Clinker-efficient cements and their application – today and tomorrow

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Abstract

The concrete standard DIN 1045-2 currently provides fixed limit formulations for the respective exposure class. The tests of cements in concrete with regard to durability (carbonation, chloride penetration, frost and freeze-thaw salt resistance) are now carried out within approvals procedures in a limit composition for the exposure class under consideration. Test results of clinker-efficient cements are shown against the assessment background of the German Institute for Building Technology (DIBt) e. g. for carbonation: This test is currently to be carried out with a water-cement ratio of w/c = 0.50. While, for example, a CEM III/A or a CEM II/C-M (S-LL) fit well into the assessment background in this test with the required limit composition, the depth of carbonation of a cement is 20 percent clinker, 30 percent blast furnace slag and 50 percent unburned limestone clearly outside. If the water-cement ratio is reduced to w/c = 0.40, the result is already in the upper range of the evaluation background. A further reduction to w/c = 0.35 leads to a result in the range of the reference cements. A further significant reduction in the clinker content in cements with a high proportion of unburnt limestone would therefore be possible if the concretes are composed accordingly.

Keywords

CO_2-efficient cements, Cement specific application rules, CEM X-technology, Carbonation, Chloride Migration, Freeze-thaw resistance, Freeze-thaw resistance with de-icer, CO_2-reduction vs. Durability, Performance-related greenhouse gas emissions

1 Introduction

The use of clinker-efficient cements accounts for around 20% of the reductions in the “climate neutrality” scenario of the VDZ [1] study “Decarbonization of cement and concrete”. The market launch of these cements is therefore of great importance and the common goal must be to align concrete production and construction accordingly. The use of clinker-efficient cements with several main components is not new. It has a long and successful tradition in many European countries, including Germany. Clinker-efficient cements have been used for many years, also because they can reduce CO_2 emissions from cement production [2]. In addition to Portland cement, the historical German cement standard DIN 1164 also defined cements with the main components blast furnace slag and trass, later also with fly ash, burnt slate and unburned limestone. The European cement standard EN 197-1 expanded the product portfolio to include cements with natural tempered pozzolana and silica fume. It therefore offers the possibility of producing cements with lower clinker contents. In this way, the clinker/cement factor has been reduced to an average of 71% in recent decades. In the climate neutrality scenario, a value of 53% is aimed for in 2050. The normative basis is the new cement standard EN

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197-5. In CEM II/C cements, the clinker content can be reduced to as little as 50% by mass. For example, cements can be produced with 20% by mass of unburnt limestone and up to 30% by mass of another main component such as blast furnace slag, fly ash or burnt shale (**Table 1**).

Table 1 New cement types CEM II/C and CEM VI [EN 197-5:2021]

Main types	Notation of the products (types of common cement)		Composition (percentage by mass [a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calcareous				
	Name	Abbreviation	K	S	D [b]	P	Q	V	W	T	L [c]	LL [c]	
CEM II	Portland-composite	CEM II/C-M	50-64	‹---36-50---›									0-5
CEM VI	Composite cement	CEM VI (S-P)	35-49	31-59	–	6-20	–	–	–	–	–	–	0-5
		CEM VI (S-V)	35-49	31-59	–	–	–	6-20	–	–	–	–	0-5
		CEM VI (S-L)	35-49	31-59	–	–	–	–	–	–	6-20	–	0-5
		CEM VI (S-LL)	35-49	31-59	–	–	–	–	–	–	–	6-20	0-5

[a] The values in the table refer to the sum of the main and minor additional constituents.

[b] The proportion of silica fume is limited to 10 %.

[c] The proportion of limestone (sum of L, LL) is limited to 6-20 %.

[d] The number of main constituents other than clinker is limited to two and these main constituents shall be declared by designation of the cement.

These cements can make a significant contribution to climate protection and at the same time have good performance. They are therefore well suited for many structural engineering applications. By using CEM II/C M for interior components and "normal" exterior components (with exposure requirement XC1-4, XF1), up to 20% specific CO_2 emissions can be saved in the mentioned application areas. CEM VI cements, which also contain up to 20% by mass of unburnt limestone, enable the clinker content in the cement to be further reduced to up to 35% by mass. Even if their use will remain limited to selected applications in the coming years, these cements will become increasingly important because of their even lower CO_2 footprint.

This article presents essential steps to further reduce the clinker/cement-factor and is based in part on statements e. g. in [3, 4] as well as several editions of the VDZ-Mitteilungen.

2 Application of CEM II/C-M-cements

2.1 Introduction

In a study on the properties of mortar and concrete using CEM II/C-M (S-LL) VDZ evaluated the results of own investigations and data from other sources and published them in issue 10/2019 of the "beton" magazine [5]. From this study, exemplary results for CEM II/C-M (S-LL) cements for carbonation and freeze-thaw resistance are presented below. The results are compared with the evaluation criteria customary in Germany and with the properties of concrete with cements that have been used in practice for many years. These are e. g. concretes with cement types CEM I, CEM II/A LL, CEM II/B-S, CEM II/B-M (S-LL) or CEM III/A.

2.2 Carbonation

In **Figure 1** shows the carbonation depths of concrete - determined according to DAfStb booklet 422 - with a cement content of 260 kg/m^3 and a water-cement ratio w/c = 0.65. For exposure class XC3, concrete in Germany must have this composition and meet the requirements of strength class C20/25.

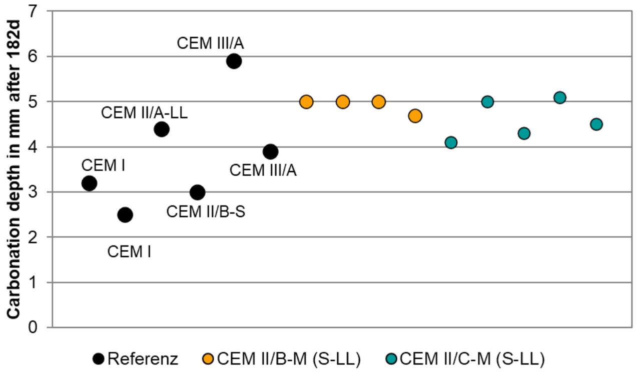
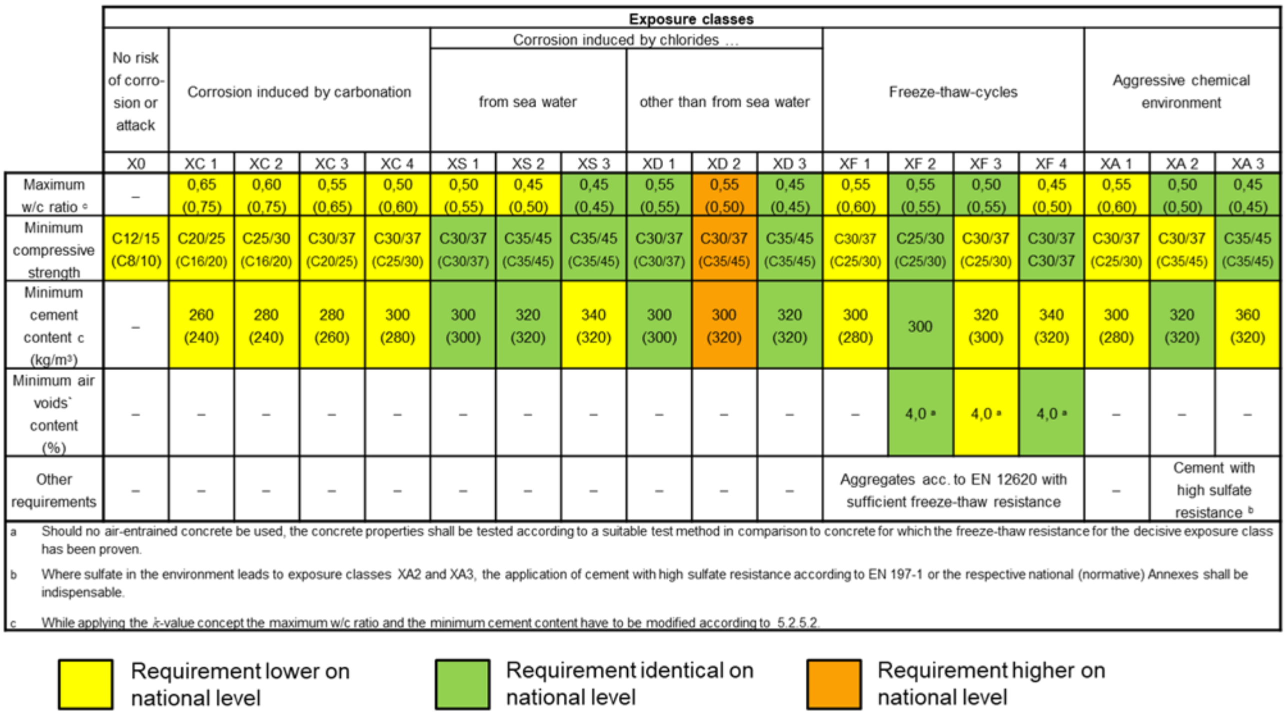


Figure 1 Carbonation depths of concretes with a cement content of 260 kg/m^3 and a water/cement ratio of 0.65 [9]

The concretes with the cement types CEM II/B-M (S-LL) and CEM II/C-M (S-LL) are classified between a concrete with CEM I and a concrete with CEM III/A. These are concretes that are permitted for exposure class XC3 according to DIN 1045-2 and have therefore been in practical use for a long time. In comparison with other countries in Europe, Germany has relatively high w/c ratios and low minimum cement contents in some (common) exposure classes: XC1: 0.75 vs. 0.65, XC4: 0.60 vs. 0.50, XF1: 0.60 vs. 0.55, XC3: 0.65 vs. 0.55 (**Figure 2**).

The regulations in Germany date from a time when the proportion of Portland cement in the domestic market share of cements in Germany was more than 70%. Today, the market share of Portland cement is below 30 % in Germany. These concrete technological boundary conditions were therefore not yet geared towards enabling consistently clinker-efficient cements with a clinker/cement factor in the order of magnitude of 0.50 or less, possibly with a proportion of unburned limestone LL of at least 20% or higher. There is also no differentiation according to the type of cement within an exposure class. Concrete for an XC4 exterior member shall be made with a maximum water cement ratio of 0.60. The cements CEM I to CEM III/B can be used. **Figure 2** shows the relationship between the clinker content in the concrete and the carbonation rate for concretes with water/cement ratios between 0.59 and 0.65. According to DIN 1045-2, these concretes are suitable for exposure classes XC4 and XC3. In addition, data for a further reduced w/c value are included. The following becomes clear: according to current practical application, the permissible carbonation rates should be around 9 mm/a$^{0.5}$ for XC3 and around 7 mm/a$^{0.5}$ for XC4. Previously, based on reliability considerations, values of around 4-5 mm/a$^{0.5}$ were intended for the concrete covers used today within the implementation of the Exposure Resistance Classes ERC Concept acc. to the new EUROCODE 2 in Germany. This would mean that the water/cement values would have to be reduced or the clinker content would have to be increased; or both.

Table 2 Application rules for cement: EN 206 vs. NAD in Germany (DIN 1045-2)



	Exposure classes																	
	No risk of corrosion or attack	Corrosion induced by carbonation				Corrosion induced by chlorides …						Freeze-thaw-cycles				Aggressive chemical environment		
						from sea water			other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c ratio [c]	–	0,65 (0,75)	0,60 (0,75)	0,55 (0,65)	0,50 (0,60)	0,50 (0,55)	0,45 (0,50)	0,45 (0,45)	0,55 (0,55)	0,55 (0,50)	0,45 (0,45)	0,55 (0,60)	0,55 (0,55)	0,50 (0,55)	0,45 (0,50)	0,55 (0,60)	0,50 (0,50)	0,45 (0,45)
Minimum compressive strength	C12/15 (C8/10)	C20/25 (C16/20)	C25/30 (C16/20)	C30/37 (C20/25)	C30/37 (C25/30)	C30/37 (C30/37)	C35/45 (C35/45)	C35/45 (C35/45)	C30/37 (C30/37)	C30/37 (C35/45)	C35/45 (C35/45)	C30/37 (C25/30)	C25/30 (C25/30)	C30/37 (C25/30)	C30/37 C30/37	C30/37 (C25/30)	C30/37 (C35/45)	C35/45 (C35/45)
Minimum cement content [c] (kg/m³)	–	260 (240)	280 (240)	280 (260)	300 (280)	300 (300)	320 (320)	340 (320)	300 (300)	300 (320)	320 (320)	300 (280)	300	320 (300)	340 (320)	300 (280)	320 (320)	360 (320)
Minimum air voids` content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0 [a]	4,0 [a]	4,0 [a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregates acc. to EN 12620 with sufficient freeze-thaw resistance				–	Cement with high sulfate resistance [b]	

[a] Should no air-entrained concrete be used, the concrete properties shall be tested according to a suitable test method in comparison to concrete for which the freeze-thaw resistance for the decisive exposure class has been proven.

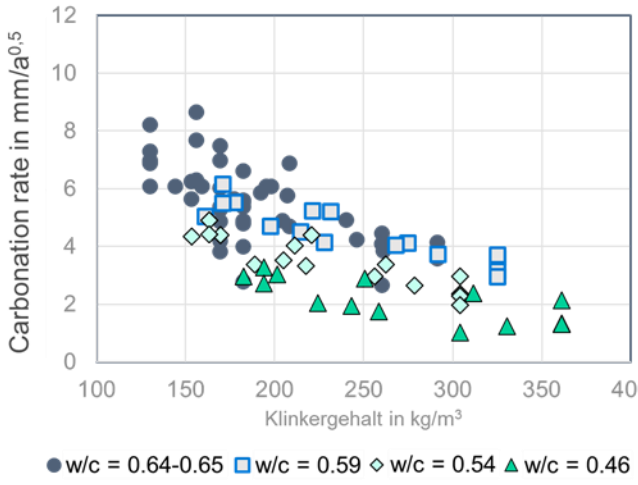
[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, the application of cement with high sulfate resistance according to EN 197-1 or the respective national (normative) Annexes shall be indispensable.

[c] While applying the k-value concept the maximum w/c ratio and the minimum cement content have to be modified according to 5.2.5.2.

🟨 Requirement lower on national level

🟩 Requirement identical on national level

🟧 Requirement higher on national level



- XC3 -concrete (w/c = 0.64-0.65): Carbonation rate up to 9 mm/a^{0,5}
- XC4-concrete (w/c = 0.59): Carbonation rate up to 7 mm/a^{0,5}

- Concrete with d_{max} = 16 mm
- Paste content: 280-290 l/m³
- Carbonation test: DAfStb Heft 422 ~ Chamber test acc. to EN 12390-10 with natural CO_2-concentration

Figure 2 Carbonation rate dependent on clinker content and water-cement ratio

The introduction of performance-related evidence (e. g. the Exposure Resistance Classes ERC Concept) as an alternative to the descriptive rules of the concrete construction standards can represent a useful addition. Since it is impossible to prevent concrete from also being tested using the descriptive approach, it must be ensured that contradictions to the descriptive system are kept within limits and that what has already been achieved in terms of decarbonization and resource efficiency is not counteracted. For the situation in Germany, it was therefore the goal that at least concretes with about 50% clinker in the cement, e. g. B. CEM III/A 42.5 N or CEM II/C-M (S-LL, V-LL, T-LL) can also be used under ERC without changing the currently valid limit formulations, the concrete cover and the after-treatment regime.

2.3 Freeze-thaw resistance with de-icer

For exposure class XF4, concrete in Germany must have a minimum cement content of 320 kg/m^3, a maximum water-cement ratio of 0.50 and a content of artificial air voids of at least 3.5% to 5.5% by volume, depending on the largest particle size. The compressive strength must meet the requirements for compressive strength class C30/37. In the DIBt approval process, the CDF process is used in combination with the BAW limit value [11]: The scaling after 28 FTC may not exceed 1.5 kg/m^2. **Figure 3** shows the scaling after 28 FTW. Some of the concretes with CEM II/C-M (S-LL) are also beyond the limit value. A general approval for exposure class XF4 is therefore not possible.

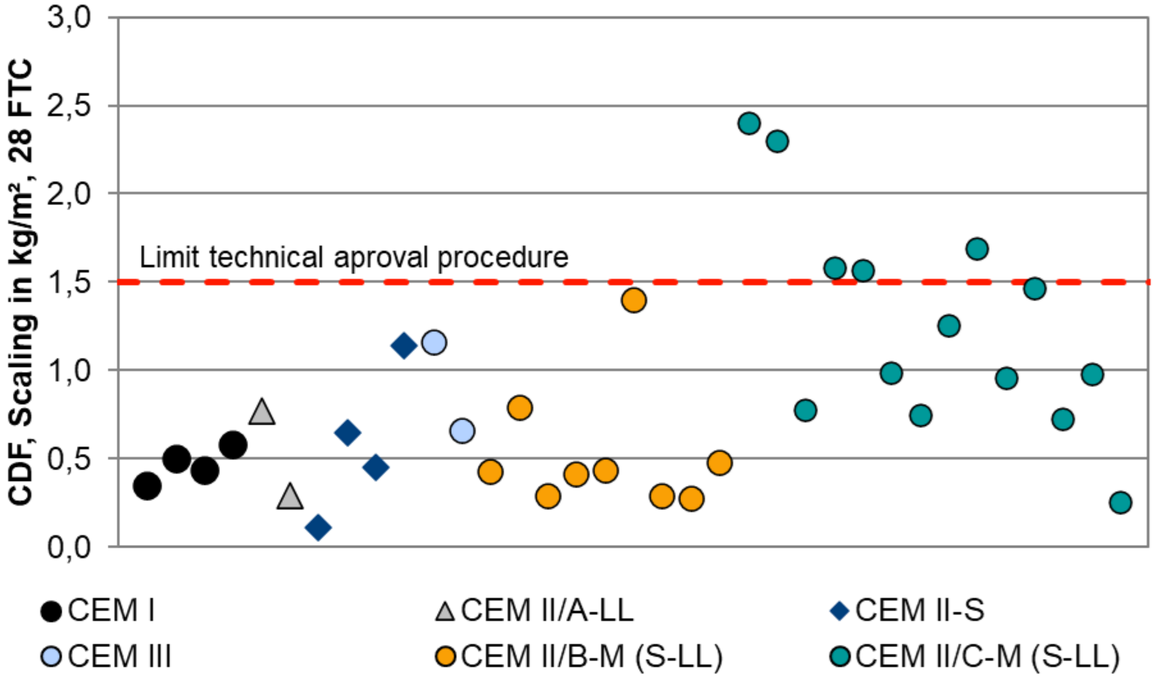


Figure 3 Scaling of concrete with a cement content of 320 kg/m^3, a water/cement ratio of 0.5 and an air content of 5.0 ± 0.5% by volume using the CDF method [9]

2.4 Technical approvals and application rules

Based on the evaluation in [5] the new German concrete standard DIN 1045-2 contains application rules for CEM II/C-M (S-LL) cements. The possible applications were discussed with science, building supervision, public builders and the construction industry. As a result, CEM II/C-M (S-LL) cements, such as CEM II/B-M (S-LL, V-LL, T-LL) cements, can in future be used in accordance with DIN 1045-2 with the exception of components with high water saturation and frost (XF3) as well as exposure to frost and de-icing salts (XF2, XF4) in all exposure classes (**Table 9**).

The normative regulation is also implemented in DIBt approvals: For the cements CEM II/B-M (S-LL, V-LL, T-LL) and CEM II/C-M (S-LL) without special properties, proof of durability only needs to be provided for XF2, XF3 and XF4 are provided. The new Portland composite cements CEM II/C-M, for which a number of general building authority approvals are available, can therefore be used for at least all exposure classes except XF2, XF3 and XF4. Concrete for normal building construction (internal components XC1 and external components XC4/XF1) can be produced with CEM II/C-M (S-LL) cements depending on availability. This is important insofar as about 65% of the in-situ concrete in Germany is used in these exposure classes. With proof in the approval, approval can also be given in XF2, XF3 and XF4. Such approvals are also available. The following types of cement can therefore be used in all exposure classes:

- Portland cement CEM I,
- Portland slag cements CEM II/A-S und CEM II/B-S,
- Portland burnt shale cements CEM II/A-T und CEM II/B-T,
- Portland limestone cements CEM II/A-LL,
- Portland fly ash cements CEM II/A-V und CEM II/B-V,
- Portland composite cements CEM II/A-M with S, LL, T, V bzw. D (1),
- Portland composite cements CEM II/B-M with S, T, V bzw. D (1),
- Portland composite cements CEM II/B-LL, CEM II/B-M and CEM II/C-M with (technical approval for the application “az”),
- Blast furnace cement CEM III/A (2),
- Blast furnace cement CEM III/B (3).

1) (D-V) not in XF2/XF4.

2) Exposure class XF4: CEM III/A of strength class ≥ 42.5 N or strength class 32.5 R with up to 50 % by mass of blast furnace slag.

3) CEM III/B may only be used in XF4 for the following applications:

a) Seawater components: w/c ≤ 0.45; Minimum strength class C35/45 and c ≥ 340 kg/m^3

b) Scraper tracks: w/c ≤ 0.35; Minimum strength class C40/50 and c ≥ 360 kg/m^3; Observance of DIN 19569-1

Artificial air pores can be dispensed with in both cases.

3 Further clinker efficiency in cement and concrete

3.1 Introduction

The decisive question is which concept can be used in the future to achieve the highest possible clinker and thus CO_2 efficiency while at the same time ensuring durability of the concrete. The concrete standard DIN 1045-2 currently provides fixed limits for the respective exposure class. So far, the following has applied to the use of cements: Use is either permitted or excluded. There is no variation in the limit composition depending on the performance of the cement. In practice, this approach has the advantage of being simple and not prone to errors. It is not optimal for resource efficiency and CO_2 reduction insofar as the deemed-to-satisfy rules come from times when the proportion of Portland cements in domestic shipments was still around 80 percent and there was no idea of CEM II/C and CEM VI cements. The tests of cements in concrete with regard to durability (carbonation, chloride penetration, frost and freeze-thaw salt resistance) are today carried out in a limit composition for the exposure class under consideration. These limiting compositions are borrowed from the concrete standard DIN 1045 - 2. In particular, a crucial parameter is the maximum water-cement ratio. A corresponding change in the boundary conditions in the test, e. g. B. a lowering of the water-cement ratio is possible in laboratory tests, but was not feasible under building regulations. This is changing now.

3.2 Case study lab

3.2.1 Introduction

In research projects [11, 12], cements with a high proportion of unburned limestone were produced and their performance in mortar and concrete was examined. Reference concretes were produced according to table F2.1 and F2.2 of DIN 1045-2. For the concretes with the new cements with a high limestone content, the water-cement ratio was reduced while maintaining the paste content and a constant slump was set by using superplasticizers. A lower consistency class was selected for concrete B4 in order to prevent the artificially introduced air voids from being ventilated too much. **Table 3** shows the Concrete composition.

Table 3 Concrete composition

	Concrete B1	Concrete B2	Concrete B3	Concrete B4
1	2	3	4	5
Cement content in kg/m^3	320	365	390	320 – 390
Water/Cement ratio	0.50	0.40	0.35	0,50 – 0,35
Air content in %	no requirement			4,5 ± 0,5
Paste content incl. aggregates <125μm in l/m^3	290 ± 5	290 ± 5	290 ± 5	290 ± 5
Flow table class acc. to DIN 1045-2	F3 - F4	F3 - F4	F3 - F4	F2 - F3

The resistance to chloride penetration and the freeze-thaw resistance of concretes in the CIF method was tested on concrete B1 to B3. The freeze-thaw resistance of concrete was determined using the CDF method on concrete B4.

The depth of carbonation was carried out on concrete prisms with the dimensions 40 mm x 40 mm x 160 mm and a grading curve A8/B8. This corresponds to the boundary conditions in the approval procedure of the German Institute for Building Technology (DIBt) for cements. Mortars with a water/cement ratio of w/c = 0.50 were produced without the use of superplasticizers with a cement content of 450 g per mixture. Mortars with a water/cement ratio of w/c = 0.40 were prepared with a cement content of 500 g per mix in order to maintain a constant paste content, mortars with w/c = 0.35 with 535 g per mix. Half of the prisms were stored in water at a temperature of (20 ± 1) °C for 7 days, the other half in water at a temperature of (20 ± 1) °C for 28 days. The specimens were then stored at a temperature of (20 ± 2) °C and a relative humidity of (65 ± 5) %. The carbonation depths after 140 days of storage serve to classify the results of earlier approval tests, as published in [13] (see

Figure 4).

3.3 Carbonation

With cements of a minimum clinker content of 20 % and a content of unburned limestone as a main constituent up to 50 % CO_2 efficiency could be increased significantly. For the time being these cements will be called CEM Y. First results [12] indicated that from a technical point of view new territory is entered regards cement production, cement properties and cement application.

Figure 4 show that a further significant reduction in the clinker content in cements with a high proportion of unburned limestone would be possible if the concretes are composed accordingly. With the same amount of slag, fly ash and calcined clay at global scale, a much greater volume of sustainable and durable concrete can be produced but exacting concrete technology measures will be needed.

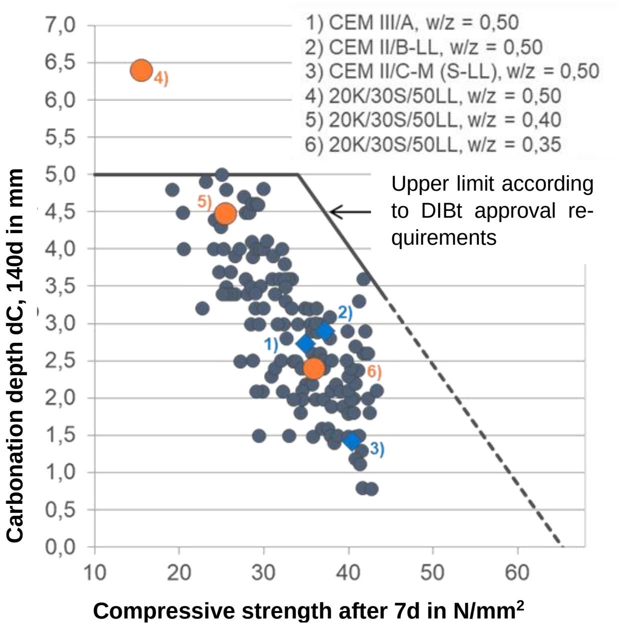


Figure 4 Carbonation: test results of clinker-efficient cements [12] against the assessment background of the German Institute for Building Technology (DIBt).

If the water-cement ratio is reduced to w/c = 0.40, the result is already in the upper range of the evaluation background. A further reduction to w/c = 0.35 leads to a result in the range of the reference cements. A further significant reduction in the clinker content in cements with a high proportion of unburnt limestone would therefore be possible if the concretes are composed accordingly.

3.3.1 Chloride ingress

The resistance of the concrete to chloride penetration was determined using a rapid method [14, 15] on concrete B1 to B3. The specimens (cubes 150 mm) for determining the migration coefficient were covered in the formwork for 1 day and then stored under water at a temperature of (20 ± 1) °C until testing. At the age of 28 and 91 days, a cylinder with a diameter of 100 mm was drilled out of the center of a cube. A test piece with a height of 50 mm was sawn out of each cylinder. The test specimens were further stored under water.

Figure 5 shows results for Portland cement and cements with 50 % unburned limestone at the age of 35 and 98 days. Portland cement concretes do not have high resistance to chloride penetration. The values for concrete with 50% unburnt limestone are even higher.

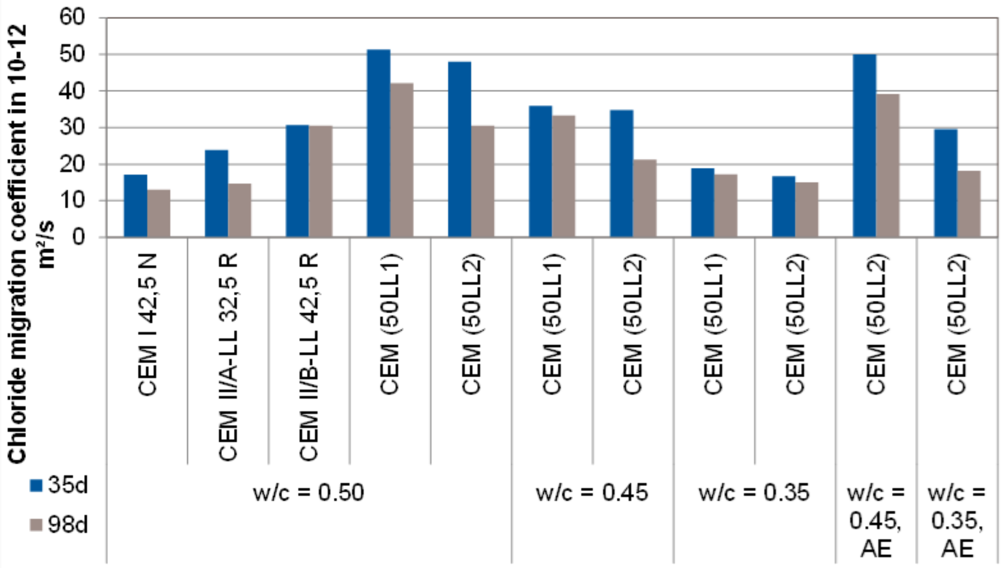
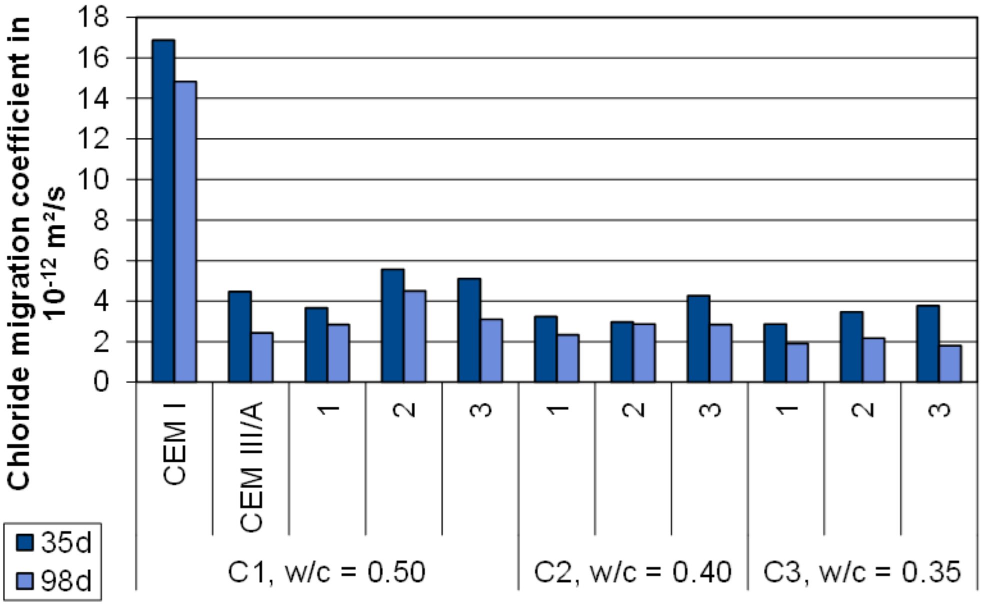


Figure 5 Chloride migration coefficient of concrete with Portland cement and cements with 50 % unburned limestone [11]



Cement 1: 50 % clinker, 30 % blast furnace, 20 % limestone

Cement 2: 35 % clinker, 35 % blast furnace, 30 % limestone

Cement 3: 20 % clinker, 30 % blast furnace, 50 % limestone

Figure 6 Chloride migration coefficient of concrete with Portland cement and cements with 50 % unburned limestone [12]

All concretes with cements 1-3 in **Figure 7** showed very low chloride migration coefficients - i.e. very high resistance to the penetration of chlorides - regardless of the water-cement ratio. This eliminated a major weakness of the cements examined in [11], which only contained limestone as a further main component. In the cements examined in the research project, 30% by mass of blast furnace slag was sufficient, regardless of the ratio of clinker to limestone, to ensure a high resistance to chloride penetration for applications such as in hydraulic engineering.

3.3.2 Freeze-thaw resistance

The Freeze-thaw resistance of concretes was determined using the CIF method according to CEN/TR 15177. For these tests, 5 test specimens with the dimensions 150 mm x 110 mm x 70 mm were produced for each concrete. 5 specimens each were protected from drafts and drying out in the molds for 24 hours at an air temperature of (20 ± 2) °C, 6 days under water at (20 ± 1) °C (pre-storage) and then 21 days at stored at a temperature of (20 ± 2) °C and a relative humidity of (65 ± 5) %. 2 to 7 days before the end of this dry storage, the side surfaces of the specimens were sealed with aluminum foil with butyl adhesive. At the age of 28 days, the 7-day capillary suction of the test specimens began. Following the capillary suction, 56 freeze-thaw changes were performed. The scaling and the relative dynamic modulus of elasticity were determined. The results are shown in **Figure 7** and **Figure 8** as mean values of 5 test specimens each.

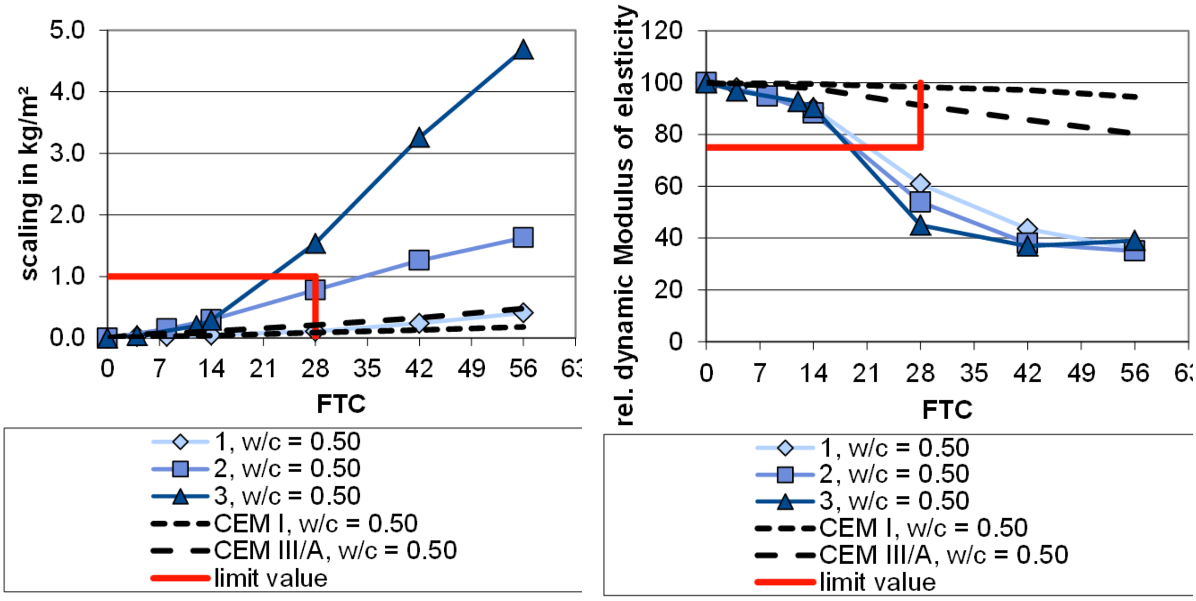


Figure 7 Scaling and rel. dynamic modulus of elasticity of concretes with water-cement ratios w/c = 0.50; 28d pre-storage [12]

In the event of freeze-thaw attack without de-icing agents, with unsuitable constituents or unsuitable concrete composition internal structural damage is to be expected in lab tests, which can be described by the relative dynamic modulus of elasticity.

Figure 7 shows, that concrete with cements 1-3 and w/c = 0.50 did not meet the criteria within the CIF-test. A lowering of the water/cement value to w/c = 0.40 led to a significantly lower decrease in the relative dynamic modulus of elasticity. The concrete with CEM (50K,30S,20LL) is below the limit value (without figure). If the water-cement ratio drops further to w/c = 0.35, the concretes with CEM (35K,30S,35LL) and CEM (20K,30S,50LL) are also below the limit value (**Figure 8**).

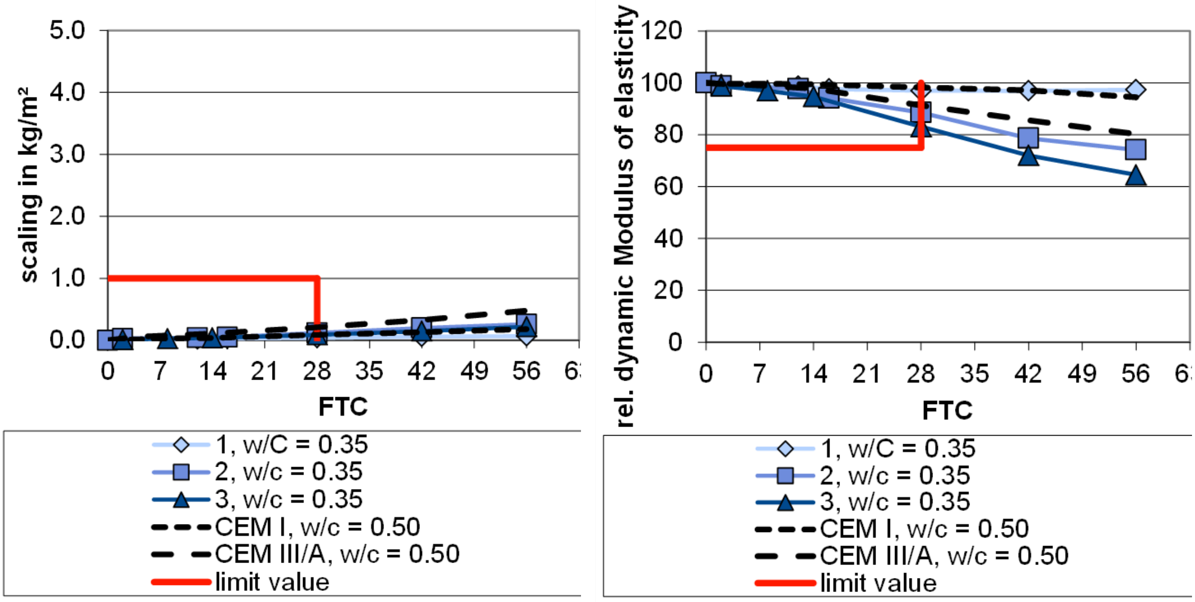


Figure 8 Scaling and rel. dynamic modulus of elasticity of concretes in the CDF test [12]

3.3.3 Freeze-thaw resistance with de-icer

The freeze-thaw resistance of concrete was determined using the CDF method in accordance with DIN EN 12390-9. For the tests on frost resistance, 5 test specimens with the dimensions 150 mm x 110 mm x 70 mm were produced for each concrete. The specimens were stored in the molds for 24 hours, protected from drafts and drying out, at an air temperature of (20 ± 2) °C, 6 days under water at (20 ± 1) °C (pre-storage) and then 21 days at a temperature of (20 ± 2) °C and a relative humidity of (65 ± 5) %. 2 to 7 days before the end of this dry storage, the side surfaces of the specimens were sealed with aluminum foil with butyl adhesive. At the age of 28 days, the 7-day capillary suction of the test specimens in a 3% sodium chloride solution began. Following the capillary suction, 28 freeze-thaw cycles were performed in a 3% sodium chloride solution. The scaling and the relative dynamic modulus of elasticity were determined.

Following capillary suction, 28 freeze-thaw changes were performed in 3% sodium chloride solution. The scaling and the relative dynamic modulus of elasticity were determined. The results are shown in **Figure 10** as mean values of 5 specimens per concrete.

In the event of a freeze-thaw attack with de-icer, unsuitable constituents or unsuitable concrete composition mainly will result in scaling.

Figure 10 shows that the test cements in the selected concretes did not have sufficient freeze-thaw resistance. However, the CEM III/A 42.5 N reference cement showed a similar scaling. Extending the pre-storage, possibly not under water but shrink-wrapped in foil so as not to increase the degree of saturation, could contribute to lowering the scaling.

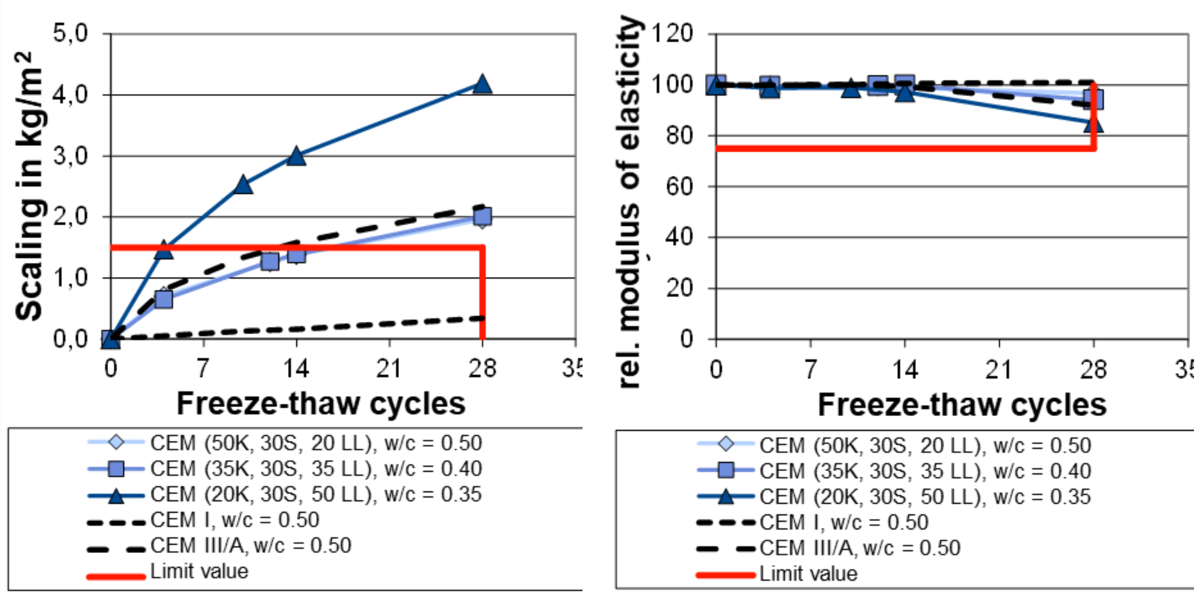


Figure 9 Scaling and rel. dynamic modulus of elasticity of concretes in the CDF test [12]

3.3.4 Case study field: CO2 efficient concrete for a new high-rise building in Berlin

During the construction of the EDGE East Side Berlin, CO_2-optimized concrete was used on the 32nd and 33rd floors (exposure class XC1). The composition of the concrete C40/50 is given as “Concrete 1” in **Table 4**. In comparison to the CSC benchmark for a C40/50 a CO_2 reduction of 57 % was achieved.

Table 4 EDGE East Side Berlin, CO_2-optimized concrete: Composition acc. to German concrete standard 2022 and acc. to future CEM X-technology [6, 7, 8]

Component	Concrete standard 2022 “Concrete 1”	CEM X-technology “Concrete 2”
	kg/m^3	
Cement	240 (CEM III/A)	365 (28 % clinker, 38 % slag, 34 % limestone filler)
Limestone filler	125	---
Water	127	
w/c	0.53	0.34
Aggregates	1901	
Admixtures (ref. to cement weight)		
Master Glenium 700	1.0 %	0.6 %
Master Suna SBS 6080	1.0 %	0.6 %
CO_2 -content	130	
CSC benchmark DE	300	
CO_2 saving	57 %	

Around 500 m^3 of concrete were placed on 12 concreting days. Some of the concrete was pumped at 25 m^3/h over a distance of up to 285 m. As the concrete had a low water content the stability against segregation and the sensitivity against temperature was an issue. Therefore, an AI-based, accompanying (online) quality assurance system was installed [6, 7, 8].

4 CEN Technical Report “Sustainable building with concrete”

A CEN Technical Report “Sustainable building with concrete” is under preparation. The CEN/T will have two parts. Part 1 [16] has the intention to give guidance, what measures can be taken in daily business already today to contribute to decarbonisation, resource efficiency and sustainability in the concrete sector. Part 2 [17] shows further measures and potentials to contribute to decarbonisation, resource efficiency and sustainability in the concrete sector in the medium and long term.

Table 5, which is taken from Part 1, shows in line 5 the average CO_2 emissions associated with the production of one cubic meter of concrete today in Germany – expressed as Global Warming Potential (GWP) in kg CO_2 equivalents per cubic meter of concrete, based on the environmental product declarations for concrete (for more information see [18]). As a guide, the table also contains values for concretes that would be 20 % or 30 % better than the average or up to 20 % above the current average with regard to the greenhouse gas emissions required for their production.

Table 5 Orientation values for greenhouse gas emissions from concrete (Case study Germany) [20]

1	**Designation**	**C20/25**	**C25/30**	**C30/37**	**C35/45**	**C45/55**	**C50/60**
2		Greenhouse gas emissions in kg CO_2-Equivalent/m^3 concrete					
3	Concrete for example with CEM VI or similar	125	138	153	171	200	210
4	Concrete for example with CEM III/A, CEM II/C or similar	142	158	175	195	229	240
5	Concrete, current average [1)]	178	197	219	244	286	300
6	Concrete with CEM I	213	237	261	286	312	325
	[1)] GWP values without incineration of waste in clinker production						

In addition to a classification based on the unit "kg CO_2-Equivalent per m^3 of concrete", **Table 6** shows a representation taking into account the performance of the concrete, i. e. "CO_2-Equivalent per (m^3 concrete x MPa)".

Table 6 Orientation values for performance-related greenhouse gas emissions from concrete (Case study Germany) [20]

1	**Designation**	**C20/25**	**C25/30**	**C30/37**	**C35/45**	**C45/55**	**C50/60**
2		Performance-related greenhouse gas emissions[1)] in kg CO_2-Equivalent/(m^3 x MPa)					
3	Concrete for example with CEM VI or similar	4,3	4,1	3,7	3,5	3,4	3,3
4	Concrete for example with CEM III/A, CEM II/C or similar	4,9	4,6	4,3	4,0	3,9	3,8
5	Concrete, current average	6,1	5,8	5,3	5,0	4,8	4,7
6	Concrete with CEM I	7,3	7,0	6,4	5,8	5,3	5,1
	[1)] Calculation of the values based on average compressive strength f_{cm}, cube: Example C20/25, line 3: $125/(f_{ck} + 4) = 125/29 = 4.3$.						

This illustration shows the following:

- In the higher strength classes, the performance-related greenhouse gas emissions are lower than in the lower strength classes.
- This performance-related consideration makes sense if the higher strength is used by reducing the component dimensions, i. e. if the building is slim and CO_2 is saved in the production of the component.
- If higher strengths are justified for static reasons or due to the exposure class, without any material savings being possible, the CO_2 efficiency of the concrete can be described on the basis of these values.

The applicability according to exposure classes according to DIN 1045-2, Tables F.3.1 to F.3.3 must be taken into account. The values in lines 4, 5 and 6 can in principle be used for all concretes or concrete components for normal building construction (internal components XC1 and external components XC4/XF1).

It should be emphasized that when specifying the concrete raw materials or concretes to be used, the structural requirements and the locally available resources must always be observed. Thus, it depends on good communication between those involved in the construction.

As shown above, the environmental impacts caused by the cement can be reduced by reducing the proportion of clinker in the concrete. The (local) availability on the market of the "substitutes" must be taken into account, but also that ecologically optimized concrete compositions can only be compared with conventional compositions if they can also guarantee constant strength, durability and quality.

In the production of precast concrete parts, for example, the concrete has a high early strength in order to achieve the shortest possible stripping times. Precast plants therefore often use higher concrete compressive strength classes with which the cross-sectional dimensions can be reduced. The recipes can be further optimized from an economic and ecological point of view thanks to the production conditions in the precast factory under permanent quality control.

Figure 10 shows that the greater the concrete compressive strength, the greater the global warming potential per m^3 of concrete. In relation to the concrete compressive strength, however, the specific global warming potential of concrete decreases with increasing compressive strength class (see also **Table 6**). Correct assessment of the environmental impact of a building material can therefore only be made in connection with the specific building task and the boundary conditions there – i. e. at the building level.

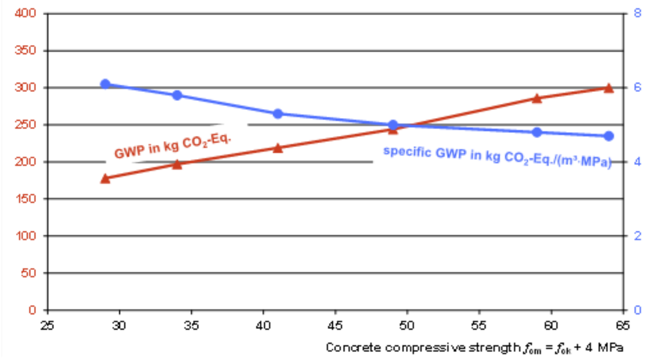


Figure 10 Relationship between concrete compressive strength and global warming potential (GWP) or performance-related global warming potential (specific GWP); Values from Table 5, line 5 and Table 6, line 5

As part of the Concrete Sustainability Council (CSC), a global certification system was established, which is intended to provide companies in the concrete, cement and aggregate sector with information on the extent to which they are operating in an ecologically, socially and economically responsible manner in the production of concrete (CSC concrete certificate). The CSC works in the implementation with so-called regional system operators. In Germany, this task has been taken over by the German Ready-Mixed Concrete Association (Bundesverband der Deutschen Transportbetonindustrie BTB) and operates this system (source: www.csc-zertifikation.de).

A new “CO_2 module” as a voluntary, additional module to the CSC concrete certificate has been established. Its aim is to create transparency with regard to the greenhouse gas emissions associated with concrete production and to divide CO_2-reduced concretes into four CO_2-classes (see **Table 7** and

Table 8).

Table 7 CO_2-classes according to [19]: Description

CO_2-class	**Description**
Level 1	Reduction of greenhouse gas emissions by at least 30 % compared to an average concrete with CEM I.
Level 2	Reduction of greenhouse gas emissions by at least 40 % compared to an average concrete with CEM I.
Level 3	Reduction of greenhouse gas emissions by at least 50 % compared to an average concrete with CEM I.
Level 4	Reduction of greenhouse gas emissions by at least 60 % compared to an average concrete with CEM I.

Table 8 CO_2-classes according to [19]: Maximum permitted greenhouse gas emissions

CO_2 -classes	C20/25	C25/30	C30/37	C35/45	C45/55	C50/60
Maximum permitted greenhouse gas emissions [net [1] kg CO_2 eq/m^3]						
Industry benchmark	213	237	261	286	312	325
GWP value for average concrete (informative)	178	197	219	244	286	300
Level1 (↓ ≥ 30 %)	149	166	183	200	218	228
Level2 (↓ ≥ 40 %)	128	142	157	172	187	195
Level3 (↓ ≥ 50 %)	107	119	131	143	156	163
Level4 (↓ ≥ 60 %)	85	95	104	114	125	130
1) GWP values without incineration of waste in clinker production						

The CO_2 module is a certification at product level and does not replace an environmental product declaration (EPD) according to DIN EN 15804.

Today, CO_2 -reduced concretes of levels 3 and 4 can only be applied in very few exceptional cases in accordance with the building regulations. Possible restrictions regarding the durability of the concrete, the construction and the availability of suitable constituents must be taken into account. The feasibility of each project must be clarified individually with the concrete producer.

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Table 9

Areas of application for CEM II-M cements with three main components according to DIN EN 197-1, EN 197-5, DIN 1045-10, and FE cements as well as CEM I-SE and CEM II-SE according to DIN 1164-11 for the production of Concrete according to DIN 1045-2:2023; Table F.5.

Exposure class X = valid scope ○ = for concrete acc. to this standard not applicable				No corrosion/ attack risk	Corrosion of the reinforcement										Attack on concrete										prestressing steel compatibility
					corrosion caused by carbonation				corrosion caused by chlorides						Freeze-thaw attack				Aggressive chemical exposure			Wear			
									other chlorides than sea water			Chlorides from sea water													
				XO	**XC1**	**XC2**	**XC3**	**XC4**	**XD1**	**XD2**	**XD3**	**XS1**	**XS2**	**XS3**	**XF1**	**XF2**	**XF3**	**XF4**	**XA1**	**XA2**^{d}	**XA3**^{a}	**XM1**	**XM2**	**XM3**	
CEM II	**A**	**M**	S-D; S-T; S-LL; D-T; D-LL; T-LL; S-V^{i}; V-T^{i}; V-LL^{i}	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
			S-P; S-Q D-P; D-V^{i}; D-Q P-V^{i}; P-T; P-Q P-LL; Q-V, Q-T, Q-LL	X	X	X	X	X	X	X	X	X	X	X	X	○	X	○	X	X	X	X	X	X	X^{f}
	B		S-D; S-T; D-T; S-V^{i}; V-T^{i}	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
			S-P; S-Q, D-P; D-V^{i}; D-Q P-T; P-Q, P-V^{i} Q-V, Q-T	X	X	X	X	X	X	X	X	X	X	X	X	○	X	○	X	X	X	X	X	X	X^{f}
			S-LL^{k}, V-LL^{k} T-LL^{k} *)	X	X	X	X	X	X	X	X	X	X	X	X	○	○	○	X	X	X	X	X	X	X^{f}
			S-LL; D-LL; P-LL; Q-LL, V-LL^{i} T-LL	X	X	X	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	X^{f}
	C		S-LL **)	X	X	X	X	X	X	X	X	X	X	X	X	○	○	○	X	X	X	X	X	X	X^{f}

Footnotes not listed;

*) The limestone content of the cements (S-LL), (V-LL) and (T-LL) is limited to 20% by mass. Compliance with the maximum permissible limestone content must be declared by the manufacturer of the cement

*) The limestone content of the cement CEM II/C-M (S-LL) is limited to 20% by mass in EN 197-5.