is shale, clay or slate

Heated in kiln to about 2200 deg. F



Gas bubbles form in softened material

Gas bubbles remain after cooling

Clinker is crushed and screened

ESCS Manufacturing Plants in US

16 plants in the US

See www.escsi.org for member company locations

Relative Density of LWA vs. NWA

Relative density for rotary kiln expanded LWA

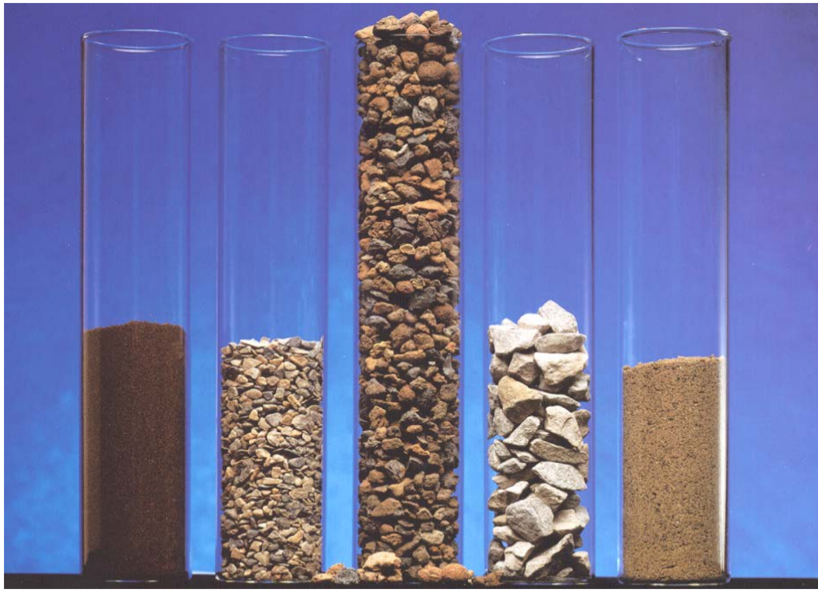
- **Range from 1.3 to 1.6**

Relative density for NWA

- **Range from 2.6 to 3.0**

Twice the volume for same mass

Half the mass for the same volume



1 lb. of each aggregate

LWA is 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

Visit ESCSI website or contact LWA supplier for more info on properties of LWA and LWC

Material Properties for LWC Design

- Density
- Compressive strength
- Modulus of elasticity
- Tensile strength
- Creep & Shrinkage
- Coefficient of thermal expansion
- Shear
- Development of reinforcement
- Strength limit state
- Prestress losses

Data for LWC girders at Concrete Tech

Concrete Tech has recently developed and used a high-strength LWC girder mix

- Design compressive strength of 10.6 ksi based on analysis of production cylinder data
- Fresh density target was 123 pcf with max of 128 pcf
- Used for 3 PS concrete girder projects in WA
- A large body of material property data has been collected for this LWC mix
- Data will be presented and published at PCI's National Bridge Conference in March 2016 by Chapman & Castrodale (2016)

Spectrum of Concrete Density

Definitions for "All LWC" and "Sand LWC" in 7th Edition of AASHTO LRFD Specs and in ACI 318

All LWC	Sand LWC	NWC
0.090 – 0.105	0.110 - 0.125	0.135 - 0.155
LW Fine	NW Fine	NW Fine
LW Coarse	LW Coarse	NW Coarse

- Density ranges shown are approximate (kcf)
- Sand LWC is most common type of LWC
  - Density depends on LWA type & other mix requirements

Spectrum of Concrete Density

New definition for LWC has been adopted for LRFD Specs: LWC contains LWA (AASHTO M 195)

Lightweight Concrete	NWC
[0.095 to] < 0.135	0.135 - 0.155
LW Fine ⇔ NW Fine	NW Fine
LW Coarse ⇔ NW Coarse	NW Coarse

- No more types: “all LWC” and “sand LWC”
- Designer specifies the density
  - Ready mix supplier develops mix to meet requirements
  - Depends on LWA type & other mix requirements

Specifying Density of LWC

"Equilibrium density" of LWC usually specified

- Density after moisture loss has occurred
- Defined in ASTM C 567
  - Method to compute from mix design is given

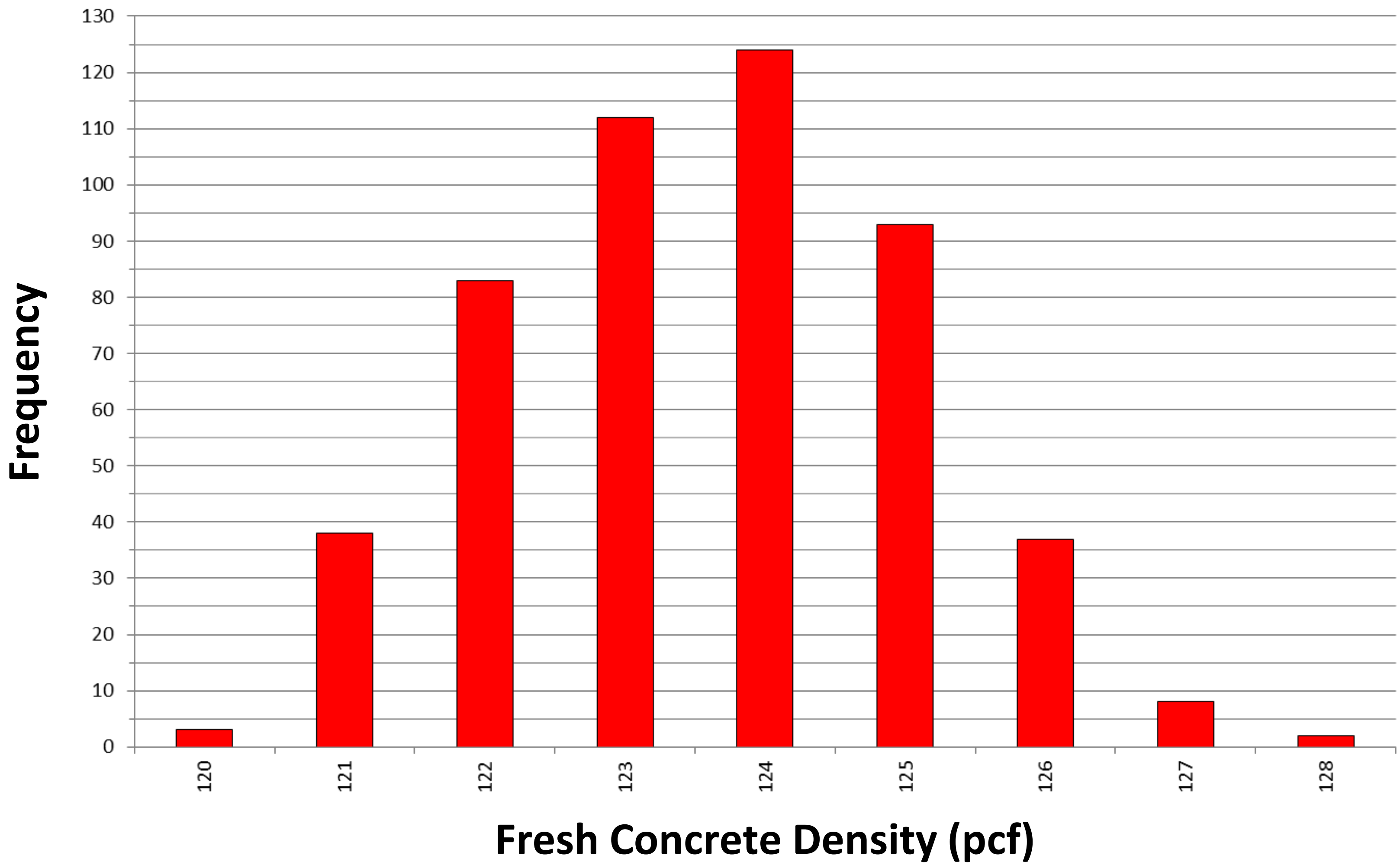
"Fresh density" needed for QC during casting

- Supplier may establish fresh density
- Designer may specify a fresh density
  - Must correspond to specified equilib. density
- Use for handling loads at early age

Allowance for reinforcement must be added when computing dead loads (typically taken as 5 pcf)

Fresh Density

Data from Concrete Tech LWC girders – ASTM C138



Design Compressive Strength, f'_c

Minimum compressive strength by ASTM C330 for structural LWA

- 2,500 psi

Most LWAs can achieve

- 5,000 psi

Some LWAs may achieve

- 7,000 to 10,000 psi

Densities generally increase as strength increases

Contact LWA and/or ready mix suppliers to determine availability of mix with desired strength and density

Strength & Density of Concrete

Equilibrium Densities for LW and NW Concrete

Concrete Strength, f'_c	Sand LWC	NWC	% Reduction in Density
3 ksi	112 pcf	143 pcf	21.7%
4.5 ksi (Deck)	110 pcf	145 pcf	24.1%
6 ksi	114 pcf	146 pcf	21.9%
8 ksi	117 pcf	148 pcf	20.9%
10 ksi	122 pcf	150 pcf	18.7%

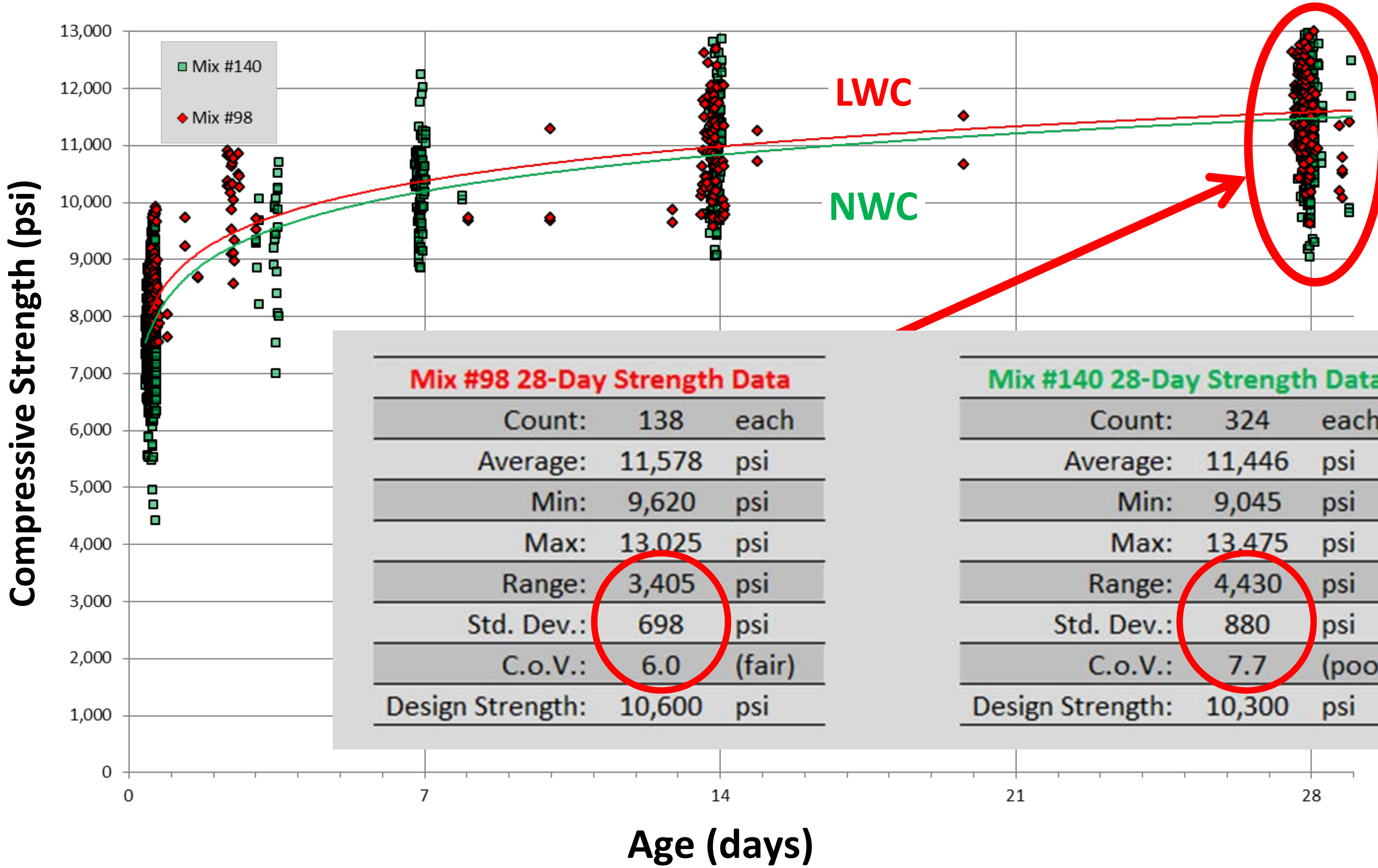
Notes:

LWC densities are for selected mixes from one LWA supplier

NWC densities computed using expression in LRFD Table 3.5.1-1

Design Compressive Strength, f'_c

Data from Concrete Tech LWC girders – ASTM C39



Mix #98 28-Day Strength Data		
Count:	138	each
Average:	11,578	psi
Min:	9,620	psi
Max:	13,025	psi
Range:	3,405	psi
Std. Dev.:	698	psi
C.o.V.:	6.0	(fair)
Design Strength:	10,600	psi

Mix #140 28-Day Strength Data		
Count:	324	each
Average:	11,446	psi
Min:	9,045	psi
Max:	13,475	psi
Range:	4,430	psi
Std. Dev.:	880	psi
C.o.V.:	7.7	(poor)
Design Strength:	10,300	psi

Modulus of Elasticity, E_c

Modulus is lower for LWC because LWA is less stiff

New equation to estimate E_c was adopted in 2014:

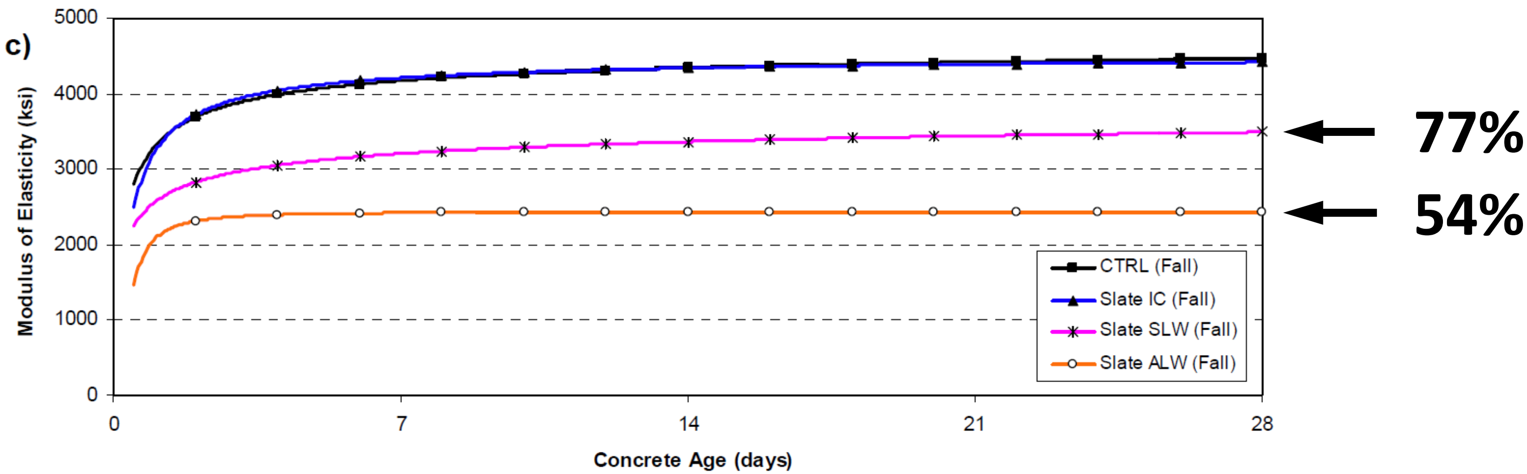
$$E_c = 121{,}000\ K_1\ w_c^{2.0}\ f'^{\,0.33}_c \qquad (5.4.2.4\text{-}1)$$

Assuming f'_c = 6 ksi & K_1 = 1.0		$E_c/E_{c\ NWC}$
• For w_c = 0.145 kcf:	E_c = 4,595 ksi	1.00
• For w_c = 0.130 kcf:	E_c = 2,890 ksi	0.80
• For w_c = 0.115 kcf:	E_c = 2,890 ksi	0.63
• For w_c = 0.100 kcf:	E_c = 2,186 ksi	0.48

Reduction is now greater with larger exponent on w_c

Modulus of Elasticity, E_c

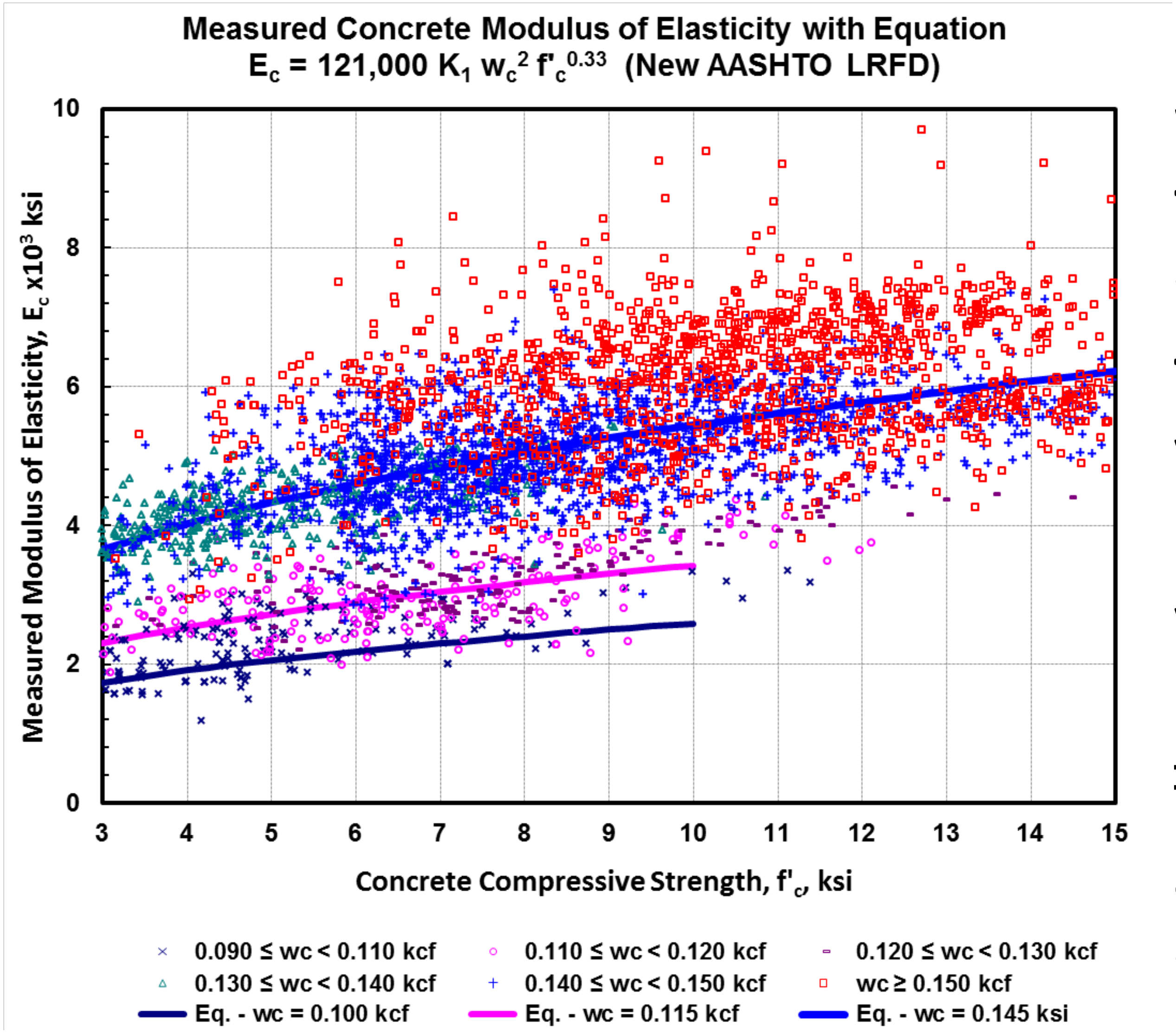
Data from study by Byard and Schindler (2010)



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

- Sand LWC: $(120/145)^2 = 0.68$
- All LWC: $(105/145)^2 = 0.52$
- Note that reduction in E_c from w_c does not depend on f'_c

Modulus of Elasticity, E_c



Measured data were collected as part of NCHRP 12-64 (Report 595)

We must recall that the equation is only an estimate

There is significant variability in E_c for all unit weight ranges

Variation from calculated can easily be $\pm$ 20%

Strong NWAs can also produce low E_c mixes

Modulus of Elasticity, E_c

For an NCDOT project, E_c data for similar deck and girder mixes were reviewed to determine K_1 values for LRFD Eq. 5.4.2.4-1 (old version) Castrodale & Hanks (2015)

$K_1 = 0.85$ was used for the girder concrete

- Measured E_c was close to, but always greater than, the computed modulus for all cylinders tested

If default value of $K_1 = 1.0$ had been used in design

- Measured E_c would be 10 to 15% < the assumed E_c
  - Well within expected variation for E_c

Use of $K_1 = 1.0$ appears reasonable for LWC designs

- NCHRP 733 came to same conclusion

Tensile Strength

Design specifications have assumed that the tensile strength for LWC is lower than for NWC

Reduction factors have been included in the design specifications to account for this

- **Factors can be based on splitting tensile strength, f_{ct}, which represents the tensile strength of LWC**
- **More typically, reduction factors were used that were based on concrete type: all or sand LWC**
- **Major update to LRFD related to LWC was just adopted that addresses these factors**

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 NWC is used, λ shall be taken as 1.0.**
- **Assumed f_{ct} for NWC = $\sqrt{f'_c}$ /4.7 (ksi) $\approx$ 6.7 $\sqrt{f'_c}$ (psi)**

Concrete Density Modification Factor, λ

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

- **Definition is based only 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**

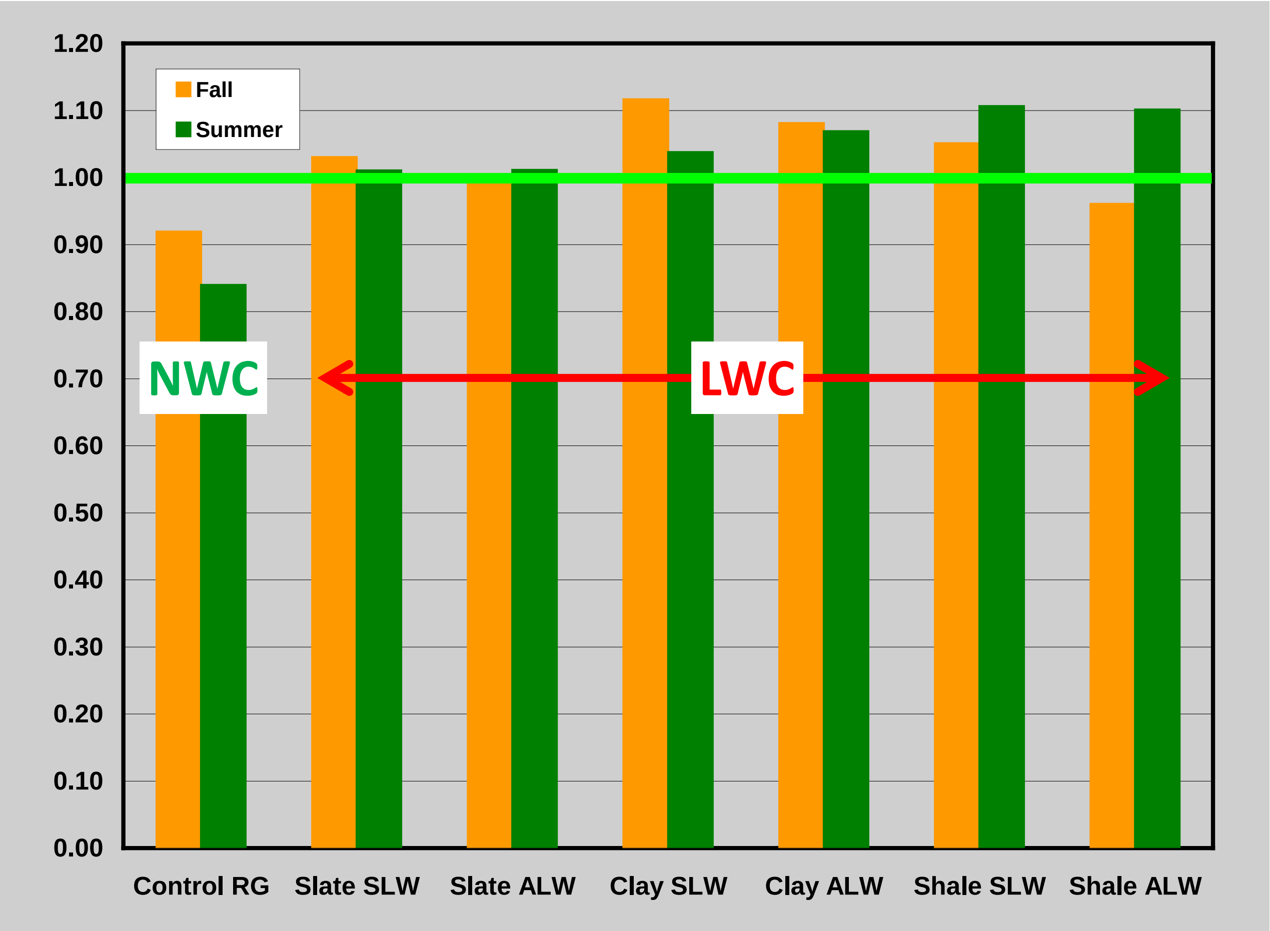
Tensile Strength

Recent tests demonstrate that LWC has tensile strength close to or exceeding strength assumed for NWC

- **10 ksi PS girder mix at Concrete Tech**
  - Measured f_{ct} = 700 psi at 28 days
  - $6.7 \sqrt{f'_c} = 670$ psi $\Rightarrow$ could use $\lambda = 1.0$
- **NCHRP Report 733**
  - Average f_{ct} for LWC was $0.25\sqrt{f'_c} > f'_c/4.7 \Rightarrow$ use $\lambda = 1.0$
- **Study by Byard & Schindler (2010)**
  - 4.5 ksi bridge deck mixes using LWA from 3 sources
  - Average f_{ct} for each LWC was $> f'_c/4.7 \Rightarrow$ use $\lambda = 1.0$
  - Average f_{ct} for NWC control mixture made with river gravel was $< f'_c/4.7$ [see next slide]

Tensile Strength

$$\frac{\text{Measured } f_{ct}}{6.7\sqrt{f'_c}}$$



Data from Byard & Schindler (2010)

- **LWC reached NWC f_{ct} - only 1 exception $\Rightarrow \lambda \approx 1.0$**
- **NWC was less than expected in this case $\Rightarrow \lambda < 1.0$**

Tensile Strength

Since current data indicate that the assumed reduction in tensile strength for LWC is not occurring

- **Designers should consider specifying**

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

- **Especially for elements where shear governs design**

When specified, the f_{ct} requirement is intended for mix design qualification

- **Test should not be used for field acceptance**
- **Consult local LWA and/or ready mix suppliers**

Creep and Shrinkage

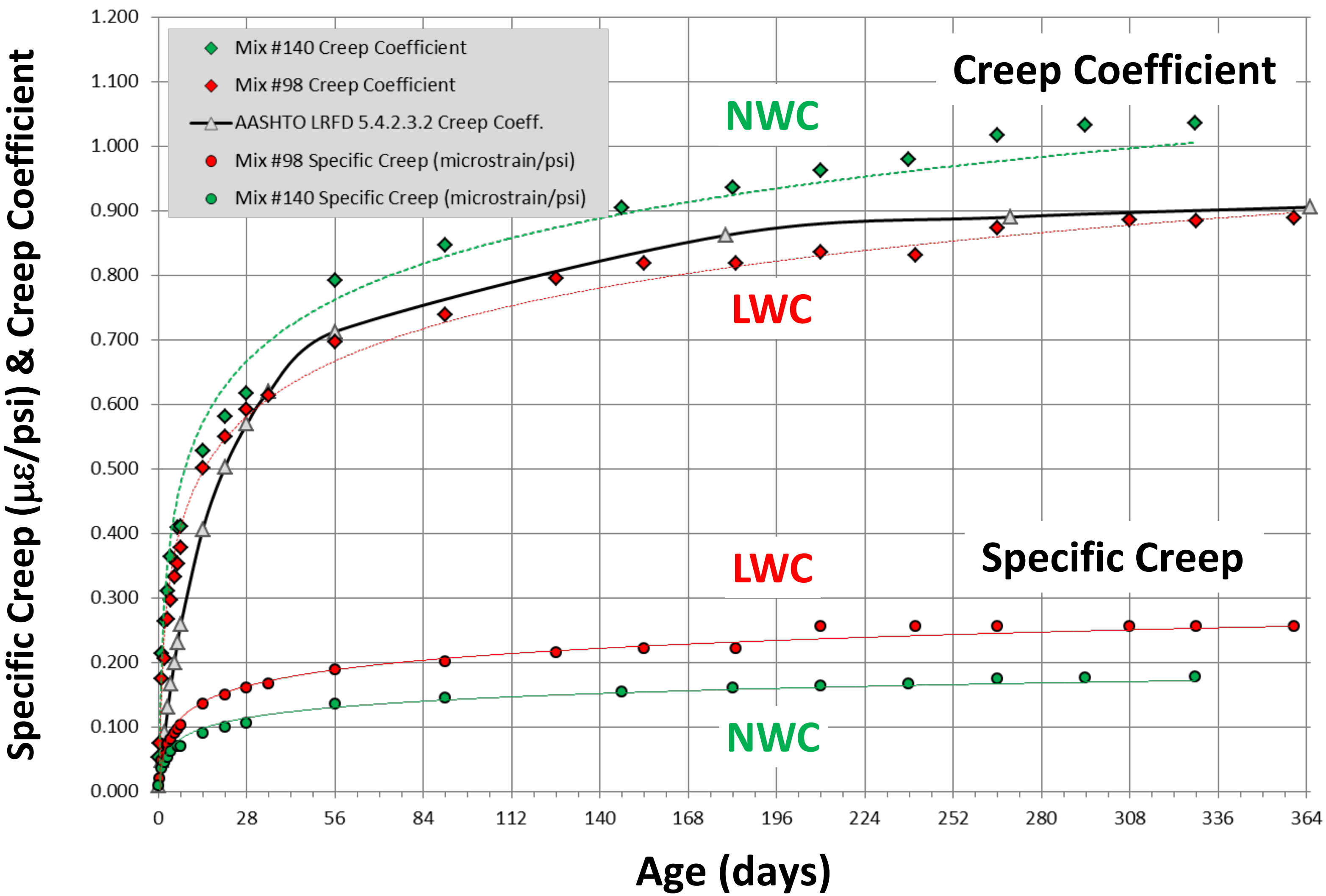
Historically, it has been assumed that LWC has greater creep and shrinkage than NWC

However, recent tests of LWC for girders have indicated that creep and shrinkage for LWC is very similar to values for NWC

- Especially for higher strength mixes used for PS girders

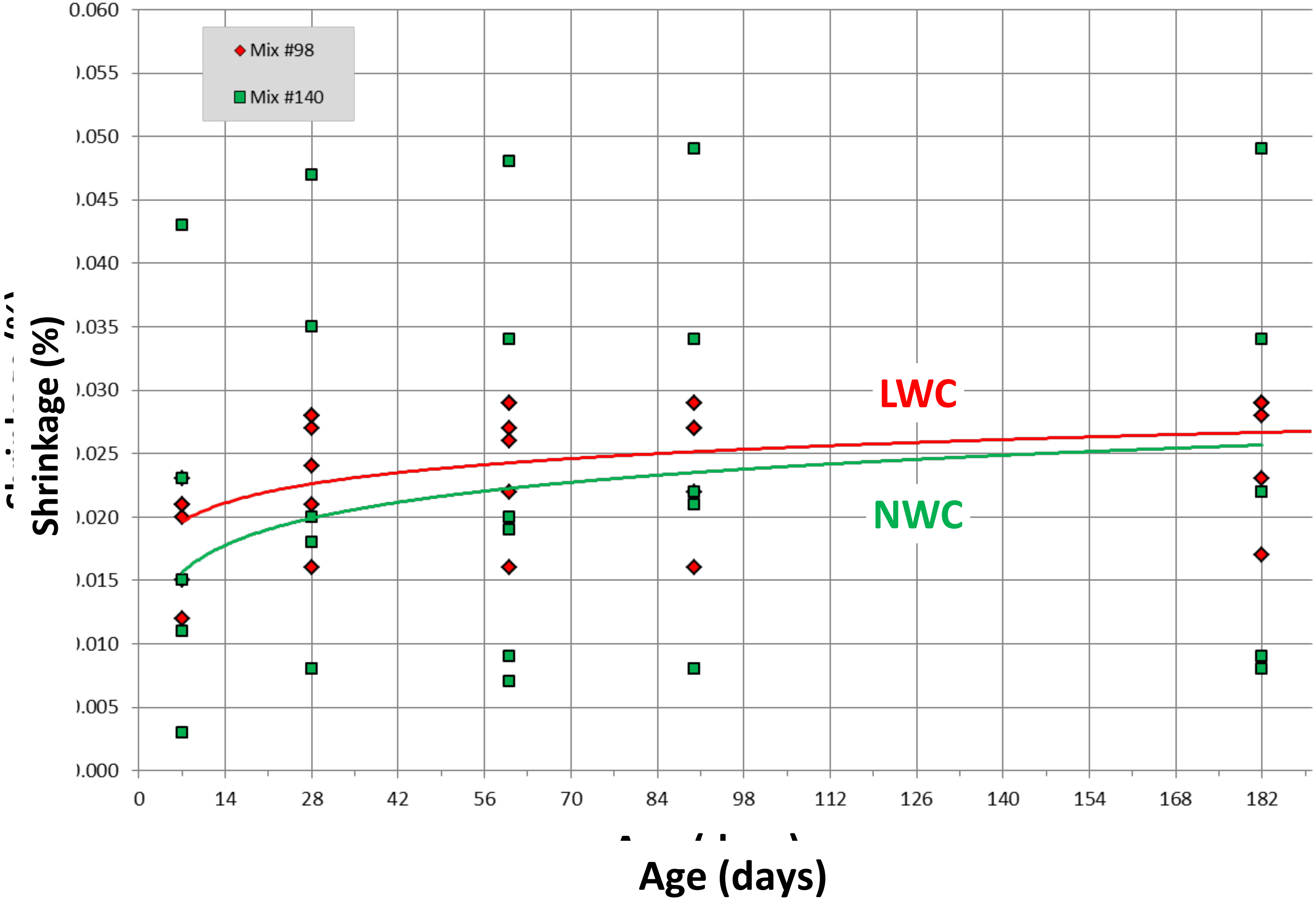
Creep

Data for ASTM C512 from Concrete Tech



Shrinkage

Data for ASTM C157 from Concrete Tech



Creep & Shrinkage

Comments on LWC data from Concrete Tech

- **Creep and shrinkage were both very close for LWC and NWC**

Mixture proportions

- **LWC: 800 lbs of Type III cement + 135 lbs of fly ash**
- **NWC: 752 lbs of Type III cement + no fly ash**
- **With a significantly higher cementitious content, the LWC mixture would be expected to have higher shrinkage – but did not**

Creep & Shrinkage

Conclusions from NCHRP Report 733

- **AASHTO model for shrinkage generally predicted shrinkage of LWC better than ACI 209 or CEB MC90**
- **For LWC girder mixes, AASHTO model for creep generally predicted creep coefficients better than ACI 209 or CEB MC90**
- **For LWC deck mixes, creep coefficients were considerably higher than predicted by the AASHTO model and were better predicted by the ACI 209 model**

Creep & Shrinkage

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

They have found

- **The total creep and shrinkage deformations of LWC are not significantly different from NWC of the same quality**
- **The equations in the AASHTO LRFD for estimating creep and shrinkage effects can be used without modification**

Summary of Design using LWC – NCHRP 733

Many of the investigated design provisions were found to adequately address the behavior of prestressed concrete members containing LWC

- **Changes were proposed for three sections**
  - **5.4.2.6-Modulus of Rupture**
  - **5.5.4.2-Resistance Factors**
  - **5.8.2.2-Modifications for Lightweight Concrete**
  - **These proposed changes were addressed in the recently adopted package of changes related to LWC**

Current AASHTO refined loss method is appropriate for LWC girders with LWC decks

Effect of LWC Properties on Designs

- **Camber**
- **Prestress Losses**

- **These quantities involve the interaction of several material properties**
- **There is uncertainty in the predictions even for NWC**
- **Remainder of presentation will discuss these quantities**

Camber and PS Losses from NCHRP 733

Results reported for tests of laboratory and full-scale specimens

- **See report for more results**

Camber and PS Losses from NCHRP 733

Cambers and deflections appeared reasonable

Table 40. Measured and calculated downward deflection from deck concrete.

Beam	Camber (in.)			
	Moment-Area w/ Measured E_c	Moment-Area w/ Measured E_c	Traditional Method	Measured Camber
T2.8.Min	-0.16	-0.15	-0.16	-0.14
T2.8.Typ	-0.16	-0.15	-0.16	-0.14
BT.8.Typ	-0.16	-0.15	-0.17	-0.20
BT.8N.Typ	-0.15	-0.14	-0.13	-0.11
BT.10.Typ	-0.16	-0.16	-0.17	-0.17
BT.10.Min	-0.15	-0.16	-0.15	-0.15

Table 42. Camber at testing.

Beam	Camber (in.)								
	PCI Mult.	PCI Improved Multipliers			AAEM				Measured
		AASHTO	ACI 209	CEB MC-90	AASHTO	ACI 209	CEB MC-90	AASHTO w/meas E_c	
T2.8.Min	1.18	1.13	1.23	1.37	0.78	0.91	1.03	0.74	0.68
T2.8.Typ	1.18	1.11	1.21	1.34	0.79	0.87	1.04	0.73	0.69
BT.8.Typ	1.48	1.40	1.53	1.73	1.23	1.35	1.56	1.37	1.22
BT.8N.Typ	1.05	0.96	1.06	1.18	0.75	0.83	0.96	0.94	1.24
BT.10.Typ	1.47	1.42	1.56	1.84	1.30	1.44	1.72	1.34	1.41
BT.10.Min	1.48	1.40	1.52	1.71	1.22	1.33	1.52	1.25	1.41

Camber and PS Losses from NCHRP 733

Compare measured & AASHTO effective prestress

- **Measured values 5 – 15% > predicted (less PS loss)**

Table 30. Measured and estimated ~~prestress losses~~ effective prestress

Beam	Initial Stress (ksi)	Time After Transfer (days)	Prestress (ksi)		Measured/ Calculated
			Measured f_{pe}	Calculated f_{pe}	
1.NW1.5A	200	207	175	167	1.05
1.NW1.5B	200	207	174	167	1.05
1.LW1.5A	199	NA	NA	NA	NA
1.LW1.5B	199	NA	NA	NA	NA
2.LW3.5A	199	139	172	152	1.13
2.LW3.5B	199	139	172	152	1.13
3.LW2.5A	203	83	177	163	1.09
3.LW2.5A	203	83	177	163	1.09
3.NW1.6A	198	83	177	168	1.05
3.NW1.6B	198	83	176	168	1.05
2.LW3.6A	200	139	174	153	1.14
2.LW3.6B	200	139	176	153	1.14

Camber and PS Losses from NCHRP 733

Compare measured & AASHTO elastic shortening losses

- **Measured losses higher than calculated**

Table 32. Early change in prestress. *Only ES Loss shown*

Beam	At Elastic Shortening (ksi)			**Meas. /Calc**
	Calculated with Meas. E_c	Calculated with Calc. E_c	Measured	
T2.8.Min	-22.8	-22.1	-25.8	**1.17**
T2.8.Typ	-22.8	-22.1	-25.9	**1.17**
BT.8.Typ	-19.5	-17.4	-20.5	**1.18**
BT.8N.Typ	-15.8	-13.1	-19.6	**1.50**
BT.10.Typ	-17.6	-17.3	-20.5	**1.18**
BT.10.Min	-17.6	-17.3	-18.3	**1.06**

Camber and PS Losses from NCHRP 733

Compare measured and predicted total PS loss

- Measured losses are ≤ predicted

Table 35. Total change in prestress from prior to release to testing.

Beam	Prestress Loss (ksi)							
	AASHTO Refined			AAEM				Measured
	AASHTO	ACI 209	CEB MC-90	AASHTO	ACI 209	CEB MC-90	AASHTO w/meas E_c	
T2.8.Min	-42.3 (0.82)*	-45.4 (0.76)	-45.6 (0.76)	-39.2 (0.88)	-43.7 (0.79)	-43.7 (0.79)	-41.9 (0.83)	-34.6
T2.8.Typ	-41.5 (0.77)	-45.6 (0.70)	-44.6 (0.72)	-38.0 (0.84)	-41.2 (0.78)	-42.1 (0.76)	-39.7 (0.81)	-32.1
BT.8.Typ	-38.5 (0.63)	-43.6 (0.56)	-42.3 (0.57)	-36.1 (0.67)	-41.2 (0.59)	-38.9 (0.63)	-40.2 (0.61)	-24.3
BT.8N.Typ	-28.9 (1.01)	-32.6 (0.89)	-30.4 (0.96)	-24.7 (1.18)	-26.5 (1.10)	-25.9 (1.12)	-30.6 (0.95)	-29.1
BT.10.Typ	-39.5 (0.59)	-45.3 (0.52)	-45.2 (0.52)	-36.9 (0.63)	-43.0 (0.54)	-41.7 (0.56)	-38.3 (0.61)	-23.4
BT.10.Min	-38.3 (0.52)	-43.0 (0.46)	-41.3 (0.48)	-35.9 (0.55)	-41.0 (0.49)	-37.8 (0.53)	-37.0 (0.54)	-19.9

*Number in parentheses in each cell is the ratio of measured loss to calculated loss.

AASHTO
-42.3 (0.82)*
-41.5 (0.77)
-38.5 (0.63)
-28.9 (1.01)
-39.5 (0.59)
-38.3 (0.52)

- Total losses range from 50% of predicted
- To nearly equal to predicted

Camber and PS Losses from NCHRP 733

Results at time of testing show "good agreement with AASHTO calculations of prestress loss."

Summary of prestress loss evaluation

- **Elastic shortening losses were greater than expected**
- **Total losses were up to 50% lower than predicted**
- **Therefore, time dependent losses (CR + SH) must be less than predicted (my conclusion)**

Camber and PS Losses

Paper by Castrodale & Harmon (2006)

Compared LWC & NWC designs for same spans

- **Design variables**
  - **AASHTO Type II & PCI BT-72 girders**
  - **Span length and girder spacing**
  - **Concrete density**
    - **NWC: 145 pcf for girder & deck**
    - **LWC: 120 pcf for girder & 115 pcf for deck**
  - **Girder concrete strengths: f'_{ci} & f'_c**
  - **Deck concrete strength: f'_c = 4.5 ksi for all designs**
  - **Number of strands**

Parameters for Design Comparisons

	Girder Spacing (ft)	Span (ft)	Girder f'$_{ci}$ (ksi) NWC	Girder f'$_{ci}$ (ksi) LWC	Girder f'$_c$ (ksi) NWC	Girder f'$_c$ (ksi) LWC	Strands Size (in.)	Strands No. of Strands NWC	Strands No. of Strands LWC
AASHTO Type II	7.5	58	5.5	5.0	6.5	6.5	0.5	24	22
PCI BT-72	5.5	135	5.0	4.5	7.0	7.0	0.6	32	28
PCI BT-72	8.5	122	6.0	6.0	7.0	7.0	0.6	36	32
PCI BT-72	10.5	118	7.5	6.5	8.5	7.5	0.6	44	38
PCI BT-72	10.5	118	7.5	7.5	8.5	8.5	0.6	44	44
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design									

Designs used LWC or NWC for both the girder & deck

- f'$_{ci}$ & f'$_c$ could be reduced for some LWC designs
- Fewer strands were required for LWC designs

Camber at Release

	Girder Spcg (ft)	Net Camber at Release (in.)		
		NWC	LWC	% Chng.
AASHTO Type II	7.5	1.190	1.767	+48%
PCI BT-72	5.5	2.078	2.689	+29%
PCI BT-72	8.5	2.594	3.407	+31%
PCI BT-72	10.5	2.559	3.739	+46%
PCI BT-72	10.5	2.559	3.495	+37%
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design				

- **Cambers at release increase up to > 1" or 29 to 48%**
  - **Caused by combination of decreased E_c & self-weight**
- **Cambers at erection increase up to > 2", but by about same percentage**

Final Camber with all Dead Loads

	Girder Spcg (ft)	Final, with all Dead Loads (in.)		
		NWC	LWC	% Chng.
AASHTO Type II	7.5	1.285	2.297	+79%
PCI BT-72	5.5	1.574	2.482	+58%
PCI BT-72	8.5	2.714	4.052	+49%
PCI BT-72	10.5	2.738	4.634	+69%
PCI BT-72	10.5	2.738	4.318	+58%
Shaded cells - LWC design using same concrete strengths and number of strands as NWC design				

- Cambers at full DL increase up to < 2” or 49 to 79%
- Percentage change is greater than release & erection
- Cambers can be reduced by adding strands – see Castrodale & Hanks (2015)

Live Load Deflections

	Girder Spcg (ft)	Live Load Deflection (in.)		
		NWC	LWC	% Chng.
AASHTO Type II	7.5	-0.632	-0.843	+33%
PCI BT-72	5.5	-0.988	-1.327	+34%
PCI BT-72	8.5	-0.992	-1.331	+34%
PCI BT-72	10.5	-0.972	-1.375	+41%
PCI BT-72	10.5	-0.972	-1.304	+34%

Live load deflection increases from 33 to 41% (up to 0.4")

Greater than change in E_c, which was about 25%

Prestress Losses – Initial

	Girder Spcg (ft)	Initial Effective Prestress, f_{pi} (ksi)		
		NWC	LWC	% Chng.
AASHTO Type II	7.5	183.0	178.4	-3%
PCI BT-72	5.5	184.2	180.8	-2%
PCI BT-72	8.5	181.4	178.0	-2%
PCI BT-72	10.5	179.1	174.1	-3%
PCI BT-72	10.5	179.1	172.3	-4%

- **Initial effective prestress – 2 to 4% reduction**
  - **Initial loss was increased because of lower E_c, even with fewer strands**

Prestress Losses – Final

	Girder Spcg (ft)	Final Effective Prestress, f_{pe} (ksi)		
		NWC	LWC	% Chng.
AASHTO Type II	7.5	149.0	146.8	-2%
PCI BT-72	5.5	155.4	155.0	-0%
PCI BT-72	8.5	146.2	145.8	-0%
PCI BT-72	10.5	135.3	135.6	+0%
PCI BT-72	10.5	135.3	127.6	-6%

- **Final effective prestress – only a slight reduction**
  - **Except larger change for non-standard design (bott. row)**
  - **Lower time-dependent losses because of fewer strands**

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More references can be supplied

Thank you!

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Rotary Kiln Structural Lightweight Aggregate