Lightweight Concrete for Long Span Bridges

WBES

September 25, 2007

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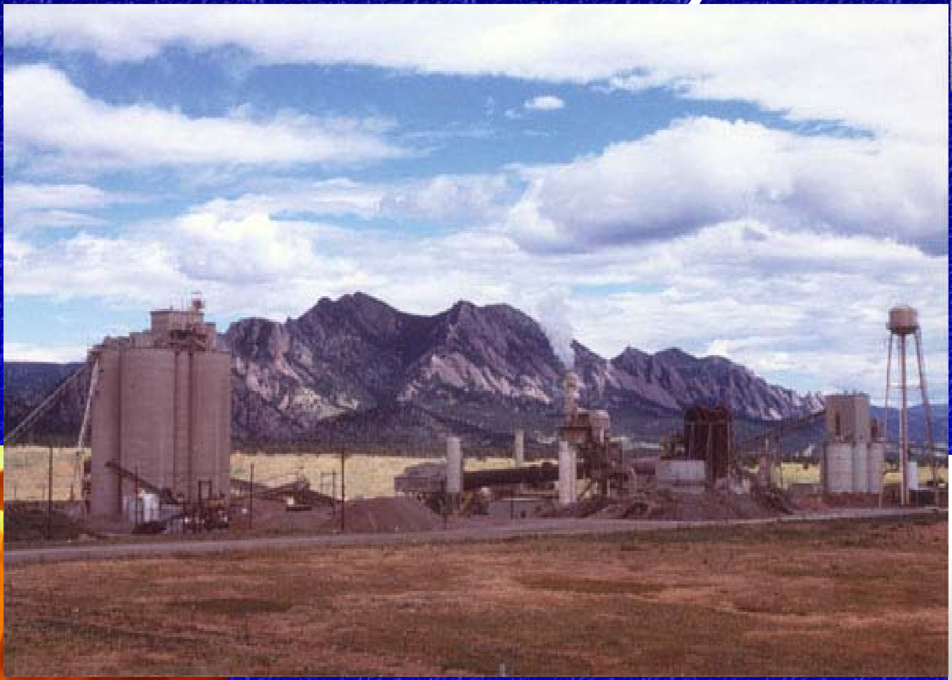
TXI

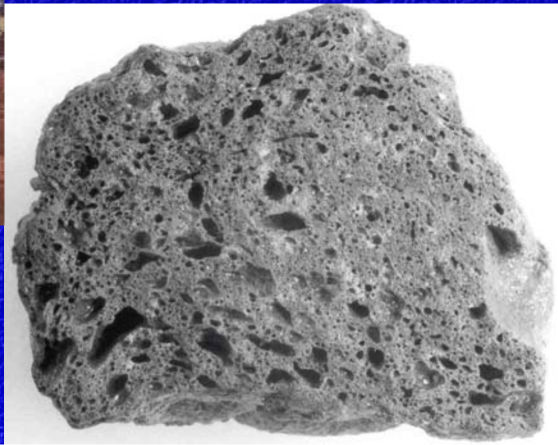
Dallas, TX

Structural Lightweight Aggregate

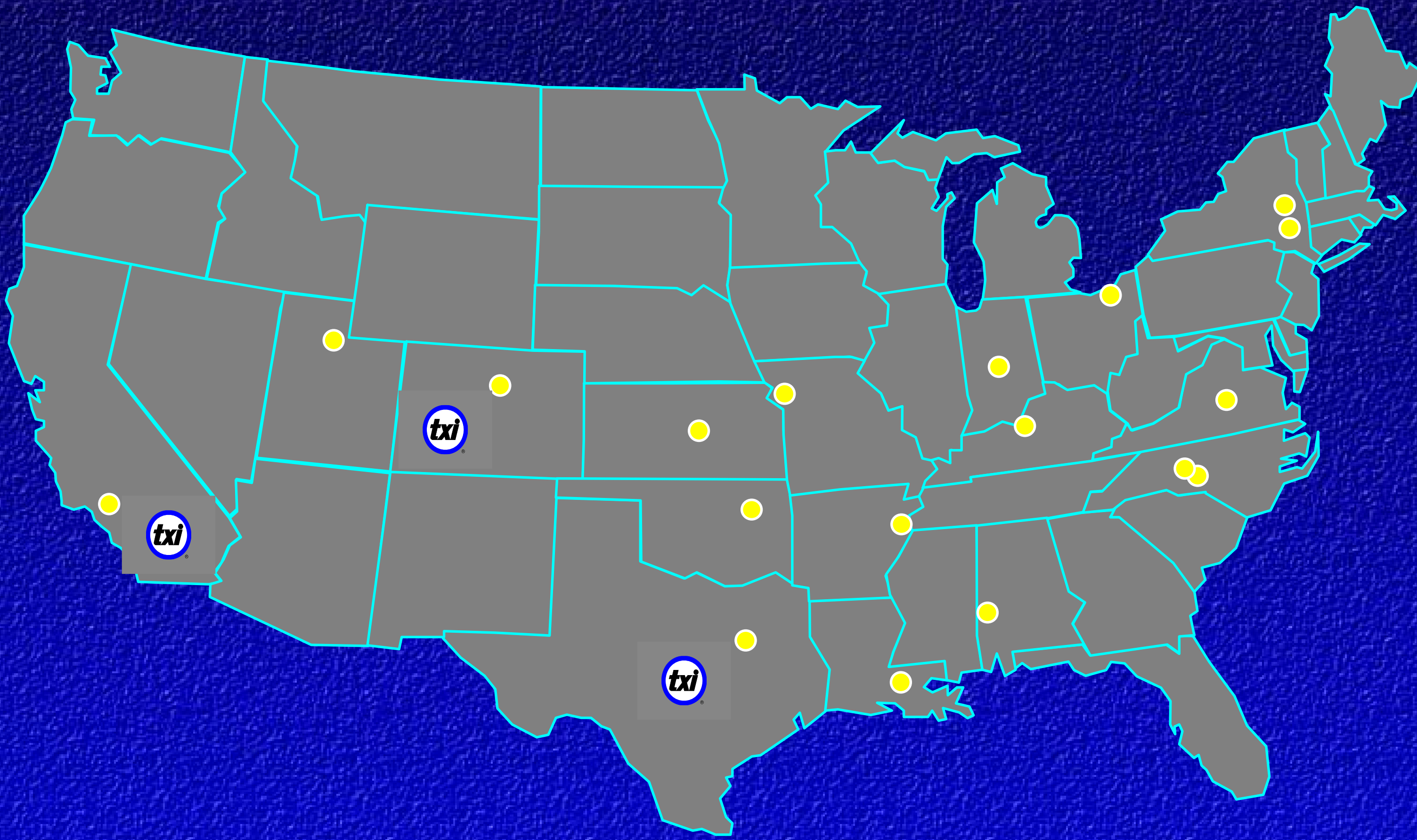
Manufactured aggregate

- ***Expanded shale, clay or slate***
- ***Manufactured in a rotary kiln***





ESCS Manufacturing Plants in US



18 plants in the US

See www.escsi.org for all locations

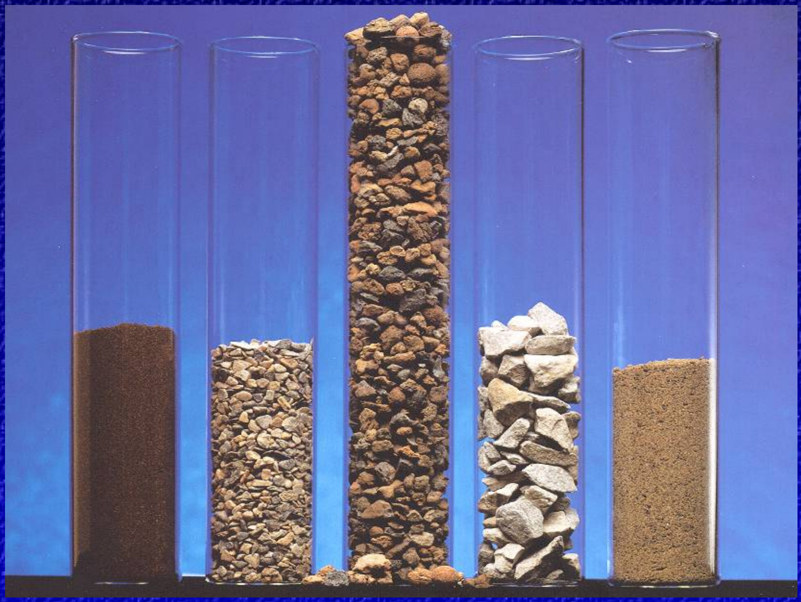
Relative Density of Lightweight vs. Normalweight Aggregate

Lightweight aggregates expanded in a rotary kiln

- ***Range from 1.3 to 1.6***

Normalweight aggregates

- ***Range from 2.5 to 3.0***



Soil Gravel ESCS Agg. Limestone Sand

1 lb. of each material

Definitions of Lightweight & Normal Weight Concrete

Lightweight concrete

- ***Typical density range of 103 to 125 pcf***
- ***AASHTO LRFD Specs: "… air-dry unit weight not exceeding 0.120 kcf …"***
- ***"All lightweight" – fine and coarse aggregates are lightweight***
- ***"Sand lightweight" – lightweight coarse aggregate and normal weight sand***
- ***Density is checked during casting***

Definitions of Lightweight & Normal Weight Concrete

Lightweight concrete

- ***Typical density range of 103 to 125 pcf***
- ***AASHTO LRFD Specs: "… air-dry unit weight not exceeding 0.120 kcf …"***

Normal weight concrete

- ***Typical density range of 140 to 150 pcf***
- ***AASHTO LRFD Specs: "Concrete having a weight between 0.135 and 0.155 kcf."***
- ***Density is not a criteria for acceptance***

Density Range of Structural Concrete

Lightweight concrete

- ***110 to 125 lbs per cubic foot***

Normalweight concrete

- ***140 to 150 lbs per cubic foot (155 in WA)***

Specified density concrete

- ***Between the above ranges***
- ***Combination of LW and NW aggregates***
- ***Especially useful for reducing loads for handling, transportation and erection***
- ***Not in design specifications***

Specifying Density of Lightweight Concrete

"Equilibrium density" of LWC is now specified

- *Equilibrium density defined in ASTM C 567*
  - *Density after moisture loss has occurred*
  - *Calculation is standard method for estimating*

"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*

Be sure to add reinforcement allowance when computing dead loads (typically 5 pcf)

Specifying Density of Lightweight Concrete for Bridges

114 – 132 pcf	*Fresh*
	4-12 pcf difference
110 – 125 pcf	*Equilibrium*
	3 pcf difference
107-122 pcf	*Owen Dry*

Design Compressive Strengths for LWC

Minimum compressive strength by ASTM

- ***2,500 psi***

Most ESCS LWA can achieve

- ***5,000 psi***

Some ESCS LWA may achieve

- ***7,000 to 10,000 psi***

Work with LWA supplier to get mix design with desired strength, density and other properties

Density Range of Structural Concrete

Table 1 Concrete Densities for Range of Compressive Strengths (Castrodale & Harmon – PCI 2007)

Concrete Strength	LWC Density	NWC Density	% Reduction in Density
4.5 ksi (Deck)	112 pcf	145 pcf	22.8%
6 ksi	115 pcf	146 pcf	21.2%
8 ksi	117 pcf	148 pcf	20.9%
10 ksi	122 pcf	150 pcf	18.7%

Notes:

LWC densities are equilibrium densities

NWC densities are computed using LRFD equations

Density Range of Structural Concrete

Table 1 Concrete Densities for Range of Compressive Strengths (Castrodale & Harmon – PCI 2007)

Concrete Strength	LWC Density	NWC Density	% Reduction in Density
4.5 ksi (Deck)	112 pcf	150 pcf	25.3%
6 ksi	115 pcf	151 pcf	23.8%
8 ksi	117 pcf	153 pcf	23.5%
10 ksi	122 pcf	155 pcf	21.3%

Notes:

LWC densities are equilibrium densities

NWC densities are increased based on WSDOT practice

Design Considerations

Specifications address LWC

- **Modifiers for shear, development len., etc.**
  - **Can typically design for them**
- **Reduced modulus of elasticity**
  - **Increases elastic shortening loss & cambers**
  - **Can be beneficial for substructures & decks**
- **Time dependent effects: CR, SH & Losses**
  - **Current research is demonstrating that these effects are not significantly different for HS LWC**

Specifications do not address SDC

Why use LWC in Bridges?

- *Improved structural efficiency by reducing weight (dead load) of structure*
- *Reduced handling, transportation and erection costs for precast components*
- *Enhanced durability*

Which lead to

- *Reduced initial and long-term costs*
- *Accelerated project delivery in some cases*

Improved Structural Efficiency

Using LWC typically reduces structure weight 15 to 25% compared to normalweight concrete

- ***Increased spans or wider girder spacings***
- ***Reduced structure mass for seismic designs***
- ***Reduced foundation and bearing loads***
- ***Reduced reinforcement and prestressing***
- ***Increased deck width on existing superstructure***
- ***Increased live load rating with existing superstructure***

Reduced Weight of Precast Components

Improved construction efficiency

- Reduced handling loads in the plant
- Reduced shipping loads
- Reduced number of shipments
- Reduced erection loads
- Larger pieces for same weight

Reduced loads or shipments mean

- Reduced equipment requirements
- Reduced costs

Accelerated Bridge Construction with LWC

Achieved by reducing construction time and improving structural efficiency

- ***Lighter pieces to handle, ship and erect***
- ***Bigger precast pieces = fewer pieces***
- ***Fewer shipments to site = reduced shipping cost & congestion at site***
- ***Fewer spans and substructure units***
- ***Fewer piles and/or smaller footings***
- ***Reduce or eliminate modifications to existing structure for rehabs***

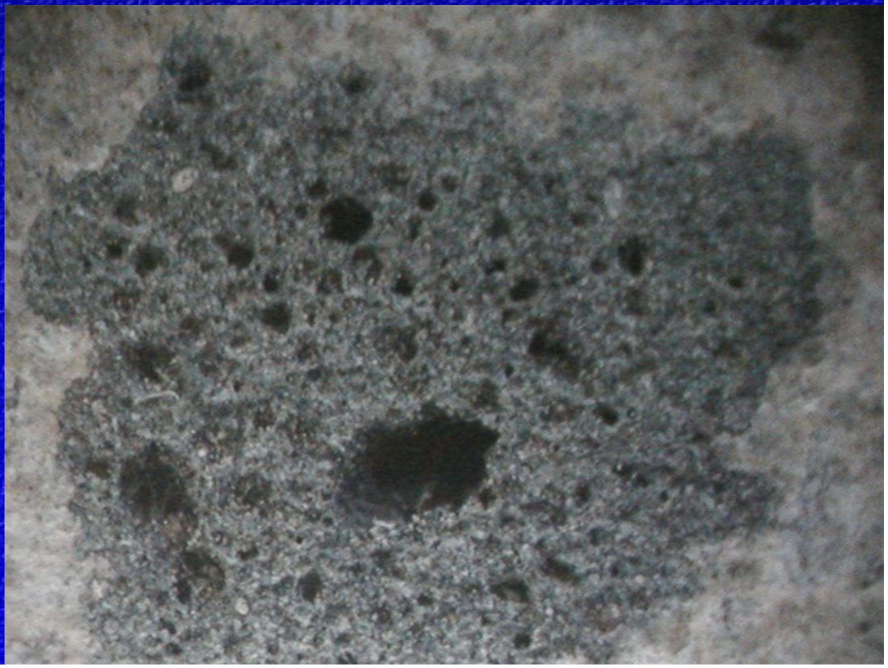
Enhanced Durability

- Bond between aggregate and paste
- Elastic compatibility
- Internal curing
- Reduced modulus of elasticity
- Freeze-thaw performance
- Resistance to chloride intrusion
- Wear and skid resistance

Bond between Aggregate and Paste

Improved bond between cement paste and lightweight aggregates

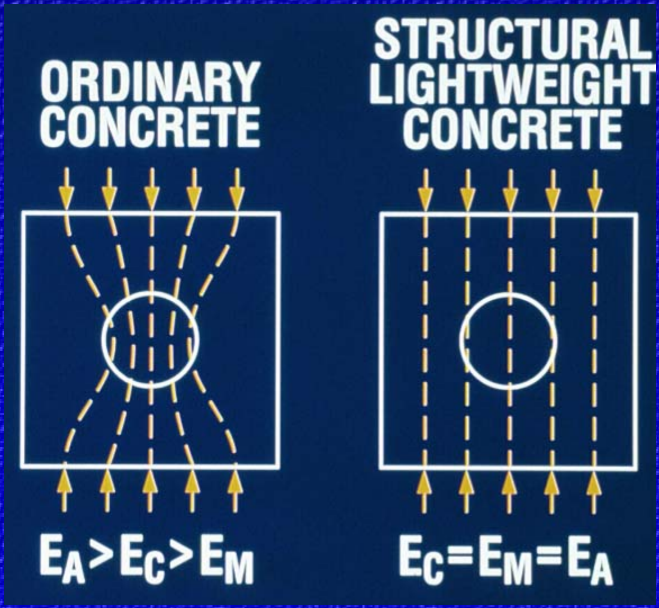
- ***Cellular structure and irregular surface of aggregate (mechanical bond)***
- ***Chemistry of the aggregates and cement (pozzolanic bond)***
- ***Transition zone***
- ***Improves durability by reducing micro-cracking***



Elastic Compatibility

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

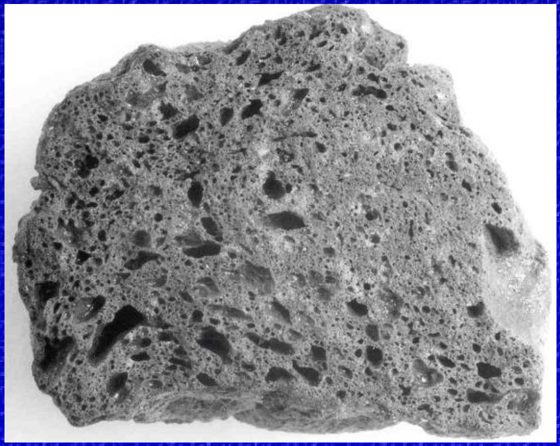
- ***Reduces stress concentrations that form around stiffer normalweight aggregate***
- ***Reduces microcracking, autogenous shrinkage, and shrinkage cracking***
- ***Improves durability by reducing micro-cracking***



Internal Curing

Absorbed moisture within lightweight aggregate 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*
  - *Can reduce shrinkage*
- *Improves tolerance of concrete to improper curing*



Reduced Modulus of Elasticity

NCHRP Report 380 "Transverse Cracking in Newly Constructed Bridge Decks" (1996)

- ***"Using low-elasticity aggregates should therefore reduce thermal and shrinkage stresses, and the risk or severity of transverse cracking."***
- ***Recommends using concretes with a low cracking tendency***
  - ***Low early modulus of elasticity***
  - ***Low early strength concrete***

Lightweight concrete provides lower modulus but retains strength and durability

Durability and Safety

LWC bridge decks have demonstrated

- *Excellent freezing and thawing performance even when lightweight aggregate is exposed*
- *Excellent resistance to chloride penetration at level of reinforcement*
- *Uniform wear*
- *Non-polishing aggregate*
- *High skid resistance*
- *Quieter pavement?*

Resistance to Chloride Intrusion

LWC has improved resistance to Cl^- intrusion

Silver Creek Overpass, UT constructed in 1968

Chloride content after 23½ years in service

Depth	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	

Resistance to Chloride Intrusion

San Francisco-Oakland Bay Bridge

- Upper deck constructed with lightweight concrete in 1936 – still in service today

Cores of LW upper deck taken in 1979

- Surface was highly contaminated with Cl^-
- Concentration < 1.0 lb/cy with depth
- No spalling

Cores of NW deck on approaches taken in 1984

- Cl^- content up to 10 lb/cy found to 4" depth
- Some spalling on NW decks

Boulevard Bridge, Richmond, VA

- Two lane bridge
- LWC deck
- Replaced after 34 years in service

- Minimal wear
- Uniform wear
- No deterioration
- No corrosion

Examples of Bridge Construction Projects using LWC

Rehabilitation Projects

New Construction

Woodrow Wilson Bridge, Washington, DC

Deck replaced in 1983

LWC full depth deck panels

- Allowed thicker slabs
  - Improved stiffness and durability
- Allowed wider deck
  - 38 ft to 44 ft roadway width
- Improvements could be made without strengthening the existing superstructure
- Precast decks reduced impact on traffic

No deterioration after 13 years of service

Lewis & Clark Bridge, OR & WA

Completed in 2004

Deck replacement on existing truss spans

Full-width precast deck units with steel floorbeam system were prefabricated to speed construction

LWC was used to

- *Reduce weight for installation of units*
- *Reduce load on existing truss spans*

Coleman Bridge, 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*

Lightweight 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 the steel required in new trusses*

San Francisco-Oakland Bay Bridge, CA

Completed in 1936

Upper deck was LWC

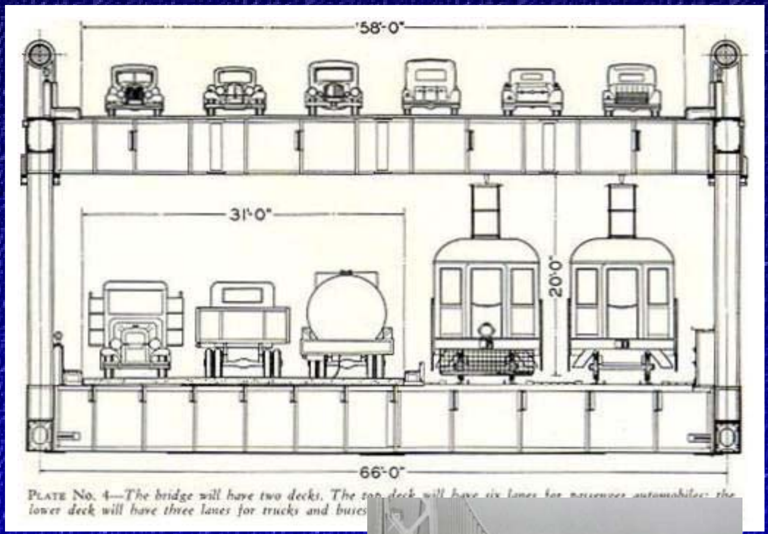
- *Reduced load on bridge*

Lower deck reconfigured for highway traffic in 1958

New lower deck was LWC

- *Reduced load on bridge*

Both LWC decks are still in service



Chesapeake Bay Bridges, Annapolis, MD

First bridge built in 1952

LWC deck in suspension spans

- Reduced load on bridge

NWC decks were deteriorated in 1975

- Replaced with LWC decks

Second bridge built in 1975

- LWC in all decks because of good performance on first bridge

US 23-119 over Shelby Creek, KY

Completed in 1991

SDC for spliced girders to achieve 218'-6" spans

- Alternate design to a steel structure
- Reduced weight for handling (125 - 130 pcf)
- Largest girder > 72 tons

Trendsetting bridge still in service

Route 33 Bridges at West Point, VA

Two demonstration projects now completed

LWC girders and decks

- Large bulb-tee approach spans
- Two 200'-240'-240'-200' spliced units with haunched pier segments on each bridge
- Reduced foundation requirements

Research being conducted with project

LWC CIP Segmental Box Girder Bridges in CA

Parrots Ferry Bridge (1978)
Northern CA

Napa River Bridge (1977)
Napa, CA

New Benicia-Martinez Bridge (2007)
Also LWC Deck on Ex. Truss (1962)

Raftsundet Bridge, Norway

Variable depth, cast-in-place, post-tensioned, segmental concrete box girder bridge

Four span continuous unit crossing a deep fjord used for shipping

Constructed using balanced cantilever method

Located 186 miles north of the Arctic Circle

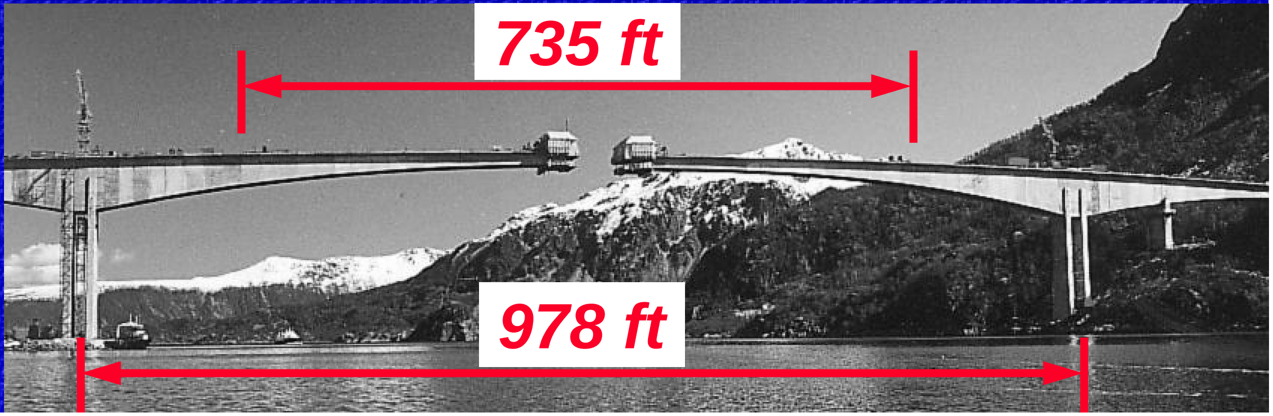
Bridge opened in 1998

Raftsundet Bridge, Norway

The central 735 ft (224 m) of the main span is high performance lightweight concrete

- *Hardened density of 125 lb/ft^3 (19.75 kN)*
- *28-day compressive strength (cube) of more than 8,700 psi (60 MPa)*

A significant testing program proved that lightweight concrete could be successfully pumped



Floating Bridges

Bergsøysundet Bridge - Norway

- Completed in 1992
- 7 LWC pontoons in 844 m floating portion
- Pontoons are 34 x 20 x 5 to 7 m

Nordhordland Bridge – Norway

- Completed in 1994
- 10 LWC pontoons in 1246 m floating portion
- Pontoons are 42 x 20.5 x 7.38 m
- LWC deck in cable-stay main span

Floating Bridges

Norwegian floating bridges

- Same LWC specification for both bridges
- LWC used to reduce draft
  - Ecological considerations
  - Reduced wave loads

2nd Lake Washington Bridge (Evergreen Point)

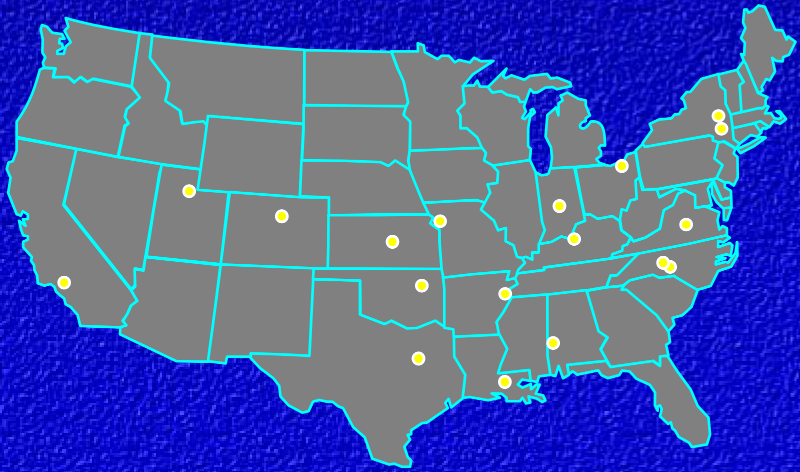
- Completed in 1963
- Some portion of pontoons is LWC
- Difficult to find information

Cost of Lightweight Concrete

Increased cost of aggregate

- Additional processing

- Shipping from the manufacturing plant



Cost Comparison for LW Concrete Deck

From Holm & Bremner, 2000		LWA & LWC	NWA & NWC	Relative Cost
		A	B	A/B (%)
Cost of coarse aggregate	\$/ton	45	10	450%
Coarse aggregate for 1 yd^3 of concrete	lb	900	1710	--
Cost of coarse aggregate for 1 yd^3 of concrete	\$/yd^3	20.25	8.50	238%
Cost increase with lightweight aggregate	\$/yd^3	11.75	--	--
Typical cost of concrete delivered to project, including small increase for additional cement in lightweight concrete	\$/yd^3	85	70	121%
Cost of concrete in-place, including formwork, reinforcement, conveying, finishing and curing	\$/yd^3	365	350	104%

LWA – Lightweight aggregate; LWC – Lightweight concrete
NWA – Normal weight aggregate; NWC – Normal weight concrete

Cost Premium for Lightweight Deck Concrete

Typical range of cost premium per CY of deck concrete

- Assuming 8 in. thick deck

Cost / CY	Cost / SF
$20 / CY	$0.49 / SF
$25 / CY	$0.62 / SF
$30 / CY	$0.74 / SF
$40 / CY	$0.99 / SF
$50 / CY	$1.23 / SF

Cost Premium for LWC Girders

- $30 / CY cost premium for LWC
- Girder spacing of 10 ft

Girder Section	Cost Prem. / LF	Cost Prem. / SF
PCEF XB3147	$5.39 / LF	$0.54 / SF
PCEF XB6347	$7.12 / LF	$0.71 / SF
PCEF XB9547	$8.85 / LF	$0.89 / SF
PCI BT-54	$5.08 / LF	$0.51 / SF
PCI BT-63	$5.50 / LF	$0.55 / SF
PCI BT-72	$5.92 / LF	$0.59 / SF

Cost Comparisons for Lightweight Concrete

Simple comparisons neglect important factors

- ***Reduced handling and transportation costs***
- ***Reduced erection costs***
- ***Reduced time of construction***
- ***Reduced strand and reinforcement***
    - ***For one bridge, a 20-25% reduction in post-tensioning has been estimated***
- ***Reduced cost of substructure & foundations***
    - ***For some bridges, a 10-20% reduction in pilings or foundation costs has been estimated***

Cost Comparisons for Lightweight Concrete

To take full advantage of potential cost reductions from using LWC

- *Typically requires a complete preliminary design including foundations*
- *Increased effort in early design phases*

Can pay large dividends in reduced construction costs

The real test ...

- *Many bridges have been successfully constructed using lightweight concrete*

Rugsundet Bridge, Norway

Completed in 2000

Using LWC in center span of box girder allowed design alternate

- Increased main span from 564 ft to 623 ft using same quantity of post-tensioning
- Moved foundations into shallower water or to the edge of the water
- Reduced length of ballast-filled side spans
- Shortened overall length of structure 33 ft

LWC alternate bid was 15% less than NWC bid

For more information, please call, or visit
www.txi.com or www.escsi.org

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