Durability of Lightweight Concrete for Bridges

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ESCSI

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Rotary Kiln Structural Lightweight Aggregate

Introduction

Many engineers are reluctant to use lightweight concrete (LWC) in bridge construction

They are concerned about the durability of LWC exposed to weather and traffic conditions experienced by bridges.

They expect that the apparently porous lightweight aggregate (LWA) could not provide durability that is comparable with normalweight concrete (NWC)

However, laboratory and field experience demonstrate that LWC can provide (and has provided) excellent durability for decks and other bridge elements

Introduction

Satisfactory durability of LWC is demonstrated using

- **Data from research**
- **Test data**
- **Field experience**

Information will be presented for several bridges with LWC decks (and a few with girders) demonstrating the good long-term performance of LWC in the field

Overview of Presentation

Introduction

- **Durability of Concrete for Bridges**
- **Common Concerns about LWC Durability**
- **Conclusions from 2 Engineers in 1980s**

Features of LWC that affect Durability

Field and Laboratory Durability of LWC

Long-Term Performance – Project Examples

Durability of Concrete for Bridges

Key characteristics of any durable concrete

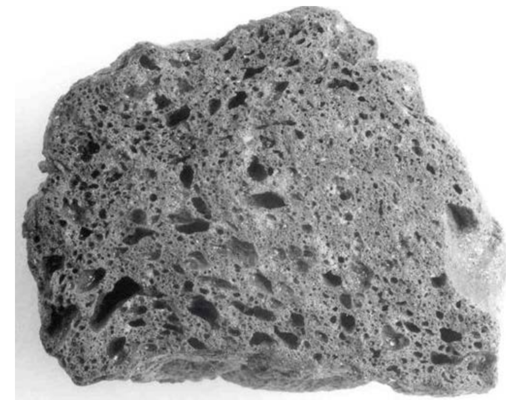
- Low permeability
- No cracks … or at least tight and few
- Proper internal structure to resist freezing and thawing
- Resistance to wear from traffic or water

Also very important, but not discussed here

- Design details
- Quality of construction

Common Concerns about LWC Durability

- LWA looks like a sponge so it must be very permeable and prone to freeze-thaw damage
- LWA appears to be soft, so it must wear excessively



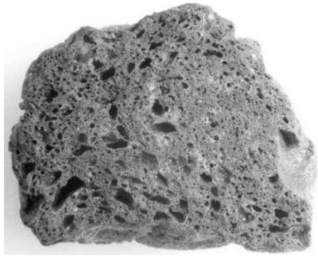
- LWC can’t be durable if ground or grooved
- LWC bridges had problems in the past
- LWA floats in concrete
- LWC is difficult to finish
- Contractors and suppliers are not familiar with LWC

These are addressed in Castrodale & Harmon (2008)

Properties of Lightweight Aggregates

LWA are manufactured by expanding raw materials at high temperatures

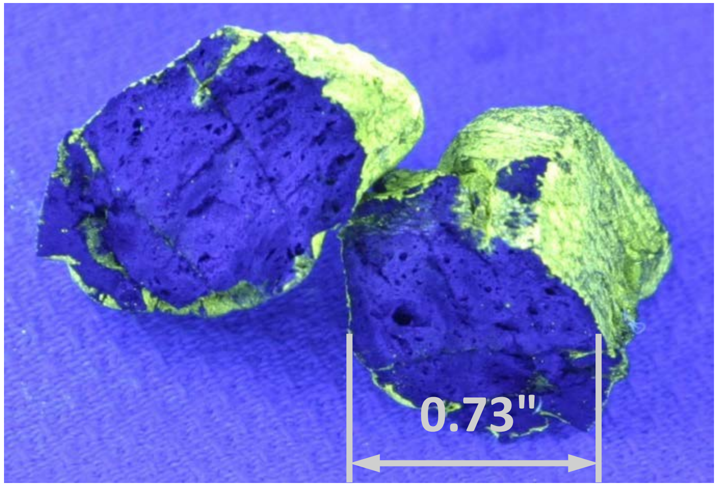
- **Heating produces a porous vitrified ceramic material**
  - **Hardness equivalent to quartz**
  - **Pores reduce density**
  - **Pores increase absorption**



- **But not like a sponge – all pores are <u>not</u> connected**

Expanded slate aggregate immersed in water with fluorescent yellow dye for 180 days, then split open.

Absorption at test was 8% by mass.



Conclusions from 2 Engineers in 1980s

FHWA Report "Criteria for Designing LWC Bridges" prepared by T.Y. Lin International - 1985

"Although there is no consensus of opinion concerning the suitability of lightweight concrete for bridge structures, nor concerning experiences with its performance, it should be noted that the material does have sufficient record of successful applications to make it a suitable construction material for buildings and ships, as well as for bridges."

"Sufficient information is available on all aspects of its performance for design and construction purposes."

Conclusions from 2 Engineers in 1980s

Dr. Ben Gerwick, Jr. in a published lecture – 1984

LWC has the following properties

- **Greater ductility**
- **Fewer microcracks**
- **Better high cycle fatigue endurance**
- **Less cracking from thermal & other strains**
- **Enhanced protection of rebar from corrosion**

"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."

Features of LWC that affect Durability

- **Interfacial transition zone or "contact zone"**
- **Internal curing**
- **Elastic compatibility of LWA with paste**
- **Lower modulus of elasticity**
- **Lower coefficient of thermal expansion**
- **Improved fire resistance**
- **Greater thermal resistance – lower daily temp Δ**
- **LWA provides pores for expansive reactions**
- **Fine LWA may act like entrained air**

Contact Zone

The layer of cement paste surrounding each particle of aggregate

Two distinct characteristics

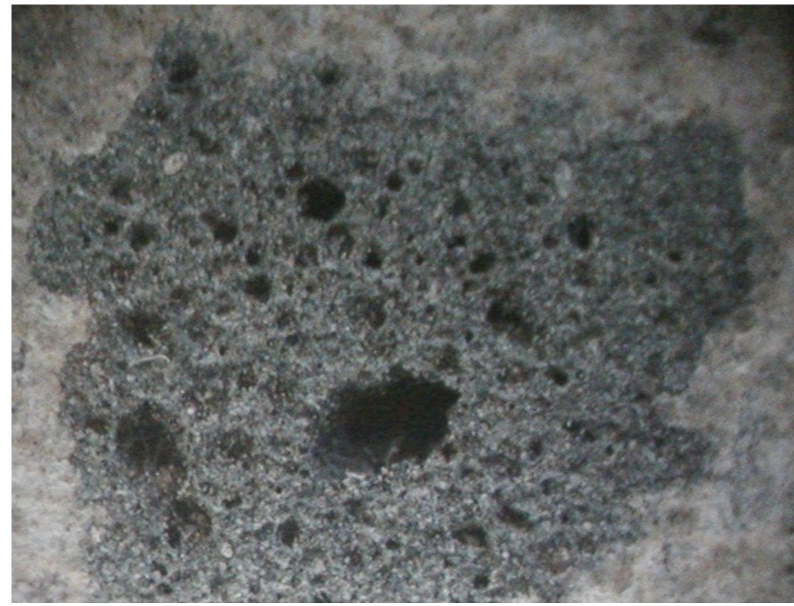
- **mechanical adhesion of the cementitious matrix to the aggregate surface**
- **physical and chemical characteristics of the layer of paste at the aggregate surface**

Critical to the structural and durability performance of the concrete

Contact Zone

Bond between cement paste and LWA is improved compared to normal-weight aggregates (NWA)

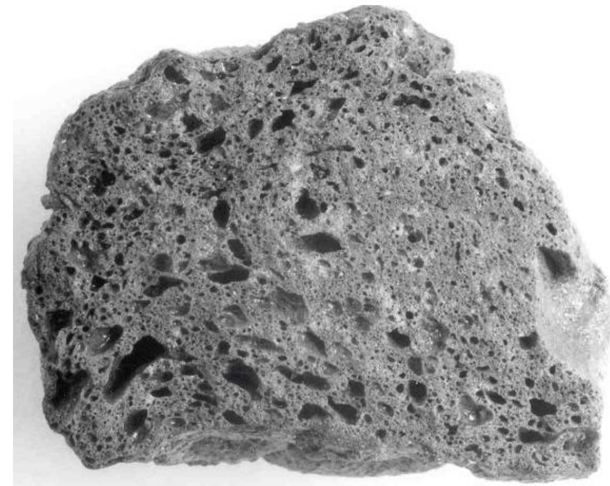
- **Cellular structure and irregular surface of LWA (mechanical bond)**
- **Slightly pozzolanic nature of LWA (chemical bond)**
- **Improves durability and structural behavior by reducing micro-cracking**



Internal Curing

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**



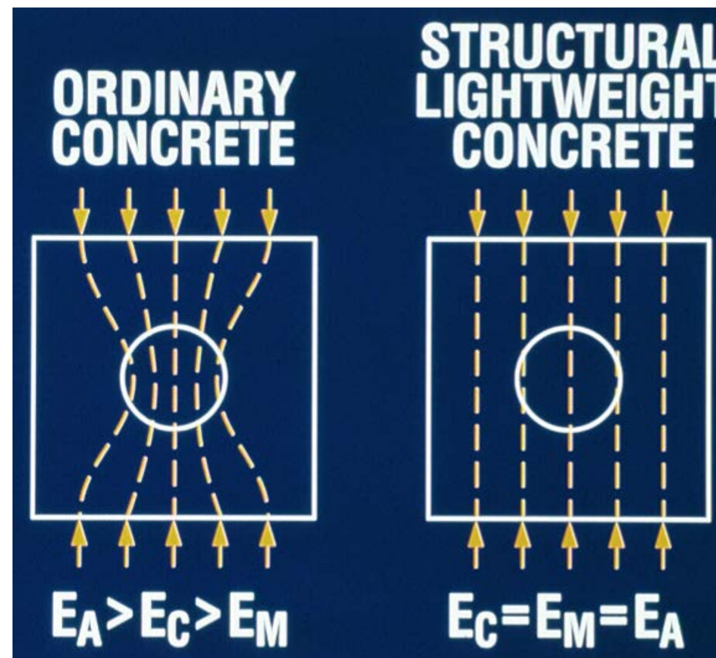
- **Improves durability and structural behavior**
- **Improves tolerance of concrete to improper curing**
- **Occurs with all types of LWC**

See Weiss, et al. (2012)

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 normal weight aggregate particles**
- **Reduces microcracking, autogenous shrinkage, and shrinkage cracking**
- **Improves durability by reducing micro-cracking**



Reduced Modulus of Elasticity

Modulus for LWC is typically 50 to 75% of the modulus for NWC of the same strength

Consider in design for camber, deflections & PS losses

Reduction is beneficial for decks & other elements where deformations are restrained

- Lower modulus results in lower stresses from restrained thermal & imposed deformations
- Reduces cracking tendency

Low modulus aggregates were recommended to reduce early age deck cracking by Brown, et al., in NCHRP Report 380 (1995)

Modulus of Elasticity, Ec

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

Average as % of Control value	93%	69%	49%

Data from study by Byard & Schindler (2010)

Coefficient of Thermal Expansion, CTE

The CTE for LWC is typically less than NWC

Typical values

- **NWC: 4.7 to 6.5 x 10^{-6} in./in./°F [ACI 209]**
- **LWC: 4 to 5 x 10^{-6} in./in./°F [ACI 213]**

AASHTO LRFD – Article 5.4.2.2

If better information is not available

- **NWC: 6.0 x 10^{-6} in./in./°F**
- **LWC: 5.0 x 10^{-6} in./in./°F**

Coefficient of Thermal Expansion, CTE

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

Average as % of Control value 95% 83% 66%

Data from study by Byard & Schindler (2010)

Concrete Cracking Tendency Tests

Research for ESCSI by Byard & Schindler (2010)

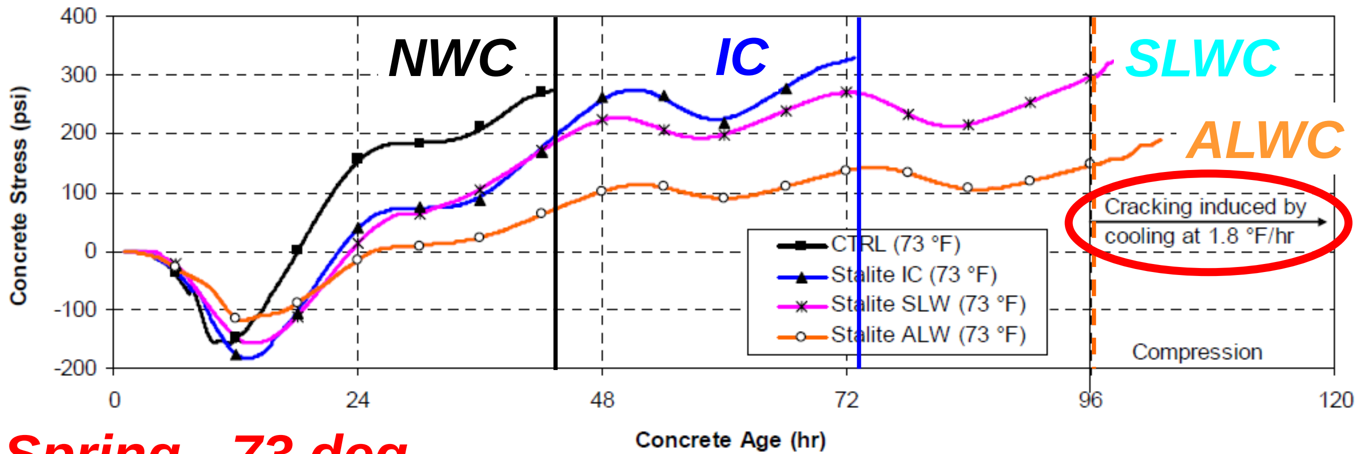
Testing uses cracking tendency frames

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

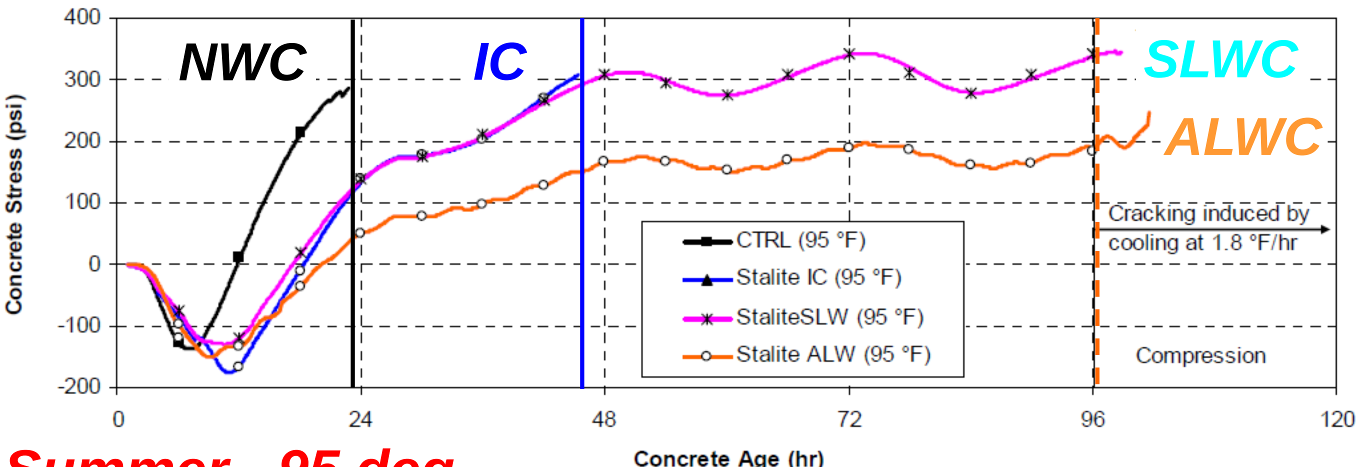
Mixtures tested

- **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)

Field and Laboratory Durability of LWC

- **Freezing-Thawing Resistance**
- **Resistance to Chloride Penetration**
- **Abrasion Resistance**

Freezing-Thawing Resistance

A comprehensive study of all major types of aggregate available to the New York Thruway was conducted by Walsh in 1959-1962.

Test slabs were subjected to over 200 cycles of freezing and thawing and over 100 applications of deicing chemicals over several years.

At the end of the study, the researcher noted that the LWC decks had superior performance.

Walsh (1967)

Freezing-Thawing Resistance

Conclusions of research study on LWC at Purdue Univ. (JTRP-98-17 V 2)

- **In general, resistance of LWC to freezing & thawing was far superior to the NWC used in the research**

Mix	LWCH	LWCHS	LWCHF	NWC
W/C	0.42	0.42	0.42	0.42
No air drying prior to testing				
No. of cycles	216	108	216	300
Durability Factor	0.50	0.21	0.45	0.74
With air drying prior to testing *In AASHTO M 195*				
No. of cycles	304	304	304	---
Durability Factor	0.96	0.92	0.99	---

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)

Resistance to Chloride Penetration

San Francisco-Oakland Bay Bridge upper deck

- Originally built with all LWC concrete in 1936 – still in service today – overlays have protected the LWC

Cores of upper deck taken in 1979

- Surface was highly contaminated with chloride
- Concentration < 1.0 lb/cy with depth
- No spalling on LWC decks

Cores of NW deck on approaches taken in 1984

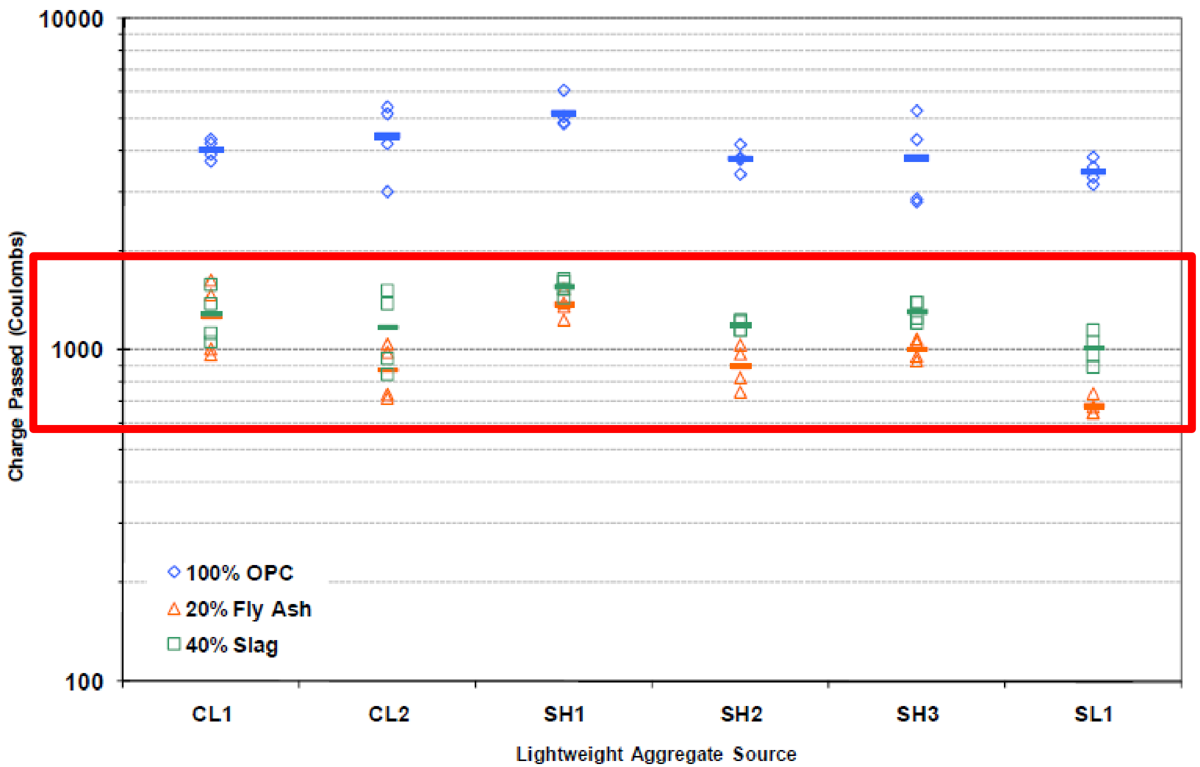
- Chloride content up to 10 lb/cy found to 4" depth
- Some spalling on NWC decks

TY Lin Int'l (1985)

Resistance to Chloride Penetration

Permeability test data - NCHRP Report 733, Appendix F

- Mixes with 0.40 w/cm and 752lb TCM



- LWC achieved good results with SCMs

Resistance to Chloride Penetration

From US Navy MHP Phase II Final Report

- **Each precast plant used a different LWA**

Table 19 – Chloride Ion Penetrability Based on the Cumulative Charge Passed After 6 Hours (56 Days and 365 Days of Curing) ***(According to ASTM C1202)***

Manufacturer	Type of Concrete	Maturity	Charge Passed (coulombs)[1]	Chloride Ion Penetrability
Coreslab	Light Weight	56 days	2589	Modrate
		365 days	561	Very Low
Bellingham	Light Weight	56 days	4324	High
		365 days	1061	Low
Clark Pacific Co.	Light Weight	56 days	1317	Low
		365 days	333	Very Low

[1] *Navy Target Criteria was not to exceed 1500 coulombs @ 60 days.*

- **LWC can achieve good results at 56 days**
- **Significant reduction in results with age**

Abrasion Resistance

LA Abrasion Test results from NCDOT Approved Coarse Aggregate list (2013)

- **Average all 175 sources** **31.3%**
- **Range all sources** **12% to 53%**
- **Stalite - Gold Hill** **31%**
- **Stalite - Aquadale** **27%**

NCDOT requirements - Std Specs 1014-2 (D)

- **General requirement** **55%**
- **for f'_c > 6 ksi** **40%**

Long-Term Performance – Project Examples

- Boulevard Bridge, Richmond, VA
- Suwanee River Bridge, FL
- Lewis & Clark Bridge / Columbia River, OR & WA
- US 17 over York River, Yorktown, VA
- San Francisco – Oakland Bay Bridge, CA
- Coronado Bridge, San Diego, CA
- Francis Scott Key Bridge, Baltimore, MD
- I-26 over Green River, Flat Rock, NC
- Segmental Bridges in US & CA

Boulevard Bridge, Richmond, VA

- Two lane toll bridge
- All LWC deck replaced after 34 yrs in service (100 pcf)
- LWA was exposed

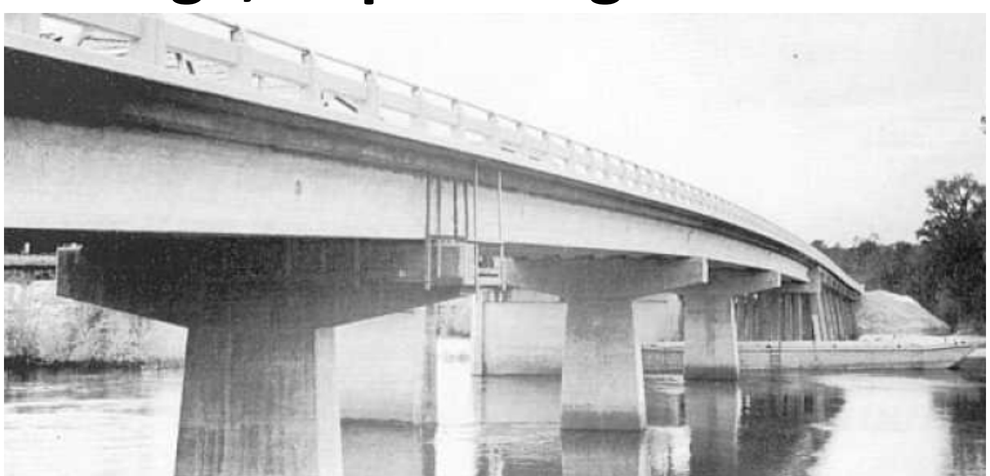
- Wear was minimal
- Wear was uniform
- No deterioration
- No corrosion

Suwanee River Br. at Fanning Springs, FL

In 1964, FDOT built their first bridge with sand LWC girders and deck over the Suwanee River at Fanning Springs

In 1968, FDOT tested the bridge to evaluate behavior of the LWC elements

In 1992, after 28 years in service, FDOT retested the bridge, duplicating the initial tests



Suwanee River Br. at Fanning Springs, FL

After comparing data from the two tests, researchers concluded:

"Deflection and strain data, when taken as a whole, indicate no increase in flexibility over time. When measurement uncertainty is included, most of the individual measurements may be considered as essentially the same."

These tests showed that this bridge experienced no degradation in behavior from fatigue or other effects

Brown, et al. (1995)

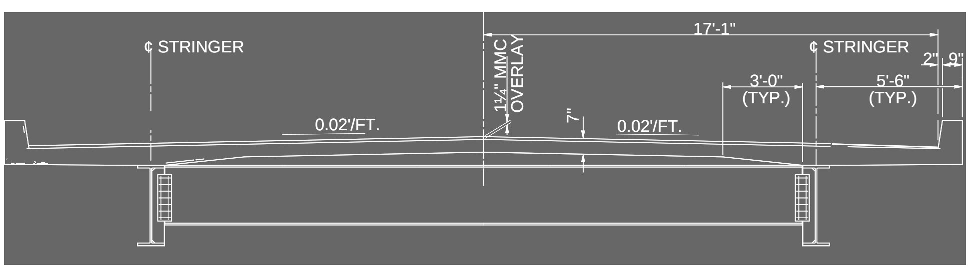
Lewis & Clark Br. / Columbia River, OR & WA

Deck was replaced in early 2000s with ABC techniques

- **LWC was used for new deck**
- **Panels weighed about 5% less than original**

Bridge was constructed in 1930s

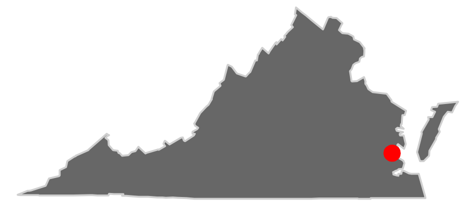
- **Original deck was LWC – lasted about 70 years**



US 17 over York River, Yorktown, VA

Original structure completed in 1952

- 26 ft wide with 2 lanes



Bridge replaced in 1996

- 74 ft wide with 4 lanes and shoulders

Sand LWC deck option was selected based on cost savings and good experience in VA

With reduced deck weight

- The pier caps only had to be widened
- Reduced structural steel

Castrodale & Robinson (2008)

US 17 over York River, Yorktown, VA

Ground and transversely grooved

San Francisco-Oakland Bay Bridge, CA

Early use of LWC in a bridge project

- **Built in 1936 using all LWC for the upper deck of suspension spans**
- **Lower deck was reconfigured for highway traffic in 1958 using LWC**
- **Both decks are still in service today**

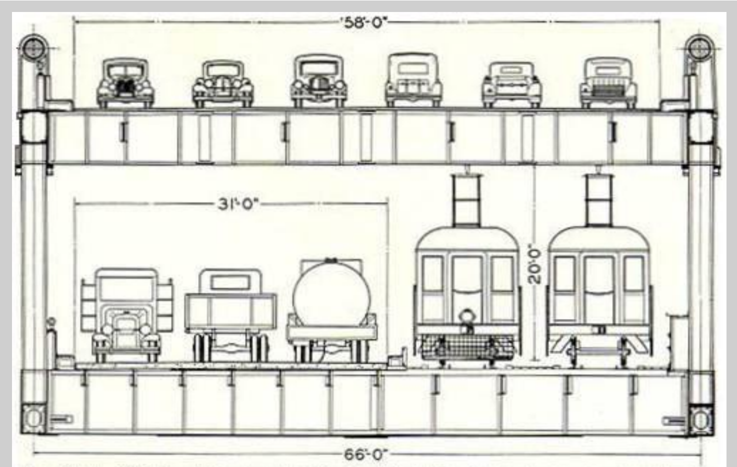


PLATE No. 4—The bridge will have two decks. The top deck will have six lanes for passenger automobiles; the lower deck will have three lanes for trucks and buses—it will also have two standard gauge electric railway tracks.

Coronado Bridge, San Diego, CA

Constructed in 1969

Prestressed concrete girders used for approach spans

Concrete properties

- f'_c up to 6,000 psi; air-dry density = 115 pcf

LWC allowed economical shipping from prestress plant located > 100 miles from site

- Girders up to 117 ft long shipped by truck
- 151 ft long girders shipped by rail

Still in service after over 40 years

ESCSI (2001)

Francis Scott Key Bridge - Baltimore, MD

I-695 over the Baltimore Harbor

- **Opened to traffic in 1977**
- **8,636 ft main structure**
- **1,200 ft main span with 722 ft back spans**
- **> 12 M vehicle crossings each year**

Sand LWC deck is exposed - no wearing surface

- **112 pcf fresh**
- **108 pcf air dry**
- **Nearly 40 yrs in service**
- **No major deck work**

Wolfe (2008)

I-26 / Green River, East Flat Rock, NC

Bridges built in 1968

Continuous steel girders & floor beams

- LWC deck on 3 main spans

Bridge Length:	1,050 ft
Main Span:	330 ft
Deck width:	34.8 ft
No. of Lanes :	2

ADT: 24,500 in 2004

Deck Rating (2008): 6

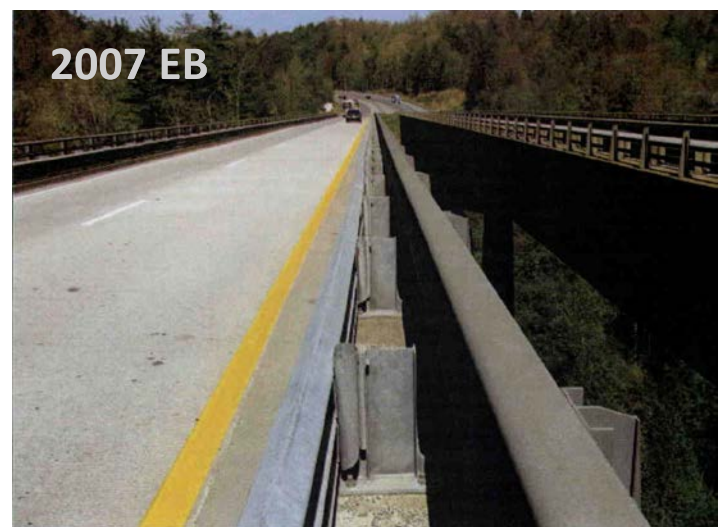


Photo from NCDOT inspection report

Castrodale & Robinson (2008)

LWC Segmental Conc. Bridges in US & CA

Bridge	Year Built	Max. Span	Depth @ Midspan	Depth @ Pier
Corpus Christi – TX *	1972			
Pine Valley – CA *	1974	450’		
Napa River – CA	1977	250’	7.75’	12.0’
Parrots Ferry – CA	1979	640’	8.0’	32.0’
Lake Nokoma – CA	1999	328’	7.4’	18.0’
Benicia-Martinez – CA	2008	659’	14.9’	37.4’
* - LWC not used for these bridges				

References (1)

Castrodale, R. W., and K. S. Harmon. 2008. "Durability of Lightweight Concrete Bridges," Paper 48, *The PCI-FHWA National Bridge Conference, Orlando, Fla*., PCI, Chicago.

T.Y. Lin International. 1985. *Criteria for Designing Lightweight Concrete Bridges.* FHWA-RD-85-045. McLean, Va.: Federal Highway Administration.

Gerwick, B. C., Jr. 1985. "Lessons from an Exciting Decade of Concrete Sea Structures," *Concrete International*, V. 7, No. 8, August, pp. 34-37.

Weiss, J., Bentz, D., Schindler, A. and P. Lura. 2012. "Internal Curing – Constructing More Robust Concrete," *STRUCTURE*, January, pp. 10, 12-14.

Krauss, P. D., and Rogalla, E. A. 1996. *Transverse Cracking in Newly Constructed Bridge Decks.* Report 380. National Cooperative Highway Research Program. Washington, DC: Transportation Research Board.

Byard, B. E., and A. K. Schindler. 2010. *Cracking Tendency of Lightweight Concrete*. Auburn, AL: Highway Research Center.

References (2)

Walsh, R. J. 1967. “Restoring Salt-Damaged Bridges,” *Civil Engineering-ASCE*. V. 37, No. 5, May 1967, pp. 57-59.

Ramirez, J., Olek, J., Rolle, E., and Malone, B. 2000. *Performance of Bridge Decks and Girders with Lightweight Aggregate Concrete.* Report FHWA/IN/JTRP-98/17, Joint Transportation Research Program. Purdue University, West Lafayette, Ind. (2 volumes).

ESCSI. 2001. “Back-up Statistics to Building Bridges and Marine Structures with Structural Lightweight Concrete,” Information Sheet # 4700.4, Expanded Shale, Clay and Slate Institute (ESCSI), Chicago, Ill.

Cousins, T., Roberts-Wollmann, C. & Brown, M.C. 2013. *High-Performance/High-Strength Lightweight Concrete for Bridge Girders and Decks*. Report 733. National Cooperative Highway Research Program. Washington, DC: Transportation Research Board.

References (3)

Brown, W. R., III, Larsen, T. J., and Holm, T. A., "Long-Term Service Performance of Lightweight Concrete Bridge Structures," *International Symposium on Structural Lightweight Aggregate Concrete*, Sandefjord, Norway, June 1995, pp. 167-184. *Reprint is available for download at www.ESCSI.org*.

Castrodale, R.W. & Robinson, G.M. 2008. “Performance of Lightweight Concrete Bridge Decks,” Paper 75, *Concrete Bridge Conference*, St. Louis, Ill., May 2008. Skokie, IL: National Concrete Bridge Council.

Wolfe, W. H. 2008. “Lightweight Concrete Bridge Deck Performance in Severe Climates,” Lightweight Concrete Workshop at the Concrete Bridge Conference, St. Louis, Ill., May 2008.

Thank you!

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