bulletin 4

state-of-art report

fib
CEB-FIP



Lightweight Aggregate Concrete

Codes and standards



Lightweight Aggregate Concrete

Codes and standards

State-of-art report prepared by

Task Group 8.1

August 1999

Subject to priorities defined by the Steering Committee and the Praesidium, the results of *fib*'s work in Commissions and Task Groups are published in a continuously numbered series of technical publications called 'Bulletins'. The following categories are used:

category	minimum approval procedure required prior to publication
Technical Report	approved by a Task Group and the Chairpersons of the Commission
State-of-Art report	approved by a Commission
Manual or Guide (to good practice)	approved by the Steering Committee of *fib* or its Publication Board
Recommendation	approved by the Council of *fib*
Model Code	approved by the General Assembly of *fib*

Any publication not having met the above requirements will be clearly identified as preliminary draft.

This Bulletin N° 4 has been approved as a *fib* State-of-art report in April 1999 by *fib* Commission 8 'Concrete', and has been assessed by selected reviewers chosen by the Steering Committee.

The former 'Joint CEB/FIP Working Group on Lightweight Aggregate Concrete' started in 1995. CEB and FIP merged in 1998 into *fib*. The Working Group continued then as *fib* Task Group 8.1 with the same title. The members have changed somewhat during this period and are in the concluding stage in 1999:

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Cover photo: Heidrun Tension Leg Platform, world's first floating production platform, utilising 65'000 m^3 of largely slipformed C 60 lightweight aggregate concrete. 'Special mention' by the jury of the FIP 1998 Award for outstanding structures, category of civil engineering structures (photo: courtesy Jan Moksnes).

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Preface

The work of TG 8.1 has been arranged in four tasks
1. Case studies
2. Codes and standards. State-of the-Art Report
3. MC 90: Needed Amendments and Suggested Extensions
4. Identification of research needs

The present report constitutes the deliverable from Task 2, specified as follows in the terms of reference: "As a background for an extension of MC 90 the present international consensus on LWAC should be documented in a state of the art report, similar to FIP SR 90/1 / CEB Bulletin d' Information No. 197". Conclusions, in the form of recommended approaches or recommended research items, will not be found in the present report, but in the reports on Task 3 and Task 4 presently under elaboration. In some cases, however, comments from TG 8.1 on the contents in codes and standards are added under the heading "discussion".

To allow an easy comparison with MC 90, the main headings in the present report are the same as in MC 90 up to and including Chapter 12, whereas the present Chapter 13 corresponds to Appendix d in MC 90. First level subheadings refer to specific sections in MC 90. Further subheadings refer to the various documents quoted (with abbreviated titles). Full titles of these documents are found in Chapter 14. Rules quoted from the documents are identified by referring to section numbers and numberings of figures and tables in the documents quoted. To distinguish between headings in the present document and headings in documents quoted, the quoted headings are written in Italics. Normally North American and European (CEN) documents are quoted, and supplemented by additional (national) documents, manuals, research papers etc. when found significant.

In spite of recent efforts to standardise notation, the quotations reveal that notations are not identical in the different documents in all cases. Examples are characteristic cylinder strength denoted as f_{ck}, f_{cck} or $f_{ck,cyl}$ in different documents. Also, acronyms may differ. Since the present document is supposed to be used by specialists, it is hoped that notations and acronyms will usually not cause confusion. Where deemed necessary, an explanation has been added as an editorial remark.

The approach implies that issues or clauses in different documents, deemed to be of less importance might have been excluded. Neither the list of topics, nor the quotations, should be expected to be complete, and the original documents may have to be consulted to get full information. Also, a translation of quotations into English may imply shadings as compared with the original meaning.

Trondheim, August 1999

Ivar Holand

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1. Basis of design

1.1 Representative values of material properties (MC 90, Section 1.4.4)

NB 22, Section 1.6.4
In mix design, a lightweight aggregate quality shall be chosen providing sufficient strength potential of the LWAC.

For lightweight concrete with a required characteristic strength
$f_{cck} > 64$ N/mm^2 (ρ /2200 kg/m^3)^2
where ρ is the oven-dry density of the concrete, a sufficient strength potential is achieved if, within 90 days, it is documented a characteristic compressive strength minimum 15 % higher than required to fulfil the specified strength class at 28 days. The documentation shall be in accordance with ISO 4012.

(Editor's note: See also Section 2.1, under sub-heading NS 3473.)

1.2 Partial factors (MC 90, Section 1.6.2.4)

CEB-FIP HSC/HPC 95, Section 1.6.2.4

Proposed extension of MC90:
γ_c should for high strength concrete be increased by the factor
$\gamma_{hsc} = 1/(1.1 - f_{ck}/500)$
$50 < f_{ck} < 100$ MPa

2. Material properties

2.1 Concrete grades (MC 90, Section 2.1.1.2)

BBK 94, Section 2.4.1
Grades K8 and K12 may only be used for lightweight aggregate concrete. The application requires execution class II or I.

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 to be applied in accordance with Table 1. 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.

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The maximum aggregate diameter, d_{max}, is limited to 25 mm. For Strength classes LB 25 and higher a further reduction of d_{max} is recommended. A minimum cement content of 300 kg/m³ is required. The cement content should not exceed 450 kg/m³. The minimum mixing time for LWAC is 90 seconds.

Table 1 Strength classes and their application

Concrete Group	Strength class	Nominal strength [1]	Mean strength	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	
LWAC B II	LB 25	25	29	Plain, reinforced and prestressed LWAC	Also for dynamic loads
	LB 35	35	39		
	LB 45	45	49		
	LB 55	55	59		

[1] Editor's note: Cube strength measured on 200-mm cubes.

ENV 1992-1-4, Section 3.1.2.4

(103) For design calculations, the concrete strength classes and the characteristic compressive strengths can be obtained from Table 3.106.

Table 3.106 Strength classes and the characteristic compressive cylinder[1] strength f_{lck} of lightweight aggregate concrete (in N/mm²)

Class	LC 12/15	LC 16/20	LC 20/25	LC 25/30	LC 30/37	LC 35/45	LC 40/50	LC 45/55	LC 50/60
f_{lck}	12	16	20	25	30	35	40	45	50

[1] Editor's note: "Cylinder" added by the editor for clarification

Concrete of strength classes LC 12/15 or less, and concrete of classes higher than LC 50/60 should not be used unless their use is appropriately justified. For prestressed concrete, classes lower than LC 30/37 should not be used for pre-tensioned and lower than LC 25/30 not for post-tensioned work.

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prEN 206-1, Section 4.3.1

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 8 Compressive strength classes for lightweight aggregate concrete

Compressive strength class	Minimum characteristic cylinder strength $f_{ck,cyl}$ N/mm^2	Minimum characteristic cube strength [1] $f_{ck,cube}$ N/mm^2
LC 8/9	8	9
LC 12/13	12	13
LC 16/18	16	18
LC 20/22	20	22
LC 25/28	25	28
LC 30/33	30	33
LC 35/38	35	38
LC 40/44	40	44
LC 45/50	45	50
LC 50/55	50	55
LC 55/60	55	60
LC 60/66	60	66
LC 70/77	70	77
LC 80/88	8	88
[1] Other values may be used if the relationship between these and the reference cylinder strength is established with sufficient accuracy and is documented		

JASS 5, Section 16.1

a. This section shall be applicable to concrete in which manufactured lightweight aggregate is used for all or part of the aggregate. The scope of application shall be as specified in the Special Provisions.

(Editor's note: "Special Provisions" refers to JASS Section 28, containing specific expressions related to JASS Sections 2 through 27.)

JASS 5, Section 16.2

a. The types of lightweight aggregate concrete shall be Type 1 and Type 2.
b. The specified design strength and air-dry unit weight of these types shall be in the ranges shown in Table 16.1.
c. Lightweight aggregate concrete proportioned as high durability concrete shall be in accordance with Section 3.4.
d. The slump shall not be more than 21 cm.
e. The minimum unit cement content shall be 320 kg/m^3, and the maximum water-cement ratio shall be 0.55. When the specified design strength is more than 27 N/mm^2, the former 340 kg/m^3, the latter 50 %.
f. The maximum water content shall be 185 kg/m^3.

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Table 16.1 – Maximum Specified Design Strength and Air-Dry Unit Weight of LWAC

Type of concrete	Maximum specified design strength (N/mm^2)	Ranges of air-dry unit weight w (t/m^3)
Type 1 lightweight concrete	36	$1.7 \leq w \leq 2.1$
Type 2 lightweight concrete	27	$1.4 \leq w < 1.7$

JSCE, Part 2, Commentary for Sec 20.3 (1)
The practical range for strength of LWAC is up to 60 MPa.

NS 3473, Sections 7.2, 7.3 and 11.1.1
Load bearing structures of reinforced concrete shall normally not be designed in grades lower than C 25. For lightweight aggregate concrete, the grade LC 15 may be used. Prestressed reinforced structures shall not be designed with grades lower than C 35 or LC 35.

(Editor's note: Numbers refer to cube strength measured on 100-mm cubes. Grades are specified with reference to cube strengths and cylinder strengths as well, in a Table (Table 5)).

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

$f_{cck} \leq f_{cck2} (\rho/\rho_1)^2$

where $f_{cck2} = 94$ N/mm^2, $\rho_1 = 2200$ kg/m^3 and ρ is the oven-dry density (kg/m^3)

For normal density concrete of grade higher than C 85 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.

For LWAC it is additionally required that:
If $f_{cck} > 64 (\rho/\rho_1)^2$ it shall be verified by testing that a characteristic strength of concrete at least 15% higher than the required strength can be produced. The verification may be done by testing a concrete with the same recipe, but with a reduced effective water/binder ratio or by additional curing beyond 28 days.

(Editor's note: The requirement has been introduced to avoid long-term failure caused by insufficient strength of aggregates.)

Discussion:
The lower and upper limits for strength grades vary. In particular, the strength grades accepted in Japan are much lower than in Europe. The ratios of cylinder strength to cube strength according to ENV 1992-1-4, Section 3.1.2.4 are about 0.8, whereas the default values given in prEN 206-1 correspond to ratios about 0.9.

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2.2 Density (MC 90, Section 2.1.2)

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, Table 1 gives the volumetric density γ, which shall be used for moist concrete.

Table 1 - Volumetric mass ρ and volumetric weight γ for lightweight aggregate concrete

Aggregate	ρ (dry) [kg/m^3]	γ*) [kN/m^3]
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 bulk density of loosely packed aggregates in hundreds (in kg/m^3). The number 1630 after Aardelite represents the loose bulk density of dry aggregates (kg/m^3).		
*) reinforcement excluded		

DIN 4219 T.1, Section 5.2.3

LWAC is classified in density classes as shown in Table 2

Table 2 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 ρ (kg/m^3)	800-1000	1010-1200	1210-1400	1410-1600	1610-1800	1810-2000

ENV 1992-1-4, Section 3.1.2.1

(103) In ENV 206, Clause 7.3.2, lightweight aggregate concrete is classified according to its density as shown in lines 1 and 2 of Table 3.105 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.

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

Table 3.105 Density classes and corresponding design densities of LWAC according to prEN 206-1

Density class		1.0	1.2	1.4	1.6	1.8	2.0
Oven-dry density ρ (kg/m^3)		901-1000	1001-1200	1201-1400	1401-1600	1601-1800	1801-2000
Density (kg/m^3)	Plain concrete	1050	1250	1450	1650	1850	2050
	Reinforced concrete	1150	1350	1550	1750	1950	2150

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The numbers 5,6,7 and 8 after Liapor give the bulk density of loosely packed aggregates in hundreds (in kg/m^3). The number 1630 after Aardelite represents the loose bulk density of dry aggregates (kg/m^3).		
*) reinforcement excluded		

DIN 4219 T.1, Section 5.2.3

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ENV 1992-1-4, Section 3.1.2.1

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Density (kg/m^3)	Plain concrete	1050	1250	1450	1650	1850	2050
	Reinforced concrete	1150	1350	1550	1750	1950	2150

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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 + 0,7ρ/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

$k_l = 0.4 + 0.6\rho/2300$

where ρ is the volumetric mass in kg/m^3 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

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

where ρ denotes the upper limit of the oven-dry density in line 2 of Table 3.105 (kg/m^3) (see Section 2.2).

JSCE Part 1, Section 3.2.1

a) Flexural strength (Modulus of rupture):

$f_{bk} = 0.42 f'^{2/3}_{ck}$ for ordinary concrete

$f_{bk} = 0.7 \times 0.42 f'^{2/3}_{ck}$ for LWAC

b) Tensile strength:

$f_{tk} = 0.23 f'^{2/3}_{ck}$ for ordinary concrete

$f_{tk} = 0.7 \times 0.23 f'^{2/3}_{ck}$ for LWAC

NS 3473, Sections 11.1.1 and 11.1.3

The characteristic tensile strength of of concrete may be determined by testing splitting tensile strength for cylindrical specimens at 28 days, according to ISO 4108. For lightweight aggregate concrete the moisture conditions in the specimen at testing shall be given special consideration. Tensile strength shall be tested continuously at least corresponding to testing of compressive strength for class extended inspection.

Design tensile strength for LWAC f_{tn} shall, if not based on testing, be taken as design tensile strength for NWC (specified in a table, Table 5) multiplied by the factor

$$(0.15 + 0.85\rho/\rho_1)$$

where $\rho_1 = 2200$ kg/m^3

If LWA is used also in the fine fractions, the tensile strength reduced according to the formula above shall be reduced by 15%.

2.4 Modulus of elasticity (MC 90, Section 2.1.4.2)

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^3. (Editor's note: transferred to SI units as in ACI 213 R-87, Section 4.6.)

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BBK 94, Section 2.4.4

For lightweight aggregate concrete the values given for normalweight 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 2.

Table 2 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^2	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_{lcm} 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 ρ denotes the upper limit of the oven-dry density in line 2 of Table 3.105 (kg/m^3).

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_{lcm}-values in accordance with ISO 6784.

JSCE, Part 1, Section 3.2.4

Modulus of Elasticity

f'_{ck} (MPa)		18	24	30	40	50	60	70	80
E_c (GPa)	Ordinary concrete	22	25	28	31	33	35	37	38
	LWAC	13	15	16	19	-	-	-	-

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 $(\rho/\rho_1)^2$, where $\rho_1 = 2200$ 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 ρ between 1400 and 2500 kg/m^3.

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Discussion:
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.

2.5 Stress-strain diagrams for structural analysis (MC 90, Section 2.1.4.4)

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 1.

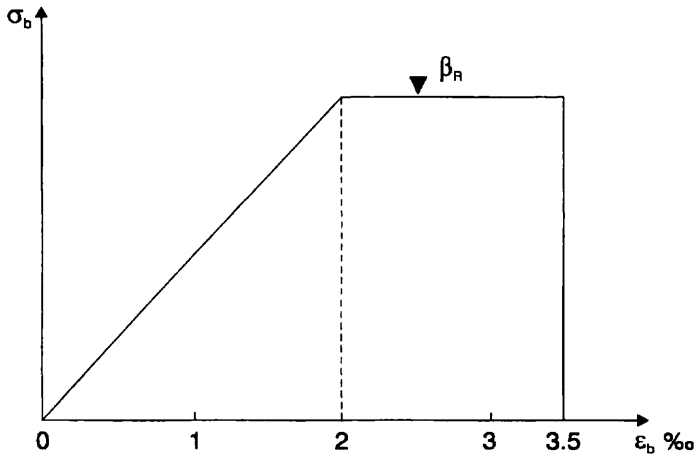


Figure 1 Stress-strain diagram for lightweight aggregate concrete

(Editor's note: β_R is in German termed "Rechenwert" and is supposed to correspond approximately to $0.85f_{ck}$ in MC 90 and in EC 2, where f_{ck} is the characteristic cylinder strength.)

ENV 1992-1-4, Section 4.2.1.3.3 a)
(103) 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 $\in_{1cl}$ at the peak stress f_{1c} (compressive stress σ_{1c} and strain $\in_{1c}$ are both taken as negative).

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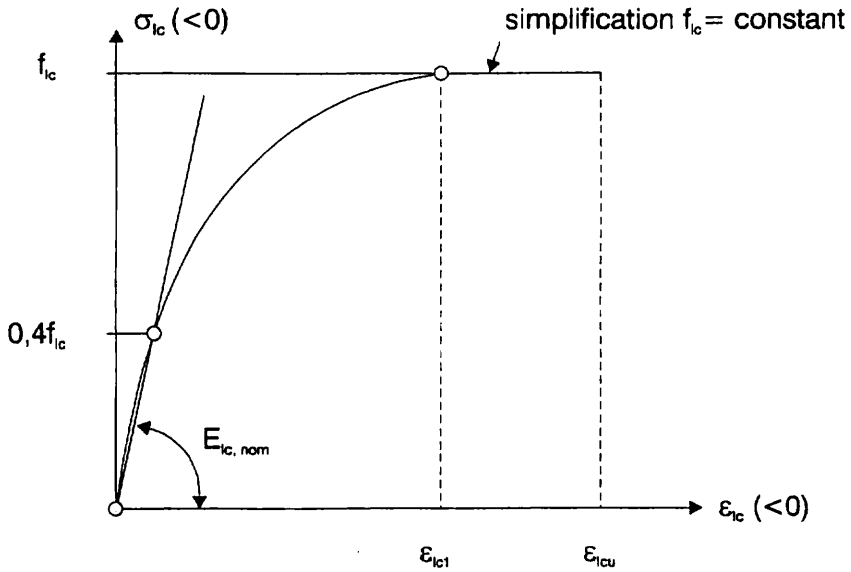


Figure 4.101 Schematic stress-strain diagram of LWAC for structural analysis

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

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

2.6 Thermal expansion (MC 90, Section 2.1.8.3)

ACI 213 R-87, Section 4.17
Approximate values are 7 to 11×10^{-6} mm/mm/°C depending on the amount of natural sand used.
Ranges for normal weight aggregates are 9 to 13×10^{-6} mm/mm/°C for siliceous aggregates and 6 to 9×10^{-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 8×10^{-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.

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2.7 Creep and shrinkage (MC 90, Section 2.1.6.4)

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

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

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

where k_2 is the factor in 2.4.

For values of f'_{ck} between 15 and 25 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

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

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

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

For normal density concrete values of shrinkage are also multiplied by a factor k_t depending on the age of the concrete. For LWAC the factor k_t shall be

$$k_t = t/(t + h_m)$$

where
$h_m = 2A_b/O_b$ (mm)
A_b = cross section of the member and
O_b = perimeter of the member in contact with the atmosphere
t = age of the concrete (days) at the moment considered

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 final values of the creep coefficient shall be reduced by the factor k defined by:

LB 8 to LB 15: $k = 1.3\ E_{lb}/E_b$

LB 25 to LB 55: $k = 1.0\ E_{lb}/E_b$

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

LB 8 to LB 15: k = 1.5

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

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

The creep strain so derived and the basic shrinkage strains should be multiplied by the factors η_3 and η_4 respectively given in Table 3.107.

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Table 3.107 - Factors for the evaluation of the creep coefficient and shrinkage strain

Concrete strength class	Factors for	
	Creep η_3	Shrinkage η_4
LC 12/15, LC 16/20	1.3	1.5
LC 20/25 to LC 50/60	1.0	1.2

JSCE, Part 1, Section 3.2.8

The Creep coefficient is shown in the Table below.

		Age when introduction of prestressing or loading				
		4-7 days	14 days	28 days	3 months	1 year
Outdoor	Ordinary concrete	2.7	1.7	1.4	1.3	1.1
	LWAC	2.0	1.3	1.1	1.0	0.8
Indoor	Ordinary concrete	2.4	1.7	1.5	1.3	1.1
	LWAC	1.8	1.3	1.1	1.0	0.8

NS 3473, Section 9.3.2

For lightweight aggregate concrete the creep coefficient ϕ can be assumed equal to the value of normal concrete multiplied by a factor $(\rho/\rho_1)^{2.0}$ for $\rho \geq 1800$ kg/m^3. For $\rho \leq 1500$ kg/m^3, a factor 1.3 $(\rho/\rho_1)^{2.0}$ can be used. For intermediate values of ρ linear interpolation may be applied (ρ_1 =2200 kg/m^3)

2.8 Fatigue (MC 90, Section 2.1.7)

JSCE, Part 1, Section 3.2.2

$$f_{rd} = k_1 f_d \left(1 - \frac{\sigma_p}{f_d}\right)\left(1 - \frac{\log N}{K}\right)$$

where $K = 10$ for LWAC

$K = 17$ for ordinary concrete

σ_p: stress due to permanent loads

f_d: design strength

$k_1 = 0.85$ for compression and flexural compression

$k_1 = 1.0$ for tension and flexural tension

3. General models

3.1 Local compression (MC 90, Section 3.3)

JSCE, Part 1, Section 3.2.4

d) Bearing strength:

$f'_{ak} = \eta f'_{ck}$ for ordinary concrete

$f'_{ak} = 0.7 \times \eta f'_{ck}$ for LWAC

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where $\eta = \sqrt{A/A_a} \leq 2$

A : concrete area of distributed bearing stress

A_a : concrete area where bearing stress acts directly

NS3473, Section 12.9.3

The capacity formula is substituted by

$F_{cd}=A_1 f_{cd} (A_2/A_1)^{1/2} \leq 3 A_1 f_{cd}$ for NDC

$F_{cd}=A_1 f_{cd} (A_2/A_1)^{1/3} \leq 2 A_1 f_{cd}$ 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 σ_1 the following relation holds

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

3.2 Confinement (MC 90, Section 3.5)

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.

4. Data for prestressing

4.1 Transfer of load from the tendon-anchorage assembly (MC 90, Section 4.7.2)

CUR 39, Part 1, Section 9.13.2:

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

5. Structural analyses

CUR 39 gives detailed rules, related to NEN 6720.

6. Verification of the ultimate limit states

6.1 Stress-strain diagrams for cross-section design (MC 90, Section 6.2.2.2)

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

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weight and lightweight aggregate concrete. In a similar manner, certain of the basic coefficients can be shown to apply to both lightweight and normalweight 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 lightweight aggregate concrete 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 + 0,7ρ/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 (see below). The standard parabolic-rectangular diagram may also be used provided that the maximum value is reduced by 5 %.

ENV 1992-1-4, Section 4.2.1.3.3 b)
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.

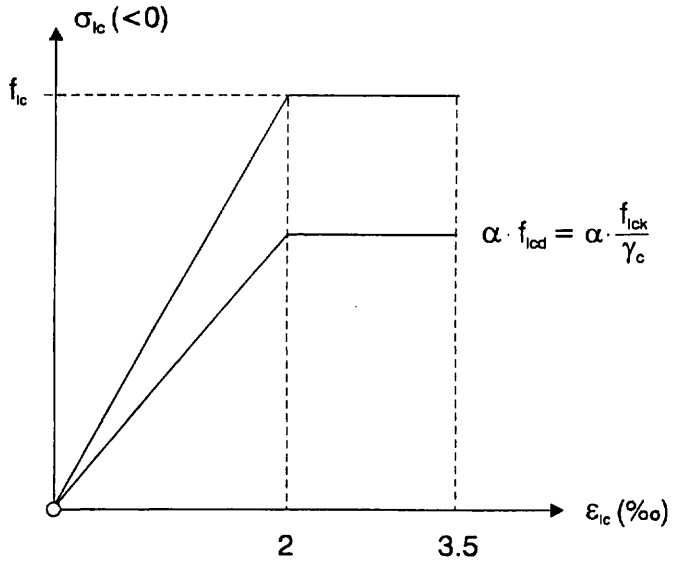


Figure 7.3 - Bi-linear stress-strain diagram for the design of cross sections made with LWAC

The design concrete strength is defined by

$$f_{lcd} = f_{lck}/\gamma_c$$

The design diagram is derived from the chosen idealised diagram by a reduction of the stress ordinate of the idealised diagram by a factor α/γ_c, in which

γ_c is the partial coefficient for concrete (see 2.3.3.2 in ENV 1992-1-1)

α is a coefficient taking account of long-term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied

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The additional reduction factor α 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: α is for NC taken = 0.85 for the parabolic-rectangular diagram, remaining details omitted.)

JSCE, Part 1, Section 3.2.3

The stress-strain curve may be assumed the same as for ordinary concrete. However, the real stress-strain curve is different to some extent, such as more linear up to the peak stress, less initial stiffness, and greater decrease in stress after the peak stress.

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 C 85 and for all grades of lightweight aggregate concrete the values of E_{cn} and ϵ_{co} shall be determined by testing of the actual type of concrete.

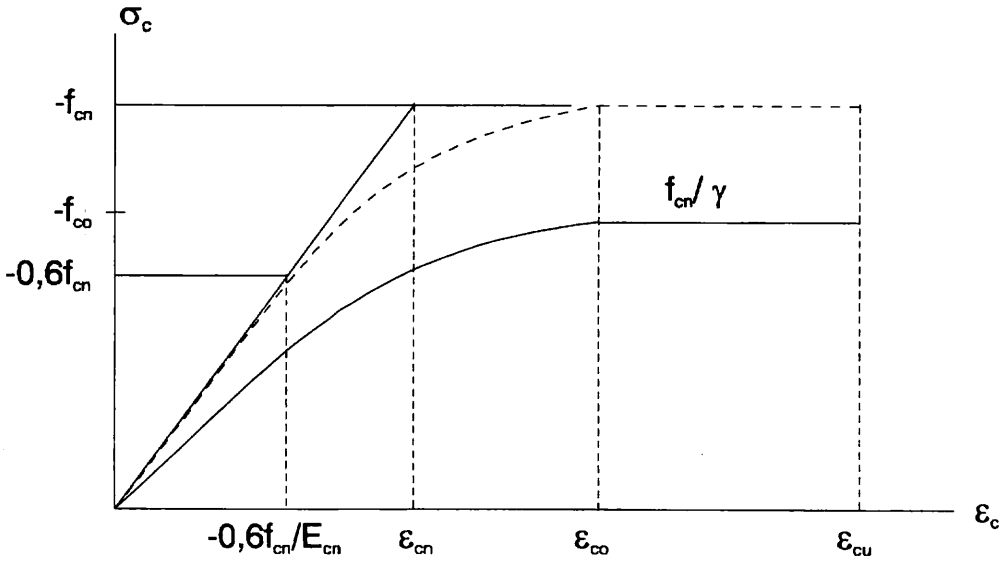


Figure 2 General stress-strain diagram for concrete in compression, to be used for capacity calculations

For lightweight aggregate concrete of grades LC 15 to LC 45, a bilinear stress-strain diagram may be assumed, having a proportionality limit $\epsilon_{co} = -2‰$ and the strain limit

$$\epsilon_{cu} = \epsilon_1\ (0.15 + 0.85\ \rho/\rho_1)$$

where $\epsilon_1 = -3.5‰$ and $\rho_1 = 2200\ kg/m^3$

(Editor's note: LC numbers refer to cube strengths. f_{cn} is a concrete compressive strength that has been reduced as compared with the test compressive strength, so as to represent the strength in the structure. The diagram is identical to the diagram in ENV 1992-1-4, Fig 4.102, reproduced above, except that ϵ_{cu} is a function of density.)

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Discussion:
Similar diagrams are found also in other standards. 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 diagrams specified for LWAC in these documents 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 LC 12 to LC 74 (referred to cylinders) is given. However, for all grades of LWAC the parameters in the diagram shall be determined by testing.

6.2 Shear strength (MC 90, Section 6.3.3)

ACI 318-95, 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 $\sqrt{f'_c}$.

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 $0.63\sqrt{f_{cu}}$ or 4 N/mm^2.

Table 5.3 Values of v_c, design shear stress for grade 20 LWAC

$100\ A_s/bd$	$v_c\ N/mm^2$
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

A_s area of tension steel
b width or effective width of the section or flange in the compression zone
d effective depth of the tension reinforcement

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CUR 39, Part I, Section 8.2

The formula for τ_2 (largest allowable shear stress) shall be replaced by

$$\tau_2 = 0.2k_1 f'_h k_n k_\theta \leq 6.0\, k_\theta \text{ N/mm}^2$$

(Editor's note: k_1 is a factor defined in Section 2.3 in the present document.)

For shear force to be taken by reinforcement the angle θ shall not be smaller than $30° / k_1$.

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

The upper limit for the concrete shear strength of slabs 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.) The shear reinforcement is increased by 15% compared with normalweight concrete for strut inclination smaller than 45°. The minimum shear reinforcement is increased by 25 %. The design value for the minimum stirrup cross section is increased by 20 %.

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 τ_{Rd} should be taken as

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

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

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

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

$$\nu = 0.6 - f_{lck}/235 \geq 0.425 \quad (f_{lck} \text{ in N/mm}^2)$$

(Editor's note: Equation (4.20) in ENV 1992-1-1 reads:
$\nu = 0.7 - f_{lck}/200 \geq 0.5$ (f_{lck} in N/mm^2).)

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

JSCE, Part 1, Section 6.3.3, Commentary

Shear strength of linear member (beam and column)

$$V_{yd} = V_{cd} + V_{sd} + V_{ped}$$

where V : Design shear strength of linear member without shear reinforcement. In case of LWAC the value is reduced to 70%.

V_{sd} : Design shear strength carried by shear reinforcement

V_{ped} : Component of effective prestressing force in direction parallel to shear force

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NS 3473, Section 12.3.2
The shear tensile strength is a function of the tensile strength, which is reduced by the factor $(0,15+0,85\ \rho/\rho_1)$ for LWAC, see NS 3473 Section 11.1.1 quoted under Section 2.3 above.

NS 3473, Section 12.3.3
Design compressive strength in a compression field may in a simplified method be taken equal to 0.5 f_{cd} for lightweight aggregate concrete, where f_{cd} is the ordinary design concrete compressive strength.

(Editor's note: The case refers to compression with tensile strains in the normal direction. The corresponding reduction factor for normalweight concrete is 0.6.)

Discussion:
The common approach in the rules quoted is that the design method 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 normal density concrete by the corresponding strength of LWAC (ENV 1992-1-4).

6.3 Punching (MC 90, Section 6.4.3)

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, τ_{Rd} should be calculated according to 4.3.2.3 (104) of this Part 1-4.

6.4 Torsion (MC 90, Section 6.3.5)

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.

6.5 Slender columns (MC 90, Section 6.6.3)

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.

DIN 4219 T2, Sections 7.6 and 10
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.

The limiting span to effective depth ratio is factored by 0.9 relative to normal density concrete.

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6.6 Anchorage bond and laps (MC 90, Section 6.9)

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:
λ = lightweight aggregate concrete factor:
When lightweight aggregate concrete is used 1.3
However, when f_{ct} is specified, λ 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_l shall be multiplied by the factor k_8 , defined by $k_8 = 1/k_1$, where k_1 is defined in Section 2.3 in the present report.

For curved bars loaded in tension, the value 150 given for anchorage length l_c shall be increased to 300.

For prestressing steel the values of the anchorage length a_l 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 $10\varnothing_k$, the lap length shall be further multiplied by k_8.

If the centre to centre distance is larger than $10\varnothing_k$, the lap length shall be increased in the same manner as the anchorage length (by a factor k_8). Smaller distances require 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 $l_{bp} = \beta_b \phi/\eta_1$, where η_1 is a reduction factor for tensile strength of LWAC, see Section 2.3 in the present report.

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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 η_1 in which η_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 ϕ 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 $\phi > 132$ mm, values f_{bd} in Table 5.3 of ENV 1992-1-1 should be multiplied by
$\eta_1 * (132 - \phi)/100$ (ϕ in mm)

JSCE, Part 1, Section 3.2.4
c) Bond strength:
$f_{bok} = 0.28 f_{ck}'^{2/3} \leq 4.2$ MPa for ordinary concrete
$f_{bok} = 0.7 \times 0.28 f_{ck}'^{2/3} \leq 0.7 \times 4.2$ MPa for LWAC

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 $(0{,}15+0{,}85\ \rho/\rho_1)$ (see Section 2.3 in the present document).

Discussion:
The articles 4.2.3.5.6 and 5.2.2.2 in ENV 1992-1-4 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 η_1 expresses the ratio of decrease of tensile strength.

The rule in ENV 1992-1-4 Section 5.2.6.2 is given in spite that ENV 1992-1-4 in Section 5.1 (106) recommends that the diameter of bars embedded in lightweight concrete should not normally exceed 32 mm (see Section 9.1 in the present document).

7. Verification of serviceability limit states

7.1 Cracking (MC 90, Section 7.4)

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^2 be adopted.

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7.2 Deformation (MC 90, Section 7.5)

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^2, 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_i/h shall be reduced by 10%.

The code requires that deformations be 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^3 the values (Editor's note: for minimum thickness) shall be multiplied by $(1.65 - 0.0003\rho)$ where ρ is the density in kg/m^3.

Discussion:
Corrections of this sort are needed in national standards when span/effective depth ratios are given.

8. Durability

8.1 Requirements for special exposure conditions

ACI 318M-95, Section 4.2.2
Concrete that will be subject to the exposures given in Table 4.2.2 shall conform to the corresponding maximum water-cementitious materials ratios and minimum specified concrete compressive strength requirements of that table. In addition, concrete that will be exposed to deicing chemicals shall conform to the limitations of 4.2.3.

(Editor's note: Section 4.2.3 not quoted here).

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Table 4.2.2 Requirements for Special Exposure Conditions

Exposure condition	Maximum water-cementitious materials ratio by mass, normal density aggregate concrete	Minimum f_c', normal density and low density aggregate concrete, MPa
Concrete intended to have low permeability when exposed to water	0.50	28
Concete exposed to freezing and thawing in a moist condition or to deicing chemicals	0.45	31
For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals,salt, salt water, brackish water, seawater, or spray from these sources	0.40	35

8.2 Cover thickness (MC 90, Section 8.4.3)

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.
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.

CUR-Recommendation 39, Part I, Section 9.2

The cover shall be increased by 5 mm for surfaces that are not cast towards formwork.
Note: The increase may be omitted if the production method gives a tight and even surface.

DIN 4219 T. 2, Section 4

Instead of Tables 9 and 10 in DIN 1045, Edition December 1978, Table 1 is valid.

(Editor's note: The cover was higher for LWAC than for normalweight concrete when the standard was published in 1979. The LWAC standard has not been modified since then, whereas the cover was increased in the last version of the normalweight standard (DIN 1045) and is now sometimes higher than for LWAC.)

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Table 1 Minimum cover thickness in cm

1	2	3	4	5	6	7
Exposure	Type of member	Bar	Largest grain diameter, mm			Cover for
DIN 1045:1978 Table 10		diameter[4] d_s or d_{sv} mm	= 8	>8 =16	>16 =25	LB8-15 not less than[3]
	General	=18	1.5[1]	2.0	2,5	2.0
	Including prefab	20-22	2.0			
1	Plates and shells	=14	1.5[1]	1.5[1]		1.5[1]
		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[1]	2.0	2.5	2.0
	Prefab LB35-LB55	20 and 22	2.0			
3[2]	General	=22	2.5		3.0	
	Plates and shells Prefab LB35-LB55	=22	2.0		2.5	
4[2]	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_s = 25 mm
4.0 cm for d_s = 28 mm
1.5 d_{sv} for bundles with equivalent diameter $d_{sv} \geq 25$ mm.

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.

JSCE, Part 2, Commentary for Sec 20.2

Durability against severe weather Standard test (JIS: Japanese Industrial Standards) for durability of aggregate under severe weather, such as freezing and thawing, is not required because this test uses sulphate sodium. JIS's freezing and thawing test for concrete is only required.

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(Editor's note: The quotations indicate a tendency to require increased cover for LWAC. However, a number of standards, including North-American, allow lightweight aggregates without requiring any additional cover.)

9. Detailing

9.1 Maximum bar diameters (MC 90, Section 9.1.4)

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).

9.2 Permissible radii of bends (MC 90, Section 9.1.1.2)

CUR-Recommendation 39, Part I, Section 9.5
The minimum radius of bends shall be increased from 2.5 $Ø_k$ to 5 $Ø_k$.
If the lateral cover of the bar is less than 3 $Ø_k$ the minimum bending radius shall, for bars with a diameter equal to or larger than 16 mm, be increased to 10 $Ø_k$.
The minimum radius of bend of prestressing steel of 15 $Ø_k$, respectively 20 $Ø_k$, shall be increased to 30 $Ø_k$.

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 16.7
a. Bend shapes and dimensions of reinforcement bars at end and intermediate portions shall be in accordance with 11.2.d. For lightweight concrete with a specified design strength of more than 27 N/mm^2, free ends of reinforcement shall be bent at an angle of more than 135° and shall have an extra length of more than 8d.
b. Length of development and lap splices shall be in accordance with 11.8.b or 11.9.b. For lightweight aggregate concrete with specified design strength of 270 kgf/cm^2, the values corresponding to normal concrete with a specified design strength of 240 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%.

9.3 Bundled bars (MC 90, Section 9.1.5)

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 $\phi \leq$ |20| mm.

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NS 3473, Section 12.8.2.
There are no special restrictions on bundles for LWAC.

9.4 Post-tensioned bars, tensile splitting reinforcement (MC 90, Section 9.1.6)

CUR-Recommendation 39, Part I, Section 9.11.9
Detailed rules are given concerning the area of reinforcement bars in combination with post-tensioned bars.

10. Limit Measures

No information available.

11. Practical construction

No information available.

12. Quality assurance and quality control

12.1 Control of materials (MC 90, Section 12.2.4)

NB 22, Section 1.5.2

This specification defines the producer's declaration of the LWA, acceptance control and testing of the aggregate before and during concrete production.

If not stated else in the project specification, the types of tests and minimum frequency are given in Table 1. The alternative giving the highest frequency shall be applied.

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Table 1 Testing frequency and extent for LWA by declaration, acceptance and concrete production

Control (responsible)	Specified tests	Minimum testing frequency	Minimum testing extent	Reference [1]
Declaration (LWA manufacturer)	- bulk density - particle density - crushing resistance - particle size distribution - content of crushed particles - content of fines - water absorption - chloride content - total sulphur content	- first production with raw materials from a new source - first production after any major change of the production conditions - every 10.000 m^3 produced LWA - twice a year	set of five parallel tests, each including two specimens	1.5.3 1.5.4 1.5.5 1.5.6 1.5.7 1.5.9 1.5.10
	- loss of ignition - frost resistance	- first production with raw materials from a new source - first production after any major change of the production conditions	set of five parallel tests, each including two specimens	1.5.10
Production control (LWA manufacturer)	- moisture content - bulk density - particle size distribution - content of fines - particle density - absorption	- periodically once a day - periodically every 500 m^3 LWA	two parallel samples	1.5.3 1.5.4 1.5.5 1.5.7 1.5.8 1.5.9
Acceptance control (contractor)	- bulk density - particle density - particle size distribution - moisture content - water absorption	- every delivery - periodically every 1000 m^3 LWA	three parallel samples	1.5.3 1.5.4 1.5.5 1.5.8 1.5.9
Control prior to and during concrete production [2] (concrete producer / contractor)	- moisture content	- periodically once a day - periodically every 300 m^3 LWAC	three parallel samples	1.5.8 1.6.6

[1] Reference to the relevant paragraphs in NB 22

[2] Note that the control shall be performed so early in the interval that mix design modifications are possible to implement if necessary

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JASS 5, Section 16.8

a. Test and inspection for lightweight aggregate concrete shall be in accordance with Section 13.3.
b. Quality control and inspection for lightweight aggregate concrete with specified design strength less than 27 N/mm^2 shall be in accordance with Section 13.4.
c. Quality control and inspection for lightweight aggregate concrete with specified design strength more than 27 N/mm^2 shall be as specified in the Special Provisions. Unless otherwise specified, quality control and inspection shall be in accordance with Section 13.4.
d. 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 (16.2) below from the design mix proportions. The tolerance between W_w and the actual unit weight shall be ±3.5%.

$$W_w = G_0(1+p_G/100)+S_0(1+p_S/100)+S'_0(1+p'_S/100)+C_0+W_0 \quad (kg/m^3) \qquad (16.2)$$

where

W_w = calculated unit weight of the fresh concrete based on designed mix proportions (kg/m^3)
G_0 = lightweight coarse aggregate content in designed mix proportions, oven-dry (kg/m^3)
S_0 = lightweight fine aggregate content in designed mix proportions, oven-dry (kg/m^3)
S'_0 = normal weight fine aggregate content in designed mix proportions, oven-dry (kg/m^3)
C_0 = unit cement content in designed mix proportions, oven-dry (kg/m^3)
W_0 = unit water content in designed mix proportions (kg/m^3)
p_G = 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 (%)

NB 22, Section 1.6.2

If LWA is used, adequate strength potential shall always be documented. (Editor's note: See Section 1.2 in the present report.)

If *non-absorbing* LWA is used, sampling of specimens and compliance control shall be performed as for NDC. If *absorbing* aggregates are used, the need for additionally re-mixing and the need for testing the demoulding density shall be determined.

The compliance control shall be based on specimens cast at delivery.

Minimum testing frequency and extent are given in Table 2. The testing frequency alternative giving the most frequent testing shall be preferred.

(Editor's note: Definitions of *absorbing* and *non-absorbing* in NB 22 are:

Absorbing LWA: LWA absorbing more than 1 weight % water during one hour immersion in pure water.

Non-absorbing LWA: LWA absorbing less than 1 weight % water during one hour immersion in pure water.)

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Table 2 Testing frequency and extent for LWAC

Control	Specified tests	Minimum testing frequency	Minimum testing extent	References[1)]
initial documentation [2)]	by applying absorbing LWA: demand for re-mixing	at any major changes of the mix proportions, mixing equipment or transport system, production conditions or equipment	two parallel tests (before and after remixing), each including compressive strength and demoulding density of three specimens tested at 7 and 28 days	1.6.3
	- compressive strength potential - The ratio f_{cck}/f_{ck} [3)] - Density	every new concrete mix design	five parallel specimens of each type tested after 28 days and, if necessary, after 90 days	1.6.4 1.6.5
Production control, hardened concrete	- demoulding density - f_c or f_{cc} [3)]	- once every shift - periodically every 100 m^3 produced concrete - if visual control indicates irregularities	- three specimens (cubes) tested after 7 and 28 days - for every 20th test, additionally three cylinders tested for strength at 28 days	1.6.4 1.6.5

1) References to the relevant chapter in NB 22

2) Initial testing shall be performed on a test production representing at least 5 m^3 concrete (for instance single batches mixed in an auto-mixer)

3) For LWAC, NS 3473 requires that the strength requirement shall be fulfilled for cylinders. However, it opens for a running production control based on cubes provided the ratio f_{cc}/f_c is established. PrEN 206-1 § 4.3.1 has similar requirements, but allows that the ratios f_{cc}/f_c in Table 8 of the standard are applied if the ratio is not established by testing.

12.2 Control of execution (MC 90, Section 12.2.5) (see also 13.6 Inspection)

NB 22, Section 1.6.2

If *non-absorbing* LWA is used, sampling of specimens and compliance control shall be performed as for NDC. If *absorbing* aggregates are used, the need for additionally re-mixing and the need for testing the demoulding density shall be determined.

(Editor's note: *non-absorbing* and *absorbing aggregates* defined in NB 22 as quoted in reference to Section 1.6.2 under Section 12.1 above).

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NB 22, Section 1.6.3

If *absorbing aggregates* are used, it shall be documented that the mix water absorption and subsequent air evacuation from the LWA in fresh concrete does not have any significant negative impact on the concrete quality. The documentation shall be based on the following:

The compressive strength, determined in accordance with ISO 4012, of specimens cast and transported using the current mixing and transportation system, shall not be significantly lower than the compressive strength of specimens cast of the same batch after a one minutes re-mixing performed 60 minutes after the mix water addition.

NB 22, Section 1.6.6

The requirements given in the standards for maximum water-binder ratios in relation to exposure classes are also valid for LWAC.

The water-binder ratio shall be based on the effective water content of the mix. The effective water content is: Total water content (incl. possible surface water of the aggregates) minus the water absorbed in the aggregates at the time of setting. The water absorbed in the aggregates at the time of setting w_{abs}, shall be determined as :

$$w_{abs} = 1.0 * w_{1hm} \quad (1)$$

where: w_{1hm} is determined according to prEN 1097-6:1997 appendix "C" with the following modifications:

- The initial moisture content and condition shall be the same as for the LWA actually used in the concrete production
- w_{1hm} is measured after one hour immersion

If LWA with particle size < 2 mm is applied, the test and calculation procedure has to be given in the project specification.

NB 22, Section 1.6.7

When air entrainment of the concrete is required, the air content shall be measured according to ASTM C-173 "Air content of freshly mixed concrete by the volumetric method". If NS 3659 (the pressure method) is applied in the running production control, the relationship between these two methods shall be established and documented for the actual concrete composition.

pr EN 206-1, Section 5.4.2

The water absorption of coarse lightweight aggregate in the fresh concrete shall be taken as the value obtained at 1 hour based on the method given in Annex C of prEN 1097-6:1997 using the as-used initial moisture state instead of the oven-dry state.
Note: For fine lightweight aggregate, the test method and criteria should follow the provisions valid in the place of use of the concrete.

(Editor's note: The same requirements for water/cement ratios to ensure durability applies for light-weight concrete as for heavy-weight and normal-weight concretes)

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prEN 206-1, Section 5.4.3
Where the air content of the concrete is to be determined, it shall be measured in accordance with prEN 12350-7 for normal-weight and heavy-weight concrete and in accordance with ASTM C-173 for light-weight concrete.

prEN 206-1, Section 8.1
In the case of lightweight concrete produced with unsaturated aggregates, the samples shall be taken at the place of delivery.

13. Concrete technology (MC 90, Appendix D)

13.1 General (MC 90, Section d.1)

prEN 206-1, Section 1
Editor's note: The standard states in the scope that "...This standard applies to normal-weight, heavy-weight and light-weight concrete". This statement blocks the CEN members to establish or keep national standards in parallel with EN 206-1 on lightweight concrete.

JASS 5, Section 16.1
b. 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.

13.2 Definitions (MC 90, Section d.3)

The following definitions of *lightweight aggregates* are used in international and national codes and standards:

DIN 4226-T.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 7549.1 (Italy): This standard deals only with expanded clay and shale having a loose bulk density of not more than 1000 kg/m^3.
BS 3797 (UK): Aggregate having a loose bulk density of 400 to 1200 kg/m^3 for fine aggregate or 250 to 1000 kg/m^3 for coarse aggregate.
NEN 3543 (The Netherlands): This standard concerns lightweight aggregates, manufactured (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^3 or less.
PN-86/B-23006 (Poland): Subject of this standard are lightweight aggregates, mineral by PN-78/B-01100 and manufactured of mineral origin by PN-79/B-01100 of volume density to 1800 g/dm^3, intended for lightweight aggregate concrete of volumetric density not greater than 1800 kg/m^3.
ACI 318-95, Section 2.1 (USA): Aggregate with a dry, loose weight of 1120 kg/m^3 or less.
prEN 13055 - 1: Aggregate of mineral origin having a particle density not exceeding 2,00 Mg/m^3 (2000 kg/m3) or a loose bulk density not exceeding 1,20 Mg/m^3 (1200 kg/m^3)

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prEN 206-1: Aggregate of mineral origin having a particle density not exceeding 2000 kg/m3 when determined according to prEN 1097-6 or a loose bulk density not exceeding 1200 kg/m^3 when determined according to prEN 1097-3.

The following definitions of *lightweight aggregate concrete* are used in international and national codes and standards:

UNI 7548.1 (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 aggregate concrete is characterised by the fact that its density is not greater than 1850 kg/m^3.
PN-91/B-06263 (Poland): Concrete of volumetric density in dry state not bigger than 2000 kg/m^3, 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/m3 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 ACI 318-95 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^3. 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 kg/m^3 consisting of or containing a proportion of manufactured or natural lightweight aggregates having a particle density of less than 2000 kg/m^3.
prEN 206-1: Concrete having an oven-dry density of not less than 800 kg/m^3 and not more than 2000 kg/m^3. It is produced using lightweight aggregate for all or part of the total aggregate.

13.3 Aggregates (MC 90, Section d. 4.3)

ACI 213R - 87
Section 3.7 - Pumping structural lightweight concrete

(Editor's note: The section contains detailed rules for pumping of LWAC. The guide is under revision and is hence not quoted.)

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

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JASS 5, Section 16.3

a. Manufactured lightweight aggregates shall confirm 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). When the specified design strength is more than 27 N/mm^2, the manufactured lightweight aggregate shall be of such a quality that the design strength of concrete of mixture A in accordance with the above notification at the age of 28 days (standard water curing) is not less than 42 N/mm^2.

b. The maximum size of the manufactured lightweight aggregate shall be as specified in the Special Provisions. Unless otherwise specified, the maximum size is 15 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 ±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.

NB 22, Section 1.5.1

The requirements for LWA are given in prEN 13055-1 with the alterations and additions stated in this specification.

This specification is valid for LWA of mineral origin with dry bulk density less than 1200 kg/m^3 or with dry particle density not exceeding 2000 kg/m^3. The definition includes:

1. LWA manufactured from natural materials and/or industrial by-products
2. Natural materials
3. Industrial by-products
4. Re-cycled materials

LWA shall not contain substances in quantities and forms, which adversely effect suitability of the LWA for the intended use or cause corrosion of the reinforcement.

Different or additional requirements might be necessary for some particular types of LWA. This includes also recycled LWA.

NB 22, Section 1.5.3

Loose bulk density for all fractions shall be declared at production by the manufacturer and determined in accordance with prEN 1097-3. Mean bulk density shall be in the range of ± 15 %, with a maximum of ± 100 kg/m^3 of the manufacturer's declared value.

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NB 22, Section 1.5.4
The LWA shall have uniform strength properties. Dry particle density shall be determined according to prEN 1097-6 and be declared by the manufacturer for each fraction put on the market. Individual values shall not vary by more than ±10 % nor shall the mean value vary by more than ± 75 kg/m^3 of the manufacturer's declared value.

NB 22, Section 1.5.5
The particle size distribution shall be determined in accordance with prEN 933-1 and be declared by the manufacturer. The particle distribution within a specified fraction shall be smooth and shall not contain more than 15 % undersize or 10 % oversize (of total weight).

The sieve which 100 % material passes shall be specified.

If specified, the particle size distribution of aggregates containing LWA shall be given on a volume basis based on each fraction's grading according to prEN 933-1 and particle density according to prEN 1097-6. The particle density within each aggregate fraction may be considered constant.

NB 22, Section 1.5.6
The manufacturer shall declare the content of crushed particles within each fraction, given as % of total weight.

NB 22, Section 1.5.7
The content of fines (particles < 0.063 mm) in coarse LWA (> 4 mm) shall be declared by the manufacturer and not vary by more than ± 2 % (of total weight).

For fine LWA (1- 4 mm), the content of fines (particles < 0.063 mm) shall be declared by the manufacturer, and not vary by more than ± 5 % (of total weight).

NB 22, Section 1.5.8
Moisture content of the LWA shall be calculated as mass percent moisture relative to the dry mass according to prEN 1097-5.

NB 22, Section 1.5.9
At declaration, the sorptivity of dry aggregates shall be determined by the manufacturer in accordance with SINTEF's test procedure KS70 119, equivalent to a one hour absorption in prEN 1097-6. The method gives the water absorption of aggregates first dried at 105 °C to constant mass, cooled and then immersed in water for 1 hour. The absorption shall also, within the same test routines, be recorded after 24 hours and one week. The mean value at delivery for particles > 4 mm with dry particle density higher than 1000 kg/m^3, shall not vary by more than ± 20 % of the declared value.

Before batching the aggregate, the absorption properties of the LWA shall be determined by a similar procedure as above, but the LWA shall have the same moisture condition as for the LWA added to the concrete mixer (i.e. surface dry, or moist surface, or dry core or moist core).

(Editor's note: There is no guidance in the document for how to document water absorption in LWA < 2 mm.)

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NB 22, Section 1.5.10

Chloride content shall be determined in accordance with prEN 1744-1.

Total Sulphate content shall be determined in accordance with prEN 1744-1. The mean value shall, when corrected for density, not exceed 1 % SO_3.

$$Corrected\ value = Measured\ value \frac{dry\ loose\ bulk\ density}{1500}$$

Total sulphur content shall be determined in accordance with prEN 1744-1. The mean value shall, when corrected for density, not exceed 2.0 % S. LWA with higher total sulphur content may be accepted if long time experience can document that the particular LWA causes no detrimental reactions in concrete.

Potential alkali-reactivity: The LWA and LWAC shall as for ordinary aggregates and concrete comply with NB Publication no 21

Loss of ignition shall, when required, be determined in accordance with prEN 1744-1.

pr EN 13055-1, Section 4

Requirements are specified for the documentation of:

- Loose bulk density
- Particle density
- Particle geometry
- Aggregate size
- Particle size distribution
- Fines
- Water absorption
- Crushing resistance
- Resistance to disintegration
- Loss on ignition
- Chemical substances like chlorides and humus

Requirements are specified for:

- Maximum contents of sulphates and total sulphur
- Testing
- Factory production control
- Designation, delivery, supply and labelling

pr EN 206-1, Section 5.1.3

General suitability is established for normal- and heavyweight aggregates conforming to prEN 12620 and lightweight aggregates conforming to prEN 13055-1

13.4 Specification and production (MC 90, Sections d. 8-d. 9)

JASS 5, Section 16.4

a. An air-entraining agent, an air-entraining and water-reducing agent or an air-entraining and high-range water reducing agent, in accordance with 4.5 shall be used for lightweight aggregate concrete.

b. The standard air content shall be 5%.

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c. When concrete pump is used, unit cement content and sand aggregate ratio shall be adjusted properly so as to prevent the coarse aggregate particles from rising to the surface, slump loss by pumping and blockage of the pipelines.

d. 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.

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

where

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

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

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

C_0 = unit cement content in designed mix proportions, oven-dry (kg/m^3)

JASS 5, Section 16.5

a. The ready-mixed concrete plant shall, in principle, be a JIS accredited plant for lightweight aggregate concrete, intended to be purchased.

b. 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.

c. The lightweight aggregate presoaked shall be used so as to prevent slump loss during delivery by a truck agitator and to decrease the water absorption into aggregate by pressure at pumping.

JSCE, Part 2, Section 20.5

a) Air-entrained concrete is to be used for LWAC as principle. (Sec 20.5.1 (2) of Part 2 (Construction))

b) Water-cement ratio necessary for ordinary concrete should be reduced by 5% for LWAC when frost damage is considered. (Sec 20.5.2 (2) of Part 2 (Construction))

c) Slump is to be between 5 and 12 cm. (Sec 20.5.3 of Part 2 (Construction))

d) Air for ordinary concrete is to be increased by 1% for LWAC. (Sec 20.5.4 (1) of Part 2 (Construction))

e) Water absorption and surface moisture for both fine and coarse aggregate are preferably indicated in mix proportion. (Commentary for Sec 20.5.5 (2) of Part 2 (Construction))

***NB 22, Section 1.6.3* Demand for remixing**

Editor's note: Demands for remixing are referred to in Sections 12.1 Control of materials and 12.2 Control of execution, see references to Sections 1.6.2 and 1.6.3.

prEN 206-1, Section 9.8

For light-weight concrete batched with unsaturated aggregates, the period from initial mixing to the end of final-mixing (e.g. re-mixing in a truck mixer) shall be prolonged till the water absorption of the aggregates and subsequent evacuation of air from the light-weight aggregates does not have any significant negative impact on the hardened concrete properties.

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13.5 Transportation and placing (MC 90, Section d.10)

prEN 206-1, Section 9.6.1
Knowledge, training and expertise of personnel involved in production and production control shall be appropriate to the type of concrete, e.g. high strength concrete, lightweight concrete.

(Editor's note: The CEN Standard is highlighting the need for special expertise in batching and transporting LWAC by this statement.)

prENV 13670-1, Section 1
The standard states in the scope that:
(5) Additional or different requirements should be considered and, if required, given in the project specifications when using lightweight aggregate concrete.

JASS 5, Section 16.6
a. 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.
b. When placing, appropriate methods and consolidating tools shall be selected to avoid segregation of the aggregates.
c. 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.

JSCE, Part 2, Section 20.7
When a concrete pump is used, LWAC is to be superplasticized concrete.

NB 22, Section 1.6.8
LWAC shall not be placed by pumping unless specimens sampled from production tests with current equipment and production conditions show that the pumping process does not adversely affect the properties of the hardened concrete. Pumping of LWAC is accepted by this specification provided the loss of compressive strength of pumped concrete is not lowered by more than 10 % compared to samples taken from the unpumped concrete. The required characteristic strength shall be achieved also for specimens sampled from the pumped concrete.

prEN 206-1, Section 8.4
(5) Light-weight aggregate concrete shall not be pumped unless it is documented that pumping has no significant effect on strength of the hardened concrete

NB 22, Section 1.6.9
The maximum concrete temperature for LWAC shall not exceed 65 °C, unless it is documented that higher temperatures will not impair the long term quality of the hardened concrete with the same composition and exposed the actual environment.

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13.6 Inspection (MC 90, Section d.18) (see also 12.2 Control of execution)

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 (Editors note: cube strength) $f_{ck} > f_{ck1}(\rho/\rho_1)^{2.0}$ where $f_{ck1} = 55$ N/mm^2 and $\rho_1 = 2200$ kg/m^3.

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

14. References, Source Documents

The following documents have been selected as important source documents. Many of the documents have been quoted in the present State-of-the-Art Report. Abbreviations used for documents referred to are given in italics.

Quotations from German and Swedish documents are unofficial translations into English made in the present project.

CEB/FIP:

- FIP State of Art Report: Lightweight aggregate concrete for marine structures, FIP 1978.
- FIP Manual of Lightweight Aggregate Concrete Surrey University Press, Glasgow and London 1983.
- FIP Working Group on Lightweight Concrete, Final Report (June 1985).
- *CEB-FIP HSC 90.* High Strength Concrete Joint FIP/CEB State-of-the-Art Report CEB Bulletin 197,1990.
- *CEB-FIP HSC/HPC 95.* CEB-FIP Working group on High Strength/High Performance Concrete: Recommended Extensions to the Model Code 90. Research Needs. CEB Bulletin 228, July 1995.

CEN:

- *ENV 1992-1-4.* ENV 1992-1-4:1994 Eurocode 2: Design of concrete structures - Part 1-4: General rules - Lightweight aggregate concrete with closed structure, 1994.
- *prEN 13055-1.* Draft prEN 13055-1 Lightweight aggregates - Part 1: Lightweight Aggregates for Concrete and Mortar. November 1997.
- *prEN 206-1.* prEN 206-1/24 Concrete - Part 1: Specification, performance, production and conformity. April 1999.
- *prENV 13670-1.* prENV 13670-1 Execution of concrete structures- Part 1: Common rules. Final Draft for Voting. May 1999.

Further International:

- *Cembureau.* Lightweight Aggregate Concrete - Technology and World Applications, Cembureau, Paris 1974.

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Germany:

- *DIN 1045.* DIN 1045, Stahlbetonbestimmungen, 1988.
- *DIN 4219 T.1.* DIN 4219, Leichtbeton und Stahlleichtbeton mit geschlossenem Gefüge, 1979. Teil 1, Anforderungen an den Beton, Herstellung und Überwachung.
- *DIN 4219 T. 2.* DIN 4219, Leichtbeton und Stahlleichtbeton mit geschlossenem Gefüge, 1979. Teil 2, Bemessung und Ausführung.
- Deutscher Ausschuss für Stahlbeton, Heft 322, Grundlage für DIN 4219, 1981.
- *DIN 4226 T.1.* DIN 4226, Zuschlag für Beton, 1983. Teil 1 Zuschlag mit dichtem Gefüge; Begriffe, Bezeichnung und Anforderungen.
- *DIN 4226 T.2.* DIN 4226, Zuschlag für Beton, 1983. Teil 2 Zuschlag mit porigem Gefüge (Leichtzuschlag).
- *DIN 4226 T.3.* DIN 4226, Zuschlag für Beton, 1983. Teil 3 Prüfung von Zuschlag mit dichtem oder porigem Gefüge.
- *DIN 4226 T.4.* DIN 4226, Zuschlag für Beton, 1983. Teil 4 Überwachung (Güteüberwachung).
- *DIN 4227 T 4.* DIN 4227 Teil 4, Spannbeton; Bauteile aus Spannleichtbeton, 1986.
- *Beton-Kalender 1988.*

Italy:

- *UNI 7548.1.* UNI 7548 - Part 1 Lightweight concrete by expanded clay or shale. Definitions and classification.
- *UNI 7549.1.* UNI 7549 - Part 1 Lightweight Aggregates - Definitions, classification and grading.

Japan:

- *JASS 5.* JASS 5 Reinforced Concrete Work 1997. (JASS: Japan Architectural Standard Specification).
- Section 16 Lightweight Concrete, 1997. Unofficial English translation.
- *JSCE* Chapter 19. Chapter 19 Lightweight Aggregate Concrete 1986. (JSCE: Japan Society of Civil Engineers). Revised 1996, English translation pending.
- *JIS A 5002.* Lightweight Aggregates for Structural Concrete, 1978. (Under revision. New version expected 1999). (JIS: Japanese Industrial Standard).
- *JSCE* JSCE Japan Society of Civil Engineers. Standard Specification for Concrete Structures, Part 1 Design and Part 2 Construction, 1996. (In Japanese only. English version of the 1986 edition exists).

The Netherlands:

- *NEN 3543.* NEN 3543 Grove lichte toeslagmaterialen voor lichtbeton, 1982.
- *NEN 6720.* NEN 6720 Technische grondslagen voor bouwconstructies. TGB 1990 - Voorschriften Beton: Constructieve eisen en rekenmethoden (VBC 1995) (Regulations for concrete. Structural requirements and calculation methods).
- *CUR 39.* CUR Aanbeveling 39. Beton met grove lichte toeslagmaterialen. Redactionele bijlage bij Cement 1994 nr. 7/8.

New Zealand:

- *NZS 3101.* NZS 3101: 1995 Concrete Structures Standard.
  Part 1 - The Design of Concrete Structures.
  Part 2 - Commentary on The Design of Concrete Structures.

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Norway:
- *NS 3420.* NS 3420 Specification texts for building and construction, 2nd edition 1992 (in Norwegian).
- *NS 3473.* NS 3473 Concrete structures. Design Rules, 5th edition 1998.
- *NB 22.* Norwegian Concrete Association Publication No 22. Lightweight Aggregate Concrete. Specifications and Guidelines. 1999.

North America:
- *ACI 211.2-91.* ACI 211.2-91 Standard Practice for selecting proportions for Structural Lightweight Concrete, 1991.
- *ACI 213R-87.* ACI 213R-87 Guide for Structural Lightweight Aggregate Concrete, 1987.
- *(ACI 213R-87Rev).* ACI 213R-87 Proposed revisions, 1995.
- *ACI 318-95.* Building Code Requirements for Structural Concrete (ACI 318M-95) and Commentary - ACI 318RM-95.
- *ACI 304.5R-91.* ACI 304.5R-91 Batching, Mixing, and Job Control of Lightweight Concrete, 1991.
- *ACI SP-136.* ACI SP-136 Structural Lightweight aggregate Concrete Performance 1992.
- *ASTM C 330-89.* ASTM C 330-89 Standard Specification for Lightweight Aggregates for Structural Concrete.

Poland:
- *PN-86 B-23006.*PN-86 B-23006 Aggregates for light concrete. Polish Standardization Committee 1986
- *PN-91 B-06263.* PN-91 B-06263 Lightweight aggregate concrete. Polish Standardization Committee 1991
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Russia:
- *GOST - 10832-91.* Russian Standard GOST - 10832-91 Expanded perlite sand and crushed stone - Specifications (in Russian).
- *GOST - 9757-90.* Russian Standard GOST - 9757-90 Manufactured porous gravel, crushed stone and sand - Specifications (in Russian).
- *GOST - 25820-83.* Russian Standard GOST - 25820-83 Lightweight aggregate concrete - Specifications (in Russian).

Sweden:
- *BBK 94.* BBK 94 Concrete Structures (In Swedish).

UK:
- *BS 3797.* BS 3797.British Standard Specifications for lightweight aggregates for masonry units and structural concrete
- *BS 8110.* British Standard BS 8110:1985 Structural use of concrete.
  Part 1. Code of practice for design and construction.
  Part 2. Code of practice for special circumstances
  Part 3. Design charts for singly reinforced beams, doubly reinforced beams and rectangular columns.

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- Criteria for Designing LWAC Bridges. US Department of Transportation, Federal Highway Administration, T.Y. Lin International. Report FHWA / RD-85/045, 1985.
- Gorlov, J.P.: Manufactured Porous Aggregates and Lightweight Concrete. Stroizdat, Moscow 1987 (in Russian).
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CEB-FIP

fédération internationale du béton
the international federation for structural concrete
created from the merger of CEB and FIP