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SUMMARY

Further clinker-efficient cements (CEM II/C-M and CEM VI, (➧ Fig. 1) will be standardised in the next version of DIN EN 197-5. CEM II/C-M cements contain at least 50 mass % clinker, CEM VI cements at least 35 mass %. Other main constituents are limestone, blast furnace slag, fly ash and pozzolanas. In recent years, VDZ gGmbH has been involved in a number of research projects on the properties of concretes produced using some of these cements. The article presents the properties of fresh and hardened concrete, as well as the durability properties of concretes using CEM II/C-M (S-LL) cements from these projects and from additional literature. Where possible, the results are compared to common German assessment criteria or with the properties of concretes, for example with CEM I or CEM III/A (reference concretes). The article also includes the results of studies using CEM II/B-LL cements. CEM II/B-LL cements are already included in DIN EN 197-1, but only a few have been used in the German construction sector to date. They may become more important depending on the availability of raw materials. The exposure-dependent applications of CEM II/B-LL and CEM II/C-M (S-LL) cements can be estimated from this data.

ZUSAMMENFASSUNG

Mit der nächsten Fassung der DIN EN 197-5 werden mit CEM II/C-M und CEM VI weitere klinkereffiziente Zemente genormt sein (➧ Bild 1). CEM II/C-M-Zemente enthalten mindestens 50 M.-% Klinker, CEM VI-Zemente mindestens 35 M.-%. Weitere Hauptbestandteile sind Kalkstein, Hüttensand, Flugasche und Puzzolane. Der Verein Deutscher Zementwerke (VDZ) hat sich in den vergangenen Jahren in einer Reihe von Forschungsprojekten mit den Eigenschaften von Betonen, die mit einigen dieser Zemente hergestellt wurden, beschäftigt. In dem Beitrag werden Frisch- und Festbetoneigenschaften sowie Dauerhaftigkeitskennwerte von Betonen mit CEM II/C-M (S-LL)-Zementen aus diesen Projekten sowie weiterer Literatur dargestellt. Wo möglich, werden die Ergebnisse mit den in Deutschland üblichen Bewertungskriterien bzw. mit den Eigenschaften von Betonen beispielsweise mit CEM I oder CEM III/A (Referenzbetone) verglichen. Der Beitrag enthält zudem Ergebnisse von Untersuchungen mit CEM II/B-LL Zementen. CEM II/B-LL-Zemente sind bereits in der DIN EN 197-1 enthalten, wurden aber bisher in Deutschland im konstruktiven Bereich nur vereinzelt eingesetzt. Sie könnten aufgrund der Rohstoffverfügbarkeit ggf. eine größere Bedeutung gewinnen. Die expositionsabhängigen Verwendungsmöglichkeiten von CEM II/B-LL- und CEM II/C-M (S-LL)-Zementen können anhand dieser Daten abgeschätzt werden.

(English text supplied by the authors)

Durability properties of concretes using CEM II/C-M (S-LL) and CEM II/B-LL cements

Dauerhaftigkeitseigenschaften von Betonen mit CEM II/C-M (S-LL)- und CEM II/B-LL-Zementen

1 Database

Data from [1-8] and the anonymised data of VDZ member companies were analysed. The database includes 21 CEM II/C-M (S-LL) cements and 31 CEM II/B-LL cements used in up to four concrete compositions. For comparison, concretes using CEM I, CEM II/A-LL, CEM II/A or B-S, CEM III/A and CEM III/B from the discussed sources were adopted. The data analysed here are shown as mean values in ❱ Tables 2 to 11.

2 Standard compressive strengths of cements

❱ Fig. 2 shows the compressive strengths of standard mortars after 2, 7 and 28 d according to DIN EN 196-1. The number of results on the graph for each mean value is designated by "n". The investigated CEM II/C-M (S-LL) and CEM II/B-LL cements corresponded to the strength classes 32.5 N to 52.5 N.

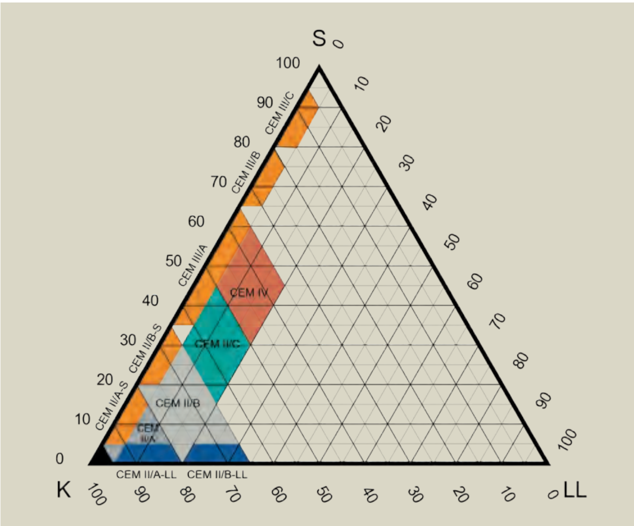

Figure 1: Cements in the K-S-LL system of the current and the revised DIN EN 197-1 and DIN EN 197-5

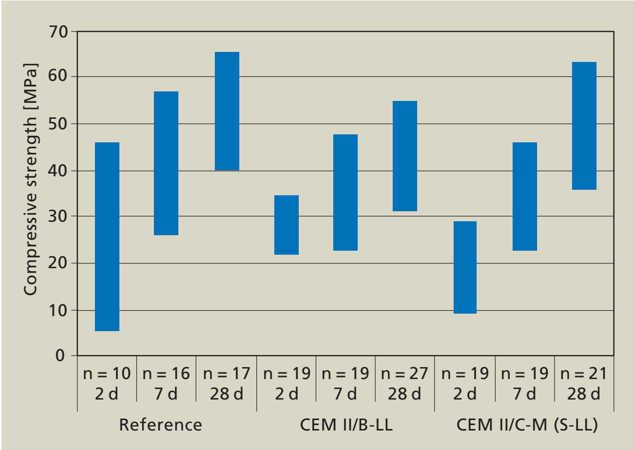

Figure 2: Standard mortar compressive strengths

3 Concretes

3.1 General

Four concrete compositions, given in ❱ Table 1, were used.

3.2 Flow diameter and concrete compressive strength

In addition to the durability properties given in Table 1, the concrete compressive strengths were determined on cubes according to DIN EN 12390-3 at the age of 28 d. Also, the flow diameter according to DIN EN 12350-5 was determined in some cases. ❱ Fig. 3 shows the flow diameter fluctuation range for concretes B1 to B4 (see Table 1) using the reference cements as well as CEM II/B-LL and CEM II/C-M (S-LL) cements. All investigated concretes were produced without superplasticizers or plasticizers. Concretes using CEM II/C-M (S-LL) and CEM II/B-LL cements show comparable flow diameters to the reference concretes used in the respective research projects.

❱ Fig. 4 shows the range of fluctuation of concrete compressive strengths. The minimum concrete compressive strengths of concretes B1, B3 and B4 using CEM II/C-M

Table 1: Concrete compositions

Concrete	Cement content [kg/m³]	Water-cement ratio	Fresh concrete air content [%]	Durability test
B1	260	0.65	–	Carbonation resistance acc. to German Committee for Reinforced Concrete (DAfStb) booklet No. 422
B2	300	0.60	–	Freeze-thaw resistance using the cube test method acc. to DIN CEN/TS 12390-9
B3	320	0.50	–	Chloride migration acc. to the Federal Waterways Engineering and Research Institute (BAW) Code of Practice "Chloride migration" and Freeze-thaw resistance using the CIF method acc. to DIN CEN/TS 12390-9
B4	320	0.50	5.0 ± 0.5	Freeze-thaw resistance with de-icing salt using the CDF method acc. to DIN CEN/TS 12390-9

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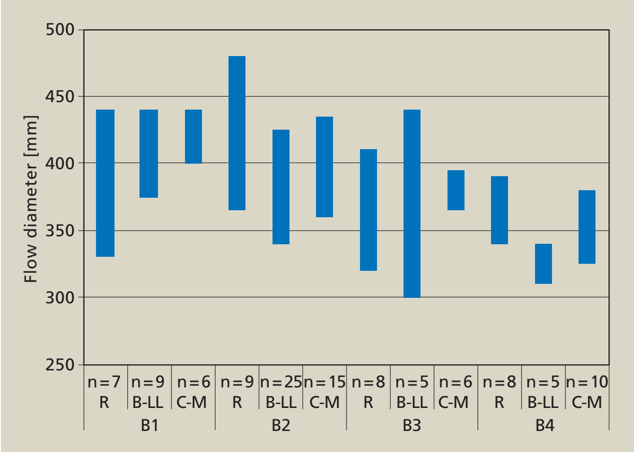

Figure 3: Flow diameters of concretes with reference cements ("R"), CEM II/B-LL ("B-LL") and CEM II/C-M (S-LL) ("C-M")

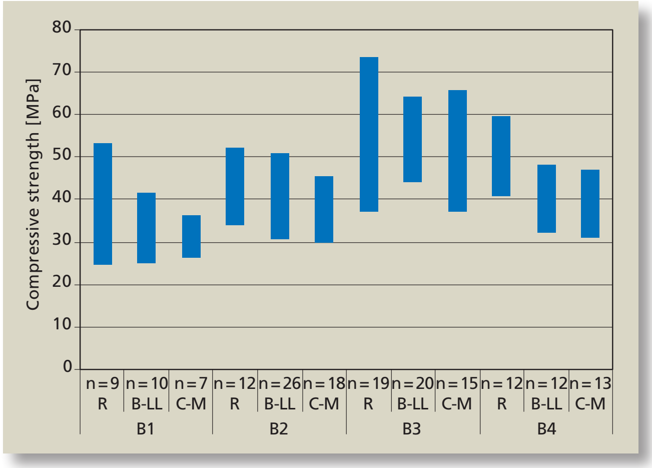

Figure 4: Compressive strengths of concretes at an age of 28 d with reference cements ("R"), CEM II/B-LL ("B-LL") and CEM II/C-M (S-LL) ("C-M")

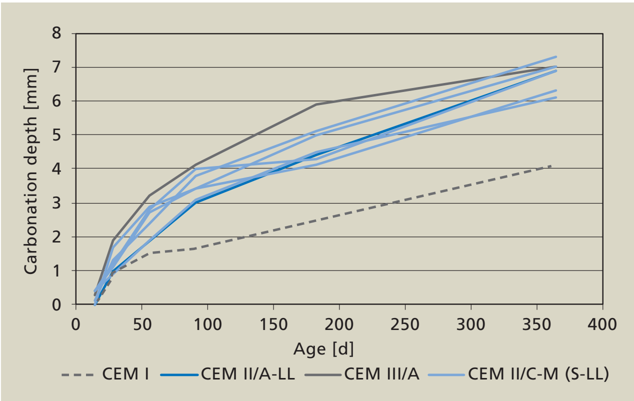

Figure 5: Carbonation of B1 concretes with CEM II/C-M (S-LL)

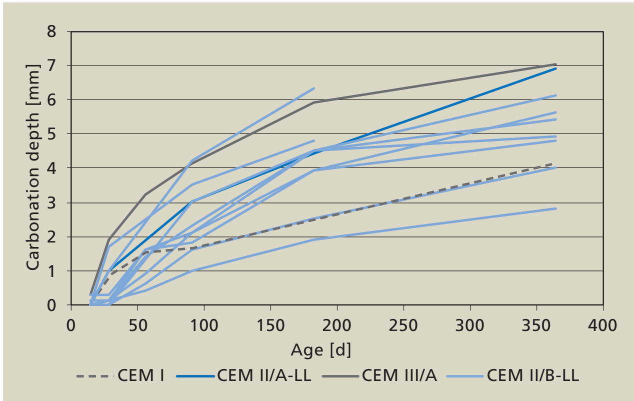

Figure 6: Carbonation of B1 concretes with CEM II/B-LL

(S-LL) and CEM II/B-LL are comparable to those of the reference concretes. However, some concretes using Portland cement display considerably greater maximum concrete compressive strengths, in particular at high water-cement ratios (w/c = 0.65). On the whole, concretes in all practically relevant compressive strengths can be produced in an adequate manner using CEM II/C-M (S-LL) and CEM II/B-LL cements.

3.3 Carbonation

For exposure class XC3, concretes in Germany must have a minimum cement content of 260 kg/m^3, a maximum water-cement ratio of w/c = 0.65 and a minimum compressive strength class C20/25. The carbonation depths of concretes of this composition up to an age of 365 d were determined in a number of evaluated literature references according to DAfStb booklet No. 422. ❱ Fig. 5 and 6 show the carbonation depths of concretes with nine CEM II/B-LL and five CEM II/C-M (S-LL) cements. According to DIN 1045-2, both CEM I and CEM III/A cements are approved in this exposure class. Concretes using CEM I and CEM III/A therefore span the field of conventional carbonation depths in this data compilation. In addition, the respective carbonation depths of a concrete using a CEM II/A-LL are shown in each case.

❱ Fig. 7 summarises the carbonation depths after 182 d. The concretes using CEM II/B-LL and CEM II/C-M (S-LL) cements are located between a concrete with CEM I and a concrete with CEM III/A.

In the German Institute for Building Technology approval procedure, the depth of carbonation is tested on prisms based

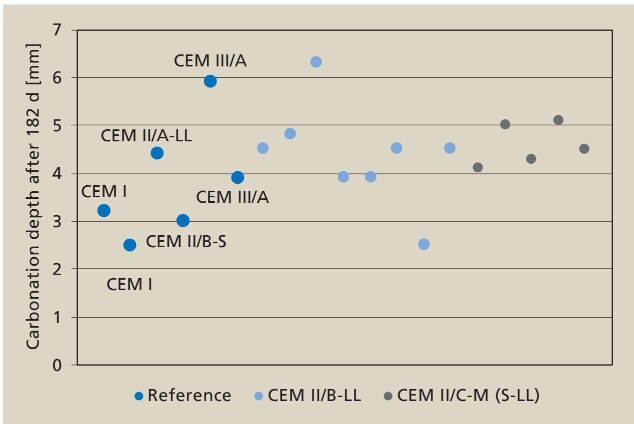

Figure 7: Carbonation depths of B1 concretes aged 182 d

on DIN EN 196-1. Gravel sand with an A8/B8 grading curve is used as aggregate. The water-cement ratio is w/c = 0.50. One half of the prisms are stored under water until aged 7 d, the other half at 20 °C until aged 28 d. Following this storage, the respective compressive strengths are determined. The carbonation depth is determined after storage in a climate at 20 °C, 65 % relative humidity and natural CO_2 concentration at the age of 147 and 168 d, respectively. ❱ Fig. 8 shows the results against the German Institute for Building Technology evaluation background. The data basis is less than that of the concrete tests with w/c = 0.65. Nevertheless, the results can be classified against the evaluation background as a function of the compressive strength and in principle confirm the observations made on the w/c = 0.65 concretes.

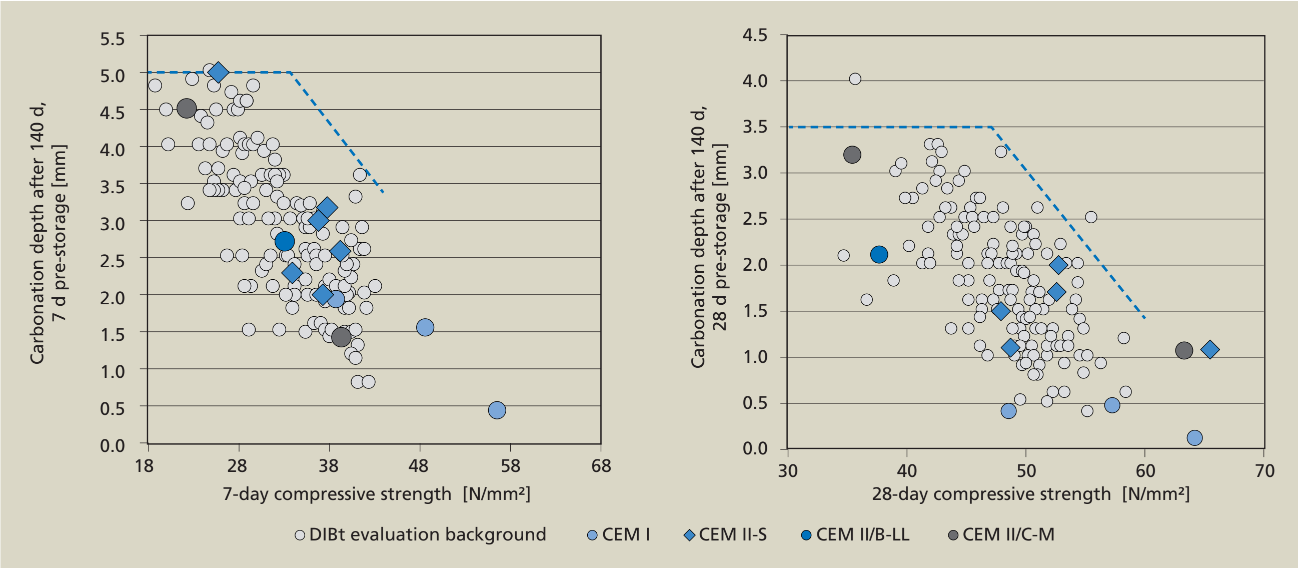

Figure 8: Carbonation of German Institute for Building Technology (DIBt) fine concrete prisms

3.4 Resistance to chloride penetration

For the exposure classes XD2 and XS2, concretes in Germany must have a minimum cement content of 320 kg/m³, a maximum water-cement ratio of w/c = 0.50 and a minimum compressive strength class C35/45. The resistance to chloride penetration of concretes of this composition was determined in various evaluated literature references according to the Federal Waterways Engineering and Research Institute Code of Practice "MDCC" [9]. The chloride migration coefficients, measured at the age of 28 d, are shown in ❱ Fig. 9. All investigated concretes using CEM II/C-M (S-LL) pass the Federal Waterways Engineering and Research Institute's XD2/XS2 criterion. The concretes using CEM II/B-LL are generally located between the Federal Waterways Engineering and Research Institute's XD2/XS2 criterion and the criterion adopted in Germany for technical approvals, among other things for cements, and is thus of the same order of magnitude as concretes using Portland cements. However, some of the concretes using CEM II/B-LL are also located above the approval criterion.

3.5 Freeze-thaw resistance using the cube test method

For exposure class XF1, concretes in Germany must have a minimum cement content of 280 kg/m³, a maximum water-cement ratio of w/c = 0.60 and a minimum compressive strength class C25/30. For XF3, a maximum allowable water-cement ratio of w/c = 0.50 applies for a minimum cement content of 320 kg/m³.

In German Institute for Building Technology approval studies [10] for cements, suitability for exposure class XF3 for concretes with a minimum cement content of 300 kg/m³ and a water-cement ratio of w/c = 0.60 was examined over many years using the cube method according to prEN 12390-9. The limit value is 10 % by mass scaling after 100 freeze-thaw cycles (FTC).

The freeze-thaw resistance of concretes of this composition was determined from a number of analysed literature references. ❱ Fig. 10 shows the scaling after 100 FTC. All concretes using CEM II/C-M (S-LL) cements comply with the acceptance criterion. Some concretes using CEM II/B-LL are even located beyond the limit value.

3.6 Freeze-thaw resistance using the CIF method

In German Institute for Building Technology approval procedures, the CIF method according to prEN 12390-9 can also be used for verification of freeze-thaw resistance for the XF3 exposure class. A maximum allowable decrease of the relative dynamic elastic modulus of 75 % after 28 FTC of the value prior to freeze-thaw exposure is applied as a limit value [11]. The test is carried out on a concrete with a cement content of 320 kg/m³ and a water-cement ratio of w/c = 0.50 (B3).

The results are shown in ❱ Fig. 11. The CIF method is far more likely to lead to a negative evaluation and thus appears

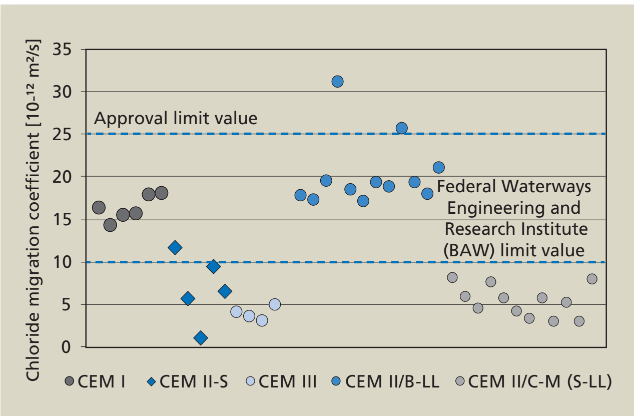

Figure 9: Resistance to chloride penetration of B3 concrete

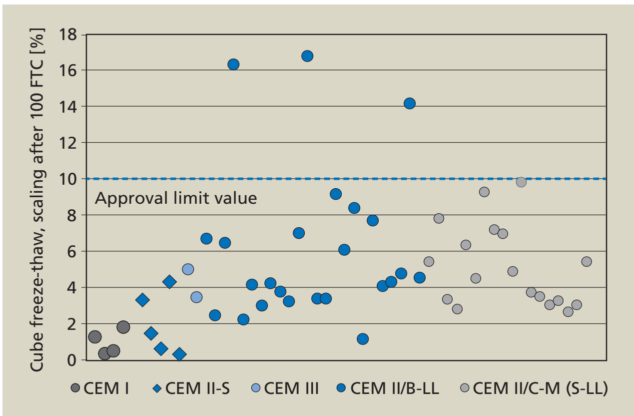

Figure 10: Scaling of B2 concrete in freeze-thaw cube test

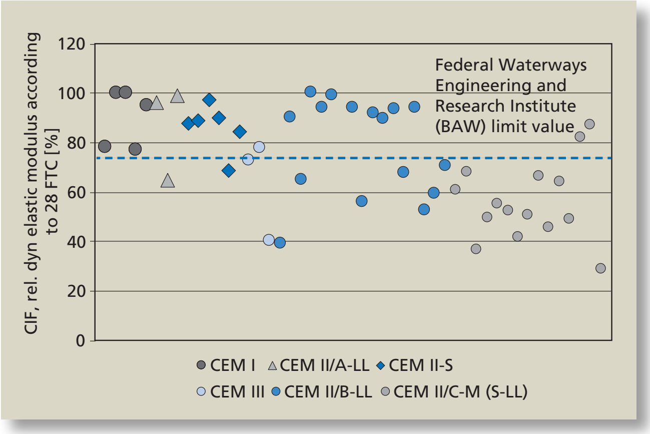

Figure 11: Relative dynamic elastic modulus of B3 concretes using the CIF method

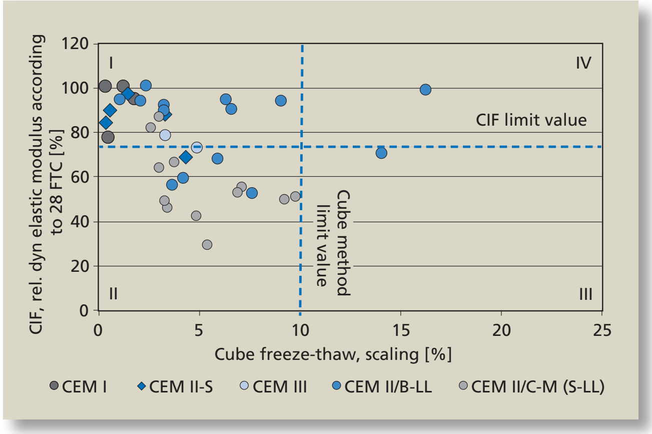

Figure 12: Comparison of CIF results (B3 concrete) with the results of the cube method (B2 concrete)

to be the more stringent test method for evaluating suitability for exposure class XF3. This is also shown by a direct comparison of both freeze-thaw test methods (❱ Fig. 12). In around 60 % of the tests on concretes B2 and B3 using identical cements, the test methods lead to the same assessment (quadrants I and III). A negative assessment using the CIF test and a simultaneous positive evaluation using the cube test (quadrant II) occurs in around 40 % of cases investigated.

Exclusion from use in exposure class XF3 based on the results of the CIF test does not necessarily mean that the cements cannot be used in components exposed to freeze-thaw attack. According to [12], concretes with maximum scaling of 10 % by mass after 100 freeze-thaw cycles using the cube method are at least suitable for use in exposure class XF1.

3.7 Freeze-thaw resistance with de-icing salt using the CDF method

For exposure class XF4, concretes in Germany must have a cement content of at least 320 kg/m³, a maximum water-cement ratio of w/c = 0.50, an artificial air voids content, dependent on the maximum aggregate size, of at least 3.5 to 5.5 %, and a minimum compressive strength class C30/37. In German Institute for Building Technology approval procedures, the CDF method is used in combination with the Federal Waterways Engineering and Research Institute limit value [11]: scaling after 28 FTC may reach a maximum of 1.5 kg/m^2.

The freeze-thaw resistance with de-icing salt was determined from a number of evaluated literature references for concretes of this composition using the CDF method. ❱ Fig. 13 shows the scaling after 28 FTC. All investigated concretes using CEM II/B-LL cements comply with the acceptance criterion. Some concretes using CEM II/C-M (S-LL) are even located beyond the limit.

4 Final remarks

The analysis of in-house investigations and of data from the literature presented here reveals that important specifications for fresh and hardened concrete properties for internal and external components can be met by CEM II/B-LL and CEM II/C-M (S-LL) cements.

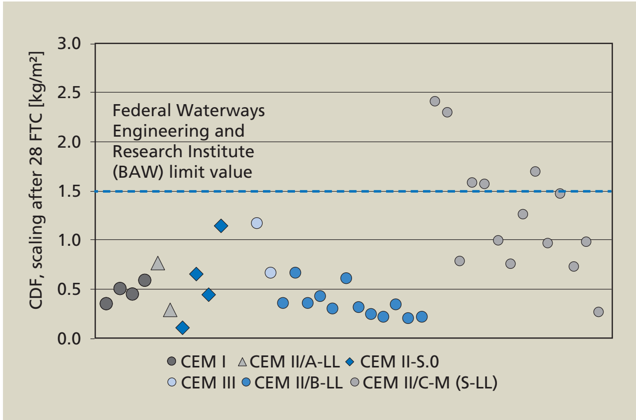

Figure 13: Scaling of B4 concrete using the CDF method

Currently, around 7 million tonnes of blast furnace slag are available annually in Germany and around 21 million tonnes in Europe [13]. By the year 2035, it is assumed that around 6.7 million tonnes will be available in the lower and around 8.9 million tonnes in the upper scenarios of Bundesverband Baustoffe – Steine und Erden (German Building Materials Association) [14]. Domestic German cement shipments currently amount to around 29 million tonnes annually [15]. If cement use of around 56 % in ready-mixed concrete is assumed, this corresponds to around 16 million tonnes. Internal and external components (XC1 and XF1/XC4) are estimated to account for around 65 %, i.e. around 10.5 million tonnes of cement.

For CEM II/C-M (S-LL) cements, 30 mass % of blast furnace slag is required in the limit composition (sulphate agent free). Mathematically, around 3.2 million tonnes of blast furnace slag would be required to manufacture all internal and external components made of ready-mixed concrete in Germany using CEM II/C-M (S-LL) cements. According to the forecasts discussed above, this quantity will continue to be available in the medium term, whereby regional differences in availability do exist.

CEM II/CM (S-LL) cements and CEM II/B-LL cements therefore have the potential to be used in a large proportion of concrete construction in Germany in terms of both their technical properties and the availability of the raw materials required for their production, and so contribute to the reduction of CO_2 emissions from concrete construction.

5 Data

Table 2: Composition of the reference cements and mortar compressive strengths

Cement	Origin	Composition			Mortar compressive strength [MPa]		
		K [mass %]	S [mass %]	LL [mass %]	2 d	7 d	28 d
CEM I	[8]	100	0	0	45.8	56.9	64.4
CEM I	[4]	100	0	0	23.9	39.4	51.2
CEM I	[3]	100	0	0	–	–	57.7
CEM I	[5]	100	0	0	–	48.9	57.4
CEM I	[5]	100	0	0	–	39.2	48.7
CEM I	[6]	100	0	0	–	–	–
CEM II/A-LL	[4]	80	0	20	21.5	34.5	43.9
CEM II/A-LL	[5]	80	0	20	–	28.5	40.2
CEM II/A-LL	A	unknown			22.5	40.5	49.7
CEM II/A-S	A	unknown			25.6	47.1	61.4
CEM II/A-S	[8]	80	20	0	20.8	34.0	47.9
CEM II/B-S	[4]	65	35	0	18.6	35.1	53.7
CEM II/B-S	A	unknown			22.0	38.9	57.3
CEM II/B-S	[5]	65	35	0	–	37.8	52.6
CEM II/B-S	[5]	65	35	0	–	27.2	51.2
CEM II/B-S	[5]	65	35	0	–	39.3	65.4
CEM III/A	[2]	unknown			–	–	–
CEM III/A	[6]	unknown			–	–	–
CEM III/A	A	55	45	0	–	–	–
CEM III/B	[8]	20	80	0	–	–	–

Table 3: Concrete compressive strengths and flow diameters of the concretes with reference cements

Cement	Origin	Flow diameter [mm]				Concrete compressive strength after 28 d [MPa]			
		B1	B2	B3	B4	B1	B2	B3	B4
CEM I	[8]	330	–	320	–	53.3	–	67.6	–
CEM I	[4]	440	470	410	380	34.5	37.8	55.7	44.0
CEM I	[3]	–	470	410	380	–	35.8	55.7	44.0
CEM I	[5]	–	385	–	350	–	52.2	73.4	59.3
CEM I	[5]	–	365	–	340	–	38.5	59.1	45.4
CEM I	[6]	–	–	–	–	38.9	–	61.5	–
CEM II/A-LL	[4]	430	480	400	390	31.6	–	52.0	44.5
CEM II/A-LL	[5]	–	–	375	–	–	–	45.5	–
CEM II/A-LL	A	–	–	–	–	–	34.0	51.2	41.4
CEM II/A-S	A	415	–	360	–	–	41.2	53.2	41.6
CEM II/A-S	[8]	–	–	–	–	35.1	–	49.1	–
CEM II/B-S	[4]	420	430	–	350	35.9	43.5	57.0	41.3
CEM II/B-S	A	–	–	–	–	–	34.7	54.4	40.3
CEM II/B-S	[5]	–	390	–	370	–	36.4	60.6	50.2
CEM II/B-S	[5]	–	–	–	–	–	–	–	–
CEM II/B-S	[5]	–	385	375	–	–	50.9	70.2	–
CEM III/A	[2]	405	465	–	360	36.0	41.4	55.5	42.0
CEM III/A	[6]	–	–	–	–	42.3	–	62.1	–
CEM III/A	A	–	–	–	–	–	40.1	51.6	42.6
CEM III/B	[8]	370	–	360	–	24.8	–	36.1	–

– no data available; A anonymised cement industry data

Table 4: Durability-relevant parameters of concretes with reference cements

Cement	Origin	Carbonation depth after 182 d [mm]	Cube freeze-thaw, scaling [%]	Chloride migration coefficient [10^{-12} m²/s]	CIF, rel. dyn elastic modulus [%], 28 FTC	CDF, scaling, 28 FTC [kg/m²]
		B1	B2	B3	B3	B4
CEM I	[8]	–	–	16.3	78.4	–
CEM I	[4]	3.2	1.2	14.3	100.4	0.4
CEM I	[3]	–	0.4	15.5	100.4	0.5
CEM I	[5]	–	0.5	15.6	77.3	0.4
CEM I	[5]	–	1.8	17.8	94.9	0.6
CEM I	[6]	2.5	–	18.0	–	–
CEM II/A-LL	[4]	4.4	–	28.2	96.1	0.8
CEM II/A-LL	[5]	–	–	–	64.9	–
CEM II/A-LL	A	–	0.9	–	99.0	0.3
CEM II/A-S	A	–	3.3	11.6	88.0	0.1
CEM II/A-S	[8]	–	–	–	88.8	–
CEM II/B-S	[4]	3.0	1.5	5.7	97.3	0.7
CEM II/B-S	A	–	0.6	1.1	90.0	0.5

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Cement	Origin	Carbonation depth after 182 d [mm]	Cube freeze-thaw, scaling [%]	Chloride migration coefficient [10^{-12} m²/s]	CIF, rel. dyn elastic modulus [%], 28 FTC	CDF, scaling, 28 FTC [kg/m²]
		B1	B2	B3	B3	B4
CEM II/B-S	[5]	–	4.3	9.4	68.7	1.1
CEM II/B-S	[5]	–	–	–	–	–
CEM II/B-S	[5]	–	0.4	6.6	84.3	–
CEM III/A	[2]	5.9	5.0	4.0	72.7	1.2
CEM III/A	[6]	3.9	–	3.5	–	–
CEM III/A	A	–	3.4	2.9	78.0	0.7
CEM III/B	[8]	–	–	4.8	40.1	–

Table 5: Composition of CEM II/B-LL cements and mortar compressive strengths

Cement	Origin	Composition			Mortar compressive strength [MPa]		
		K [mass %]	S [mass %]	LL [mass %]	2 d	7 d	28 d
LL-1	[8]	65	0	35	25.2	33.2	37.8
LL-2	[2]	70	0	30	33.8	42.1	48.0
LL-3	[2]	65	0	35	22.0	33.2	40.8
LL-4	[4]	75	0	25	27.9	42.6	49.6
LL-5	[4]	70	0	30	24.1	32.8	42.8
LL-6	[4]	65	0	35	22.1	32.2	39.7
LL-7	[3]	65	0	35	–	–	39.7
LL-8	[3]	65	0	35	–	–	46.9
LL-9	[3]	65	0	35	–	–	54.7
LL-10	[3]	65	0	35	–	–	49.5
LL-11	[3]	70	0	30	–	–	–
LL-12	[3]	65	0	35	–	–	–
LL-13	[3]	65	0	35	–	–	46.9
LL-14	[3]	65	0	35	–	–	46.5
LL-15	[3]	65	0	35	–	–	48.0
LL-16	[3]	65	0	35	–	–	46.5
LL-17	[5]	75	0	25	–	–	–
LL-18	[7]	70	0	30*)	32.5	45.6	52.6
LL-19	[7]	70	0	30	30.2	45.9	53.3
LL-20	[7]	70	0	30*)	32.1	47.5	53.5
LL-21	[7]	70	0	30	33.1	46.2	53.0
LL-22	[7]	70	0	30*)	32.6	46.1	50.4
LL-23	[7]	70	0	30	32.7	46.6	53.8
LL-24	[7]	70	0	30	30.9	46.4	54.0
LL-25	[7]	70	0	30*)	33.7	45.6	51.6
LL-26	[7]	70	0	30*)	34.6	45.2	50.5
LL-27	[7]	70	0	30*)	34.0	47.8	53.3
LL-28	[7]	70	0	30*)	33.8	46.9	54.0
LL-29	[7]	70	0	30*)	31.9	46.7	53.0
LL-30	[7]	70	0	30*)	33.0	46.3	53.9

Table 6: Concrete compressive strengths and flow diameters of concretes with CEM II/B-LL

Cement	Origin	Flow diameter [mm]				Concrete compressive strength after 28 d [MPa]			
		B1	B2	B3	B4	B1	B2	B3	B4
LL-1	[8]	–	–	–	–	28.8	–	44.8	–
LL-2	[2]	–	425	–	340	–	41.9	58.8	47.9
LL-3	[2]	–	395	–	335	–	37.9	53.6	38.5
LL-4	[4]	400	400	–	–	34.2	41.3	55.3	42.5
LL-5	[4]	400	380	390	–	36.8	37.6	46.0	41.5
LL-6	[4]	440	380	440	–	28.7	34.2	43.7	32.4
LL-7	[3]	–		–	–	–	30.7	43.7	–
LL-8	[3]	–	390	–	–	–	41.5	55.9	43.3
LL-9	[3]	–	400	–	–	–	39.9	–	–
LL-10	[3]	–	410	–	–	–	40.7	–	–
LL-11	[3]	–		390	–	–	–	46.0	–
LL-12	[3]	–		–	–	–	–	52.2	–
LL-13	[3]	–	400	–	–	–	40.4	–	37.8
LL-14	[3]	–	400	–	330	–	40.7	53.3	35.8
LL-15	[3]	–	410	–	310	–	42.6	–	37.2
LL-16	[3]	–	410	–	–	–	38.8	–	39.8
LL-17	[5]	–	–	–	–	–	–	49.7	–
LL-18	[7]	–	380	–	–	–	43.2	–	–
LL-19	[7]	425	410	–	–	41.6	45.8	58.4	–
LL-20	[7]	395	390	–	–	24.9	42.0	64.0	–
LL-21	[7]	405	375	–	–	33.5	40.9	54.5	–
LL-22	[7]	405	345	–	–	28.0	42.2	50.8	37.2
LL-23	[7]	375	375	–	–	37.4	42.7	–	–
LL-24	[7]	405	385	405	–	–	42.6	53.9	–
LL-25	[7]	–	360	–	–	–	43.0	56.0	–
LL-26	[7]	–	395	–	–	–	43.5	–	–
LL-27	[7]	–	340	300	–	–	50.8	62.4	42.2
LL-28	[7]	–	365	–	–	–	42.6	–	–
LL-29	[7]	–	355	–	–	38.0	44.7	55.0	–
LL-30	[7]	–	360	–	–	–	43.9	–	–

– no data available; A anonymised cement industry data / *) $CaCO_3$ content of limestone does not correspond to DIN EN 197-1 specifications

Table 7: Durability-relevant parameters of concretes with CEM II/B-LL

Cement	Origin	Carbonation depth after 182 d [mm]	Freeze-thaw, scaling [%]	Chloride migration coefficient [10^{-12} m^2/s]	CIF, rel. dyn elastic modulus [%], 28 FTC	CDF, scaling, 28 FTC [kg/m^2]
		B1	B2	B3	B3	B4
LL-1	[8]	–	–	–	39.1	–
LL-2	[2]	–	6.6	–	90.0	0.4
LL-3	[2]	–	–	–	65.1	0.7
LL-4	[4]	4.5	2.4	–	100.4	0.4
LL-5	[4]	4.8	6.4	–	94.1	0.4
LL-6	[4]	6.3	16.3	–	98.8	0.3
LL-7	[3]	–	–	17.7	–	–
LL-8	[3]	–	2.1	–	93.8	0.6
LL-9	[3]	–	4.1	–	–	–
LL-10	[3]	–	3.0	–	–	–
LL-11	[3]	–	–	17.1	–	–
LL-12	[3]	–	–	19.3	–	–
LL-13	[3]	–	4.2	–	–	0.3
LL-14	[3]	–	3.7	–	55.7	0.2
LL-15	[3]	–	3.2	–	–	0.2
LL-16	[3]	–	7.0	–	–	0.3
LL-17	[5]	–	–	31.0	–	–
LL-18	[7]	–	16.7	–	–	–
LL-19	[7]	3.9	3.3	18.4	91.6	–
LL-20	[7]	–	3.3	16.9	89.5	–
LL-21	[7]	3.9	9.1	19.2	93.5	–
LL-22	[7]	4.5	6.0	18.7	67.8	0.2
LL-23	[7]	2.5	8.3	–	–	–
LL-24	[7]	–	1.1	25.6	94.2	–
LL-25	[7]	–	7.7	19.2	52.5	–
LL-26	[7]	–	4.0	–	–	–
LL-27	[7]	–	4.3	17.8	59.1	0.2
LL-28	[7]	–	4.8	–	–	–
LL-29	[7]	4.5	14.1	20.9	70.4	–
LL-30	[7]	–	4.5	–	–	–

– no data available

Table 8: Composition of CEM II/C-M (S-LL) cements and mortar compressive strengths

Cement	Origin	Composition			Mortar compressive strength [MPa]		
		K [mass %]	S [mass %]	LL [mass %]	2 d	7 d	28 d
C-M-1	[1]	50	30	20	20.9	39.6	63.3
C-M-2	[8]	50	30	20	13.8	31.7	47.4
C-M-3	[8]	50	30	20	9.0	22.5	35.6
C-M-4	A	unknown			12.5	25.7	41.1

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Cement	Origin	Composition			Mortar compressive strength [MPa]		
		K [mass %]	S [mass %]	LL [mass %]	2 d	7 d	28 d
C-M-5	A	unknown			13.5	28.1	45.4
C-M-6	A	unknown			16.0	30.2	47.2
C-M-7	A	unknown			18.2	35.0	48.7
C-M-8	A	unknown			16.9	30.6	46.3
C-M-9	A	unknown			17.5	31.1	46.9
C-M-10	[2]	60	20	20	19.6	34.6	52.0
C-M-11	[2]	50	30	20	14.0	30.3	49.1
C-M-12	[2]	50	40	10	14.1	30.8	53.9
C-M-13	[2]	60	20	20	20.5	37.7	54.8
C-M-14	[2]	60	20	20	18.5	32.6	52.1
C-M-15	[2]	50	40	10	15.5	37.0	59.5
C-M-16	[2]	50	40	10	14.3	31.7	57.3
C-M-17	[3]	50	30	20	–	–	50.9
C-M-18	[3]	50	30	20	–	–	51.1
C-M-19	A	unknown			29.2	45.7	60.6
C-M-20	A	unknown			27.3	45.8	63.0
C-M-21	A	unknown			26.2	44.0	63.4

Table 9: Concrete compressive strengths and flow diameters of concretes with CEM II/CEM II/C-M (S-LL)

Cement	Origin	Flow diameter [mm]				Concrete compressive strength after 28 d [MPa]			
		B1	B2	B3	B4	B1	B2	B3	B4
C-M-1	[1]	–	–	–	–	–	–	59.9	–
C-M-2	[8]	–	–	–	–	30.0	–	42.6	–
C-M-3	[8]	400	–	380	–	26.5	–	36.0	–
C-M-4	A	–	385	–	360	–	30.8	–	31.0
C-M-5	A	–	380	–	350	–	29.7	–	31.0
C-M-6	A	–	365	–	–	–	35.2	–	–
C-M-7	A	–	385	–	–	–	36.6	–	–
C-M-8	A	–	365	–	–	–	32.8	–	–
C-M-9	A	–	360	–	–	–	34.4	–	–
C-M-10	[2]	400	410	–	355	36.1	40.1	57.1	38.4
C-M-11	[2]	420	435	–	370	32.6	38.9	53.1	35.0
C-M-12	[2]	425	430	395	380	32.2	40.4	54.2	39.0
C-M-13	[2]	440	400	380	340	34.5	43.8	64.5	41.6
C-M-14	[2]	–	385	380	325	–	42.7	58.9	44.4
C-M-15	[2]	435	425	365	360	36.3	42.9	56.9	40.5
C-M-16	[2]	–	395	370	340	–	45.3	59.7	46.9
C-M-17	[3]	–	420	–	–	–	41.7	54.0	–
C-M-18	[3]	–	420	–	360	–	40.3	58.1	43.3
C-M-19	A	–	–	–	–	–	42.5	50.1	45.3
C-M-20	A	–	–	–	–	–	40.6	53.3	44.5
C-M-21	A	–	–	–	–	–	42.4	54.1	42.5

– no data available

Table 10: Durability-relevant parameters of concretes with CEM II/CEM II/C-M (S-LL)

Cement	Origin	Carbonation depth after 182 d [mm]	Freeze-thaw, scaling [%]	Chloride migration coefficient [10^{-12} m²/s]	CIF, rel. dyn elastic modulus, 28 FTC [%]	CDF, scaling, 28 FTC [kg/m²]
		B1	B2	B3	B3	B4
C-M-1	[1]	–	–	–	60.9	–
C-M-2	[8]	–	–	–	68.4	–
C-M-3	[8]	–	–	–	37.1	–
C-M-4	A	–	–	5.4	–	2.4
C-M-5	A	–	–	7.8	–	2.3
C-M-6	A	–	–	3.3	–	–
C-M-7	A	–	–	2.8	–	–
C-M-8	A	–	–	6.3	–	–
C-M-9	A	–	–	4.5	–	–
C-M-10	[2]	4.1	8.0	9.2	49.5	0.8
C-M-11	[2]	5.0	5.8	7.2	55.2	1.6
C-M-12	[2]	4.3	4.5	7.0	52.6	1.6
C-M-13	[2]	5.1	7.6	4.9	42.0	1.0
C-M-14	[2]	–	5.6	9.8	50.8	0.8
C-M-15	[2]	4.5	4.1	3.8	66.3	1.3
C-M-16	[2]	–	3.3	3.5	45.8	1.7
C-M-17	[3]	–	5.6	3.0	64.1	1.0
C-M-18	[3]	–	3.0	3.3	49.0	1.5
C-M-19	A	–	5.1	2.6	82.0	0.7
C-M-20	A	–	3.0	3.0	87.0	1.0
C-M-21	A	–	7.9	5.4	29.0	0.3

Table 11: Carbonation depth according to German Institute for Building Technology (DIBt) method

Cement	Origin	Compressive strength after 7 d [MPa]	Compressive strength after 28 d [MPa]	Carbonation depth after 7 d pre-storage, 140 d main storage [mm]	Carbonation depth after 28 d pre-storage, 140 d main storage [mm]
CEM I	[8]	56.9	64.4	0.4	0.1
CEM I	[5]	48.9	57.4	1.5	0.5
CEM I	[5]	39.2	48.7	1.9	0.4
CEM II/A-S	[8]	34.0	47.9	2.3	1.5
CEM II/B-S	[5]	37.8	52.6	3.2	1.7
CEM II/B-S	[5]	39.3	65.4	2.6	1.1
CEM III/B	[8]	25.9	40.4	5.0	3.8
CEM II/B-LL	[8]	33.2	37.8	2.7	2.1
CEM II/C–M (S-LL)	[1]	39.6	63.3	1.4	1.1
CEM II/C–M (S-LL)	[8]	22.5	35.6	4.5	3.2

– no data available; A anonymised cement industry data

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