Specifying Lightweight Concrete for Bridges: Reduced Density & Enhanced Durability

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Introduction

Lightweight concrete (LWC) has been used in bridges in the US since commercial production began in 1920

- Benefits of reduced density are obvious, especially for long-spans, large PC elements for ABC, and seismic applications
- Benefits of enhanced durability are less obvious, but can be equally important, such as reduced cracking, lower permeability, and increased service life

Some designers have used LWC successfully

But many designers are reluctant to use LWC

Designers often don’t know how to specify LWC

Outline of Presentation

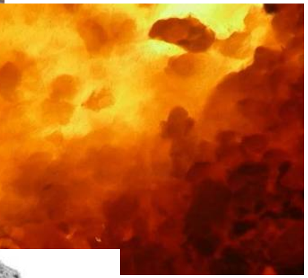
- **Brief introduction to lightweight aggregate (LWA) & LWC**
- **Benefits of reduced density**
- **Benefits of enhanced durability**
- **Specifying LWC**

Lightweight aggregate (LWA)

Manufactured in USA since 1920

Raw material is shale, clay or slate

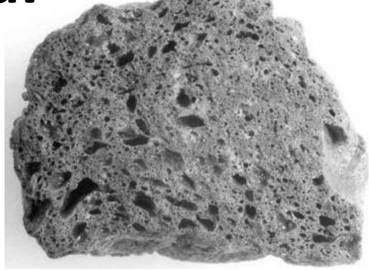
Heated in rotary kiln to about 1200°C



Gas bubbles form in softened material

Gas bubbles remain after cooling

Clinker is crushed and screened



Relative Density of LW vs. NW Aggregate

Relative density for rotary kiln expanded lightweight aggregates

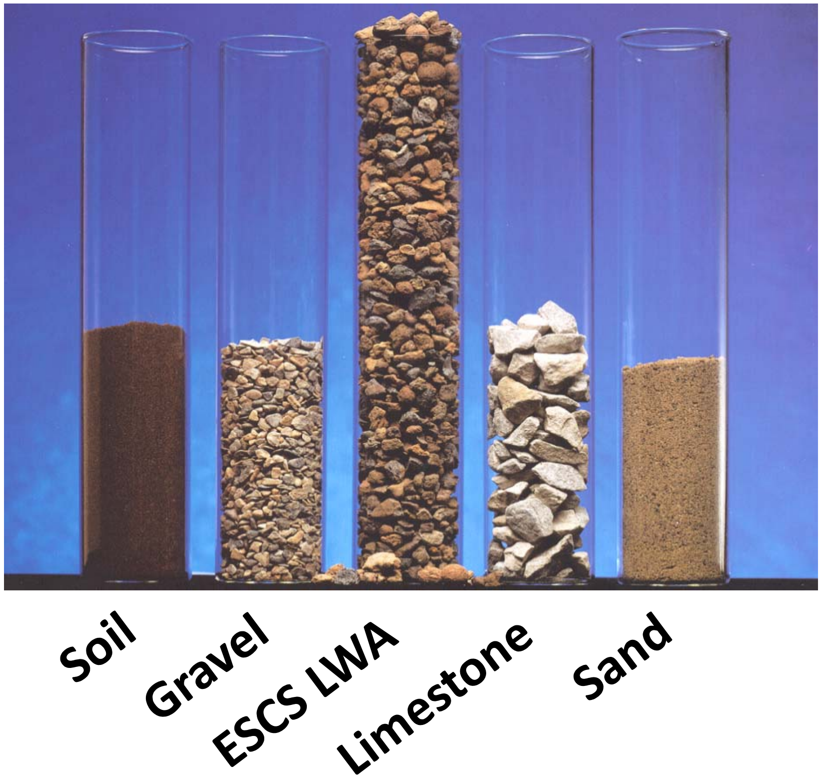
- Range from 1.3 to 1.6

Relative density for normal weight aggregates (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

Physical Properties of LW Aggregates

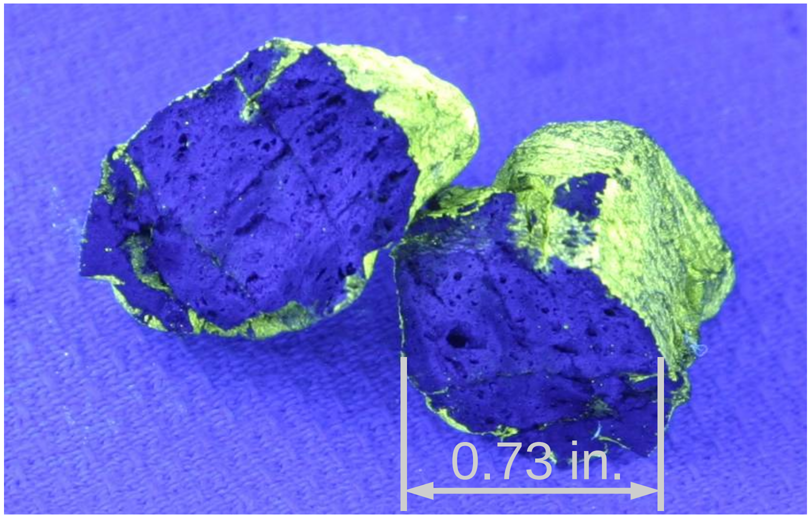
Vitrified ceramic material

- Hardness equivalent to quartz

Porous aggregate

- Reduces density
- Increases absorption
  - Limited connectivity of pores

An expanded slate LWA particle soaked in water with fluorescent yellow dye for 180 days, then split open.
Absorption at time of test was 8% by mass.



Reduced Concrete Density

New definition for LWC in LRFD Specs:

- LWC contains LWA conforming to 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 specs
  - Mix depends on type of LWA & other requirements

Benefits of Reduced Concrete Density

- **Longer spans**
  - **Rugsundet Bridge – 10% longer main span with same PT**

Rugsundet Bridge, Norway

CIP segmental box girder

Peer review of NWC design led to use of LWC for center of main span

- Increased main span from 564 ft to 623 ft (+10%)
- Used same quantity of post-tensioning
- Moved foundations out of deep water
- Reduced length of ballast-filled side spans
- Shortened overall length of structure 33 ft

Bid for LWC design was 15% less than NWC bid

Contractor wanted to pump the LWC

- Owner did not allow pumping LWC
- LWA from USA to allow LWC to be pumped

Benefits of Reduced Concrete Density

- **Longer spans**
  - **Rugsundet Bridge – 10% longer main span with same PT**
- **Reduced seismic loads**
  - **Benicia Martinez Bridge – Reduced foundation cost**

Benicia-Martinez Bridge, California, USA

I-680 over the Carquinez Strait north of San Francisco

- Cast-in-place box girder
- 82 ft wide deck
- 658 ft maximum spans

LWC was used for the entire box girder cross-section

- LWC was used for the full length of 6500 ft long bridge except for pier segments
- Reduced seismic forces, foundations & cost
- If research on LWC ductility had been completed at the time of design, the bridge would have been LWC from the top of the footing

Benefits of Reduced Concrete Density

- Longer spans
  - Rugsundet Bridge – 10% longer main span with same PT
- Reduced seismic loads
  - Benicia Martinez Bridge – Reduced foundation cost
- **Reduced structure weight with poor foundations**
  - **Rte 33 Bridges at West Point, VA**

VA Route 33 Bridges at West Point, VA

Bridges carry VA Rte 33 over the Mattaponi and Pumunkey Rivers at West Point, VA

Each bridge has two 200'-240'-240'-200’ PT concrete spliced girder units with haunched pier segments

- LWC was used for spliced girders and deck to reduce foundation loads

Completed in 2006 and 2007

Benefits of Reduced Concrete Density

- Longer spans
  - Rugsundet Bridge – 10% longer main span with same PT
- Reduced seismic loads
  - Benicia Martinez Bridge – Reduced foundation cost
- Reduced structure weight with poor foundations
  - Rte 33 Bridges at West Point, VA
- **Reuse of foundations**
  - **I-5 Span Replacement over Skagit River**

I-5 Bridge Repair over Skagit River, WA

Truss span collapsed when struck by over-height load in May 2013 – north of Seattle, WA

Temporary span installed quickly

Winning design/build team used sand LWC deck girders for permanent span replacement

- Total span weight limited to 915 tons
  - LWC was required to meet limit
- Girders 162.3 ft long
- Design fresh density = 123 pcf
- Design f'_c = 9 ksi

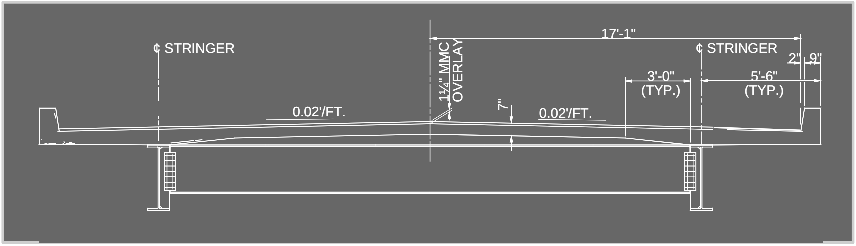
Benefits of Reduced Concrete Density

- Longer spans
  - Rugsundet Bridge – 10% longer main span with same PT
- Reduced seismic loads
  - Benicia Martinez Bridge – Reduced foundation cost
- Reduced structure weight with poor foundations
  - Rte 33 Bridges at West Point, VA
- Reuse of foundations
  - I-5 Span Replacement over Skagit River
- **Reduced weight of precast elements for ABC**
  - **Lewis & Clark Bridge, OR/WA – SPMT to install new deck**

Lewis & Clark Bridge, OR/WA

Deck replacement on an existing truss using SPMTs

- Sand LWC precast deck units with steel floor beams
- Sand LWC density = 119 pcf
- Max. deck unit weight = 92 t
  - Sand LWC saved about 14 t

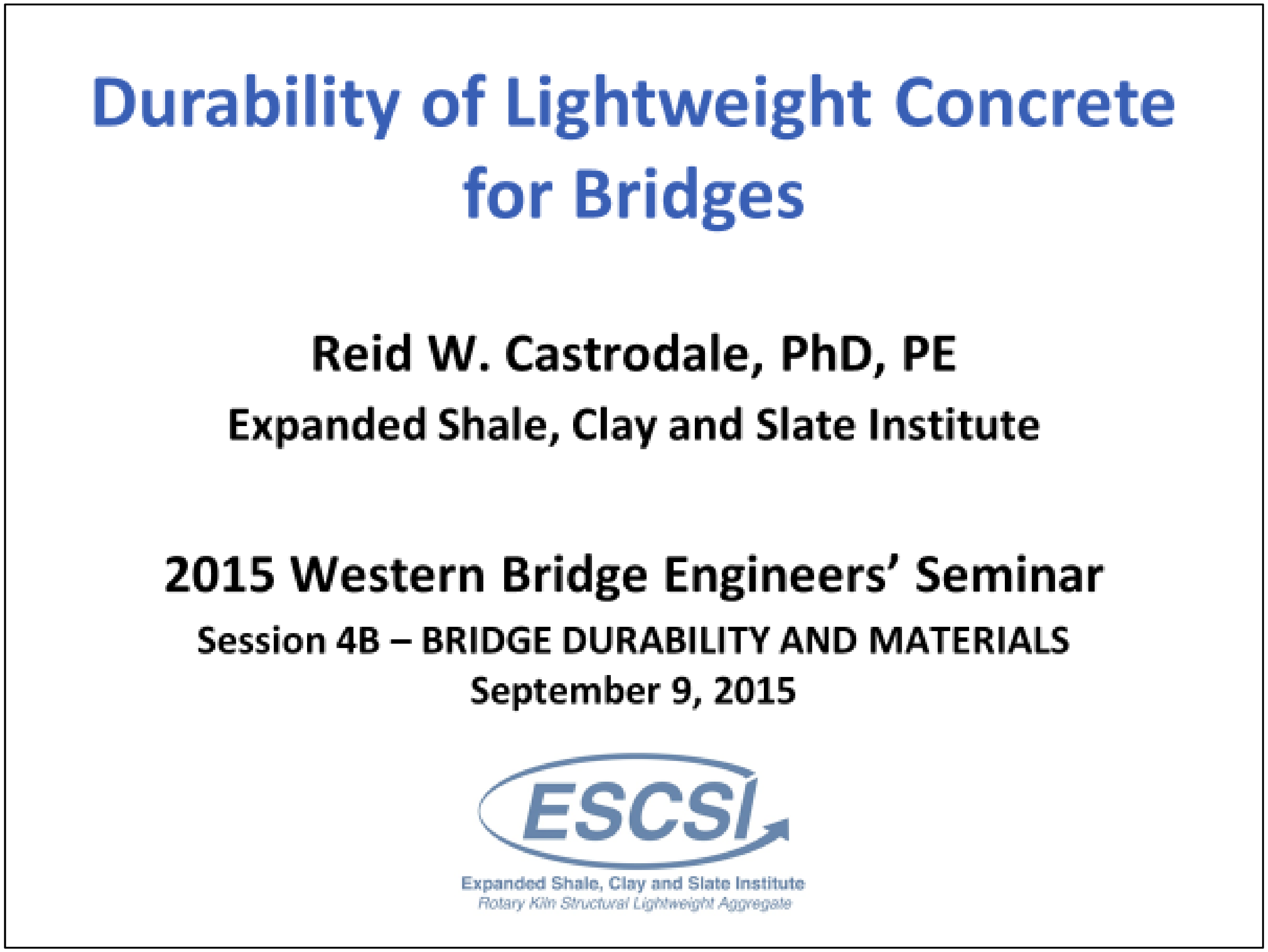


Existing deck was LWC

- In service for 73 yrs

Benefits of Enhanced Durability of LWC

See presentation on this topic from WBES 2015



Durability of Lightweight Concrete for Bridges

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Features of LWC that Enhance Durability

- **Improved quality of interfacial transition zone (ITZ)**
- **Elastic compatibility of LWA with paste**
- **Internal curing with prewetted LWA**
- **Lower modulus of elasticity**
- **Lower coefficient of thermal expansion**
- **Lower shrinkage**
- **Tensile strengths often in the range of NWC**

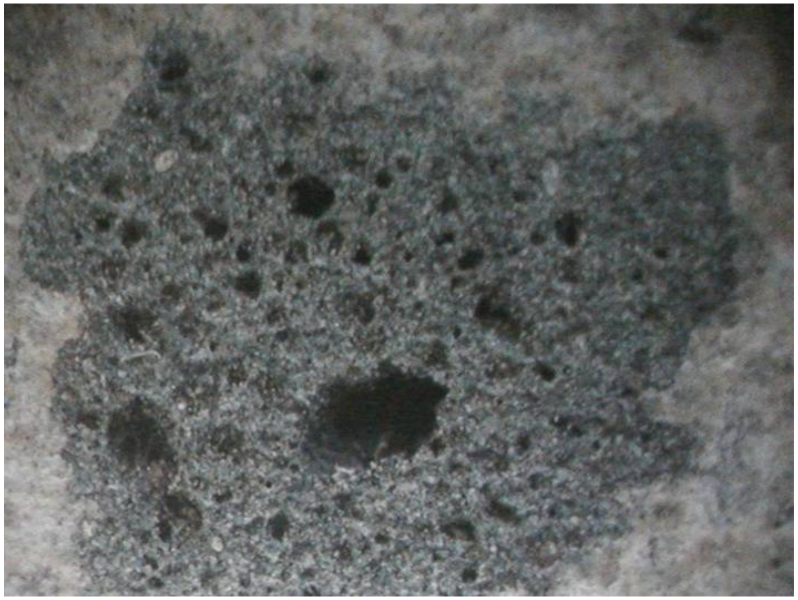
These features result in many benefits including

- **Lower permeability**
- **Reduced cracking**
- **Longer service life**

Contact Zone

Bond between cement paste and LWA is improved compared to NWA

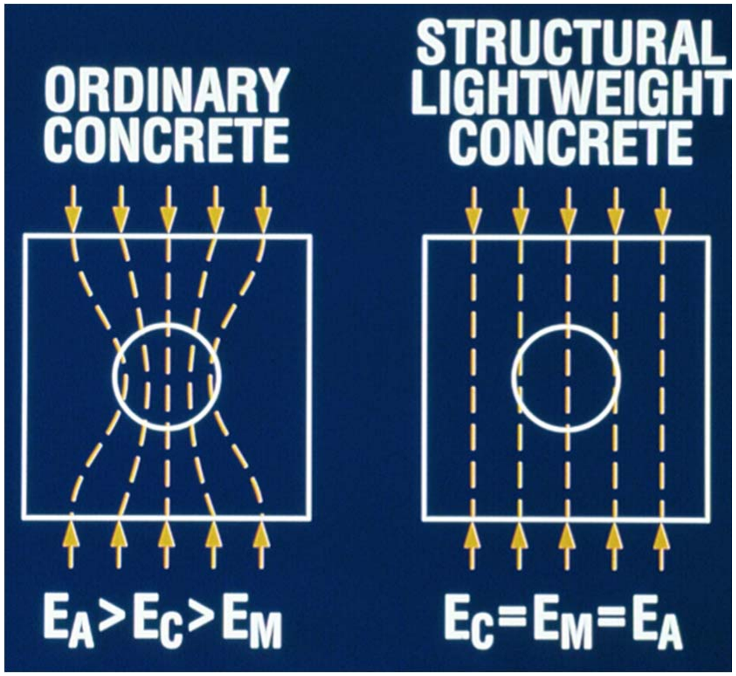
- **Cellular structure and irregular surface of aggregate (mechanical bond)**
- **Slightly pozzolanic nature of the aggregate (chemical bond)**
- **Improves durability and structural behavior by reducing micro-cracking around aggregate**



Elastic Compatibility

Modulus of elasticity of lightweight aggregates are closer to the modulus of the cement paste than normalweight aggregates

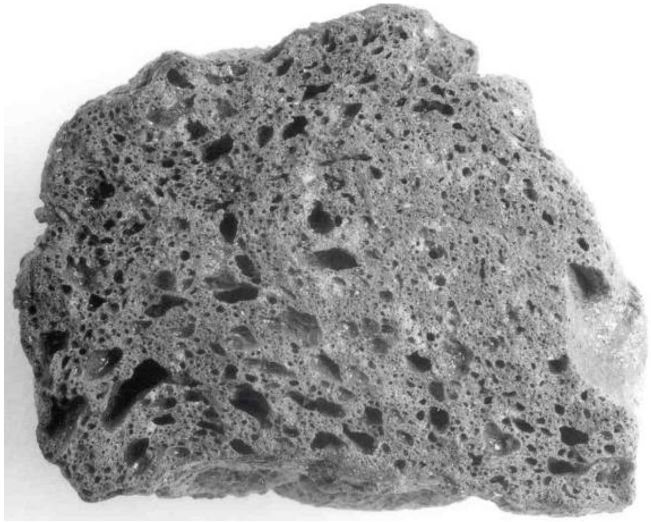
- **Reduces stress concentrations that form around stiffer normalweight aggregate**
- **Reduces microcracking, autogenous shrinkage, and shrinkage cracking**
- **Improves durability by reducing micro-cracking around aggregate**



Internal Curing with Prewetted LWA

Absorbed moisture within LWA is released over time into the concrete providing enhanced curing

- **More complete hydration can occur**
- **Especially helpful for high performance concrete that is nearly impermeable to externally applied curing moisture**
- **Improves durability and structural behavior**
- **Improves tolerance of concrete to improper curing**



Internal Curing with Prewetted LWA

Test pour for 10 Mgal water tank - Highlands Ranch, CO

- **Internal Curing vs. No Internal Curing**
- **Concrete placed at 92 deg F air temp. & 20% RH**
- **No conventional curing**

Modulus of Elasticity, E_c

Reduced stiffness of LWC results in less cracking when subjected to strains

Data for one example

Modulus of Elasticity (ksi)	Control	Internal Curing	Sand LWC	All LWC
Control	4650	--	--	--
Slate	--	4350	3525	2550
Clay	--	4275	2825	2025
Shale	--	4300	3300	2250

LWC average as % of Control value 93% 69% 49%

Data from study by Byard & Schindler (2010)

Coefficient of Thermal Expansion, CTE

Reduced CTE of LWC results in less strain when subjected to a change in temperature

Data for one example

Coefficient of Thermal Expansion (με/°F)	Control	Internal Curing	Sand LWC	All LWC
Control	6.2	--	--	--
Slate	--	5.9	5.1	4.3
Clay	--	5.8	5.1	4.0
Shale	--	6.0	5.2	4.0

LWC average as % of Control value 95% 83% 66%

Data from study by Byard & Schindler (2010)

Tensile Strength, f_{ct}

Reduction factors in design specs are used to account for potentially lower tensile strength of LWC

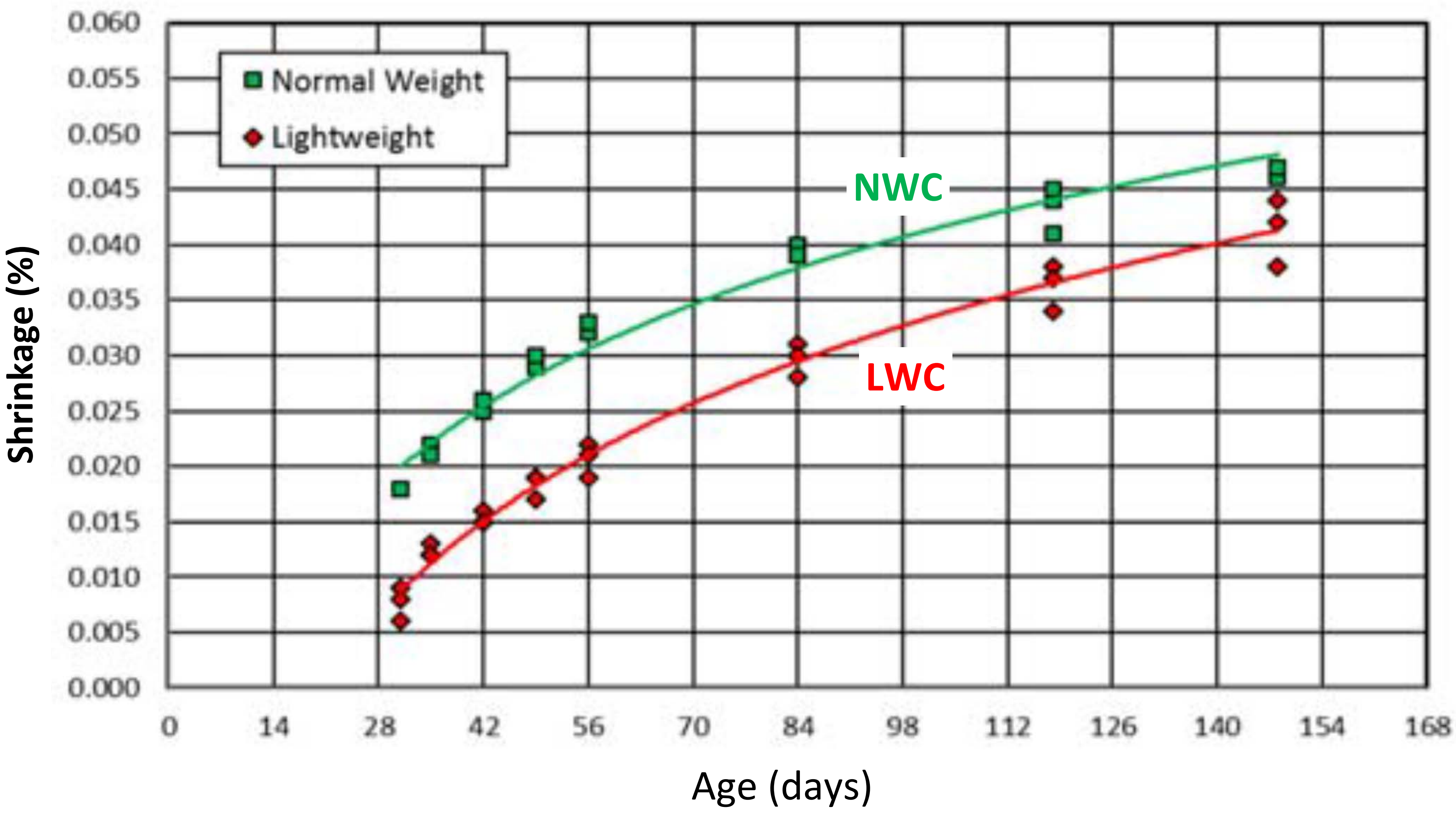
Recent tests demonstrate that LWC has tensile strength close to or exceeding strength assumed for NWC

- **10 ksi PS girder mix at Concrete Tech**
  - **Measured f_{ct} = 700 psi at 28 days**
  - **$\sqrt{f'_c} / 4.7 = 672$ psi $\Rightarrow$ use $\lambda = 1.0$**
- **NCHRP Report 733**

  $0.21\sqrt{f'_c}$
  - **Average f_{ct} for LWC was $0.25\sqrt{f'_c} > \sqrt{f'_c}/4.7 \Rightarrow$ 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 $\lambda = 1.0$**

Shrinkage

Data for ASTM C157 from Concrete Tech girders



Resistance to Chloride Penetration

LWC has improved resistance to chloride penetration

Silver Creek Overpass in UT was constructed in 1968

Chloride content after 23½ years in service

Depth	Sand LWC Deck	NWC Appr. Slab
0" to ½"	36.7 lbs / CY	20.5 lbs / CY
½" to 1"	18.0 lbs / CY	18.0 lbs / CY
1" to 1½"	7.7 lbs / CY	15.7 lbs / CY
1½" to 2"	0.5 lbs / CY	---

From ESCSI (2001)

Concrete Cracking Tendency Tests

Research for ESCSI by Byard & Schindler (2010)

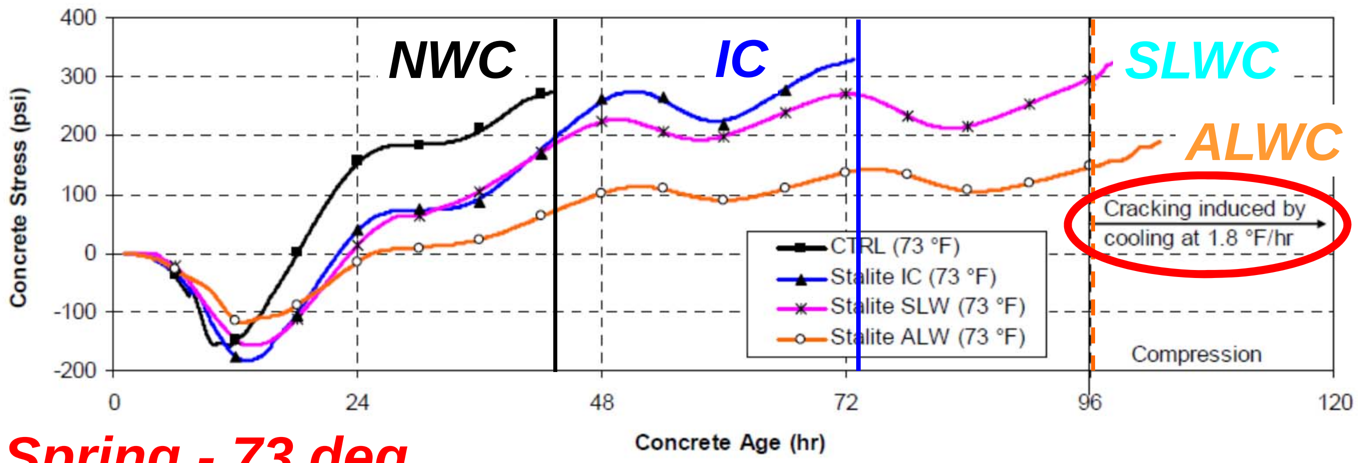
Testing uses cracking tendency frames

- **Restrained shrinkage**
- **Concrete temperature is controlled to match expected variation in bridge deck**

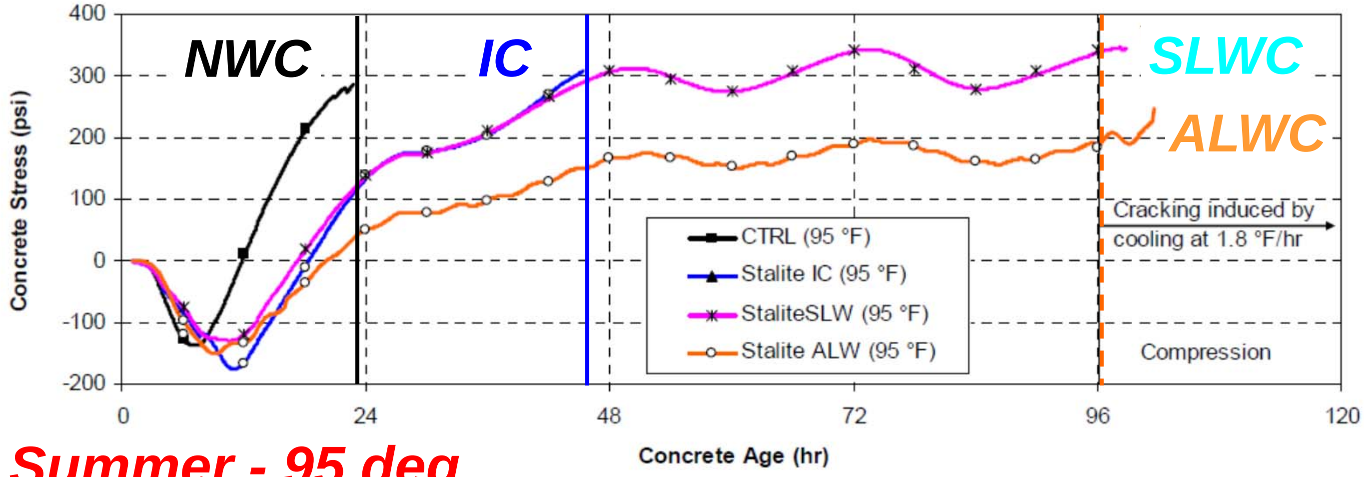
Mixtures tested

- **3 types of LWA**
- **3 LWC mixes**
- **NWC control river gravel**

Cracking Tendency Test Results



Spring - 73 deg.



Summer - 95 deg.

Sand LWC & All LWC did not crack during test, but were forced to crack at end of test

Results for slate LWA shown

Complete results in report

Figures from Byard and Schindler (2010)

Service Life Modeling

Tourney Consulting Group has recently completed testing LWC and modeling of LWC for bridges

Using STADIUM® software, results showed an expected increase in service life over the NWC control

- 25% for “sand lightweight concrete”
- 32% for “all lightweight concrete”
- 25% for “internally cured concrete” with partial replacement of NW sand with LW sand
- 76% for “inverted mixture” with complete replacement of NW sand with LW sand

Other investigators have reported similar results

Ductility and Seismic Applications

Testing at UCSD & NCSU has demonstrated that LWC has adequate ductility for use in columns and joints designed for seismic activity

- “LWC, when properly detailed, will perform as well as normal weight concrete” – UCSD
- “The strength of the lightweight concrete shear-resisting mechanism appears to be lower than the normal-strength mechanism when subjected to reversed cyclic loads” - NCSU
- However, the “reduction in shear demand will more than compensate for the reduced strength of the concrete shear-resisting mechanism” - NCSU

Mass Concrete

Properties of sand LWC compared to NWC

- **Reduced modulus of elasticity (E_c)**
  - **About 70% of NWC**
- **Reduced coefficient of thermal expansion (CTE)**
  - **About 85% of NWC**
- **Approximately the same tensile strength**

Considering only these parameters:

- **For a given temperature change, stress in sand LWC would be 70% x 85% = 60% of the stress in NWC**
- **Cracking tendency should be significantly reduced**

LWC also has insulating properties, cooling more slowly

Ben Gerwick, Jr., on LWC in 1984 Lecture

"When confined, it has greater ductility, due to progressive crushing of the aggregate. There are far fewer microcracks between paste and aggregate resulting in better high cycle fatigue endurance. The lower modulus accommodates thermal and other deformation strains with less cracking. Finally, the protection of the reinforcing steel from corrosion under severe environmental exposure appears to be enhanced."

"Thus we have a superior material available, originally chosen for its lighter density, which now appears justified for use in sophisticated structures for many other reasons as well."

Specifying LWC

So now you want the benefits of LWC …

But how do you specify it?

Specifying LWC

Most DOT Standard Specifications do not address LWA and LWC

Items to address in a special provision

- Lightweight aggregate
- LWC properties
- LWC test methods
- Batching, placing and finishing of LWC

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

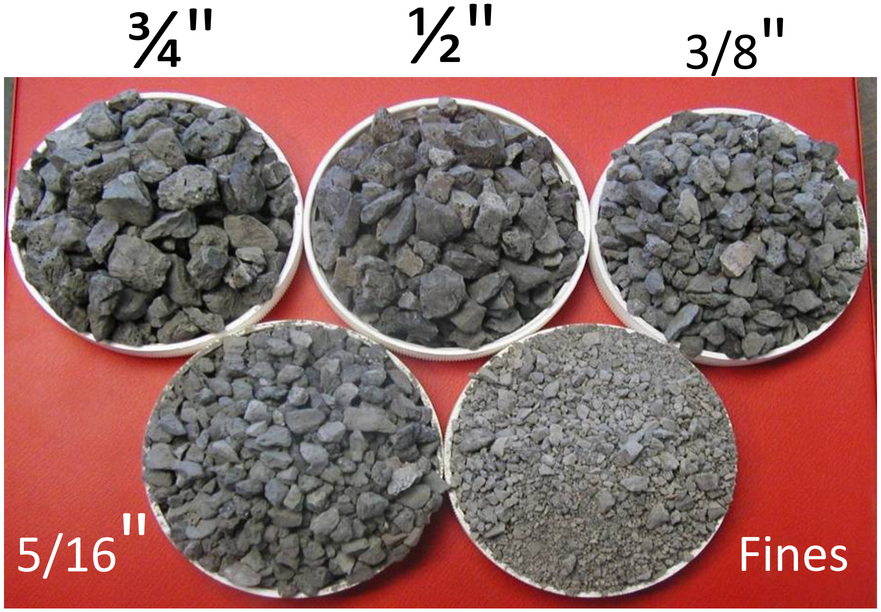
Density is specified & checked, so more QC attention

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

Some DOT specifications indicate maximum absorption for LWA

- This is not necessary or recommended
- Performance of LWA and LWC is not directly related to absorption of LWA
- LWC should simply satisfy the appropriate design and performance requirements

Specifying Properties of LWC

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

Durability properties can also be specified

Specifying density is the unique feature in LWC specifications

- Equilibrium and/or fresh density specified
- No longer necessary to specify the type of LWC, i.e., "all" or "sand" LWC
- Concrete supplier may use blends of aggregate to achieve target densities

Specifying Density of LWC

"Equilibrium density"

- Density after moisture loss has occurred
- Defined in ASTM C567
  - Usually computed from mix design
- Density for long-term design loads

"Fresh density"

- Required as QC check during placement
- Designer may specify a fresh density
- Supplier may establish fresh density from a specified equilibrium density
- Density for handling loads at early age

Specifying Density of LWC

Contract documents must clearly indicate intended type of density being specified

- Equilibrium and/or fresh

Tolerances for concrete density

- Maximum limit with no minimum is preferred
- Any +/- limit needs to realistically account for variation in other constituents like air & water

Contract documents should indicate LWC density used for dead load calculations

- Typical allowance for reinforcement is 5 pcf
- Allowance is greater for heavily reinforced sections

Specifying Properties of LWC

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

- Over-specifying concrete properties will drive up the cost of the project

Be careful when reusing special provisions from other projects

Specifications related to Construction

Special provisions should require a pre-pour meeting including the LWA supplier

- Discuss all aspects of delivery, placement and field testing

A trial LWC placement is recommended

- Include LWA supplier
- Use concrete placement equipment
- Place in mockup
- Whole team needs to understand the few special issues related to LWC

Specifications related to Construction

Moisture conditioning (prewetting) LWA

- Especially important for concrete placed by pumping
- If not adequately prewetted, slump loss may occur

Some specs indicate how long to sprinkle and how long to drain for prewetting LWA

Method for prewetting LWA is not critical

- Some LWA is vacuum saturated or requires soaking
- Other LWA can be prewetted just by sprinkling

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

LWC Test Methods & Production Tips

Typical Testing Issues for Special Provisions

Density testing

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

LA Abrasion Test Modification

- **Recommend modifying procedure to charge cylinder with <u>volume</u> 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 are not in ASTM C666, they can be missed by testing labs not familiar with LWC**

Batching

Absorbed water affects batch weights

- Another reason to make sure that the target absorption has been achieved

Batching prewetted LWA can be a challenge in freezing weather

- It has been done in Norway with protected stockpiles
- Some concrete suppliers batch LWA dry in the winter and add water to account for absorption during batching and transport

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 – Unit Weight

Density is a specified quantity, so the unit weight bucket should be carefully calibrated

Example – 105 pcf fresh density specified

- **1/3 CF bucket with 105 pcf concrete = 35 lbs**
- **35 lbs / 0.33 = 106.1 pcf**
- **NO GOOD > 105 pcf max.**
- **35 lbs x 2.99 = 104.7 pcf**
- **1 / 2.99 = 0.334**
- **35 lbs / 0.334 = 104.8 pcf**

ASTM gives density of water to 5 significant digits, so bucket calibration factors should reflect this

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)

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Questions?

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