Lightweight aggregate concrete – characteristics of hardened concrete

Guideline 1
Production and
fresh concrete properties

▶ **Guideline 2**
Lightweight aggregate concrete –
characteristics of hardened
concrete

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Introduction

Lightweight aggregate concrete (LWAC) is defined as concrete with lower density than normal density concrete (NDC). LWAC has been successfully used for many decades in various constructions were the purpose usually has been to reduce weight.

This guidelines will focus on mechanical properties of the hardened concrete and compare the lightweight concrete with the normal density concrete. NDC is used as a reference since the characteristics are well known by use, experience and through norms.

The guideline will handle several mechanical properties and explain how and why the LWAC is different. Together with this guideline an attachment is added which summaries the specific text in the national norms that relates to LWAC. Some specific properties, results and experience are not conclusive. The guideline is based on results from the references and general experience. The national norms are definitive for construction and design of structures.

FIGURE 1

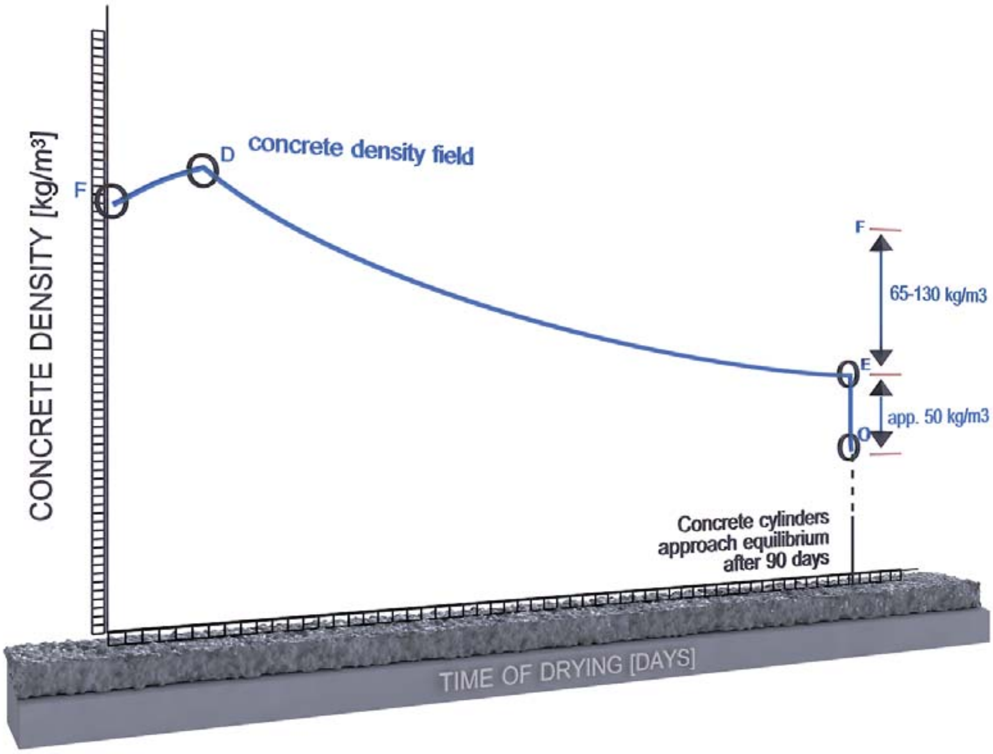


Figure 1

Concrete density versus time of drying for structural concrete (Holm 1994 – modified)

F *Fresh density is measured during manufacturing and is in accordance with the mix design density.*

D *Demoulded density is usually 20-50 kg/m^3 higher than F.*

E *Equilibrium density is dependent on the environment but can range from D to O. American studies conclude that E is 50 kg/m^3 higher than O and the ACI 213 concludes that E is 65-130 kg/m^3 below F.*

O *Oven dry density is used by the norms for calculating other mechanical properties. The Eurolightcon literature defines O to be 100-200 kg/m^3 lower than F while The Norwegian guidelines NB 23 recommend using 150 kg/m^3.*

2

Density

The cardinal reason for using LWAC in structures is the reduced weight achieved by lighter concrete. The fresh and demoulded density of NDC is usually 2300-2400 kg/m^3 while LWAC is defined as concrete with dry density < 2000 kg/m^3 with an approximately fresh density of 2150 kg/m^3.

The norms are limiting and defining the lower accepted density of LWAC. Most mechanical properties of LWAC are related to the density and the compressive strength and it is therefore necessary for the construction norms to limit the use of very light concrete. Such concrete may not comply with the experiences which has formed the regulations in the norms.

The low density of LWAC is usually achieved by using light weight aggregate (LWA) in combination with a normal density binder and sand with high density. Other composition is also possible and not prevented by the norms. To achieve LWAC with low density also fine LWA can replace fine dense sand.

LWA has a porous, partly open structure of pores of different sizes surrounded by solid and strong clay or shale material. Consequently, the LWA will in more or less extend absorb water both during outdoor storage and during mixing and transportation.

The density of a specific LWAC mix may therefore vary in function of the initial moisture level of the LWA and increase during mixing, transportation and placing.

Most of this moisture will later be desorbed to the binder or dry out and the structure will find equilibrium with its environment. Therefore different types of LWAC densities are referred to.

Using and understanding the correct term of density is certainly important if design weight matters. Figure 1 explains the differences of densities measured at different times and can be used as a guide for what density is expected when during service time.

FIGURE 2

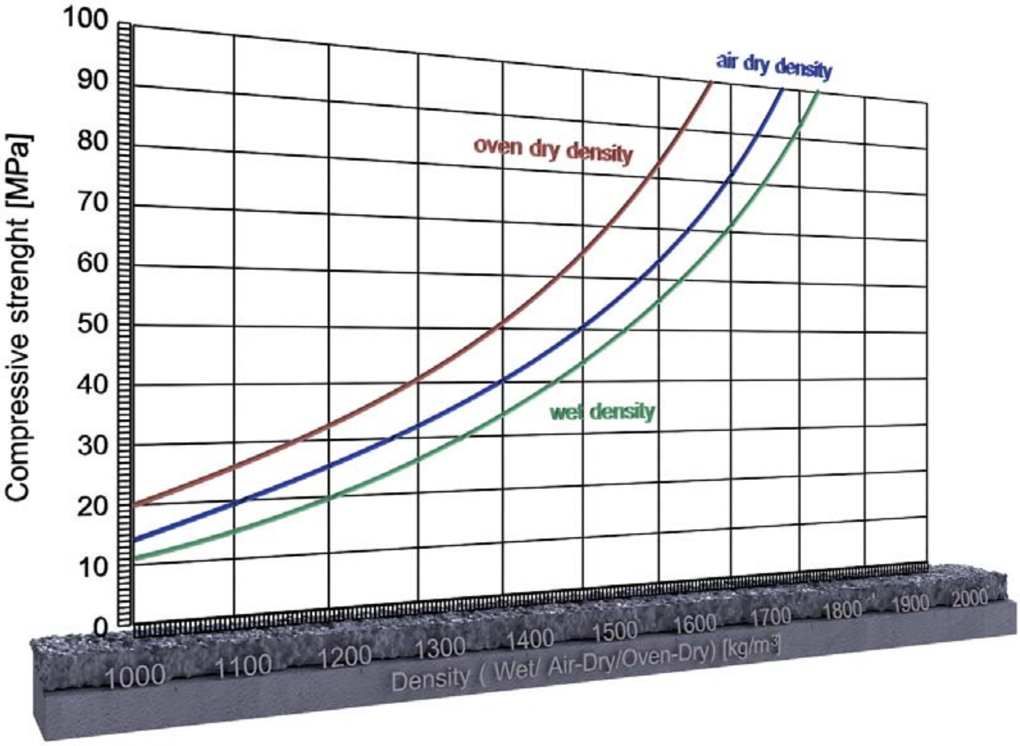


Figure 2

Maximum achievable compressive strength based on wet, air dry and oven dry density (Punkki 1992)

Table 1

Strength growth for LWAC and NDC in percentage of 28 days for high performance mixes (NB 23-1999)

	7d [%]	28 d [%]	90 d [%]
NDC	70	100	107-112
LWAC	90	100	100-105

3

Compressive strength

The other important property of LWAC is the compressive strength which together with the density is used to calculate or estimate the other mechanical properties.

All aggregates have a specific strength ceiling. To stress the aggregate close to the strength limit is not recommended since brittle mechanical properties will occur. From an academic point of view maximum achievable compressive strength is of interest. Figure 2 estimate maximum achievable compressive strength based on wet, air dry and oven dry density.

In contrast to NDC, LWAC mortar and aggregate has relatively similar strength and stiffness. Dense normal aggregate (NDA) is considerably stiffer than the mortar and takes therefore more of the force and transverse stress and strain in the crucial aggregate - mortar interface zone will initiate micro cracking. After moulding of the LWAC, LWA will absorb mixing water and reduce the w/b-ratio in the interface zone. During hardening the cement is consuming water and the moist LWA will desorb water to the interface zone resulting in a high degree of hydration and less micro cracks. The micro cracks will therefore first occur at a higher stress level. The ability of the LWA to handle and distribute micro cracks is limited and resulting in a more rapid fracture pattern. The stress – strain diagram for LWAC is therefore more linear and final strain is lower. The relatively low initial LWA strength contributes more to the total strength of the LWAC and limits the maximum strength. The mortar strength is relatively less important and a weak aggregate can in less extent be compensated by a strong mortar.

The development of maximum strength is rapid in LWAC and 90% of the 28d compressive strength is achieved after 7d in a high performance mix. The similar figure for NDC is about 70%. From 28 d to 90d the strength development for LWAC is considerably lower than NDC. This is important to note since the calculation regulations are taking strength growth between 28d and 90d for granted. Consequently, the norms have limited the maximum strength of LWAC based on density or alternatively demand documentation of late strength growth.

Another issue to note is the relative difference in cylinder and cube compressive strength comparing LWAC with NDC. Norms usually accept the use of cubes for measuring compressive strength. A fixed value is used to calculate the cube strength to cylinder strength which is used in the calculations. For LWAC the cube and cylinder strength are more similar than for NDC. It is therefore recommended to make the documentation with cylinders or determine by tests the specific relationship between them. A higher grade of compressive strength may be achieved by this way.

FIGURE 3

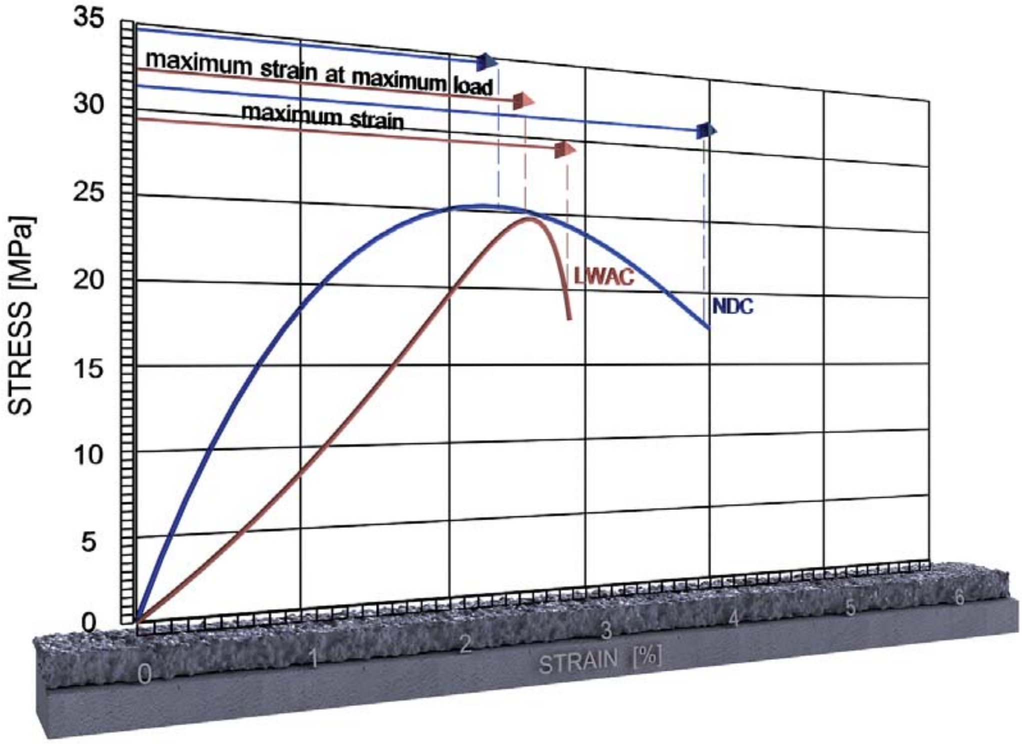


Figure 3

Schematic figure of stress – strain diagram of LWAC and NDC. The LWAC has a more linear form and manage less maximum strain, but the maximum strain at maximum load is somewhat higher.

4 Modulus of elasticity and stress – stain relationship.

The E-modulus is defined as the stiffness of a material and results from the stress – strain diagram. As for compressive strength, the E-modulus is a function of the individual ingredient moduli, their relative proportion and the bond between the aggregate and the binder.

There seems to be a good correlation between E-modulus and compressive strength and tests indicates no considerable influence of LWA type. Stress-strain relationships for LWAC are generally characterized by a more linear ascending curve, more limited plastic strain and a steeper descending branch, but with a higher maximum strain at maximum load than NDC.

A schematic figure of stress – strain diagram of LWAC and NDC is displayed in Figure 3. The LWAC has a more linear form and manage less maximum strain, but the maximum strain at maximum load is somewhat higher. The linear, brittle behavior is usually enhanced with increasing strength. Comparing LWAC and NDC with similar compressive strength the E-modulus of LWAC is about 20-30% lower. The calculation regulations in the norms use formulas that are close to most measured values.

PICTURE 4

Picture 4

Close look at a shear and bond fracture of a LWAC beam of very low density.

5 Flexural and splitting tensile strength, shear and bond

Traditionally, tensile strength has been defined as a function of compressive strength. The tensile strength is a combination of the LWA strength, binder strength and the interface zone between the LWA and the paste. LWA has considerably less tensile strength than NDA but the binder and the contact zone in LWAC is stronger for comparable concrete. There are therefore not significant differences in tensile strength. ACI 213 claim LWAC splitting tensile strength to be 75%-100% of NDC with similar compressive strength. In the Eurolightcon project, the tensile strength was claimed to be at 5-15% of compressive strength for LWAC. For lighter and more brittle LWAC the difference may be bigger.

In the norms the tensile strength for LWAC is reduced, but this is an adaptation to be able to calculate shear, bond and reinforcement anchorage. For exact estimation of tensile strength, tests can be performed with actual mix design.

From a shear and bond perspective LWAC behave fundamentally the same way as NDC with similar strength. For high strength LWAC the shear capacity may be predicted by modified tensile strength. For low strength and low density LWAC the shear capacity may be lower than predicted and tests with actual mix should be executed. If necessary, shear and bond capacity can be increased by the addition of polymers.

TEST SET UP

Picture 5

Test set up for shear test of LWAC lintel.

6 Shrinkage and creep

Drying shrinkage and autogenous shrinkage is the two main forms of shrinkage. The driving force for both types is removal of water in the paste pore system inducing pore contraction and shrinkage of the concrete. The size of the autogenous shrinkage is directly related to the quantity of cement in the mix. For making a LWAC with same compressive strength as for NDC a larger cement quantity is usually used. At the same time the E-modulus is lower for LWAC. Consequently, the shrinkage for LWAC is expected to be higher but slower.

By the use of presaturated LWA the situation is completely altered. High degree of water absorbed in the pore structure of the LWA will be available to moisture the paste pore structure during consume of paste water. Recent studies and report indicates that the internal curing may eliminate at least early shrinkage completely. The internal curing will also effect and enhance the degree of cement hydration.

In general, shrinkage for LWAC is little documented and the norms usually do not separate LWAC and NDC.

Creep is deformation of the matrix over time due to external force or load. The volume proportion of matrix and aggregate are similar for LWAC and NDC, but the stiffness of LWA is usually lower than NDA.

The creep is therefore expected to be higher for low density LWAC (30% for <1500 kg/m^3) and more and less similar for denser LWAC >1800 kg/m^3 compared to same strength NDC.

FIGURE 4

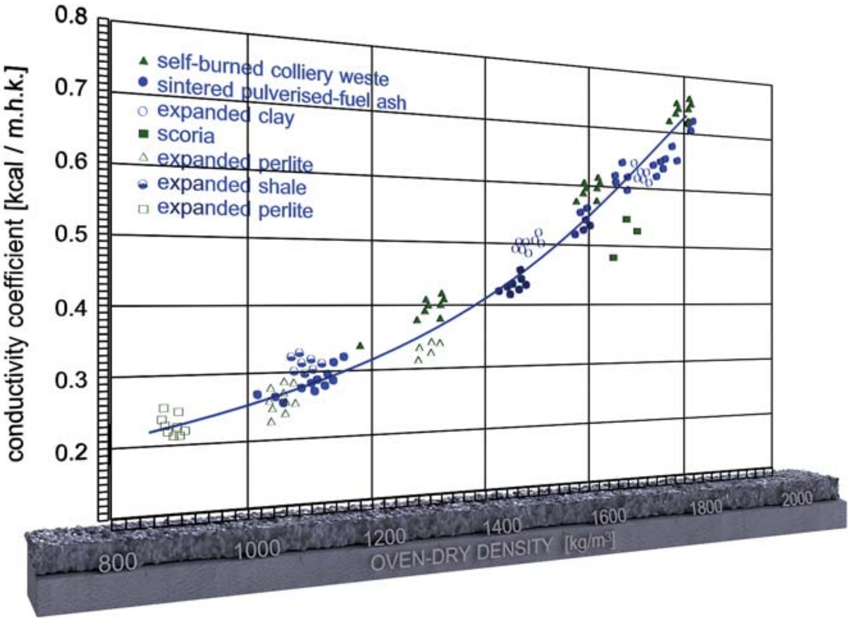


Figure 4

Relationship between thermal conductivity and oven-dry density for lightweight aggregate concrete (based on Lo-Shu, 1980)

7 Thermal properties and fire resistance

Thermal conductivity is considerably lower for LWAC than NDC because of the porous structure of the LWA. LWAC can be used to enhance the insulation of a structure. Conductivity is directly related to the density and moisture level of the concrete - see figure 4.

The specific heat is independent on density and is similar for all concrete = 1 J/kgK, but note that specific heat is defined as energy per weight. Thus a light weight structure has lower specific heat than a dense structure. This is important to consider when planning massive structures which need cooling.

The coefficient for thermal expansion is somewhat lower for LWAC than NDC. In addition the E-modulus is lower and maximum strain at maximum load for LWAC is somewhat higher, results in better resistance for thermal cracking than NDC.

Several factors are involved when characterizing fire resistance of LWAC. In general, LWAC will resist better against a slow cellulose fire but worse against a rapid hydrocarbon fire compared to NDC. Polypropylene fibers can help fire resistance during hydrocarbon fire.

8 Durability

The main question concerning durability for concrete is corrosion steel reinforcement caused by reduced concrete pH (carbonation) or chloride penetration.

The LWA is porous, partly open and penetration of gas and water is likely to happen. The LWAC usually consist of a dense matrix with low w/b ratio and very high performance interface zone. The permeability of LWAC is dependent on the individual permeability of the three components. In LWAC with low w/b ratio, the paste has a finer pore system than the LWA. This will limit the ability of the aggregate to contribute in the capillary water transport through the concrete. When the w/b is increased, the capillary resistance in the paste will be reduced, making - in theory - the aggregates able to participate in the water transport. For medium and high strength LWAC the permeability is expected to be better or similar than NDC. For low strength LWAC or very light LWAC a more open concrete can be expected.

Long term studies of various LWAC structures do not indicate that LWAC is more exposed for durability problems than NDC. The norms do not handle LWAC any different than NDC.
The porous LWA will as long the aggregate is dry result in better or similar frost resistance for LWAC as for comparable NDC. The frost resistance is reduced if high degree of water saturation of the LWA occurs. High performance NDC and LWAC can perform very well without air entrainers as long the v/b ratio is low enough and the concrete strength is high enough.

References:
Eurolightcon: LWAC Material Properties: State of the Art: 1998
ACI 213R-03: 2003
NB 23: 1999
Factors controlling properties of LWAC: PhD Thesis: Punkki 1992

APPENDIX A

References projects:

Ref. 01: Guggenheim Museum, Bilbao, Spain; LWAC floor slabs

Ref. 02: Tunnel vaults of light weight concrete

Ref. 03: Snarøya Church, Norway

Ref. 04: The Polar Sea Cathedral, Tromsø, Norway

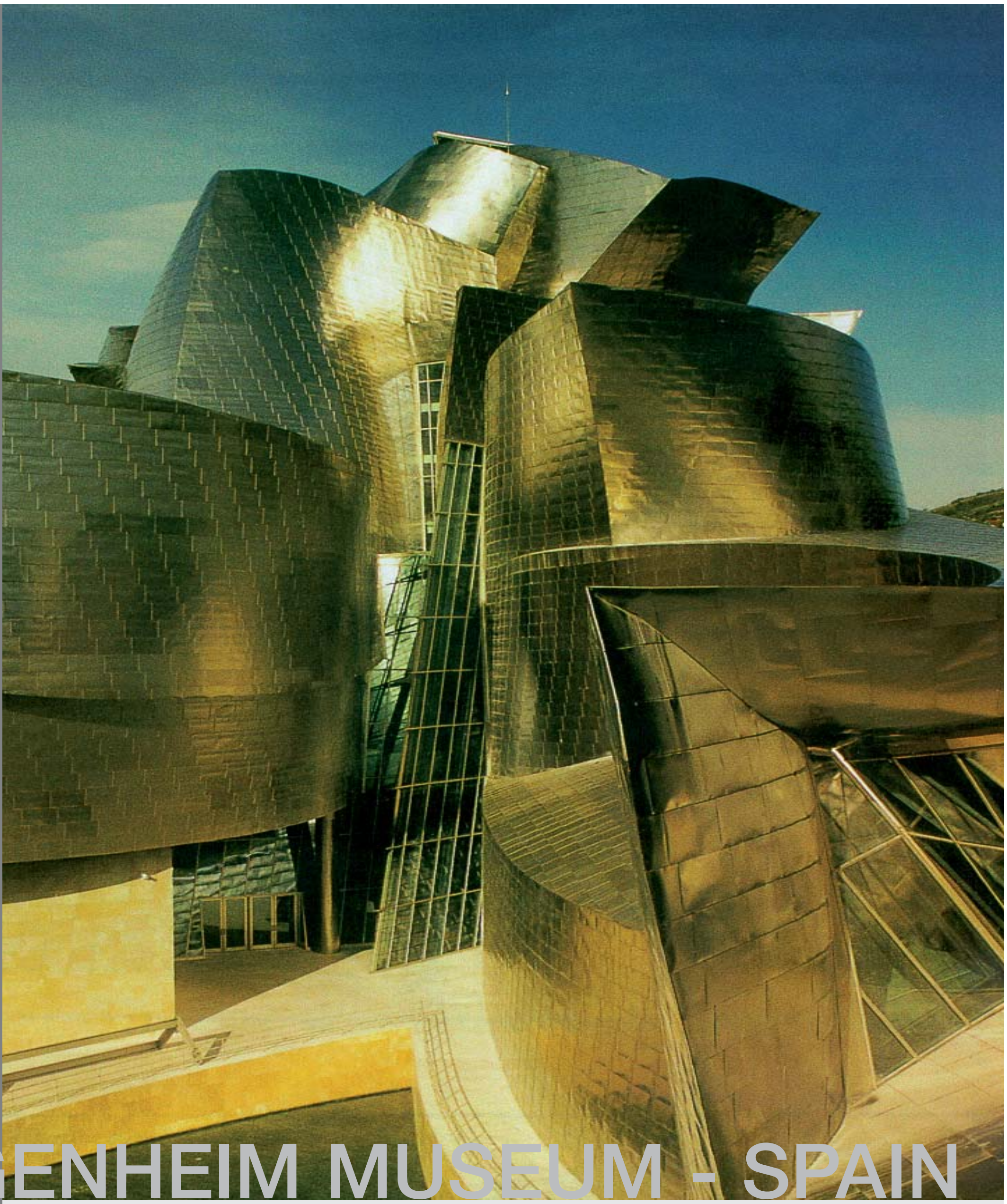
Ref. 05: The Troll West floating platform

Ref. 06: Bridge - Spain

Ref. 07: EXPO '98, Pavilion of Portugal, Portugal

Ref. 08: Bridge - Portugal

MUSEUM



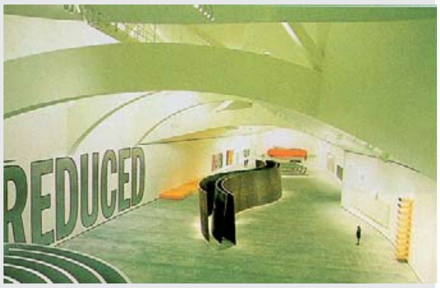
Ref. 01

GUGGENHEIM MUSEUM - SPAIN

Key data

General:	
Gross building area::	28.000 m^2
Public opening:	October 1997
LWAC volume:	4.800 m^3
Light weight concrete LC25:	
Compressive strength:	25 MPa
Fresh density:	1700 kg/m^3
Dry oven density:	1600 kg/m^3
Slump	8-10 cm
Light Weight Aggregate:	Arlita F-5
Water cement ratio (nominal):	0.60
E-modulus:	18000 Mpa

References:
[1]: Javier Lopez Ovejero, Adiros Ligeros S.A: "Arlite Floor Slabs at the Guggenheim Museum in Bilbao, Madrid , Spain, 1997
[2]:Frank O. Gehry: "Guggenheim Museum Bilbao". The Salomon R. Guggenheim Foundation. New York 1997,1998.
[3]:ECCS No. 91-5: "Architechture Steel".



Guggenheim Museum, Bilbao, Spain; LWAC floor slabs

Team involved:

Client:
Consorcio del Proyecto Guggenheim Bilbao
Architect:
Frank O.Gehry and Associates
Consultant:
IDOM/SOM
Contractor:
Ferrovial and Lauki
LWA supplier:
Aridos Ligeros S.A.

Recognised as one of the most representative work of architecture of the late 20th century, the Guggenheim Museum is the masterpiece of one of the foremost American architects of nowadays, Frank O. Gehry.
In order to reduce the weight of the structures due to the special soil conditions, floor slabs was cast using Light Weight Aggregate Concrete (LWAC).

General description
The Guggenheim Museum in Bilbao, Spain provides a unique architectural view using traditional construction materials like steel and glass in combinations with special ones like titanium, Spanish limestone and LWAC.
To design this precious jewel of the Spanish city of Bilbao, the engineers had to solve a tremendous problem, the poor quality of the soil on the shore of the Nervion river, mostly made up of industrial waste accumulated during decades of steel production.
The weight of the gigantic structure of the Museum had to be reduced in every possible way. One of the most important actions taken was the choice of a super light floor slab structure, designed with a zincated steel corrugated plate (galvanized), connected to a concrete slab 60 to 80 mm thick.
The system is light by itself, but the use of expanded clay in the concrete reduced the total weight roughly 30 %. This concrete was used in every single horizontal structure, even the roof, and a total of 4.400 m3 of LC-25 was placed by means of pneumatic pumps.

Construction:
To be able to achieve the design density with a compressive strength of 25 MPa, the readymix plant used a mix provided by Aridos Ligeros, consisting of ARLITA F-5, a special lightweight product with a bulk density of 550 kg/m^3, particle density of 900 kg/m^3 and a size range between 3 and 8 mm.
The concrete was made in the nearby plant of Cavia in Ortuella, transported by truck and placed by pneumatic pumps.

Figure 6

Ref. 02

VÆRE TUNNEL - NORWAY

The tunnel is a part of the new highway system from Oslo to the swedish border and is scheduled to be completed in 2009.

The Være Tunnel was rehabilitated in 2004 with the LWAC slabs and the Road Department is still monitoring the frost values behind the slabs.

A total amount of >120000 m^2.
LWAC slabs need about 27.000 m^3 Leca LWA which is contracted by Spenncon and will be supplied from May 2007.
The future is bright for this construction method and it is good reason to expect several new supplies.

Tunnel vaults of light weight concrete

Arch shaped light weight aggregate concrete (LWAC) precast slabs with low density are a considerably challenge from both a constructive and concrete technology point of view. Through several years it has been performed development and full scale testing of physical characteristics of the tunnel concept. Now, another tunnel is under construction.

The reason for using LWAC instead of normal density concrete in tunnel vault is the increased frost insulation with about 4 times. In northern countries frost inside tunnels may lead to ice formation behind the concrete vault and the concrete or loose rock may be pushed out and fall down into the tunnel with severe consequences. The solution so far has been a combination of normal density concrete slabs and an insulation material.

Unfortunately, most insulation materials are combustible and in addition many materials release toxic gases while burning. New fire protection requirements from EC was supported by the Chief Executive in the Road Department and combustible insulation materials are now being phased out. LWAC in not combustible and with an addition of poly propylene fibers the slabs has proven to manage heavy hydrocarbon fire without spalling.

In addition to fire- and frost protection the LWAC slabs must prevent ground water leakage into the tunnel and also support as a mechanical protection between the rough blasted mountain surface and the traffic. A LWAC density of <1400 kg/m^3 with a characteristic compressive strength of >15 MPa was required.

To achieve the requirements at the Være Tunnel, Leca 2-4 mm and 4-10 mm from Leca Rælingen was used together with a high performance cement paste. For such concrete with large volume of LWA, the LWA quality is essential to achieve best possible characteristics.

In addition the LWAC must be workable and fill the form and create smooth surfaces without honeycombs. The result was a concrete density of 1350 kg/m^3 and an average compressive strength of almost 20 MPa. The requirements for the surface were satisfied.

CHURCH

Ref. 03

SNARØYA CHURCH - NORWAY

Structural features:

The church roof and walls are plate and shell structures without effective stiffeners except for at the boundaries. The walls are founded directly on rock and partly on casted piles to rock. The LWA concrete used in the roof is of higher strength than the LWA concrete used in the walls. This is because the roof slab has relatively long spans and therefore larger local bending moments with less beneficial axial force than the walls.

References:
[1] Harald Hille, pers. com.
[2] Østbye/Falk Frederiksen/Espelin: "Snarøya Kapell", Betongen i dag no. 5. 1968, Norwegian, Oslo, Norway.



Snarøya Church, Norway

Situated close to Oslo, Snarøya Church offers a special architectonic view of a church constructed with the use of light weight aggregate concrete (LWAC). The church was constructed in the sixties.

Team involved:

Architect:
Odd Østbye/ Harald Hille
Design:
Siv.ing. Ole Falk Frederiksen A/S
Contractor:
Johan Olsen & Sønner
LWA supplier:
a.s. Norsk Leca

Key data

General:

Number of seats:	250
Opened:	1968
Costs:	NOK 1.25-1.45 mill

LWA concrete walls.
LWAC B-200 with characteristic cube strength 20 MPa and density 1400 kg/m^3.

Leca 400 3-10 mm	770	Liters/m^3.
Sand	630	kg/m^3.
Cement	420	kg/m^3.
Density (dry)	1420	kg/m^3.

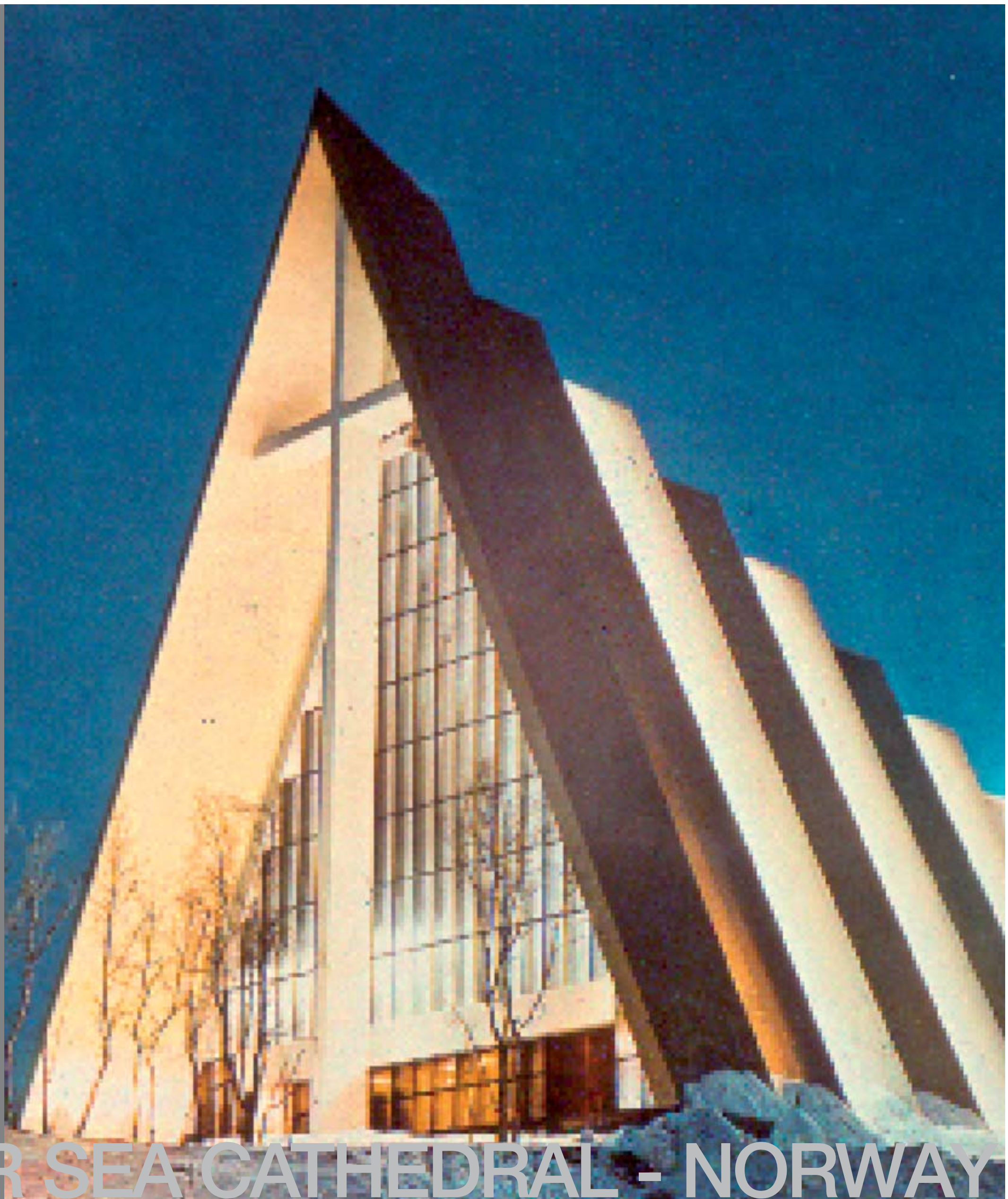
LWA concrete roof slab.
LWAC B-250 with characteristic cube strength 25 MPa and density 1600 kg/m^3.

Leca 400 3-10 mm	700	Liters/m^3.
Sand	680	kg/m^3.
Cement	450	kg/m^3.
Density (dry)	1550-1650	kg/m^3.

The reasons for applying LWAC
The architect wanted to use concrete as construction material to get a uniform material look on large surfaces combined with relatively large spans. The insulation ability and the low dead weight made the LWAC very suitable for these purposes.

Architectural features:
The church is situated in flat surroundings, but integrated in a local rock crag. The entrance was placed on top of the rock crag, and the high church walls was curved around down to the flat surroundings. All walls consist of parts of curves and straight lines, in the church corners separated by windows in whole height, giving a special light inside the church The walls are a little inclined.

CHATHEDRAL

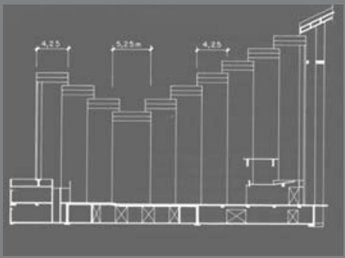


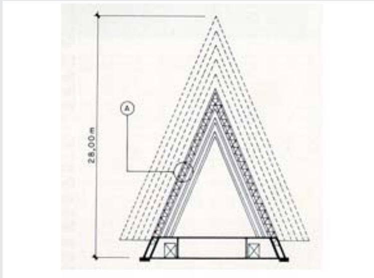
Ref. 04

POLAR SEA CATHEDRAL - NORWAY

Structural features:
The roof consists of 10 inclined section, rising from the floor level, with a 2.1 m difference between each section. The roof plates were designed to support dead load and wind loads. Snow loads were not taken into account because the roof inclination us more than 60°, actually 67°. The roof plates are stiffened by trusses with chords embedded in the same plates, while the diagonals are architectural details fully expressed. Load tests were carried out in order to control the plate strength by using two half size scale models. The results proved pure tension failures of reinforcement with no sign of bond or shear failures. The real load failure was about 10% higher than the theoretically calculated. The plated were reinforced by two layers of galvanised steel mesh Ê5c150mm in two directions.
The lightweight structure consists of LWAC with characteristic compression strength at 25 MPa and a density of 1650 kg/m3. The concrete is casted in situ. There have been no durability problems reported by using LWAC in the structure. The code used NS 427 did not contain the use of LWAC, and the project is therefor adjusted to use of normal concrete.

References:
[1]Jan Inge Hovig, "Ishavskatedralen, arkitektens ide", Betongen i dag, no. 5 (Norwegian) 1966
[2] Ivar Vamnes, "Ishavskatedralen, den konstruktive løsning", Betongen i dag, no. 5 (Norwegian) 1966





The Polar Sea Cathedral, Tromsø, Norway

Situated in the city of Tromsø and surrounded by the Tromsdalstinden mountains, the Polar Sea Cathedral is with its very special architecture been one of the most famous tourist attractions in northern part of Norway. The cathedral was constructed in the mid sixties. The special roof and main structure consist of lightweight concrete.

Team involved:

Client:
Tromsøysund County
Architect:
Jan Inge Hovig
Design:
Dr. Ing. A.Aas-Jakobsen AS
Contractor
Ing. F. Selmer A/S
LWA supplier:
a.s Norsk Leca

General description

The building is located in a site close to the Tromsø River and the Tromsø Bridge in the northern part of Norway. Tromsø is characterised with the 3 month long polar night and is known for a lot of snow in the wintertime. The church comprises a main 740- seat nave with a 90-seat chapel in a lower level. The architectural shapes derived from the analysis of the particular site conditions and from the need to keep a constant and uninterrupted relation between interior spaces and landscaping.

The most outstanding building feature is the inclined roof consisting of lightweight concrete sections, which enabled to meet important insulation requirements and to reduce the structure weight. The use of lightweight concrete allowed reducing the structural load about 50% as compared with a conventional rib structure with inner insulation. It was obtained a high degree of insulation with no thermal bridges, involving considerable cost savings

Key data

Maximum height of church:	28 m
Number of seats:	740 + 90
Number of roof sections:	10
Roof section width:	4.25 m
Roof section thickness:	0.3 m
Construction period:	1964-1965
LWA:	Leca 400, 3-10 mm
Measured density concrete:	1650 kg/m^3
Cement	175 kg

FLOATING PLATFORM

Ref. 05

THE TROLL WEST

The Troll West is a floating platform operating at the North Sea oilfield with the same name 70 km north west of Bergen, Norway. The concrete structure is installed at a water depth between 315-340 metres. 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 planed to install an extra floater unit. Research and studies concluded that use of concrete with lower density would solve the problem. During the construction period, there was developed and utilised a new concrete were natural coarse aggregate was partly replaced by LWA (Light Weight Aggregate). The MND (Modified Normal Density) concrete has a density reduction of about 10%, but still maintain most of the mechanical properties from ND (Normal Density) concrete.

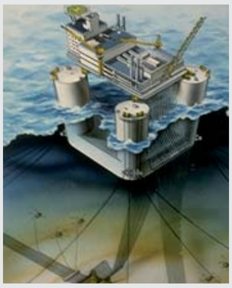
Some key data for the project

Master Plan	**May. 92**
Contract award	Jan. 93
Start of construction in dry dock	Jun. 93
Tow-out from dry dock	Oct. 94
Ready for module mating	Feb. 95
Complete installation	Nov. 95

Key Data

Water depth	315-340	metres
Concrete floater weight	192 000	tonnes
Concrete, C 75	19 000	m^3
Concrete, MND 75	21 000	m^3
Reinforcement (ordinary)	17 500	tonnes
Reinforcement (pre-stressed)	3 400	tonnes
Column diameter	29.0	metres
Column spacing (width)	101.5	metres
Total height concrete floater	65	metres
Wall thickness	0,4-0,9	metres
Reinforcement ratio	294-414	kg/m^3
Prestressed reinforcement ratio	55-104	kg/m^3

Application of high strength LWA concrete for tension leg platforms
A large displacement is necessary to achieve the buoyancy required for a floating platform. The hull of the platform has to withstand large hydrostatic pressures. A high strength concrete shell

is ideal for such forces. High strength normal density concrete and high strength light weight aggregate concrete was already utilised in many structures in Norway and the experience with the material was well known. The bottom pontoon slabs and the beginning of shafts were built in dry dock, and then towed out on water for gliding the platform shafts. The Troll West was original planed with HSND concrete. To give the construction enough buoyancy in “out of dock situ”, and to give the structure improved general floating properties an extra floater unit was planed installed. Further studies concluded that use of concrete with lower density had several advantageous properties. During the construction time a new type of concrete where normal coarse aggregate was partly replaced by LWA to reduce the total weight was developed and utilised, the MND concrete. The use of MND concrete was introduced while the structure was under construction. Therefore only 21000 m3 of total 40000 m3 concrete used was MND. The MND is used in the 4 columns and at the top of the bottom pontoon. The rest of the shaft structure used ND C75 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. The MND concrete has a density reduction of about 10%, still maintain most of the mechanical properties from ND concrete. 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 design life required following demands to the concrete: Chloride diffusion coefficient D< 30 mm^2/year, w/(c+s) < 0.38 and maximum curing temperature was <700C.

Team involved:

Client:
Norsk Hydro.
Design:
Kværner Concrete Construction
Contractor
Kværner Concrete Construction
Sub Contractor:
NCC Eeg-Henriksen
Concrete supplier:
Ølen Betong
LWA supplier:
Norsk Leca

Concrete mix design
The reduced weight is achieved by replacing some of the natural coarse aggregate with lightweight materials made of expanded clay. The other constituents are the same as used for ND concrete of high strength. The objective of the research project (SINTEF 92-93) was to determine and document the effect on mechanical properties. The results revealed a slightly reduced compressive strength, reduced E-modulus and fracture energy, and slightly increased tensile strength while replacing some of the coarse aggregate by LWA. The density was reduced by 200 kg/m^3 by replacing 50% of the natural coarse aggregate with Leca 800. 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/m^3 for 4-8 and 8-12 mm and gives a concrete with better mechanical properties then the existing Leca 750. The dry particle density is 1450 kg/m^3 that is considerably lighter then normal aggregate density at approximately 2600 kg/m^3.

Constituents (kg/m^3)

Natural sand 0-5 mm (dry weight)	911
Natural coarse aggregate 5-20 mm dry weight	455
LWA Leca 800 4-12 mm (dry weight)	240
Air-entraining admixture	1
Superplasticizer	7
Cement (High strength Norcem)	420
Silica fume (dry weight)	12
w/(c+s) corrected for water absorption	0.38

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

		req.	mean	st.dev.	charact.
Slump	(mm)	>			
Wet density	(kg/m^3)	<			
7 day density	(kg/m^3)	<			
7 day strength	(MPa)				
28 day density	(kg/m^3)	< 2250	±30 2220		
28 strength	(MPa)	>75			80
E- Modulus	GPa	32	±3 31,9		

Compressive strength is measured on 100 mm cubes. Cylinder/cube strength ratio is between 0.86-0.89. Density of hardened concrete is measured on water stored cubes.
The MND concrete had good resistance to chloride diffusion and complied with the demand, but the contractor needed to install water pipelines to reduce the curing temperature.

Ref. 06

3 HIGHWAY BRIDGES - SPAIN

Puente de los Santos – (Google Earth)

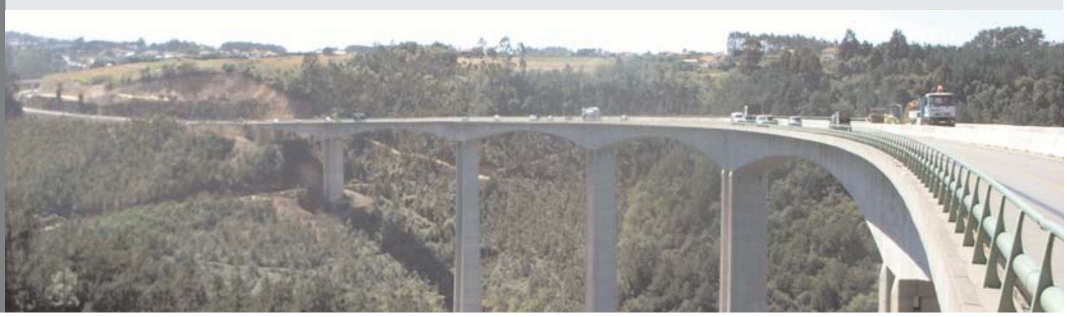
Structural features:

Lightweight structural concrete has been used in renovation and enlargement in 3 important motorway projects in Spain, namely the A-8 and A-6 motorways.

On the motorway Autovia del Cantábrico (A-8), on the specific part from Barres to Ribadeo, the old bridge “Puente de los Santos” was enlarged to receive another traffic lane in each direction. To be able to execute such a project on an old bridge, Lightweight structural concrete was the obvious solution.

The same situation was the case on the bridge “viaducto Rio San Pedro”, also on A-8, but in between Dueñas and Novellana.

On the motorway A-6, the bridge over the river Esla was rehabilitated to be able to receive the new and more intense traffic load.





Puente de los Santos –
During the construction work

viaducto San Pedro

Contractor's responsible for execution of the Project and application of the lightweight concrete:

A-8, Enlargement of "Puente de los Santos": Dragados
A-8, Enlargement of "viaducto Rio San Pedro": UTE Cudillero
A-6, rehabilitation of the bridge of the river Esla: Freyssinet Acciona

In all 3 of the above mentioned case stories, the main idea by the project engineers was to use the already existing infrastructures. In case of demolition of the old structures and building new bridges, it would have been more expensive and for sure take a lot more time to execute. Using lightweight structural concrete the engineers managed to save both money and time and in a sustainable way utilize already existing infra structures, even though they earlier was designed for different loads and stresses.

In all 3 projects ARLITA F7 was used as the lightweight agrégate. Due to the complexity of the structures, different concrete mix designs were used, with densities from 650kg/m^3 to 1.850kg/m^3 and respective compressive strength from 2MPa to 60MPa.

Year of the 3 projects: 2008

Puente de los Santos –
Preparation work for the
enlargement work


NATIONAL PAVILION

Ref. 07

EXPO'98 PORTUGUESE NATIONAL PAVILION, LISBON, PORTUGAL

Overview of roof slab

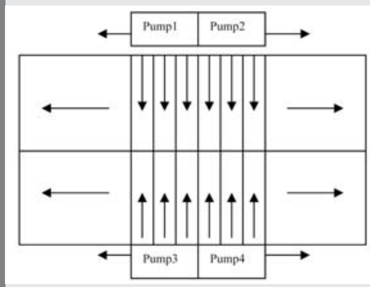
The Expo'98-Lisbon International Exposition took place in 1998, focusing on the oceans and their future importance. A number of exceptional structures were made for the event, one of the most spectacular being the Portuguese National Pavilion including the sagged parabolic membrane slab roof cast by means of Light Weight Aggregate Concrete (LWAC). The dimensions of the canopy are 65 m x 50 m, and the slab thickness is 20 cm.

General description

The Portuguese National Pavilion consists of the main 3 storey multipurpose building and the slab canopy, which is described in the following. The pavilion provided conditions for the reception of delegations present at Expo'98. The canopy structure is a 20 centimetre thick parabolic membrane concrete slab hanging from prestressed tendons anchored along the two short sides into slabs placed on top of a reinforced concrete structure of shear walls and stiffeners. LWAC was chosen as material due to low dead weight, so that the horizontal forces in roof and supports could be reduced to a minimum at the same time as appropriate strength and stiffness was maintained. The total weight of the roof was reduced by approximately 430 tons using LWAC. It is the first time that a structure of this type is casted with LWAC in Portugal.

Key data

General data:	
Data of execution:	autumn 1997
Type of structure:	Suspended slabs (canopy)
Total length in plan view:	65 m
Total width in plan view:	50 m
Slab thickness:	0.2 m
Sag:	3 m
Longitudinal slope:	0.3 m
Minimum height above floor:	10.0 m
Typical centre distance tendons:	0.6 m
Light weight concrete:	
LWAC LC 25	750 m^3
Quoted strength:	LC 25
Achieved strength fck:	30 MPa
Standard deviation:	2,6 MPa
Quoted maximum density:	1850 kg/m^3
Achieved fresh density onsite:	1835 kg/m^3
Workability (slump):	16 cm



Scheme for Pouring Concrete

Team involved:

Ready mix concrete supplier:
Betecna Betao Pronto S.A
Contractors: Construtora do Tamega, OPCA, H. Hagen, Obrecol
LWA supplier: Leca Portugal

Pumping details:

Presaturation of LWA:	17%
Maximum pumping distance:	60 m
Type of pump:	Piston pump
Pump pressure:	100-150 bar
Production:	80 m^3/h
Decline of workability:	From 16-8 cm

Mix design:

Cement:	Portland Type I 42.5 420 kg/m^3
Fly ash:	100 kg/m^3
Silica fume:	MS 610 from MBT 15 kg/m^3
LWA:	Leca 2-4 (1,6-5,5 mm) 234 kg/m^3
Sand:	1,5-2,5 mm 587 kg/m^3
Sand:	0-1,5 mm 251 kg/m^3
Water:	196 kg/m^3
SP:	Rheobuild 561 MBT 6 l/m^3

The mix design gives a theoretical density at 1828 kg/m^3. The LWA used are supplied from Leca Portugal, which belong to the Exclay International family. The particle size is from 1,6 mm to 5,5 mm. Bulkdensity is 500 kg/m^3 and particle density is 900 kg/m^3.

Concrete development:

In order to provide the adequate weight and resistance for the concrete, Betecna – Betao Pronto developed a special concrete. Several tests were made in order to obtain the best results regarding absorption of water by expanded clay, and the modifications of concrete properties was evaluated carefully.

Construction:

The cast of the roof over more than 3900 m^2 of falsework started with a central strip 2.5 m wide. It continued with the help of 4 concrete pumps with a production of 80 m^3 per hour in accordance with Figure 1. The average delay at working casting joints was no more that 45 minutes in order to get a full continuity in the bottom surface of the slab. The concrete placing took 10 hours and was done in one operation.

Knowing that an error of 1% in the cable force would cause a deviation of 10% of the longitudinal slope of the roof, special emphasis had to bed put on the posttensioning procedures.

Structural system:

The sagged roof will induce large horizontal forces at top of the shear wall with stiffeners. Due to the use of LWAC, these forces are minimised. The shear walls insure the force transfer for the horizontal loads from dead-weight, wind and earthquake between the roof and the underground pile foundations. The roof itself is a 20 centimetre thick parabolic membrane LWAC slab. The membrane tension due to sag is compensated by using long posttension cables anchored in support slabs on top of the shear walls.

References:
[1] A.Segadães Tavares, Rui R. Vieira: "Expo'98 Portuguese National Pavilion. A Large Use of Light Weight Structural Concrete, Lisbon, Portugal
[2]: Rui Monteiro: The Portuguese Pavilion – Expo 98, Lisbon, Portugal.

Ref. 08

BRIDGE OVER THE RIVER CÁVADO – PORTUGAL

Bridge over
Rio Cávado
(Google Earth)

Structural features:

Lightweight structural concrete was used to renovate the deck of the bridge “Ponte de Fão” over Rio Cávado, located in Esposende in the North of Portugal. The bridge was inaugurated in 1892, why it certainly was time for renovation. In 1986 the bridge was classified as a construction of public interest – a monument of steel structure.

Lightweight concrete has also been used in other renovation / rehabilitation bridge projects in Portugal.

Leca®

Quality control of the LW concrete at site.

Execution of the lightweight ready mixed concrete.

Bridge over the river Cávado

By using lightweight concrete for renovation of the deck, the old steel structure would not “suffer” for additional loads and the structural / economical aspects would be solved in the best way.

The lightweight concrete developed for this project was a LC30/33, with a density less than 1.700kg/m3.

Volume: more than 400m3 of LC30/33

Year: 2006 / 07

Project: Lisconcebe

Execution: Mota-Engil Engenharia / Qualibetão

Final aspect of the new lightweight bridge deck.

Specific conditions for Lightweight Aggregate Concrete (LWAC) in the Norwegian norms.

This overview intends to identify and explain what characters are different for LWAC compared directly to Normal Density Concrete (NDC) for the two Norwegian norms NS 3473 and NS-EN 206.

LWAC is defined as concrete with lower density than normal density concrete NDC were parts or all normal density aggregate (NDA) are changed with Lightweight aggregate (LWA). The LWA is usually based on expanded clay or expanded shale. In Norway Expanded clay is most common.

Following norm is covering LWA: Følgende standard dekker lettilslag: NS-EN 13055-1 Lightweight aggregates. Part 1: Lightweight aggregates for concrete, mortar and grout. (Lette tilslag, Del 1: Lette tilslag for betong, mørtel og injiseringsmasse.)

The author takes reservations for any inconsistencies in this work and recommends the users themselves to study the norm and use this overview as and guide and introduction to the norms.

Part 1: Specific differences between LWAC and NDC in accordance to NS 3473

▶ In paragraph 3.30 is LWAC defined as concrete with oven dry density Ú between 800 and 2000 kg/m^3 and NDC is defined as concrete with oven dry density $p > 2000$ kg/m^3. Note that the definition is concerning oven dry density and that density measured during site conditions is higher (see guidelines). Note also that the regulations in NS 3473 is only valid for LWAC with oven dry density >1200 kg/m3. There exist no regulations covering LWAC with density between 800 and 1200 kg/m3.

▶ In paragraph 7.2.2 is extended control required for structures were characteristic compressive strength $f_{cck} > f_{cck}1(p/p_1)^2$ were $f_{cck1} = 45$ N/mm^2 and $p_1 = 2200$ kg/m^3.

▶ In paragraph 7.3 accept the norm the use of both NDA and LWA in the same mix. Lower strength grade for load bearing structure is LB 12 and for pre stressed structures LB 30.

▶ In paragraph 7.4 "Additional requirements for use of LWA" is the norm demanding that the requirement in NS-EN 206-1 with the national appendix NS 3465 is complied with. In addition it is demanded that were the water absorption of concrete can make any influence this should be tested under current situation.

▶ In paragraph 9.2 can the E-modulus in serviceability limit state $E_{c\text{ be calculated}}$ by the use of cylinder compressive strength f_{cc}. For LWAC the E-modulus is reduced with $(p/p_1)^2$ were $p_1 = 2200$ kg/m^3.

▶ In paragraph 9.3 shall the creep index Ê be multiplied with $(p/p_1)^2$ were $p > 1800$ kg/m^3, $1,3(p/p_1)^2$ for $p < 1500$ kg/m^3 and for densities in between, linear interpolation. $p_1 = 2200$ kg/m

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▶ In paragraph 11.1.1 is the compressive strength grades for LWAC LB 12 to LB 75. Note that CEN uses the term LC and that CEN has two grades less than NS 3473. It is also required that LWAC of all grades comply with the cylinder compressive strength in each grade even though the regular testing is performed with cubes. A relation between cubes and cylinders has to be established. In addition the use of light and strong LWAC is limited by following expression $f_{cck} < f_{cck2}(p/p_1)^2$, $f_{cck2} = 95$ N/mm^2 and $p_1 = 2200$ kg/m^3. Most concretes will not be affected by this limitation. Tensile strength is reduced by $(0,15 + 0,85\ p/p_1)$, $p_1 = 2200$ for ftk and ftn. If LWA is used as both coarse and fine aggregate the expression shall be reduced further with 15%. In addition, the norm requires that for LWAC with intended compressive strength $f_{cck} > f_{cck3}$(Ú/Ú1)2, f_{cck3} = 65 N/mm² and p_1 = 2200, a proof by testing that a characteristic compressive strength of 15% more than anticipated can be achieved. This can be proven by either reducing the w/b-ratio or by extending the curing time. This requirement is for many LWAC mixes hard to comply with and should be considered at early stage in planning.

▶ In paragraph 11.1.6 it is required that concern must be taken regarding the moisture level of the concrete when testing splitting tensile strength.

▶ Paragraph 11.3 requires that the E-modulus Ecn and strain at maximum stress ∏co shall be tested for LWAC and NDC >B75. Alternatively a simplified bilinear stress-strain diagram may be used.

▶ In paragraph 12.3.3.3 concerning shear and frame work method capacity for compressive rupture, the constant figure for LWAC is 0,5 while for NDC is 0,6 in f_{c2d}.

▶ In paragraph 12.9 another expression is used for LWAC than NDC in 12.9.2 and 12.9.3. In paragraph 12.9.5 the expression for bending reinforcement around a core the diameter D must be multiplied with 1,5 for LWAC.

▶ In paragraph A.7.3.5 calculations of forces the average density for LWAC is p + 175 kg/m³ which are 50 kg more than NDC. The difference is caused by higher potential water absorption for LWAC.

▶ In paragraph A 12.4.4 capacity for compressive rupture by torsion. Use 0,5 instead of 0,6 in the expression Tccd= 0,6 $_{fcd}A_0t_c$ for LWAC.

▶ In paragraph A 12.5.3 calculation of average tension stress between cracks the Dmax is 0 for LWAC.

▶ In paragraph B 3.2-B 3.8 the minimum dimensions for beam, walls, columns etc for fire protection is stated in the table. Use LWAC with quartzeous sand will reduce the minimum dimensions required in table B1.

▶ I tabellen under punkt B 3.2- B 3.8 oppgis minste dimensjon for bjelker, søyler, vegger osv. ved brannmotstand kan dimensjonene reduseres for lettbetong med kvartsholdig tilslag som angitt i tabell B.1.

Part: Specific differences between LWAC and NDC in accordance to NS-EN 206.

▶ Paragraph 3.1.8 defines LWAC as concrete with density between 800 and 2000 kg/m³ in oven dry condition and can be manufactured by LWA as partial or full aggregate replacement.

▶ Paragraph 3.1.16 defines the LWA as mineral with particle density under 2000 kg/m³ bulk densities less than 1200 kg/m³

▶ In paragraph 4.3.1 Compressive strength grades is in this norm mentioned as LC and not LB as in NS 3473. In addition this norm covers more compressive strength grades than NS 3473.

▶ Paragraph 4.3.2 states density grades for LWAC as D1,0 to D2,0. The grades refers to oven dry LWAC. Note that LWAC can be described by intentional figures for densities between the stated grades. This can be interpreted like i.e. a concrete with density of 1750 kg/³ can be manufactured.

▶ In paragraph 5.5.2 the tolerance of intentional density is ± 100 kg/m³. This is in accordance with the density grades that jump 200 kg/m3 for each grade.

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