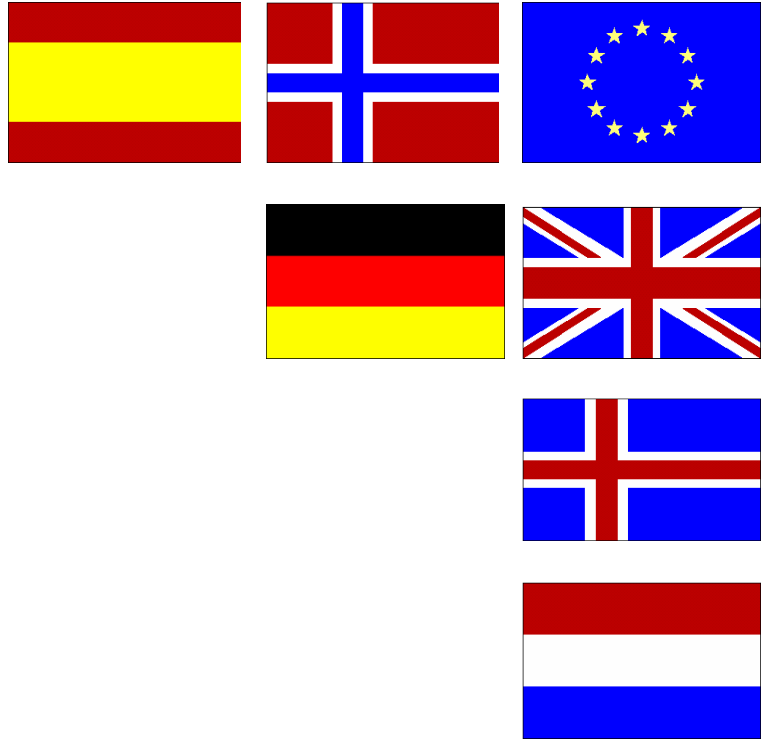


# EuroLightCon



European Union – Brite EuRam III

## Definitions and International Consensus Report

EuroLightCon  
Economic Design and Construction with  
Light Weight Aggregate Concrete

Document BE96-3942/R1, April 1988

Project funded by the European Union  
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Contract BRPR-CT97-0381, Project BE96-3942



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Although the project consortium does its best to ensure that any information given is accurate, no liability or responsibility of any kind (including liability for negligence) is accepted in this respect by the project consortium, the authors/editors and those who contributed to the report.

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The European Union – Brite EuRam III

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Contract BRPR-CT97-0381, Project BE96-3942

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## PREFACE

The lower density and higher insulating capacity are the most obvious characteristics of Light-Weight Aggregate Concrete (LWAC) by which it distinguishes itself from ‘ordinary’ Normal Density Concrete (NDC). However, these are by no means the only characteristics, which justify the increasing attention for this (construction) material. If that were the case most of the design, production and execution rules would apply for LWAC as for normal weight concrete, without any amendments.

LightWeight Aggregate (LWA) and LightWeight Aggregate Concrete are not new materials. LWAC has been known since the early days of the Roman Empire: both the Colosseum and the Pantheon were partly constructed with materials that can be characterised as lightweight aggregate concrete (aggregates of crushed lava, crushed brick and pumice). In the United States, over 100 World War II ships were built in LWAC, ranging in capacity from 3000 to 140000 tons and their successful performance led, at that time, to an extended use of structural LWAC in buildings and bridges.

It is the objective of the EuroLightCon-project to develop a reliable and cost effective design and construction methodology for structural concrete with LWA. The project addresses LWA manufactured from geological sources (clay, pumice etc.) as well as from waste/secondary materials (fly-ash etc.). The methodology shall enable the European concrete and construction industry to enhance its capabilities in terms of cost-effective and environmentally friendly construction, combining the building of lightweight structures with the utilisation of secondary aggregate sources.

The major research tasks are:

**Lightweight aggregates:** The identification and evaluation of new and unexploited sources specifically addressing the environmental issue by utilising alternative materials from waste. Further the development of more generally applicable classification and quality assurance systems for aggregates and aggregate production.

**Lightweight aggregate concrete production:** The development of a mix design methodology to account for all relevant materials and concrete production and in-use properties. This will include assessment of test methods and quality assurance for production.

**Lightweight aggregate concrete properties:** The establishing of basic materials relations, the influence of materials characteristics on mechanical properties and durability.

**Lightweight aggregate concrete structures:** The development of design criteria and -rules with special emphasis on high performance structures. The identification of new areas for application.

The project is being carried out in five technical tasks and a task for co-ordination/management and dissemination and exploitation. The objectives of all technical tasks are summarised below. Starting point of the project, the project baseline, are the results of international research work combined with the experience of the partners in the project whilst using LWAC. This subject is

dealt with in the first task.

Tasks 2-5 address the respective research tasks as mentioned above: the LWA itself, production of LWAC, properties of LWAC and LWAC structures.

Sixteen partners from six European countries, representing aggregate manufacturers and suppliers, contractors, consultants research organisations and universities are involved in the EuroLightCon-project. In addition, the project established co-operation with national clusters and European working groups on guidelines and standards to increase the benefit, dissemination and exploitation.

At the time the project is being performed, a Working Group under the international concrete association FIB (the former CEB and FIP) is preparing an addendum to the CEB-FIP Model Code 1990, to make the Model Code applicable for LWAC. Basis for this work is a state-of-the-art report referring mainly to European and North-American Standards and Codes. Partners in the project are also active in the FIB Working Group.

General information on the EuroLightCon-project, including links to the individual project partners, is available through the web site of the project: <http://www.sintef.no/bygg/segment/elcon/>

At the time of publication of this report, following EuroLightCon-reports have been published:

R1 Definitions and International Consensus Report. April 1998

R1a LightWeight Aggregates – Datasheets. Update September 1998

## SUMMARY

The objectives and the scope of the EuroLightCon-project, addressed in the Preface, deal with all aspects of LWAC: properties of the LWA, concrete mix (design), properties of LWAC and LWAC structures including design rules.

Task 1 is considered to be the base line of the project: the state-of-the-art with regard to all relevant aspects of LWA and LWAC is addressed and white spots are identified, which are to be dealt with to reach the objectives of the project. The results are presented in two reports:

This report deals with definitions and international consensus a.o. by means of standards and codes of practice. In the second report (R2, 'Properties of LWA and LWAC – a state-of-the-art'), the performance of LWA and LWAC will be dealt with.

Chapter 4 describes LWA and LWAC in general. Starting point are the many definitions in (inter)national standards and a description of types of the aggregates (from natural sources and artificially produced). Several production processes are described. As an annex to this report, an overview of many LWAs is presented by means of datasheets, presenting relevant properties of the material (report R1a). Definitions and properties of LWAC are discussed briefly.

The state-of-the-art, with regard to experience, developments and research, is discussed in Chapter 5. This is mostly done on a national basis. The development and application of LWAC strongly depended on locally available raw materials (e.g. natural materials in Iceland, expanded clay in Germany and LWA on basis of fly ash in the United Kingdom and the Netherlands).

Codes and Standards are dealt with in two Chapters. Chapter 6 addresses on both international and national bases how LWA and LWAC are dealt with in these standards. Relevant information is included.

Chapter 7 is mainly based on the work of the joint CEB-FIP working group on LWAC, preparing an extension of the Model code with LWAC.

All standards from Chapter 6 are compared with regard to the requirements, which account specifically for LWAC. Following subjects are addressed: basis of design, material properties, general models, prestressing, structural analysis, ultimate limit states and serviceability limit states, durability, detailing, fire resistance, quality assurance and control and finally concrete technology. It appeared that the consensus between all separate standards is limited. National traditions and availability of materials play an important role here.

The report is concluded in Chapter 8 by the identification of white spots, based upon the classification as in Chapter 7. The white spots are considered to be a guideline for the technical tasks to come in particular Task 5 which aims to develop design criteria and design rules for LWAC structures.

### Keywords

Lightweight aggregate (LWA); natural, artificial, production, definitions, properties  
 Lightweight aggregate concrete (LWAC); definitions, production and application  
 Standards, codes of practice; LWA, LWAC, design rules, technology, production and execution

## 1 INTRODUCTION

The base-line for the project is formed by the existing available results of international research work combined with the existing experience and research carried out by the partners in the project whilst using LWAC.

As research and product development in the different partner-countries are mainly concentrated on nationally available LWA up till now, whilst these materials originate from different resources (both primary and secondary sources), there is a strong need to analyse and to define the different results in accordance with the structural properties of LWAC and the way different national codes are formulated in this subject. As a necessary step in the project this has to result in common accepted definitions and classifications. In fact this is considered to be an essential precondition for the execution of the project.

Presently, a Working Group under the international concrete associations CEB and FIP (merging to FIB) is preparing an addendum to the CEB-FIP Model Code 1990, to make the Model Code applicable for LWAC. Basis for this work is a state-of-the-art report referring mainly to European and North-American Standards and Codes. Partners in the project are also active in the CEB-FIP Working Group and will co-ordinate both the activities, to avoid doubles.

The input from the Working Group, and in particular its chairman Prof. Ivar Holand is acknowledged with thanks.

It is the objective of Task 1 to produce a base-line consensus report based on technology of LWAC and constituent LWAs. To reach the objective, Task 1 has been divided into two sub-tasks:

Sub-task 1.1 deals with definitions, international consensus by means of national and international standards and/or codes of practice and properties of the lightweight materials itself. The results of which are reported in the present report.

Sub-task 1.2 deals with the identification of LWA- and LWAC performance. The parameters identifying the performance of LWAC (important for ensuring practical acceptance of the material) are dealt with (e.g. strength development, modulus of elasticity, shear behaviour, fracture energy, workability and workability retention, heat of hydration and the resistance to deterioration and durability aspects). The results of sub-task 1.2 will be presented in a separate report.

(Previously defined) standards and the state-of-the-art form an important part of the present report for LWAC, including technical developments.

Furthermore it was felt necessary to include an extensive overview of available LWA-materials by means of standardised data sheets, presenting relevant properties and data of these materials. Since Task 1 is considered to be the base line for the tasks to follow, it was anticipated to identify white spots.

## 2 GENERAL DESCRIPTION OF LWA AND LWAC

In literature many definitions are used to describe lightweight aggregates (LWA) and lightweight aggregate concrete (LWAC). In this chapter an overview is given of these definitions. For LWA the definitions used in codes and standards as well as a general description of the types of LWA are described. In addition datasheets of lightweight aggregates are presented in addition to this report (document BE96-3942/MG/R1a).

### 2.1 Lightweight aggregate

#### 2.1.1 Definitions in codes and standards

Following definitions are used in international codes and standards:

**DIN 4226-2** (Germany): ‘Lightweight aggregate is a mixture of uncrushed and/or crushed grains for natural and/or manufactured minerals’.

No limits are given for the density. Perlite, Vermiculite and expanded glass are not covered by this standard.

**UNI 7549 - part 1** (Italy): This standard deals only with expanded clay and shale having a loose bulk density of not more than 1000 kg/m<sup>3</sup>.

**BS 3797** (UK): ‘Aggregate having a loose bulk density of 400 to 1200 kg/m<sup>3</sup> for fine aggregate or 250 to 1000 kg/m<sup>3</sup> for coarse aggregate’.

**NEN 3543** (The Netherlands): This standard concerns lightweight aggregates, artificial (mostly sintered products) as well as from natural origin with a nominal grain size of at least 4 mm for structural concrete with a density of 2000 kg/m<sup>3</sup> or less.

**PN-86/B-23006** (Poland): ‘Aggregates for lightweight aggregate concrete’. ‘Subject of this standard are lightweight aggregates, mineral by PN-78/B-01100 and artificial of mineral origin by PN-79/B-01100 of volume density to 1800 g/dm<sup>3</sup>, intended for lightweight aggregate concrete of volumetric density not greater than 1800 kg/m<sup>3</sup>’.

**ACI 318-95, section 2.1** (USA): ‘Aggregate with a dry, loose weight of 1120 kg/m<sup>3</sup> or less’.

**prEN** (CEN/TC 154): ‘Aggregate of mineral origin having a particle density not exceeding 2000 kg/m<sup>3</sup> or a loose bulk density not exceeding 1200 kg/m<sup>3</sup>, including:

- natural aggregates;
- aggregates made from natural materials and/or from by-products of industrial processes;
- by-products of industrial processes;
- recycled aggregates’.

**prEN 206**: ‘Aggregate of mineral origin having a particle density not exceeding 2000 kg/m<sup>3</sup> or a loose bulk density not exceeding 1200 kg/m<sup>3</sup>’.

## 2.1.2 Description of types of LWA

Many different types of LWA are used throughout the world. A wide range of materials complies with the definitions stated in the former paragraph. In this paragraph the basic description of LWA is given, divided into artificially produced LWA and naturally occurring and other LWA.

### 2.1.2.1 Artificially produced lightweight aggregates

The principal artificially produced lightweight aggregates are made from clay, shale, slate or pulverised-fuel ash, subject to a process of either expansion (bloating) or agglomeration. During expansion the material is heated to fusion temperature at which point pyroplasticity of the material occurs simultaneously with the formation of gas. Agglomeration occurs when some of the material fuses (melts) and the various particles are bonded together.

To achieve proper expansion the raw material should satisfy the following requirements:

- It should contain sufficient gas producing constituents, and
- Pyroplasticity should occur simultaneously with the formation of gas.

The required gas formation can be brought about by various reactions:

- Decomposition and combustion of sulphides and carbon compounds from about 400°C upwards
- Expulsion of water of hydration from clay minerals at about 600°C
- Removal of CO<sub>2</sub> from carbonates at about 900°C
- Reduction of Fe<sub>2</sub> O<sub>3</sub> at about 1100°C causing the liberation of oxygen.

### *General manufacturing processes*

To induce the expansion of the raw material, most artificial lightweight aggregates undergo some form of heat treatment during their manufacture. This is usually carried out in rotary kilns, vertical shaft kilns, sinter strands or foaming beds as follows:

#### **Rotary kiln**

A rotary kiln consists of a long steel cylinder lined internally with refractory bricks and capable of rotating about its longitudinal axis, which is inclined at an angle of about 5° to the horizontal. The length of the kiln depends in part upon the composition of the raw material to be processed but is usually thirty to sixty meters. The prepared raw material is fed into the kiln at the higher end, while firing takes place at the lower end. During the progress of the material through the rotating kiln, the temperature of the particles gradually rises until bloating occurs. The material is then discharged into a rotary cooler, in which it is cooled with cold air.

#### **Vertical shaft kilns**

In this process the prepared raw material is fed into a vertical shaft kiln in batches. A hot jet of flue gases, entering at the centre of the base of the combustion chamber, lifts the material upwards until the force of the upward jet is dispersed sufficiently to become less than the force of gravity. Material which falls down rolls to the foot of the combustion chamber, which is in the shape of a funnel, where the flue gas again forces it upwards. This process is repeated a number of times over a period of about one minute for each batch.

**Sinter strand**

The prepared raw material is placed in loose layers, approximately 150 to 300mm thick, on a moving sinter strand and carried, under drying and ignition hoods (fired by gas or oil) in such a manner that burning, initiated at the surface, continues through the full depth of the bed. The gases formed cause expansion; however, in some cases the cellular structure results from the burning of the fuel grains and loss of moisture, and from fusion of the fine particles of the raw material.

**Foaming beds**

In this process, used exclusively in the production of foamed blast furnace slag, the slag is poured on to a foaming bed consisting of a large number of water jets set in a concrete base. The water converts to steam on contact with the molten material and penetrates into the body of the material at which point it becomes superheated. Due to the rapid expansion that takes place the material bloats to form a cellular structure. Alternative methods include spraying water on to the molten material when it is being tapped from the blastfurnace, so that the material is cooled rapidly and steam becomes trapped within it. In another method, the molten material is fed into a mill with revolving paddles and is treated directly with steam.

***Processed natural materials***

These include expanded clay, shale, slate and perlite and exfoliated vermiculite.

**Expanded clay**

Expanded clay aggregates are made from a special grade of clay suitable for bloating. The clay, after storage, is pre-treated by grinding and mixing with an additive which encourages bloating, before being passed through a rotary kiln. The kiln is fired by a mixture of pulverised coal and oil and reaches a temperature of about 1200°C. The material formed by this process consists of hard rounded particles with a smooth dense skin and a honeycomb interior. Oversize material is crushed and therefore a small proportion of the material is angular. An alternative method of manufacture involves passing the performed particles through a vertical shaft kiln, in which case the initial particle shape is largely preserved through the bloating process.

**Expanded shale**

In this process, raw shale, such as colliery waste, is crushed to approximately 10 mm, blended with ground coal or coke and then passed over a sinter strand reaching a temperature of approximately 1200°C. At this temperature the particles expand and fuse together, trapping cells of gas and air within the structure of the material. On cooling a very hard, semi-vitrified clinker is produced with a porous surface texture. After crushing, the angular particles are graded to size. In some manufacturing processes, however, the shale is initially crushed to different size fractions which are fired separately in a rotary kiln, thus producing spherical particles that do not require further crushing.

**Expanded slate**

Selected raw slate is crushed to pass a 13 mm screen and fed into a rotary kiln, which expands the slate at a temperature of about 1200°C. On discharge from the kiln, and after cooling, the material is chemically inert and has a highly vitrified internal pore structure. The material is then crushed and graded.

### **Expanded perlite**

Perlite is a volcanic glass containing water. The most common industrial process used to form a lightweight aggregate consists of crushing the rock to a graded size of approximately 1 mm and rapidly heating it to a point of incipient fusion (approximately 1800°C). At this temperature, the combined water vaporises and creates tiny bubbles in the heat-softened glass producing a cellular material of up to 20 times its original volume. In other more recent industrial process perlite particles (<100 µm) are mixed with an alkali solution and salt and passed through a granulator. The material is then dried and passed through a rotary kiln at approximately 860°C.

### **Exfoliated vermiculite**

Crude vermiculite, which resembles mica in appearance, consists of thin flat flakes containing microscopic particles of water. On being suddenly subjected to high temperatures (approximately 700-1000°C) the flakes exfoliate (expand) to many times their original volume, due to the formation of steam which forces the laminae apart. The resultant material consists of accordion-like granules containing many minute air layers.

### ***Processed by-products***

These include sintered pulverised-fuel ash, foamed blastfurnace slag and palletised slag.

### **Sintered pulverised-fuel ash**

Ash collected from the flue gases discharged from modern power stations burning pulverised fuel, known as 'fly-ash' or 'pfa' consists of minute spherical glass particles which are as fine as, if not finer than, cement. The ash is mixed with water and coal slurry in screw mixers and then fed on to rotating pans, known as pelletisers, to form spherical pellets. The 'green' pellets are then fed on to a sinter strand and combustion progresses at a temperature of about 1300°C. At this temperature the ash particles coagulate, without fully melting, to form hard brick-like spherical particles. After cooling the material is screened and graded.

### **Cold bonded pulverised-fuel ash**

No high temperatures are required. The aggregates are formed using the pozzolanic properties of the fly ash. The solids fly ash and lime are jointly transported towards powerful process mixers, where water is added until a sticky "green mix" is formed. Two large disk pelletisers form spherical pellets, due to the adhesiveness of the mixture. To strengthen the still vulnerable "green pellets", they are embedded in a constant stream of fly ash and transported to curing silos. Steam condenses on the embedding material round each pellet. The energy released indirectly warms the pellets to a temperature of 85°C. After 15 hours they leave the silo. The hardened pellets are screened into different fractions. The oversized material is crushed to a suitable size.

### **Foamed blast furnace slag**

Foamed slag is by-product of iron production and is formed by introducing water or steam into the molten material, either in foaming beds or by spraying. The material, after annealing and cooling, is angular in shape with a rough and irregular glassy texture. The internal voids occur as round cavities varying in size depending on the method of manufacture.

### **Palletised slag**

Palletised slag, like foamed slag, is by-product of iron production but is formed by subjecting the molten slag to a controlled quantity of water and passing it on to a rotating drum with fins.

The water bloats the slag whilst the rotating drum hurls the particles through the air so forming them into a semi-rounded aggregate. The material is lighter than foamed slag and has a smooth glass-like surface.

### **Expanded glass**

Recycled glass is crushed and mixed to obtain a glass mixture with restrictions to the mass percentage of alkali oxides. This mixture is pressed and next crushed into a coarse granulate. The granulate is foamed in an oven with temperatures from 700 to 850 °C for a period of 3 to 30 minutes. After a defined period of cooling, the glass has a low density (200 – 300 kg/m<sup>3</sup>); inner pores from 0.0001 to 0.5 mm and a surface layer with low permeability.

### **2.1.2.2 Naturally-occurring and other lightweight aggregates**

As opposed to the manufactured or artificial lightweight aggregates there are naturally occurring aggregates, unprocessed by-products and organic materials that can be used as lightweight aggregates.

#### ***Natural materials***

##### **Pumice**

Pumice is the oldest known lightweight aggregate and was used in Roman times. It is light and strong enough to be used in its natural state, but it has variable qualities dependent upon its source. The cellular structure of pumice, and hence its low density, is created by the formation of bubbles or voids when gases contained in molten lava flowing from volcanoes become trapped on cooling. The cells are elongated and parallel to one another and are sometimes interconnected. It is chemically inert and usually has silica content of approximately 70%.

##### **Scoria**

Scoria is used as a term for the material often found in and around volcanic craters and differs from pumice in the way that it is denser and has a different pore structure than pumice. The pore structure of scoria is coarser and the glassy walls between the pores are thicker and the overall strength of scoria is higher than of pumice. Pumice is the material made from the lava richer in silica (rhyolitic), hence the light colour, while scoria originates from the lava melt with less silica content (basaltic) and has a darker colour than can be reddish brown, red, grey or black. The silica content of the Icelandic scoria is around 50% and its chemical composition is very similar to the basalts of Iceland.

##### **Diatomite**

Diatomite is a calcined diatomaceous rock formed from minute fossil skeletons of marine life known as diatoms. It is a semi-consolidated sedimentary deposit formed in cold water environments.

#### ***Unprocessed by-products***

##### **Furnace clinker**

This type of aggregate is usually obtained from the older power stations where the boilers are fired by solid fuel in chaingrate stokers. As they are high-temperature furnaces the amount of combustible material in the residual clinker is reduced to a minimum. Clinker, which has a high

residue of unburned or partly burnt coal, will produce an unsound aggregate which, in turn, will lead to the production of concrete with poor strength and high shrinkage. In addition, because clinker contains sulphur and other compounds it will cause corrosion of steel reinforcement.

### **Furnace bottom ash**

Modern power stations use pulverised fuel for firing furnaces. The resultant ash is either collected as fly ash from the flue gasses or as furnace bottoms ash. At some power stations the bottom ash may be form 10 to 25% of the total residue and sometimes occurs in the form of clinker. Furnace bottom ash, even in the form of clinker, is very variable in chemical composition and quality. However, it is possible, after crushing and grading, to use the better grades as a lightweight aggregate. Furnace bottom ash with a high loss of ignition is not recommended for concrete that is required to have high durability.

### ***Organic materials***

#### **Wood particles**

Graded wood particles have been used as an aggregate for many years, but some pre-treatment of the material is necessary otherwise the tannin, soluble carbohydrates, waxes, resins and other aromatic oils which wood contains could affect the hydration of cement. Various processes are available, but with most softwood it is merely necessary to mix in lime or to boil the particles in water to which ferrous sulphate has been added.

#### **Plastic particles**

Expansible plastic particles, such as polystyrene, take the form of plastic beads in which an expanding agent has been dissolved. The plastic is softened in steam heat, and the agent forces the beads to expand. Initially the beads are approximately 1 mm in diameter, but they expand during manufacture to about three or four times their original size. After expansion the beads may be coated with resin or cement.

### **2.1.3 LWA Datasheets**

General information concerning the different LWAs is presented in datasheets. The datasheets of available lightweight aggregates, collated by the partners in the project, are presented in an additional document (document BE96-3942/MG/R1A).

The data sheets contain information regarding:

1. commercial name
2. supplier/manufacturer
3. general properties
4. densities
5. crushing resistance
6. water absorption
7. loss on ignition
8. chloride content
9. sulphate content
10. chemical composition
11. production locations
12. years of experience of application in concrete

An example of a datasheet is presented in Figure 2.1

Figure 2.1 – Example of an LWA-Datasheet (Hekla Pumice, F 8/16 W)

Commercial name	Hekla Pumice, F 8/16 W	
Supplier	Jarðefnaíðnaður hf Nesbraut 1, IS-815 Thorlákshöfn, Iceland	
General properties	Pumice	
Material	Open, rounded or angular	
Particle geometry	8 – 16 mm	
Aggregate size	80 %	
Porosity		
Density		
Loose bulk density	300	kg/m <sup>3</sup>
Particle density		kg/dm <sup>3</sup>
Crushing resistance		kN
Water absorption		
In 30 minutes	80	% m/m
In 24 hours	100	% m/m
Loss on ignition	1.4	% m/m
Chloride content		% m/m
Sulfate content	~ 0	% m/m
Chemical composition		
SiO <sub>2</sub>	66	% m/m
Al <sub>2</sub> O <sub>3</sub>	16	% m/m
Fe <sub>2</sub> O <sub>3</sub>	2	% m/m
CaO	3	% m/m
Production locations		
Number	1	
Countries	Iceland	
Years of experience of application in concrete: 14		

## 2.2 Lightweight aggregate concrete

### 2.2.1 Definitions

The following definitions are used in national codes and standards:

**UNI 7548 – part 1 (Italy):** ‘Lightweight aggregate concrete is made with lightweight aggregates i.e. made by replacing some or all of the ordinary aggregates with lighter aggregates. Lightweight concrete is characterised by the fact that its density is not greater than 1850 kg/m<sup>3</sup>.’

**PN-91/B-06263 (Poland):** ‘Concrete of volumetric density in dry state not bigger than 2000 kg/m<sup>3</sup>, made of cement lightweight aggregate of mineral origin, water and possible mineral additives and chemical admixtures’.

**ACI 213-87 (USA):** ‘Structural LWAC is concrete which a) has a minimum compressive cylindrical strength at 28 days of 17.24 MPa, b) has a corresponding air-dry unit weight not exceeding 1850 kg/m<sup>3</sup> and c) consists of all LWA or a combination of LWA and normal weight aggregates’.

**ACI 318-95 (USA):** ‘Concrete containing lightweight aggregate that conforms to ACI318-95 Section 2.1 and has an air-dry unit weight as determined by "Test Method for Unit Weight of Structural Lightweight Concrete" (ASTM C 567), not exceeding 1840 kg/m<sup>3</sup>. In this code, lightweight concrete without natural sand is termed "all-lightweight concrete" and lightweight

concrete in which all of the fine aggregate consists of normal weight sand is termed "sand-lightweight concrete".

**ENV 1992-1-4:** 'Concrete having a closed structure and an oven-dry density of not more than  $2000 \text{ kg/m}^3$  consisting of or containing a proportion of artificial or natural lightweight aggregates having a particle density of less than  $2000 \text{ kg/m}^3$ '.

**prEN 206:** 'Concrete having an oven-dry density of not less than  $800 \text{ kg/m}^3$  and not more than  $2100 \text{ kg/m}^3$ . It is produced using lightweight aggregate for all or part of the total aggregate'.

## 2.2.2 Properties and production of LWAC

Concrete is a heterogeneous material whose properties depend both on the properties of the individual components and their compatibility. In order to design and produce lightweight aggregate concrete with required properties, the properties of the aggregate must also be known.

The properties of these lightweight aggregates can differ greatly from each other. They depend mainly on the raw material, and the process of manufacture. In the case of aggregates from naturally occurring materials, which require further processing, the production process can influence the properties.

The properties of aggregates from materials that occur as industrial by-products can only be altered to a limited extent, i.e. by the processes of bloating, foaming, sintering, agglomerating and crushing. Aggregates consisting of naturally occurring materials have properties, which depend mainly upon their origin and source.

The great influence of the properties of lightweight aggregates on the properties of the lightweight aggregate concrete is evident from the fact that the aggregates make up approximately 75% of the total volume of the concrete. The most important properties of concrete influenced by the aggregates are workability, strength, modulus of elasticity, density, durability (resistance against fire and frost), thermal conductivity, shrinkage and creep.

By knowing the properties of the aggregates it is generally possible to predict the properties of the lightweight concrete produced.

Lightweight aggregate concrete is, in general, produced either for structural purposes or for thermal insulation purposes. When the concrete is used for structural purposes the following properties are decisive: high strength with low density, high modulus of elasticity, and low rate of shrinkage and creep. When producing lightweight aggregate concrete for insulation purposes, a low thermal conductivity is required. The thermal conductivity increases with decreasing density; therefore the density of the concrete must be as low as possible. However, the strength must be sufficiently high so that the component part (construction part) is able to carry its self-weight. In some cases load bearing functions are required. The EuroLightCon-project relates to structural applications.

The most suitable aggregates for structural lightweight concrete are expanded clay, shale and slate, sintered pulverised-fuel ash and sintered slate and colliery waste. Natural pumice and scoria have also been applied. Adequate strength for structural lightweight aggregate concrete can be obtained with foamed and expanded blastfurnace slag, but the density of the concrete made with these aggregates tends to be high. When manufacturing lightweight aggregate concrete for thermal insulation purposes, aggregates with low density must be used. To reach a density of lower than  $800 \text{ kg/m}^3$  suitable aggregates are perlite, vermiculite, diatomite, pumice and expanded plastic particles.

Their strengths, however, are very low. A concrete density below 800 kg/m<sup>3</sup> for structural LWAC can also be reached if one uses expanded clay and expanded glass.

The experience from production of high-strength LWAC shows that uniform moisture content of the lightweight aggregates is important to produce concrete with consistent properties. This can be achieved by keeping a low initial moisture content (0-5%), or as the other extreme to apply saturated LWA. Furthermore, the experience has shown that a uniform density is difficult to obtain if the water content of the LWA varies between batches during construction. For not saturated LWA, it has therefore been concluded that lightweight aggregates are to be sheltered from rain during storage and transportation.

In order to obtain good workability at the time of placing and compaction of the concrete, some contractors have sprayed the dry LWA with water just before adding the other constituent materials. This water will saturate the surface pore system of the aggregates and prevent undesired high mix water absorption during transportation, placing and compaction. Increased dosage of superplasticisers at the batching plant or redosing on site is used to remedy loss of consistency due to mix water absorption of the LWA, but overdose might result in undesirable retardation to set.

Pumping of LWA with aggregates of expanded clay is seldom used since the high pressure will squeeze water into the aggregates, resulting in:

- Internal pressure in the pores in the aggregates squeeze water and air out again when the pressure is released, resulting in a reduced quality of the interface between aggregate and paste
- Loss of consistency causes too high friction

Pumping of sintered LWA is more commonly done while the sintered LWA has the property to soak absorption water very quickly and is therefore good pumpable. Sintered pulverised fuel ash aggregates have been pumped successfully in the UK by either vacuum saturation of the aggregate or the addition of a water-thickening admixture to the concrete. Pumping of LWAC with pre-soaked or vacuum saturated expanded shale is commonly used in the USA.

Vibration is less efficient than for normal density concrete, but the effects are improved by:

1. Extended time of vibration
2. Reduced layer thickness
3. Increased vibrator frequency
4. Using more vibrators

### **3 STATE-of-the-ART, DEVELOPMENTS AND RESEARCH**

The state-of-the-art of LWA and LWAC is presented in this chapter. The most recent technical developments and research results are incorporated. The chapter has been divided into a general state-of-the-art and national research results, which are presented on a per country basis.

#### **3.1 General state-of-the-art**

##### **3.1.1 History**

Basically, lightweight aggregate concrete is not a new material. It has been known since the early days of the Roman Empire; both the Colosseum and the Pantheon were partly constructed with materials that can be characterised as lightweight aggregate concrete (aggregates of crushed lava, crushed brick and pumice).

The development of LWA has been very much in dependence on the locally available raw materials. Thus both in Germany and Norway a broad variety of LWA types have been developed based on expanded clay (Liapor and Leca), ranging from very low density to high strength products. In the Netherlands and UK, on the other hand, a technology has been developed for producing LWA on the basis of fly ash (Lytag, Aardelite). The American variety of expanded shale has, however, not been utilised in European production, while the use of natural stone is the normal way in Iceland, where a technology is being developed on basis of their natural, volcanic LWA. These materials are available in different types and weights in great amount. Pumice, being the lightest, gives a structural LWAC from 800 kg/m<sup>3</sup>, while Scoria formed in basaltic eruptions may give LWAC from 1400 kg/m<sup>3</sup>.

##### **3.1.2 Experience**

In the USA as many as 104 World War II ships were built in LWAC, ranging in capacity from 3 to 140000 tons. Their successful performance led to an extended use of structural LWAC in buildings and bridges. A concluding ACI Committee remark states the most important reasons for selecting LWAC; the reduction of dead load, the flexibility in design, the saving of construction cost and superior long-term durability.

Also in Europe these arguments have been important in selecting LWAC for bridge construction. As well in Germany as in the Netherlands and Norway there are several references to successful application of LWAC for long span bridges. In Norway, recently two floating bridges and the superstructures of six conventional bridges have been constructed wholly or partly in LWAC.

The offshore oil activities have offered opportunities to utilise LWAC for platform construction. From the 1950s a large number of small and simple platforms built partly of LWAC have been installed in shallow waters off the coast of the Gulf of Mexico. In the 1980s two exploratory oil drilling platforms were constructed partly of LWAC for the ice-infested waters of the Beaufort Sea. An important break-through was the selection of LWAC for four platforms in the North Sea. The platforms are recently completed. These structures used are made in specially designed

high performance LWAC and a semi-light “modified normal density (MND)” concrete. The MND concrete was developed to solve special structural and weight problems and designed for a 75 MPa strength requirement at a density of 2.250 kg/m<sup>3</sup>. The North Sea structures have been constructed using especially high strength LWA of the Liapor and Leca types.

The current situation regarding LWA production in the UK is that there are only two producers remaining. These are Lytag who produce sintered PFA aggregates and Pellite who produce foamed slag aggregate. LWAC has been used extensively in the past for floors in office buildings. LWAC structures are quite rare in the UK although an offshore gravity base containing 35000 m<sup>3</sup> of LWAC has been completed for the North Sea. In the recent past LWAC has been used for a number of grandstand roofs in sports stadia. There appears to be a reluctance to use LWAC in major concrete structures based primarily on the additional cost and the lack of awareness of the properties of high quality LWAC and the possible savings in overall cost.

The utilisation of LWAC based on the Icelandic materials has been limited, partly due to insufficient quality in earlier years when the material and production know-how was low. In recent years, research has shown that high quality, durable concrete can be produced from these materials with economic benefit. Special pumice concrete for housing has been developed with high heat insulation capacity and workability. Use of structural LWAC in Iceland is increasing slowly, and the market needs improved quality classification systems and design rules before a substantial break-through can be expected. Increasing amounts of these LWA types are being exported.

In Spain LWA is available from just a couple of relatively small manufacturers. It has been like that since at least twenty years ago. Regarding LWAC, it has not been used, except for a very few minor structures, for structural purposes. Instead, LWAC has been used on buildings for roof insulation purposes mainly. The Torre Picasso was built with LWA from the Spanish ARLITA.

During the period 1960-1973 about 15 long span bridges were built in LWAC across the big rivers in the Netherlands. Calculations, including decreased costs for foundation because of the lower dead load, learned that these bridges have given an economic advantage of 5-10% in total building costs. The used LWA was based on expanded clay. Much effort has been put in the development of LWA production on basis of fly ash, resulting in new products like Lytag and Aardelite. The use of that LWA in concrete concerning mix design, execution, mechanical properties and structural behaviour were well explored in a national research project. The research resulted in a CUR Recommendation. In the beginning of 1970, several concrete highway bridges and a long span river crossing were using Lytag as LWA. There is an increasing use of LWAC in precast products. From an economic point of view all the applications appear to be attractive, despite of the somewhat higher material costs, and result in lower investments as to total building costs. Recent product development of LWA is concentrated on the use of other waste/secondary materials in combination with fly ash for the production of Lytag. Similar developments are under way in the UK.

Extensive research and development on LWA and LWAC has been carried out as well in Europe as in North America and Japan. In USA especially the research on lightweight aggregate concrete for marine arctic structures carried out by ABAM Engineers and Mobil R&D has contributed to the state-of-the-art. Within the framework of ACI, however, valuable results and recommendations are published relating to the use of LWAC also for other purposes; and of specific interest are the in-service performance investigations carried out evaluating early LWAC

structures in severe climates. The Concrete Society (UK) has prepared reports on economic advantages of LWAC for buildings and bridges, and from the British Cement Association has come a comprehensive up dating of knowledge on structural LWAC. In Norway several major research projects have addressed LWAC, both relating to high performance and very light structures. These projects have provided basic relations both regarding materials/production properties and structural performance mostly relating to German and Norwegian LWA. Research of similar kind has been carried out in Iceland and The Netherlands for their local materials.

In 1995, the Norwegian Concrete Association arranged the first International Symposium on Structural LWAC. The proceedings of this event form today the most updated document on this technology. One of the clearest conclusions was the difference in use and public acceptance of these materials from country to country.

While high strength LWAC for structures exposed to a chloride rich environment and modified normal density (MND) concrete have gained a considerable market share in Norway, such applications are presently not accepted on the Dutch market. It is of particular importance to the Dutch partners to open the way for these materials in the considerable market for bridges and fly-overs. At the same time, while LWAC for use in buildings has close to no tradition in Norway, such applications are commonly used elsewhere in the world.

The great variety in types of LWA applied in the different countries very much reflects its use. In the Netherlands and in the UK, LWA produced from fly ash from coal-operated power plants dominates the market. In spite of competitive price, this LWA has hardly any export due to lack of acceptance abroad, i.e. commonly accepted documentation of performance or standards. This is also the case for the Icelandic natural volcanically produced pumice. In the Netherlands however about 50% of the produced Lytag is exported to the neighbour countries.

For LWA produced by expanded clay, the dominant LWA in Spain, Germany and Norway, dry aggregates are normally batched to the mixture in these countries. This is a tradition that is in sharp contrast with the North American, where the use of presaturated aggregates is mandatory to ensure quality according to their recommendations.

At the Sandefjord Symposium, the Japanese delegation presented their work for the first time to develop a new generation of LWA representing a quantum leap concerning strength, density and absorption properties. A pilot production of this LWA based on expanded powder ground from lava, has already taken place, and efforts are today concentrated on reducing the cost for full-scale production.

In the construction industry, the placing of concrete by pumping is regarded as mandatory to obtain cost-effective production of major structures. For LWAC with the strictest requirements on density, strength and hydrocarbon fire performance, German or Norwegian LWA based on expanded clay have been applied. Such qualities are with present technology not possible to pump without destroying the final performance of the material. However, during the construction of the gravity-based structure for the Hibernia field, the Canadians applied a US produced LWA based on expanded slate. This concrete was pumpable.

## 3.2 Production, application and research results per country

### 3.2.1 Germany

#### Production

A new type of expanded glass named 'LIAVER' was introduced in 1996 as lightweight sand. The particle sizes range from 0,25 to 4 mm. The particle density ranges from 290 to 540 kg/m<sup>3</sup>, depending on the grading.

LWA from processed natural materials are produced in Germany by several manufactures. These LWAs are: expanded clay, expanded shale, expanded perlite and expanded glass. Besides these processed natural materials several manufacturers provide foamed blast furnace slag. Pumice and Lava are available from natural resources in the Neuwied basin.

#### Application

In 1996 approximately 13% of the manufactured LWA went into structural LWAC. Only one third of the structural LWAC was ready-mix concrete while the major part was used for precast concrete elements.

Two recent and outstanding LWAC constructions in Germany are the Commerzbank Tower in Frankfurt/Main and the first application of high performance LWAC (LWAC 35/45,  $\rho_a = 1,35 \text{ kg/dm}^3$ ) for the curved facade of the Kai-Center in Düsseldorf.

#### Research

A research project on the freeze-thaw resistance of high performance LWAC will be finished soon.

At the University Leipzig a research project is dealing with bond behaviour of LWAC. The focus is LWAC for composite structures such as bridge decks and floors for high rise buildings.

### 3.2.2 Iceland

#### Production

Since 1930, pumice has been used in the building industry in Iceland. Currently, two types of natural LWA (pumice and scoria) are used and the most of the production is exported to other European countries.

#### Application

In the past, pumice has been used for structural cast in place concrete, mainly in housing. In recent years the concrete has been developed for better freeze-thaw resistance and less moisture absorption and such concrete with extremely low unit weight has been used for element production for industrial halls. Besides this, pumice has been used for masonry block making and as a thermal insulating material.

Scoria, on the other hand, has mainly been used for production of masonry blocks besides being used as fill (lower bearing layer) in roads, as fill for the foundation of houses and as fill in air-fields and harbours.

#### Research

At the Icelandic Building Research Institute (IBRI) some thorough investigations have been carried out on the properties and behaviour of pumice as a lightweight aggregate in concrete as well as studies on concrete made from a mixture of pumice and scoria.

During the eruption in Heimaey 1973 a study was performed on the scoria erupted and estimation is made on the amount of useable scoria to be 1,5 million cubic metres.

Over 20 years ago, an extensive study was done in Iceland on several lightweight aggregates for concrete. The materials tested included both pumice and scoria from several locations in Iceland. These materials were expected to yield concrete with density in the range of 1100 - 1800 kg/m<sup>3</sup> (scoria) and 800 - 1700 kg/m<sup>3</sup> (pumice), accordingly compressive strengths of these would be 2,5 - 30 MPa for cement content 150 - 450 kg/m<sup>3</sup> for both materials.

A research study was carried out at IBRI during the years 1990 - 1991 on concrete made of scoria and sand mix. It showed that concrete can be made of scoria having dry bulk densities of 500 - 1100 kg/m<sup>3</sup> with a wet concrete density of 1000 to 1700 kg/m<sup>3</sup> having cement content from 120 kg/m<sup>3</sup> up to 470 kg/m<sup>3</sup>. The according compressive strength was from very small up to 30 MPa in the strongest one. Of the main conclusions, it was found that the concrete qualities were dependent on the quality and type of sand mixed in with the scoria. The sand has to have a wide grading curve and rounded shape to balance the low rheological qualities of the scoria (which is very angular and has a rough surface).

Ongoing research deals with classification of LWA for different strength categories of LWAC. Also, experiments have been done on improving the pumice grains by coating them with high quality cement paste.

Studies and experiments are being made on structural behaviour of LWAC elements compared with the Eurocode.

Development of different types of LWAC elements traditionally made from other materials is under way.

### 3.2.3 United Kingdom

#### Production

The position in UK is that there are three commercially LWAs produced in UK: Lytag, Pellite and Furnace bottom ash (FBA). Pellite and FBA are used almost entirely for non-structural purposes, i.e. manufacture of blockwork.

In addition imported aggregates include Liapor, Granulex, Aardelite and Arlita

In the past, the range of LWAs available in the UK was wider than at present with the following materials available (manufactured in UK); Leca (expanded clay), Aglite (expanded shale) and Solite (expanded slate).

However, Lytag dominates the current UK market for structural LWAC with occasional imports. Lytag is currently manufactured at one plant in NE England.

#### Application

Whilst the use of LWAC in UK construction is not particularly common, certain structural applications have proved popular, i.e.:

- Office block floors (using profiled metal decking filled with LWAC)
- Grandstands in Sports Stadia
- Bridge refurbishment

Two more recent applications of LWAC in major structures are:

- The secondary containment cladding for the above of the pressurised water nuclear power-plant at Sizewell B
- The construction of the BP Harding field gravity base tank for the North Sea

These applications will be considered individually.

***Flooring***

The use of thin lightweight aggregate concrete slabs acting compositely with profiled metal decking, connected with shear studs to the floor beams has become very popular for floor construction in medium rise office buildings in the UK.

This system has been applied to many structures in London particularly the Broadgate development and the 235m Canary Warf Tower.

In most cases the LWAC was pumped into position which is normally achieved using a thickening agent to prevent excessive water absorption into the LWA.

In the case of the Canary Warf Tower, the aggregate was vacuum saturated with water before use. Successful pumping was achieved up to 250 m.

***Grandstand Beams***

Another area where LWAC has been exploited in UK is the roof beams for Grandstands in Sports Stadia. As the use of columns at the front of the roof restricts the view of the public, long unsupported roof beams are inevitable.

LWAC has been used in the roof beams of a number of major stadia (Good-wood, Doncaster and Watford for example).

At the South Stand of Twickenham Rugby Stadium, prestressed beams (35 m long) were constructed using 60 MPa LWAC for the front 23 m and normal density concrete for the rear 12 m. At Newcastle Football Stadium, the roof beams are 31.5 m long, again with the front 23.5 m cast in LWAC (70 MPa, air dry density 1950 kg/m<sup>3</sup>). The beams were precast off site and prestressed. Two main benefits were claimed for using LWAC for the part of the beams.

The reduction in weight (22%) improved handling, transport and erection leading to reductions in the project costs.

Reduction in dead weight leading to economy of materials use and savings in the frame and foundation design.

***Harding Gravity Base Tank***

This structure is an 85,000t base with three functions:

1. Support for a 23,000t heavy-duty jack-up production, drilling and accommodation facility.
2. Drilling template
3. Storage facility for up to 500,000 barrels of crude oil. Oil export is normally via offshore tank. The GB is used for oil storage during weather downtime.

This post-tensioned concrete structure was built in a lightweight aggregate concrete containing Lytag LWA. The 56-day mean characteristics compressive strength was 55 MPa with a saturated density (characteristic) of 1920 kg/m<sup>3</sup>. The storage cells in the GBT were slipformed.

The advantages of using LWAC were that the entire structure could be constructed in a dry dock thus eliminating expensive 'wet site' construction.

Extensive laboratory testing demonstrated that the LWAC was very resistant to thermal cracking and would not be affected by direct exposure to hot crude oil.

**3.2.4 The Netherlands****Production**

The manufacturing of LWA in the Netherlands started in the early seventies with Korlin, expanded clay. Aardelite followed in 1982 and Lytag in 1993. Both last founded plants use fly ash from coal fired power-stations as raw material. In spite of the fact that Korlin was very suitable

for the use in structural concrete the production of it was stopped in 1977. Throughout the years there has always been an ongoing import of LWAs in the Netherlands. Before the attendance of Korlin and Lytag, LWAC structures were mainly made with Liapor from Germany and Isol from Belgium. The lower quality concrete by then was made from Pumice and Lava both imported from Germany.

Today foreign LWAs, like Argue, Fibro, Lava, Leca and Liapor are imported for the production of building blocks, hydroculture, soil-improvement and fillings.

Out of the present LWA production in the Netherlands 50% is exported to the neighbour countries.

The presence of LWAC in the Netherlands is mainly based on the concrete-properties as saving of weight, easy handling, insulation and the governmental support as it comes to the use of secondary materials.

### **Application**

The applications of Aardelite are:

- Buildings blocks, B5-B15
- In place cast structural concrete, B25-B30

The applications of Lytag are:

- Building- and pavement blocks, B5-B15
- In place cast structural concrete, B25-B35
- Prefab concrete as: Load bearing interior cavity sheets, and dividing walls, beams, girders and piles, B45
- Self-supporting system floors in prestressed or traditional reinforced concrete, B45-B60

The most appealing LWAC structures made from Lytag concrete are:

- The Pleyroute bridge across the River Rhine near Arnhem, the Netherlands (cantilever).
- The Canary Wharf Tower in London, United Kingdom (steel structure with concrete-metal deck floors, 230 metres high).
- Commerzbank Tower in Frankfurt, Germany (steel/concrete structure with concrete-metal deck floors, 300 metres high).

### **Research**

Before 1985 most built LWA constructions were based on the knowledge of expanded clay. Together with the introduction of Lytag and later Aardelite a national research project was started up. Contributions were made by several building-industry-servicing organisations. The research resulted in CUR-Recommendation 39, 'Concrete with coarse lightweight aggregates', as an addition to the Dutch design rules, which was published in 1994. CUR-Recommendations are widely accepted to be pre-standards.

Apart from research programmes, many experiments on LWAC are carried out by end-users in preparation to their product certificates.

### **Conversion of waste materials and secondary materials**

As a result of increasing environmental awareness, the need arose in the Netherlands at the beginning of the 1980's to convert waste materials from industry into less harmful substances, or even into re-usable raw materials. Distinction is made between high-grade and low-grade materials. The high-grade involves an advanced recycling process already developed before the

1980's, whereby the residual value of the waste, in relation to the raw material, makes extra processing economically attractive (e.g. paper, glass, rags and scrap). Today in the Netherlands, timber incineration, soil decontamination companies, iron foundries and waste incineration/treatment plants provide many tons of low-grade waste materials, part of which can be used in new products.

When it comes to developing methods for re-using low-grade waste, coal-fired electricity generating plants play an important role. There are now two fly-ash processing companies, producing Lytag (B.V. Vasim) and Aardelite (Provag B.V.) respectively.

Until now, apart from the fly-ash processing companies, developments have only led to laboratory studies. The best known of these is the 'ECO-gravel' process, the conversion of dredged silt into aggregate for use in concrete products and in road and hydraulic engineering.

### 3.2.5 Belgium

#### Production

Since years LWA from expanded clay is manufactured in Belgium. Trade names are Argex and Isol. The production of Isol, LWA that was suitable for use in structural concrete, stopped in 1990. Situated geographically next to the Netherlands, Lytag and Aardelite are imported. In the opposite way Argex is exported to France, Germany and the Netherlands.

#### Application

The applications of Argex are:

##### *Civil engineering:*

- Reducing the vertical load of the mass of embankments
- Reducing horizontal loads of the mass of fillings and the hydrostatic pressure
- Compensation method: Foundations on Argex-filling instead of pile foundation or soil improvement.
- Filling up of spaces under suspended grounds, floors and other constructions in connection with water overload.
- Provision of green areas

##### *Building industry:*

- Lightweight building-blocks, B5-B10
- Dividing walls, B10

#### Research

Except the research carried out in commission of the manufacturers/users on behalf of their product properties, there are no ongoing research projects with respect to LWA or LWAC in Belgium.

### 3.2.6 France

#### Production

Since the 1970's two types of LWAs are manufactured in France. Granulex, expanded shale and Agri 16, expanded clay.

### **Application**

The applications of Granulex are:

- LW building-blocks and concrete, B5
- Semi LW building blocks and concrete, B5-B15
- Isolation-concrete, B15-B20
- Prefab concrete, B20-B35
- Structural concrete, B30-B40

### **3.2.7 Norway**

#### **Production**

Norsk Leca started the production of LWA based on expanded clay using one single kiln in 1954. The production capacity was less than 100 000 m<sup>3</sup> per year. Today the total production capacity in Norway is nearly 1 million m<sup>3</sup>, based on four rotary kilns. Use of expanded clay in lightweight masonry was focused on, and the strength requirements were moderate. Thus the standard product had a bulk density of about 350 kg/m<sup>3</sup> (particle density 650-700 kg/m<sup>3</sup>). The application of lightweight aggregates in marine structures motivated higher strengths, and a production of stronger Leca started in 1985. The present standard classes for high-strength Leca are 600, 700 and 800, where the numbers denote bulk density. However, the production is flexible, and other densities can also be produced.

#### **Application**

Liapor has been imported from Germany for application in high-strength concrete (in addition to the use of high-strength Leca). Other types of lightweight aggregates have only been used for testing purposes.

#### *Buildings*

The original standard quality, Leca 350, allows production of LWAC 25, and the possibilities in making LWA concrete were investigated at an early stage. An interesting project from this period is the church called Ishavskatedralen (The Arctic Ocean Cathedral) in Tromsø, built in the early sixties. The main use of LWA concrete in buildings has, however, mainly been in precast floor slabs and wall panels. During the last 5 to 10 years the consumption in this field has been about 100 000 m<sup>2</sup> per year.

A recent example of lightweight aggregate concrete cast on site is 'Colloseum Park' an office block being constructed in Oslo in 1997. To restrict weight LWAC 45 with a deforming density of 1750 kg/m<sup>3</sup> was chosen. A special Leca with bulk density 670 kg/m<sup>3</sup> was produced for the purpose. Obtained grade was LWAC50. About 8500 m<sup>3</sup> lightweight aggregate concrete were used in this project.

#### *LWAC in marine structures*

Offshore structures where lightweight aggregate concrete has been used are listed in Table 5.1.

The Snorre tension leg platform, installed in 310 m of water in the North Sea, is a steel structure anchored to the sea by tethers and four concrete foundations (templates) partly produced with lightweight aggregate concrete.

For the Heidrun tension leg platform, installed in 1995 in 345 m of water, the complete hull, including the main beams carrying a steel deck, is made of high performance lightweight aggregate concrete.

In order to improve the buoyancy of the Troll A platform (installed in 1995 in 325 m of water) dur-

ing tow-out to the field, a semi-lightweight or "modified normal density" (MND) concrete mixture with an in-situ density of 2250 kg/m<sup>3</sup> was developed by Norwegian Contractors a.s. This concrete concept was also partly used in the Troll B catenary anchored floater.

*Table 5.1 - LWAC in offshore structures*

Name	Type	Grade	Density kg/m <sup>3</sup>	Aggregate	Completed	Volume LWAC m <sup>3</sup>
Snorre	Template	LC60	1900	Liapor 8	1991	1100
Troll A	Gravity	LC75 (MND)	2250	Leca 800	1995	66 000
Heidrun	Tension leg	LC60	1950	Liapor 8	1995	65 000
Troll B	Buoyant	LC75 (MND)	2250	Leca 800	1995	20 000

These applications illustrate a primary advantage of lightweight aggregate concrete as compared with normal density concrete, namely the possibility to tailor the density to a specific need, and thereby achieve an optimum design.

#### *Bridges*

Since 1989, high performance LWAC (LC55 - LC60, fresh densities 1850 - 1950 kg/m<sup>3</sup>) have been utilised in several bridges in Norway, see Table 5.2. Two of these are floating bridges built as horizontal arches (Bergsøysundet bridge and Nordhordland bridge), with only pontoons in LWAC. The superstructures of the remaining bridges were built wholly or partly in LWAC.

*Table 5.2 - Bridges with LWAC in Norway*

Name	Type	Length m	Completed	Volume LWAC m <sup>3</sup>
Sandhornøya	Cantilevering	374	1989	1300
Boknasundet	Cantilevering	385	1991	2500
Eidsvoll	Beam	320	1992	2600
Bergsøysundet	Pontoon	914	1992	4800
Nordhordland	Pontoon/ Cablestayed	1246	1993	8500
Støvset	Cantilevering	420	1993	1100
Grenland	Beam/ Cablestayed	236/372	1996	1000
Raftsundet	Cantilevering	711	1998	2200

#### *Durability*

In general, all durability tests performed demonstrate that the present LWAC exhibit high resistance to the most common deterioration mechanism in the Norwegian marine environment, namely chloride induced corrosion of the reinforcement. The good durability performance is supported by the experience from condition controls of the structures. In some cases, the structures might be exposed to extensive freezing and thawing. Also the frost resistance, in terms of scaling in salt water, proves to be good, even without air entraining admixtures.

## Research

The development of the high performance LWA concretes for marine environments has depended on a high and continuous research activity. Typical for Norwegian concrete research is a strong and active involvement of industry and technology end-users. This is also the case for LWA concrete research. Due to the interest and strong position in offshore construction, Norwegian Contractors a.s played a leading role, in close co-operation with international oil companies represented in the North Sea. At present there are no offshore applications, and other national concrete related industries have been leading in research, first of all the contractor Selmer ASA, the material producers Norcem a.s (cement), Elkem a/s Materials (silica fume) and a.s Norsk Leca (LWA), as well as and the Public Norwegian Road Administration.

SINTEF has, in co-operation with Norwegian University of Science and Technology, supplied research results by projects in material and structural laboratories and assisted in development and documentation of materials and design and production methods, also related to specific structures, e. g. off-shore platforms, ordinary bridges and floating bridges, as well as in specific pre-projects (e. g. a submerged road tube).

The most extensive Norwegian research projects on LWA concrete are listed below:

### *High Strength Concrete (1986 - 1993)*

The typical 28-day cylinder compressive strength/fresh density of the LWAC included in the project was 80 MPa/1950 kg/m<sup>3</sup>. The main topics studied were mechanical properties, structural performance and design rules.

### *High Strength Concrete Materials (1988 -1992)*

The typical 28-day compressive cylinder strength and fresh density of the LWAC ranged from 35 to 80 MPa and 1500 to 1950 kg/m<sup>3</sup>, respectively. The main topics were production, mechanical properties and strength/density optimisation.

### *LWA Concrete for Floaters (1989 -1992)*

The objective was to develop LWAC with cylinder strengths in the range of 30 to 45 MPa with lowest possible density, i. e. 1400 to 1550 kg/m<sup>3</sup> (fresh concrete), with adequate material and production properties for use in floating production platforms.

### *Lightcon (1993 -1995)*

The project had the objective to provide a basis for a more advanced utilisation of LWA concrete including a life time model. The condition control and documentation of the production phase of existing structures in marine environments is of major importance here in order to control the expected and achieved properties and to explain possible deviations. Another main activity was the study of the structural performance of typical concrete with fresh concrete in the range of 1500 kg/m<sup>3</sup> based on lightweight aggregates only.

### *LettKon (1996 - 2000)*

The project is organised as a Norwegian mirror project to the European project EuroLightCon. The objectives of the programme are to develop LWA concrete to a competitive alternative to other materials, consolidate and further develop Norwegian technology on high-strength LWA concrete, extend the knowledge on more ordinary qualities of LWA concrete, and develop cost effective solutions.

### **3.2.8 Spain**

#### **Production**

There are some sources of natural LWA in Spain, located on ancient volcanic areas and very specially on the Canary Islands, where most of the aggregates are of volcanic nature.

Expanded clay produced by the rotary kiln dry system is the only manufactured LWA available in Spain. The first and only plant operating in the country was set up in 1974 in the surroundings of Madrid. Since then, the company Aridos Ligeros has been steadily producing ARLITA.

#### **Application**

Most of the production goes into isolating and dead load reduction for buildings. About 10% of the 1995 production were used for structural purposes. Most of it, however, is uncontrolled on site production of concrete for refurbishment of floor slabs.

Recently, the Guggenheim Museum (Frank O. Gehry) and two Underground lines (Foster Associates), both of them in Bilbao, are the most outstanding works developed with LWAC floor slabs.

#### **Research**

Continuous research has been done upon LWAC since the first application in 1979.

The main concern in the past years has been relied on pumping know-how. During 1998, these experiences will go on in order to achieve a pumpable high performance LWAC with a dry density below  $1.500 \text{ kg/m}^3$ .

## **4 GENERAL DESCRIPTION OF CODES AND STANDARDS**

Many codes and standards are applicable to LWA and LWAC. A general description is given to get a clear view of the different ways of handling LWA and LWAC. A distinction is made between European and national descriptions. In chapter 5 a detailed comparison of the codes and standards is presented.

### **4.1 European standards**

At a European level a number of committees are or have been involved in preparing standards, recommendations or codes of practice for LWA and/or LWAC.

In this Section these different groups are highlighted in order to be able to see the differences between them. Every group is described in a short general way, with respect to the subject they are focusing on and the document they are preparing.

#### **4.1.1 prEN 206**

prEN 206 concerns 'Concrete - Performance, production and conformity'. This European standard was drawn up by CEN/TC 104 'Concrete', prepared by its sub committee SC 1 'Revision of ENV 206'. This standard together with parts of prEN EEE (Execution of concrete structures) supersedes the European Prestandard ENV 206 : 1990 which was the basis for the preparation of this standard. ENV 206 concerned 'Concrete - Performance, production, placing and compliance criteria'. This European Prestandard was prepared by Technical Committees CEN/TC94 'Ready mixed concrete - Production and delivery ' and CEN/TC 104 'Concrete - Performance, production, placing and compliance criteria.

Aspects in ENV 206 relating to execution have been moved to be prepared by a separate standard to be prepared by CEN/TC104/SC2.

prEN 206 is only operable along with product standards for constituent materials and related concrete test methods. These product and test method standards are under preparation.

For aggregates the relevant standards which are prepared by CEN are TC154, will be titled 'Aggregates for concrete including those for use in roads and pavements' and 'Lightweight aggregates - Part 1 : Lightweight aggregates for concrete and mortar', see next paragraph.

PrEN 206 and prEN EEE referred to in this report are draft versions sent for European inquiry in summer 1997 and winter 1998. Then CEN schedule is to get these standards approved during 1998-99. Provided a sufficient number of 'yes'-votes, all national standards in the CEN member-countries have to be withdrawn within six months.

#### **4.1.2 prEN(CEN/TC 154/SC 5)**

This prEN which concerns 'Lightweight aggregates - Part 1 : Lightweight aggregates for concrete and mortar' was prepared by CEN/TC 154/SC 5, Lightweight aggregates, of Technical Committee CEN/TC 154, Aggregates.

The standard is applicable to aggregates with loose bulk densities between 300 to 1200 kg/m<sup>3</sup>. Aggregates with loose bulk densities above 1200 kg/m<sup>3</sup> are covered by:

- prEN TC154/SC1: ‘Aggregates for mortars’
- prEN TC154/SC2: ‘Aggregates for concrete including those for use in roads and pavements’

It is divided into two parts as follows:

- Part 1: Lightweight aggregates for concrete and mortar.
- Part 2: Lightweight aggregates for applications other than concrete and mortar.

No existing European Standard is superseded.

#### **4.1.3 ENV 1992-1-4:1994**

The ‘Structural Eurocodes’ comprise a group of standards for the structural and geotechnical design of buildings and civil engineering works. They cover execution and control only to the extent that is necessary to indicate the quality of the construction products, and the standard of the workmanship needed to comply with the assumptions of the design rules. Until the necessary set of harmonised technical specifications for products and for the methods of testing their performance are available, some of the ‘Structural Eurocodes’ cover some of these aspects in informative Annexes.

The European Commission initiated the work of establishing a set of harmonised technical rules for the design of building and civil engineering works, which would initially serve as an alternative to the different rules in force in the various Member States and would ultimately replace them. These technical rules became known as the ‘Structural Eurocodes’.

CEN Technical Committee 250 is responsible for all Structural Eurocodes. Separate sub-committees have been formed for 9 Eurocodes concerning different materials.

EN 1992 Eurocode 2 concerns the design of concrete structures. Part 1-4 of this Eurocode 2 concerns ‘General Rules – Lightweight aggregate concrete with closed structure’ and is published as a European Prestandard in 1994 (ENV 1992-1-4:1994). This part of Eurocode 2 complements ENV 1992-1-1 ‘Basis of design and actions on structures’.

#### **4.1.4 Joint CEB-FIP (FIB) working group on LWAC**

CEB (Comité Euro-International du Béton) and FIP (Fédération Internationale de la Précontrainte) have decided to supplement their present Model Code 90 by design rules for structural lightweight aggregate concrete.

The Joint CEB-FIP (FIB) Working Group on LWAC was appointed in 1995 and has 11 members from various European countries as well as from Australia, Canada, Japan and USA.

In the terms of reference, endorsed by FIP and CEB, Structural Lightweight Aggregate Concrete is defined as a concrete containing lightweight aggregates, suitable for use in load-bearing structures irrespective of strength and density. Experience and research results are only available within a restricted range. Thus, in the work performed by the new Working Group the need for documentation of suggested rules implies that recommendations have to be limited to a reasonably well known domain. As a pragmatic limitation, strengths will be limited to be range of strength classes LWAC16 to LWAC80 (numbers referring to cylinder strengths) and densities to demoulding densities above 1200 kg/m<sup>3</sup>. For the same reason restrictions must be imposed on LWA types, strengths and densities. The Working Group during the completion of the work will specify such limitations.

In principle, the work is to cover all aspects of the utilisation of structural lightweight aggregate

concrete, referring to concrete as a product, structural design, execution, test methods and quality assurance.

The work started in the summer of 1995 and the draft reports are scheduled to be completed in 1998. CEB and FIP are world-wide organisations. In Europe, however, the results from the work are of particular interest as input for several committees and task groups active in European standardisation through CEN.

The second draft of the report on codes and standards was made available for the EuroLightCon-project. It concerns a comparison of standards with MC 90. The considered codes and standards are from United Kingdom, Germany, Netherlands, Japan, Sweden, New-Zealand, Norway, CEN and USA:

1. BBK 94
2. BS 8110
3. DIN 4219
4. ENV 1992-1-4
5. EN 206
6. JASS 5
7. NS 3473
8. CUR-Recommendation 39
9. ACI 318-95
10. NZS 3101
11. ACI 213R-87
12. ACI 11.2

Because of the importance of the work of the joint working group to the EuroLightCon project, it is incorporated in chapter 7 of this report.

## **4.2 National standards**

### **4.2.1 Germany**

A German standard for aggregate for concrete and mortar (DIN 4226) exists. Part 2 of this standard deals with 'Aggregate of porous structure (lightweight aggregate): terms, designation and requirements'. DIN 4226; Part 2 excludes the use of Very light and weak LWA such as Perlite, Vermiculite and expanded glass.

Additional requirements are put on manufactured LWA. These are loss on ignition and the resistance to disintegration

For use in structural LWAC the homogeneity of the LWA has to be proven for the following characteristics: loose bulk density, particle density and the crushing resistance.

In addition to these tests the user is requested (DIN 1084, Part 1 'Control (quality control) of plain and reinforced concrete structures; concrete BII on sites') to control the moisture content of each shipment and also the moisture content of the material in stock in an appropriate frequency.

DIN 4226, part 3 'Aggregate for concrete; Supervision (quality control)' lists all necessary tests and gives the minimum frequency for each test.

The influence of variations in particle density and crushing resistance on the compressive strength and the density of LWAC is controlled with standard concrete having the following

composition: cement content: 350 kg/m<sup>3</sup> (CEM I 42.5R), water-cement ratio 0.50, coarse aggregate content: 440 dm<sup>3</sup>/m<sup>3</sup> and the water absorption of the aggregate is taken into account so that the compaction measure of the concrete is in between 1.15 and 1.20 (DIN 1048, Part 1) after a setting period of 15 minutes.

The frequency of the various tests is defined in DIN 4226, Part 4 ('Aggregates for concrete; Supervision (Quality control)') for factory production control and third party control.

The German standard for structural lightweight aggregate concrete is DIN 4219. This standard is split into two parts. Part 1 is named 'LWAC and reinforced LWAC with closed texture; requirements for the concrete, manufacture and quality control'. Part 2 'LWAC and reinforced LWAC with closed texture; design and construction' is based on the German standard DIN 1045 for the concrete and reinforced concrete. DIN 4219 - 2 gives only information where deviations exist between the design of LWAC and normal weight concrete.

#### 4.2.2 United Kingdom

The use of LWA and LWAC in UK are covered by the following codes and standards:

- LWA: BS 3797: 1990 - Specification for lightweight aggregates for masonry units and structural concrete.
- LWAC: BS 8110 Part 2: 1985 - Structural use of Concrete: Code of Practice for Special Circumstances.

BS 3797, LWA encompasses the following types of LWA:

1. Pumice
2. Expanded clay, shale and slate
3. Processed PFA
4. Furnace Bottom Ash
5. Foamed Blastfurnace Slag
6. Pelletised Expanded Blastfurnace Slag
7. Clinker

Limitations are placed on:

1. Particle size distribution (grading)
2. Sulphate content
3. Loss of ignition
4. Density

In the structural code (BS 8110), the use of LWAC is covered in one section (Section 5) of Part 2 of the code. This states that LWAC structures can generally be designed in accordance with the code requirements for normal density concrete but with certain specific provisions for LWAC.

It should be noted that many other UK codes permit the use of LWAC. The bridge designs code (BS 5400) includes a statement that 'in considering lightweight aggregate concrete, the properties of any particular type of aggregate can be established more accurately than for most naturally occurring materials. The engineer should therefore obtain specific data direct from the aggregate producer in preference to using tabulated values taken from British Standard codes of practice or specifications. However, even in the bridge code there is a penalty on cover.

Two UK standards actually prohibit the use of LWAC:

- BS 8007: Design of concrete structures for retaining aqueous liquids.
- BS 6349 Part 1: Maritime Structures

The prohibition comes in form of a limitation on the maximum water absorption of the aggregates to 3 % thus excluding LWA. This is based on the (incorrect) assumption that a porous aggregate would lead to permeable concrete.

### 4.2.3 The Netherlands

NEN 6720:1995 deals with the technical principles for building structures; regulations for concrete (structural standards and test methods). NEN 6722:1988 concerns the execution. The technological standards, preparation and testing are dealt with in NEN 5950:1995.

For LWA, in 1982 NEN 3543 was published 'Coarse lightweight aggregates for lightweight aggregate concrete'. The more general standard for aggregates is NEN 5905 'Aggregates for concrete. Materials with a density of at least 2000 kg/m<sup>3</sup>'. The new standard was published in May 1997. The main issue is that the standard deals with all aggregates with a particle density of more than 2000 kg/m<sup>3</sup> for the use in concrete. No distinction is being made between natural aggregates and aggregates manufactured from industrial by-products, industrial by-products or recycled aggregates. The basis for the standard are the CUR-Recommendations which have been prepared for natural broken aggregates and the experience with these materials in concrete.

Aggregates with a particle density of less than 2000 kg/m<sup>3</sup> are still dealt with in a standardised way in NEN 3543. Extensive research has been performed on (concrete with) the LWAs Lytag, Aardelite and Liapor. The first results have been presented in CUR report 89-3 'Lytag as aggregate for concrete' (CUR research committee PD-9). In a later stage, CUR-report 173 'Structural behaviour of concrete with coarse lightweight aggregates' has been published (1995). Again only concrete with Lytag, Aardelite and Liapor were considered.

CUR research committee C 75 'LWAC' initiated further research on LWAC. In 1994 CUR-Recommendation 39 'Concrete with coarse LWA' was published. This recommendation deals with additions to NEN 6720, NEN 5950 and NEN 6722.

ENV 1992-1-4: Eurocode 2: Design of concrete structures - Part 4: The use of LWAC with closed structures was taken into account when the CUR-Recommendation was prepared.

As mentioned before, CUR-Recommendations are widely accepted to be pre-standards.

### 4.2.4 Belgium

Following standards are applicable to lightweight aggregates:

- NBN B 11-051/052
- NBN B 11-151/152
- NBN B 11-251/252/253/254/255

### 4.2.5 Norway

Design rules for structural lightweight aggregate concrete are found in Norwegian Standard NS 3473 Concrete Structures. Design Rules (see chapter 5). This standard is under revision.

## 4.2.6 Austria

Austria has several standards for different types of LWA.

### Expanded clay

The Austrian standard for expanded clay is ÖNORM B 3233 'Expanded clay; quality requirements and test methods'. The standard lists four preferred grain fractions. For these grain fractions five density classes are given (Table 6.1)

Table 6.1 - Preferred grain fractions and densities

Class	I	II	III	IV	V
Grain fraction* [mm]	kg/m <sup>3</sup>	kg/m <sup>3</sup>	kg/m <sup>3</sup>	kg/m <sup>3</sup>	kg/m <sup>3</sup>
0/3 (0/4)	400 ... 600	600 .. 800	800 ... 900	900 ... 1000	> 1000
3/7 (4/8)	300 ... 450	450 ... 600	600 ... 700	700 ... 800	> 800
7/12 (8/16)	250 ... 350	350 ... 450	450 ... 550	550 ... 650	> 650
12/20 (16/25)	200 ... 300	300 ... 400	400 ... 500	500 ... 600	> 600

\* ISO-values

ÖNORM B 3233 gives minimum requirements regarding the grain strength of expanded clay that is used for LWAC.

Table 6.2 - Particle strength requirements

Class	Grain fraction [mm]		
	3/7 (4/8)	7/12 (8/16)	12/20 (16/25)
	N/mm <sup>2</sup>	N/mm <sup>2</sup>	N/mm <sup>2</sup>
I	1,0	0,8	0,5
II	2,0	1,2	0,8
III	3,0	1,6	1,2
IV	4,0	2,0	1,5
V	5,0	2,5	1,8

### Blast-furnace slag

ÖNORM 3313 'Blast-furnace slag: general' and ÖNORM 3317 'Aggregates made out of blast-furnace slag for concrete'.

### Expanded blast-furnace slag and porous blast furnace chips

ÖNORM 3314 'Expanded blast-furnace slag and porous blast furnace chips'.

### Structural lightweight aggregate concrete

The Austrian standard for LWAC is ÖNORM B 4200, part 11 'Lightweight concrete: production and quality control'. The concrete dry density for structural LWAC starts at 810 kg/m<sup>3</sup> and is limited to 2000 kg/m<sup>3</sup>. The use of normal weight aggregate is restricted to a maximum diameter of 4 mm and limited to 40 % of the total concrete volume. Requirements are given pertaining strength class and cement content for reinforced LWAC (Table 6.3).

Table 6.3 - Requirements for different LWAC classes

	strength class	Min. cement content [kg/m <sup>3</sup> ]	Max. effective w/c ratio
Plain LWAC	LB 80	110	-
Reinforced LWAC Only quasi static loading	LB 160	300	0.60
Reinforced LWAC	LB 225	300	0.60
Pre-stressed LWAC	LB 300	300	0.60

The maximum aggregate diameter,  $d_{\max}$ , is limited to 22 mm. Strength classes are defined as given in Table 6.4

Table 6.4 - Definition of strength classes

Strength class	Mean cubic strength at 28 days (200 mm cubes) [N/mm <sup>2</sup> ]
LB 80	8
LB 120	12
LB 160	16
LB 225	23
LB 300	30
LB 400	40
LB 500	50

#### 4.2.7 Italy

The use of LWA and LWAC in Italy are covered by the following codes and standards:

**LWA:** UNI 7549 - Lightweight aggregates consists of 12 parts. Each part describes one specific test for LWA.

**LWAC:** UNI 7548 Part 1 - Lightweight concrete with clay or shale - Definition and classification and Part 2 „Determination of density“. Part 1 defines three classes for LWAC (Table 6.5).

Table 6.5 - Classes for LWAC

Class	Characteristic compressive Strength $\beta$ [N/mm <sup>2</sup> ]	Density [kg/m <sup>3</sup> ]
LC <sub>1</sub>	$\beta < 15$	$\rho < 1200$
LC <sub>2</sub>	$15 \leq \beta \leq 25$	$1200 \leq \rho \leq 2000$
LC <sub>3</sub>	$25 < \beta$	$1200 \leq \rho \leq 2000$

In order to define a LWAC the characteristic compressive strength and the density are needed. The density has to be rounded to the next 50 kg/m<sup>3</sup>. Besides this definition LWAC is dealt with in accordance with the rules for normal weight concrete.

#### 4.2.8 Japan

The standard for concrete in general and also for lightweight aggregate concrete is JASS 5 ‘Reinforced Concrete Work’.

#### 4.2.9 USA

The most commonly used LWAs are expanded shale, clay and slate. Applicable codes and standards are from the American Society for Testing & Materials and the American Concrete Institute. The codes and standards, which are specifically made for structural LWAC, are:

- ASTM C 330, Specification for Lightweight Aggregates for Structural Concrete
- ASTM C 567, Test Method for Unit Weight of Structural Lightweight Concrete
- ASTM STP 169 C, Significance of Test and Properties of Concrete and Concrete-Making Materials. Chapter 48, 'Lightweight Concrete and Aggregates'
- ACI 211.2, Standard Practice for Selecting Proportions for Structural Lightweight Concrete
- ACI 304.5R, Batching, Mixing, and Job Control of Lightweight Concrete

In ACI 318 'Building Codes Requirements for Reinforced Concrete' attention is paid to lightweight aggregate concrete. The Expanded Shale, Clay and Slate Institute (ESCSI) made a brochure (no. 4020) entitled 'Structural Lightweight Concrete in the Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (ACI 318R-95)'. The brochure is designed to serve as an aid in locating and applying the provisions, which specifically covers structural lightweight concrete. Comments from ESCSI on the Building Code as well as the Commentary from ACI Code are enclosed in this ESCSI brochure. Aspects, which are dealt with, are:

- durability requirements
- concrete quality, mixing, and placing
- details of reinforcement
- analysis and design
- strength and serviceability requirements
- shear and torsion
- development of splices of reinforcement
- composite concrete flexural members
- special provisions for seismic design
- structural plain concrete

## 5 COMPARISON OF CODES AND STANDARDS

In this chapter a detailed comparison of the codes and standards is presented. The second draft of the state-of-the-art report on the codes and standards of the joint CEB/FIP Working Group has been integrated totally and has been supplemented with some new views from Germany and the United Kingdom. The ‘editor’s notes’ are from the chairman of the Working Group, Prof. Ivar Holand.

### 5.1 Basis of design

Partial factors

#### CEB-FIP HSC/HPC, Section 1.6.2.4

*Proposed extension of MC90:*

$\gamma_c$  should for high strength concrete be increased by the factor

$$\gamma_{\text{hsc}} = 1/(1.1 - f_{\text{ck}}/500)$$

$$50 < f_{\text{ck}} < 100 \text{ MPa}$$

### 5.2 Material properties

#### 5.2.1 Concrete grades

##### BBK 94, Section 2.4.1

Grades K8 and K12 may only be used for lightweight aggregate concrete. The application requires execution class I or II.

##### BS 8110 Part 2, Section 5.3

The characteristic strength of lightweight aggregate concrete should be selected from the preferred grades in BS 5328. Grades below 20 should not be used for reinforced concrete.

##### DIN 4219 T.1, Section 5.2.2

LWAC is classified in strength classes LB 8 to LB 55 (Editor's note: cube strength measured on 200-mm cubes)

The differences between the characteristic strength and the mean strength are smaller for LWAC than those for NC, because the standard deviation is smaller due to the use of manufactured aggregate. For LB 55 a special approval is necessary.

The maximum aggregate diameter,  $d_{\text{max}}$ , is limited to 25 mm. For Strength classes LB 25 and higher a further reduction of  $d_{\text{max}}$  is recommended. A minimum cement content of 300 kg/m<sup>3</sup> is required. The cement content should not exceed 450 kg/m<sup>3</sup>. The minimum mixing time for LWAC is 90 seconds.

Table 7.1 - Strength classes and their application

Concrete Group	Strength class <sup>1)</sup>	$f_{c,ck}$ class	$f_{c,m}$	Application	
LWAC B I	LB 8	8	11	For plain concrete. For reinforced LWAC only for walls and curtain walls and parapet, which only designed for their dead weight and wind loads	No dynamic loads
	LB 10	10	13		
	LB 15	15	18	Plain and reinforced LWAC	Also for dynamic loads
	LB 25	25	29	Plain, reinforced, prestressed LWAC	
LWAC B II	LB 35	35	39		
	LB 45	45	49		
	LB 55	55	59		

<sup>1)</sup> Cube strength measured on 200 mm cubes.

#### ENV 1992-1-4, Section 3.1.2.4

For design calculations, the concrete strength classes and the characteristic compressive strengths can be obtained from Table 7.2.

Table 7.2 – Strength classes

Class	LWAC 12/15	LWAC 16/20	LWAC 20/25	LWAC 25/30	LWAC 30/37	LWAC 35/45	LWAC 40/50	LWAC 45/55	LWAC 50/60
$F_{1ck}$	12	16	20	25	30	35	40	45	50

Concrete of strength classes LWAC 12/15 or less, and concrete of classes higher than LWAC 50/60 should not be used unless their use is appropriately justified. For prestressed concrete, classes lower than LWAC30/37 should not be used for pre-tensioned and lower than LWAC25/30 not for post-tensioned work.

#### prEN 206, Section 4.3.1 (the draft might be revised)

When concrete is classified in respect to its compressive strength, Table 7 or 8 applies. (Editor's note: Table 7 applies to normal and heavyweight concrete)

Table 7.3 - Strength classes for lightweight aggregate concrete (Table 8 in prEN 206)

Strength class	$f_{ck,cyl}$ N/mm <sup>2</sup>	$f_{ck,cube}$ N/mm <sup>2</sup>
LC8/9	8	9
LC12/13	12	13
LC16/18	16	18
LC20/22	20	22
LC25/28	25	28
LC30/33	30	33
LC35/38	35	38
LC40/44	40	44
LC45/50	45	50
LC50/55	50	55
LC55/60	55	60
LC60/66	60	66
LC70/77	70	77
LC80/88	80	88

**JASS 5, Section 15.1**

1. This section shall be applicable to concrete in which artificial lightweight aggregate is used for all or part of the aggregate. The scope of application shall be as specified in the Special Provisions.
2. The lightweight aggregate concrete to be covered by this Section shall be of a specified design strength not more than 225 kgf/cm<sup>2</sup> and an air-dry unit weight between 1.4 and 2.0 t/m<sup>3</sup>.

**JASS 5, Section 15.2**

1. The types of lightweight aggregate concrete shall be Type 1 and Type 2.
2. The specified design strength and air-dry unit weight of these types shall be in the ranges shown in Table 5.1. When lightweight aggregate concrete is to be proportioned as high-durability concrete and high-strength concrete, ranges of the specified strength shall be in accordance with Sections 17 and 18, respectively. (Editors note: Sections 17 and 18 deal with high durability and high strength concrete).
3. The specified design strength and air-dry unit weight shall be as specified in the Special Provisions.
4. The slump shall not be more than 21 cm.
5. The minimum unit cement content shall be 300 kg/m<sup>3</sup>, and the maximum water-cement ratio shall be 60 %.

Table 7.4 - Specified Design Strength and Air-Dry Unit Weight of LWAC

Type of concrete by aggregate	Aggregate		Specified design strength (MPa)	Air-dry unit weight $w$ (kg/dm <sup>3</sup> )
	Coarse Aggregate	Fine aggregate <sup>1</sup>		
Type 1 lightweight concrete	Artificial Lightweight Aggregate	Sand, manufactured sand, slag, fine aggregate	15 18 21 22.5	$1.7 \leq w$
Type 2 lightweight concrete	Artificial Lightweight Aggregate	Artificial LWA with or without a partial substitution by sand, manufactured sand, or slag fine aggregate	15 18 21 22.5	$1.4 \leq w < 1.7$

**NS 3473, Sections 7.2.3 and 11.1.1**

Load bearing structures of reinforced concrete shall normally not be designed in grade lower than C25. For lightweight aggregate concrete, the grade LWAC15 may be used. Prestressed reinforced structures shall not be designed with grades lower than C35 or LWAC35. (Editor's note: Cube strength measured on 100-mm cubes).

The highest grade for LWAC is LWAC 85 with a required characteristic cylinder strength of 74 MPa, under the additional condition

$$f_{ck} < f_{ck2} (\rho/\rho_2)^{1.5}$$

where  $f_{ck2} = 105 \text{ N/mm}^2$  and  $\rho_2 = 2200 \text{ kg/m}^3$

The general limitation of the characteristic cylinder strength ( $f_{cck}$ ) is given by:

$$f_{cck} \leq f_{cck2} (\rho/2200)$$

where  $f_{cck}$  is 94 (MPa) and  $\rho$  is the oven-dry density (kg/m<sup>3</sup>)

In the proposed revision of NS 3473 it is additionally required for LWAC that:

If  $f_{cck} > 64 (\rho/2200)$  it shall be documented that the potential characteristic strength of concrete with the specific type of LWA is at least 15% higher than required strength. This may be achieved either by additional curing beyond 28 days and/or by mixing the concrete with a reduced effective water/binder ratio.

For normal density concrete of grade higher than C85 and lightweight aggregate concrete of all grades, it shall be documented by testing that the concrete satisfies the requirements on the characteristic compressive cylinder strength. This also applies if the regular compliance control of the concrete production is performed by testing the compressive cube strength.

<sup>1</sup> Including combinations of sand, manufactured sand, and slag fine aggregate.

## 5.2.2 Density

### CUR-Recommendation 39, Part I Section 5.1.1.6

In practice the concrete almost always contains a certain amount of moisture. By determining the dead load of the structure this moisture must be included. Hence, the next table gives the volumetric density  $\gamma$ , which shall be used for moist concrete.

Table 7.5 - Volumetric mass  $r$  and volumetric weight  $g$  for lightweight aggregate concrete.

Aggregate	$\rho$ (dry) [kg/m <sup>3</sup> ]	$\gamma^*$ [kN/m <sup>3</sup> ]
Aardelite 1630	2000	21.0
Liapor 5	1600	17.0
Liapor 6	1700	18,0
Liapor 7	1800	19,0
Liapor 8	1900	20,0
Lytag	1850	19.5
The numbers 5,6,7 and 8 after Liapor give the volumetric mass of loosely packed aggregates in hundreds (in kg/m <sup>3</sup> ). The number 1630 after Aardelite represents the volumetric mass of dry aggregates (kg/m <sup>3</sup> ).		
*) reinforcement excluded		

### DIN 4219 T.1, Section 5.2.3

LWAC is classified in density classes as shown.

Table 7.6 - Density classes according to DIN 4219 T.1

Density class	1.0	1.2	1.4	1.6	1.8	2.0
Oven-dry density $\rho$ (kg/m <sup>3</sup> )	800-1000	1010-1200	1210-1400	1410-1600	1610-1800	1810-2000

### ENV 1992-1-4, Section 3.1.2.1

In prEN 206, Clause 7.3.2, lightweight aggregate concrete is classified according to its density as shown in lines 1 and 2 of the Table below. In addition, the Table gives corresponding densities for plain and reinforced concrete with normal percentages of reinforcement which may be used for design purposes in calculating self-weight or imposed permanent loading.

The contribution of the reinforcement to the density may alternatively be determined by calculation.

Table 7.7 - Density classes and corresponding design densities of LWAC according to prEN 206

Density class		1.0	1.2	1.4	1.6	1.8	2.0
Oven-dry density $\rho$ (kg/m <sup>3</sup> )		901-1000	1001-1200	1201-1400	1401-1600	1601-1800	1801-2000
Density	Plain concrete	1050	1250	1450	1650	1850	2050
(kg/m <sup>3</sup> )	reinforced concrete	1150	1350	1550	1750	1960	2150

### prEN 206, Section 4.3.2

Concrete is classified on basis of its oven-dry density. Where lightweight concrete is classified by density following Table applies. Alternatively, the density of lightweight concrete and heavyweight concrete may be specified as a target value.

Table 7.8 - Classification of lightweight aggregate concrete

Density class	LWAC 1,0	LWAC 1,2	LWAC 1,4	LWAC 1,6	LWAC 1,8	LWAC 2,1
kg/m <sup>3</sup>	≥800 and ≤1000	>1000and ≤1200	>1200 and ≤1400	>1400 and ≤1600	>1600 and ≤1800	>1800 and ≤2100

**NS 3473, Section 7.3:**

The concrete shall have an oven dry density in the range from 1200 kg/m<sup>3</sup> to 2200 kg/m<sup>3</sup>.

The mean value of oven dry (105-°C) density for three specimens after 28 days shall not deviate more than 75 kg/m<sup>3</sup> from the required value. Nor shall any individual value deviate more than 100 kg/m<sup>3</sup>.

For calculation of actions, an average density of ( $\rho + 150 \text{ kg/m}^3$ ) can be used for normally reinforced structures.

**5.2.3 Tensile strength and fracture properties****ACI 318-95, Section 5.1.4**

Where design criteria in 9.5.2.3, 11.2, and 12.2.4 provide for use of a splitting tensile strength value of concrete, laboratory tests shall be made in accordance with 'Specification for Lightweight Aggregates for Structural Concrete' (ASTM C 330) to establish value of  $f_{ct}$  corresponding to specified value of  $f'_c$ .

**BBK 94, Section 2.4.2**

For lightweight aggregate concrete the tensile strengths specified for normal weight concrete shall be reduced by the factor  $(0,3 + 0,7\rho/2400)$

**CUR-Recommendation 39, Part I Section 6.1.2**

The value of the tensile strength for normal density concrete shall be multiplied by the factor

$$k_1 = 0.4 + 0.6\rho/2300$$

where  $\rho$  is the volumetric mass in kg/m<sup>3</sup> according to Section 5.2.2.

**ENV 1992-1-4, Section 3.1.2.3**

In the absence of more accurate data, an estimate of the tensile strength can be obtained by multiplying the  $f_{ct}$ -values calculated from equations (3.2) to (3.4), or obtained from Table 3.1 in clause 3.1.2.4 of ENV 1992-1-1 by a coefficient

$$\eta_1 = 0.40 + 0.60\rho/2200$$

where  $\rho$  denotes the upper limit of the oven-dry density in line 2 of Table 3.105 (kg/m<sup>3</sup>).

**NS 3473, Sections 11.1.1 and 11.1.3**

Tensile in situ strength  $f_p$  shall be multiplied by the factor  $(0.3 + 0.7\rho/\rho_1)$ , where  $\rho_1 = 2400 \text{ kg/m}^3$ , if the tensile strength is not determined by testing.

For LWAC the moisture conditions in the specimen at testing shall be given special consideration by determining the characteristic tensile strength of the concrete by testing the splitting tensile strength.

## 5.2.4 Modulus of elasticity

### ACI 318-95, Section 8.5.1

Modulus of elasticity  $E_c$  for concrete shall be permitted to be taken as  $w_c^{1.5} 0.043 \sqrt{f'_c}$  for values of  $w_c$  between 1440 and 2480 kg/m<sup>3</sup> (Editor's note: transferred to SI units as in ACI 213 R-87, Section 4.6).

### BBK 94, Section 2.4.4

For lightweight aggregate concrete the values given for normal density concrete shall be reduced by multiplication by  $\rho/2400$ .

### CUR-Recommendation 39, Part I Section 6.1.3

The values of  $E_b$  for normal density concrete shall be multiplied by the factor  $k_2 = (\rho/2300)^{1.5}$

### DIN 4219 T.2, Section 6.1

Displacements under service loads may be calculated by using a constant E-modulus, equal for tension and compression, as shown in Table 7.9.

Table 7.9 - Design values for modulus of elasticity

Density class	1.0	1.2	1.4	1.6	1.8	2.0
Modulus of elasticity MN/m <sup>2</sup>	5000	8000	11 000	15 000	19 000	23 000

(Editor's note: "Design value" is the translation of the German "Rechenwert").

### ENV 1992-1-4, Section 3.1.2.5.2

An estimate of the mean values of the secant modulus  $E_{1cm}$  for lightweight aggregate concrete can be obtained by multiplying the values in Table 3.2 or according to equation (3.5) in ENV 1992-1-1 by the coefficient

$$\eta_E = (\rho/2200)^2$$

where  $\rho$  denotes the upper limit of the oven-dry density in line 2 of Table 3.105 (kg/m<sup>3</sup>).

The values so obtained are approximate. Where accurate data are needed, e.g. where deflections are of great importance, tests should be carried out to determine the  $E_{1cm}$ -values in accordance with ISO 6784.

### NS 3473, Section 9.2.2

If the modulus of elasticity of lightweight aggregate concrete is not determined by testing, the modulus of elasticity shall be reduced by multiplying by a factor  $(\rho/\rho_1)^{1.5}$

$\rho$  - oven dry density of lightweight aggregate concrete

$$\rho_1 = 2400 \text{ kg/m}^3$$

### NZS 3101:Part 1, Section 3.8.1.2

The modulus of elasticity,  $E_c$ , of concrete shall be taken as  $(3320 \sqrt{f'_c} + 6900) (\rho/2300)^{1.5}$  for values of  $\rho$  between 1400 and 2500 kg/m<sup>3</sup>.

## 5.2.5 Stress-strain diagrams for structural analysis

### DIN 4219 T.2, Sections 6.2

For short-term loads above the service loads, displacements may be calculated (e. g. for verification of buckling safety) by using the linear-constant diagram in Figure 7.1.

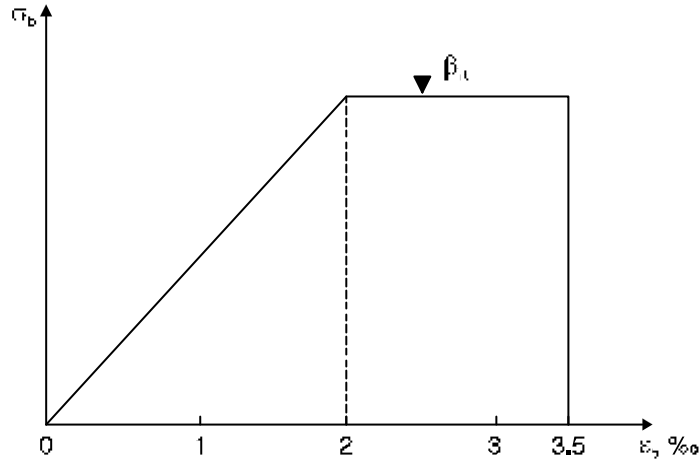


Figure 7.1 - Stress-strain diagram for lightweight aggregate concrete

(Editor's note:  $\beta_R$  is in German termed "Rechenwert" and is supposed to correspond approximately to  $0.85f_{ck}$  in MC90 and in EC2, where  $f_{ck}$  is the characteristic cylinder strength).

The descending branch of the stress-strain diagram is closely related to more brittleness of the LWAC compared to normal density concrete.

### ENV 1992-1-4, Section 4.2.1.3.3 a)

For non-linear or plastic analysis (see Appendix 2 of ENV 1992-1-1), or for the calculation of second order effects (Appendix 3 of Part 1-1), stress-strain diagrams for short term loads as shown schematically in fig 4.101 may be used. They are characterised by the modulus of elasticity  $E_{1c, nom}$ , the concrete compressive strength  $f_{1c}$ , and the strain  $\epsilon_{1c1}$  at the peak stress  $f_{1c}$  (compressive stress  $\sigma_{1c}$  and strain  $\epsilon_{1c}$  are both taken as negative).

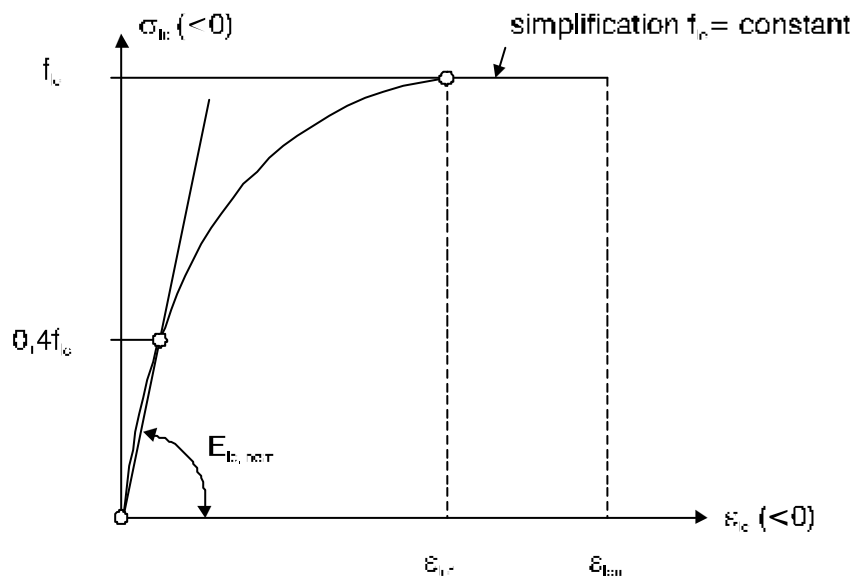


Figure 7.2 - Schematic stress-strain diagram of LWAC for structural analysis

(Editor's note: For details regarding the parameters, see ENV 1992-1-4)

Other idealised stress-strain diagrams may be used, e.g. a bi-linear diagram.

## 5.2.6 Thermal expansion

### ACI 213 R-87, Section 4.17

Approximate values are  $7$  to  $11 \times 10^{-6}$  mm/mm/°C depending on the amount of natural sand used. Ranges for normal weight aggregates are  $9$  to  $13 \times 10^{-6}$  mm/mm/°C for siliceous aggregates and  $6$  to  $9 \times 10^{-6}$  mm/mm/°C for those made with limestone aggregates the values in each case depending on the mineralogy of specific aggregates.

### DIN 4219 T.2, Section 5.4

(Editor's note: The rules are the same as in ENV 1992-1-4 (see below)).

### ENV 1992-1-4, Section 3.1.2.5.4

The coefficient of thermal expansion depends mainly on type of aggregates used and varies over a wide range.

For design purposes where thermal expansion is of no great importance, the coefficient may be taken as  $8 \times 10^{-6}$ /°C. however, the actual value may be significantly higher.

The differences between the coefficients of thermal expansion of steel and of lightweight aggregate concrete need not to be considered in design.

## 5.2.7 Creep and shrinkage

### CUR-Recommendation 39, Part I Sections 6.1.5 and 5.1.6

The creep coefficient shall be multiplied by the factor  $k_4$  defined by

$$k_4 = k_2 \quad \text{for } f'_{ck} \geq 25 \text{ N/mm}^2$$

$$k_4 = 1.3 k_2 \quad \text{for } f'_{ck} = 15 \text{ N/mm}^2$$

where  $k_2$  is the factor in 5.2.4.

For values of  $f'_{ck}$  between  $15$  and  $25 \text{ N/mm}^2$  the factor  $k_4$  may be interpolated linearly between  $k_2$  and  $1.3 k_2$ .

The values of shrinkage shall be multiplied by the factor  $k_5$  defined by

$$k_5 = 1.2 \quad \text{for } f'_{ck} \geq 25 \text{ N/mm}^2$$

$$k_5 = 1.5 \quad \text{for } f'_{ck} = 15 \text{ N/mm}^2$$

For values of  $f'_{ck}$  between  $15$  and  $25 \text{ kg/mm}^2$  the factor  $k_5$  may be interpolated linearly between  $1.2$  and  $1.5$ .

The factor  $k_t$  shall be replaced by  $k_t = t/(t + h_m)$

Where  $k_t$  = factor depending on the time of applying the load,  $t$  = time of applying load in days,  $H_m = 2A_b/O_b$ ,  $A_b$  = surface area and  $b$  = circumference

### DIN 4219 T.2, Section 6.3.2

(Editor's note: The rules are the same as specified in Table 3.107 in ENV 1992-1-4 (see below), whereas the strength class limits in the first column are slightly different).

The creep coefficient shall be reduced by the factor  $k$  defined by:

$$\text{LB 8 to LB 15: } k = 1.3 E_{1b}/E_b$$

$$\text{LB 25 to LB 55: } k = 1.0 E_{1b}/E_b$$

The shrinkage coefficient shall be multiplied by the factor  $k$  defined by:

$$\text{LB 8 to LB 15: } k = 1.5$$

$$\text{LB 25 to LB 55: } k = 1.2$$

### ENV 1992-1-4 Section 3.1.2.5.5

In the absence of test results, Tables 3.3 and 3.4 in 3.1.2.5.5 of Part 1-1 of ENV 1992 can be taken as basis for a calculation, subject to the following modifications: The final value for the creep coefficient  $\phi(\infty, t_0)$  can be reduced by the ratio

$$\eta_2 = E_{1cm}/E_{cm}$$

The creep strain so derived and the basic shrinkage strains should be multiplied by the factors  $\eta_3$  and  $\eta_4$  respectively given in Table 7.10.

Table 7.10 - Factors for the evaluation of the creep coefficient and shrinkage strain of LWAC

Concrete strength class	Factors for	
	Creep $\eta_3$	Shrinkage $\eta_4$
LWAC 12/15, LWAC 16/20	1.3	1.5
LWAC 20/25, LWAC 50/60	1.0	1.2

### NS 3473, Section 9.3.2

For lightweight aggregate concrete the creep coefficient  $\phi$  can be assumed equal to the value of normal concrete multiplied by a factor  $(\rho/\rho_1)^{1.5}$  for  $\rho \geq 1800 \text{ kg/m}^3$ . For lightweight aggregate concrete,  $\rho \leq 1500 \text{ kg/m}^3$ , a factor  $1.2 (\rho/\rho_1)^{1.5}$  can be used. For intermediate values of  $\rho$  linear interpolation may be applied ( $\rho_1 = 2400 \text{ kg/m}^3$ )

## 5.2.8 Fatigue

Editor's note: No information has been found.

## 5.3 General models

### 5.3.1 Local compression

#### NS3473 section 12.9.3

The capacity formula  $F_{cd} = A_1 f_{cd} (A_2/A_1)^{1/2} \leq 3 A_1 f_{cd}$  for NDC  
is substituted by  $F_{cd} = A_1 f_{cd} (A_2/A_1)^{1/3} \leq 2 A_1 f_{cd}$  for LWAC

#### DIN 4219 T.2, Section 7.5

The dimensions of the partially loaded surface  $A_1$  shall in both directions be at least 50 mm.

For the largest pressure  $\sigma_1$  the following relation holds

$$\sigma_1 = (\sigma_{cd}/2.1) (A/A_1)^{1/3} \leq 1.0 \sigma_{cd}$$

### 5.3.2 Confinement

#### NS3473 section 12.1.5

Strength increase due to confinement reinforcement is allowed for normal density concrete only.

#### DIN 4219 T.2, Section 7.4

For confined compression members the increase in load-carrying capacity due to confinement reinforcement should not be considered.

## 5.4 Data for prestressing

### 5.4.1 Transfer of load from tendon-anchorage assembly to concrete

#### CUR-Recommendation 39, Part 1, Section 9.13.2:

The minimum cover  $3\varnothing_k$  mentioned under a, respectively  $4\varnothing_k$  mentioned under b shall be increased by 5 mm, in which  $\varnothing_k$  refers to the diameter of the tendons [mm].

## 5.5 Structural analysis

CUR-Recommendation 39 gives detailed rules, related to NEN 6720.

## 5.6 Verification of the ultimate limit states

### 5.6.1 Stress- strain diagrams for cross-section design

#### ACI 213R-87, Section 5.9

The strength design requirements in ACI 318 for flexural computation and for combined axial compression and bending apply to structural lightweight aggregate concrete. Where the code requires a differentiation due to the reduced modulus, the equations are suitably modified.

For example, the code assumes the maximum compressive strain in the extreme fibre to be 0.003. Tests have shown this to be a reasonably conservative assumption for both normal weight and lightweight aggregate concrete. In a similar manner, certain of the basic coefficients can be shown to apply to both lightweight and normal weight concrete.

The basic philosophy in the design for flexural capacity is that failure will occur by yielding of the steel rather than by crushing of the concrete. The formulas have been prescribed to insure this type of performance, and hence the properties of the concrete, once adequate strength is maintained, are not of major importance to ultimate safety of structures. Tests of LWAC-members to failure have verified the ultimate strength design of the members.

#### BBK 94, Section 3.6.2

The strain limits given should for lightweight aggregate concrete be reduced by multiplication by the factor  $(0,3 + 0,7\rho/2400)$

#### DIN 4219 T.2, Section 7.3

The stress-strain diagram is the same as the bilinear diagram in ENV 1992-1-4:1994. The standard parabolic-rectangular diagram may also be used provided that the maximum value is reduced by 5 %.

**ENV 1992-1-4, Section 4.2.1.3.3b****b) Stress distribution for cross section design**

The idealised parabolic-rectangular stress-strain diagram in Figure 4.2 of ENV 1992-1-1 may be used. However, for lightweight aggregate concrete the preferred idealisation for cross-section design is the bilinear diagram in Figure 7.3.

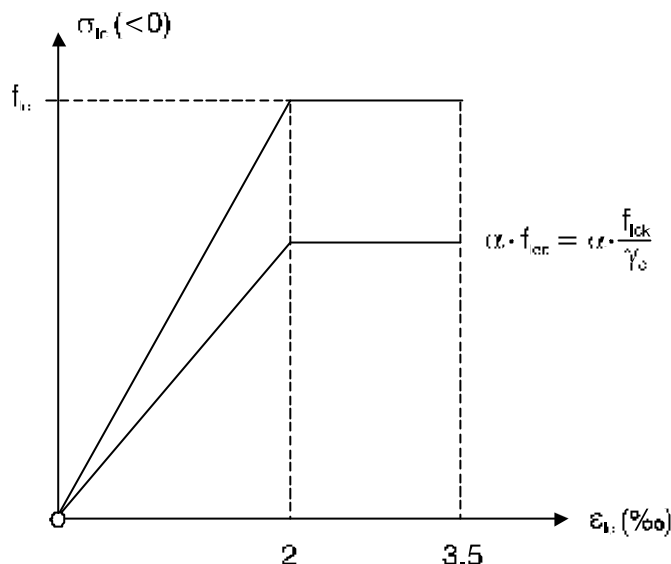


Figure 7.3 - Bi-linear stress-strain diagram for the design of cross sections made with LWAC

The design concrete strength is defined by  $f_{1cd} = f_{1ck}/\gamma_c$

The design diagram is derived from the chosen idealised diagram by a reduction of the stress ordinate of the idealised diagram by a factor

$$\alpha/\gamma_c$$

$\gamma_c$  is the partial coefficient for concrete (see 2.3.3.2 in ENV 1992-1-1)

$\alpha$  is a coefficient taking care of long term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied

The additional reduction factor  $\alpha$  for sustained compression may generally be assumed to be [0.77] for the parabolic-rectangular diagram and [0.80] for the bi-linear diagram. (Editor's note:  $\alpha$  is for NDC taken = 0.85 for the parabolic-rectangular diagram, remaining details omitted)

**NS 3473, Sections 11.3.1 and 11.3.3**

Normal density concrete and lightweight aggregate concrete can be assumed to have a stress-strain relationship as given in Figure 2.

(Editor's note:  $\epsilon_{cu} = \epsilon_{co} + 1.5 (\epsilon_{co} - \epsilon_{cn})$ , for other parameters see the original document).

For concrete grades higher than C85 and for all grades of lightweight aggregate concrete the values of  $E_{cn}$  and  $\epsilon_{co}$  shall be determined by testing of the actual type of concrete.

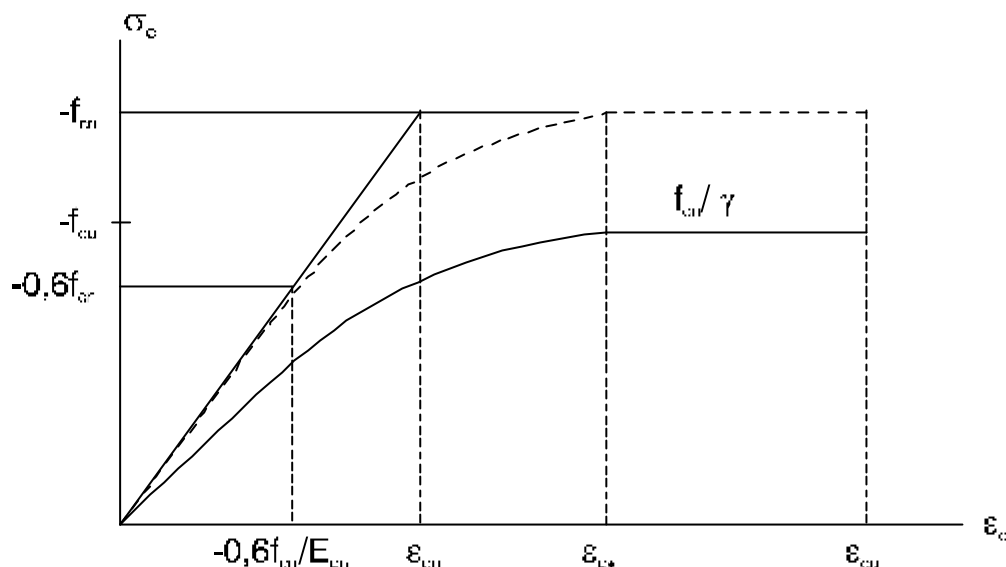


Figure 7.4 - General stress-strain diagram for concrete in compression, to be used for capacity calculations

For lightweight aggregate concrete of grades LWAC15 to LWAC45, a bilinear stress-strain diagram may be assumed, having a proportionality limit  $\epsilon_{co} = -2\text{‰}$  and the strain limit

$$\epsilon_{cu} = \epsilon_1 (0.3 + 0.7 \rho/\rho_1)$$

where  $\epsilon_1 = -3.5\text{‰}$  and  $\rho_1 = 2400 \text{ kg/m}^3$

(Editor's note: The diagram is identical to the diagram in ENV 1992-1-4, Fig 4.102, reproduced above, except that  $\epsilon_{cu}$  is a function of density).

## 5.6.2 Shear strength

### ACI 11.2, Section 11.2.1

Provisions for shear strength  $V_c$  apply to normal weight concrete. When lightweight aggregate concrete is used, one of the following modifications shall apply:

11.2.1.1 When  $f_{ct}$  is specified and concrete is proportioned in accordance with 5.2, provisions for  $V_c$  shall be modified by substituting  $1.8 f_{ct}$  for  $\sqrt{f'_c}$ , but the value of  $1.8 f_{ct}$  shall not exceed  $\sqrt{f'_c}$ .

### Section 11.2.1.2

When  $f_{ct}$  is not specified, all values of  $\sqrt{f'_c}$  affecting  $V_c$  and  $M_{cr}$  shall be multiplied by 0.75 for "all-lightweight" concrete and 0.85 for "sand-lightweight" concrete. Linear interpolation shall be permitted when partial sand replacement is used.

### BS 8110 Part 2, Section 5.4

The shear resistance and shear reinforcement requirements for lightweight aggregate concrete members should be established in accordance with BS 8110 Part 1 except that for concrete grades of 25 or more, the design concrete shear stress  $v_c$  should be taken as 0.8 times the values given in table 9.3 of BS 8110 Part 1: 1985. For grade 20 concrete, the values in table 5.3 should be used. In no case should the shear stress  $v$  exceed the lesser of  $\sqrt{f'_{cu}}$  or  $4 \text{ N/mm}^2$ .

Table 7.11 - Values of  $v_c$ , design shear stress for grade 20 LWAC

100 $A_s/bd$	$v_c$ N/mm <sup>2</sup>
0.15	0.25
0.25	0.30
0.50	0.37
0.75	0.43
1.00	0.47
1.50	0.53
2.00	0.59
≥3.00	0.68

**CUR 39, Part I, Section 8.2**

The formula for  $\tau_2$  shall be replaced by

$$\tau_2 = 0.2k_1f_bk_nk_\theta \leq 6.0 k_\theta \text{ N/mm}^2$$

where  $k_1$  is the factor defined in 5.2.3.

For shear force to be taken by reinforcement the angle  $\theta$  shall not be smaller than  $30^\circ / k_1$ .

**DIN 4219 T. 2, Sections 8.2, 8.3 and 8.4**

The values for the concrete shear strength in DIN 1045 shall be reduced by the factor 0.6. (Editor's note: Values for LWAC 8 and LWAC 10 are given in a table, but are considered to be of restricted interest here, and are not included).

Stirrups and shear reinforcement of welded wire fabric reinforcement made of B ST 500/550 R should only be considered with allowable design strength of 240 MPa.

**ENV 1992-1-4, Section 4.3.2.3**

Elements not Requiring Design Shear Reinforcement ( $V_{sd} < V_{Rd1}$ )

Addition after Application Rule (3):

(104) This section of ENV 1992-1-1 applies with the provisions that:

- a. Table 4.8 of Part 1-1 should not be used
- b. In equation (4.18) in Part 1-1, the basic design shear strength  $\tau_{Rd}$  should be taken as

$$\tau_{Rd} = 0.25 * f_{1ct,k0.05} / \gamma_c$$

with  $f_{1ct,k0.05}$  according to 3.1.2.3 of this part 1-4

(Editor's note: The formula is the same as for NDC, only the characteristic strength as function of strength grade is different)

- c. Equation (4.20) in ENV 1992-1-1 is replaced by

$$v = 0.6 - f_{1ck} / 235 \geq 0.425 \text{ (} f_{1ck} \text{ in N/mm}^2 \text{)}$$

(Editor's note: Equation (4.20) in ENV 1992-1-1 reads:

$$v = 0.7 - f_{1ck} / 200 \geq 0.5 \text{ (} f_{1ck} \text{ in N/mm}^2 \text{)}$$

The factor  $v$  expresses the effective compressive strength of the concrete in cracked compression fields (shear compression).

### **NS 3473, section 12.3.1.**

The shear tensile strength is a function of the tensile strength, which is reduced by the factor  $(0,3+0,7 \rho/\rho_1)$  for LWAC, see section 5.2.3.

## **5.6.3 Punching**

### **ENV 1992-1-4, Section 4.3.4.5.1**

Slabs or Foundations without Punching Shear Reinforcement

Addition after Application Rule (2):

In Equation (4.56) in ENV 1992-1-1,  $\tau_{Rd}$  should be calculated according to 4.3.2.3 (104) of this Part 1-4.

## **5.6.4 Torsion**

### **BS 8110 Part 2, Section 5.5**

The torsion resistance and reinforcement for lightweight aggregate concrete beams should be calculated as for normal density concrete except that the values given in table 2.3 for  $v_{t,min}$  and  $v_{tu}$  should be multiplied by 0.8.

## **5.6.5 Slender columns**

### **BS 8110 Part 2, Section 5.7**

#### *5.7.2 Short and slender columns*

The division between 'slender' and 'stocky' walls and columns is reduced from  $L/h = 15$  to  $L/h = 10$  (where  $L$  = effective height and  $h$  = thickness or depth of cross section)

#### *5.7.3 Slender columns*

In 3.8.3.1 of BS 8110: Part 1. 1985 the divisor 2000 in equation 34 should be replaced by the divisor 1200.

### **DIN4219 T2**

The limiting span to effective depth ratio is factored by 0.9 relative to normal density concrete. If the slenderness of columns ( $\lambda = \sqrt{s_k / i}$ ),  $s_k$  = effective length,  $i$  = radius of inertia) exceeds 100, a special permission is required for each single case.

## **5.6.6 Anchorage bond and laps**

### **ACI 318-95, Section 12.2.4**

The factors for use in expressions for development length of deformed bars and deformed wires in tension in Chapter 12 are as follows:

$\lambda$  = lightweight aggregate concrete factor:

When lightweight aggregate concrete is used 0.55

However, when  $f_{ct}$  is specified,  $\lambda$  shall be permitted to be taken as  $\sqrt{f'_c}/1.8f_{ct}$ ,

but not less than 1.0

When normal weight concrete is used: 1.0

**BS 8110: Part 2, Section 5.9**

Anchorage bond stress and lap lengths in reinforcement for lightweight aggregate concrete members should be established in accordance with 3.12.8 of BS 8110: Part 1: 1985, except that the bond stresses should not exceed 80 % of those calculated for normal-weight concrete.

For foamed slag or similar aggregates it may be necessary to ensure that bond stresses are kept well below the above maximum values for reinforcement which is in a horizontal position during casting, and the advice of the manufacturer should be obtained.

**CUR-Recommendation 39, Part I Sections 9.6, 9.7, 9.8**

For straight bars the values of the anchorage length  $a_1$  shall be multiplied by the factor  $k_8$ , defined by  $k_8 = 1/k_1$ , where  $k_1$  is defined in Section 5.2.3 in the present report.

For curved bars loaded in tension, the value 150 given for  $l$  shall be increased to 300. For prestressing steel the values of the anchorage length  $a_1$  shall be multiplied by the factor  $k_8$ .

If the centre to centre distance of bars that shall be spliced in the same section is less than  $10\phi_k$ , the lap length shall be further multiplied by  $k_8$ .

If the centre to centre distance is larger than  $10\phi_k$ , the lap length shall be increased in the same manner as the anchorage length (by a factor  $k_8$ ). Smaller distances shall apply an additional increase, also by the factor  $k_8$  (totally thus a factor  $(k_8)^2$ ).

**ENV 1992-1-4, Sections 4.2.3.5.6, 5.2.2.2, 5.2.2.3 and 5.2.6.2**

Section 4.2.3.5.6 (Anchorage of pre-tensioned members)

Sub-clause 4.2.3.5.6 (3) of ENV 1992-1-1 applies with the provision that equation (4.12) is replaced by  $l_p = \beta_b \phi / \eta_1$ , where  $\eta_1$  is the reduction factor for tensile strength of LWAC, see section 2.3 in the present report

## Section 5.2.2.2

Addition after Application Rule (3)

This clause of ENV 1992-1-1 applies with the provision that the design values  $f_{bd}$  given in Table 5.3 of Part 1-1 are multiplied by  $\eta_1$  in which  $\eta_1$  is given by equation (3.106) in 3.1.2.3 of this Part 1-4.

## Section 5.2.2.3

The basic anchorage length required for the anchorage of a bar of diameter  $\phi$  is  $l_b = (\phi/4) * (f_{yd}/f_{bd})$ . Values for  $f_{bd}$  are according to clause 5.2.2.2 of this Part 1-4.

## Section 5.2.6.2

For bar diameters  $\phi > |32|$  mm, values  $f_{bd}$  in Table 5.3 of ENV 1992-1-1 should be multiplied by  $\eta_1 * (132 - \phi)/100$  ( $\phi$  in mm)

**NS3473 section 12.8.5.**

The concrete contribution to the bond strength is a function of the tensile strength which for LWAC is reduced by the factor  $(0,3+0,3 \rho/\rho_1)$ , see section 5.2.3.

## 5.7 Verification of serviceability limit states

### 5.7.1 Cracking

#### DIN 4219 T.2, Section 9

Calculated tensile stresses shall for LWAC not exceed 80% of limit values given in DIN 1045.

#### ENV 1992-1-4, Section 4.4.2.2

When the time of cracking can not be established with confidence to be less than 28 days, it is suggested that a minimum tensile strength of  $[2.5]$  N/mm<sup>2</sup> be adopted.

### 5.7.2 Deformation

#### BS 8110 Part 2, Section 5.6

The rules refer to direct calculation. Alternatively, for normal structures, members may be checked by using the span/effective depth ratios given in 3.4.6.3 of BS 8110: Part 1. 1985 except that for all beams and for slabs where the characteristic imposed load exceeds 4 kN/m<sup>2</sup>, the limiting span/effective depth ratio should be multiplied by 0.85.

#### DIN 4219 T.2, Sections 7.2 and 10

7.2: The ratio of the moduli of elasticity for reinforcement and LWAC may be assumed to be  $n = 15$  (for service loads).

10: By simplified verification by limitation of the beam slenderness according to DIN 1045, Edition December 1978 Section 17.7.2, the allowable slenderness  $l/h$  shall be reduced by 10%.

The code requires that deformations are calculated using a bilinear stress-strain diagram. The parabolic-rectangular diagram may be used, provided the maximum value is reduced by 5 %.

#### NZS 3101:Part 1, Section 3.3.2.2

(a) For structural lightweight concrete having a density in the range of 1450-1850 kg/m<sup>3</sup> the values (Editor's note: for minimum thickness) shall be multiplied by  $(1.65 - 0.0003\rho)$  where  $\rho$  is the density in kg/m<sup>3</sup>.

## 5.8 Durability

#### BS 8110: Part 2, Section 5.2

The required nominal cover has been increased by 10 mm as compared with normal density concrete for conditions of exposure moderate, severe, very severe and extreme.

#### CUR-Recommendation 39, Part I Section 9.2

The cover shall be increased by 5 mm provided that no surface treatment is applied.

Note: The increase may be omitted if the production method gives a tight and even surface.

#### DIN 4219 T. 2, Section 4

The cover was higher for LWAC than for NC when the standard was published in 1979. The LWAC was not modified since than while cover was increased in the last version of the NC standard and is now sometimes higher than for LWAC. The cover for durability is increased by 5 mm relative to those specified for normal density concrete

Table 7.12 - Minimum cover thickness

1	2	3	4	5	6	7
Exposure	Type of member	Bar diameter <sup>4)</sup> d <sub>s</sub> or d <sub>sV</sub> mm	Largest grain diameter, mm			Cover for
DIN 1045:1978 Table 10			= 8	>8 =16	>16 =25	LB8-15 not less than <sup>3)</sup>
	General	=18	1.5 <sup>1)</sup>	2.0	2,5	2.0
	Including prefab	20-22	2.0			
1	Plates and shells	=14	1.5 <sup>1)</sup>	1.5 <sup>1)</sup>		1.5 <sup>1)</sup>
		16 and 18		2.0	2.5	
		20 and 22	2.0			2.0
	General	=22	2.0		2.5	
2	Plates and shells	=18	1.5 <sup>1)</sup>	2.0	2.5	2.0
	Prefab LB35-LB55	20 and 22	2.0			
3 <sup>2)</sup>	General	=22	2.5		3.0	
	Plates and shells Prefab LB35-LB55	=22	2.0		2.5	
4 <sup>2)</sup>	General	=22	3.5		4.0	
	Plates and shells Prefab LB35-LB55	=22	3.0		3.5	

1) For welded wire fabric with single bars of more than 8.5-mm diameter or double bars of more than 6.5-mm diameter the cover shall nevertheless be at least 2.0 cm.  
2) Regarding additional requirements for lightweight aggregate concrete see DIN 4219, Part 1, Dec 1979, Section 5.2.7  
3) For LB 8 and LB 10 the bar diameter shall not exceed 16 mm.  
4) For thick reinforcement bars the cover shall nevertheless be at least  
3.5 cm for diameter d<sub>s</sub> = 25 mm  
4.0 cm for d<sub>s</sub> = 28 mm  
1.5 d<sub>sV</sub> for bundles with equivalent diameter d<sub>sV</sub> ≥ 25 mm.

**ONORM 3314**

The cover for durability is increased by 5 mm relative to those specified for normal density concrete.

**ENV 1992-1-4, Section 4.1.3.3**

The protection of reinforcement against corrosion depends upon the continuing presence of a surrounding alkaline environment provided by an adequate thickness of good quality, well cured concrete. The thickness of cover required depends both upon the exposure conditions and on the concrete quality. The quality of cover in lightweight aggregate concrete is more sensitive to poor workmanship than in normal weight concrete and, for this reason, special care is needed to ensure the required standards of workmanship are achieved.

## 5.9 Detailing

### 5.9.1 Maximum bar diameters

ONORM 3341

The maximum reinforcement diameter shall not exceed 26 mm for strength classes LB 225 and less.

#### ENV 1992-1-4, Section 5.1

The diameter of bars embedded in lightweight aggregate concrete should not normally exceed 32 mm (see 5.2.6 of ENV 1992-1-1).

### 5.9.2 Permissible radii of bends

#### CUR-Recommendation 39, Part I Section 9.5

The minimum radius of bends shall be increased from  $2.5 \varnothing_k$  to  $5 \varnothing_k$ .

If the lateral cover of the bar is less than  $3 \varnothing_k$  the minimum bending radius shall, for bars with a diameter equal to or larger than 16 mm, be increased to  $10 \varnothing_k$ .

The minimum radius of bend of prestressing steel of  $15 \varnothing_k$ , respectively  $20 \varnothing_k$ , shall be increased to  $30 \varnothing_k$ .

#### ENV 1992-1-4, Section 5.2.1.2

This clause of ENV 1992-1-1 applies with the provision that the minimum diameters of mandrels given in Tables 5.1 and 5.2 of ENV 1992-1-1 should be increased by 30 %.

#### JASS 5, Section 15.7

- a. Bend shapes and dimensions of reinforcement bars at end and intermediate portions shall be in accordance with 10.2.d.
- b. Length of development and lap splices shall be in accordance with 10.5.b. For lightweight aggregate concrete with specified design strength of  $270 \text{ kgf/cm}^2$ , the values corresponding to normal concrete with a specified design strength of  $240 \text{ kgf/cm}^2$  shall be applied.

#### NS 3473, section 12.9.5.

When the compressive stresses in the concrete in the bend is decisive, the minimum bending diameter is increased by 50%.

### 5.9.3 Bundled bars

#### CUR-Recommendation 39, Part I Section 9.4

Bundling is not accepted.

#### ENV 1992-1-4, Section 5.2.7.1

Bundles of bars should not be used unless their use is justified by experience or test data. In that case, Section 5.2.7 of ENV 1992-1-1 applies, however with the limitation  $\phi \leq \underline{20}$  mm.

#### NS 3473, section 12.8.2.

There are no special restrictions on bundles for LWAC.

### 5.9.4 Post-tensioned bars, tensile splitting reinforcement

#### CUR-Recommendation 39, Part I Section 9.11.9

Detailed rules are given concerning the area of the cut section of reinforcement bars in combination with post-tensioned bars.

## 5.10 Fire Resistance

### BS 8110

The required nominal cover to meet specified periods of fire resistance has been reduced by 5 to 15 mm, depending on the duration of the fire exposure.

## 5.11 Practical construction

No information available.

## 5.12 Quality assurance and quality control

### 5.12.1 Control of materials

#### JASS 5, Section 15.8

- a. Quality control and inspection shall be in accordance with Section 12
- b. Control and inspection of the unit weight of ready-mixed concrete at the unloading point and of site-mixed concrete immediately after mixing shall be performed based on the unit weight of the fresh concrete calculated by equation (15.2) below from the design mix proportions. The tolerance between  $W_w$  and the actual unit weight shall be  $\pm 3.5\%$ .

$$W_w = G_0(1+p_c/100)+S_0(1+p_s/100) +S'_0(1+p'_s/100)+C_0+W_0 \text{ (kg/m}^3\text{)}$$

where

$W_w$  = calculated unit weight of the fresh concrete based on designed mix proportions (kg/m<sup>3</sup>)

$G_0$  = lightweight coarse aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$S_0$  = lightweight fine aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$S'_0$  = normal weight fine aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$C_0$  = unit cement content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$W_0$  = unit water content in designed mix proportions (kg/m<sup>3</sup>)

$p_c$  = water absorption of lightweight coarse aggregate at the time of use (%)

$p_s$  = water absorption of lightweight fine aggregate at the time of use (%)

$p'_s$  = water absorption of normal fine aggregate at the time of use (%)

## 5.13 Concrete technology

### 5.13.1 General

#### PrEN 206, Section 1 'Scope'

The standard states in the scope that "... Additional or different requirements may be necessary for lightweight concrete .... Note: the additional or different requirements may be given in specific European Standards or in provisions valid in the place of use of the concrete."

This statement creates the need for the CEN members on a national basis to establish these needed regulations to make EN 206 fully operative for LWAC.

### **JASS 5, Section 15.1**

The contractor, prior to the start of the work, shall establish the materials and equipment, proportioning, and methods of mixing, transporting, placing, curing, and quality control of the unit weight of the fresh concrete for the lightweight aggregate concrete work, and these shall be subject to the approval of the architect/Engineer.

### **5.13.2 Definitions**

Reference is made to Chapter 2.

### **5.13.3 Aggregates**

#### **ACI 318-95, Section 3.3.1**

Concrete aggregates shall conform to one of the following specifications:

- 'Specifications for Concrete Aggregates' (ASTM C 33)
- 'Specification for Lightweight Aggregates for Structural Concrete' (ASTM C 330)

#### **CUR-Recommendation 39, Part II, Section 5.4.2**

Coarse light aggregates shall be chosen so as to correspond with product specifications in Appendix A of CUR 39. (Editor's note: Specifications for Aardelite, Lytag and Liapor).

Other aggregates may be used provided that their use is justified by testing according to a specific CUR procedure.

#### **JASS 5, Section 15.3**

- Artificial lightweight aggregates shall conform to JIS A 5002 (Lightweight Aggregates for Structural Concrete), and shall be of the quality accredited in accordance with the Notification of the Ministry of Construction (No. 32 by Building Guidance Div., Housing Bureau, January 1991).
- The maximum size of the artificial lightweight aggregate shall be as specified in the Special Provisions. Unless otherwise specified, the maximum size shall be 15 mm or 20 mm.

#### **NS 3473, Section 7.3**

Requirements on the concrete and lightweight aggregate shall be given in the production documents.

Lightweight aggregate concrete which is used in load-bearing structures shall have a lightweight aggregate of expanded clay, expanded shale, or sintered pulverised ash from coal power plants, or other aggregates with corresponding properties. Mixes of light and normal weight aggregates can be used.

The lightweight aggregate shall have uniform strength properties, stiffness, density, degree of burning, grading etc. The dry density shall not vary more than  $\pm 7.5\%$

If the water absorption of the concrete is important, this property shall be determined by testing under conditions corresponding to the conditions to which the concrete will be exposed.

### 5.13.4 Specification and production

#### JASS 5, Section 15.4

- An air-entraining agent, an air-entraining and water-reducing agent or an air-entraining and high-range water reducing agent, in accordance with 3.5 shall be used for lightweight aggregate concrete.
- The standard air content shall be 5%.
- Designed mix proportions shall be established so that the assumed air-dry unit weight,  $W_d$ , obtained from next equation is near and less than the air-dry unit weight specified in the Special Provisions.

$$W_d = G_0 + S_0 + S_0' + 1.25 C_0 + 120 \text{ (kg/m}^3\text{)}$$

where

$G_0$  = lightweight coarse aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$S_0$  = lightweight fine aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$S_0'$  = normal weight fine aggregate content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

$C_0$  = unit cement content in designed mix proportions, oven-dry (kg/m<sup>3</sup>)

#### JASS 5, Section 15.5

- The ready-mixed concrete plant shall, in principle, be a JIS accredited plant for lightweight aggregate concrete, intended to be purchased.
- When a plant not accredited as above is to be used, the state of quality control in the plant shall be thoroughly examined, and the ability of the plant to manufacture the concrete of the required quality shall be verified by trial mixing. The proposed plant shall be subject to approval by the Architect/Engineer.

### 5.13.5 Transportation and placing

#### PrEN 206, Section 9.2.6.1 'Personnel'

This CEN Standard is highlighting the need for special expertise in batching and transporting LWAC by the statement "Knowledge, training and expertise of personnel involved in production and production control shall be appropriate to the concrete category and the type of concrete, e.g. high strength concrete, lightweight concrete."

#### PrEN EEE, Section 8.7, 'Concrete special execution methods'

"Execution with special concrete such as lightweight concrete, high strength concrete, heavy-weight concrete, under water concrete etc. shall conform to standards or in provisions valid in the place of use in the concrete."

This statement creates a need for the CEN members to establish these needed regulations on a national basis to make EN EEE fully operative for LWAC.

#### JASS 5, Section 15.6

- Lightweight aggregate concrete shall be transported by methods which will minimise segregation, spillage, and change in quality, with due consideration to proportioning, portions to be placed, volume to be placed per unit time, and execution conditions.
- When placing, appropriate methods and consolidating tools shall be selected to avoid segregation of the aggregates.
- The lightweight coarse aggregate, which appears on the concrete surface, shall be worked back into the mortar by tamping or towelling, to obtain a smooth concrete surface.

### 5.13.6 Inspection

#### NS 3473, Section 7.1.3

Inspection class *extended inspection* shall be used if at least one of the following conditions is met: which are designed with lightweight aggregate concrete of grade having characteristic strength  $f_{ck} > f_{ck1}(\rho/\rho_1)^{1.5}$  where  $f_{ck1} = 55 \text{ N/mm}^2$  and  $\rho_1 = 2400 \text{ kg/m}^3$

(Editor's note: The quoted clause is one among several conditions)

## 6 IDENTIFICATION OF WHITE SPOTS

Task 1 of the project results in important input for the other tasks. Subtask 1.1 should identify the white spots that are the basis for further research.

The white spots are based on the detailed comparison of codes and standards and are summarised in this chapter. It is mentioned that the discussions in the state-of-the-art report of the joint CEB-FIP (FIB) Working Group (see Chapter 7) form the basis for this chapter.

### 6.1 Basis of design

Regarding partial factors it is mentioned that since an increased brittleness is a common characteristic for LWAC and high-strength normal density concrete, an increase of the  $\gamma_m$ -factor should be considered also for LWAC and start at a lower strength class than for normal density concrete. A similar increase is implied in the in situ strength defined in NS 3473, but is not found in other documents.

The question whether the increased brittleness of concrete with high strength/density ratio should be taken into account by introduction of increased  $\gamma_m$ -factors or by modification of relevant strength parameters needs further discussion.

### 6.2 Material properties

#### Concrete grades

The lower and upper limits for strength grades vary; in particular the strength grades accepted in Japan are much lower than in Europe. The CEB/FIP Working group suggests the following limitations: Grades for structural lightweight aggregate concrete should not be lower than LWAC10, and not higher than LWAC 80.

The ratios of cylinder strength to cube strength according to ENV 1992-1-4, Section 3.1.2.4 are too small, and more correct values should be specified.

Such values are found in prEN 206. Even if actual ratios depend on a number of parameters, and thus are uncertain, values similar to those in prEN 206 are close to an average from tests, and should be recommended.

The need for density-related strength limits as defined in NS3473 should be further discussed. The consequences for utilising LWA concrete with compressive strength approaching the potential strength limit of the respective LWA types should be addressed.

#### Density

The oven-dry density has been found to give the best correlation between strength and stiffness values of LWA and ND concrete. The values in the codes are sometimes given in classes with a

range of  $200 \text{ kg/m}^3$ , having its origin from standardisation and sales purposes in connection with sound and heat insulation.

This classification is not so relevant for structural design. Due to the expected sensitivity to the self-weight of typical LWAC structures, more accurate values are needed both for the oven-dry density and the in-situ density. A more accurate procedure than just adding  $100 \text{ kg/m}^3$  to the oven-dry density is needed.

Guidelines for specification of realistic target densities dependent on aggregate types, concrete strength and mixing procedures should be established. The structural codes should specify acceptable tolerances on the target densities. As a basis for the choice of realistic tolerances, the variations in density should be examined at sites.

### **Tensile strength and fracture properties**

The most characteristic difference in mechanical behaviour between normal density concrete and LWAC is the more pronounced brittleness of LWAC. This phenomenon is yet not completely understood. Test methods being able to classify the brittleness of different concretes should be further considered.

The tensile strength of LWAC tested by standard laboratory methods is often reported to be about the same, or only slightly less than the tensile strength of normal density concrete of the same compressive strength. However, the structural codes introduce significant reduction factors decreasing the tensile strength with decreasing density.

The main reason is that the tensile strength is used, not only for prediction of direct tensile strength, but also as a strength parameter in prediction of the ultimate strength, particularly the shear strength of slabs and the strength of reinforcement bond anchorage. Tests on reinforced concrete have shown that reduction factors are necessary to predict the shear and bond strength of LWAC elements with the same equations applied for normal density concrete.

The introduced reduction factors in different codes and standards are quite similar, and a better approximation is hardly possible without distinguishing between the types of aggregates.

The shear cracking strength of relatively high strength All-LWAC is found to be lower than that of LWAC with natural sand. Thus, it seems necessary to introduce a more restrictive factor for especially brittle LWAC types. More tests are needed for verification of improved factors.

### **Modulus of elasticity**

The rules are mainly qualitatively in agreement about supplementing the variation of E-modulus with strength for normal density concrete, with a reduction factor as a function of density. However, exponents vary between 1 and 2. This fact indicates that the issue should be studied more closely and possibly more parameters (e.g. type of aggregate) should be considered.

### **Stress-strain diagrams for structural analysis**

Realistic and complete stress-strain diagrams are needed only when the structural analysis takes into account the non-linear material properties of the concrete.

When a linear elastic response is assumed, a realistic E-modulus is needed only when section forces due to restrained imposed deformations and/or second order effects are analysed. The simplified bi-linear diagrams prescribed in some standards may be sufficient as a basis for simplified plastic analysis including control of rotational capacity of plastic hinges. In both cases the assumptions concerning tensile cracking are important.

For non-linear structural analysis, i.e. finite element methods, stress-strain diagrams being as realistic as possible ought to be used. Diagrams where the ascending branch, the peak stress/strain, the length of the yield plateau and the descending branch are dependent on the characteristics of the actual concrete should therefore be developed.

### **Creep and shrinkage**

The factors for creep and shrinkage of LWAC compared to normal density concrete are about 1.0 to 1.5, but differ slightly between countries. The development of creep and shrinkage with time is different for LWAC mainly due to the water reservoir in the aggregate. This topic should be further addressed in this project.

### **Fatigue**

In general a basic understanding of fatigue, where the micro-behaviour differs from that for normal density concrete is needed.

## **6.3 General models**

### **Local compression**

Only the German and Norwegian standard deals with local compression. There is, however, a factor of 2 between the permitted stresses in the two cases. At transfer of large forces to local sections, as for instance anchorage of prestressing cables, problems with spalling of the concrete cover have been observed for force positions relatively close to the surface. This spalling is specially occurring when the spacing of the surface reinforcement in the force direction is relatively close. Thus, further work is needed within this topic both with respect to stress levels and reinforcement detailing.

### **Confinement**

Special confinement reinforcement is sometimes used to increase the strength and ductility of a structure. Tests on columns and beams with dense stirrup reinforcement have shown that confinement is less effective in LWA- than ND-concrete. Thus it is not allowed to increase the strength with confinement for LWAC in neither the Norwegian nor the German standard. This problem is relatively closely related to local compression and should be further investigated before a final conclusion on confinement behaviour of LWAC can be drawn.

## 6.4 Verification of the ultimate limit states

### Stress-strain diagrams for cross-section design

The present standards mainly choose a simple approach, adopting the standard parabola-rectangle diagram, possibly with a simple modification, or a bilinear diagram.

BBK 94 and NS 3473 are exceptions. In the bilinear diagram specified for LWAC there is a reduction of the ultimate strain with reduced density of LWAC. In NS 3473, moreover, a general diagram, valid for all grades of LWAC from LWAC12 to LWAC74 (referred to cylinders) is given. However, for all grades of LWAC the parameters in the diagram shall be determined by testing.

It is essential to provide a solution that includes a simple approach for usual applications, which allow a more economic utilisation of the material design. As a basis for discussion is suggested by the CEB-FIP Working group:

For strength calculations a bilinear stress-strain diagram may be applied.

For cylinder strength/dry density ratios not exceeding a defined limit a standard diagram according to ENV 1992-1-4 Fig 4.102, but with a variable  $\epsilon_{cu}$  may be used. For higher cylinder strength/dry density ratios the slope of the ascending part and the ultimate strain shall be based on testing the actual type of concrete.

However, this topic needs further investigation.

### Shear strength

The common approach in the rules quoted is that the design method for normal density concrete is kept unchanged, whereas the shear capacity as referred to strength grade is reduced for LWAC. The reduction is done by reduction factors (0.8 in BS 8110 Part 2 and 0.6 in DIN 4219 T.2) or by replacing the design tensile strength of NC by the corresponding strength of LWAC in ENV 1992-1-4.

This problem needs further investigation and reference is made to the spot on 'Tensile strength and fracture properties' in section 6.2.

Also with respect to shear compression, there is still work to be done. In ENV 1992-1-4 the capacity is reduced by about 15% compared to normal density concrete. The reduction will probably depend on the brittleness of the concrete and further tests are needed for this verification. For sections with heavy shear reinforcement the risk of splitting of the cross sections and spalling of the concrete cover should also be considered.

### Punching

Punching is very closely connected to the shear problem. Tests are, however, needed for a verification of the design models.

### Torsion

In torsion, the problem with spalling of corners and cover may be more pronounced than for normal density concrete.

### Slender columns

The division between slender and stocky walls and columns should be analysed.

**Anchorage bond and laps**

The articles 4.2.3.5.6 and 5.2.2.2 of ENV 1992 refer to pre-tensioned members and ordinary reinforced members respectively. Both clauses require that the transmission length is increased by a factor  $1/\eta_1$ , where  $\eta_1$  expresses the ratio of decrease of tensile strength.

The bond strength of LWAC is expected to be more sensitive to bar diameter, distance between the bars and detailing of the transverse reinforcement than normal density concrete. Besides, the danger of progressive failure is assumed to be more predominant for LWAC. The standards, then, generally put restrictions on the bond and anchorage properties of LWAC compared to normal density concrete.

Some work is already done regarding bond of LWAC, but still more is needed, particularly concerning large diameters, bundles and lap-splices. The restrictions are in general covered by a reduction of the tensile strength, but as for shear there should probably be a factor taking into account the brittleness of the concrete.

**6.5 Verification of serviceability limit states****Cracking**

The two clauses in Section 7.7 deals with the tensile strength of plain concrete.

However, there is also need for more work to be done within crack width and crack distance calculations.

**Deformation**

Corrections are needed in standards when span/effective depth ratios are given.

**6.6 Durability**

White and grey spots concerning durability are described in the state-of-the-art report (sub-task 1.2, document BE96-3942/MG/R2).

**6.7 Detailing**

Some confusion exists between the detailing requirements for the reinforcement in clauses with special address to LWAC in the standards. The topics covered are the maximum bar diameter, permissible radii of bends, bundle bars and post-tensioned bars, tensile splitting reinforcement. More work is needed to co-ordinate and improve these approaches.

**6.8 Production and execution**

CEN/TC 104/SC 1 and SC 2 have not been able to work out a set of complete requirements for the production (prEN 206) nor the execution on site (prEN EEE) for the use of LWAC. The reason for this is the broad variety of LWA on the European market. These LWAs are generally characterised by big differences in amount and rate of water absorption.

There is a need to develop a set of harmonised general applicable European rules for handling all these different LWAs.

## **7 NOMENCLATURE**

LWA	Lightweight aggregate
LWAC	Lightweight aggregate concrete
NDA	Normal density aggregate
NDC	Normal density concrete
w/b	water binder ratio
w/c	water cement ratio
CEB	Comité Euro-international du Béton
CEN	Comité Européen de Normalisation
CTR	Cost Time Resources (form)
EN	European Standard
FIB	Fédération Internationale du Béton
FIP	Fédération Internationale de la Précontrainte
MG	Management Group
TC	Technical Committee (CEN)
TG	Task Group
TLG	Task Leaders Group