Chapter 9

High-Performance Lightweight Concrete

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CHAPTER 9

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9.5 The Federation International Du Beton has graciously granted Expanded Shale, Clay and Slate Institute (ESCSI) permission to present the following case study information on completed major lightweight concrete structural projects. This information is reported in the fib bulletin #8 "*Lightweight Aggregate Concrete",* fib, CP 88, CH-1015, Lausanne, Switzerland.

Appendix 9A *"Benefits of Lightweight HPC",* Holm and Ries, HPC Bridge Views Issue No. 17, Sept/Oct. 2001.

Appendix 9B *"Lightweight HPC on Route 106 Bridge in Virginia",* Ozyildirim, HPC Bridge Views, Issue No. 32, Mar/Apr. 2004

Appendix 9C *"Lightweight Aggregate Concrete in Norwegian Bridges",* Helland, HPC Bridge Views, Issue No. 11, Sept/Oct. 2000.

Chapter 9 High-Performance Lightweight Concrete

9.0 Introduction

While it is clearly understood that high strength and high performance are not synonymous, one may consider the first modern use of high-performance concrete to be when the American Emergency Fleet Corporation built lightweight concrete ships with specified compressive strengths of 5,000 psi (35 MPa) during 1917 to 1920. Commercial normalweight concrete strengths of that time were approximately 2,500 psi (17 MPa).

Lightweight concrete has achieved high strength levels by incorporating various pozzolans (fly ash, silica fume, metakaolin, calcined clays, and shales) combined with mid-range and/or high-range water-reducing admixtures. Because of the durability concerns the w/cm for bridges and marine structures has been specified to be less than 0.45, and for severe environments, a significantly lower w/cm has been specified.

While structural lightweight aggregates are capable of producing concrete with compressive strengths in excess of 5,000 psi (35 MPa), several lightweight aggregates have been used in concrete that developed compressive strengths from 7,000 to 10,000 psi (48 to more than 69 MPa). In general, an increase in density will be necessary when developing higher compressive strengths. High-strength lightweight concrete with compressive strengths of 6,000 psi (41 MPa) is widely available commercially and testing programs on lightweight concrete with a compressive strength exceeding 10,000 psi (69 MPa) are ongoing.

9.1 Structural Efficiency of Lightweight Concrete

The entire hull structure of the USS Selma and 14 other concrete ships were constructed with 5,000 psi, high-performance lightweight concrete in the ship building program in Mobile, Alabama starting in 1917. The structural efficiency as defined by the strength/density (S/D) ratio of the concrete used in the USS Selma was extraordinary then and now. Improvements in structural efficiency of concrete since that time are shown schematically in Figure 9.1 and show an upward trend with the introduction of prestressed concrete, followed by other high-strength concrete applications. Most increases came as a result of improvements in the cementitious matrix brought about by new generations of admixtures such as high-range water-reducers, and the incorporation of high-quality pozzolans such as silica fume, metakaolin, and fly ash. History reveals, however, that the first major breakthrough came as a result of the lightweight concrete ship-building program in 1917.

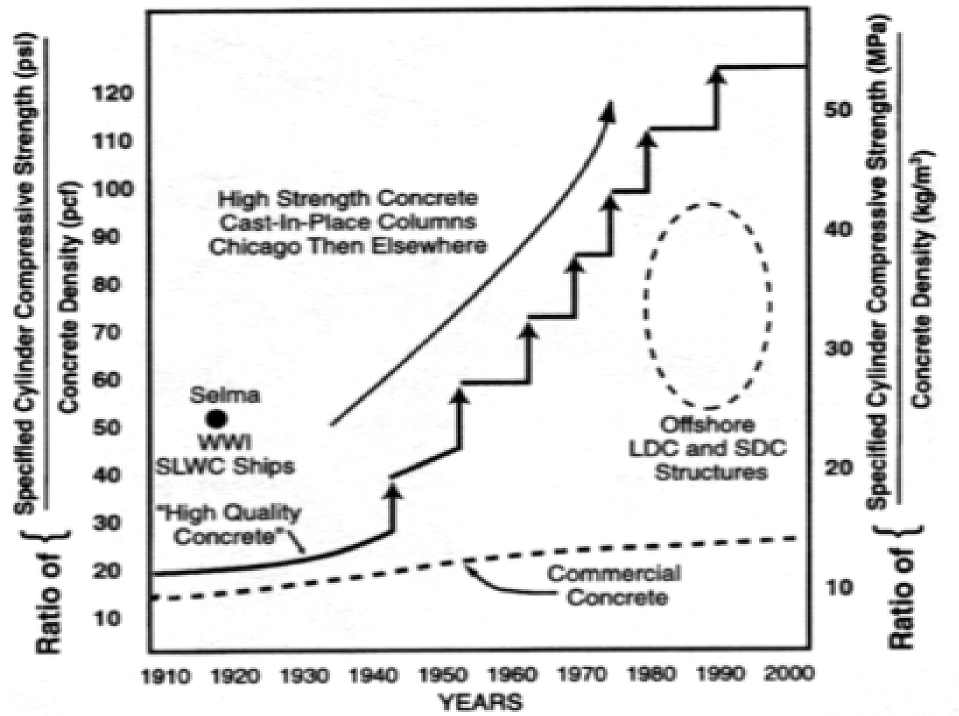


Figure 9.1. ***The structural efficiency of concrete. The ratio of specified compressive strength to density (psi/ [lb/ft³]) (Holm and Bremner 1994).***

9.2 Applications of High-Performance Lightweight Concrete in Building Frames

Among the thousands of structures in North America incorporating high-strength lightweight concrete, the following examples have been selected for their pioneering and unique characteristics.

Post-Tensioned Federal Post Office and Office Building

The 450 ft (140 m) multipurpose building constructed in 1967 with five post-tensioned office floors and 27 office tower floors was the first major New York City building application of post-tensioned floor slabs. Concrete tensioning strengths of 3,500 psi (24 MPa) were routinely achieved for 3 days for the 30 x 30 ft (9 x 9 m) floor slabs with a design target strength of 6,000 psi (41 MPa) at 28 days. Approximately 30,000 yd^3 (23,000 m^3) of lightweight concrete were incorporated into the floors and the cast-in-place architectural envelope, which serves a structural as well as an aesthetic function. (Holm and Bremner 1993).

The North Pier Apartment Tower, Chicago, 1991

This project used high-performance lightweight concrete floor slabs as an innovative structural solution to avoid construction problems associated with the load transfer from high-strength normalweight concrete columns through the floor slab system. ACI 318 requires a maximum ratio of column compressive strength, which in this project was 9,000 psi (62 MPa) and the intervening floor slab concrete to be less than 1.4. By using high-strength lightweight concrete in the slabs with a strength greater than 6,430 psi (44 MPa), the floor slabs could be placed using routine placement techniques, thus avoiding scheduling problems associated with the mushroom technique (Fig 9.2). In the mushroom technique, the high-strength column concrete is overflowed from the column and intermingled with the floor slab concrete. The simple technique of using high-strength floor slab concrete in the North Pier project avoided delicate timing considerations that were necessary to avoid cold joints (Holm and Bremner 1994).

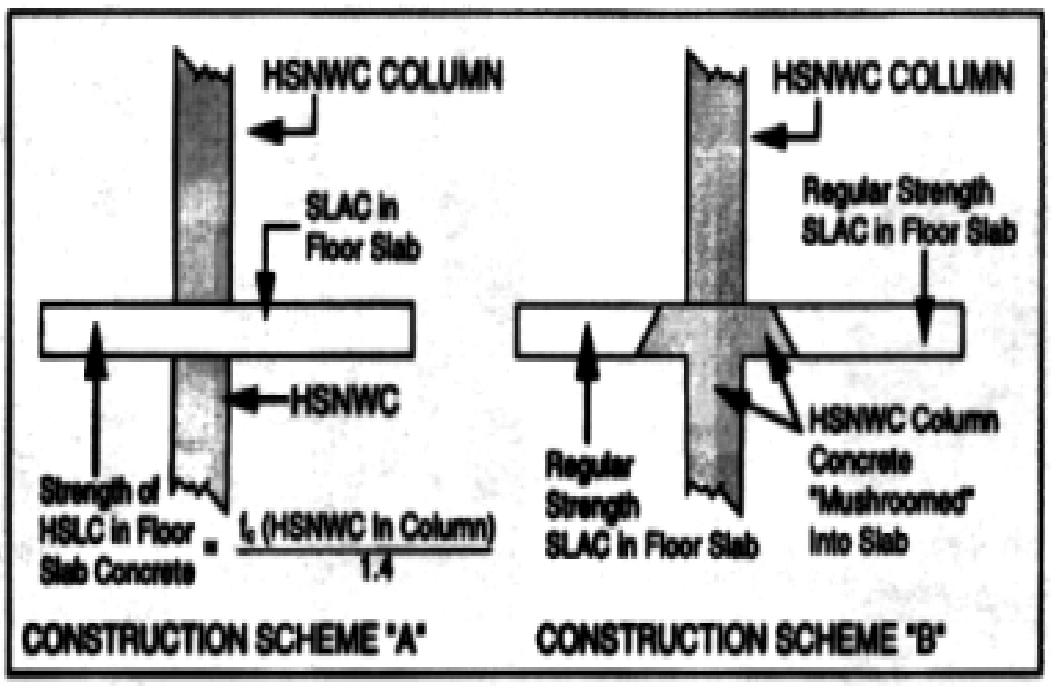


Figure 9.2. ***Alternative construction schemes for transfer of high-strength normalweight concrete column loads through floor slabs (Holm and Bremner 1994)***

The Bank of America, Charlotte, N.C.
This concrete structure is one of the tallest buildings in the southeastern United States with a high-strength concrete floor system consisting of 4-5/8 in. (117 m) thick slabs supported on 18 in. (460 mm) deep post-tensioned lightweight concrete beams centered on 10 ft (3.0 m). The lightweight concrete floor system was selected to minimize the dead weight and to achieve the required 3 hour fire rating (Fig. 9.3 and Table 9.1).

Figure 9.3. ***Bank of America, Charlotte, N.C. (from Holm and Bremner 1994, with permission of Edward Arnold Publishers, London).***

Table 9.1. Mixture proportions and physical properties for concrete pumped on Bank of America project, Charlotte, N.C., 1991

Mixture no.	1	2	3
Mixture proportions			
Cement, Type III, lb/yd³ (kg/m³)	550 (326)	650 (385)	750 (445)
Fly ash, lb/yd³ (kg/m³)	140 (83)	140 (83)	140 (83)
LWA 20 mm to No. 5 lb/yd³ (kg/m³)	900 (534	900 (534)	900 (534)
Sand, lb/yd³ (kg/m³)	1370 (813)	1287 (763)	1203 (714)
Water, lbs/yd³ (L/m³)	296 (175)	304 (180)	310 (184)
WRA, fl oz/yd³ (L/m³)	27.6 (0.78)	31.6 (0.90)	35.6 (1.01)
HRWRA, fl oz/yd³ (L/m³)	53.2 (1.56)	81.4 (2.31)	80.1 (2.27)
Fresh concrete properties			
Initial slump, in. (mm)	2-1/2 (63)	2 (51)	2-1/4 (57)
Slump after HRWRA, in. (mm)	5-1/8 (130)	7-1/2 (191)	6-3/4 (171)
Air content %	2.5	2.5	2.3
Unit weight, lb/ft³ (kg/m³)	117.8 (1887)	118.0 (1890)	118.0 (1890)
Compressive strength, psi (MPa)			
4 days	4290 (29.6)	5110 (35.2)	5710 (39.4)
7 days	4870 (33.6)	5790 (39.9)	6440 (44.4)
28 days (average)	6270 (43.2)	6810 (47.0)	7450 (51.4)
Splitting-tensile strength, psi (MPa)	520 (3.59)	540 (3.72)	565 (3.90)

Precast structures

High-strength lightweight concrete with a compressive strength in excess of 5,000 psi (35 MPa) has been successfully used for almost four decades by North American precast and prestressed concrete producers. Presently, there are ongoing investigations into longer-span lightweight precast concrete members that may be feasible from a trucking/lifting/logistical point of view.

The 1994 Wabash River Bridge is a good example where a 17% density reduction was realized. The 96 lightweight prestressed post-tensioned bulb-tee girders were 175 ft (53.4 m) long, 7.5 ft6 (2.3 m) deep, and weighed 96 tons (87.3 metric tons) each. The 5-day strengths exceeded 7,000 psi (48 MPa). High-performance concrete was used because it saved the owner $1.7 million, or 18% of the total project cost. (ESCSI 2001).
Parking structure members with 50 to 60 ft (15 to 18 m) spans are often constructed with double tees with an equilibrium density of approximately 115 lb/ft³ (1850 kg/m³). This mass reduction is primarily for lifting efficiencies and lowering transportation costs.

Precast lightweight concrete has frequently been used in long-span roof framing as was the case in the 120 ft (37 m) long single tees used in 1974 in the University of Nebraska sports center.

In 1997 The Chateau on the Lake, Branson, Missouri used 128 ft. (39m) lightweight concrete double tees, with density of 110 lb/ft³ (1760 kg/m³) and concrete strength of 6,000 psi (41 MPa). The structural lightweight concrete mixture design used 3/4" x No. 4 (19.0 mm x 4.75 mm) coarse aggregate from a New Market Missouri plant and Meremac River sand fines. A 7.5 sack (320 kg cement) air entrained mixture with high range water reducing admixture was used to achieve specified minimum release strengths of 45000 pis (31.0 MPa) and specified minimum 28 day strengths of 6,000 psi (41.4 MPa). The mixture was proportioned with 17.75 loose cubic feet (0.50 m³) of coarse lightweight aggregate per cubic yard (0.765 m³) of concrete to achieve the specified density 110 pcf (1760 kg/m³) maximum. The average 28 day strength was over 6,400 psi (44.1 MPa) and the 28 day camber ranged between 4 5/8 and 6 1/4 inches (117.5 mm – 158.8 mm).

Double Tee, Chateau on the Lake, Branson, Missouri

The 110 pcf (1760 kg/m³) specified maximum density restricted the weight of each member to 80,400 pounds (36,470 kg). This reduction in weight was critical in facilitating stripping, handling and hauling of the double tees. During stripping, one end of the double tee was jacked up and blocked and then the process was repeated for the opposite end. This allowed the 30 x 60 ft (9.1 m x 18.3 m) travelift and 90 ft. (27.4 m) spreader beam to complete the stripping process without having to overcome the surface tension forces from the form.

9.3 Applications of High-Performance Lightweight Concrete in Bridges

More than 500 bridges have incorporated lightweight concrete into decks, beams, girders, or piers. Transportation engineers generally specify higher concrete strengths primarily to ensure high-quality mortar fractions (high compressive strength combined with high air content) that will minimize maintenance. Several mid-Atlantic state transportations authorities have completed more than 20 bridges using a laboratory target strength of 5200 psi (36 MPa), 6 to 9% air content, and a density of 115 lb/ft^3 (1840 kg/m^3). The following are the principal advantages of using lightweight concrete in bridges and the rehabilitation of existing bridges:

- Increased width or number of traffic lanes;
- Increased load capacity;
- Balanced cantilever construction;
- Reduction in seismic inertial forces;
- Increase cover with thicker slabs without increasing the weight;
- Improve deck geometry with thicker slabs; and
- Longer spans save pier costs.

Increased number of lanes during bridge rehabilitation

Thousands of bridges in the United States are functionally obsolete with inadequate low load capacity or an insufficient number of traffic lanes. To remedy limited lane capacity, Washington, D.C. engineers replaced a four-lane bridge originally constructed with normalweight concrete with five new lanes made with lightweight concrete providing a 50% increase in one-way, rush-hour traffic without increasing the deadload or replacing the existing structure, piers, or foundations. Similarly, on Interstate 84, crossing the Hudson River at Newburgh, N.Y., three-lanes of lightweight concrete replaced two-lanes of normalweight concrete allowing increased traffic in both east- and west-bound lanes.

Increased load capacity

The elevated section of the Whitehurst Freeway was widened by approximately 8 ft. as well as upgraded from a H20 to an HS20 loading criteria during the rehabilitation of the Washington, D.C., corridor system structure with only limited modifications to the steel framing superstructure. Because of the constraints on the canal side of the bridge structure (several buildings were within 2 ft. (0.6 m) of the existing parapet), the bridge was widened toward the Potomac River side. A typical cross-section is shown in Fig. 9.4.

The original bridge deck was a 7.5 in. (191 mm) thick slab with a 2 in. (50 mm) asphalt overlay. An improved load-carrying capacity was obtained because of the significant dead load reduction brought about by using 8" of lightweight concrete to replace the normalweight concrete and asphalt overlay used in the original deck slab (Fig.9.5).

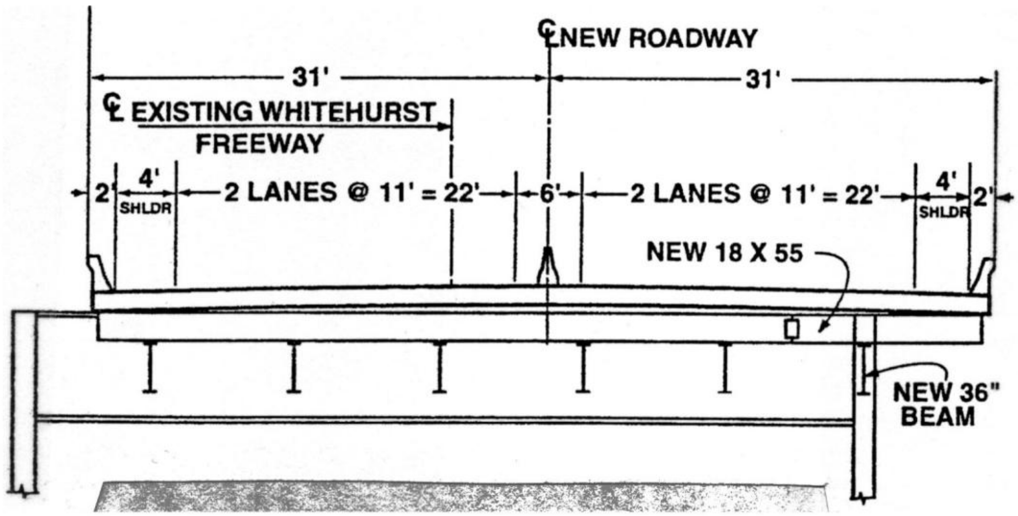


Figure 9.4. ***Typical Cross Section of Whitehurst Freeway***

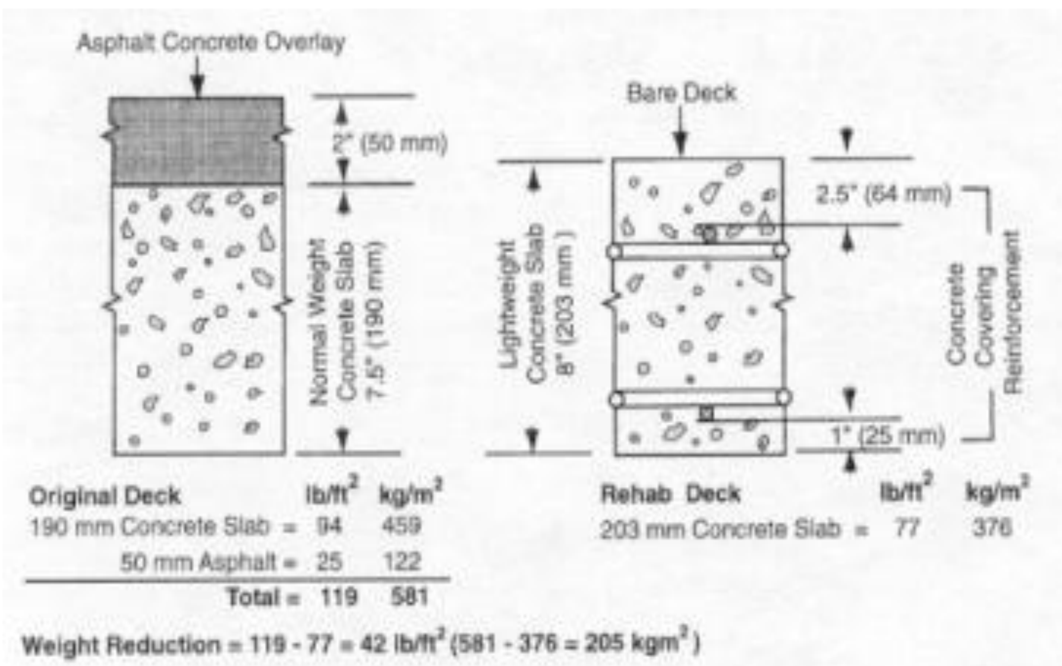


Figure 9.5. ***Original and rehabilitated decks for Whitehurst Freeway (Stolldorf and Holm 1996).***

The original elevated freeway structure was designed for HS20 live loads according to the AASHTO 1941 specifications. With the replacement of the significantly lighter lightweight concrete deck, the structural steel framing required minimal strengthening resulting in little interruption at the street level below. The bridge substructure was upgraded to HS20 live load criteria (Fig. 9.6) (Stolldorf and Holm 1996).

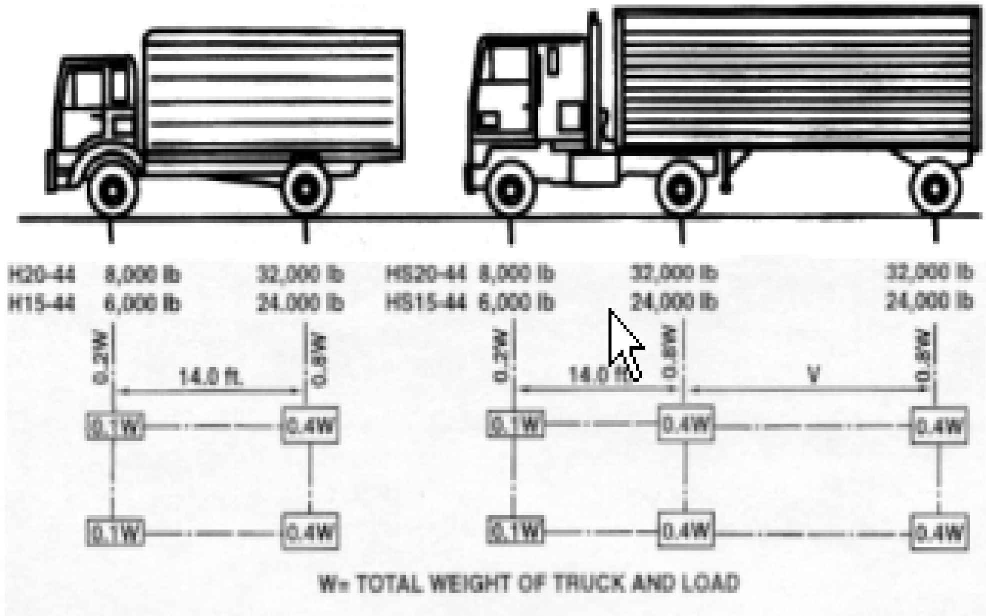


Figure 9.6. ***AASHTO H20-44 and HS20-44 loadings (Stolldorf and Holm 1996)***

Balanced Cantilever Construction - Bridges incorporating both lightweight and normalweight concrete spans

A number of bridges have been constructed where high-performance lightweight concrete has been used to achieve balanced load-free cantilever construction. On the Sandhornoya Bridge, completed in 1989 near the Arctic Circle city of Bodo, Norway, the 350 ft (110 m) side spans of a three-span bridge were constructed with high-strength lightweight concrete with a cube strength of 8100 psi (55 MPa) that balanced the construction of the center span of 505 ft (154 m) that used normalweight concrete with a cube strength of 6500 psi (45 MPa) (Fergestad 1996).

The Raftsundet Bridge in Norway, also north of the Arctic Circle, with a main span of 978 ft (298m), was the longest concrete cantilevered span in the world when the cantilevers were joined in June 1998; 722 ft (220 m) of the main span was constructed with high-strength, lightweight-aggregate concrete with a cube strength of 8700 psi (60 MPa). The spans and piers in normalweight concrete had a cube strength of 9400 psi (65 MPa) (Fig.9.7) (ESCSI #4700.0 2001).

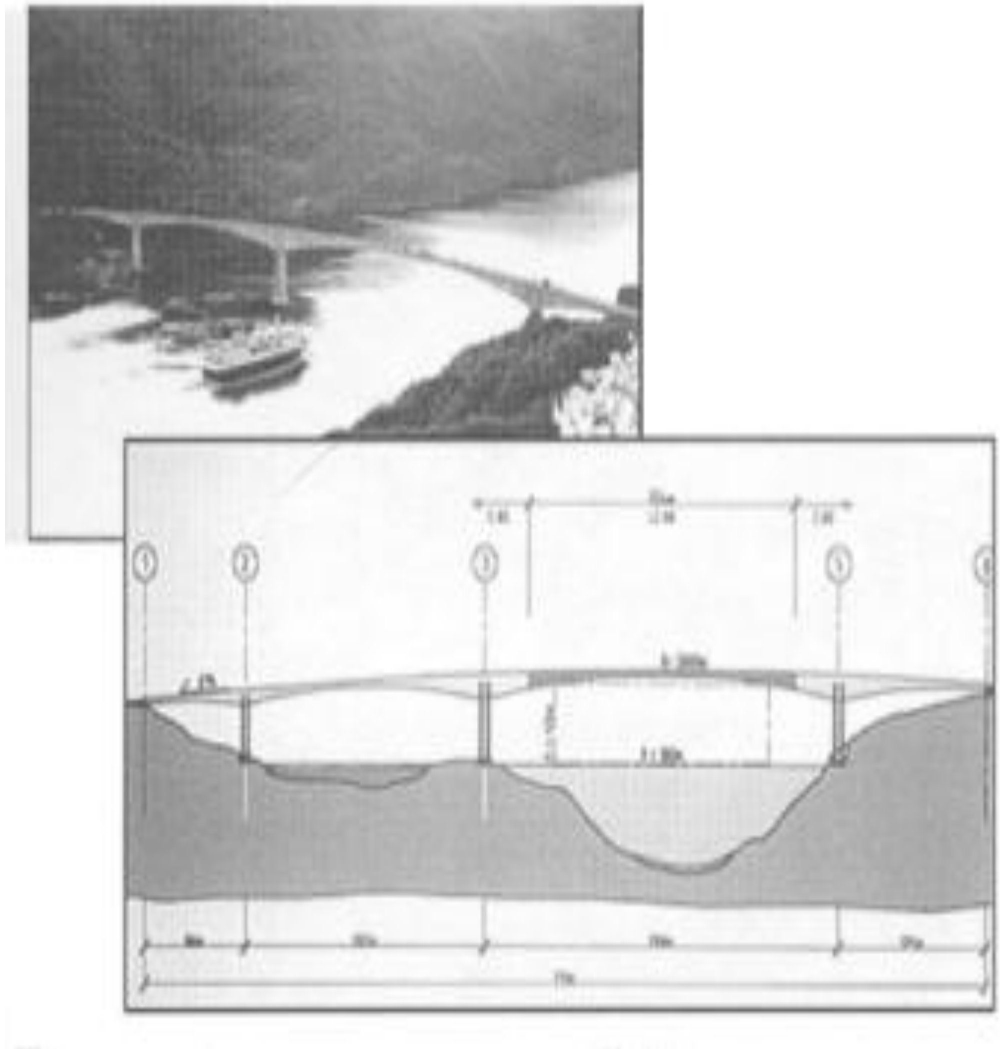


Figure 9.7. ***Raftsundet Bridge (ESCSI 2001)***

Long Span Precast Bridge Members Using Specified Density Concrete

The 1994 Wabash River Bridge is a good example where a 17% density reduction was realized. The 96 lightweight prestressed post-tensioned bulb-tee girders were 175 ft. (53.4 m) long, 7.5 ft. (2.3 m) deep, and weighed 96 tons (87.3 metric tons) each. The 5-day strengths exceeded 7,000 psi (48 MPa). High-performance concrete was used because it saved the owner $1.7 million, or 18% of the total project cost. (ESCSI 2001)

Wabash River Bridge, 231 Bypass

9.4 Applications of High-Performance Lightweight Concrete in Marine Structures

Structural Efficiency

Because offshore concrete structures may be constructed in shipyards or graving docks located considerable distances from the permanent site, then floated and towed to the project site, there is a special need to reduce mass and improve structural efficiency. Mass reduction is especially needed where shallow-water conditions mandate lower draft structures. The improved structural efficiency or strength/weight ratio of lightweight concrete is even more pronounced when submerged as shown below:

The density ratio

$$\frac{\text{(heavily reinforced normalweight concrete)}}{\text{(heavily reinforced lightweight concrete)}}$$

$$\text{In air: } \frac{2.50}{2.00} = 1.25 \left[\frac{156}{125} = 1.25\right]$$

$$\text{Submerged: } \frac{2.50-1.00}{2.00-1.00} = 1.50 \left[\frac{156-62.4}{125-62.4} = 1.50\right]$$

Tarsiut Caisson Retained Island 1981

The first arctic structure using high-performance lightweight concrete was the Tarsiut Caisson retained island built in Vancouver, British Columbia, and barged to the Canadian Beaufort Sea (Fig. 9.8). Four large, prestressed concrete caissons 226 x 50 x 35 ft (69 x 15 x 11 m) high were constructed in a graving dock in Vancouver, towed around Alaska on a submersible barge, and founded on a berm of dredged sand 25 mi (40 km) from shore. the extremely high concentration of reinforcement resulted in a steel-reinforced concrete density of 140 lb/ft^3 (2240 kg/m^3). The use of high-strength specified density lightweight concrete was essential to achieving the desired floating and draft requirements. (ESCSI #4700.0 2001).

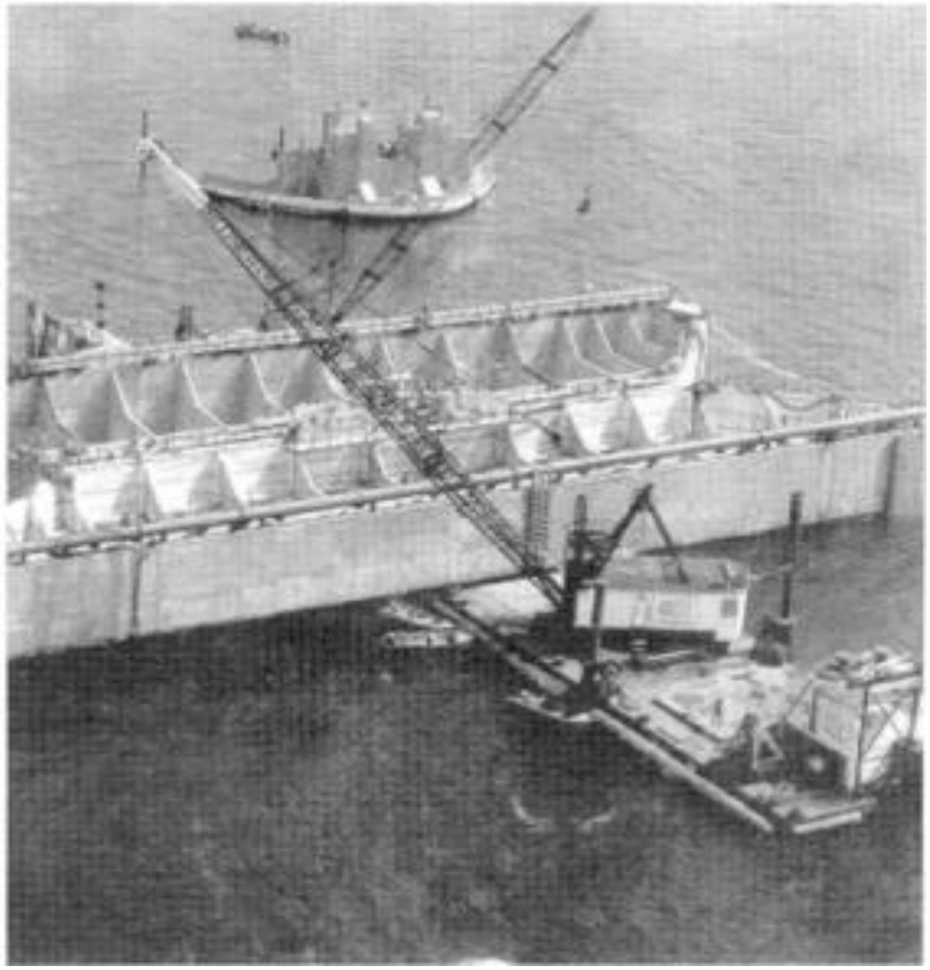


Figure 9.8. ***Tarsuit Caisson Retained Island (from Concrete International 1982).***

Heidron floating platform, 1996

Because of the deep water, 1130 ft (345 m), over the Heidron oil fields, an early decision was made to improve buoyancy and construct the first floating platform with high-performance lightweight concrete. The hull of the floating platform, approximately 91,000 yd^3 (70,000 m^3), was constructed entirely of high-strength specified density lightweight concrete with a maximum density of 125 lb/ft^3 (2000 kg/m^3). Heidron was built in Norway and towed to the North Sea. A mean density of 121 lb/ft^3 (1940 kg/m^3), a mean 28-day cube compressive strength of 11460 psi (79 MPa), and a documented cylinder/cube strength ratio of 0.90 to 0.93 are reported in reference (fib#8 2000) (ESCSI #4700.0 2001).

Hibernia oil platform, 1998

The Exxon Mobile Oil Hibernia offshore gravity-based structure is a significant application of specified-density concrete. To improve buoyancy of the largest floating structure built in North America, lightweight aggregate replaced approximately 50% of the normalweight coarse fraction in the high-strength concrete used (Fig. 9.9). The resulting density was 135 lb/ft^3 (2160 kg/m^3). Hibernia was built in a dry dock in Newfoundland, Canada, and then floated out to a deep water harbor area where construction continued. When finished, the more than 1-million ton structure was towed to the Hibernia North Sea oil field site and set in place on the ocean floor. A comprehensive testing program was reported by Hoff et al. (1995).

Figure 9.9. ***Hibernia Offshore Platform (ESCSI 2001)***

Floating bridge pontoons

High-performance lightweight concrete was used very effectively in both the cable-stayed bridge deck and the separate but adjacent floating concrete pontoons supporting a low-level steel box-girder on Nordfordland Floating Bridge near the city of Bergen, Norway, see section 9.5. The pontoons are 138 ft (42 m) long and 67 ft (20.5 m) wide and were cast in compartments separated by watertight bulkheads. The design of the compartments was determined by the concept that the floating bridge would be serviceable despite the loss of two adjacent compartments due to an accident.

Braddock Gated Dam
U.S. Army Corps of Engineers
Monongahela River, Pittsburgh PA.

Braddock Gated Dam

In initiating the final phase of modernizing the locks and dams on the Monongahela River, the U.S. Army Corps of Engineers, Pittsburgh District, used float-in and in-the-wet technology to build the new Braddock dam. This is the first use of such technology for an inland navigation project in the United States, and was employed to eliminate the cost and construction time associated with a conventional cofferdam for mass concrete construction. The new Braddock dam design was fabricated as two large, hollow-core segments. Unlike such applications used for offshore structures, the inland application was limited by navigational draft, and lock and bridge clearances. This restricted the overall dimensions and mass of the segments. The use of lightweight concrete in a significant portion of the two large dam segments was essential to the success of the design. Good planning, an understanding of the concrete materials, and quality control were critical to project success (Tasillo, Neeley and Bombich).

Modular Hybrid Pier
San Diego, CA

Modular Hybrid Pier
The U.S. Navy is currently testing a modular hybrid pier that may provide an inexpensive and long range solution for the replacement of existing piers; many of which are more than 40 years old. Built with high-performance structural lightweight concrete, the pier can support 140 ton mobile cranes. The pier is intended to be repair free for 100 years, twice as long as a typical pier, clearly in keeping with the philosophy of sustainable development.

9.5 FIB Bulletin #8 Lightweight Aggregate Concrete

The Federation International Du Beton has graciously granted the ESCSI Institute permission to present the following case study information on completed major lightweight concrete structural projects. This information is reported in fib bulletin #8 "*Lightweight Aggregate Concrete*", Case Postale 88, CH-1015 Lausanne, Switzerland and reprinted with permission.

TWA Terminal at Kennedy airport, New York

The complex is outstanding in the search for new architectural expressions. It also represents an early and most interesting example of the application of lightweight concrete. The three block development is dominated by the lightweight concrete shell roof covering the main building, characterized by an original structural concept. The properties of strength and weight of this material allowed the realization of a symbolic and expressionist structure.

TWA Terminal at Kennedy airport, New York

The Structure

The main shell roof consists of four double-curved canopies in lightweight concrete. Total covered area is 5100 m^2. Each canopy is bound by two exterior and two interior edge beams. The four Y-shaped sculptured buttresses of reinforced concrete, 7.60 m high, carry the entire weight of the roof. The thickness of the shell varies from 18 to 28 cm.

The concrete mixing and placing operations were directed from a control center. The lightweight concrete within each shell was placed on 0.75 m^3 loads in balanced symmetrical pours. Each shell was cast monolithically in a continuous pour of 24 to 30 hours.

The lightweight concrete

The main characteristics of the mix were:

Cement type 1	365	kg/m^3
Natural sand	740	kg/m^3
“Norlite” LWA (expanded shale)	600	kg/m^3
Entrained air	6	%
Effective w/c	0.38	
Slump	13	cm
Density at 28 days	1850	kg/m^3
Compressive cyl. strength at 28 days	35	MPa
Total volume of lightweight concrete:	2200	m^3

Team involved

Client:	TWA
Architects:	Eero Saarinen & Associates
Structural engineers:	Ammann & Whitney
Contractors:	Grove, Shepard, Wilson & Kruge

List of references

1. G. Bologna “TWA terminal at Kennedy airport, New York”, “Lightweight aggregate concrete” CEMBUREAU 1974

Marina City Towers, Chicago

Constructed in 1962, the 180 m high Marina City Towers have become part of the anthology of concrete architecture in USA. The project is a most striking early result of search for new architectural design principles based on development of reinforced concrete technology. Each tower includes parking facilities and 896 apartment units.

To reduce the dead load, 19000 m³ lightweight concrete were used in the floors slabs.

Marina City Towers, Chicago

The towers

The towers consist of 64 stories with an outer diameter of 39 m. Slab thickness in the apartment floors is 12.7 cm. The central cores containing five elevators and utilities shafts were slip-formed. 16 beams and slabs connect the cores to two rings of 16 columns each. The floor slabs were designed as continuous plates, 15 per floor, spanning from 2.44 to 6.50 m.

The lightweight concrete

The main characteristics of the mix were:

Cement type 1	310	kg/m^3
Natural sand	415	kg/m^3
"Materialite" LWA (expanded shale)	830	kg/m^3
Entrained air	5-8	%
Effective w/c	0.64	
Slump	10	cm
Density at 28 days	1680	kg/m^3
Compressive cylinder strength at 28 days	25	MPa
Modulus of Elasticity	16	GPa

Team involved

Client:	Marina City Building Corporation
Architects:	Bertrand Goldberg Associates
Contractors:	McHugh Construction Company
	Brighton Construction Company

List of references

1. G. Bologna "Marina City Towers, Chicago", "Lightweight Aggregate concrete", CEMBUREAU 1974.

Nations Bank Corporate Center, Charlotte, North Carolina

When completed in 1992, the 60 story, 252 m high Nations Bank corporate center was the tallest building in the Southeast and the third tallest all-concrete building in the USA. More than 23000 m³ of lightweight concrete was used to realize the visions articulated by the architect Cesar Pelli. "The owner wanted to put Charlotte on the map and give it a skyline. They wanted the tallest, thinnest and most efficient building possible, and one that was not extravagant.

Nations Bank Corporate Center, Charlotte, N.C.

Structural system

A number of different feasible structural systems were investigated. Main demands of the owner were economy and clear spans providing 15 m column free space from the core to the perimeter. In the final phase of design, several contractors priced 6 steel-concrete composite and 4 all-concrete alternative. All the concrete designs turned up to be significant more cost beneficial than the steel schemes.

The chosen design is a reinforced concrete perimeter with NWC columns spaced at 3 m. The floor system consists of 12 cm LWAC slabs supported by 45 cm deep post-tensioned beams. The beams are cast with NWC and span up to 15 m. The shallow floor design allowed the use of 3.85 m floor-to-floor height, and additional saving for the project.

The motivation for choosing LWAC was two-fold, partly to reduce the dead load, and partly to achieve Charlotte's very strict requirements for a 3-hour fire separation.

Characteristics of the LWAC
A total of more than 23000 m³ of LWAC was used. The majority of the mixed material had the following characteristics:

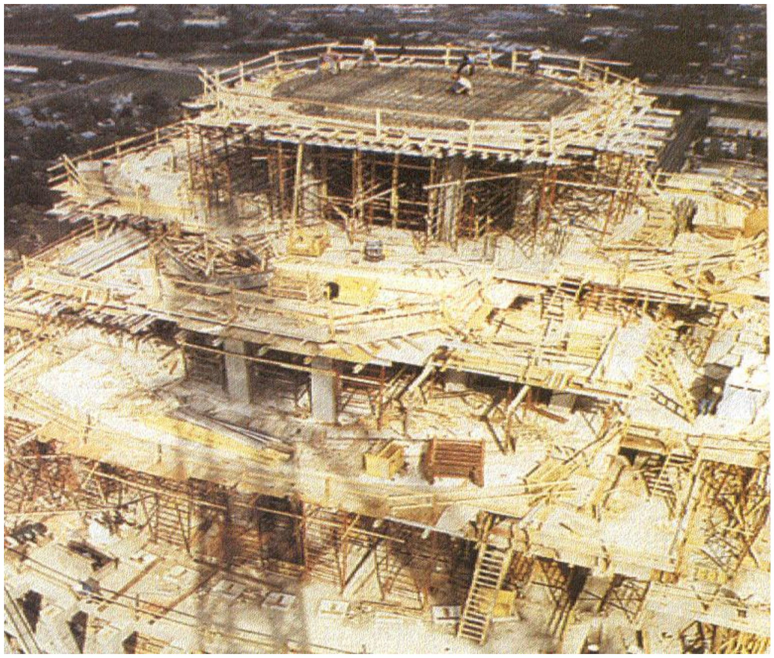
Cement type III	385	kg/m³
Fly ash	83	kg/m³
Solite LWA (expanded shale)	534	kg/m³
Natural sand	765	kg/m³
Water	175	kg/m³
Plasticizers	1.5	l/m³
High range plasticizers	4	l/m³
Average compressive cylinder strength, 28 day	47	MPa
Average splitting tensile strength	3.7	MPa
Slump	20	cm
Modules of Elasticity	25	GPa
Dry density	1890	kg/m³

The main factor governing the strength was the early (2 day) strength of 26 MPa for post tensioning.

Pumping
The LWAC was pumped all the way up to the top of the building, when completed, 252 m above ground level. The capacity was up to 65 m³/hour using an electric powered pump and a pipeline of 12.5 cm diameter.

To achieve pumpability, the LWA had to be thoroughly saturated. The producer therefore soaked continuously the aggregate during production. In addition extra moisture was added by stockpile hoses for a minimum of 48 hours prior to batching.

The LWAC floor slabs were cast at the same time as the NWC in the perimeter beams and "puddle" to avoid a cold joint.



LWA was pumped 250 m to the top of the building

Team Involved

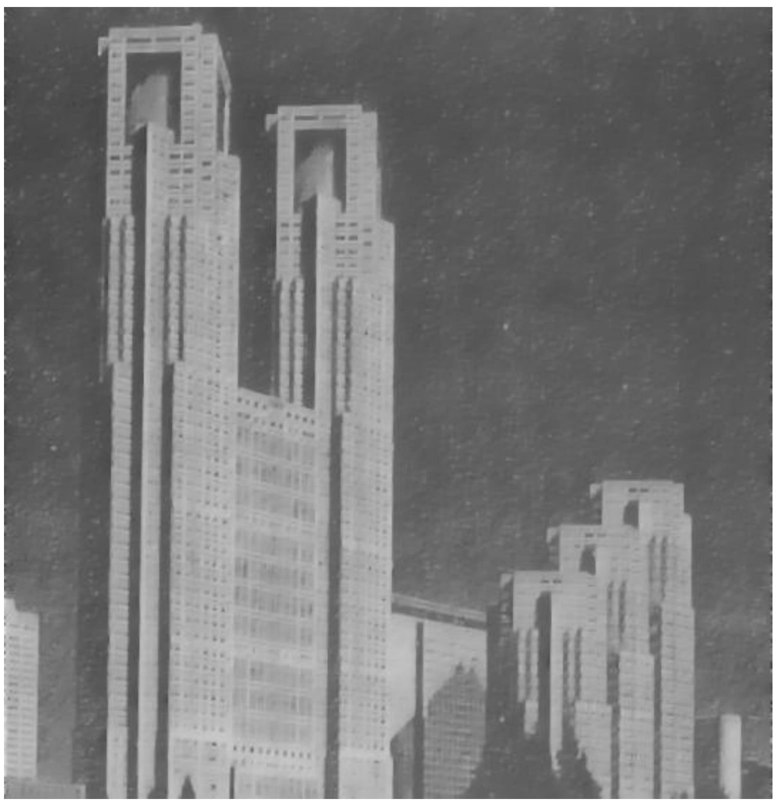
Developers:	NCNB Corporation, Lincoln Property Co., Charter Properties
Architects:	Cesar Pelli & Associates, HKS, Inc.
Structural Engineer:	Walter P. Moore and Associates
General Contractors:	McDevitt & Street

List of references:

1. J. Horvilleur, "Tallest building in the Southeast", Engineered Concrete Structures, PCA 75th anniversary, August 1991.
2. V.K. Dorries "NCNB center lifts Charlotte's skyline", Engineering News-Record, January 1992.

The new Tokyo metropolitan government building

The new city hall for Tokyo was completed in Shinjuku new metropolitan center area in 1991. The 243 m high 1st main building stands in the center with the 2nd main building located on the south and the assembly building on the east. As for the 1st main building, superstructure, in which giant pillars of 6.4 m square and giant beams of 4 m high are distributed at key locations, was employed to accomplish long span at super high rise. Steel-frame was employed for floor 2 and higher, and lightweight concrete was placed on the floor deck plate. The entire concrete placing work up to the elevation of 243 m was done directly from the ground using truck mounted pumps.



Tokyo Metropolitan Government Building

Outline of the work:

Project name:	Tokyo Metropolitan Government 1st main building construction project
Location:	8, Nishi-shinjuku 2-chrome, Shinjuku-ku, Tokyo
Design:	Tange Kenzo Urban Architectural Design
Structural Design:	Mutoh Associates
Contractors:	Consortium of 12 companies including Taisei Corp, Shimizu Corp and Takenaka Corp.
Construction period:	March 1988 to February 1991
Plottage:	14350 m²
Building area:	11100 m²
Total floor space:	195000 m²
Height:	243 m
Number of floors:	48 aboveground, 3 underground S construction for the 2nd floor and above. (floor: LWAC on deck plate.) SRC construction for the 1st floor and below. Spread funding RC construction.
Amount of concrete used:	NWC, approximately 67500 m³ LWAC, approximately 15200 m³

Overall view of the 1st main building and floor plan of a typical floor are shown in Photo and Fig. 1 respectively.

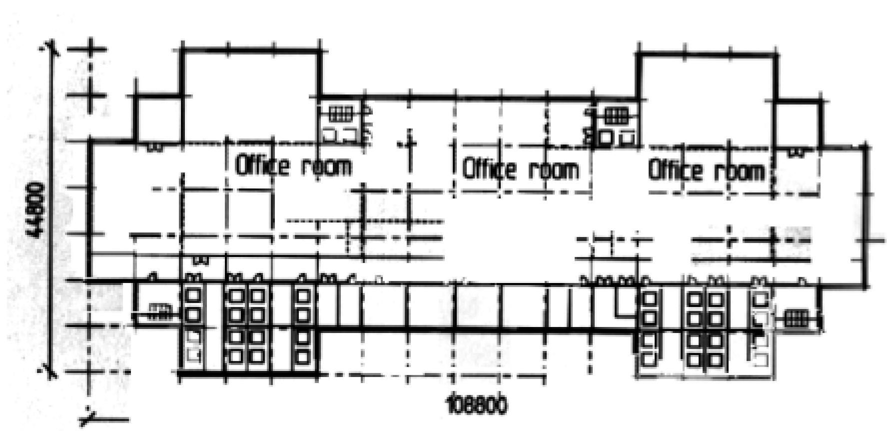


Figure 1. ***Floor plan (17-24 floors)***

Bass mass concrete

Because both the underground mat slab and the base (RC construction) consist of mass concrete of 80 cm or more in terms of minimum component part dimension, the following mix conditions were applied.

Design strength:	(standard age of 91 days), 24 MPa
Target slump:	15 cm
Target air content:	4%
Cement:	Blast furnace slag cement. Type B
Admixture:	AE water reducing agent
Amount used:	35400 m^3

Normal concrete

SRC construction is mainly employed from the rise of B3 floor up to the floor of 2nd floor aboveground plus 4 m. The reinforcing steel bars are arranged more densely than in the base section. Therefore, the following superplasticized mix was used:

Design strength:	(standard age of 28 days), 24 MPa
Target slump:	(base concrete), 15 cm
	(superplasticized concrete), 21 cm
Target air content:	4%
Cement:	Normal Portland cement
Admixture:	superplasticizer, AE water reducing agent
Amount used:	32100 m^3

Lightweight concrete

From the 2nd floor aboveground plus 4 m to 48th floor (S construction), LWAC was used mainly on the floor deck plates. Outline of the concrete used is described below.

Design strength:	(standard age of 28 days), 21 MPa
Absolute dry unit weight:	1850 kg/m^3
Coarse aggregate:	Manufactured LWA (max size: 15 mm)
Fine aggregate:	Sand, crushed sand
Target slump:	(base concrete), 18 cm, (superplasticized), 21 cm
Target air content:	5%
Cement:	Normal Portland cement
Admixture:	superplasticizer, AE water reducing agent
Amount used:	15200 m^3

Elevated pumping plan for lightweight concrete

While the height of the 1st main building is 243 m, it has been traditional common sense that the height limit for pumping of concrete directly from the ground to be 150 – 160 m. As a result of joint study by technical committee, concrete pump truck manufacturer and LWA manufacturer, a new pump truck was developed making pumping to the top floor possible.

Record of elevated concrete pumping test

The result of pressure measurement inside the concrete conveying pipe at the top floor, 48th floor, is described in Fig. 2 and Fig. 3.
When comparing the concrete before and after pumping, it was learned that slump lowered by approximately 2 cm in average and air content was reduced by approximately 1%.

Unit weight slightly increased. Furthermore, average measurement of compressive strength was almost the same before and after the pumping.

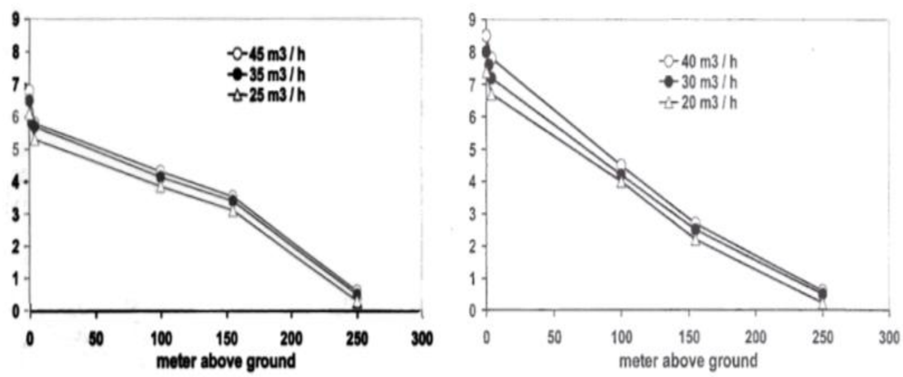


Figure 2 & 3. ***The result of pressure measurements (MPa) inside the conveying pipe while pumping to 48th floor (Results from company k in left and company L in right diagram).***

Summary

As a result of efforts made by the people from various fields involved in the project and due to remarkable advancement in concrete pumping equipment and control technology, the entire concrete work up to 243 m height was done directly from the ground using truck mounted pumps.

List of references

1. Koichi Kishiya, Takeo Suzuki, H. Watanabe, Koichi Mihara, Takakazu Ishii and Ryuji Kuwabara. "Concrete pumping up to 243 m aboveground. The new Tokyo Metropolitan Government 1st main building construction project." Concrete Journal, Vol. 29, No. 12, December 1991.

The Picasso Tower, Madrid

Built in the middle of the Azca quarter, the neuralgic business center of Madrid, the 45-story high “Picasso Tower” became in 1988 the tallest building in Spain. It is also among Europe’s highest.

The use of 10000 m^3 of lightweight aggregate concrete with specification LC 20 and dry density <1800 kg/m^3, reduced the total weight of the building by 5000 tons.

The Picasso Tower, Madrid

Key data for the project

Master plan

Architectural project	1977
Start of construction	1986
End of construction	1989

Key data

Floors under ground level	5
Floors over ground level	45
Total height	150 m
Total surface area slabs	122000 m²
Concrete in slabs, LC 20	10000 m³
Average concrete slab thickness	110 mm

Application and pumping of lightweight concrete for a high rise building

Picasso Tower is the first large-scale use of LWAC in Spain for a high rise building.

The design is a work of the architect Minoru Yamasaki, also famous for the Twin Tower of the World Trade Center in New York. The original concept of the building had to undergo many changes in order to comply with the Spanish regulations.

A 110 mm thick slab of LC 20 was used in the decks in combination with steel plate. This allowed for huge savings in steel reinforcement and in the foundation of the building. In addition to reduced foundation cost, the thin slabs give larger efficient office area.

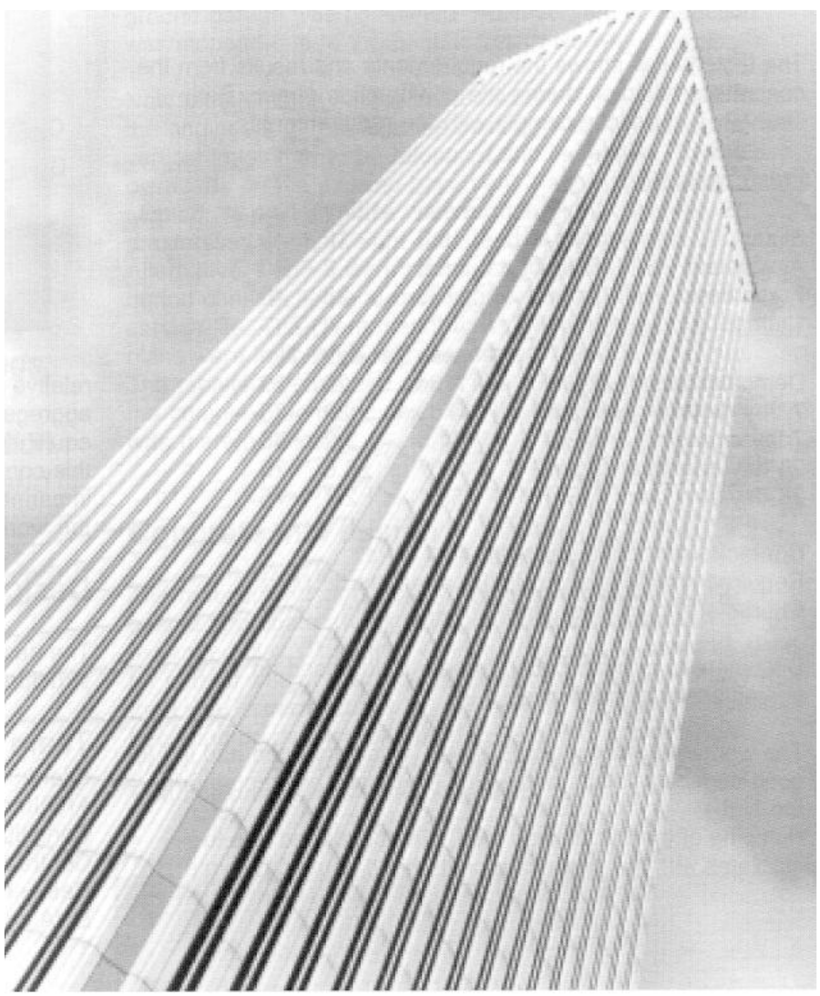
In order to reproduce the conditions at the construction site, several pumping trials were conducted in June 1986 at the dam of La Fernandina in southern Spain. A 340 m pipeline over a 120 meter high cliff was used. The extra difficulty of temperatures over 40ºC had to be managed. The Arlita lightweight aggregate was pre-saturated by immersion until a level of 40% based on dry bulk weight. The test gave valuable experience and the project team decided to pump the lightweight concrete at the Picasso Tower.

A concrete pump, Putzmeister BSA 1406 E with a variable performance of 40 to 60 m³/h depending of the height, was used at the tower. There were no intermediate pumping stages, and the concrete for the whole tower was pumped in a single line.

Characteristics of the pump	
System:	S-valve
Power:	90 kW at 3000 rpm
Maximum concrete pressure:	70 bar
Diameter of pipe:	200 mm
Capacity:	40-60 m^3/h
Pumping height:	154 m
Hydraulic pressure:	300 bar

The ARLTA product was saturated in a pool, and the concrete mix featured a resin-based additive to avoid water from penetrating the core of the expanded clay during high pressure during pumping.

The real site pumping was finished in 1988, with some slight changes in the mix.



Picasso Tower

Main concrete characteristics

The mix used is the result of a replacement of the natural coarse aggregate with spherical expanded clay, while the fine aggregate, the cement and the rest of the ingredients are the same as used for normalweight concrete.

The strength and density were achieved by using ARLITA F-7, an expanded clay with bulk density 750 kg/m³. a particle density of 1300 kg/m³ and a size of 3-8 mm. The Arlita was pre-saturated to approximately 40% by weight to achieve pumpability.

Standard Portland cement	320	kg/m³
Fly ash	120	kg/m³
Natural sand	900	kg/m³
ARLITA F7	345	kg/m³
Effective water content:	190	kg/m³
Pre-saturated water in ARLITA	138	kg/m³
Pumping aid	0.3	kg/m³
Slump (initial)	23	cm
7 day density	1845	kg/m³
7 day strength (mean – cylinder)	22.5	MPa
28 day density	1855	kg/m³
28 day strength (mean – cylinder)	30.1	MPa

Achieved characteristic cylinder strength was 22.7 MPa, compared with the requirement of 20 MPa.

Design criteria for LWA concrete

The design is based on Spanish codes

Team involved

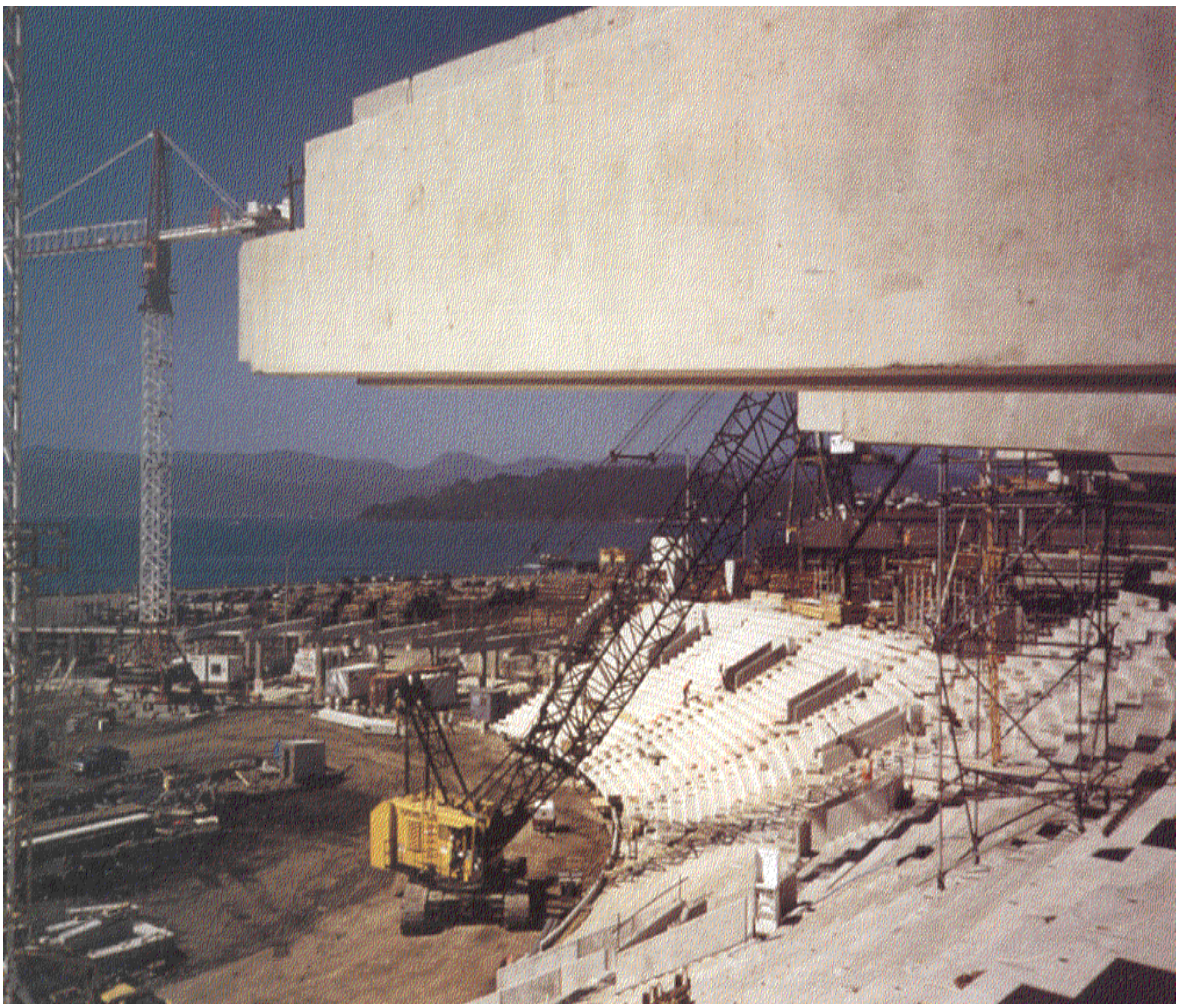
Client:	Portland Valderrivas, S.A., Immobiliaria Ason, S.A.
Architect:	Minoru Yamasaki, Genaro Alas Rodriquez
Contractor:	FCC
Readymix concrete supplier:	HYMPSA
LWA Supplier:	Arido Ligeros, S.A.

List of references

1. GONZALEZ MAS, M.A., Revista del Hormigion nº3: "El Bonbeo de Hormigon en Torre Picasso", Madrid, Spain.
2. LOPEZ, Javier, Aridos Ligeros. S.A. pers com.

The Wellington Westpac Trust Stadium

The Wellington Stadium in New Zealand's first purpose built modern sports stadium. Lightweight concrete has been used for all the precast components for the main stadium bowl structure (1). Normalweight concrete has been used for the foundations and ground floor slabs, and structural steel has been used for the roof, lighting towers and the four level administration structure frame at the northern end. The stadium, which uses expanded shale aggregate imported from California, is the first structure in New Zealand to be constructed of LWAC. Concrete with cylinder strength of 35 MPa was chosen for durability reasons and to achieve an overnight strength of 25 MPa for the efficient production of pretensioned bleachers, inclined raker beams and double tee flooring units. The design life of the stadium is 50 years.



Wellington Westpac Trust Stadium

Key data

Seating capacity	34,500
Start date	March 1998
Opening date	Dec. 31, 1999
Volume of LWA concrete	13000 m^3
Number of pieces of precast concrete	4,000

Reasons for using LWA concrete

Reduced foundations loads: The site, near the center of Wellington, comprises very weak, poorly consolidated fill dredged from the bottom of Wellington Harbor. The stadium is supported on piles approximately 12 meters long.
Reduced earthquake forces: One of New Zealand's most active fault lines is less than 200 meters from the stadium.
Reduced transport costs: The precast concrete components were manufactured in a factory 60 km from the site.
Reduced reinforcement: The reduction in self-weight has reduced the reinforcement in the precast components.
Smaller cranes: The largest pieces of precast concrete, at 32 tons, were within the capacity and reach of locally available cranes.
Fewer joints: Triple riser bleacher units required less waterproof sealant.
Longer spans: Longer span units gave better space utilization under the stadium.
Faster Construction: Larger pieces of precast concrete allowed the area to be covered faster. Flooring units could be pre-finished, without the need for site cast topping concrete – construction was not weather dependent.
Durability: The stadium is located on the edge of Wellington Harbor and is exposed to wind blown salt water.
Easy drilling: The fixings for seats and handrails were easily drilled in the relatively soft LWAC. This simplified the production of the bleacher units.

Concrete mix

LWA, Baypor F-6	0.62	m^3/m^3
13 mm NW aggregate	90	kg/m^3
Sand	715	kg/m^3
Cement	420	kg/m^3
WRDA	1100	ml/m^3
Entrained air	5	%
Wet density	1900	kg/m^3
Oven dry	1800	kg/m^3

Wellington Westpac Trust Stadium

Properties of hardened concrete

Design strength (cylinder)	35 MPa
18 hours (heat, cured, cylinder)	25 MPa
28 days strength (mean, cylinder)	44 MPa
Density	1845 kg/m³
Modulus of elasticity	20 GPa
Creep factor	3.0 long-term
Shrinkage	1250 Microstrain
Modulus of rupture (heat cured / standard cured)	4.8 MPa / 5.2 MPa
Chloride Ion diffusion (heat cured / standard cured)	4562 / 4796 Coulombs
Resistivity (SSD / seven day dry)	12030 / 13570 Ωcm

Design criteria for LWA concrete

The design is based on New Zealand Standards as a means of compliance with the New Zealand Building Code. Wellington is a very active seismic area and the Stadium is located in very close proximity to one of the region's most active fault lines. The city of Wellington is also known for its very high winds. Wind loads and earthquake forces, are determined by the requirements of NZS 4203, Design Loads.

Concrete design is in accordance with NZS 3101, Design of Concrete Structures. This Standard sets limited design parameters for LWA Concrete, but key parameters ere confirmed by testing. Pretensioned bleacher and double tee flooring elements were also load tested to verify their structural performance (2).

Team involved

Client:	The Wellington Stadium Trust
Contractor:	Fletcher Construction
Architects:	Warren & Mahoney and Bligh Lobb Sports Architecture
Structural Engineers:	Holmes Consulting Group
Services Engineers & Project Manager	Beca Carter Hollings & Ferner
Precast Concrete:	Stresscrete
Lightweight Aggregate:	Pacific Custom Materials

References

1. McSaveney L.G., "Lightweight Concrete, An Economical Choice for The Westpac Trust Wellington Stadium", Combined Concrete Industries Conference, NZ Concrete Society, Wellington 1998.
2. Park R.J.T., McSaveney L.G., and Johnstone P.J., "Wellington Stadium Precast Lightweight Concrete Members: Material Properties and Load Test Results". IPENZ Technical Conference, Auckland 1999.

Iura Port Submerged Tunnel

An undersea tunnel connecting Nishi-Mikawa (Hekinan city) and Chita district (Handa city) in Aichi Prefecture was under construction in 1997. Since the tunnel box will be towed and submerged after completion, floating and stability of floating body are indispensable requirements. On the other hand, along with the change in earthquake-resistant design rules as a result of the earthquake in the southern part of Hyogo Prefecture, thick reinforcing steel bars are densely arranged. As a result, the weight of the box element, and in particular its upper slab, increased substantially. Because of such changes in deadload, buoyancy requirements could not be met in the case of 1-4 boxes. After various studies, it was determined that lightweight concrete would be used for the upper floor plate section from economical reasons. Furthermore, low hear type blast furnace slag cement was used to prevent cracks due to temperature stress of mass concrete.

Outline of the construction

This submerged tunnel consists of a 448 m long submerged tunnel box section (consisting of 4 boxes plus final joint section) and ventilation tower and land tunnel at both ends. (Fig. 1)

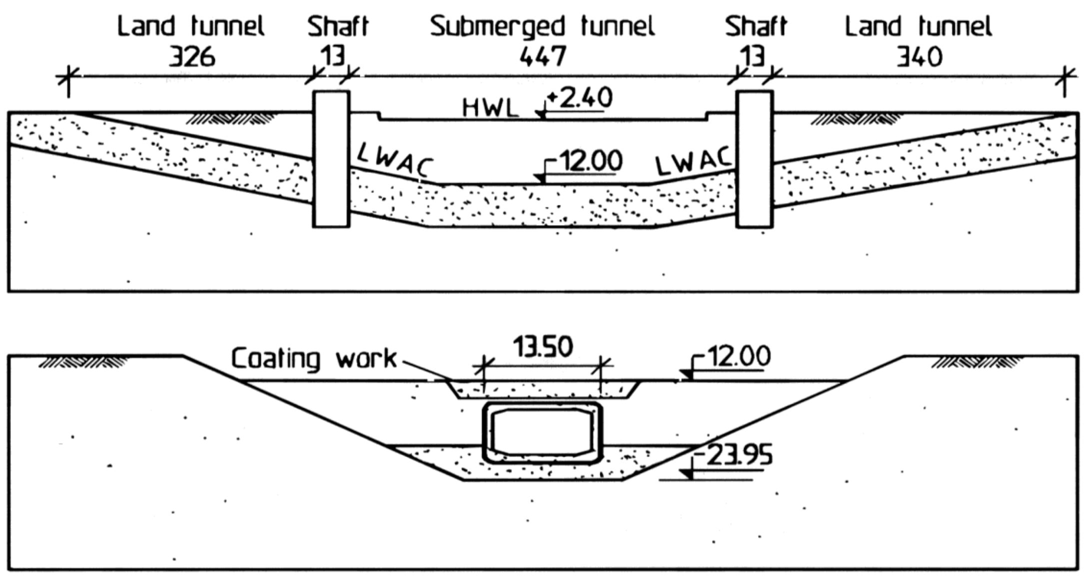


Figure 1. ***Outline of submerged tunnel***

This construction work covers building of boxes no. 1 and 2 of the 4 submerged elements. As described in Fig. 2, lower floor plate and side wall of the box have a composite structure of steel and concrete in open sandwich arrangement and upper floor slab has a reinforced concrete structure.

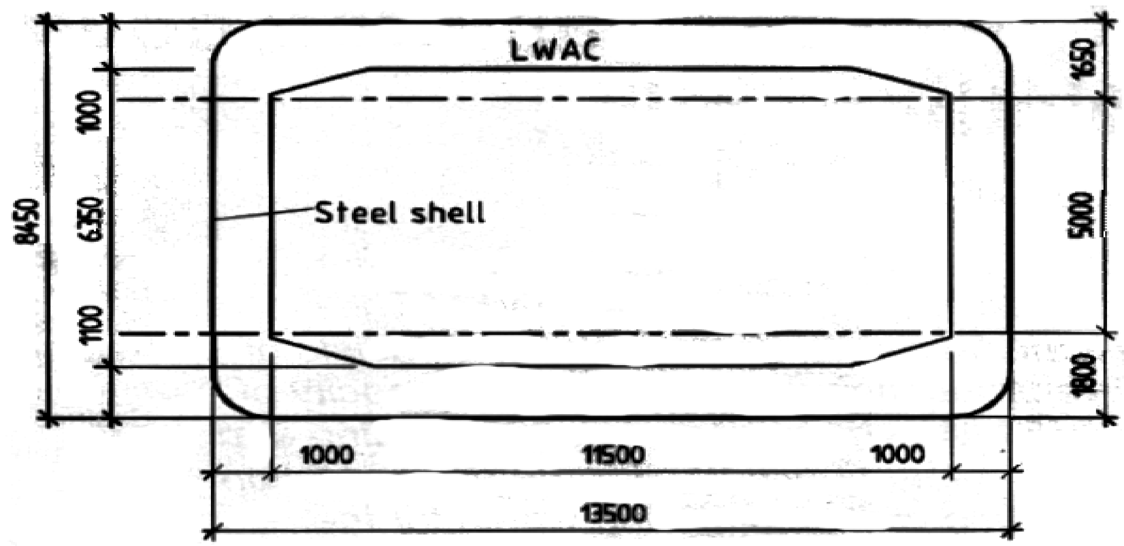


Figure 2. ***Cross section of submerged box***

Specifications of concrete

Types of concrete used for each section and major quality standards are described in Table 2. Of the 3 manufacturing plants involved, the mix proportion by plant A is as described in Table 1.

When using LWAC, LWA was used as the coarse aggregate for all cases to satisfy the requirement for unit weight (1900 kg/m³).

Table 1 Mix proportions

Mix No.		1	2	3
Max particle size (mm)		25	25	15
w/c		0.52	0.52	0.45
s/a (%)		45.0	45.0	44.3
Unit amount (kg/m³)	Water	150	152	165
	Cement	288	292	362
	Stone dust	20	30	30
	Sand	790	775	712
	Gravel	1044	1041	614
	Superplast	2.88	3.21	3.26

Furthermore, because each section is relatively large and the construction work had to be carried out during summer, there was a concern for cracks due to temperature stress. Therefore, unit cement content was minimized by use of AE and high range water reducing agent, and low heat type blast furnace slag cement was used.

Table 2 Types of concrete and major quality standards

Used location	Major quality standards	
Mix no 1 and 2 No. 1 box Lower floor plate Side wall No. 2 box Lower floor plate Upper floor plate Side wall	Aggregate	Normal density
	Cement	Low heat type blast furnace slag
	Stone dust	20 kg/m³
	Slump	18 cm
	Air content	4%
	Unit weight	2300 kg/m³
	Design Strength	30 MPa
Mix no 3 No. 1 box: Upper floor plate	Aggregate	Manufactured lightweight coarse aggregate
	Cement	Low heat type blast furnace slag
	Stone dust	30 kg/m³
	Slump	18 cm
	Air content	5%
	Unit weight	1900 kg/m³
	Design strength	30 MPa

Quality and characteristics of concrete

Reduction of workability and lowering of slump for LWAC is relatively fast comparing to that of normal concrete. When pumped, lowering of slump for LWAC was 1.0 – 2.5 cm. Pumping caused a reduction of air content in the LWAC by 0.5 – 1.0% and an increase in unit weight by 30 – 50 kg/m³.

When LWAC is consolidated by internal vibrator, its effective range is smaller than that of normal concrete and it is difficult for the concrete to spread out to all corners of the frame or around reinforcing steel bars.

Therefore, concrete placing tests were conducted by using the side mold of upper floor plate, and the needed vibration time for one location was determined to be 20 seconds.

Concrete work

Quality control of concrete was conducted on the items as listed in Table 3.

It was determined that for LWAC the minimum required vibration time by an internal vibrator for each location was 20 seconds. Furthermore, as for the section where the LWA existing above concrete surface is floating, uniformalization was attempted after hammering by a tamper Placing work of LWAC is described in photo.

Table 3 Quality control of concrete

Test Item	Test location
Slump	Manufacturing plant And unloading point After pumped
Air content	Manufacturing plant And unloading point After pumped
Unit weight	Manufacturing plant And unloading point After pumped
Chloride content	Unloading point
Concrete temperature And air temperature	Manufacturing plant And unloading point
Compressive strength Ø 10 _ 20 cm	Unloading point Sampling
Unit weight 50 _ 50 _ 50	Unloading point Sampling

List of references

1. Hajime Maruoka, Yoshio Tanabe, Nobuyuki Ohta and Yoshitaka Sato. "Construction of submerged tunnel using lightweight concrete", Concrete Journal, Vol. 36, No. 12, December 1998.

The Heidrun tension leg platform

The Heidrun floating oil-production platform was constructed in Norway from March 1993 to June 1995. The structure was installed at 345 meter water depth in the North Sea field of the same name.

Heidrun is the world's first tension leg platform (TLP) with a concrete hull and represents a break-through for high strength lightweight aggregate concrete (LWAC) as a building material in floating offshore marine environment, the design life requirement for the structure is more than 60 years.

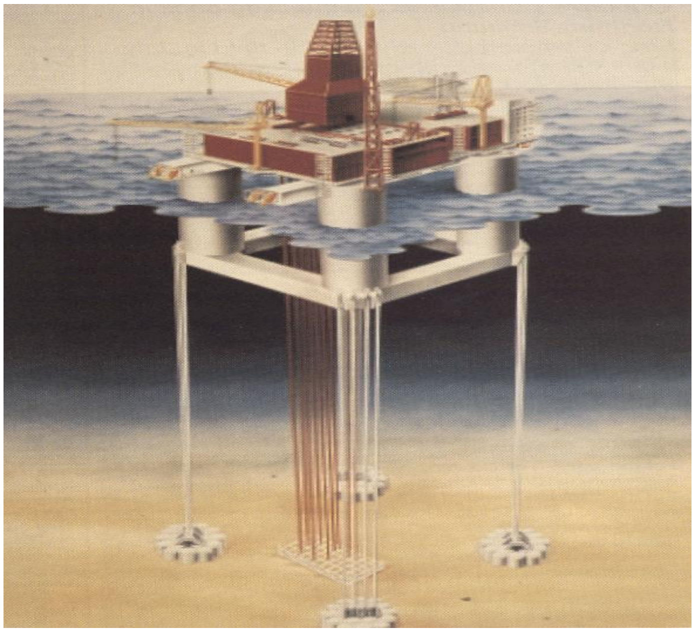
Some key data for the project

Master plan

Contract award	Dec. ‘91
Start of construction in dry dock	Mar. ‘93
Tow-out from dry dock	Oct. ‘93
Ready for Module Support Beam	Jul. ‘94
Ready for module mating	Sep. ‘94
Ready for inshore hook-up	Oct. ‘94
Ready for tow to field	Jun. ‘95
Complete installation	Jul. ‘95

Key data

Water depth	345 meter
Deck weight	65,500 tons
Hull draft (at field)	77,3 meter
Concrete, LWA-C60, hull	58000 m_
Concrete, LWA-C60, MSB	5800 m_
Reinforcement (ordinary)	27000 tons
Reinforcement (pre-stressed)	4100 tons
Column diameter	31 meter
Column spacing	80 meter



Heidrun tension leg platform

Application of high strength LWAC for tension leg platforms
A large displacement is necessary to achieve the buoyancy required for a TLP for this size. Buoyancy members of steel have to withstand large hydrostatic pressures. A high strength concrete shell which can take water pressure in direct compression is ideal for such exposure.

A concrete hull will be heavier than a steel hull. Consequently the necessary buoyancy and displacement need to be increased. The mooring tether forces tend to increase with the displacement.

However, more important is the location of the center of gravity. For a concrete platform this will be in about the same elevation as the resultant of the first order wave loads. Thus the tether forces from the concrete hull are significantly lower than those from a steel hull which shall carry the same topside weight.

Concrete material for TLP hull has several merits. Main areas of steel TLP, in particular the node intersection between the pontoon and the tether attachments to the hull, are exposed to severe fatigue. Even with the conservative fatigue criteria of NS 3473, the fatigue life of a concrete TLP will be more than adequate.

Experience from the existing offshore concrete structures shows an unequalled durability towards all kind of deterioration. A concrete structure can be reinforced to achieve a high degree of robustness against all external impacts, e.g. from ships and dropped objects. The anticipated costs for inspection, maintenance and repair of a concrete platform will therefore be small relative to its counterpart made of steel.

Concrete mix design
The mix design for Heidrun TLP has been developed over several years, starting in the mid 1980's.

The reduced weight is achieved by the use of expanded clay LWA. High workability, high strength and excellent durability was obtained by using high strength cement, silica fume, superplasticizers and air entraining agent.

Constituents

Cement HS 65	420	kg/m³
Silica	20	kg/m³
Natural sand 0-3 mm (dry weight)	720	kg/m³
Liapor 8, 4-8 mm (dry weight)	307	kg/m³
Liapor 8, 8-16 mm (dry weight)	254	kg/m³
Superplasticizer	6-9	kg/m³
Air-entraining admixture	1-3	kg/m³
w/(c+s) corrected for water abs.	0.37 +/- 0.02	

Properties of hardened concrete

The table below shows requirements and results from the concrete production during the dry dock phase. Both strength and density comply with the requirements.

	requirement	mean	st.dev
Slump	>200	250	
Fresh density	<1950	1885	
7 day density	<1940	1901	
7 day strength		70	3.0
28 day density	<1950	1943	
28 strength	>60	79	3.5

Compressive strength in MPa measured on 100 mm cubes, Documented cylinder/cube strength ratio for this concrete quality is between 0.90 – 0.93. Density on hardened concrete in kg/m³ measured on water stored cubes.

Design criteria for LWAC

The design is based on Norwegian codes supplemented by criteria specified by the Norwegian Petroleum Directorate (NPD).

NS 3473 “Concrete structures – Design rules”, covers the application of LWA concrete structures. The applicability of this code for LWA has been confirmed by comprehensive inverstigations in the research and development program “High Strength Concrete” [3]. In addition several tests have been carried out by the contractor to confirm particular details.

Team involved

Client:	Conoco, Norway Inc.
Design:	Norwegian Contractors a.s.
Contractor:	Norwegian Contractors a.s.
Tow out and installation:	Norwegian Contractors a.s.

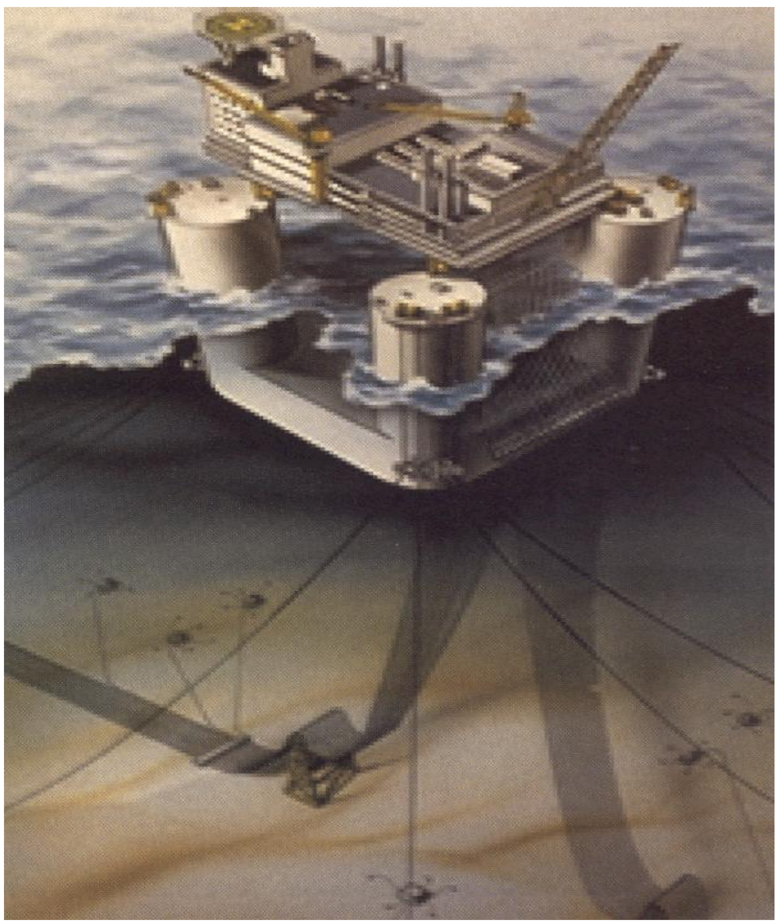
List of references

1. Haug, A.K. and Fjeld, S. “A floating Concrete Platform Hull made of Lightweight Aggregate Concrete”. High Strength Concrete Symposium, Lillehammer 1993.
2. Davenport, G.F., Fjeld, S., Gunderson, R.H., Lokken, R.T., and Wold, M.O., “Concrete tension leg platforms for the Gulf of Mexico”, Offshore Technology Conference, Houston 1990.
3. Holan, I. “High Strength Concrete in Norway: Utilization and Research”. High Strength Concrete Symposium, Lillehammer 1993.

The Troll West Floating Platform

The Troll West is a floating platform operating at the North Sea oilfield with the same name 70 km northwest of Bergen, Norway. The concrete structure was installed at a water depth between 315-340 meters in 1995. Exposed to a harsh marine environment, the design life requirement for the structure is more than 50 years.

To give the construction enough buoyancy, it was planned to install an extra floater unit. Research and studies concluded that the use of concrete with lower density would solve the problem. During the construction period, a new concrete were natural coarse aggregate was partly replaced by lightweight aggregate (LWA) was introduced. The modified normal density concrete (MND) has density reduction of about 10%, but still maintains most of the mechanical properties of normalweight concrete (NWC).



The Troll West Floating Platform

Some key data for the project

Water depth	315-340 meters
Concrete floater weight	192000 tons
Concrete, NWC, C 75	19000 m³
Concrete, MND, C 75	21000 m³
Reinforcement (ordinary)	17500 tons
Reinforcement (pre-stressed)	3400 tons
Column diameter	29.0 meters
Column spacing (width)	101.5 meters
Total height concrete floater	65 meters
Wall thickness	0.4 – 0.9 meters

Application of high strength LWAC for floating platforms

A large displacement is necessary to achieve the needed buoyancy for a floater. The hull has to withstand large hydrostatic pressures. A high strength concrete shell is ideal for such loads. High strength normalweight and lightweight concrete were already utilized in many structures in Norway and the experience with the material was well developed.

The lower part of the structure was built in a dry-dock. When reaching a sufficient bouncy, the hull was towed out in the nearby fjord for completion. All major vertical faces were slipformed.

The Troll West was originally planned with NWC. To give the construction enough buoyancy in the tow-out phase, and to give the structure improved general floating properties, an extra floater unit was planned installed. Further studies concluded that an alternative with density reduced concrete had several advantages. During the construction period a new mix where normal coarse aggregate was partly replaced by LWA to reduce the total weight, was introduced. The use of this so-called MND concrete was introduced while the structure was under construction. Therefore only 21000 m³ of the total 40000 m³ concrete ended at the top of the bottom pontoon. The rest of the shaft structure used normalweight C 75 with 3% air. The total reduction of weight is 5200 tons. The same type of concrete is also used in the gravity based (Condeep) Troll Gas platform built in Norway during the same period.

The MND concrete has a density reduction of about 10%, but still maintain most of the mechanical properties of the reference concrete NWC. The MND concrete was developed during intensive research and development at SINTEF in 1992-1993.

Exposed to a harsh marine environment, the designed lifetime for the structure is more than 50 years. This clients specification put the following requirements on the mix: Chloride diffusion coefficient D<30 mm²/year, w/(c+s) <0.38, silica fume content <5% and a maximum curing temperature <70°C.

Concrete mix design

The reduced density was achieved by replacing some of the natural coarse aggregate with LWA made of expanded clay. The other constituents are the same as used for the reference mix.

The objective of the research project (SINTEF 92-93) was to determine and document the effect on mechanical properties while replacing some of the coarse aggregate by LWA. The results revealed a slightly reduced compressive strength, reduced E-modulus and fracture energy, and slightly increased tensile strength. This was compensated by a slight reduced water-binder ratio. the density was reduced by 200 kg/m³ by replacing 50% of the natural coarse aggregate with Leca 900.

Due to the demands of strength and mechanical properties a.s Norsk Leca developed the Leca 800 for this project. The Leca 800 has a bulk density of 800 kg/m³ for the fractions 4-8and 8-12 mm and gives a concrete with better mechanical properties then the previous Leca 750. The dry particle density is 1450 kg/m³ compared to the normalweight aggregate of approximately 2600 kg/m³.

Main characteristics of the C 75 MND concrete

Cement CEM type I – 52.5	436	kg/m³
Silica fume	30	kg/m³
Natural aggregate	1347	kg/m³
Lightweight aggregate, Leca 800 4/8 & 8/12	237	kg/m³
Platicizers and stabilizers	ca 15	kg/m³
Air content	>3	%
Slump	20-26	cm
Effective w/(c+s)	0.33	
Demoulding density	2250	kg/m³
Characteristic 28 day cube strength	>75	MPA
Modulus of Elasticity	32	GPa
Cylinder / cube strength ratio	0.86 – 0.89	
Total volume of C 75 MND	21000	m³

Design criteria for LWA concrete

The design is based on Norwegian codes supplemented by criteria specified by the Norwegian Petroleum Directorate. NS 3473 "Concrete Structures – Design Rules", covers the application of both LWAC and NWC. The applicability of the normalweight provisions for this MND mix has been confirmed by comprehensive investigations in the research and development program "High Strength Concrete". In addition, several tests have been carried out by the contractor and SINTEF to confirm particular design details.

Team involved

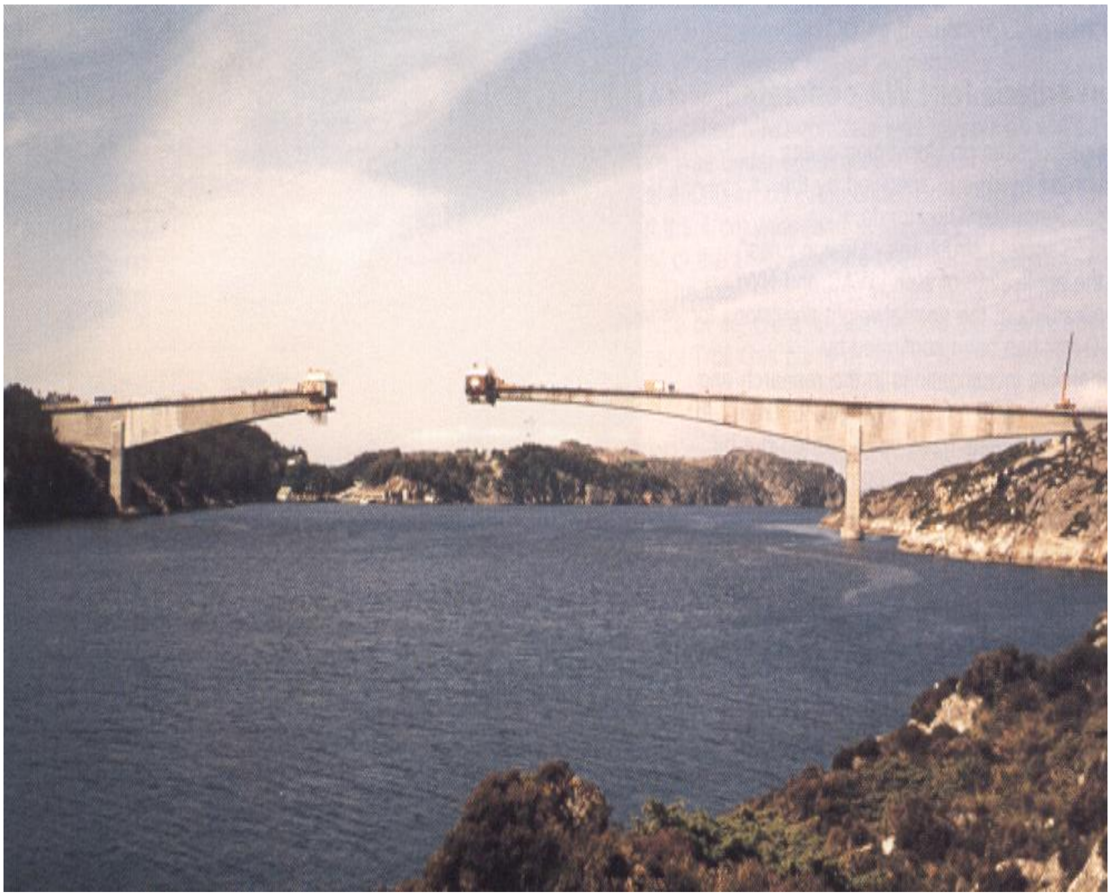
Client:	Norsk Hydro
Design and main contractor:	Kvaerner ConcreteConstruction
Subcontractor concrete works:	NCC Eeg-Henriksen
Concrete supplier:	Ølen Betong
LWA supplier:	Norsk Leca

List of references

1. S. Smeplass, T.A. Hammer, "Mechanical Properties of Modified Normal Density Concrete", SINTEF Report F93025. Trondheim, Norway 1993.
2. Arne Nǿttveit, "Troll Olje – Bygging av betongflyter", Norsk Betongday, Norwegian Concrete Association, Oslo, Norway, (Norwegian) 1994.
3. a.s Norsk Leca, "MND – Concrete, Leca 800" (Sales prospectus) Oslo, Norway 1994.
4. Bjǿrn Sjetnan / NCC, pers. com.
5. Tor Arne Hammer / SINTEF, pers. com.

The Stolma Bridge

The Stolma Bridge is a free-cantilever structure with a main span of 301 m. This is the longest span world-wide for this type of bridge (2000). The length was achieved by the use of concrete with lightweight aggregate in the mid-span. The bridge was opened for traffic in the autumn 1998.



The Stolma Bridge

General description

The municipality Austevoll south of Bergen on the western coast of Norway covers a large archipelago. The two main islands Huftarøy and Selbjørn were connected by the Selbjoørn bridge in 1979. The Stolma Bridge connects the two islands Selbjørn and Stolmen, further south-west in the municipality.

The project consists of 1800 m new road and the Stolma Bridge with its overall length of 467 m. The main span has a length of 301 m, the longest free main-span world-wide for a concrete box-girder built by the free-cantilever technique.

The total bridge length is 94 + 301 + 72 = 467 m and the girder has a total width of 9 m providing space for one pedestrian lane and two traffic lanes. Both side-spans are designed with counterweights.

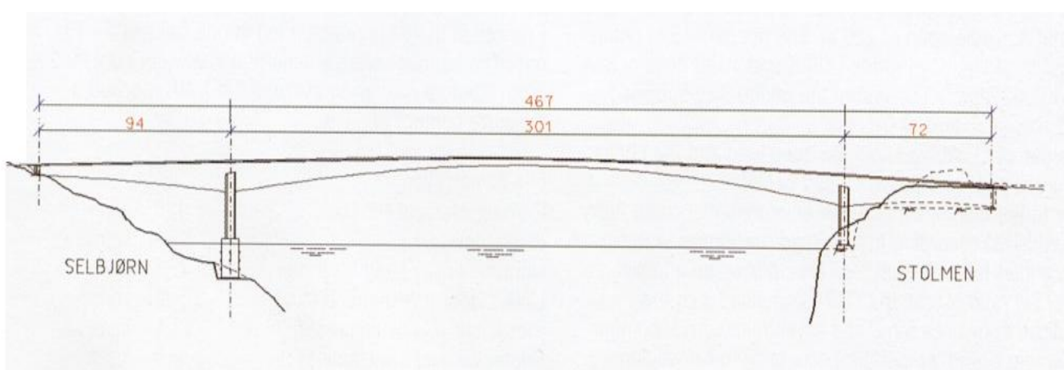
All foundations are made directly on bedrock. The foundation level at axis 2 is 17 m below sea level. The caisson for this foundation was prefabricated, floated to the bridge site and installed. The foundation has cathodic protection against corrosion by means of sacrificial anodes.

The bridge girder has a height of 15 m at the columns and 3.5 m at mid-span. A lower ratio could of aesthetic reasons be preferable, but weight optimizing and economical aspects did govern the choice.

The self-weight of the cantilever represents approximately 90 percent of the shear force at the columns. Hence optimizing the self-weight was of great importance. 1182 m of the mid-span was casted with concrete grade LC 60 with high-strength lightweight aggregate. The density of this concrete was 1931 kg/m³_. Concrete C 65 with normalweight aggregate was used for the rest of the bridge.

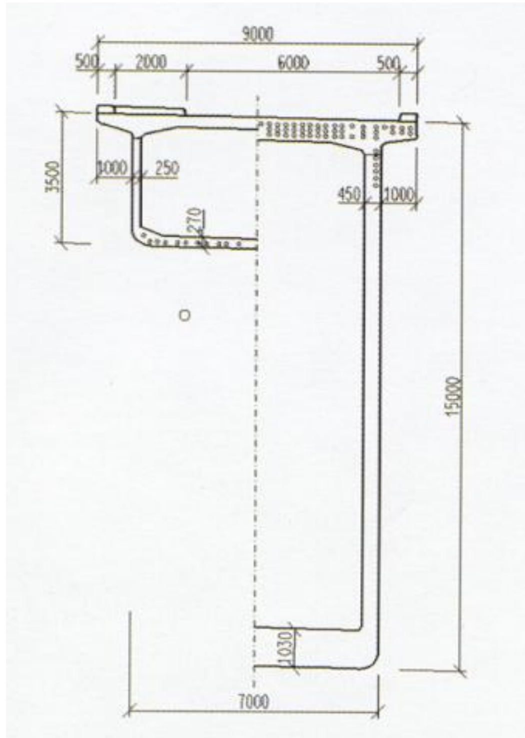
With this bridge building technique, both cantilevers from the pillar have to be in balance. By adjusting the density of the 301 m mid-span by lightweight concrete, it was possible to move the pillars to more shallow waters and reduce the cost for foundation. This resulted in a considerable cost saving compared to the scheme needed if the density of the concretes in all spans had been equal.

All corners of the cross-sections are curved to esthetical and durability reasons. This curvature also gives a reduction of the drag forces from wind. The number of post-tensioned tendons in the top slab varies from 100 over the columns to zero in the mid-span. The anchoring of this number of tendons in the short side-spans was a great challenge, and some of the tendons were installed through the webs to increase the shear resistance.



Stolma Bridge

Stolma Bridge Continued



Cross Section

Key data

Total length	467 m
Main span length	301 m
Formwork	2900 m_
Reinforcement	1850 tons
Prestressing force	99000 meter x MN
Concrete C 65	9850 m_
Concrete LC 60	1600 m_

Properties of the LWAC

<u>Mix design:</u>

Cement type CEM I-52.5	420	kg/m^3
Silica	35	kg/m^3
Natural sand (dry)	700	kg/m^3
Leca 800 4-12 mm	600	kg/m^3
Total water content	208	liters/m_
Air-entraining admixture	0,08	kg/m^3
Stabilizer Melstab	12	kg/m^3
Retarder	1	kg/m^3
Effective w/(c+2s)	0.35	
Dry bulk density Leca 800	825	kg/m^3
Dry particle density Leca 800	1450	kg/m^3

Mechanical properties

Mean cube strength $f_{c,mean}$	70.4	MPa
Characteristic cube strength f_{ck}	64,1	MPa
Demoulded density	1931	kg/m_
Density 28d cubes	1940	kg/m_

Team involved

Client	Norwegian Public Roads Administration, Count of Hordaland
Bridge design and engineering	Instanes A/S
Contractor	NCC Eeg-Henriksen Anlegg AS
Concrete supply	Øst betong

List of references

1. “The Stoma Bridge”, Structural Engineering International, May 1999
2. T.A. Thorsen, “Stolmabrua – 301 meter fritt frembygg”, Norwegian Concrete Association, Bergen, Norway, 24.10.1998
3. G. Norden, project information, pers.com.

Stǿvset Bridge, Norway

The Stǿvset free cantilever bridge crosses the Misvaerfjord some 50 km south east of Bodǿ in Norway. The bridge was constructed just north of the Arctic Circle in 1992-94. The mid span includes 950 m^3 of LWAC of grade LC-55. Due to the remote site, the concrete had to be produced on site by a small 0.5 m^3 mixer.

Stǿvset Bridge, Norway

General

The bridge consists of 3 spans. Two side spans of 100 m and middle span of 220 m. The middle 145 m of this consists of LWAC of grade LC-55 and in-situ density less than 2000 kg/m^3. The rest of the bridge was specified with a normal density C-55.

The use of LWAC reduced the dead load and the needed reinforcement and postensioned cables.

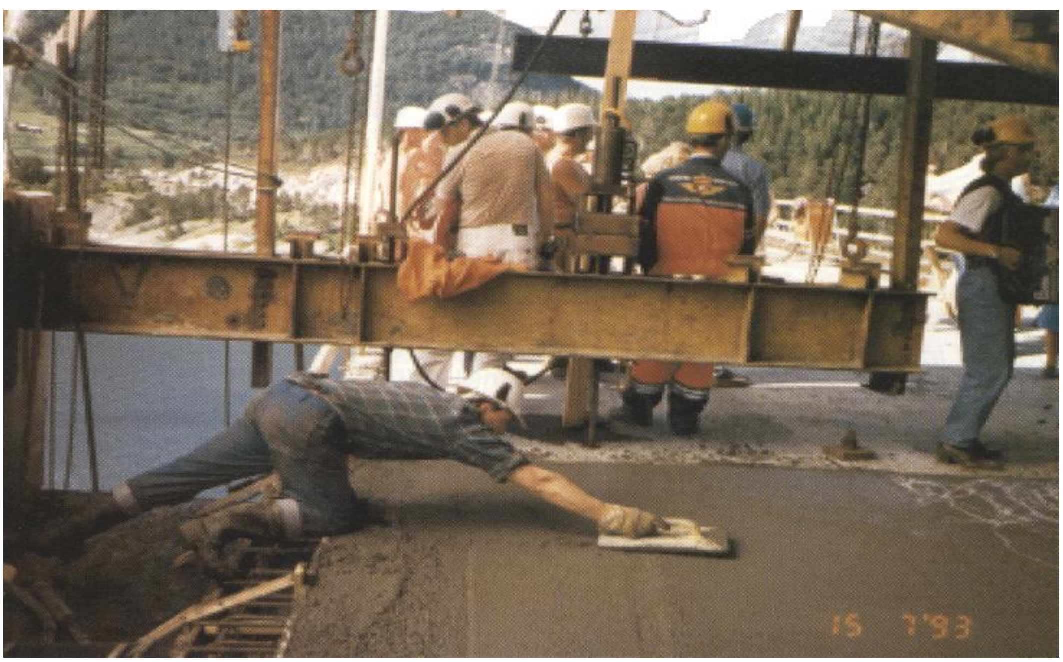
Due to the marine climate, the environmental class “Very Aggressive” according to the Road Authorities was demanded for both qualities. This implies an effective w/(c+2s) ratio of less than 0.40 combined with the application of silica fume and air entrainment. Maximum allowable curing temperature according to Norwegian standard was 65 ºC.

LWAC

Due to the long distance from any existing ready-mix plant, the contractor decided to establish his own batching plant on site. The mixer chosen was a 0.5 m³ ELBA forced action type located close to the eastern buttress. The concrete was dispatched directly into a concrete bucket and transported to the pouring section by a cable crane. Due to the short period from mixing till casting, it was impossible to apply remixing, a prerequisite if the traditional Norwegian way by adding dry LWA to the mixer should have been used. To avoid detrimental effects on the LWA-paste interface due to absorption of water in the LWA and subsequent squeezing out of air forming bubble rims on the aggregates, water saturated LWA was applied /1/. Due to logistic problems in the small batching plant, the LWA was ordered from the German producer Lias-Franken in a big-bags pre-blended in one fraction 4 – 16 mm. The big-bags were submerged in a water pool for 2 – 3 days before mixing. In average the LWA reached a moisture content of 14%.

Mix composition:

Cement, Norcem HS-65	425	kg/m³
Silica fume	30	kg/m³
Normal density sand 0-8 mm	685	kg/m³
LWA Liapor 8 (expanded clay)	520	kg/m³
Plasticizer (lignosulphonate)	1	kg/m³
Superplasticizer (melamine)	4.5	kg/m³
Air entrainment	1.5	kg/m³



Pouring of the closing gap

Effective water content was 194 kg/m³. Achieved fresh properties were a slump of 20 cm and mean air content of 5%. By applying water saturated LWA and air entrained paste, a good balance was achieved in buoyancy between the two phases and no problem with segregation was experienced. A number of cores were drilled to verify the in-situ properties. The middle strength of these was 58.2 MPa, exact the same as for the laboratory cast and curried specimens. The average cube strength was 64.5 MPa with a standard deviation of 3.7 MPa. According to ACI 214, such a low spread is characterized as "excellent". The in-situ density was 1924 kg/m³ while the oven dried specimens weighted some 140 kg/m³ less. E-modulus was 22.0 GPa.

Field Performance

Dummy panels of the LWAC with a casting and curing equivalent to the bridge have been exposed to sea-splash at the site. Field monitoring have confirmed that the characteristics concerning chloride penetrations are fulfilled. Long term monitoring of overall deflection and stains have similarly verified the design presumptions concerning the creep properties of the LWA.

Standards applied

The bridge was designed according to Norwegian Standard NS 3473. However, at that time the Norwegian standards did not give any provisions for LWA or production/execution of LWAC structures. The tender document was therefore based on project specifications on these aspects. These were supplemented by the contractor's own quality assurance procedures for LWA and LWAC.

Støvset Bridge under construction

Team involved

Client:	Norwegian Public Road Administration, County of Nordland
Design:	Johs Holt as
Contractor:	Selmer ASA

List of references

1. S. Helland, "Strength loss in un-remixed LWAC due to air evacuation from the aggregates", International Symposium on Lightweight Concrete, Sandefjord, Norway 1995.
2. H. Johnsen et al., "Construction of the Stǿvset free cantilever bridge and the Nordhordaland cable stayed bridge", Internalt Symposium on Lightweight Concrete, Sandefjord, Norway 1995.
3. J.E. Carlsen, "Chloride penetration in Stǿvset bridge", LettKon report, Norway 2000.
4. P. Takacs, T. Kanstad, T. Hynne, "Deformations of Stǿvset bridge. Measurements and analysis", Second International Symposium on LWAC, Kristiansand, Norway 2000.

The Nordhordland Floating Bridge

The Nordhordland Bridge north of Bergen in Norway, consists of a free floating bridge of 1246 m, and high level cable-stayed bride across the ship channel of 32 x 50 m. the superstructure of the floating part is a steel box girder supported on 10 concrete pontoons and connected to abutments with transition elements in forged steel. The pontoons were designed in lightweight concrete LC 55 in order to minimize the self-weight and draft of the pontoons. The floating bridge has the longest laterally unsupported span in the world (1999).

Nordhordland Floating Bridge

Key data

<u>Time Schedule:</u>

Contract award, design:	May 1990
Contract award, construction:	Aug. 1991
Completion:	Sept 1994

<u>Materials:</u>

Normalized steel in box girder: Yield strength 355 MPa typical, 540 MPa in the critical exterior span.
High strength LWAC in pontoons and main span.

<u>Geometry:</u>

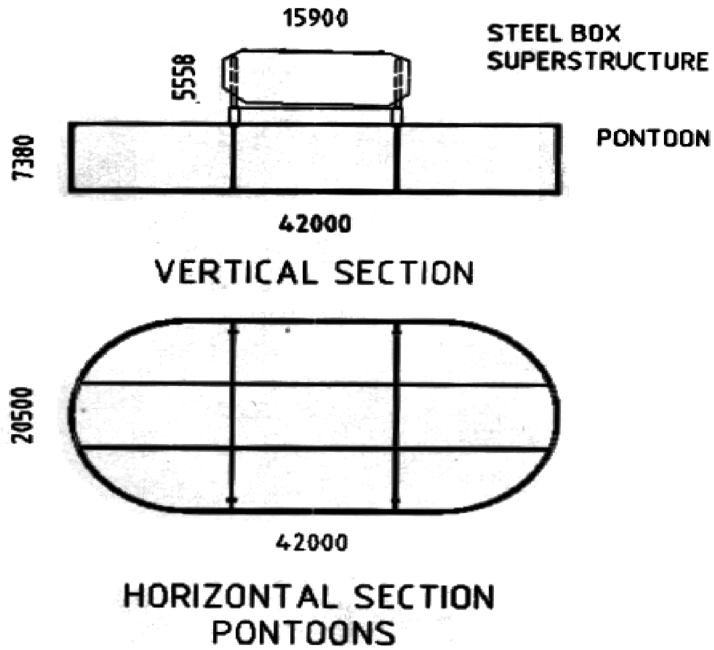
Total length between abutments:	1246 m
Length of ramp structure:	350 m
Typical span between pontoons:	113.25 m
Width deck:	10 m
Bridge deck level above water surface:	min. 11.0 m
Air draft below steel box:	5.50 m
Pontoon dimensions L/B/H=	42.0/20.5/7.38 m
Pontoon draft:	4.3 m typical, 5.6 m at end

<u>Climate</u>

Temperature:		-20 to +25ºC
Wind:	10 min. mean at elev. 10 m:	$V_{10,10}$ =26.9 m/s
Waves	Significant height:	1.76 m
	Periods:	3.6 to 5.1 s
Tidal range:		-1.40 to +1.60 m critical
		$\pm$ 0.61 m for fatigue
Sea current:		1.75 m/s

<u>Mix design for LWAC, LC55 in pontoons:</u>

Portland cement HS 65	410 kg/m³
Silica fume	33 kg/m³
Sand 0-5 mm	675 kg/m³
Liapor 8, 4-8 mm	270 kg/m³
Liapor 8, 8-16 mm	325 kg/m³
Water total	200 kg/m³
Plasticizers/superplasticizers	10-12 kg/m³



Vertical section and Horizontal section pontoons

<u>Properties of LWA concrete LC55:</u>	
Demoulding density (average)	1918 kg/m³
Cube strength (average)	70.4 MPa
Standard deviation	4.31 MPa
Modules of Elasticity	21 GPa
Nominal water/binder ratio (w/c+2s)	0.42
Effective water/binder ratio (w/c+2s)	0.33
Slump at site	20 cm

The LWA used is Liapor 7 from Lias Franken, Germany. The bulk density is 800 and the particle density 1440 kg/m³.

Design considerations

The picture shows an aerial view of the whole crossing. The pontoons and bridge girder are shown in the figure. The caisson below the ramp structure is the fixed point for the floating bridge and carries mainly horizontal forces. For this floating bridge the wave action is the most dominant force action, giving more than 50% of the total internal girder design force. The wave forces are proportional to the submerged volume of the pontoons. Two alternatives were considered for the bridge girder: Steel box and prestressed NWC box (C 65). The latter required a considerably larger pontoon of 42.0/22.0/16.5 m. Even so the total cost comparison was approximately equal but the steel alternative was selected due to a more favorable construction schedule. The pontoons are designed with 9 separate compartments, two of which can be filled with water without damaging the bridge girder excessively.

The cost savings obtained by using LWA concrete the pontoons has not been quantified in the project. However, it is obvious that a smaller dead-load results in the need for smaller pontoons. Smaller pontoons receive smaller wave action and hydrostatic forces from sea current. Due to environmental demands, the reduced drafts of the lightweight pontoons were also considered essential to interfere as little as possible with the tidal exchange of water in the fjord. The design of the concrete parts was according to NS 3473.

Construction methods

The following construction methods were used:

- Fabrication of the pontoons in a dry dock in Fredrikstad.
- Fabrication in Moss of the steel box girder in 34 segments with varying lengths 20, 36 and 42 m.
- Assembly of the steel box segments into 11 modules and shipping by barge (approx. 800 km) to a sheltered fjord near the bridge site.
- Towing of the pontoons (approx. 800 km) to the site.
- Assembly of steel box modules and pontoons for the whole 1246 m bridge.
- Floating the whole bridge in place, entering first at the fixed point on the caisson and then eased into position on the land abutment.

Towing the Nordhordland pontoons

Team involved

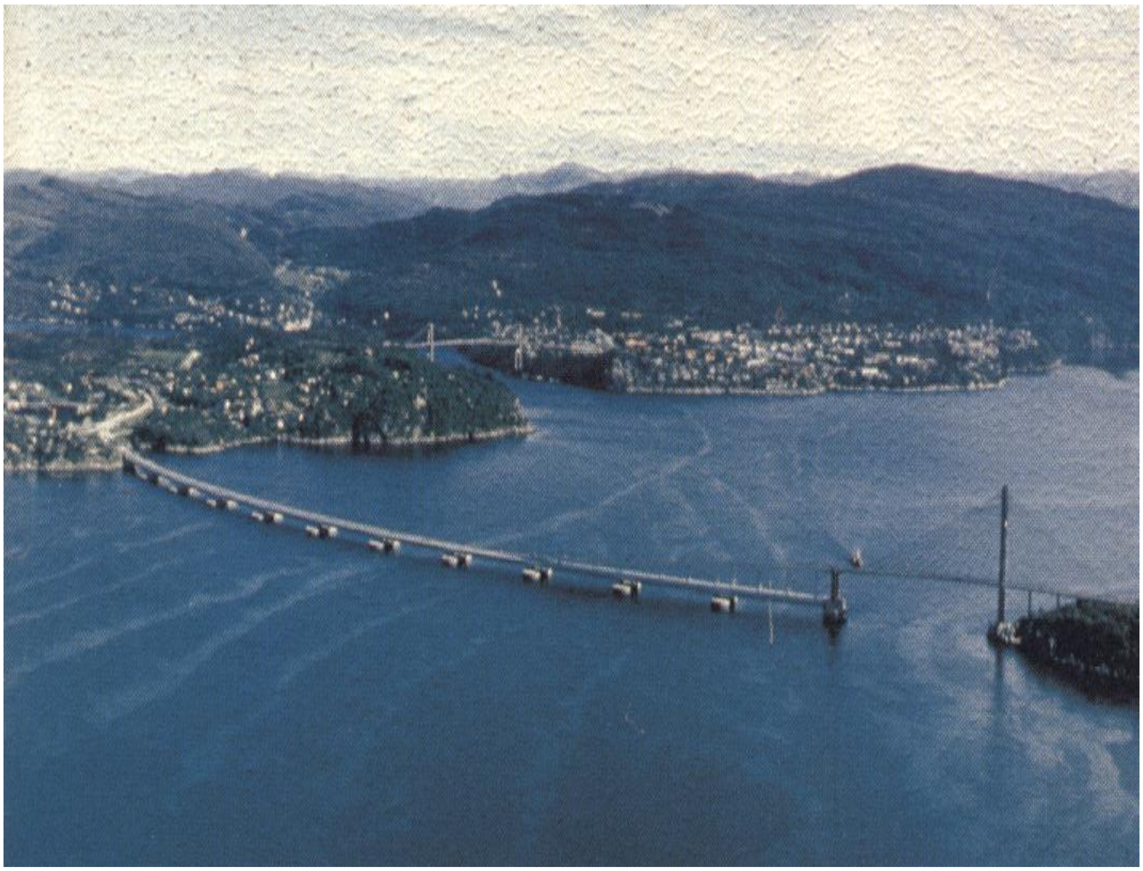
Client:	Norwegian Public Roads Administration (PRA), County of Hordaland
Design:	PRA, Bridge Department, Dr. Ing. A. Aas-Jakobsen AS, Det Norske Veritas AS
Architect:	Lund & Slaatto, Lund & Lovseth, Hindhammar-Sundt-Thomassen
Contractor:	Norwegain Contractors AS, Kvaerner, AS, A/S Veidekke

List of references

1. Jordet/Kjeken/Thorsen: "The Slahus high level bridge", Third Symposium on Straight Crossings (1994).
2. Jorgensen J.T., Rosseland S., Meland I.S., Ronne M., Teigland J., "Beskrivelse av prosjekt med lettbetong, Nordhordland Flytebru", SINTEF report STF22 A97815, Lightcon R&D programme, Trondheim, Norway 1997.
3. Heimdal E., Ronneberg H., "Production of high strength lightweight Concrete – The views of a ready mix concrete producer", N.B. – F.I.P. International Symposium on structural LWAC, Sandefjord, Norway June 1995.

The Nordhordland Cable Stayed Bridge

The Nordhordland Bridge is located north of Bergen at the West Coast of Norway. It consists of the world's longest free floating bridge of 1246 m, and a high-level cable stayed bridge crossing the ship channel of 32 x 50 m. The cable-stayed bridge has a main span of 172 m. This designed in high strength lightweight concrete (LWAC) and cantilevers from a H-shaped pylon founded on land. The main span is stabilized by back spans with a total length of 190 m.



Key data

<u>Time schedule:</u>

Contact award, design	May 1990
Contract award, construction	Aug. 1991
Completion	Sept 1993

Materials:
Stays: 7 mm galvanized wires in HDPE pipe filled with grease and with HIAM-anchors.
NWC in back span and pylon: C 45
High strength LWAC in main span: LC 55

Geometry:

Main span:	172 m
Back spans:	22+6x28=190 m
Width overall:	15.10 m
Top of pylon:	+98.0 m
Ship Channel:	HxB=32x50 m

Climate / Wind:

10 min. mean at elevation 10 m:	$V_{10,10}$=26.9 m/s
Turbulence intensity, horizontal:	0.2 $V_{10,\,z}$
Turbulence intensity, vertical	0.1 x $V_{10,\,z}$

Mix design for LWA-concrete LC55:

Portland cement type CEM I – 52.5	430 kg/m³
Silica fume	35 kg/m³
Natural sand 0-5 mm	630 kg/m³
LWA, Leca 750, 4-8 mm	295 kg/m³
LWA, Leca 750, 8-12 mm	275 kg/m³
Total water content	195 kg/m³
Platicizers / superplasticizers	7 kg/m³

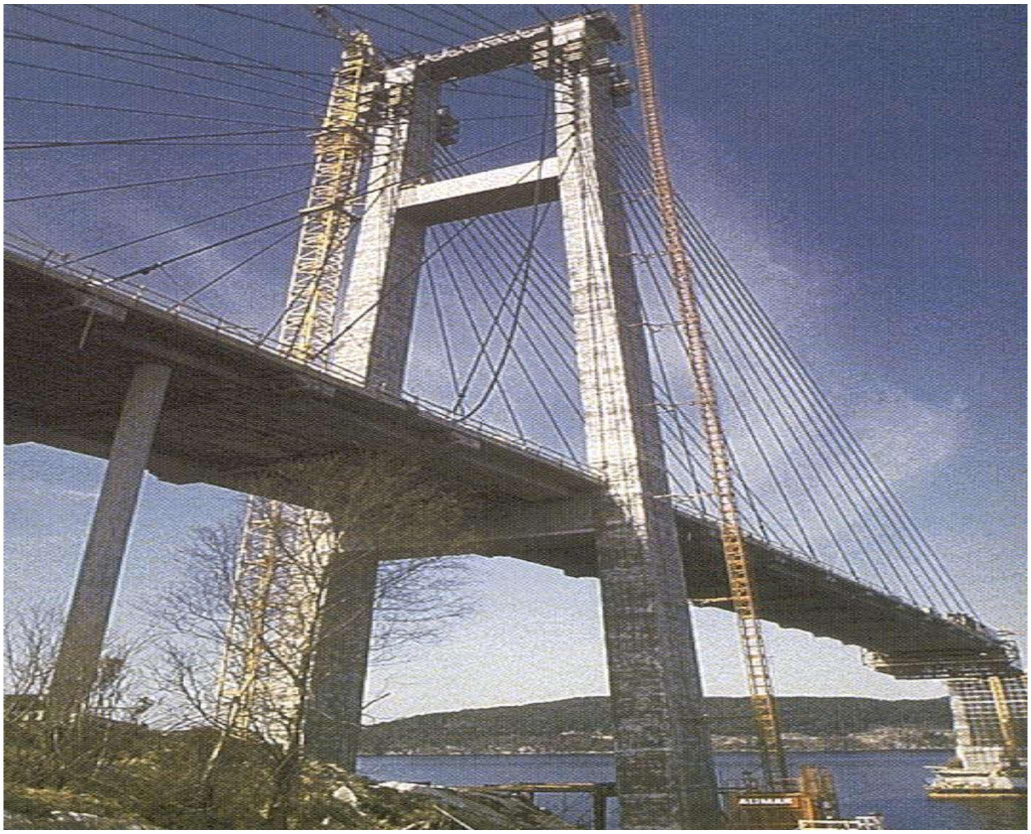
Properties of LWA concrete LC 55

Demoulding density (average)	1881 kg/m³
28 days cube strength (average)	69.9 MPa
Standard deviation	2.38 MPa
Modules of Elasticity	21 GPa
Nominal water/binder ratio (w/c+2s)	0.39
Effective water/binder ratio (w/c+2s)	0.31
Ratio cylinder strength/cube strength	0.98-1.0
Slump at site	15-20 cm

The LWA used is Leca 750 from a.s Norsk Leca. The bulk density is 750 kg/m³ and the particle density 1300 kg/m³.

Design considerations

The caisson below the ramp structure is the fixed point for the floating bridge and carries mainly horizontal forces in addition to small vertical loads from the bridge beam between the expansion joints required by the floating bridge and the cable stayed bridge respectively. For the high bridge, two designs were considered – cable stayed and arch. The cable stayed concept was tested with alternative designs of the deck in the main span. The alternatives were steel/concrete composite, NWC, C 55 and LWAC, LC 55. The design with LWAC proved the most economical, giving more savings in stay area than the cost increase due to the LWAC. Using the contract unit rates the total savings are estimated to 620000. – NOK, or 0.83% of the total contract sum. The design was according to NS 3473.



Construction methods

The following construction methods were used:

- Pylon cast by slipforming
- Side spans, span by span with fixed scaffold to the ground
- Main span by cast-in-place segments a 12 m in free cantilevering from the pylon.

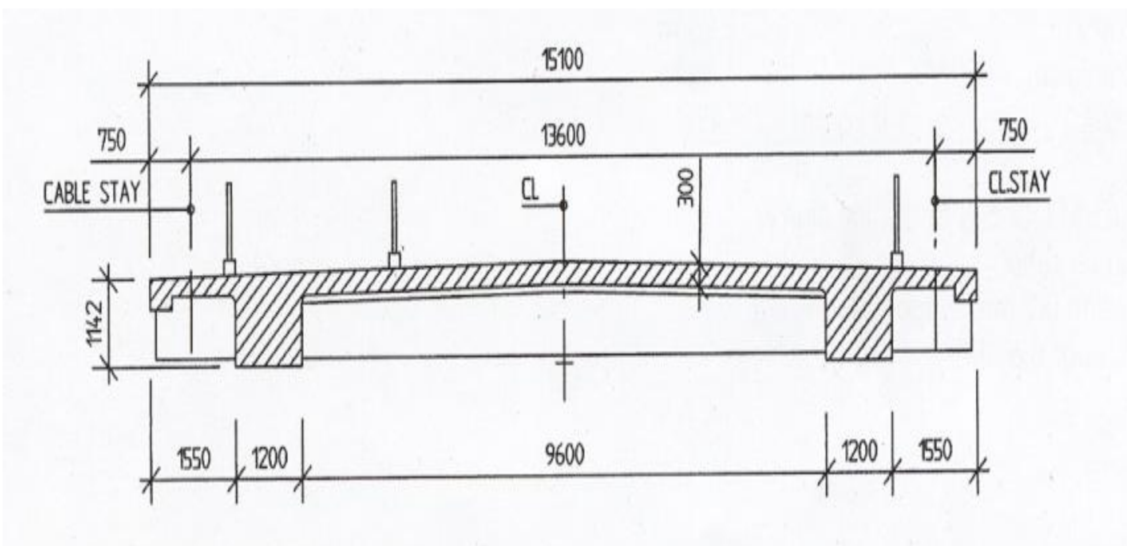
The form traveler for the main span construction was specially designed to make sue of the permanent pair of stays for a new segment as load carrying members during casting of that segment. The obtained final profile of the deck was within 35 mm of theoretical anywhere along the length of the bridge and the stay forces did not deviate by more than 5% from the theoretical. No adjustments of stay forces were thus required after the main cantilever reached the caisson.

Team involved

Client:	Norwegian Public Roads Administration (PRA), County of Hordaland
Design:	PRA, Bridge Department in ass. with Dr. Ing. A. Aas-Jakobsen AS
Architect:	Lund & Slaatto, Lund & Lovseth, Hindhammar-Sundt-Thomassen
Contractor:	Selmer ASA
Concrete Supply:	Aker Betong
LWA supply	a.s Norsk Leca

List of references

1. E. Jordet, Kjeken, Thorsen: "The Slahus high level bridge", Third Symposium on Straight Crossings, Norwegian Public Roads Admin., Oslo, Norway (1994).
2. E. Heimdal, H. Ronneberg "Production of high strength LWAC – The views of a ready mix concrete producere", N.B. – F.I.P International Symposium on Structural LWAC, Sandefjord, Norway, June 1995.



9A
"Benefits of Lightweight HPC"

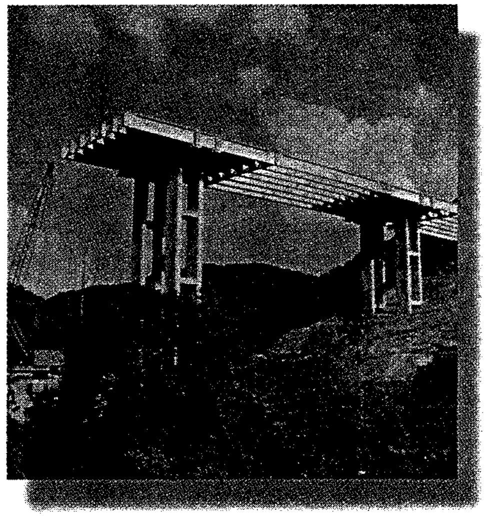
BENEFITS OF LIGHTWEIGHT HPC

Thomas A. Holm and John P. Ries, Expanded Shale Clay and Slate Institute

There are many advantages to the use of lightweight aggregate in high performance concrete. This article highlights the primary design- and construction-related benefits.

Improved Structural Efficiency (Strength/Weight)

Structural lightweight concrete is typically 25 to 35 percent lighter than normal weight concrete. This translates into lighter superstructures and smaller loads for substructure design. The award winning Shelby Creek Bridge in Kentucky provides an excellent example of structural efficiency where a 7000 psi (48 MPa) concrete compressive strength was attained with a density of less than 130 pcf (2.08 Mg/cu m).



Lightweight concrete was used on the Shelby Creek Bridge to reduce superstructure weight. (Photo courtesy of PCI.)

Reduced Seismic Forces

The new Benicia-Martinez Bridge in California is a cast-in-place concrete, post-tensioned box girder bridge situated in a high seismic zone. The bridge will be built using the balanced cantilever method. To reduce the seismic forces caused by the structure's self weight, the designers have specified a concrete density of 120 pcf (1.92 Mg/cu m) and a concrete compressive strength of 6500 psi (45 MPa).

Improved Constructibility

Constructibility and transportation issues need to be considered early in the design and planning process of any project. Since precast, prestressed concrete bridges cannot be built unless the beams can be transported, lightweight HPC is often used to comply with over-the-road state weight limitations, or to carry more members on each truck. Fewer truck deliveries (especially in restricted areas) are environmentally beneficial, safer, and generate fewer public complaints. The use of a longer crane reach or a smaller crane are added benefits.

Improved Hydration Due To Internal Curing

Lightweight aggregate containing high internal moisture contents may be substituted for conventional aggregates to provide "internal curing." High cementitious concretes with very low water-cementitious materials ratios are vulnerable to self-desiccation. These concretes benefit significantly from the added internal moisture of properly pre-wetted lightweight aggregates. Internal curing is particularly helpful for concretes containing high volumes of silica fume and other materials known to be sensitive to curing procedures. In these applications, density reduction is a positive by-product. Because of the improved cement hydration developed by the moisture released from the reservoir of water absorbed within the pores of the lightweight aggregate, the improvement in the quality of concrete over time is greater with lightweight HPC than with concrete containing normal weight aggregates.

Renovation and Repair

One of the most extensive applications of structural lightweight concrete is in bridge redecking where lower dead load is achieved. This often means that bridge widths, traffic lanes, and the thickness of structural slabs can be increased while utilizing existing piers, footings, and other structural members. The use of lightweight concrete often allows the live load capacity of older structures to be increased.

Economic Considerations

The use of lightweight aggregates, while more expensive than conventional aggregates, does not increase the total project cost. Consider the use of lightweight HPC on an 8-in. (200-mm) thick concrete bridge slab with a cost premium of $30/cu yd ($39/cu m). One cubic yard (0.76 cu m) of concrete will yield approximately 40 sq ft (3.7 sq m) of deck causing an increase in slab cost of 30/40 = $0.75/sq ft ($8.07/sq m). For a bridge with a total cost of $75/sq ft ($807/sq m) this results in a cost increase of one percent. However, this one percent material cost is offset by the reductions in the cost of slab reinforcement and the reduced size and cost of girders, piers, and foundations all due to a lower superstructure self weight of approximately 20 percent.

Durability

Lightweight concrete has been used in bridge decks for over 50 years. The excellent in-service performance in these structures as well as in marine structures and ships has demonstrated that lightweight concrete is a durable concrete. More detailed information about durability is provided in Reference 1.

Further Information

For more information on the advantages of lightweight concrete, contact your local supplier of rotary kiln expanded shale, clay, or slate lightweight aggregate. Your nearest supplier may be located by going to www.escsi.org.

Reference

1. Holm, T. A. and Bremner, T. W., "State-of-the-Art Report on High-Strength, High-Durability Structural Low-Density Concrete for Applications in Severe Marine Environments," U.S. Army Corps of Engineers, Report No ERDC/SL TR-00-3, August 2000, 116 pp. available at www.wes.army.mil/SL/INP/reports.htm. (This address is case sensitive.)

Editor's Note

This article is the second in a series that addresses the benefits of specific materials used in HPC. The benefits of silica fume were discussed in the previous edition of HPC Bridge Views.

9B

"Lightweight HPC On Route 106 Bridge in Virginia"

LIGHTWEIGHT HPC ON ROUTE 106 BRIDGE IN VIRGINIA

H. Celik Ozyildirim, Virginia Transportation Research Council

High performance concrete (HPC) bridges in Virginia have shown initial cost savings mainly due to the reduced number of beams per span, use of smaller cross-sections, and the ability to span longer distances. More benefits can be realized by reducing the dead load of the structures. The improved durability of HPC is also expected to lead to more savings over the life of the structure. Thus, the use of lightweight HPC (LWHPC) for the beams and deck for a bridge on Route 106 over the Chickahominy River, east of Richmond, Virginia, was proposed for the FHWA Innovative Bridge Research and Construction Program. The bridge, constructed in 2001, has three spans of 85 ft (25.9 m) and a width of 43.3 ft (13.2 m). The 7.9-in. (200-mm) thick deck is continuous over the two intermediate piers. Each span has five AASHTO Type IV beams spaced at 10 ft (3.05 m) centers.

Implementation of the LWHPC beams and deck was accomplished in three phases. In the first phase, a test program focused on fabricating and testing Type II and Type IV beams. In the second phase, the Type IV bridge beams were fabricated and erected. In the third phase, the concrete bridge deck was constructed. A portion of the deck over one of the piers contained synthetic fibers in the concrete for crack control. Condition surveys were performed after the placement of the deck and 2 years later.

The specified 28-day compressive strength and 28-day permeability were 8000 psi (55 MPa) and 1500 coulombs, respectively, for the beams and 4000 psi (28 MPa) and 2500 coulombs, respectively, for the deck. The specified concrete strength for detensioning the bridge beams was 4500 psi (31 MPa). The target density for the LWHPC for the beams and deck was 120 lb/cu ft (1.92 Mg/cu m). The concrete mixture proportions, which included both lightweight and normal weight aggregates, are given in Table 1. Grade 270 low-relaxation 0.5-in. (12.7-mm) diameter prestressing strands were used.

Workable concretes were obtained. The bridge beams had a concrete density about the same as that specified. Before pumping, the deck concrete had a density less than the specified value. However, samples taken after pumping had a higher density and lower air content. During sampling of the pumped concrete, there was a longer vertical drop than during the deck placement and flow of concrete was not continuous. This could have contributed to a large loss of air in the test samples, which would increase their density.

For the tests on hardened concrete, the beam samples were steam cured and the deck samples moist-cured. The measured compressive strength, flexural strength, permeability, and modulus of elasticity values are given in Table 2. The strength of the concrete with fibers was considerably lower than the strength of the concrete without fibers. This strength reduction is attributed to the addition of extra water to compensate for reduced workability due to fibers. To improve workability without adverse effect on strength, water-reducers should be used.

The results indicate that LWHPC can be produced such that the material is workable, strong, volumetrically stable, and resistant to cycles of freezing and thawing, thus leading to a long service life with minimal maintenance. Testing of prisms showed that the fibers provide residual strength expected to mitigate deck cracking. A condition survey after 2 years of exposure indicated only limited cracking including two transverse cracks above the piers in the sections with and without fibers. Based on the experience, more structures with LWHPC for beams and deck are expected to be built in the future. A 1.01-mile (1.63-km) long bridge with LWHPC beams and deck is currently under design in Virginia.

Table 1 Concrete Mix Proportions

Material	Quantities per yd^3	
	Beams	Deck(1)
Portland Cement(2)	451 lb	489 lb
Slag	301 lb	—
Pozzolan Class N	—	163 lb
Fine Aggregate NW	541 lb	1228 lb
Fine Aggregate LW	390 lb	—
Coarse Aggregate NW	605 lb	—
Coarse Aggregate LW	696 lb	900 lb
Water	255 lb	292 lb
Water Reducer/Retarder	22 fl oz	20 fl oz
HRWR	56 fl oz	33 fl oz
Calcium Nitrite	3 gal/yd^3	—
Air Entrainment	5.5 + 1.5%	6.5 + 1.5%
w/cm ratio	0.34	0.45

(1) Without fibers. Fibers were added at 9 lb/yd^3 to the deck concrete used over one pier
(2) Type II
NW = normal weight, LW = lightweight

Table 2 Properties of LWHPC

Property	Age	Beams	Deck Control	Deck Fiber
	1 day	4720	4740	3275
Compressive Strength, psi	28 days	8100	7225	4940
	1 year	7890	8915	6570
Flexural Strength, psi	28 days	640	780	740
Permeability, coulombs	(1)	917	832	1372
Modulus of Elasticity, ksi	28 days	2980	2750	2790

(1) For the bridge beams, permeability measured at 1 year after initial steam curing and subsequent drying. For deck concrete, permeability measured at 28 days after 1 week moist curing at room temperature and 3 weeks at 100°F.

Further Information

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9C

“Lightweight Aggregate Concrete In Norwegian Bridges”

LIGHTWEIGHT AGGREGATE CONCRETE IN NORWEGIAN BRIDGES

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A main characteristic of Norway is its long coastline. During the last century, a vast number of marine concrete structures have been built to facilitate communications and transportation. Since the 1970s, the discovery of large oil and gas fields off the Norwegian coast created the need for a number of gravity based as well as floating concrete production platforms.

Like the rest of the world in the late 1970s, Norway faced the problem of chloride-induced corrosion in our marine infrastructure. A program was, therefore, started to improve concrete quality and to develop models enabling us to assess the performance of these structures. This development resulted in the introduction of high strength, high performance concrete (HSC/HPC). Consequently, we were able to include concrete with characteristic cube strengths up to 15,000 psi (105 MPa) in our design code in 1989. In the same year, the Norwegian Roads Administration introduced a requirement for a water-binder ratio of less than 0.40 combined with the use of silica fume on all their infrastructure projects.

HPC lightweight aggregate concrete was used to reduce the weight of the main span on the Stolma Bridge

Lightweight Aggregate Concrete In Bridges

To help bridge designers in their efforts to create optimum structures, the Norwegian concrete industry, in the mid 1980s, started to combine the technology of HSC/HPC with that of lightweight aggregate concrete (LWAC). The first pilot project, constructed in 1987, was a 49-ft (15-m) long pedestrian bridge built with LC-60—a lightweight concrete with a cube compressive strength of 8700 psi (60 MPa). Later, ten major bridges were built with this material in Norway. These comprised free cantilever, cable stayed, and pontoon bridges. The spans of the two latest free cantilever bridges—Raftsundet at 978 ft (298-m) and Stolma at 988 ft (301-m)—represent world records.[1]

The motivation for using LWAC for free cantilevers has been twofold. Firstly, the effect of reduced dead load is obvious. Secondly, the construction method requires a balanced load on both sides of the pylon during construction. This limits the choice of span lengths and the possibility of placing pylons according to the topography. However, by being able to adjust the material density of the cantilevers, the designer achieves greater freedom.

Two of the bridges represent the revitalisation of an old concept—the pontoon bridge. Bergsøysundet (1992) with its 3000 ft (914 m) length, and Nordhordland (1993) with its 4088 ft (1246-m) length used LWAC of LC-55 (8000 psi or 55 MPa) in a total of 17 pontoons.[2] Again, dead load was important for the buoyancy, but equally important was the need to reduce the draft of the pontoons. Environmental considerations strictly limited the impact to the tidal water in the fjords.

LWAC Qualities

The structures are designed with concrete characteristic cube strengths of 8000 and 8700 psi (55 and 69 MPa) and densities in the range of 119 to 122 lb/cu ft (1900 to 1950 kg/cu m). Aggregates are made from expanded clay or shale. The specified water-binder ratio requirements have been less than 0.40, while actual ratios have been as low as 0.33. Silica fume has been used in all structures. In contrast to the North American tradition, dry lightweight aggregate has generally been used.

Field Performance

During the last 15 years, extensive research has been carried out in Norway to verify the LWAC's performance in a marine environment. This research includes the development of a service life model and laboratory and field-exposed test specimens. Typically, a number of test elements have been cast at the bridge sites and exposed in the tidal and splash zones as a part of the construction project. The results have given us the confidence that LWAC will withstand the design life of more than 100 years with comfortable margins.[3]

Ten years ago, the Roads Administration was sceptical about the use of high strength LWAC without any proven field performance. Today, their attitude has changed and they regard this technology as mature and a natural choice in the repertoire of materials needed to optimize bridge design.[4]

Codes and Regulations

All the structures have been designed according to the Norwegian Standard NS 3473. This has been updated both for HSC and LWAC several times during the 1990s. However, standards covering the materials and construction aspects of LWAC were not updated. The projects have, therefore, been constructed according to special project specifications.

The situation is changing with the new set of joint European concrete standards.[5] The parts on materials and construction have now been revised. The LWAC provisions are the fruits of major research projects in Europe[6] and represent state-of-the-art technology.

Economy

LWAC has a higher unit price as delivered from the batching plant. Savings in concrete and reinforcement quantities must compensate for this. However, reduced foundation costs, increased buoyancy, or the opportunity to apply different design concepts dominate the economy. All the LWAC structures have undergone an economical analysis to justify the choice of material. A number of these analyses are described in Reference 7.

Conclusion

To maintain the use of concrete in bridge construction, the range of material combinations had to be broadened in the 1970s and 1980s. The introduction of higher strengths and better performance in marine and de-icing salt environments was the first step. The second step was to give the designer the possibility of combining these characteristics with the freedom to specify density. Without these quantum leaps in technology, concrete's leading position in this market would have been questionable.

References

In June 2000, the Second International Symposium on Structural LWAC was held in Kristiansand, Norway. Ninety-six papers from more than 30 countries were presented. The proceedings are available from the Norwegian Concrete Association, www.betong.net.no.

The following papers give more in-depth information on the subject of this article:

1. Rosseland, S. et al., "The Stolma Bridge—World Record of Free Cantilevering"
2. Jakobsen, S. E., "The Use of LWAC in the Pontoons of the Nordhordland Bridge, Norway"
3. Helland, S., "Service Life Modelling of Marine LWAC Structures"
4. Melby, K., "Use of High Strength LWAC in Norwegian Bridges"
5. Helland, S., "LWAC in the New European Standards on Materials and Execution"
6. Mijnsbergen, J. et al., "EuroLightCon – A Major European Research Project on LWAC"
7. Fergestad, S. et al., "The Economical Potential of LWAC in 4 Different Major Bridges"