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DURAFOR - Forecast of durability properties of concrete with new clinker based cements

DURAFOR - Vorhersage der Dauerhaftigkeit von Betonen mit neuen klinkerbasierten Zementen

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Internationale Partner:
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CRIC-OCCN (Belgien)

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Forecast of durability properties of concrete with new clinker based cements

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1 Aim of project

Concrete is, after water, the most used material worldwide. In 2013, the concrete production in Europe acc. to ERMCO statistics (European ready-mixed concrete organization) was 338 million cubic meters corresponding with a turnover of 9,656 million €. Due to different climatic conditions and construction traditions, the European concrete standard EN 206 is not harmonised. Therefore, the rules for the application of concrete and the application of different cements in concrete are not the same in Europe. Every member state is allowed to have its own application document with respect to EN 206, giving, among others, different rules for the application of cements in concrete. If new cements or cements which are not well-tried and proven shall be introduced in a local market, each member state has its own technical assessment procedure or equivalent means of proof. In most cases, those procedures include durability tests on concrete. The assessment of new cements for application in concrete e. g. can follow an European technical assessment (ETA) acc. to the CPR, which will be based, among others, on durability tests.

Cement producers developing new clinker-efficient and ecologically beneficial cements need tools to predict, whether their products will fulfil the assessment criteria, defined in an ETA for cement or concrete. Characteristic values of cement with a correlation to durability test results, which were developed in this project, could be helpful and cost-efficient.

Additionally, a cement or concrete, which is tested according to an ETA, has to be quality controlled. The compressive strength, as will be shown in the respective chapter of this report, is not a sufficient criterion for durability in every case. The defined characteristic values could also be used for quality control in combination with a durability test as a calibration or initial test.

The new method for predicting concrete durability, based on mortar properties, is much more cost-efficient and time-saving compared to testing concrete durability in the stage of developing new cements and in the stage of quality control.

2 Work packages

The project was divided in five work packages (WP), described in **Table 1**.

Table 1 Work packages

No	WP	Responsible
1	Survey	CRIC-OCCN
2	Evaluation and definition of cements and main constituents	VDZ
3	Cement characterization	Smart minerals
4	Durability Concrete tests	VDZ
5	Characteristic values	VDZ

3 WP1: Survey

The laboratory tests were preceded by the evaluation of two European surveys and an European Assessment Document, EAD in order to map the range of concrete compositions used in Europe and to define the concrete compositions and durability test procedures in the project:

- CEN/TR 15868:2009 „Survey of national requirements used in conjunction with EN 206-1:2000“
- DRAFT 2 CEN/TR: European experience with performance testing for durability and the specification of durability by performance (by T. Harrison)
- CEN/TR 16563:2013: Principles of the equivalent durability procedure
- EAD 15001-00-0301: Calcium Sulphoaluminate based cements

As a result, the concretes and test methods described in chapter 6 were defined.

4 WP2 and WP3: Main constituents and cement characterization

4.1 General

In addition to 3 reference cements, which were examined by each project partner involved (CRIC, SMG, VDZ), 12 laboratory cements were prepared in 2 modifications per research site (see **Table 2** and **Table 3**) and tested to determine their standard properties. Various particle sizes of the cement main constituents were selected as modifications: In the VDZ, the fineness and chemical-mineralogical composition of the main constituents beside clinker were kept constant and either a clinker of high fineness (modification A) or a clinker of low fineness (modification B) were chosen. In the SMG, a clinker of constant fineness and chemical-mineralogical composition was combined with other main constituents of different fineness, while CRIC combined all cement components in comparable fineness. All of the project partners used a CEM I with a specific fineness for the clinker component. The clinker content in the respective CEM I was calculated with 100 M.-% (see **Table 2**). Particle size distributions and chemical analysis of all components can be found in the annex (see **Table 6** to **Table 9** and **Figure 54** and **Figure 55**).

In particular, cements with compositions according to CEM II/B-M according to currently valid EN 197-1 and CEM II/C-M and CEM VI cements according to the current draft of EN 197-1 were considered. From these 52 cements, one Portland cement as a reference and further 6 cements per project partner for work package 4 were selected.

Table 2 Assignment of the tested cements in WP 2 and 3 to the project partners (1)

No	1	2	3	4	5	6	7
Cement	CEM I	CEM II/A-LL	CEM III/A	CEM VI	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)
Composition	100 CEM I	~20 LL	>50 S	35% CEM I 20% LL 45% S	50% CEM I 20% LL 30% S	50% CEM I 20% LL 30% V	50% CEM I 20% V 30% S
Variation	1-2	1	1	2	2	2	2
CRIC	x	x	x	-	x	x	x
SMG	x	x	x	x	-	x	x
VDZ	x	x	x	x	x	-	-

Table 3 Assignment of the tested cements in WP 2 and 3 to the project partners (2)

No	8	9	10	11	12	13	14	15
Cement	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (T-LL)	CEM II/B-M (D-LL)	CEM II/B-M (V-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
Compositi-on	68% CEM I 12% LL 10% S 10% V	65% CEM I 20% LL 15% S	Werksze-mente	70% CEM I 10% D 20% LL	65% CEM I 20% LL 15% V	65% CEM I 35% LL	80% CEM I 20% S	20% CEM I 80% S
Variation	2	2	2	2	2	2	2	2
CRIC	x	-	-	x	x	x	-	x
SMG	x	x	-	-	x	-	x	-
VDZ	-	x	x	x	-	x	x	x

4.2 Compressive strength

The results of the compressive strength tests according to EN 196-1 on the reference cements, which were investigated in parallel by each project partner, are shown in **Figure 1**.

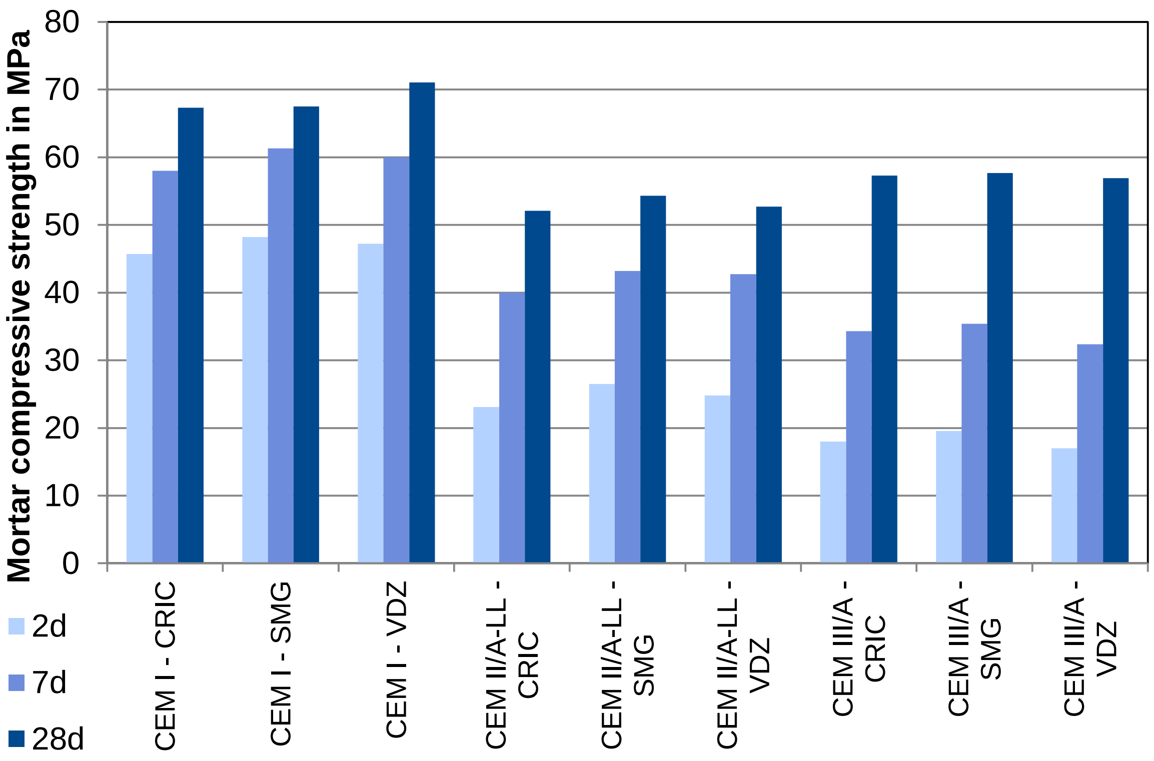

Figure 1 Mortar compressive strength of reference cements

The results of the compressive strength tests according to EN 196-1 of the test cements in 2 modifications according to **Table 2** and **Table 3** are shown in **Figure 2** and **Figure 3** and in the annex, **Table 10** to **Table 18**.

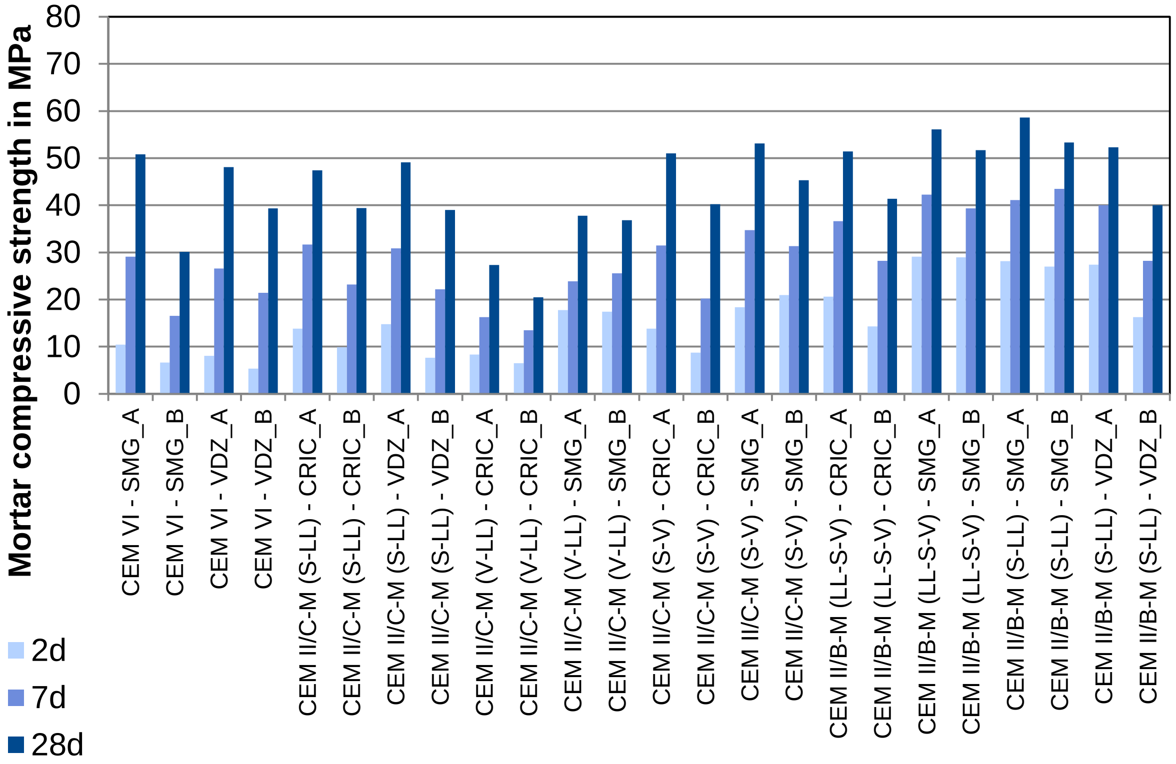

Figure 2 Mortar compressive strength of laboratory cements (1)

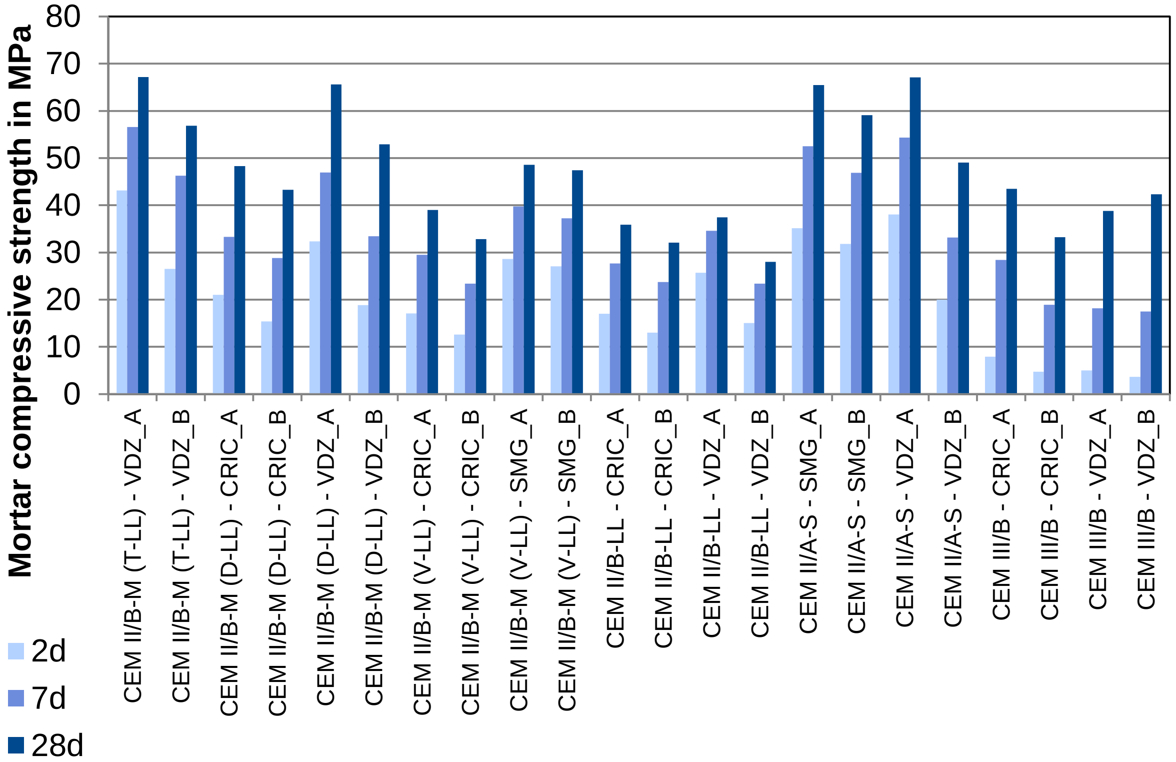

Figure 3 Mortar compressive strength of laboratory cements (2)

4.3 Selection of cements

On the basis of the results of WP 2 and WP3, the following cements were selected for work package 4 (**Table 4**). The selection was based on the following criteria:

- Focus on cements that may not be used in all exposure classes in many countries
- Cements that have different mortar properties with the same composition
- Cements that have similar mortar properties despite different starting materials

Table 4 Cements selected for WP 4

	CRIC	SMG	VDZ
1	CEM I 52,5 R	CEM I 52,5 R	CEM I 52,5 R
2	CEM II/C-M (S-LL) (A)	CEM VI (B)	CEM VI (A)
3	CEM II/C-M (V-LL) (B)	CEM II/C-M (V-LL) (A)	CEM II/C-M (S-LL) (B)
4	CEM II/C-M (S-V) (B)	CEM II/C-M (S-V) (B)	CEM II/B-M (S-LL) (A)
5	CEM II/B-M (LL-S-V) (B)	CEM II/B-M (LL-S-V) (A)	CEM II/B-LL (A)
6	CEM II/B-M (V-LL) (B)	CEM II/B-M (S-LL) (B)	CEM II/A-S (B)
7	CEM II/B-LL (B)	CEM II/B-M (V-LL) (A)	CEM III/B (A)

(A): CRIC: Clinker fine; S, LL, V fine, SMG: Clinker constant; S, LL, V fine, VDZ: clinker fine; S, LL, V constant

(B): CRIC: Clinker coarse; S, LL, V coarse, SMG: Clinker constant; S, LL, V coarse, VDZ: clinker coarse; S, LL, V constant

4.4 Chemical bound water of selected cements

The chemical bound water was determined on cement stone with a water/cement ratio of w/c = 0.40 at the age of 2d, 7d and 28d. At each given age, the hydration was stopped by grinding the respective cement stone in acetone. After that, the sample was washed with diethyl ether 2-4 times and was dried at 60°C for 60min to remove remaining diethyl ether. If the determination of the chemical bound water could not be started directly, the sample was put in a sufficient container and filled with argon.

The chemical bound water was determined by CO_2 / H_2O – IR-spectroscopy (VDZ, SMG) and by Simultaneous Thermal Analysis, STA (CRIC, all samples). The comparison of both results at different ages is shown in **Figure 4**.

The results can be found in the annex, **Table 6** to **Table 9**.

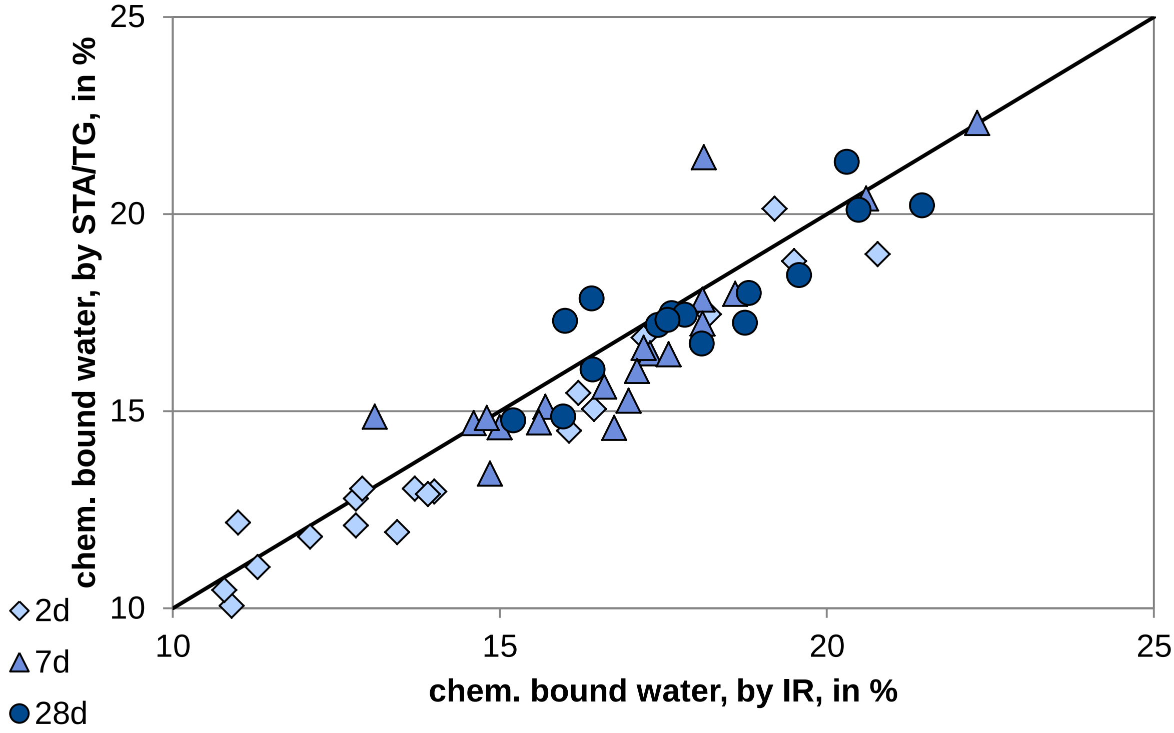

Figure 4 Comparison of chemical bound water determined by STA and IR

4.5 Porosity

The porosity of each standard mortar was determined at an age of 28d. To evaluate the correlation between porosities of mortars with the same cement but different water/cement ratios, additional mortars were produced at VDZ. The paste contents of all mortars were kept constant:

- Standard mortar: w/c = 0.50; c = 450 g
- Mortar 2: w/c = 0.45; c = 480 g
- Mortar 3: w/c = 0.55; c = 425 g
- Mortar 4: w/c = 0.65; c = 380 g

The results of all mortars are shown in **Figure 5** to **Figure 8** and in the annex, **Table 22** to **Table 24**.

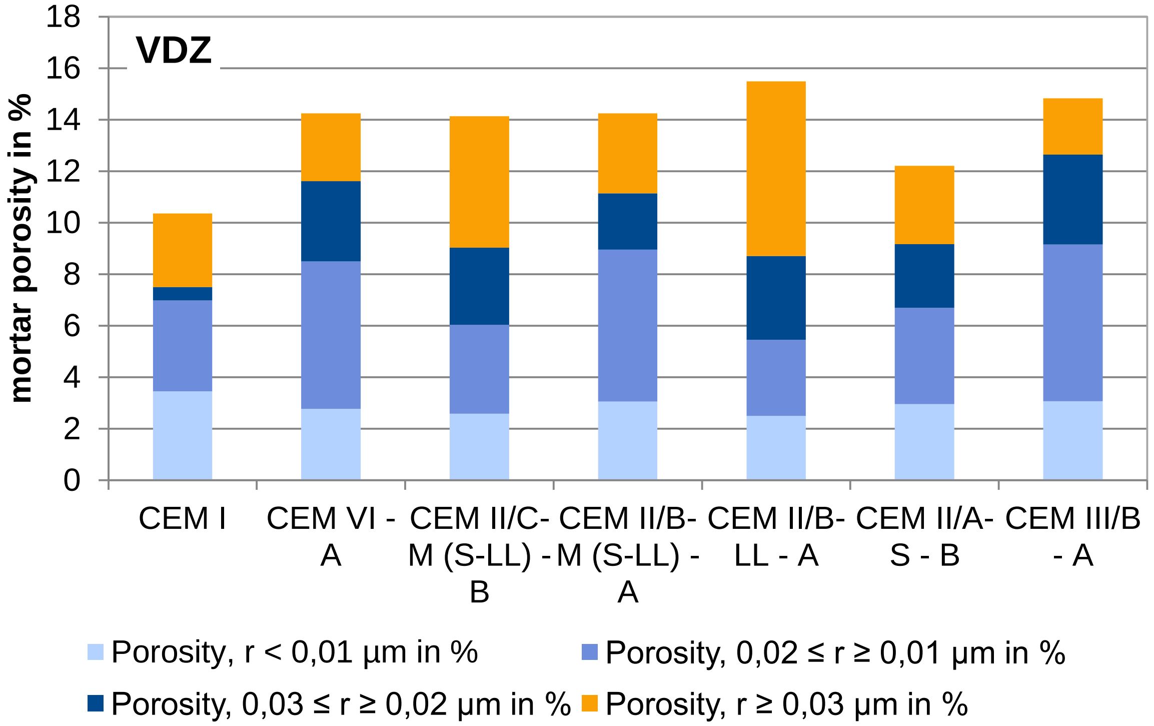

Figure 5 Porosity of standard mortars (VDZ)

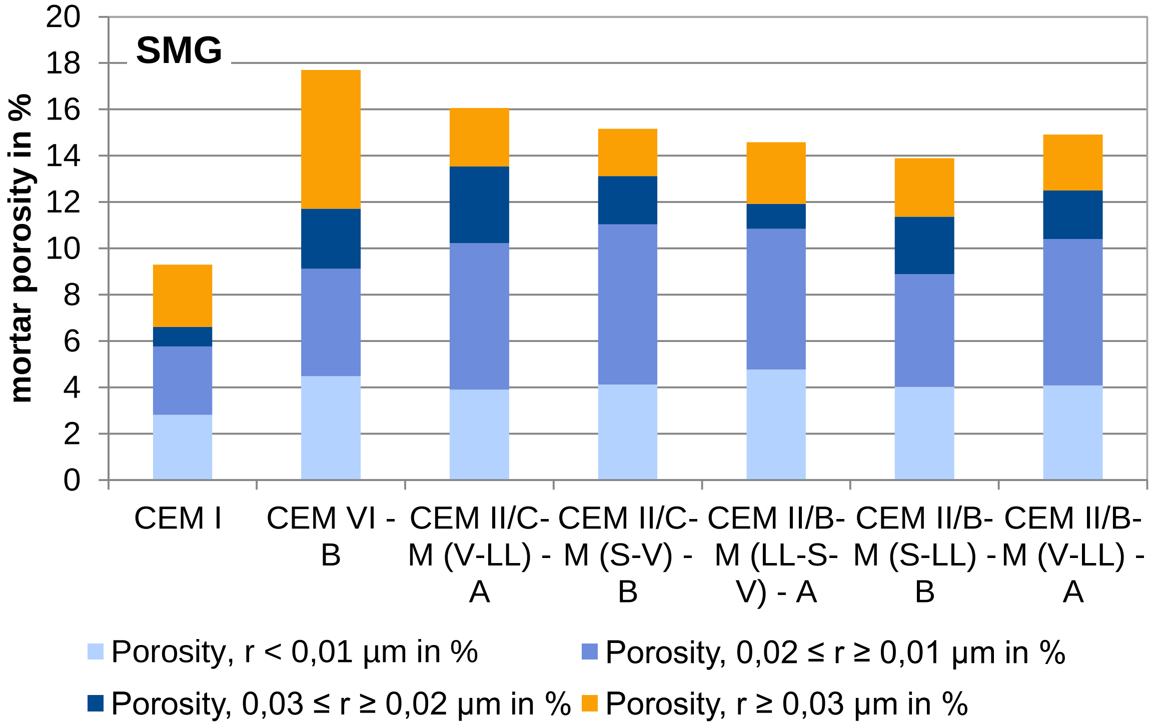

Figure 6 Porosity of standard mortars (SMG)

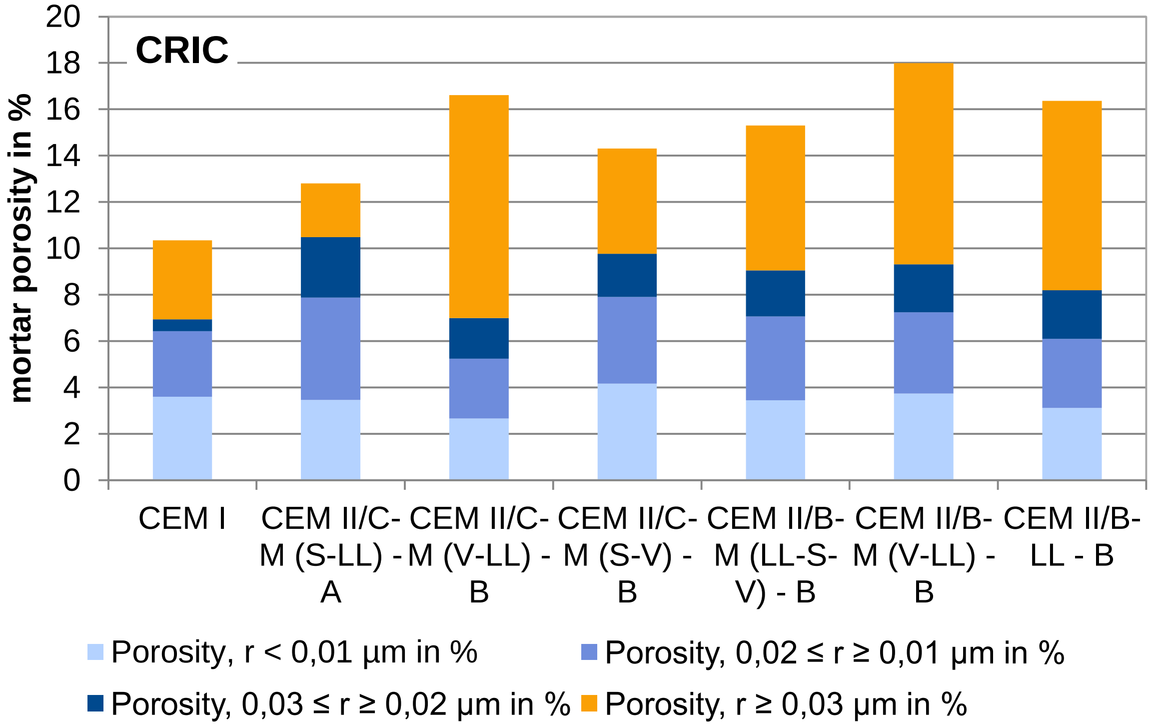

Figure 7 Porosity of standard mortars (CRIC)

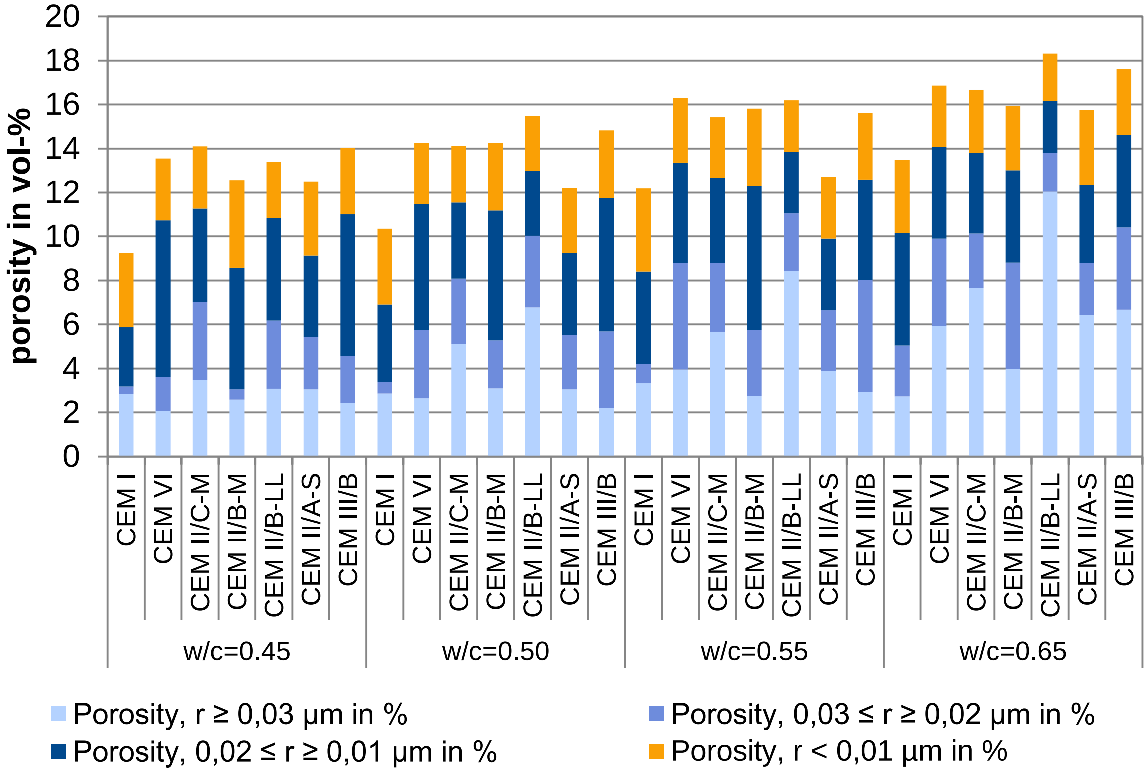

Figure 8 Porosity of mortars with different w/c ratios (VDZ)

The effect of increased or decreased water/cement ratios on the porosity p was evaluated by using Equation 1:

Equation 1 $$p(mortar) = \frac{w/c(mortar)}{w/c(standard\ mortar)} \times p(standard\ mortar)$$

Figure 9 shows, that there is a good correlation of Equation 1 with the measured results.

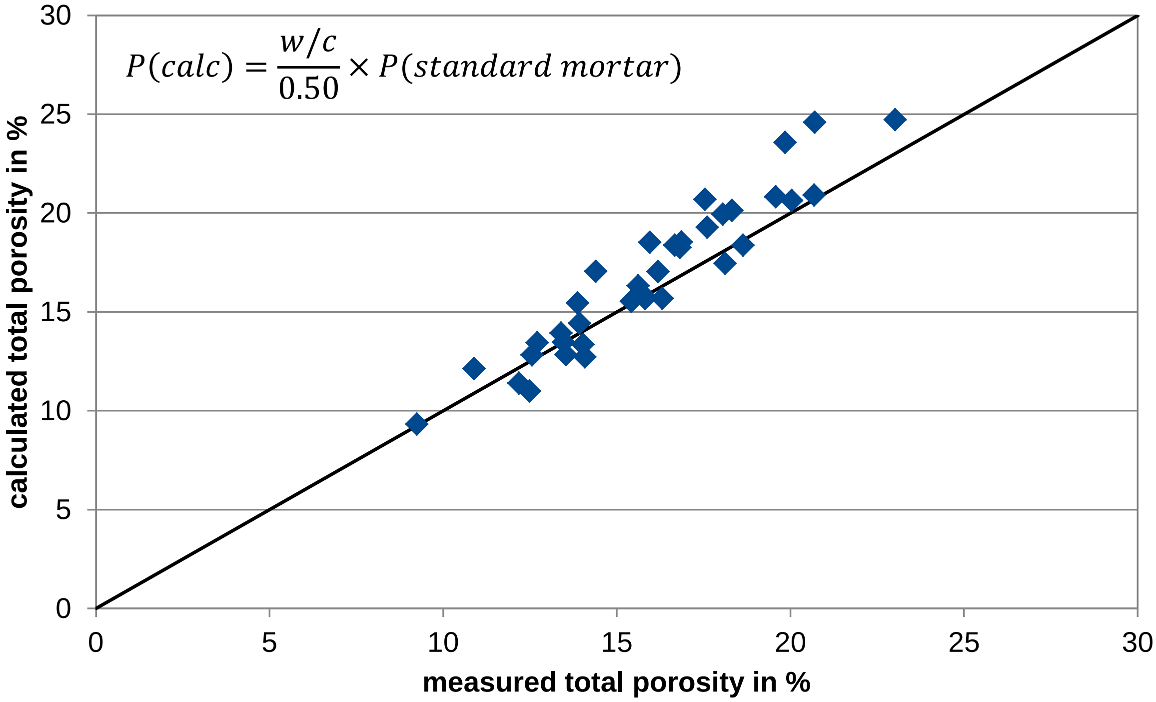

Figure 9 Comparison of measured and calculated porosity

5 WP4: Concrete compressive strength and durability

5.1 General

The definition of the concrete compositions (**Table 5**) was based on WP1. As reference concrete C1, the "EAD concrete" defined in **Table 5** was chosen for all tests except for the determination of freeze-thaw resistance with de-icing salts. Freeze-thaw resistance with de-icing salts was tested on air entrained concretes (C4 and C5). In addition to concrete C1, for each durability test, the concrete with the lowest cement content and the highest water/cement ratio in the relevant exposure class was selected from CEN/TR 15868. Thus, in addition to a large variety of different cements, a wide range of concretes common in Europe was investigated.

Table 5 Composition and testing of concretes

Concrete	Cement content in kg/m³	w/c	Air content in %	Origin	Testing acc. to
C1	350	0.50	-	EAD	Carbonation: EN 13295 with 1 % CO_2 Sulfate resistance: SIA 262, Annex D Chloride diffusion: EN 12390-11:2015 Chloride migration: NT BUILD 492 (Migration) Freeze-thaw resistance: CIF (CEN/TS 12390-9 in combination with CEN/TR 15177)
C2	260	0.65	-	CEN/TR: Germany	Carbonation: EN 13295 with 1 % CO_2
C3	300	0.55	-	CEN/TR: Austria	Sulfate resistance: SIA 262, Annex D Chloride diffusion: EN 12390-11:2015 Chloride migration: NT BUILD 492 (Migration)
C4	340	0.45	5 ± 2	CEN/TR: most used	Freeze-thaw resistance with de-icing salts: slab test CEN/TS 12390-9
C5	300	0.55	5 ± 2	CEN/TR: UK	Freeze-thaw resistance with de-icing salts: slab test CEN/TS 12390-9

5.2 Aggregates

Local aggregates with a grading curve acc. to EN 480-1 were used to produce the concretes. These were:

- VDZ – Rhein sand and gravel
- SMG – Danube sand and gravel (Bad Fischau); carbonate dominated composition
- CRIC – Limestone

The grading curves are shown in **Figure 10**.

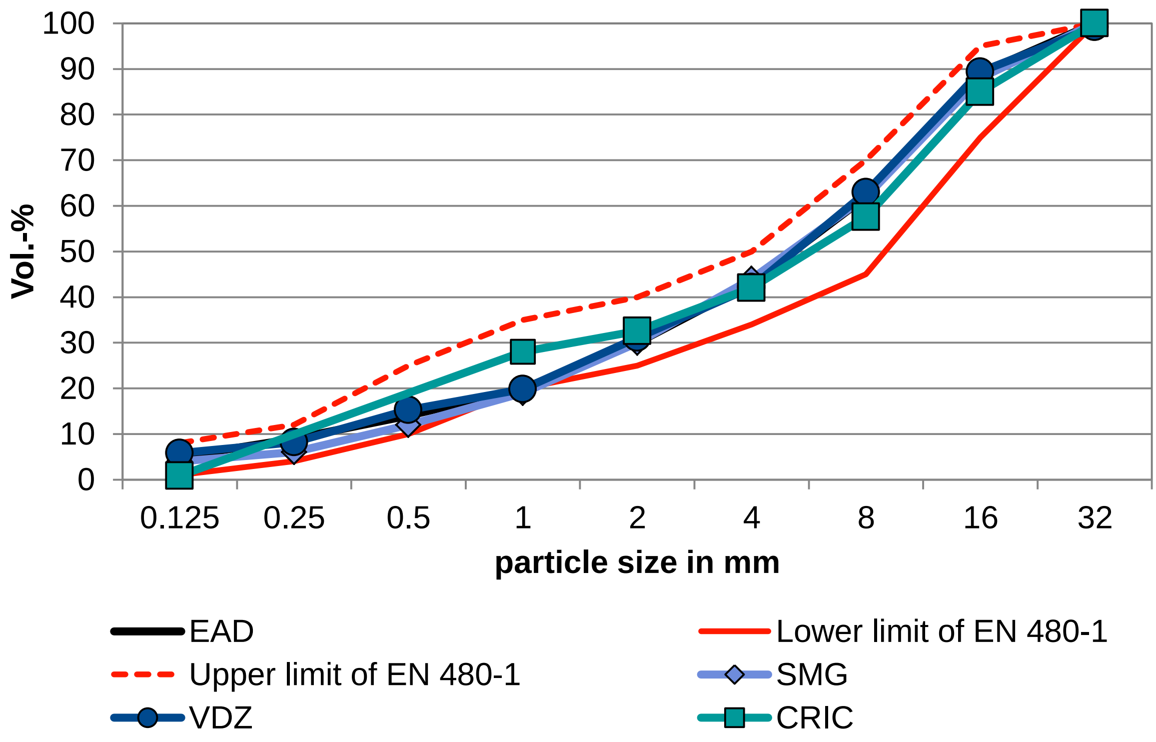

Figure 10 Grading curves of aggregates used in the project

5.3 Fresh concrete properties

In addition to the tests listed in **Table 5**, the slump acc. to EN 12350-2 or flow diameter acc. to EN 12350-5 (**Figure 11**, **Figure 13** and **Figure 15**) and the fresh concrete air content acc. to EN 12350-7 (**Figure 12**, **Figure 14** and **Figure 16**) were determined on each concrete. The results can additionally be found in the annex, **Table 25** to **Table 27**.

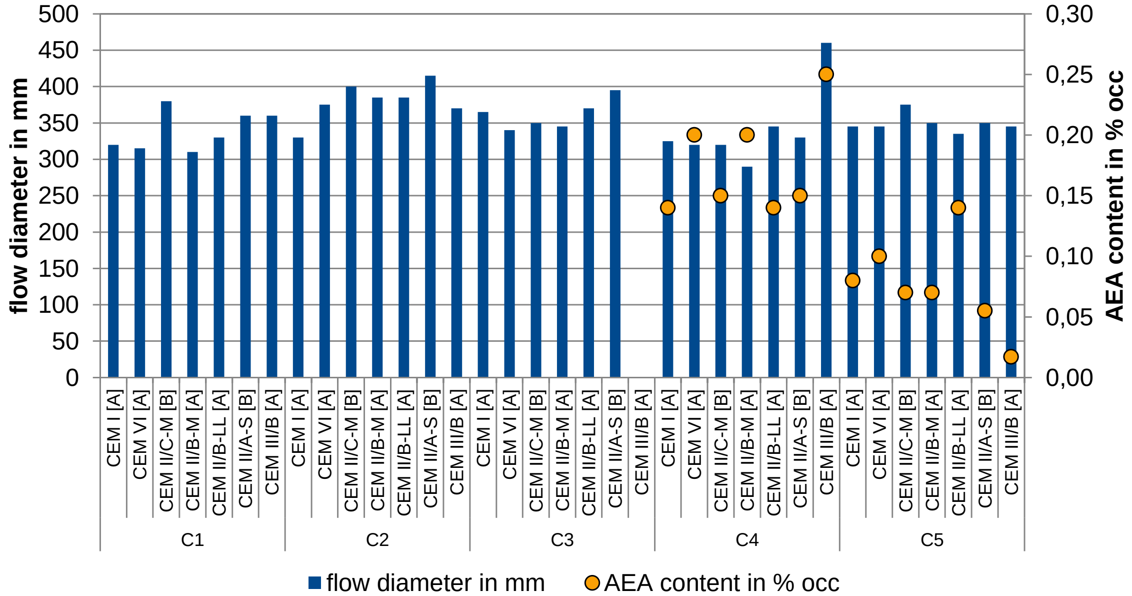

Figure 11 Flow diameters of concretes C1 – C5 (VDZ)

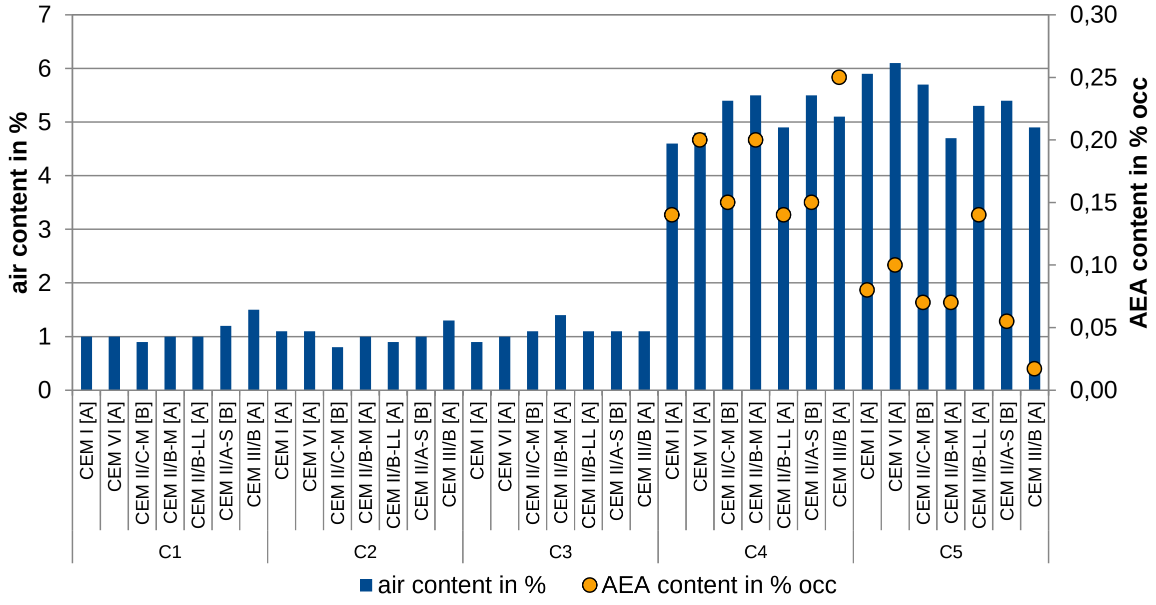

Figure 12 Fresh concrete air contents of concretes C1 – C5 (VDZ)

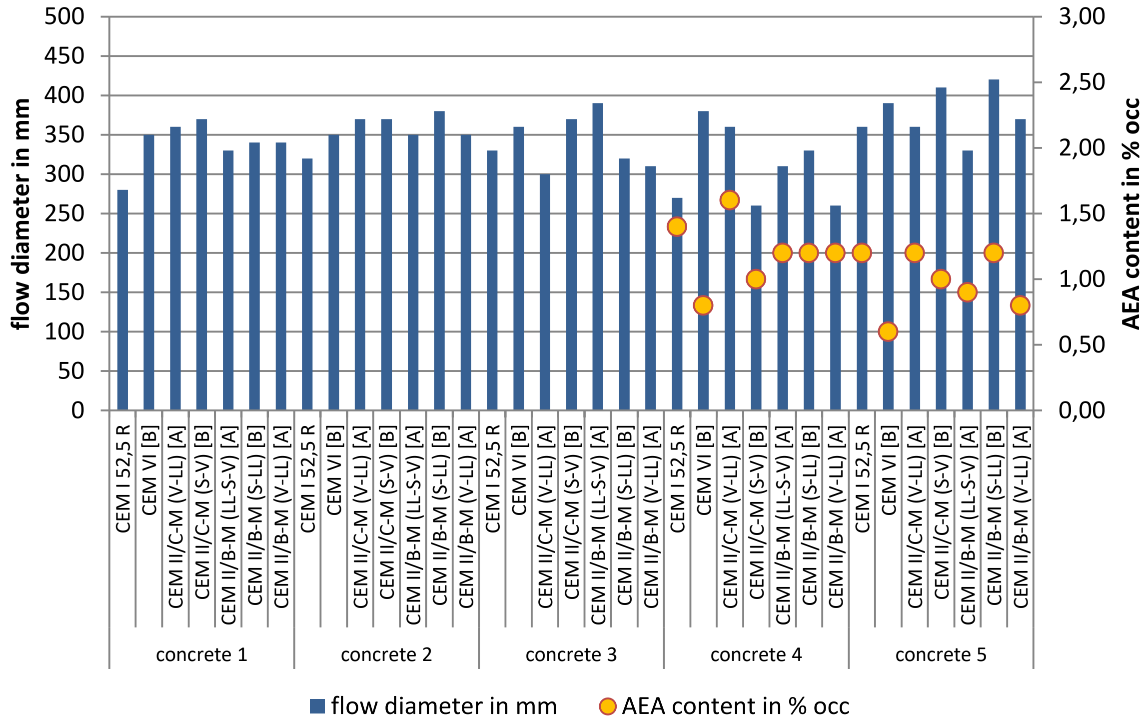

Figure 13 Flow diameters of concretes C1 – C5 (SMG)

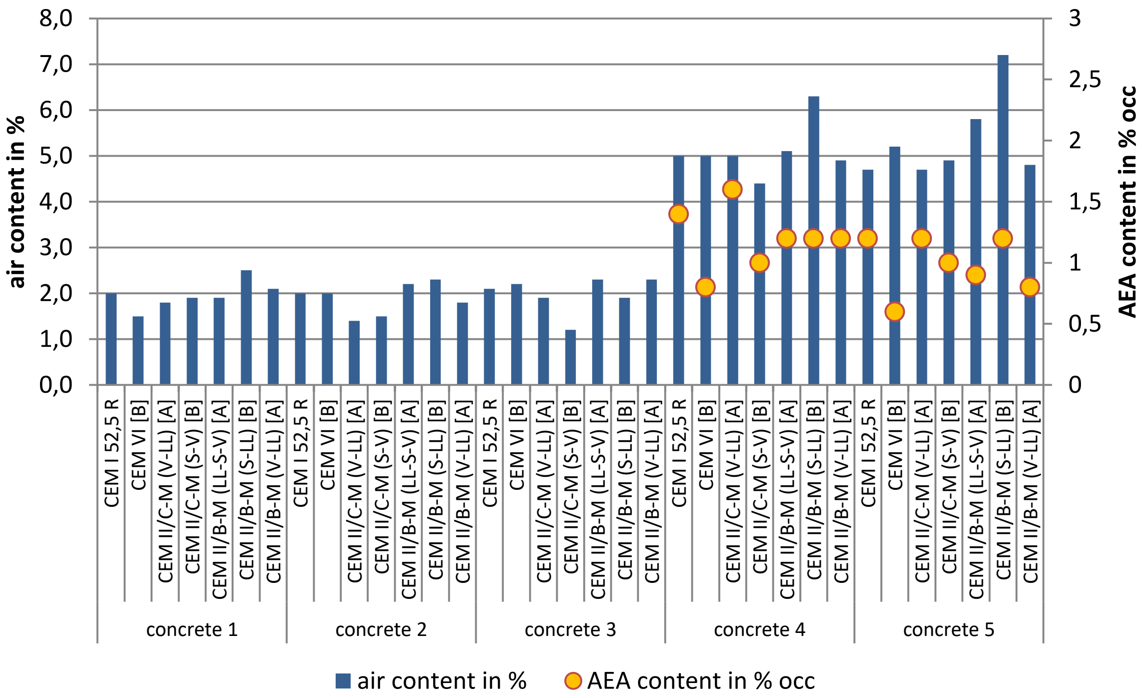

Figure 14 Fresh concrete air contents of concretes C1 – C5 (SMG)

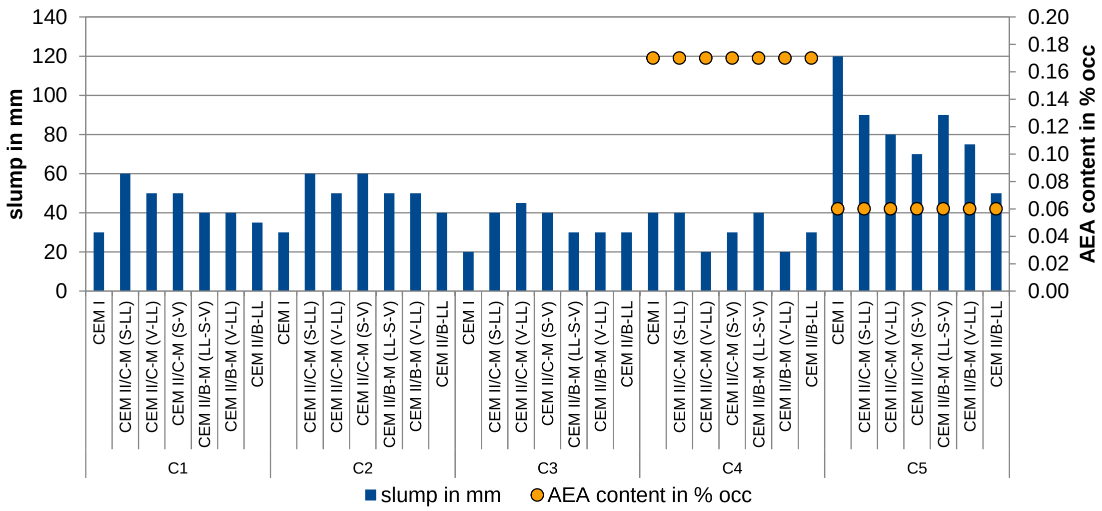

Figure 15 Slump of concretes C1 – C5 (CRIC)

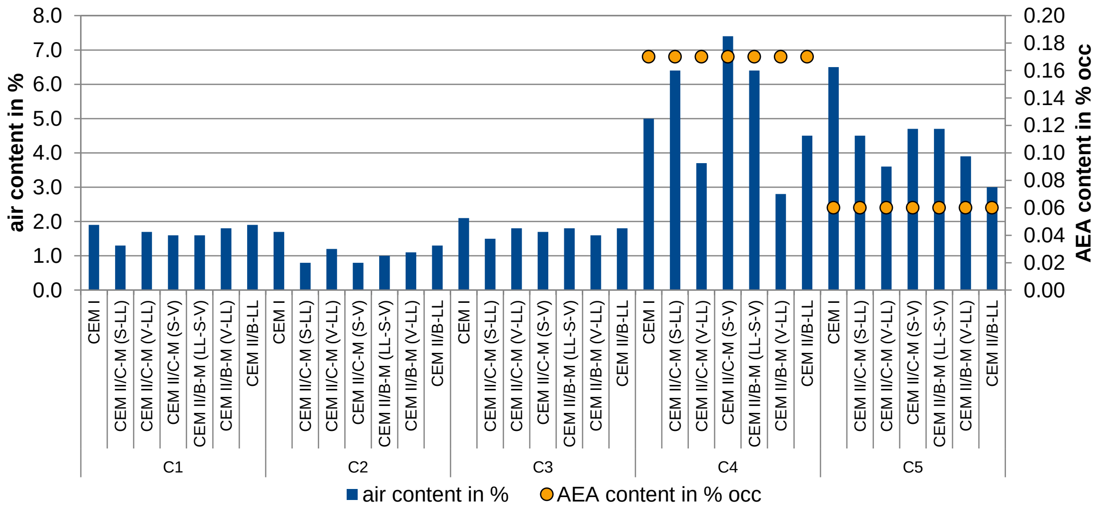

Figure 16 Fresh concrete air contents of concretes C1 – C5 (CRIC)

5.4 Compressive strength

Compressive strengths were tested acc. to EN 12390-2 at the ages of 2d and 28d. The results are shown in **Figure 17** to **Figure 21** and in the annex, **Table 25** to **Table 27**.

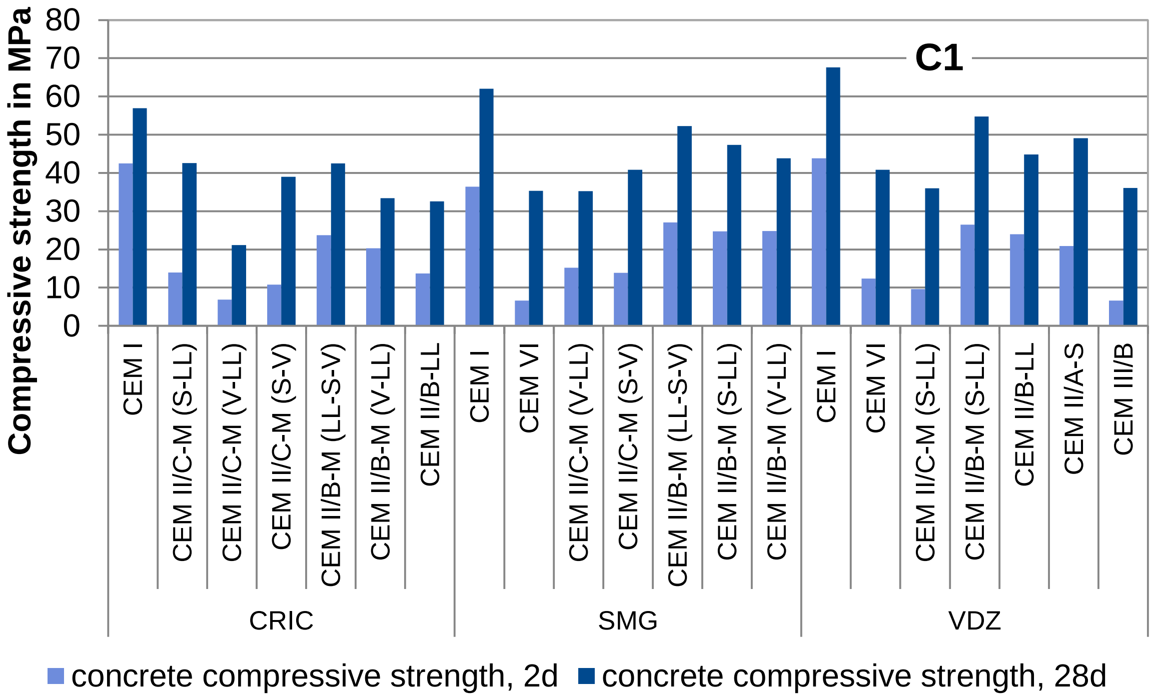

Figure 17 Compressive strengths of concretes C1

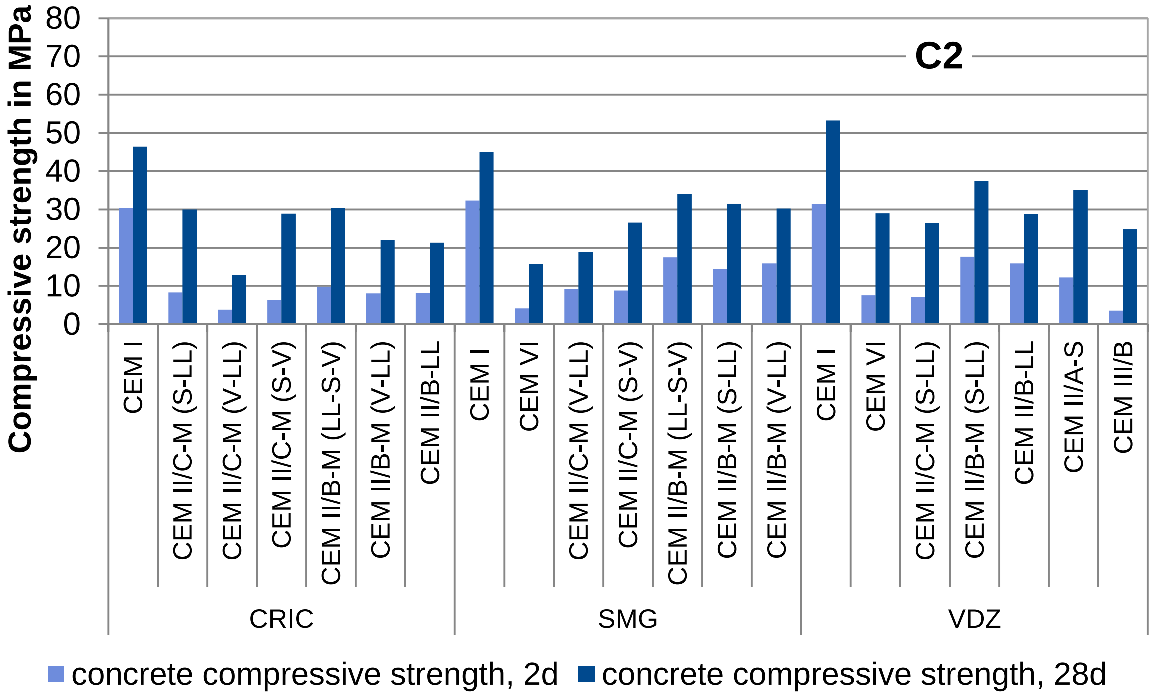

Figure 18 Compressive strengths of concretes C2

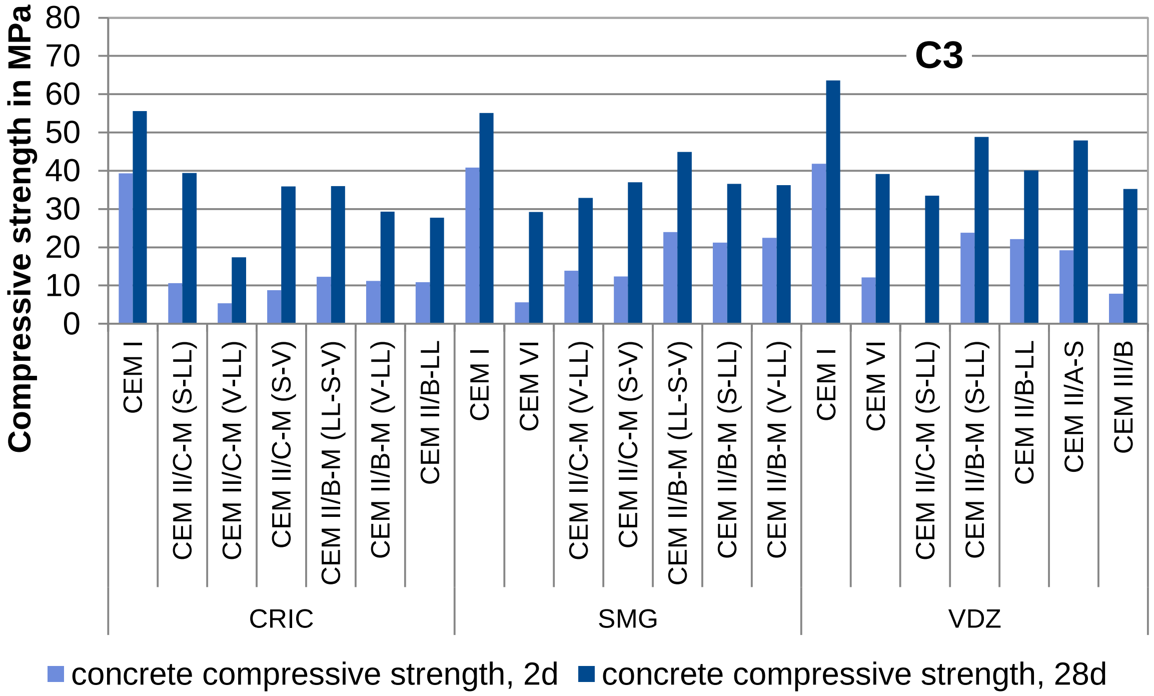

Figure 19 Compressive strengths of concretes C3

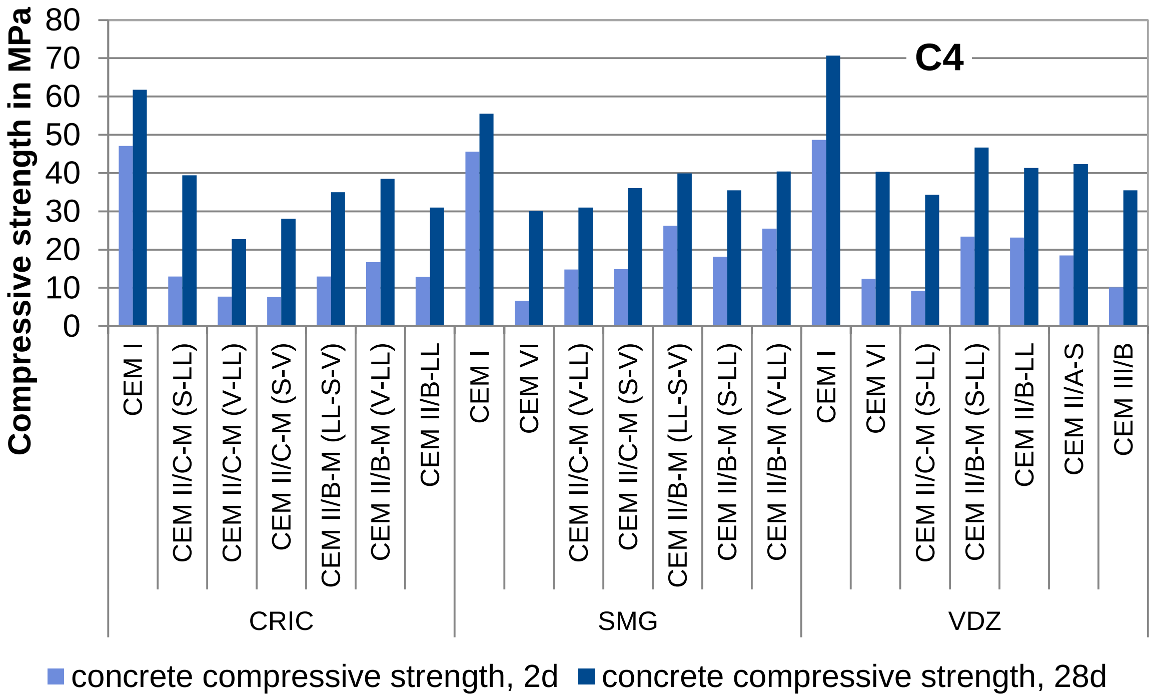

Figure 20 Compressive strengths of concretes C4

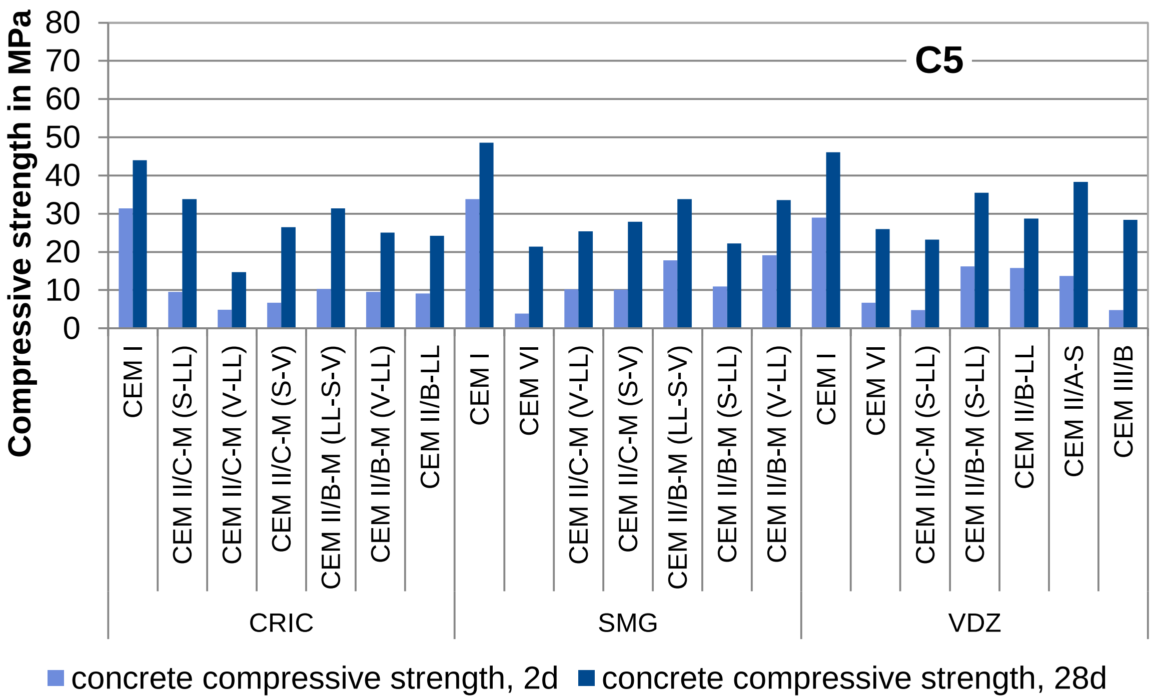

Figure 21 Compressive strengths of concretes C5

5.5 Carbonation resistance (1 % CO_2)

The carbonation resistance of concretes C1 and C2 were tested acc. to EN 13295 with 1 % CO_2 on 3 specimens per concrete. The carbonation depth was tested directly after pre-storage and before storing the specimens in the carbonation chamber and after 14, 28, 42 and 56 days. The results are shown in **Figure 22** to **Figure 24** and in the annex, **Table 28** to **Table 30**.

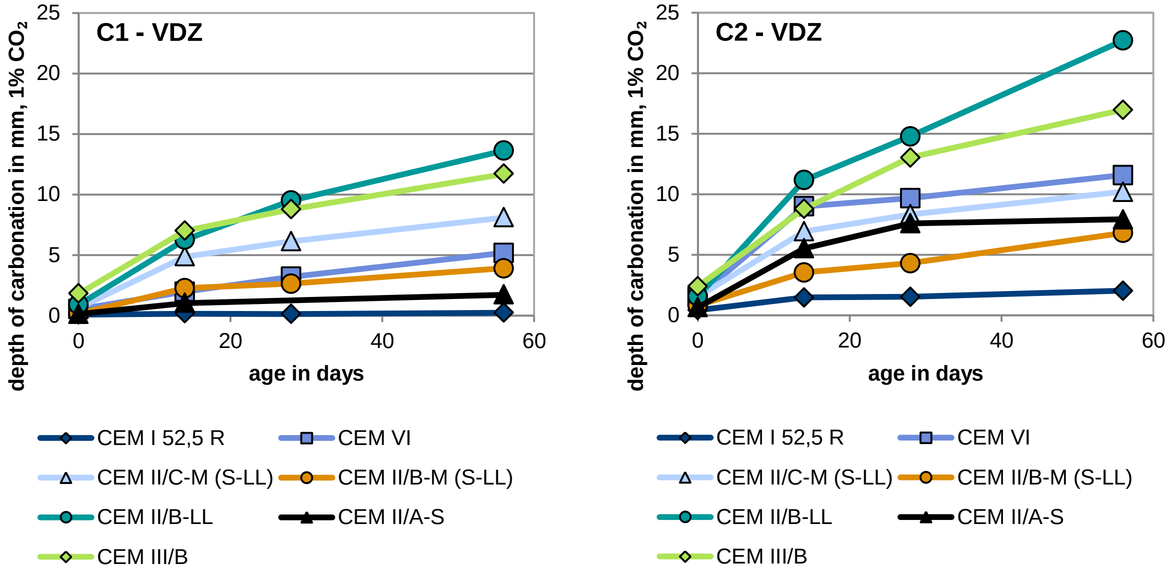

Figure 22 Carbonation depth of concretes C1 and C2 (VDZ)

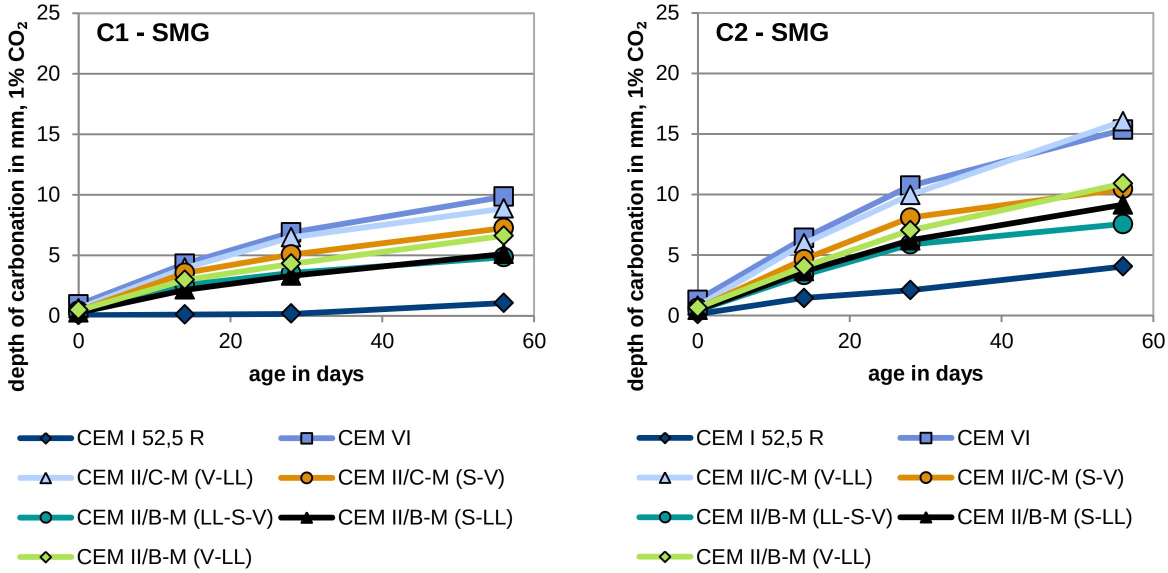

Figure 23 Carbonation depth of concretes C1 and C2 (SMG)

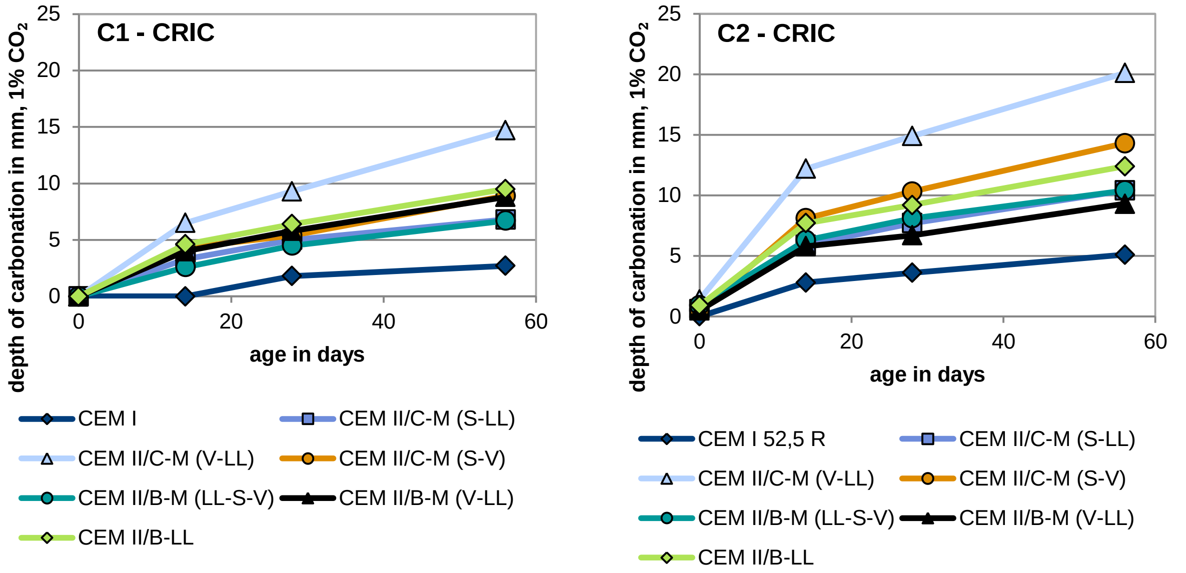

Figure 24 Carbonation depth of concretes C1 and C2 (CRIC)

5.6 Carbonation resistance (DIBT)

In addition to chapter 6.5, the carbonation resistance was tested acc. to CEN/TR 16563:2013: “Principles of the equivalent durability procedure” by VDZ. Mortar specimens with a maximum grain size of 8 mm were produced and cured under water for 7d and 28d, respectively. The compressive strength after the pre-storage and the carbonation depth after 140d in 20°C, 65% relative humidity and normal CO_2 conditions were determined. The results are shown together with the assessment background acc. to CEN/TR 16563 in **Figure 25** and in the annex, **Table 31**.

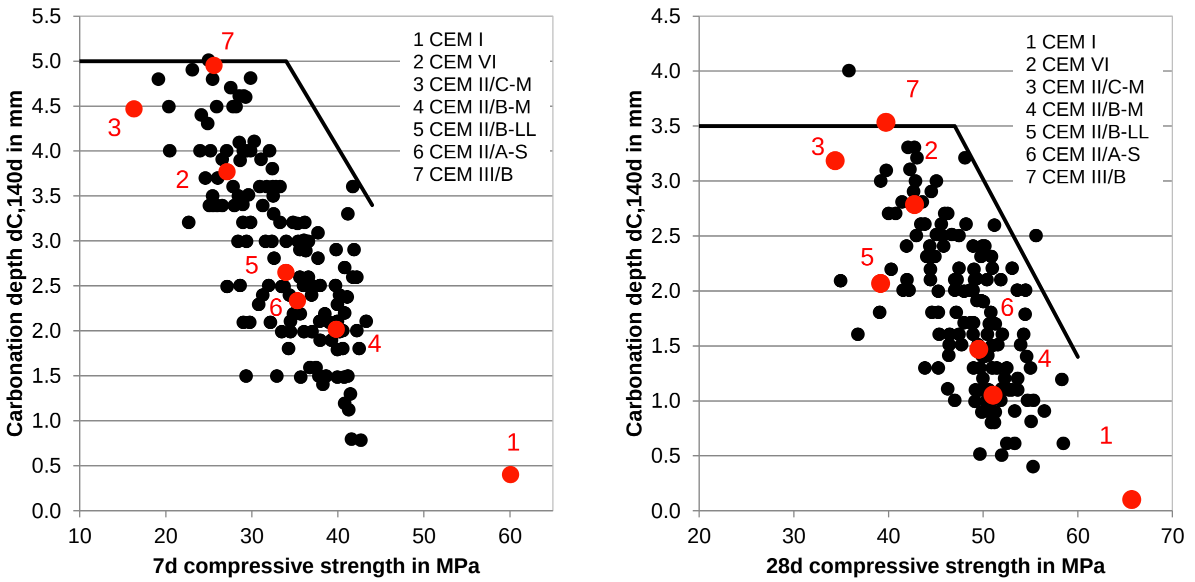

Figure 25 Carbonation depth of fine concretes (VDZ)

5.7 Chloride resistance

The Chloride diffusion coefficients of concretes C1 and C3 were determined acc. to EN 12390-11 by all project partners. The results are shown in **Figure 26** and in the annex, **Table 32** to **Table 34**.

Additionally, the Chloride migration coefficients acc. to NT Build 492 were determined by VDZ. The results are shown in **Figure 27** and in the annex, **Table 32**.

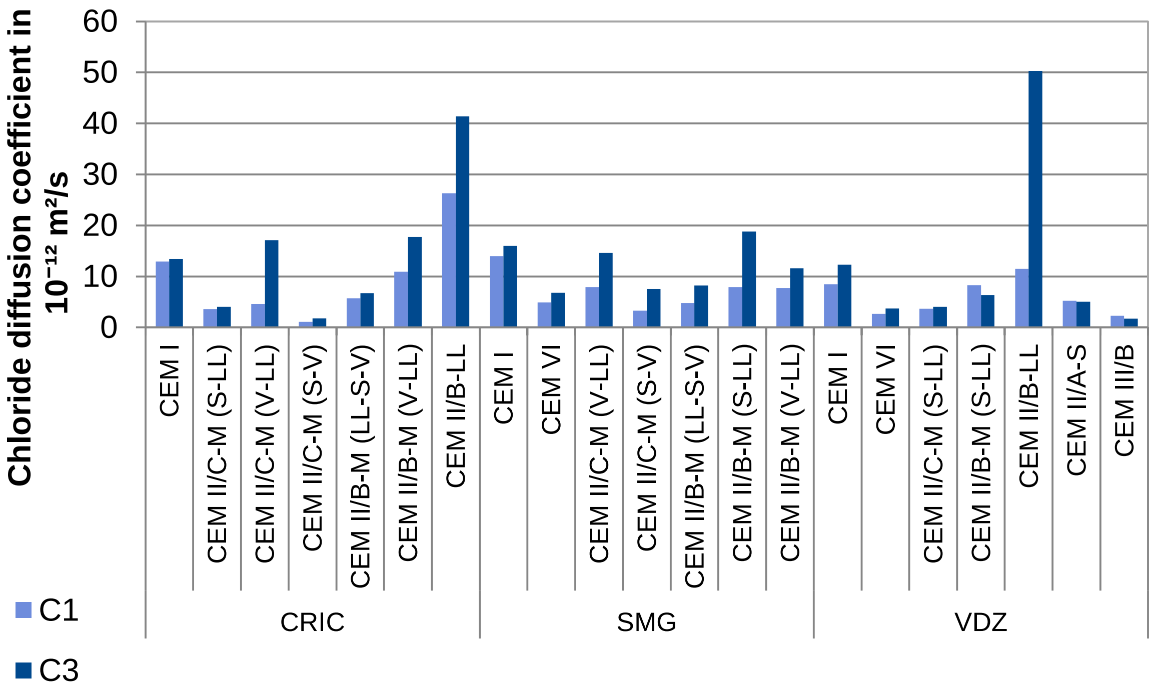

Figure 26 Chloride diffusion coefficients

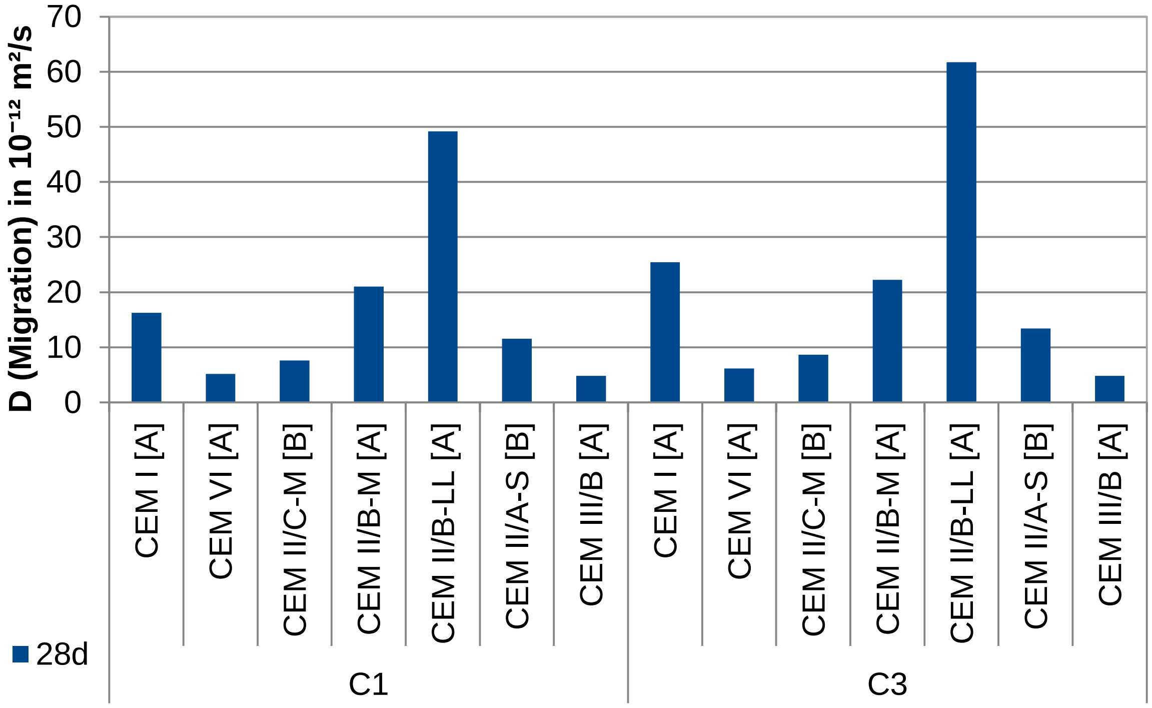

Figure 27 Chloride migration coefficients

5.8 Freeze-Thaw resistance

The freeze-thaw resistances of concretes C1 were tested with the CIF-Test (CEN/TS 12390-9 in combination with CEN/TR 15177). The scaling and the relative modulus of elasticity are shown in **Figure 28** to **Figure 30** and in the annex, **Table 35** to **Table 37**.

SMG performed the tests acc. to ONR23303. Two tests with concrete C1 using CEM I and CEM II/B-M (S-LL), respectively were repeated using the CIF tests. The relative dynamic moduli of elasticity were calculated from the comparison of both methods.

Comparing the results of concretes C1 using the reference CEM I, the following relative dynamic moduli of elasticity where determined after 28 freeze-thaw cycles:

- VDZ: 78.4 %
- CRIC: 33.0 %
- SMG: 92.1 %

It can be concluded, that the comparability of this method in this research project is weak. Therefore, the development of a characteristic value given in chapter 7.4 has to be handled with care.

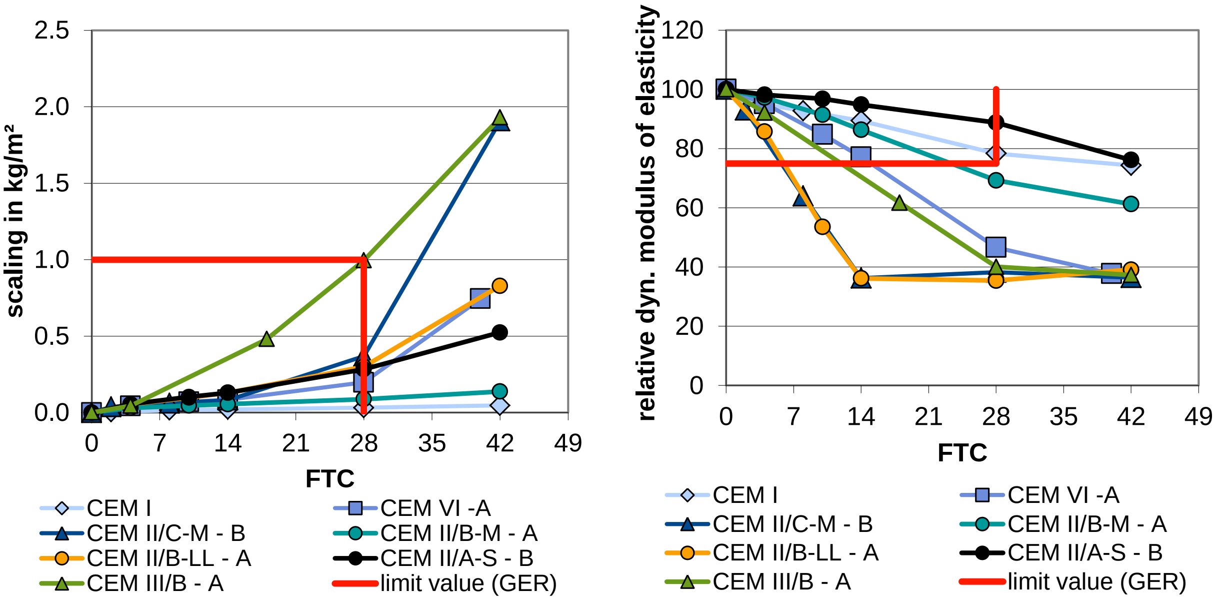

Figure 28 Scaling and the relative modulus of elasticity (VDZ)

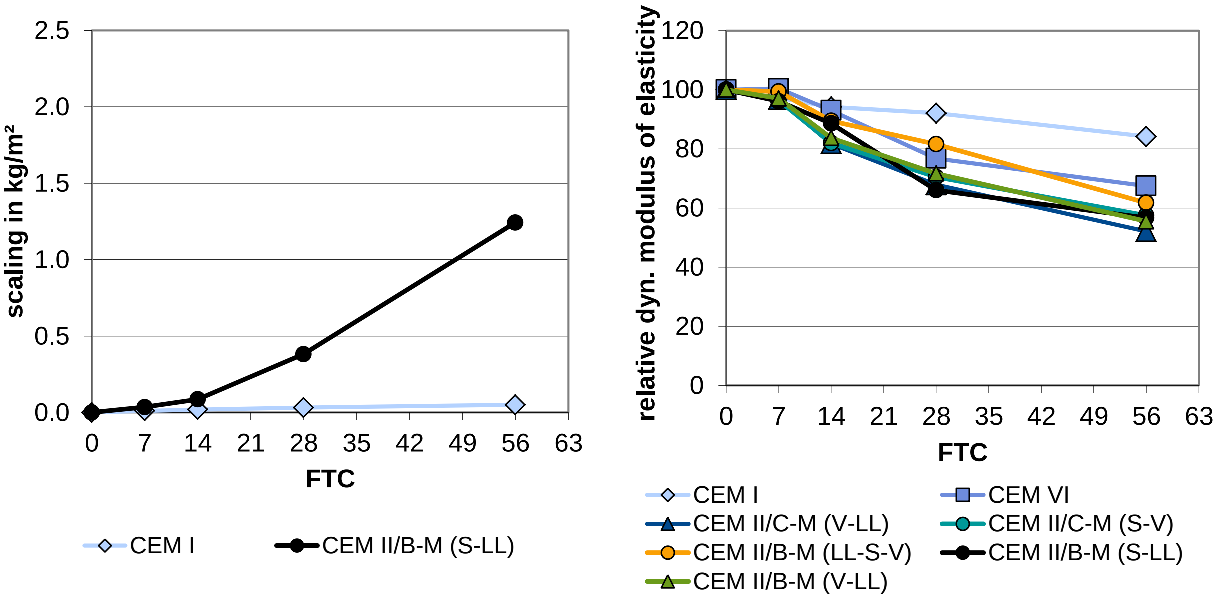

Figure 29 Scaling and the relative modulus of elasticity (SMG), RDM calculated from XF3 testing according to ONR23303; correlated with CIF tests from the CIF results of CEM I and CEMII/B-M(S-LL)

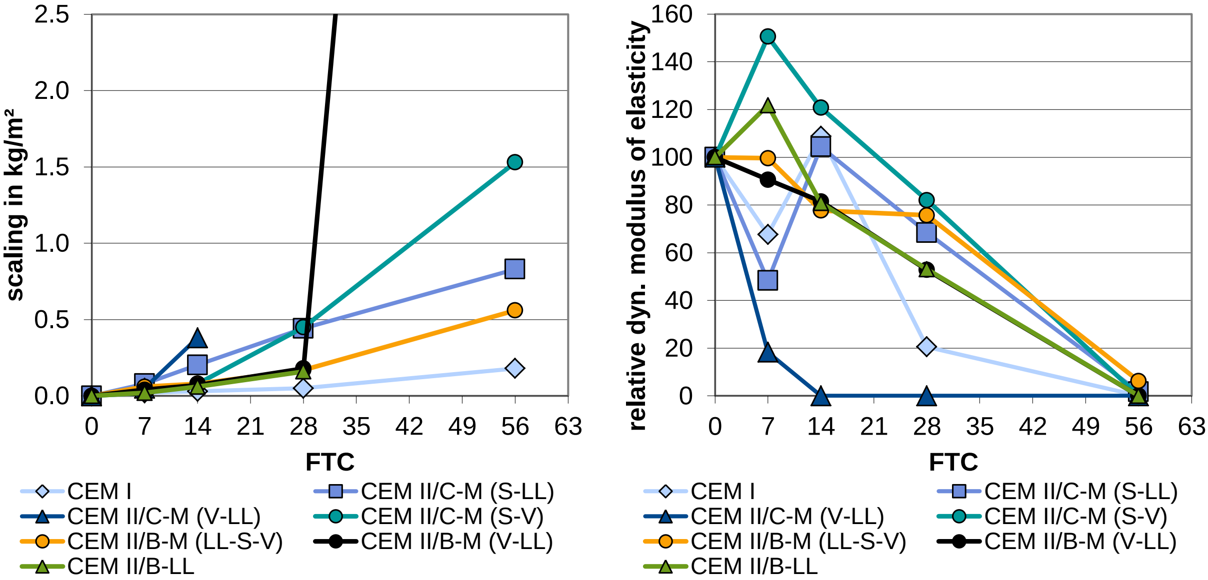

Figure 30 Scaling and the relative modulus of elasticity (CRIC)

5.9 Freeze-Thaw resistance with de-icing salts

The freeze-thaw resistances with de-icing salts of concretes C4 and C5 were tested with the slab test acc. to CEN/TS 12390-9. The scaling is shown in **Figure 31** to **Figure 33** and in the annex, **Table 38** to **Table 40**. Additionally, the surface scaling and the speed of scaling were analysed. Therefore, the last 3 points of each scaling curve were linearly interpolated. The axis intercept of the linear function was defined as surface scaling and the slope of the linear function was defined as speed of scaling. The principle is shown in **Figure 34**. The results are shown in **Figure 35** to **Figure 37** and in the annex, **Table 38** to **Table 40**.

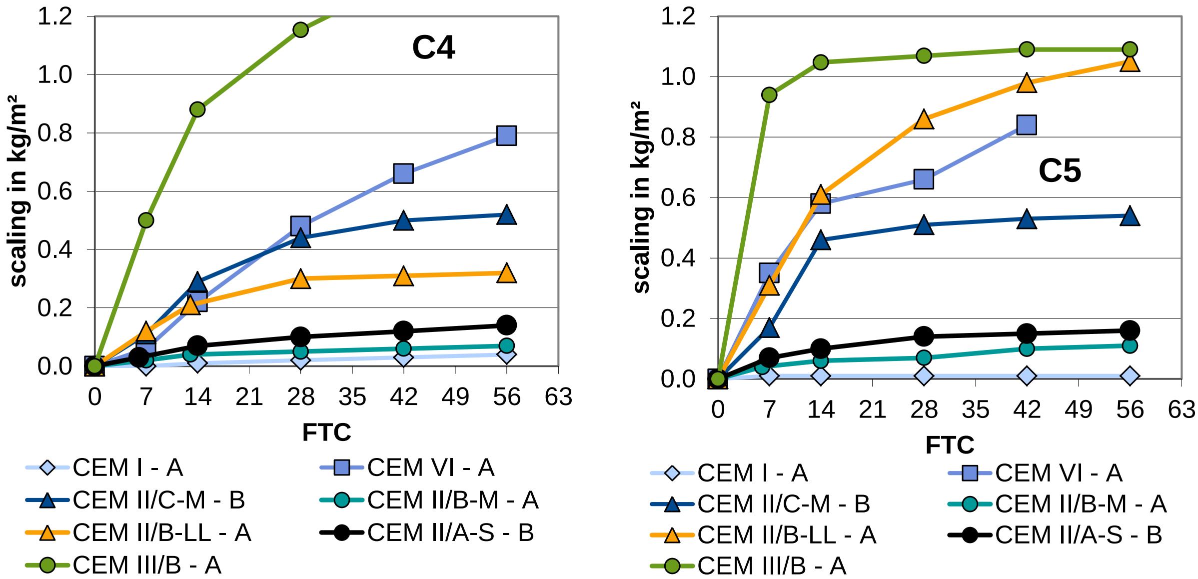

Figure 31 Scaling with de-icing salts (VDZ)

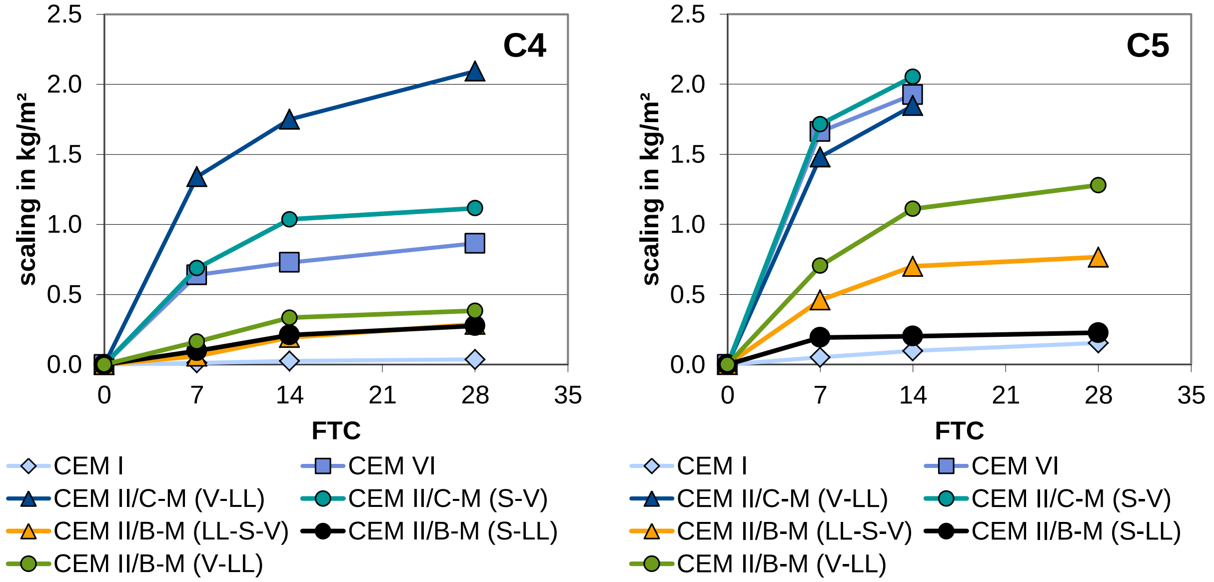

Figure 32 Scaling with de-icing salts (SMG)

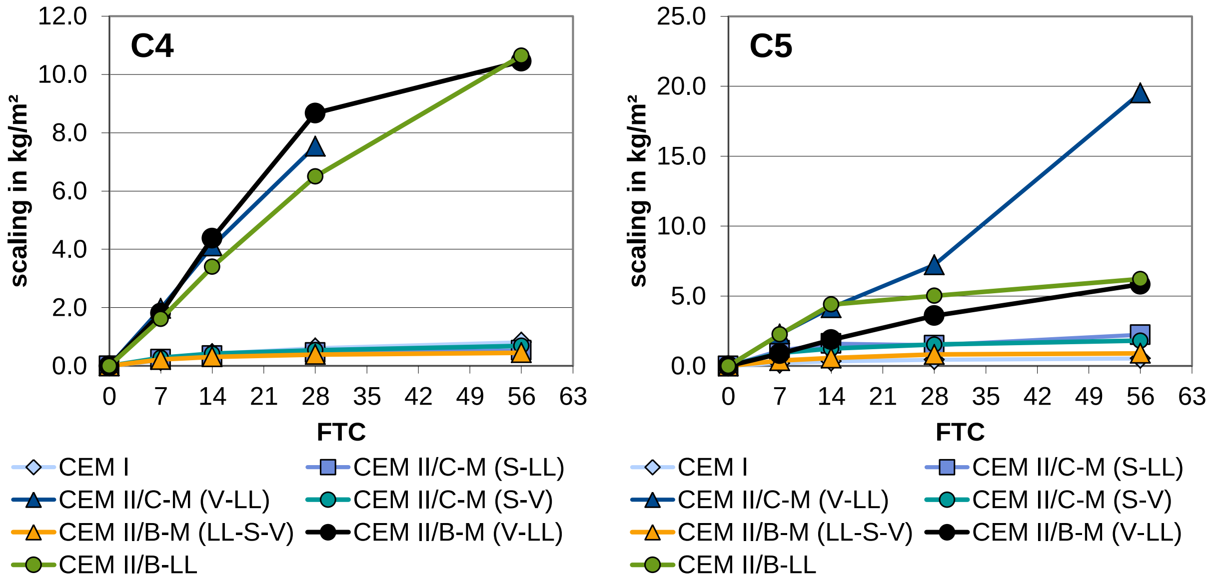

Figure 33 Scaling with de-icing salts (CRIC)

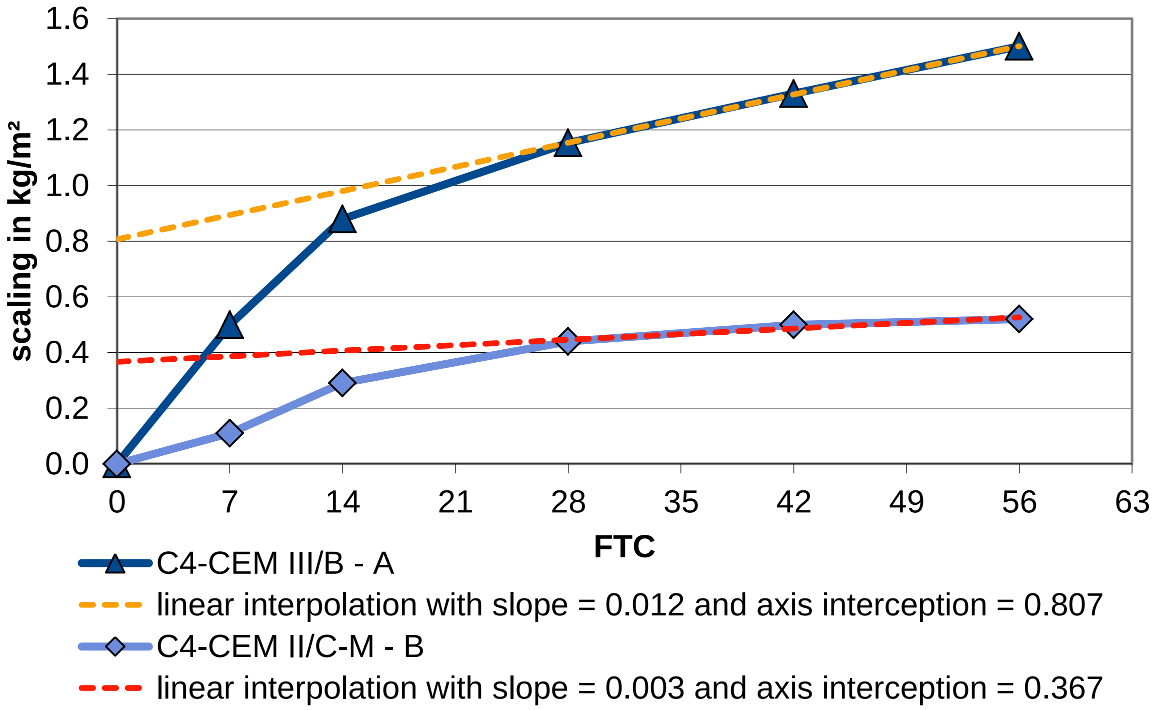

Figure 34 Surface scaling and the speed of scaling (principle)

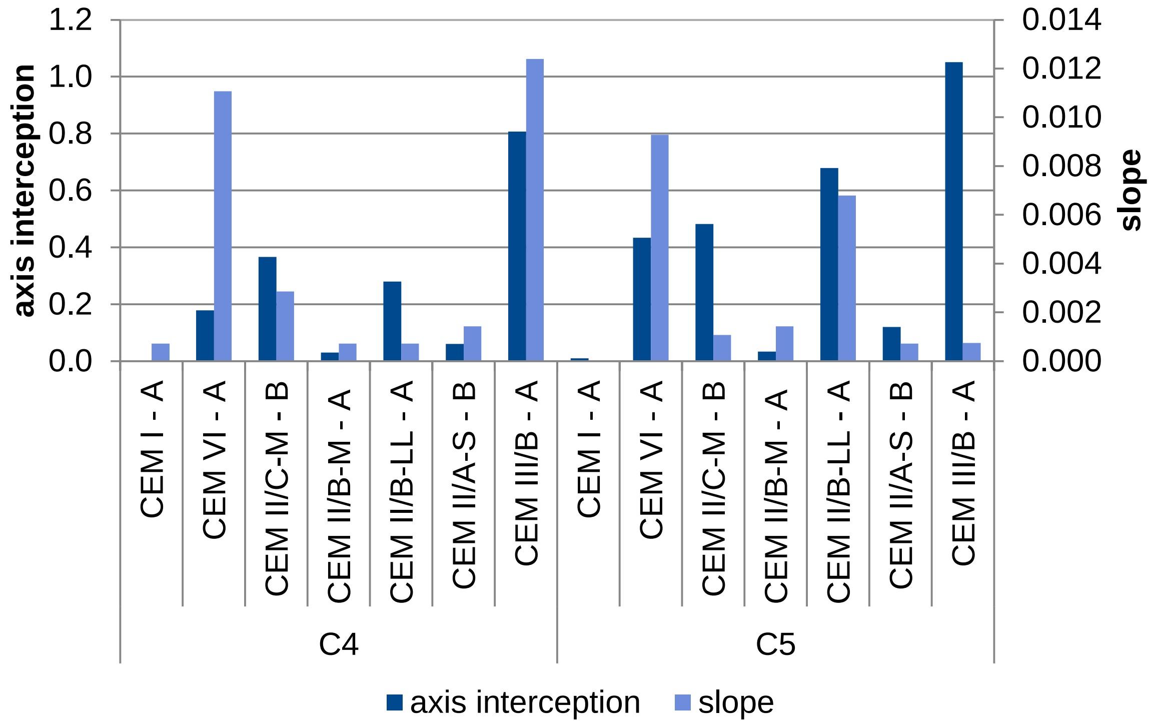

Figure 35 Surface scaling and the speed of scaling (VDZ)

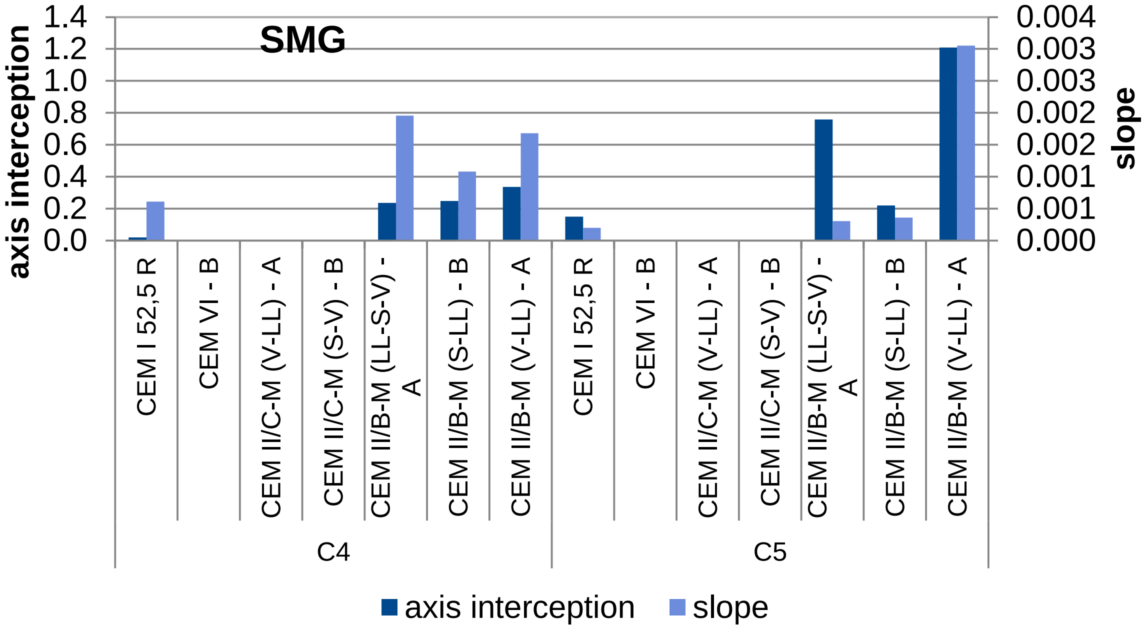

Figure 36 Surface scaling and the speed of scaling (SMG)

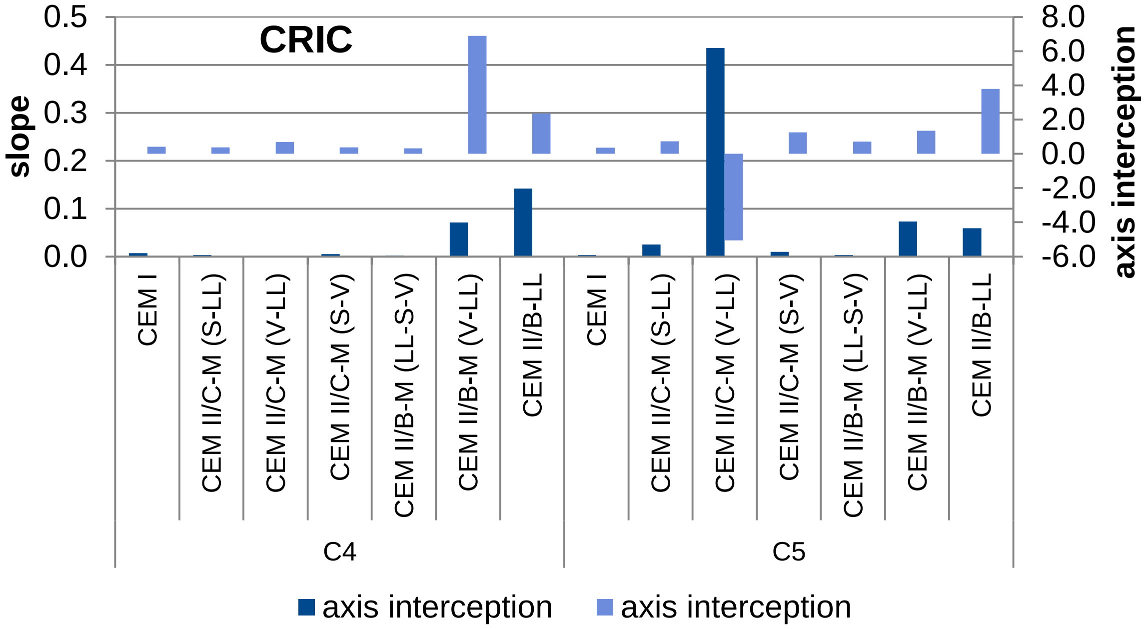

Figure 37 Surface scaling and the speed of scaling (CRIC)

6 WP5: Characteristic values

6.1 General

According to the aim of the research project to predict the concrete durability as fast and cost-efficient as possible, characteristic values were defined by using parameters which were determined on standard mortars according to EN 196-1 and on hardened cement paste. For the concrete durability, beside other influencing factors, the hydration progress and the porosity of the cement matrix is of interest. Additionally, the air content (AC) of the concrete (determined according to EN 12350-7) has an influence on the freeze-thaw resistance. As most durability tests start at the age of 28 days, the pore size distribution of standard mortars was determined at that age by mercury intrusion porosimetry according to DIN 66133 (see chapter 5.5). Additionally, the relationship between porosity and water/cement ratio was used, see **Figure 9**.

The chemical bound water (CBW) of hardened cement paste was determined at the ages of 2, 7 and 28 days (CBW2, CBW7, CBW28), see chapter 5.4.

Characteristic values (CV) are defined by systematic and empiric combination of the above mentioned parameters and a following regression analysis.

Additionally, all durability results were compared with the respective concrete compressive strength.

6.2 Characteristic values for carbonation resistance (1 % CO_2)

In **Figure 38** and **Figure 39**, the relationship between 2d- and 28d-compressive strength and the carbonation depth after 28d storage in 1 % CO_2 acc. to EN 13295 is shown.

Figure 40 shows the relationship between the carbonation depth and a characteristic value, calculated according to the following equation:

$$CV_{CO2,1\%} = \text{CBW2} \times \frac{0.50}{w/c} \times \frac{1}{P_{total}}$$

with

$CV_{CO2,1\%}$ Characteristic value for depth of carbonation acc. to EN 13295

CBW2 Chemical bound water of cement stone after 2d

w/c water/cement ratio

P_{total} Total porosity of standard mortar

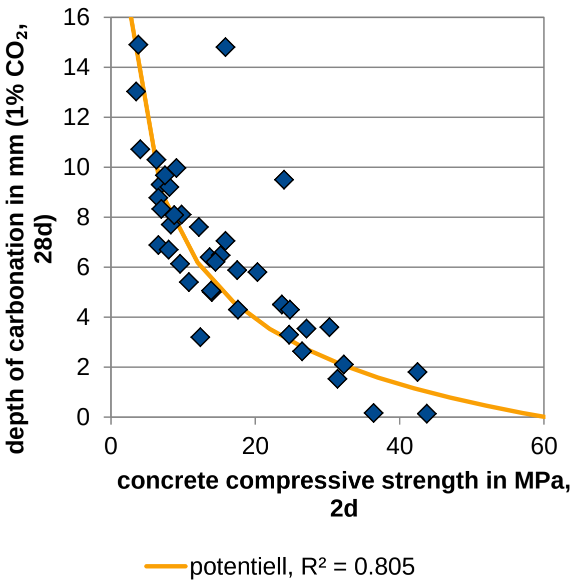

Figure 38 Concrete compressive strength (2d) vs. depth of carbonation acc. to EN 13295

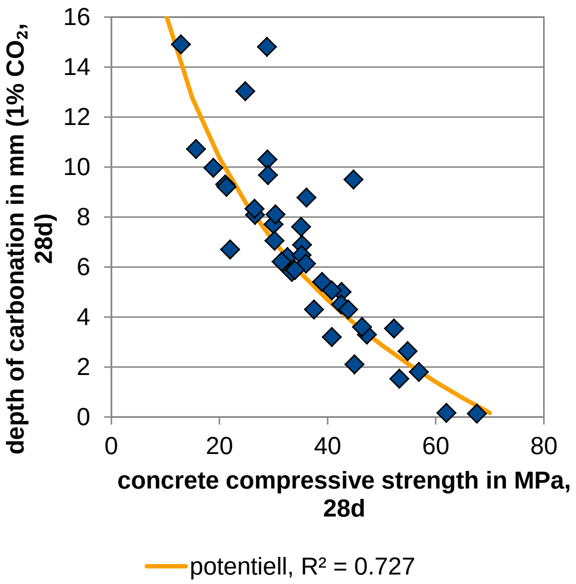

Figure 39 Concrete compressive strength (28d) vs. depth of carbonation acc. to EN 13295

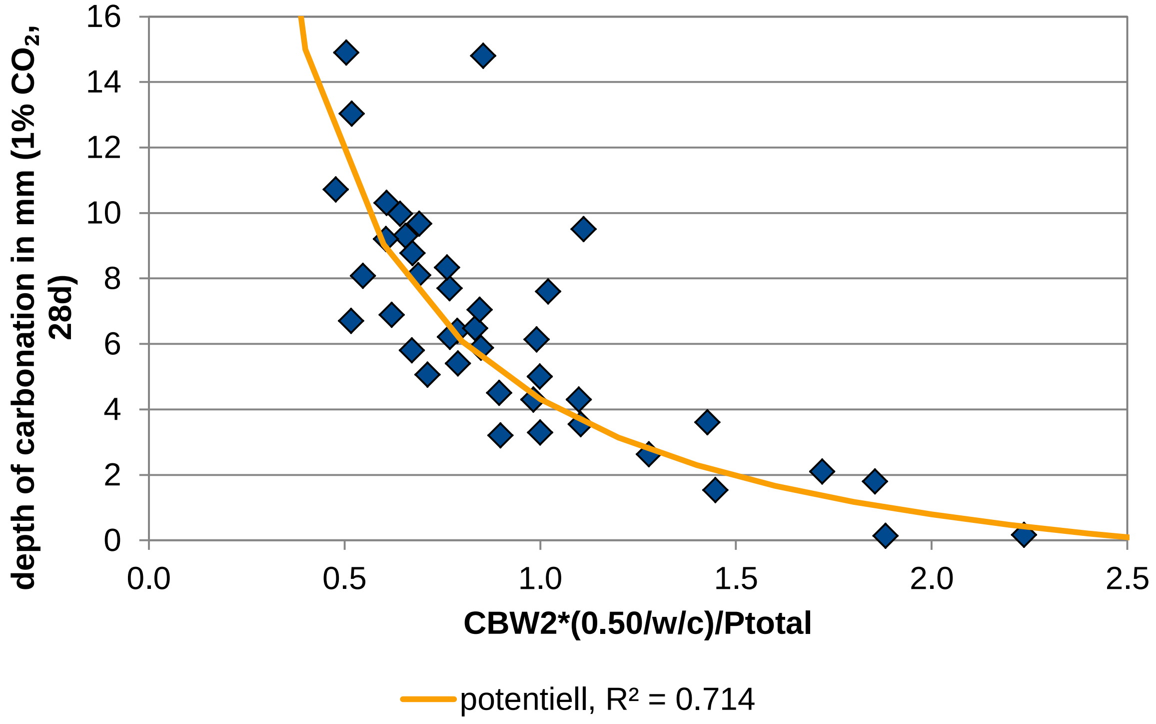

Figure 40 Characteristic value vs. depth of carbonation acc. to EN 13295

The carbonation depth after 28d storage in 1 % CO_2 acc. to EN 13295 can be described well by using either compressive strength of concrete or a characteristic value composed of porosity of standard mortar and chemical bound water of cement stone.

6.3 Characteristic values for Chloride resistance

In **Figure 41** and **Figure 42**, the relationship between 2d- and 28d-compressive strength and the Chloride diffusion acc. to EN 12390-11 is shown.

Figure 45 shows the relationship between the Chloride diffusion coefficients and a characteristic value, calculated according to the following equation:

$$CV_{Chloride} = \frac{0.50}{w/c} \times \frac{1}{\frac{P_{0.01}}{P_{total}} \times (C+LL)}$$

with

$CV_{Chloride}$	Characteristic value for Chloride diffusion acc. to EN 12390-11
w/c	water/cement ratio
$P_{0.01}$	Capillary porosity of standard mortar with pore radius r ≥ 0.01 µm
P_{total}	Total porosity of standard mortar
(C+LL)	Ratio of clinker and limestone in cement, as a measure for slag and fly ash (but without giving a zero value)

Additionally, **Figure 43** and **Figure 44** are showing the compressive strength values divided by (C+LL) in relationship to the Chloride diffusion coefficients.

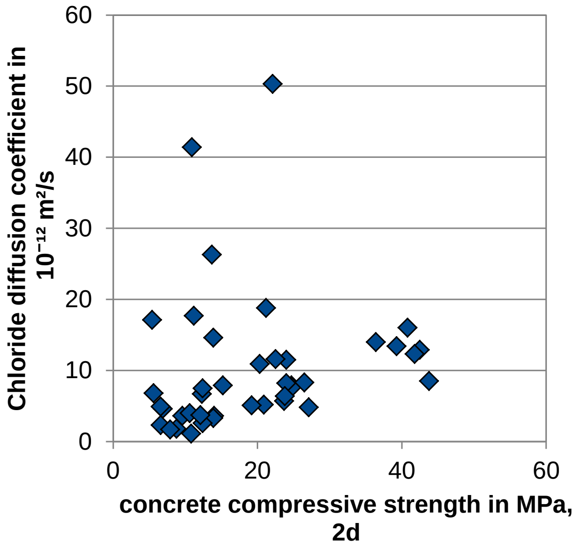

Figure 41 Concrete compressive strength (2d) vs. Chloride diffusion coefficient

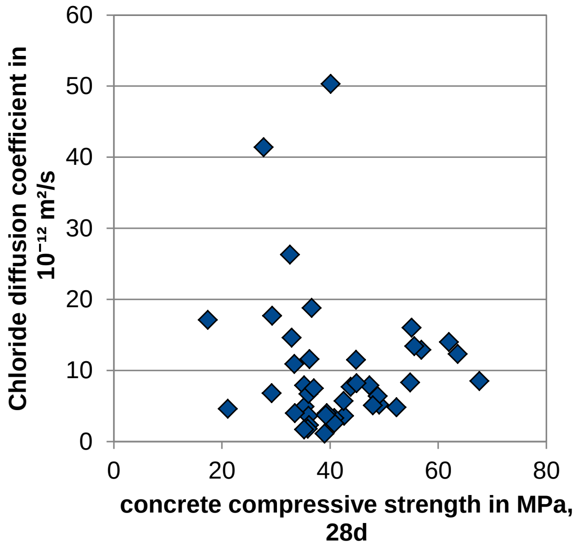

Figure 42 Concrete compressive strength (28d) vs. Chloride diffusion coefficient

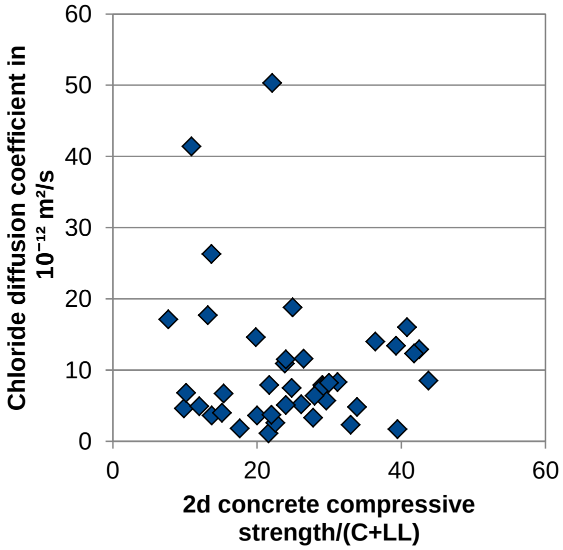

Figure 43 Concrete compressive strength (2d) /(C+LL) vs. Chloride diffusion coefficient

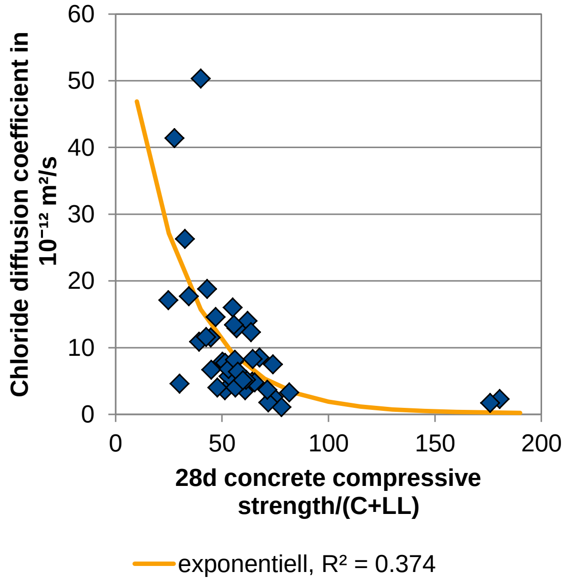

Figure 44 Concrete compressive strength (28d)/(C+LL) vs. Chloride diffusion coefficient

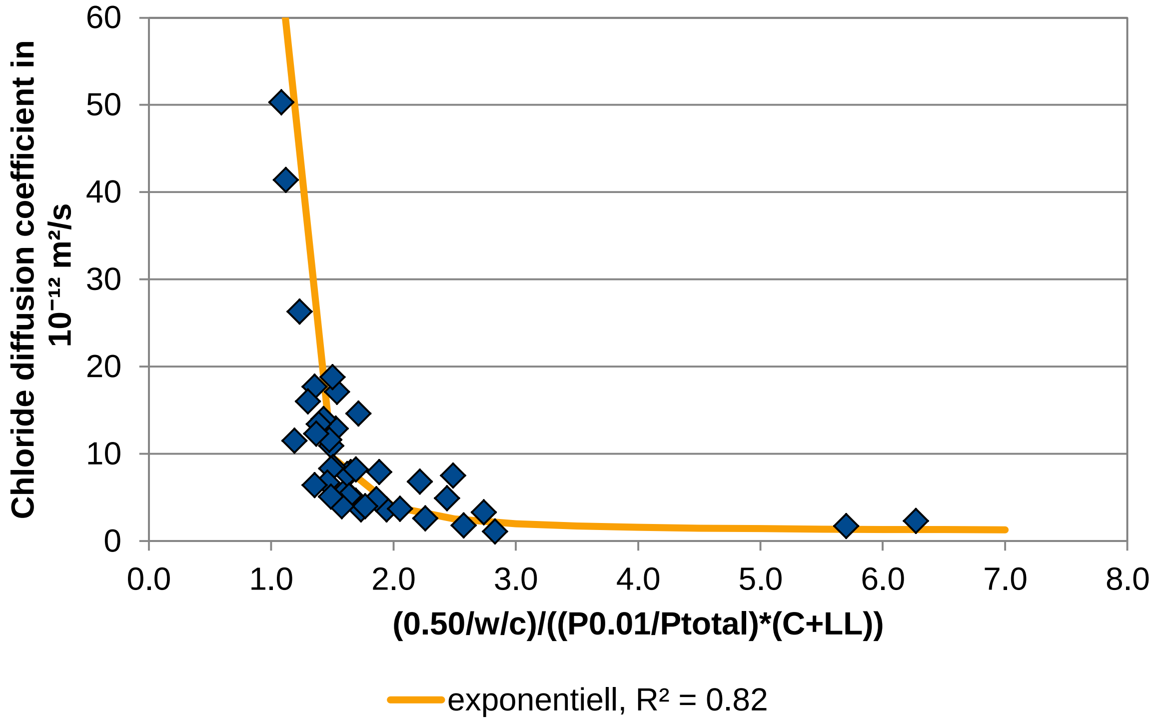

Figure 45 Characteristic value vs. Chloride diffusion coefficient

The Chloride diffusion coefficients acc. to EN 12390-11 can be described well for concretes with cements with several main constituents by using the given characteristic value composed of porosity of standard mortar and cement composition. Compressive strength seems not to be a good parameter to describe Chloride diffusion coefficients. If the 28d-compressive strength is combined with the cement composition, a weak relationship to Chloride diffusion coefficients can be found.

6.4 Characteristic values for freeze-thaw resistance (CIF)

As written in chapter 6.8, the measurement of the freeze-thaw resistance without de-icing salts, was not performed identical by the research partners. The comparability of results testing concretes with an identical reference cement CEM I is weak. Therefore, the following diagrams and calculations must be handled with care.

In **Figure 46** and **Figure 47**, the relationship between 2d- and 28d-compressive strength and the relative dynamic modulus of elasticity after 28 freeze-thaw cycles (FTC) without de-icing salts is shown.

Figure 48 shows the relationship between the relative dynamic modulus of elasticity after 28 freeze-thaw cycles and a characteristic value, calculated according to the following equation:

$$CV_{CIF} = \mathrm{CBW2} \times \mathrm{AC} \times \frac{1}{P_{0.02}/P_{total}}$$

with

CV_{CIF}	Characteristic value for CIF test acc. to EN 12390-9 or ONR23303
CBW2	Chemical bound water of cement stone after 2d
$P_{0.02}$	Capillary porosity of standard mortar with pore radius r ≥ 0.02 µm
P_{total}	Total porosity of standard mortar

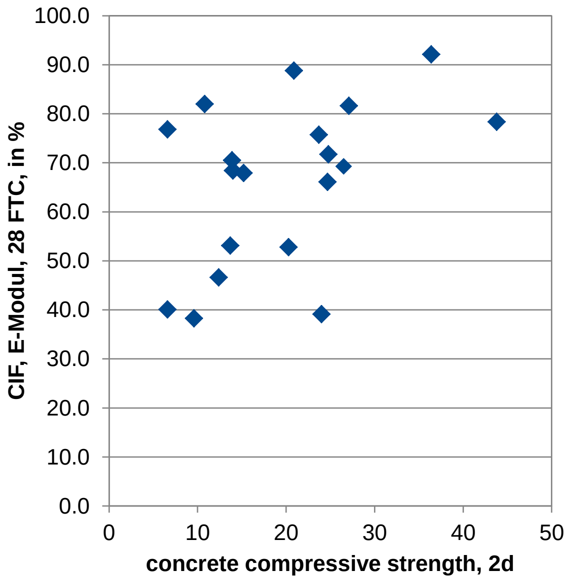

Figure 46 Concrete compressive strength (2d) vs. relative dynamic modulus of elasticity after 28 FTC

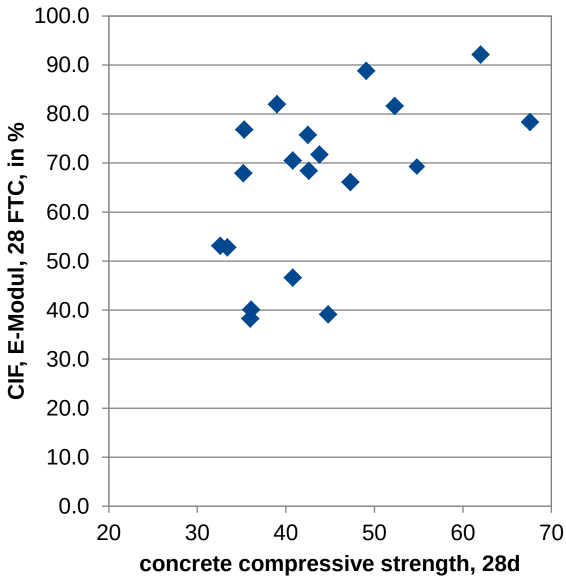

Figure 47 Concrete compressive strength (28d) vs. relative dynamic modulus of elasticity after 28 FTC

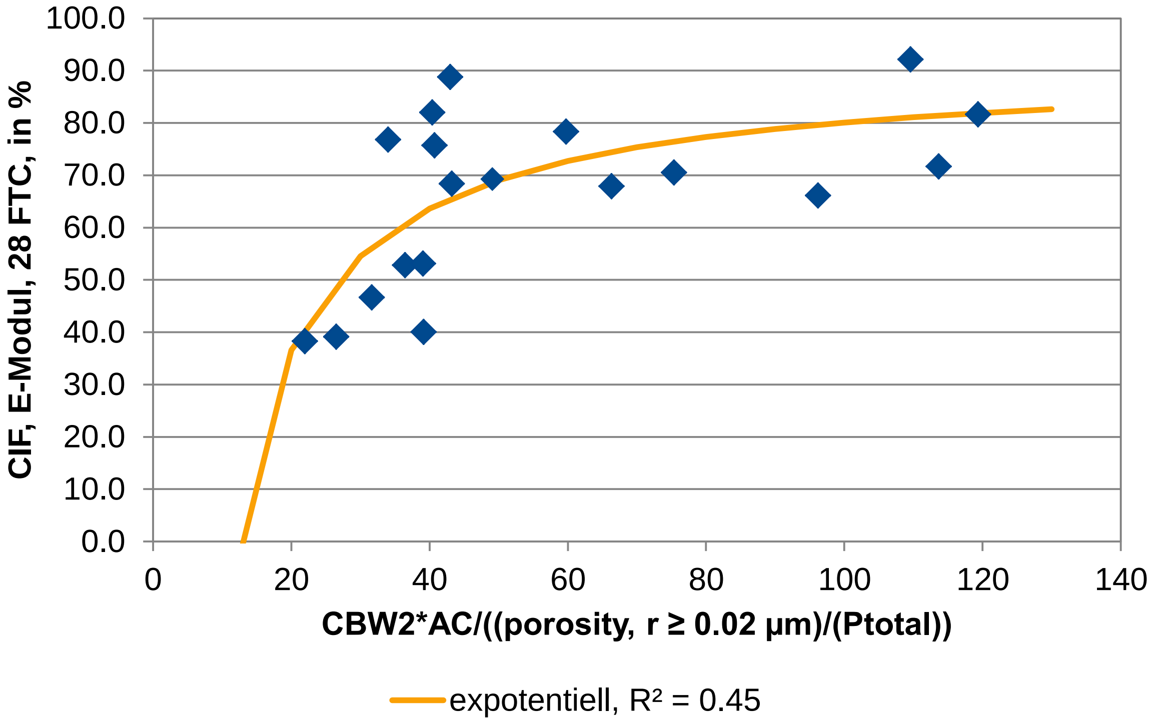

Figure 48 Characteristic value vs. relative dynamic modulus of elasticity after 28 FTC

6.5 Characteristic values for freeze-thaw resistance with de-icing salts (slab)

In **Figure 49** and **Figure 50**, the relationship between 2d- and 28d-compressive strength and the scaling in the slab test with de-icing salts is shown.

Figure 51 shows the relationship between the scaling in the slab test with de-icing salts and a characteristic value, calculated according to the following equation:

$$CV_{slab} = \text{CBW2} \times \frac{0.50}{w/c} \times \frac{AC}{P_{total}}$$

with

CV_{slab}	Characteristic value for scaling in the slab test with de-icing salts
CBW2	Chemical bound water of cement stone after 2d
w/c	water/cement ratio
P_{total}	Total porosity of standard mortar
AC	Fresh concrete air content (in range of 3.0 % to 7.5 %)

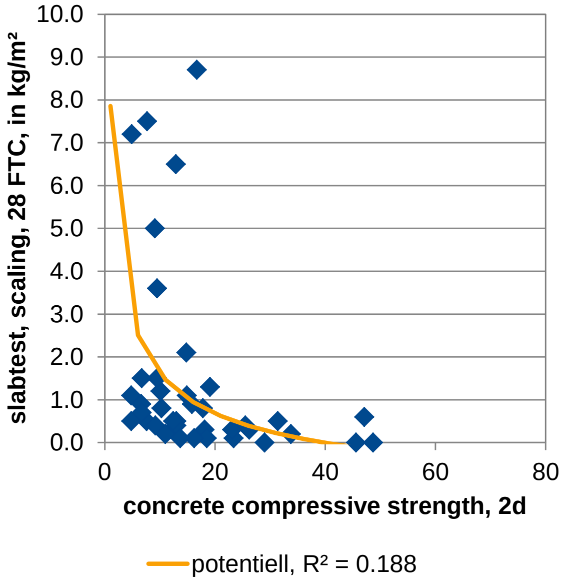

Figure 49 Concrete compressive strength (2d) vs. scaling in the slab test

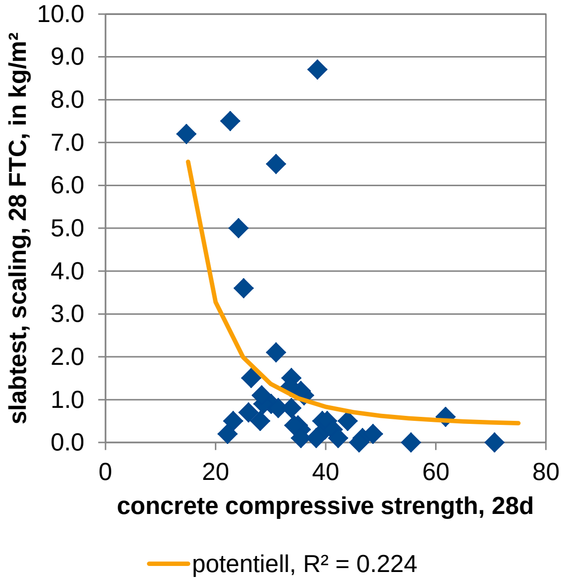

Figure 50 Concrete compressive strength (28d) vs. scaling in the slab test

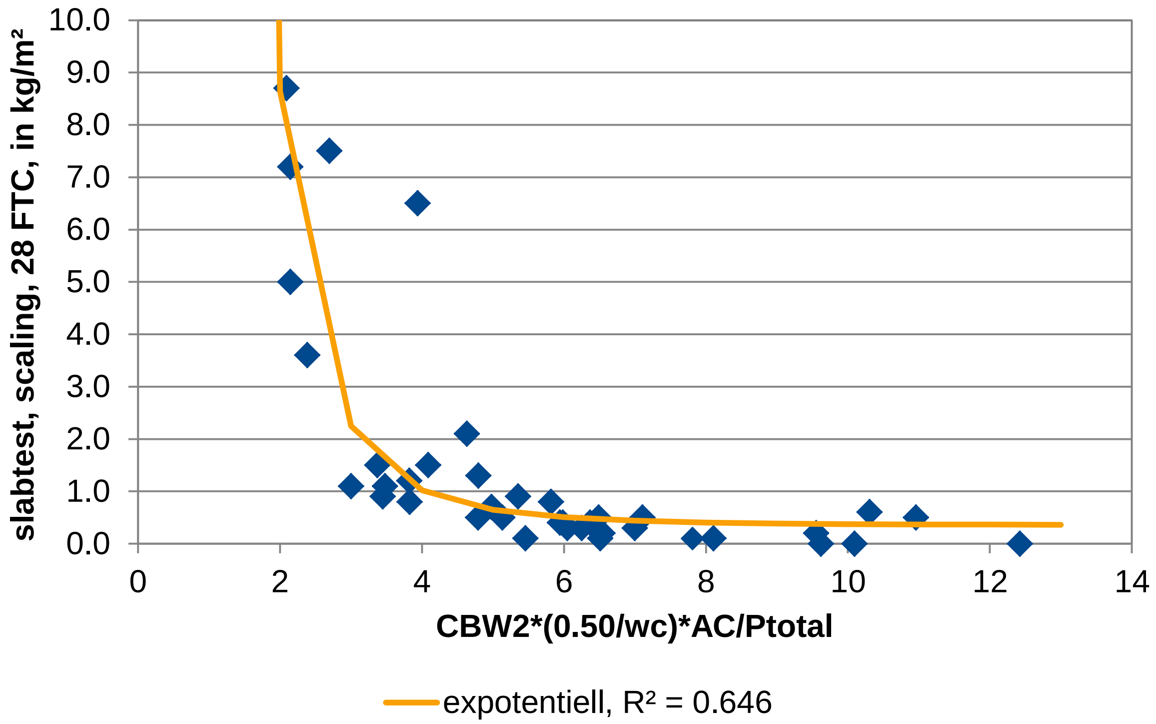

Figure 51 Characteristic value vs. scaling in the slab test

The scaling in the slab test with de-icing salts acc. to EN 12390-9 can be described well by using the given characteristic value composed of porosity of standard mortar, chemical bound water of cement stone and fresh concrete air content. A weak relationship to scaling in the slab test with de-icing salts can also be found for 2d- and 28d-compressive strength.

6.6 Characteristic values for Sulphate resistance

For Sulphate resistance acc. to SIA 262, no correlation could be found between the expansion after the 4 cycles of immersion and drying, or the expansion at the end of testing and the strength or a characteristic value. The following parameters were used for trying to find a characteristic value:

- water / cement ratio
- chemical composition of cement
- chemical bound water after 2d, 7d, and 28d
- pore size distribution of mortars
- C3A content of clinker and cement

In **Figure 52** and **Figure 53**, the relationship between 2d- and 28d-compressive strength and the expansion at the end of sulphate testing is shown.

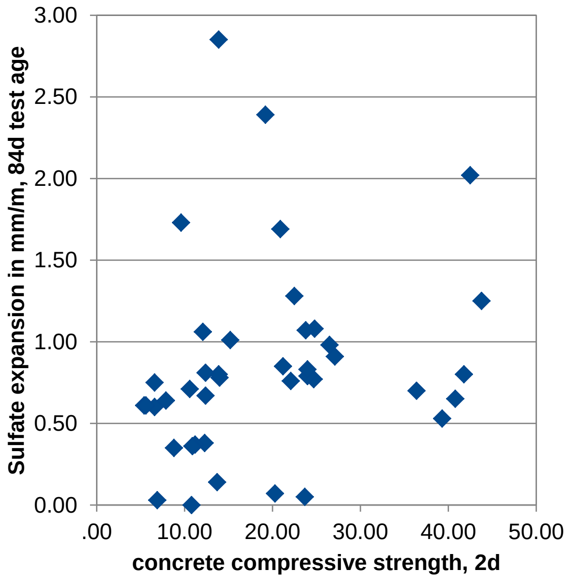

Figure 52 Concrete compressive strength (2d) vs. expansion at the end of sulphate testing

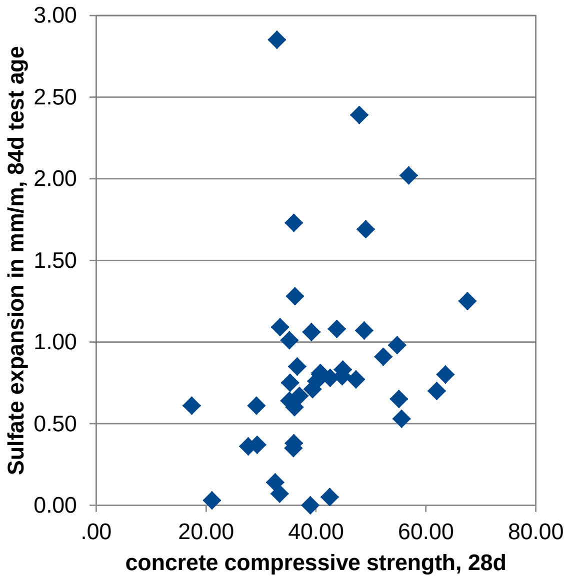

Figure 53 Concrete compressive strength (28d) vs. expansion at the end of sulphate testing

7 Conclusion

It was possible to define characteristic values for predicting the concrete durability properties “carbonation”, “Chloride diffusion” and “scaling in the slab test” by an empirical combination of parameters measured on standard mortars and cement stone. These were:

- Chemical composition of cement, given by the sum of clinker and limestone (C+LL)
- Chemical bound water after 2d (CBW2)
- Total porosity of standard mortar (P_{total}) at the age of 28 days
- Capillary porosity of standard mortar with pore radius r ≥ 0.01 µm ($P_{0.01}$) (28d)
- Capillary porosity of standard mortar with pore radius r ≥ 0.02 µm ($P_{0.02}$) (28d)
- Water / cement ratio (w/c)
- Fresh concrete air content (AC)

The defined characteristic values are

- $CV_{CO2,1\%} = \text{CBW2} \times \frac{0.50}{w/c} \times \frac{1}{P_{total}}$
- $CV_{Chloride} = \frac{0.50}{w/c} \times \frac{1}{\frac{P_{0.01}}{P_{total}} \times (C+LL)}$
- $CV_{slab} = \text{CBW2} \times \frac{0.50}{w/c} \times \frac{AC}{P_{total}}$

Since the measurement of the freeze-thaw resistance without de-icing salts was not performed identical by the research partners, the comparability of results of testing concretes with an identical reference cement CEM I is weak. Therefore, the diagrams and calculations for defining a characteristic value for the CIF test in chapter 6.4 must be handled with care.

For Sulphate resistance acc. to SIA 262, no characteristic value could be defined.

The three given characteristic values can be used for the development of new cements. It is possible to estimate the result of a concrete test for example in an ETA procedure without doing the concrete test itself. The testing of chemical bound water and mortar porosity is much cheaper and much faster than, for example, a carbonation test. The new method shall not replace the concrete testing but should give a tool for an accelerated forecast of the durability of new cements.

8 Signatures

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9 Annex

Table 6 Chemical analysis of reference cements and main constituents (VDZ)

		CEM I – A (reference)	CEM I - B	CEM II/A-LL (reference)	CEM III/A (reference)	CEM II/B-M (T-LL) - A	CEM II/B-M (T-LL) - B
CO_2	M.-%	1.8	0.9	6.4	0.7	4.2	4.8
H_2O		1.2	0.4	1.2	0.7	0.5	0.4
LOI		3.0	1.4	8.2	1.3	4.7	5.2
SiO_2		19.7	20.0	17.8	26.7	22.1	22.0
Al_2O_3		4.0	5.3	4.6	7.5	5.0	5.2
TiO_2		0.3	0.3	0.3	0.6	0.3	0.3
P_2O_5		0.2	0.2	0.2	0.2	0.2	0.2
Fe_2O_3		3.1	3.1	1.9	1.9	3.4	3.6
MnO		0.1	0.1	0.2	0.1	0.1	0.1
MgO		2.2	2.8	3.0	5.3	2.0	1.8
CaO		63.0	61.5	60.1	51.9	57.8	57.2
SO_3		3.7	3.2	3.0	3.6	3.3	3.0
K_2O		0.8	1.6	0.7	0.4	0.9	0.9
Na_2O		0.2	0.2	0.3	0.3	0.2	0.2
Na_2O-Equ.		0.7	1.2	0.8	0.6	0.8	0.8
C_3S	M.-%	77.0	51.6	-	-	-	-
C_2S		0.0	18.2	-	-	-	-
C_3A		5.6	6.3	-	-	-	-
C_4AF		9.7	10.2	-	-	-	-
Limestone content		-	-	14.6	1.5	9.2	10.6
Slag con-tent		-	-	-	55.0	-	-
Burnt shale content		-	-	-	-	15.0	15.0
Density	g/cm³	3.11	3.16	3.02	3.02	3.07	3.05
Blaine fine-ness	cm²/g	5,660	3,277	4,480	3,940	7,910	4,480

Table 7 Chemical analysis of reference cements and main constituents (VDZ, 2)

		LL	S	D
CO_2	M.-%	43.4	0.2	0.2
H_2O		0.1	0.3	1.5
LOI		43.5	0.5	1.7
SiO_2		0.7	36.1	94.4
Al_2O_3		0.1	10.3	0.9
TiO_2		0.0	0.7	0.0
P_2O_5		0.0	0.0	0.1
Fe_2O_3		0.1	0.6	0.4
MnO		0.0	0.1	0.1
MgO		0.4	8.3	0.7
CaO		54.1	42.4	0.4
SO_3		0.0	0.1	0.0
K_2O		0.0	0.4	1.0
Na_2O		<0,01	0.3	0.3
Na_2O-Equ.		0.0	0.6	0.9
TOC		0.0	-	-
Methylene blue value	g/100 g	0.1	-	-
Density	g/cm^3	2.72	2.91	2.24
Blaine fine-ness	cm^2/g	5,120	5,920	-

Table 8 Chemical analysis of reference cements and main constituents (SMG)

		CEM I - A (reference)	**CEM II/A-LL (reference)**	**CEM III/A (reference)**	**limestone**	**slag**
CO_2	M.-%	1.87	7.66	0.72	42.8	0.2
H_2O		1.25	1.39	0.79	0.2	0.2
LOI		3.01	8.04	0.65	43.0	0.4
SiO_2		19.95	17.95	26.67	1.1	36.8
Al_2O_3		4.09	4.78	7.57	0.6	12.0
TiO_2		0.24	0.28	0.62	0.0	0.6
P_2O_5		0.24	0.17	0.22	0.0	0.0
Fe_2O_3		2.98	1.86	1.87	0.1	0.9
Mn_2O_3		0.05	0.18	0.13	0.0	1.7
MgO		2.22	3.08	5.31	1.3	10.9
CaO		62.45	60.05	51.73	53.6	33.1
SO_3 (XRF)		3.68	3.05	4.27	0.0	1.9
SO_3 (wet ch.)		3.33	2.81	3.21	-	-
K_2O		0.76	0.71	0.43	0.1	1.3
Na_2O		0.27	0.33	0.37	0.0	0.5
Chlorid		0.05	0.08	0.05	-	-
C_3S	M.-%	-	69.84	-	-	-
C_2S		-	2.89	-	-	-
C_3A		-	10.26	-	-	-
C_4AF		-	6.13	-	-	-
Limestone content		-	18.5	1.7	-	-
Slag content		-	-	42.6	-	-
Density	g/cm³	3.11	3.01	3.02	2.71	2.79
Blaine fineness	cm²/g	5600	4370	3810	5400 (A) 4600 (B)	4500 (A) 1700 (B)

Table 9 Chemical analysis of reference cements and main constituents (CRIC)

		CEM I 52.5 (A)	**CEM I 42.5 (B)**	**lime-stone A**	**lime-stone B**	**Fly ash A**	**Fly ash B**	**Slag A**	**Slag B**	**Silica fume**
LOI	M.-%	2.78	0.79	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.
CO_2		1.66	0.39	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.
Insoluble		0.52	0.27	n. d.	n. d.	n. d.	90.43	n. d.	n. d.	n. d.
SO_3		2.97	1.99	0.01	0.23	0.52	0.20	2.02	0.15	0.00
Na_2O		1.16	0.37	n. d.	n. d.	1.00	0.45	0.21	0.31	n. d.
K_2O		0.84	0.48	n. d.	n. d.	3.33	4.09	0.40	0.47	n. d.
Na_2O-Equ.		0.71	0.69	n. d.	n. d.	3.19	3.14	0.47	0.62	n. d.
Cl^-		0.054	0.021	n. d.	n. d.	0.002	0.004	0.023	n. d.	n. d.
Density	g/cm³	n. d.	n. d.	n. d.	n. d.	2.27	2.1	2.85	2.91	n. d.
Blaine fine-ness	cm²/g	n. d.	n. d.	4090	3480	3180	2560	5230	4510	n. d.

n. d. not determined

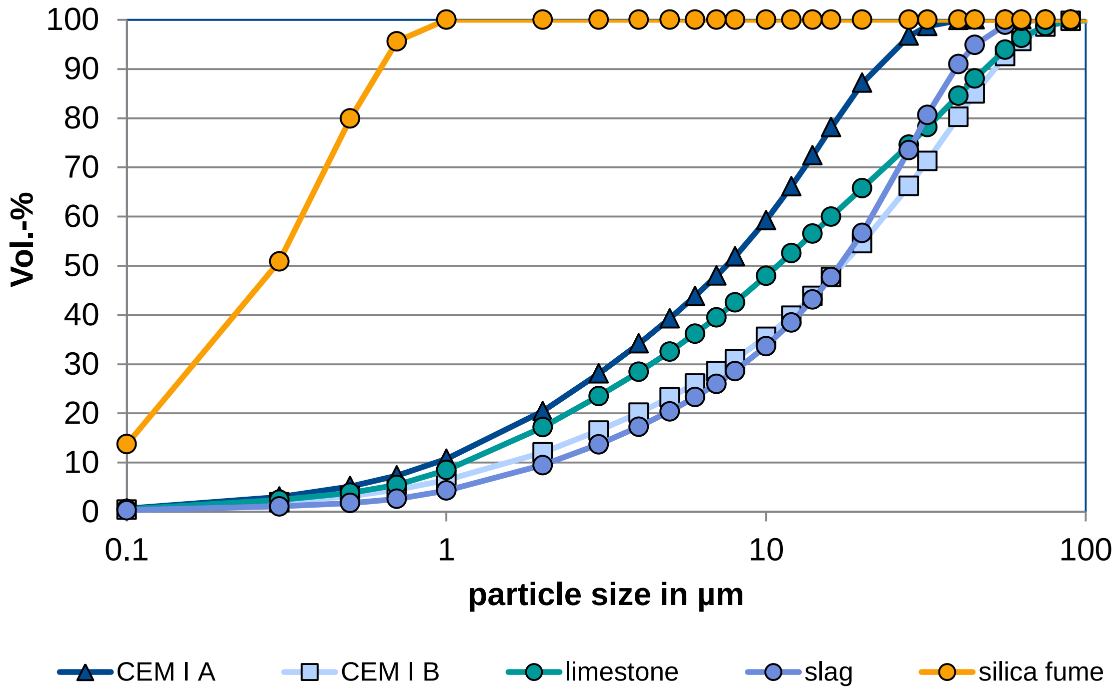

Figure 54 Particle size distributions of main constituents (VDZ)

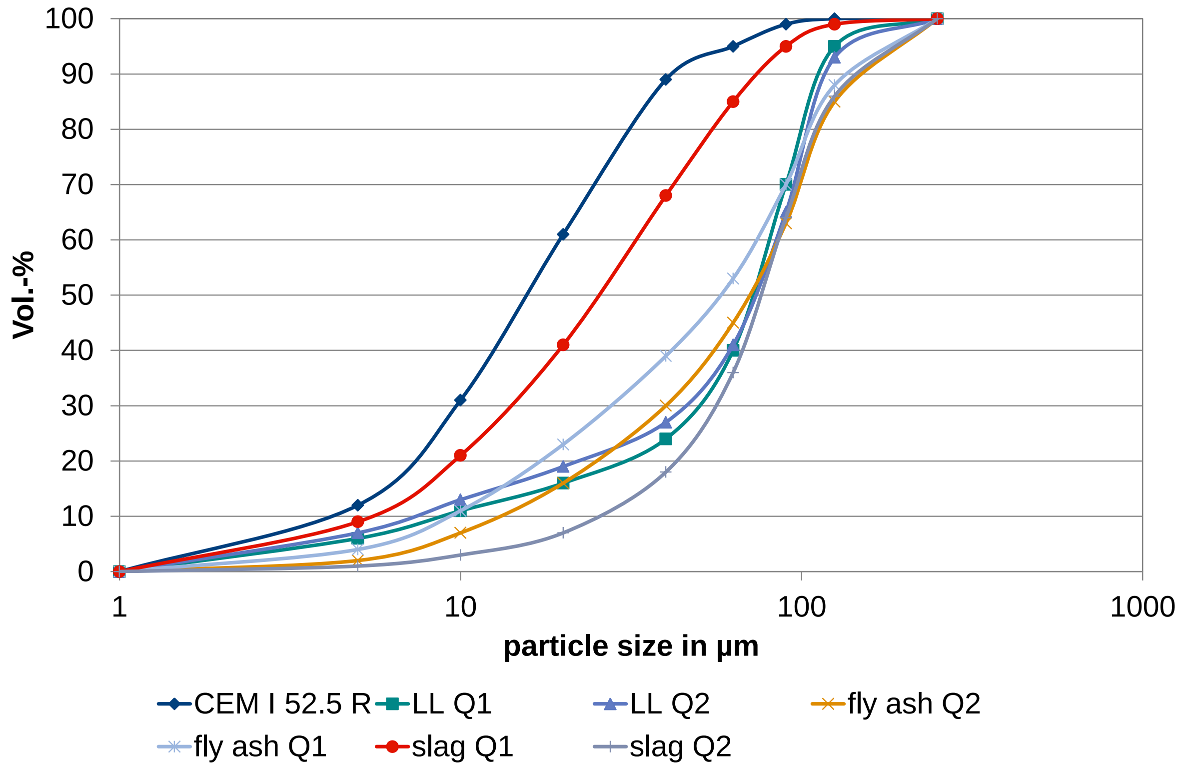

Figure 55 Particle size distributions of main constituents (SMG)

Table 10 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (VDZ, 1)

	CEM I (reference)	CEM II/A-LL (reference)	CEM III/A (reference)	CEM VI - B	CEM VI - A	CEM II/C-M (S-LL) - B	CEM II/C-M (S-LL) - A
Setting, initial in min	160	160	200	205	200	195	180
Setting, final in min	195	210	255	225	225	225	225
Water demand	31.0	28.5	32.0	28.0	29.0	28.0	29.5
Soundness in mm	0	0	0	1	1	1	0
Flow diameter in mm	157	157	164	170	180	160	169
Compressive strength in MPa, 2d	47.2	24.8	17.0	5.3	8.0	7.7	14.8
Compressive strength in MPa, 7d	60.0	42.7	32.4	21.4	26.6	22.1	30.8
Compressive strength in MPa, 28d	71.1	52.7	56.9	39.4	48.1	39.0	49.1
Compressive strength in MPa, 91d	73.9	59.7	74.6	51.1	63.4	49.1	61.4

Table 11 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (VDZ, 2)

	CEM II/B-M (S-LL) - B	CEM II/B-M (S-LL) - A	CEM II/B-M(T-LL) - B	CEM II/B-M(T-LL) - A	CEM II/B-M(D-LL) - B	CEM II/B-M(D-LL) - A	CEM II/B-LL - B
Setting, initial in min	175	155	290	150	190	175	160
Setting, final in min	210	195	345	195	240	225	210
Water demand	28.0	29.5	28.5	33.0	32.0	34.0	27.5
Soundness in mm	1	1	1	1	0	0	1
Flow diameter in mm	142	151	141	113	109	113	163
Compressive strength in MPa, 2d	16.2	27.4	26.5	43.2	18.8	32.3	15.0
Compressive strength in MPa, 7d	28.2	40.0	46.3	56.6	33.4	47.0	23.4
Compressive strength in MPa, 28d	40.0	52.3	56.9	67.1	52.9	65.6	28.0
Compressive strength in MPa, 91d	48.8	61.2	60.8	67.2	61.3	71.9	35.2

Table 12 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (VDZ, 3)

	CEM II/B-LL - A	CEM II/B-S - B	CEM II/B-S - A	CEMIII/B - B	CEMIII/B - A
Setting, initial in min	95	200	150	270	280
Setting, final in min	120	240	195	315	330
Water demand	28.5	29.0	30.5	31.5	31.5
Soundness in mm	0	1	1	0	1
Flow diameter in mm	154	141	161	160	163
Compressive strength in MPa, 2d	25.7	20.0	38.0	3.7	5.0
Compressive strength in MPa, 7d	34.6	33.1	54.3	17.5	18.2
Compressive strength in MPa, 28d	37.4	49.0	67.1	42.3	38.8
Compressive strength in MPa, 91d	42.7	59.7	76.6	66.1	63.5

Table 13 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (SMG, 1)

	CEM I (reference)	CEM II/A-LL (reference)	CEM III/A (reference)	CEM VI - A	CEM VI - B	CEM II/C-M (V-LL) - A	CEM II/C-M (V-LL) - B
Setting, initial in min	160	190	210	225	205	210	215
Setting, final in min	195	240	270	285	285	285	330
Water demand	31	28,8	31,8	29	24,8	28,8	28,2
Soundness in mm	0	0	0	1	1	1	1
Flow diameter in mm	170	181	181	179	168	180	176
Compressive strength in MPa, 2d	48.2	26.5	19.6	10.4	6.6	17.8	17.4
Compressive strength in MPa, 7d	61.3	43.2	35.4	29.1	16.5	23.9	25.6
Compressive strength in MPa, 28d	67.5	54.3	57.7	50.8	30.1	37.8	36.8

Table 14 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (SMG, 2)

	CEM II/C-M (S-V) - A	CEM II/C-M (S-V) - B	CEM II/B-M (LL-S-V) - A	CEM II/B-M (LL-S-V) - B	CEM II/B-M (S-LL) - A	CEM II/B-M (S-LL) - B
Setting, initial in min	235	270	195	190	155	155
Setting, final in min	315	345	270	240	225	210
Water demand	31,4	29,8	30,8	29,4	29,4	28
Soundness in mm	1	1	1	1	1	1
Flow diameter in mm	176	178	174	178	173	174
Compressive strength in MPa, 2d	18.4	21.0	29.1	28.9	28.2	27.0
Compressive strength in MPa, 7d	34.7	31.4	42.3	39.3	41.1	43.5
Compressive strength in MPa, 28d	53.1	45.3	56.1	51.7	58.6	53.3

Table 15 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (SMG, 3)

	CEM II/B-M (V-LL) - A	CEM II/B-M (V-LL) - B	CEM II/A-S - A	CEM II/A-S - B
Setting, initial in min	175	170	170	195
Setting, final in min	270	225	225	270
Water demand	29,6	28,2	31,6	30,6
Soundness in mm	1	1	0	0
Flow diameter in mm	175	175	166	174
Compressive strength in MPa, 2d	28.7	27.1	35.2	31.8
Compressive strength in MPa, 7d	39.7	37.3	52.5	46.9
Compressive strength in MPa, 28d	48.6	47.4	65.5	59.1

Table 16 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (CRIC, 1)

	CEM I (reference)	CEM II/A-LL (reference)	CEM III/A (reference)	CEM II/C-M (S-LL) - A	CEM II/C-M (S-LL) - B	CEM II/C-M (V-LL) - A	CEM II/C-M (V-LL) - B
Setting, initial in min	180	185	205	250	265	270	255
Setting, final in min	225	240	270	300	300	315	315
Water demand	32.5	29.5	32.5	30.0	30.5	28.5	290.
Soundness in mm	not determined		1.0	0.5	2.0	0.0	0.0
Compressive strength in MPa, 2d	45.7	23.1	18.0	13.8	9.9	8.3	6.5
Compressive strength in MPa, 7d	58.0	40.0	34.3	31.7	23.2	16.3	13.5
Compressive strength in MPa, 28d	67.3	52.1	57.3	47.4	39.4	27.3	20.5

Table 17 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (CRIC, 2)

	CEM II/C-M (S-V) - A	CEM II/C-M (S-V) - B	CEM II/B-M (LL-S-V) - A	CEM II/B-M (LL-S-V) - B	CEM II/B-M (D-LL) - A	CEM II/B-M (D-LL) - B
Setting, initial in min	290	265	230	250	180	185
Setting, final in min	360	345	270	300	285	240
Water demand	29.5	29.5	28.5	29.5	29.5	30.5
Soundness in mm	0.0	0.0	1.0	0.5	0.0	0.5
Compressive strength in MPa, 2d	13.8	8.7	20.6	14.3	21.0	15.4
Compressive strength in MPa, 7d	31.5	20.2	36.6	28.2	33.3	28.8
Compressive strength in MPa, 28d	51.0	40.2	51.4	41.4	48.3	43.3

Table 18 Setting times, water demand, soundness, flow diameter and compressive strength of mortar (CRIC, 3)

	CEM II/B-M (V-LL) - A	CEM II/B-M (V-LL) - B	CEM II/B-LL - A	CEM II/B-LL - B	CEM III/B - A	CEM III/B - B
Setting, initial in min	235	220	195	230	355	370
Setting, final in min	300	285	240	300	390	450
Water demand	29.0	29.0	29.5	29.0	31.5	32.5
Soundness in mm	0.0	0.5	1.0	1.0	2.0	1.0
Compressive strength in MPa, 2d	17.1	12.6	17.0	13.0	7.9	4.7
Compressive strength in MPa, 7d	29.5	23.4	27.7	23.7	28.4	18.9
Compressive strength in MPa, 28d	39.0	32.8	35.9	32.1	43.5	33.2

Table 19 Chemical bound water (CBW) of selected cements (VDZ)

		CEM I	CEM VI - A	CEM II/C-M (S-LL) - B	CEM II/B-M (S-LL) - A	CEM II/B-LL - A	CEM II/A-S - B	CEM III/B - A
IR	CBW in M.-%, 2d	19.5	12.8	14.0	18.2	17.2	16.2	10.0
	CBW in M.-%, 7d	20.6	15.0	16.6	18.1	17.3	17.2	13.8
	CBW in M.-%, 28d	20.3	16.4	16.0	20.5	17.6	19.6	18.1
STA	CBW in M.-%, 2d	18.8	12.1	13.0	17.5	16.9	15.5	-
	CBW in M.-%, 7d	20.4	14.6	15.6	17.8	16.5	16.6	-
	CBW in M.-%, 28d	21.3	17.9	17.3	20.1	17.5	18.4	-

Table 20 Chemical bound water (CBW) of selected cements (SMG)

		CEM I	CEM VI - B	CEM II/C-M (V-LL) - A	CEM II/C-M (S-V) - B	CEM II/B-M (LL-S-V) - A	CEM II/B-M (S-LL) - B	CEM II/B-M (V-LL) - A
IR	CBW in M.-%, 2d	20.8	11.0	13.4	10.8	16.1	13.9	16.4
	CBW in M.-%, 7d	18.1	16.8	14.9	13.1	17.6	15.6	17.0
	CBW in M.-%, 28d	-	-	16.0	-	18.8	-	18.1
STA	CBW in M.-%, 2d	19.0	12.2	11.9	10.5	14.5	12.9	15.1
	CBW in M.-%, 7d	21.4	14.6	13.4	14.9	16.4	14.7	15.3
	CBW in M.-%, 28d	22.1	15.2	14.9	12.7	18.0	16.6	16.7

Table 21 Chemical bound water (CBW) of selected cements (CRIC)

		CEM I	CEM II/C-M (S-LL) - A	CEM II/C-M (V-LL) - B	CEM II/C-M (S-V) - B	CEM II/B-M (LL-S-V) - B	CEM II/B-M (V-LL) - B	CEM II/B-LL - B
IR	CBW in M.-%, 2d	19.2	12.8	10.9	11.3	13.7	12.1	12.9
	CBW in M.-%, 7d	22.3	18.6	14.6	14.8	18.1	15.7	17.1
	CBW in M.-%, 28d	21.5	18.8	15.2	17.8	17.4	16.4	17.6
STA	CBW in M.-%, 2d	20.1	12.8	10.1	11.0	13.0	11.8	13.0
	CBW in M.-%, 7d	22.3	18.0	14.7	14.8	17.2	15.1	16.0
	CBW in M.-%, 28d	20.2	17.2	14.8	17.4	17.2	16.1	17.3

Table 22 Porosity of mortars (VDZ)

	w/c	CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
total porosity in %	0.50	10.4	14.3	14.1	14.2	15.5	12.2	14.8
porosity, r ≥ 0.01 µm in %	0.50	6.9	11.5	11.6	11.2	13.0	9.3	11.8
porosity, r ≥ 0.02 µm in %	0.50	3.4	5.8	8.1	5.3	10.0	5.5	5.7
porosity, r ≥ 0.03 µm in %	0.50	2.9	2.6	5.1	3.1	6.8	3.1	2.2
porosity, r ≥ 0.04 µm in %	0.50	2.7	2.0	3.2	2.7	4.7	2.4	1.7
total porosity in %	0.45	9.3	13.5	14.1	12.6	13.4	12.5	14.0
porosity, r ≥ 0.01 µm in %	0.45	5.9	10.7	11.3	8.6	10.9	9.1	11.0
porosity, r ≥ 0.02 µm in %	0.45	3.2	3.6	7.0	3.1	6.2	5.4	4.6
porosity, r ≥ 0.03 µm in %	0.45	2.8	2.1	3.5	2.6	3.1	3.1	2.4
porosity, r ≥ 0.04 µm in %	0.45	2.7	1.8	2.3	2.4	2.4	2.6	2.1
total porosity in %	0.55	16.3	15.4	15.8	16.2	12.7	15.6	16.3
porosity, r ≥ 0.01 µm in %	0.55	13.4	12.7	12.3	13.8	9.9	12.6	13.4
porosity, r ≥ 0.02 µm in %	0.55	8.8	8.8	5.8	11.1	6.7	8.0	8.8
porosity, r ≥ 0.03 µm in %	0.55	4.0	5.7	2.7	8.4	3.9	2.9	4.0
porosity, r ≥ 0.04 µm in %	0.55	2.4	3.4	2.3	5.9	2.8	1.9	2.4
total porosity in %	0.65	13.5	16.9	16.7	16.0	18.3	15.8	17.6
porosity, r ≥ 0.01 µm in %	0.65	10.2	14.1	13.8	13.0	16.2	12.3	14.6
porosity, r ≥ 0.02 µm in %	0.65	5.1	9.9	10.1	8.8	13.8	8.8	10.4
porosity, r ≥ 0.03 µm in %	0.65	2.7	5.9	7.7	4.0	12.0	6.4	6.7
porosity, r ≥ 0.04 µm in %	0.65	2.2	3.1	6.0	2.5	10.6	4.9	4.1

Table 23 Porosity of mortars (SMG)

	w/c	CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
total porosity in %	0.50	9.3	17.7	16.1	15.2	14.6	13.9	14.9
porosity, r ≥ 0.01 µm in %	0.50	6.5	13.2	12.2	11.1	9.8	9.9	10.8
porosity, r ≥ 0.02 µm in %	0.50	3.5	8.6	5.8	4.1	3.7	5.0	4.5
porosity, r ≥ 0.03 µm in %	0.50	2.7	6.0	2.5	2.1	2.7	2.5	2.4
porosity, r ≥ 0.04 µm in %	0.50	2.4	4.6	1.8	1.6	2.4	2.0	2.1

Table 24 Porosity of mortars (CRIC)

	w/c	CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
total porosity in %	0.50	10.4	12.8	16.6	14.3	15.3	18.0	16.4
porosity, r ≥ 0.01 µm in %	0.50	6.8	9.4	14.0	10.1	11.9	14.2	13.3
porosity, r ≥ 0.02 µm in %	0.50	3.9	4.9	11.4	6.4	8.2	10.7	10.3
porosity, r ≥ 0.03 µm in %	0.50	3.4	2.3	9.6	4.5	6.3	8.7	8.2
porosity, r ≥ 0.04 µm in %	0.50	3.2	1.7	8.5	3.3	5.0	7.4	6.5

Table 25 Fresh concrete properties and concrete compressive strength (VDZ)

		CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
Fresh concrete air content in %	C1	1.0	1.0	0.9	1.0	1.0	1.2	1.5
	C2	1.1	1.1	0.8	1.0	0.9	1.0	1.3
	C3	0.9	1.0	1.1	1.4	1.1	1.1	1.1
	C4	4.6	4.8	5.4	5.5	4.9	5.5	5.1
	C5	5.9	6.1	5.7	4.7	5.3	5.4	4.9
Flow diameter in mm	C1	320	315	380	310	330	360	360
	C2	330	375	400	385	385	415	370
	C3	365	340	350	345	370	395	not determined
	C4	325	320	320	290	345	330	460
	C5	345	345	375	350	335	350	345
Compressive strength in MPa, 2d	C1	43.8	12.4	9.6	26.5	24.0	20.9	6.6
	C2	31.4	7.5	7.0	17.6	15.9	12.2	3.5
	C3	41.8	12.1	not determined	23.8	22.1	19.2	7.9
	C4	48.7	12.4	9.2	23.4	23.1	18.5	10.1
	C5	29.0	6.7	4.8	16.2	15.8	13.7	4.8
Compressive strength in MPa, 28d	C1	67.6	40.8	36.0	54.8	44.8	49.1	36.1
	C2	53.3	29.0	26.5	37.5	28.8	35.1	24.8
	C3	63.6	39.2	33.5	48.8	40.1	47.9	35.2
	C4	70.7	40.3	34.3	46.7	41.3	42.3	35.5
	C5	46.1	26.0	23.2	35.5	28.7	38.3	28.4

Table 26 Fresh concrete properties and concrete compressive strength (SMG)

		CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
Fresh concrete air content in %	C1	2.0	1.5	1.8	1.9	1.9	2.5	2.1
	C2	2.0	2.0	1.4	1.5	2.2	2.3	1.8
	C3	2.1	2.2	1.9	1.2	2.3	1.9	2.3
	C4	5.0	5.0	5.0	4.4	5.1	6.3	4.9
	C5	4.7	5.2	4.7	4.9	5.8	7.2	4.8
Flow diameter in mm	C1	280	350	360	370	330	340	340
	C2	320	350	370	370	350	380	350
	C3	330	360	300	370	390	320	310
	C4	270	380	360	260	310	330	260
	C5	360	390	360	410	330	420	370
Compressive strength in MPa, 2d	C1	36.4	6.6	15.2	13.9	27.1	24.7	24.8
	C2	32.3	4.1	9.1	8.8	17.5	14.5	15.9
	C3	40.8	5.6	13.9	12.4	24.0	21.2	22.5
	C4	45.6	6.6	14.8	14.9	26.2	18.1	25.5
	C5	33.8	3.9	10.2	10.1	17.8	11.0	19.1
Compressive strength in MPa, 28d	C1	62.0	35.3	35.2	40.8	52.3	47.3	43.8
	C2	45.0	15.7	18.9	26.6	34.0	31.5	30.2
	C3	55.1	29.2	32.9	37.0	44.9	36.6	36.2
	C4	55.5	30.1	31.0	36.1	39.9	35.5	40.4
	C5	48.6	21.4	25.4	27.9	33.8	22.2	33.6

Table 27 Fresh concrete properties and concrete compressive strength (CRIC)

		CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
Fresh concrete air content in %	C1	1.9	1.3	1.7	1.6	1.6	1.8	1.9
	C2	1.7	0.8	1.2	0.8	1.0	1.1	1.3
	C3	2.1	1.5	1.8	1.7	1.8	1.6	1.8
	C4	5.0	6.4	3.7	7.4	6.4	2.8	4.5
	C5	6.5	4.5	3.6	4.7	4.7	3.9	3.0
slump in mm	C1	30	60	50	50	40	40	35
	C2	30	60	50	60	50	50	40
	C3	20	40	45	40	30	30	30
	C4	40	20	30	40	20	30	40
	C5	120	90	80	70	90	75	50
Compressive strength in MPa, 2d	C1	42.5	14.0	6.9	10.8	23.7	20.3	13.7
	C2	30.3	8.3	3.8	6.3	9.8	8.0	8.1
	C3	39.3	10.6	5.4	8.8	12.3	11.2	10.9
	C4	47.1	13.0	7.7	7.6	13.0	16.7	12.9
	C5	31.4	9.5	4.9	6.7	10.3	9.5	9.1
Compressive strength in MPa, 28d	C1	56.9	42.6	21.1	39.0	42.5	33.4	32.6
	C2	46.4	30.0	12.9	28.9	30.4	22.0	21.3
	C3	55.6	39.4	17.4	35.9	36.0	29.3	27.7
	C4	61.8	39.4	22.7	28.1	35.0	38.5	31.0
	C5	44.0	33.8	14.7	26.5	31.4	25.1	24.2

Table 28 Depth of carbonation, 1 % CO_2 (VDZ)

		CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
depth of carbonation in mm, 1% CO_2, C1	0 d	0.1	0.5	0.6	0.2	0.9	0.1	1.8
	14 d	0.2	2.0	4.9	2.3	6.3	1.0	7.0
	28 d	0.1	3.2	6.1	2.6	9.5	not determined	8.8
	56 d	0.2	5.2	8.1	3.9	13.6	1.7	11.7
depth of carbonation in mm, 1% CO_2, C2	0 d	0.4	1.5	1.5	0.8	1.6	0.7	2.4
	14 d	1.5	9.0	6.9	3.5	11.2	5.5	8.8
	28 d	1.5	9.7	8.3	4.3	14.8	7.6	13.0
	56 d	2.0	11.6	10.2	6.8	22.7	7.9	17.0

Table 29 Depth of carbonation, 1 % CO_2 (SMG)

		CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
depth of carbona-tion in mm, 1% CO_2, C1	0 d	0.1	0.9	0.6	0.4	0.2	0.3	0.5
	14 d	0.1	4.3	4.0	3.6	2.6	2.2	3.0
	28 d	0.2	6.9	6.5	5.1	3.5	3.3	4.3
	56 d	1.1	9.9	8.9	7.3	4.9	5.1	6.6
depth of carbona-tion in mm, 1% CO_2, C2	0 d	0.1	1.3	0.8	0.6	0.4	0.5	0.7
	14 d	1.5	6.4	6.0	4.7	3.4	3.7	4.1
	28 d	2.1	10.7	10.0	8.1	5.9	6.2	7.0
	56 d	4.1	15.4	16.1	10.5	7.6	9.2	10.9

Table 30 Depth of carbonation, 1 % CO_2 (CRIC)

		CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
depth of carbona-tion in mm, 1% CO_2, C1	0 d	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	14 d	0.0	3.3	6.5	4.3	2.6	4.0	4.6
	28 d	1.8	5.0	9.3	5.4	4.5	5.8	6.4
	56 d	2.7	6.8	14.7	8.9	6.7	8.8	9.5
depth of carbona-tion in mm, 1% CO_2, C2	0 d	0.0	0.6	1.4	0.5	0.9	0.5	0.9
	14 d	2.8	5.9	12.2	8.1	6.3	5.8	7.7
	28 d	3.6	7.7	14.9	10.3	8.1	6.7	9.2
	56 d	5.1	10.4	20.1	14.3	10.4	9.3	12.4

Table 31 Depth of carbonation, CEN/TR 16563 (VDZ)

	pre-storage	CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
depth of carbonation after 140 d storage in mm	7 d	0.4	3.8	4.5	2.0	2.7	2.3	5.0
	28 d	0.1	2.8	3.2	1.1	2.1	1.5	3.5
compressive strength in MPa	7 d	60.1	27.1	16.3	39.8	34.0	35.3	25.6
	28 d	65.7	42.8	34.4	51.1	39.2	49.6	39.8

Table 32 Chloride diffusion and migration coefficients (VDZ)

		CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
Initial Chloride content in %	C1	0.009	0.009	0.012	0.011	0.007	0.066	0.007
Correlation coefficient R^2		0.995	0.999	0.988	0.950	0.952	0.999	0.993
Chloride diffusion coefficient in 10^{-12} m²/s		8.50	2.62	3.62	8.28	11.50	5.21	2.28
Initial Chloride content in %	C3	0.018	0.014	0.009	0.025	0.030	0.019	0.009
Correlation coefficient R^2		0.999	0.993	0.928	0.995	0.997	0.999	0.993
Chloride diffusion coefficient in 10^{-12} m²/s		4.02	6.36	50.30	5.05	1.73	4.02	6.36
Chloride migration coefficient in 10^{-12} m²/s	C1	16.3	5.2	7.6	21.0	49.2	11.5	4.8
	C3	25.5	6.1	8.7	22.2	61.7	13.4	4.8

Table 33 Chloride diffusion coefficients (SMG)

		CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
Initial Chloride content in %	C1	0,013	0,013	0,016	0,008	0,020	0,029	0,030
Correlation coefficient R^2		0,991	0,983	0,991	0,995	0,994	0,996	0,993
Chloride diffusion coefficient in 10^{-12} m²/s		14.0	4.9	7.9	3.3	4.8	7.9	7.7
Initial Chloride content in %	C3	0,018	0,018	0,012	0,024	0,025	0,023	0,030
Correlation coefficient R^2		0,983	0,996	0,981	0,975	0,965	0,961	0,965
Chloride diffusion coefficient in 10^{-12} m²/s		16.0	6.8	14.6	7.5	8.2	18.8	11.6

Table 34 Chloride diffusion coefficients (CRIC)

		CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
Initial Chloride content in %	C1	0.017	0.018	0.011	0.010	0.022	0.021	0.014
Correlation coefficient R^2		not determined						
Chloride diffusion coefficient in 10^{-12} m²/s		12.9	3.6	4.6	1.1	5.7	10.9	26.3
Initial Chloride content in %	C3	0.036	0.018	0.013	0.016	0.021	0.036	0.014
Correlation coefficient R^2		not determined						
Chloride diffusion coefficient in 10^{-12} m²/s		13.4	4.0	17.1	1.8	6.7	17.7	41.4

Table 35 Freeze-Thaw resistance, CIF (VDZ)

	FTC	CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
scaling in kg/m²	4	0.01	0.04	0.04	0.03	0.05	0.06	0.04
	10	0.02	0.07	0.06	0.05	0.10	0.10	0.48
	14	0.02	0.08	0.08	0.06	0.13	0.13	1.00
	28	0.03	0.20	0.37	0.09	0.30	0.28	1.93
relative dyn. modulus of elastici-ty in %	4	96.1	95.1	93.0	97.2	85.7	98.2	92.2
	10	92.7	84.8	64.0	91.4	53.5	96.8	61.7
	14	89.4	77.2	36.3	86.3	36.2	94.8	40.1
	28	78.3	46.6	38.3	69.3	35.4	88.8	37.3

Table 36 Freeze-Thaw resistance, CIF (SMG)

	FTC	CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
scaling in kg/m²	7	0,011	n. d.	n. d.	n. d.	n. d.	0,035	n. d.
	14	0,019	n. d.	n. d.	n. d.	n. d.	0,086	n. d.
	28	0,032	n. d.	n. d.	n. d.	n. d.	0,382	n. d.
	56	0,050	n. d.	n. d.	n. d.	n. d.	1,243	n. d.
relative dyn. modulus of elastici-ty in %	7	97,3	100,4	96,7	96,4	99,4	96,1	97,1
	14	94,2	93,0	81,8	82,0	89,5	88,6	83,7
	28	92,1	76,8	67,9	70,5	81,6	66,1	71,7
	56	84,2	67,5	52,1	57,5	61,8	56,7	55,5

Table 37 Freeze-Thaw resistance, CIF (CRIC)

	FTC	CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
scaling in kg/m²	7	0.02	0.08	0.05	0.02	0.06	0.04	0.02
	14	0.03	0.20	0.38	0.08	0.08	0.07	0.06
	28	0.05	0.44	not determined	0.45	0.17	0.18	0.16
	56	0.18	0.83		1.53	0.56	15.53	not determined
relative dyn. modulus of elasticity in %	7	67.67	48.30	18.30	150.60	99.60	90.60	121.80
	14	108.82	104.40	0.00	120.80	77.70	81.50	80.80
	28	20.52	68.40	not determined	82.00	75.70	52.80	53.10
	56	0.01	1.70		0.10	6.20	0.00	not determined

Table 38 Freeze-Thaw resistance with de-icing salts, slab test (VDZ)

	FTC	CEM I	CEM VI	CEM II/C-M (S-LL)	CEM II/B-M (S-LL)	CEM II/B-LL	CEM II/A-S	CEM III/B
scaling in kg/m², C4	7	0.00	0.06	0.11	0.02	0.12	0.03	0.50
	14	0.01	0.22	0.29	0.04	0.21	0.07	0.88
	28	0.02	0.48	0.44	0.05	0.30	0.10	1.15
	42	0.03	0.66	0.50	0.06	0.31	0.12	1.33
	56	0.04	0.79	0.52	0.07	0.32	0.14	1.50
scaling in kg/m², C5	7	0.01	0.35	0.17	0.04	0.31	0.07	0.94
	14	0.01	0.58	0.46	0.06	0.61	0.10	1.05
	28	0.01	0.66	0.51	0.07	0.86	0.14	1.07
	42	0.01	0.84	0.53	0.10	0.98	0.15	1.09
	56	0.01	not determined	0.54	0.11	1.05	0.16	1.09
axis interception	C4	0.000	0.178	0.367	0.030	0.280	0.060	0.807
	C5	0.001	0.011	0.003	0.001	0.001	0.001	0.012
slope	C4	0.010	0.433	0.482	0.033	0.678	0.120	1.051
	C5	0.000	0.009	0.001	0.001	0.007	0.001	0.001

Table 39 Freeze-Thaw resistance with de-icing salts, slab test (SMG)

	FTC	CEM I	CEM VI	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (S-LL)	CEM II/B-M (V-LL)
scaling in kg/m², C4	7	0,012	0,64	1,341	0,688	0,06	0,098	0,164
	14	0,026	0,729	1,751	1,037	0,194	0,211	0,335
	28	0,037	0,865	2,094	1,116	0,287	0,277	0,384
	42	0,045	not determined			0,323	0,294	0,407
	56	0,054				0,342	0,307	0,431
scaling in kg/m², C5	7	0,051	1,661	1,481	1,714	0,46	0,193	0,705
	14	0,097	1,925	1,848	2,053	0,7	0,202	1,111
	28	0,154	not determined			0,766	0,227	1,28
	42	0,159				0,774	0,237	1,365
	56	0,159				not determined		
axis inter-ception	C4	0,020	not determined			0,235	0,247	0,337
	C5	0,149				0,758	0,219	1,208
slope	C4	0,001				0,002	0,001	0,002
	C5	0,000				0,000	0,000	0,003

Table 40 Freeze-Thaw resistance with de-icing salts, slab test (CRIC)

	FTC	CEM I	CEM II/C-M (S-LL)	CEM II/C-M (V-LL)	CEM II/C-M (S-V)	CEM II/B-M (LL-S-V)	CEM II/B-M (V-LL)	CEM II/B-LL
scaling in kg/m², C4	7	0.19	0.23	1.97	0.28	0.22	1.81	1.61
	14	0.42	0.35	4.11	0.42	0.31	4.38	3.40
	28	0.61	0.45	7.54	0.54	0.39	8.67	6.50
	56	0.81	0.53	not de-termined	0.69	0.45	10.45	10.64
scaling in kg/m², C5	7	0.20	1.11	2.28	0.94	0.38	0.88	2.26
	14	0.34	1.60	4.17	1.24	0.57	1.87	4.40
	28	0.45	1.48	7.23	1.54	0.82	3.59	5.02
	56	0.54	2.23	19.52	1.81	0.91	5.83	6.22
axis inter-ception	C4	0.410	0.375	0.685	0.385	0.325	6.890	2.360
	C5	0.007	0.003	-	0.005	0.002	0.071	0.142
slope	C4	0.350	0.735	-5.060	1.260	0.720	1.353	3.785
	C5	0.003	0.025	0.435	0.010	0.003	0.073	0.059