Evolving the well-established

Low-Clinker Cements –

Opportunities and Challenges for their Deployment

Christoph Mueller, VDZ Duesseldorf, Germany

C2 Congress: Green Cement & Concrete 2050

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Speaker

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VDZ Technology gGmbH

CV (excerpt)

Studied civil engineering at RWTH Aachen University

Research assistant at the Institute for Building Research at RWTH Aachen (ibac)

PhD in 2000

Since 2000: Research Institute of the Cement Industry, Düsseldorf (VDZ)

2007 Head of the Concrete Technology Department at VDZ

2012 Managing Director of VDZ Technology gGmbH

Since 2014 Honorary Professor at Ruhr University Bochum (RUB)

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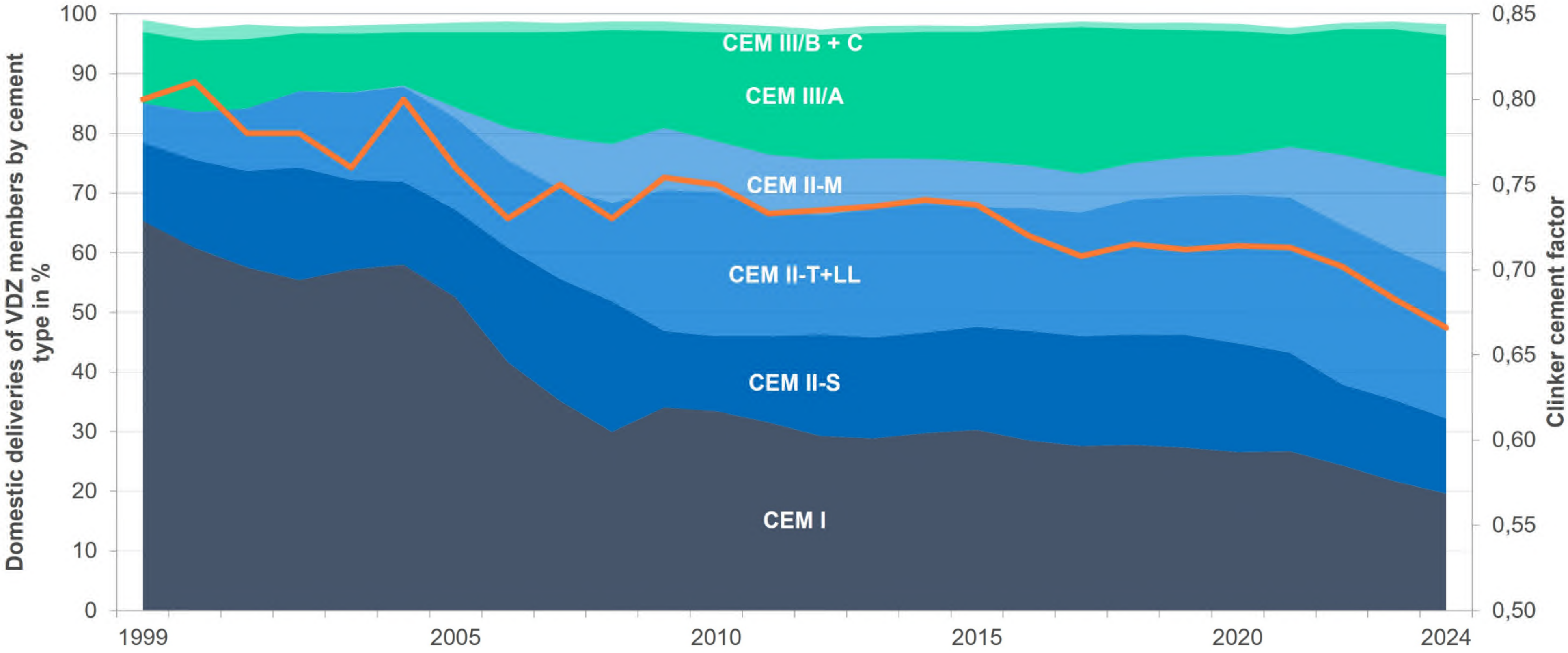
Services in Concrete technology

From the laboratory to the finished concrete structure

- VDZ – Your partner for concrete technology and structural surveys
- Quality control – Ensuring construction quality through expert support
- Structural assessment – for a longer service life for your structures
- Durability assessments as a reliable basis for decision-making
- Tests and reports on structural durability – for long-lasting structures
- Service life assessment as a secure basis for new construction, repair and long-term use
- Product optimisation and CO_2 reduction in concrete – for sustainable and high-performance solutions
- Approval tests and approval procedures – ensuring products are applied safely and efficiently
- Life cycle assessment – greater transparency and sustainability
- Sustainability assessment – successful certification with DGNB
- Material testing – comprehensive and reproducible

Development of the cement portfolio and the clinker factor

Example: Germany from 1999 to 2024 (Source: VDZ)



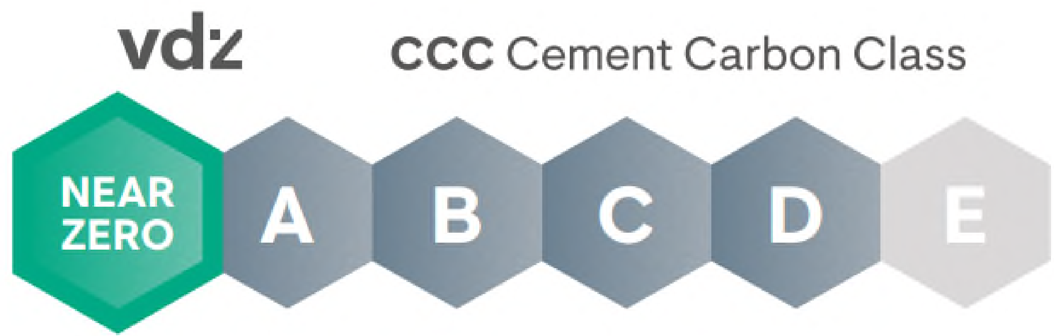
Source: VDZ
Notes: The difference from 100% is distributed among CEM IV, CEM V, and other binders.

World Cement March 2026.

https://issuu.com/palladianpublications/docs/world_cement_-_march_2026

www.vdz-online.de

Low carbon cement

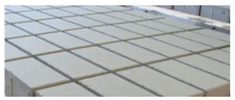


CCC-Classes for cement			Limit (GWP) CO_2 eq / tonne cement
Climate-friendly	Low emission	D	400 ≤ GWP < 500
		C	300 ≤ GWP < 400
		B	200 ≤ GWP < 300
		A	100 ≤ GWP < 200
	Near Zero	NZ	< 100

Performance of cement in mortar and concrete

What performance is needed?

Different applications require a different set of performance characteristics

Interior components (dry)		▪ Suitable (robust) fresh concrete properties ▪ Compressive strength and other linked mechanical properties
„Normal“ outdoor components		▪ Suitable (robust) fresh concrete properties ▪ Compressive strength and other linked mechanical properties ▪ Carbonation, if proven: „Strength is a proxy for durability“
Severe conditions (e. g. chloride)		▪ Suitable (robust) fresh concrete properties ▪ Compressive strength and other linked mechanical properties ▪ Durability tests (strength ≠ durability)
Possibly further requirements depending on the area of application	   	▪ Concrete goods ▪ Precast elements ▪ Screed (bagged cement) industrial floors ▪ Geotechnical works ▪ Concrete roads ▪ Railway sleepers

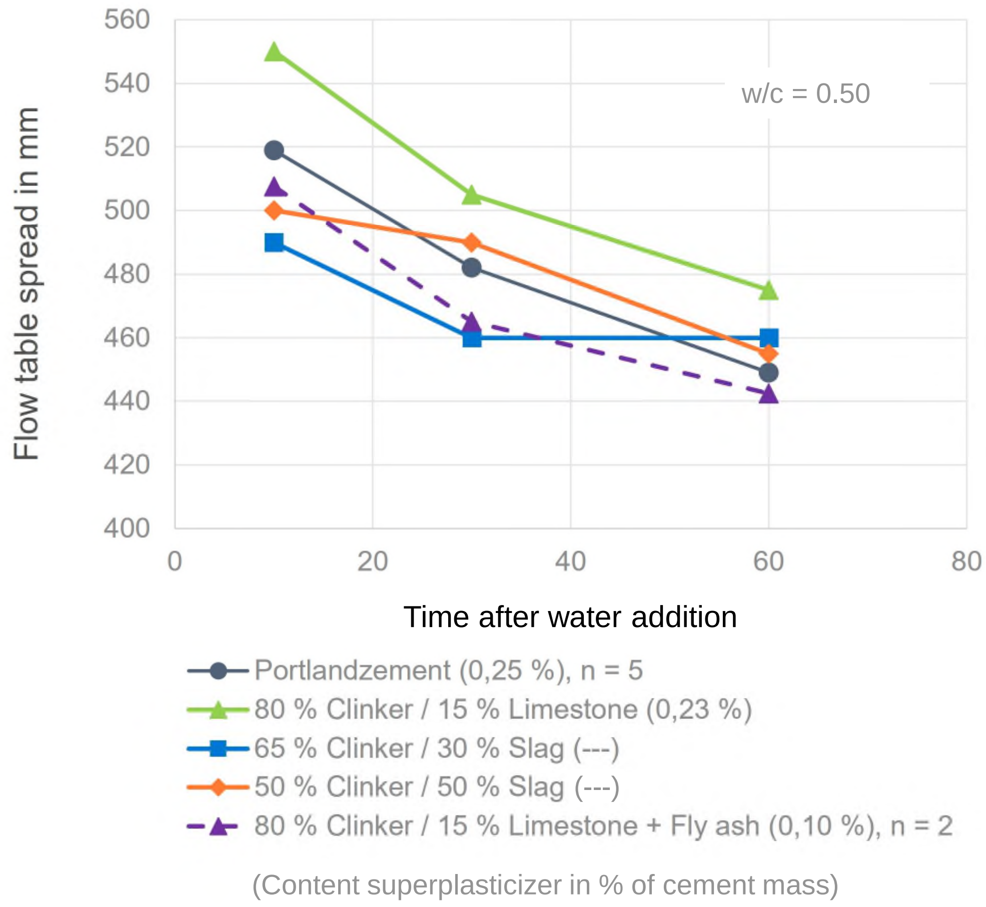
Fresh concrete properties

Fresh concrete properties

Workability

Basic principles

- Fresh concrete properties suitable for construction site conditions (weather conditions, temperature, processing influences)
- Concrete with a sufficient volume of stable and robust paste (volume cement, additions and water)
- High-performance concrete admixtures
- Under these conditions, blended cements can be used just as successfully as Portland cement
- Example: Workability (here: flow table spread over time) of concrete with blended cements comparable to concrete with Portland Cement



Source: VDZ

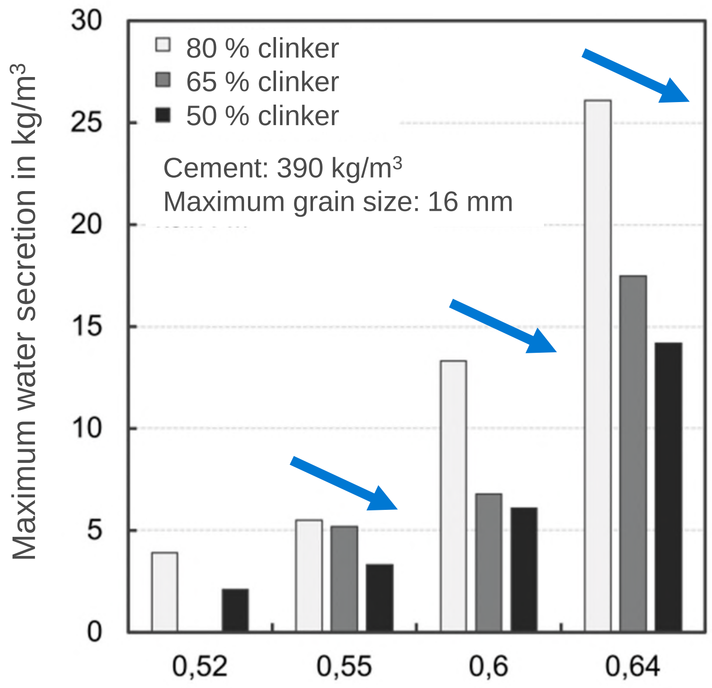
Fresh concrete properties

Water secretion (bleeding)

Basic principles

- Fresh concrete properties suitable for construction site conditions (weather conditions, temperature, processing influences)
- Concrete with a sufficient volume of stable and robust paste (volume cement, additions and water)
- High-performance concrete admixtures
- Under these conditions, blended cements can be used just as successfully as Portland cement
- Example: Water secretion (bleeding) can be reduced by using blended cement with a low clinker factor and appropriate granulometry (fineness).

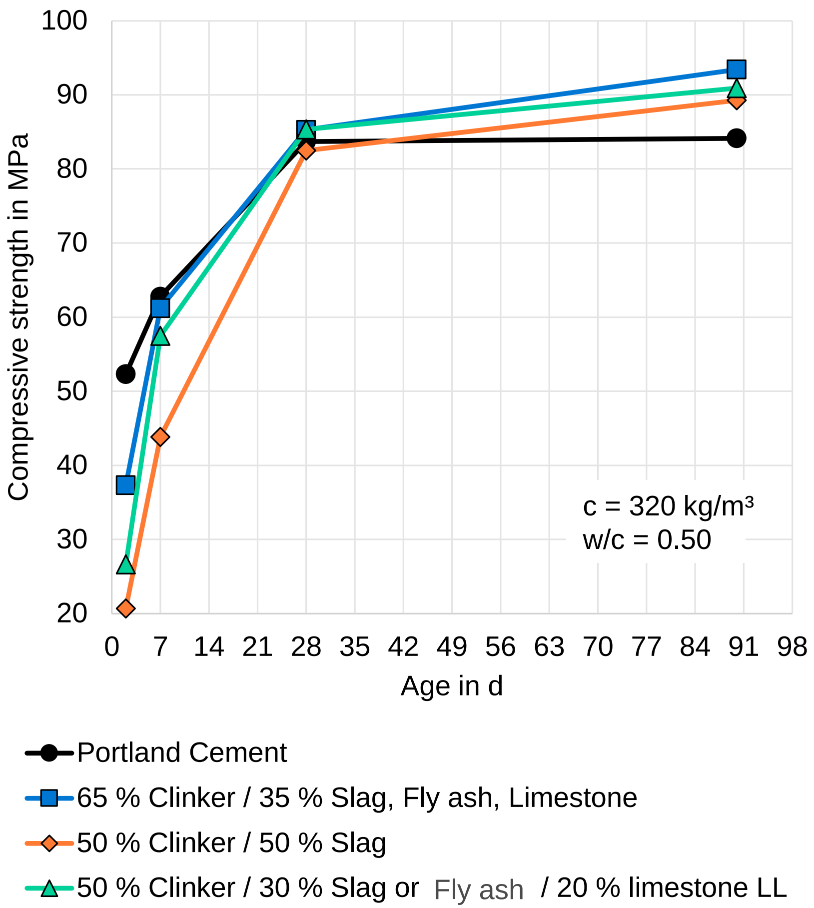
Blended cements with fly ash and max. 20 % limestone



Source: Tobias Schack, Michael Haist
Ernst & Sohn GmbH, Berlin. Beton- und Stahlbetonbau 120 (2025), Heft 1

Strength development

Strength development of concrete



- Early strength (2 days) reduced due to the replacement of clinker by inert and/or slowly reacting SCMs
- “Final” strength at 28 days not a problem
- Strength > 28 days further increasing with the use of pozzolanic or latent hydraulic materials
- Grinding will become more important
  e. g. to accelerate early strength development.

Minimum curing time

Minimum curing time = f (strength development)

No	1	2	3	4	5
Relevant Temperature T in Grad C [d]		Minimum curing time in days [a]			
		Strength development of the concrete (f_{cm2d}/f_{cm28d}) [c]			
		Fast	Medium	Slow	Very Slow
		$r \geq 0.5$	$0.3 \leq r < 0.5$	$0.15 \leq r < 0.3$	$r < 0.15$
1	$T \geq +25$	1	2	2	3
2	$+25 > T \geq +15$	1	2	4	5
3	$+15 > T \geq +10$	2	4	7	10
4	$+10 > T \geq +5$ [b]	3	6	10	15

a If the workability time exceeds 5 hours, the curing time must be extended accordingly.

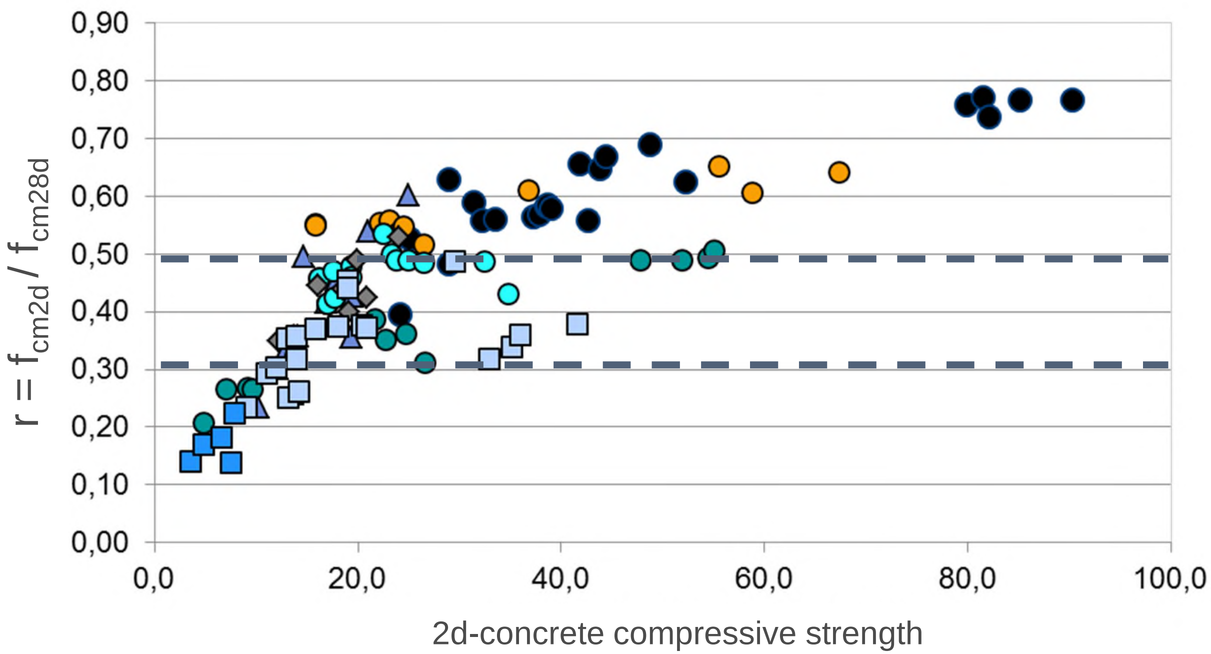
b At temperatures below 5 °C, the curing time must be extended by the time during which the temperature was below 5 °C.

c The strength development of the concrete is described by the ratio of the mean compressive strength after 2 days and after 28 days ($r = f_{cm2}/f_{cm28}$), which was determined during the initial test or on the basis of a known ratio of concrete with a comparable composition.

d The surface temperature of the concrete, or alternatively the air temperature, as the minimum value in the time interval, may be used.

Source: Example taken from German concrete standard DIN 1045-3 : 2023

Relative compressive strength of concretes ($r = f_{cm2d}/f_{cm28d}$)



- Concretes with cements of clinker factor ~ 0.8 are in the upper value range (r ≥ 0.5)
- Concretes with slag cements and ternary cements with a clinker factor of around 0.5 typically have an r-value between 0.3 and 0.5
- **Concrete with medium and slow strength development (r-value between 0.3 and 0.5) require longer moulding and curing times**

Portland cement	(95)		
Limestone cements	(80)	(70)	
Slag cements	(65)	(50)	(20)
Ternary cements (slag / limestone)	(65)	(50)	

(min clinker in %)

Minimum curing time

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Lower clinker content can require longer curing time

No	1	2	3	4	5
Relevant Temperature T in Grad C [d]		Minimum curing time in days [a]			
		Strength development of the concrete (f_{cm2d}/f_{cm28d}) [c]			
		Fast	Medium	Slow	Very Slow
		$r \geq 0.5$	$0.3 \leq r < 0.5$	$0.15 \leq r < 0.3$	$r < 0.15$
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Durability

Design for durability (steel reinforced concrete)

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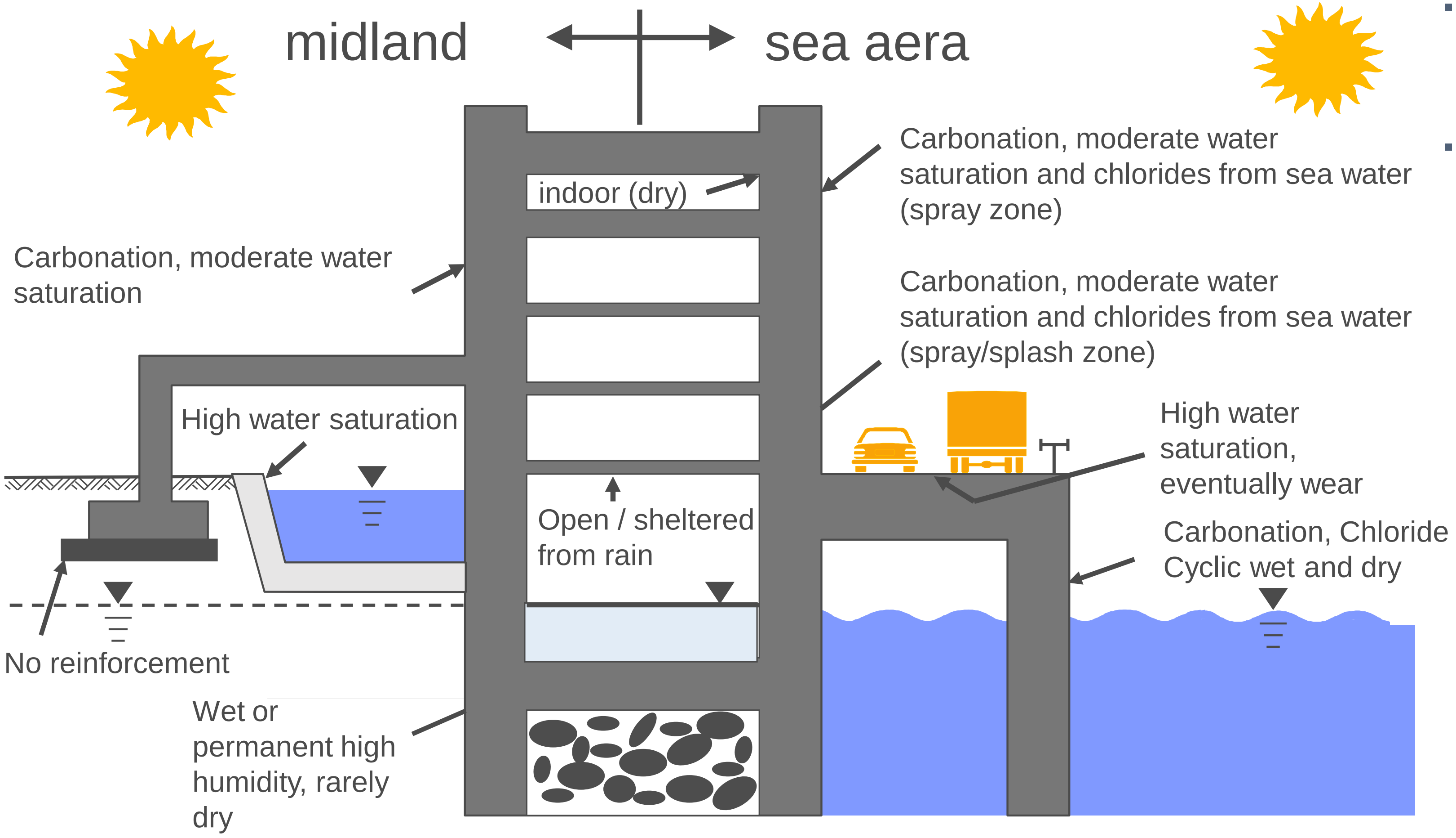

- Buildings / components exposed to different ambient conditions
- Ambient conditions dependent on the respective region, e. g.:

  - high relative humidity vs. dry conditions

  - chlorides (e. g. sea water)

  - freeze-thaw or not

Durability: Carbonation as an example

A large proportion of the cement is used in reinforced concrete. Sufficient resistance to carbonation-induced reinforcement corrosion can therefore used as a benchmark.

Carbonation: General influences regards clinker replacement

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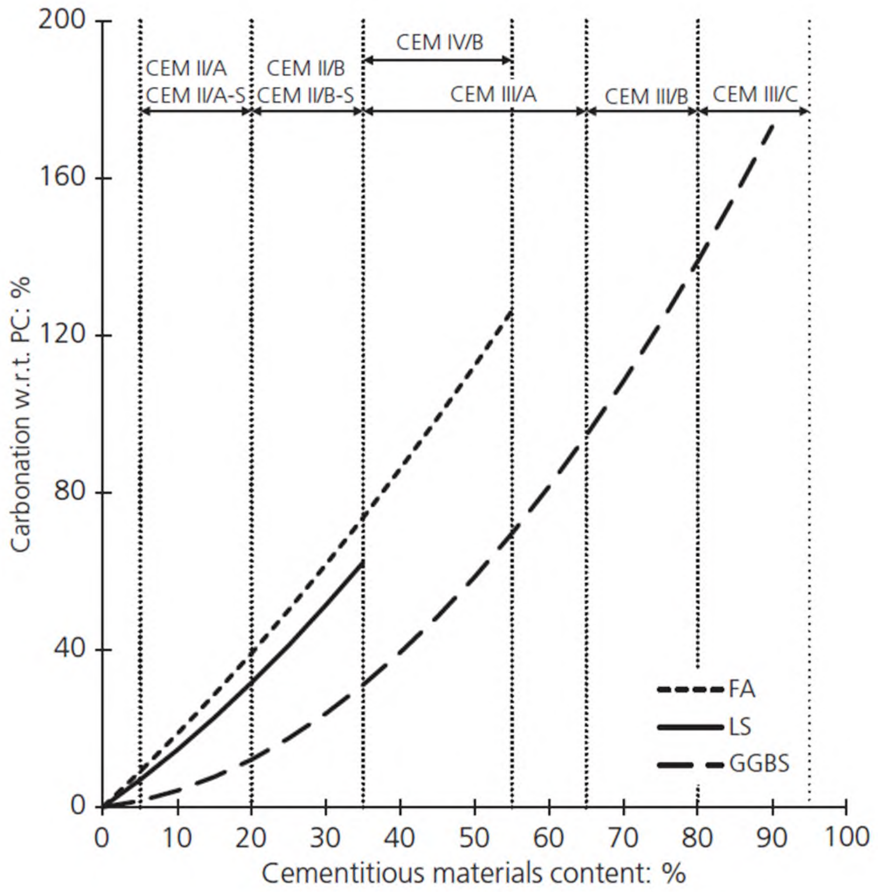
Comparison of Limestone (LS), Fly ash (FA) and GGBS concretes; effect of replacement



- Combinations of LS, FA or GGBS with Portland cement (PC) lead to increased carbonation.
- Degree of increase depends on the composition of concrete in terms of its w/c ratio and strength, maturity and pore structure as it is subjected to carbonation.
- In order to obtain comparable carbonation to PC concrete, the concrete mix design adjustment made in terms of reduction in w/c ratio or increase in compressive strength for LC and FA concretes will be more than for GGBS concrete at the same replacement level

How to deal with the different carbonation behaviour of mortar and concrete when reducing the clinker content in cement?

A. Elgalhud, R. Dhir, G. Ghataora - Carbonation resistance of concrete: Limestone carbonation resistance
Magazine of Concrete Research, 2017, 69(2), 84–106
http://dx.doi.org/10.1680/jmacr.16.00371

Introduction of new low carbon cement types

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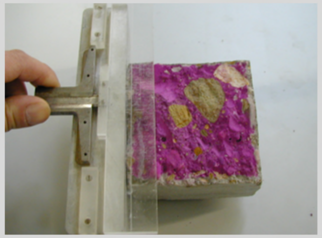
1

Lab Performance



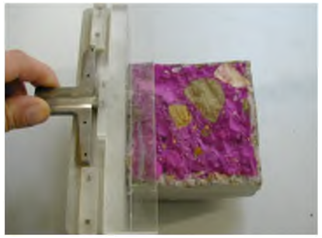
Deemed-to-satisfy

compare with well-tried and proven cements

Structure

2

Lab Performance



Modeling

e. g. acc. to fib Model code

Structure

Performance-based approach

Carbonation of concrete with different cements

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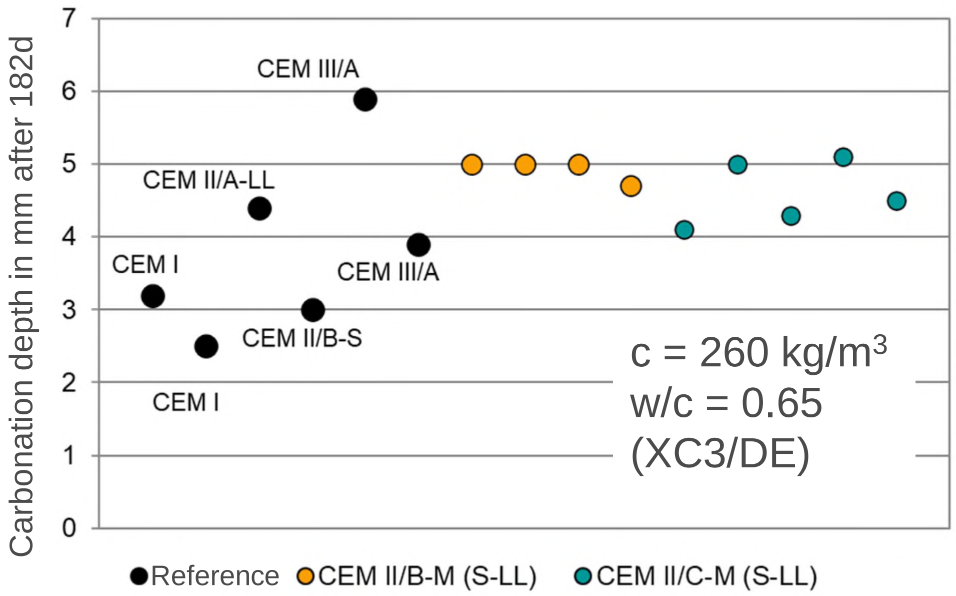
Example: Concrete for an exterior component, sheltered from rain (XC3) in Germany (DE)



Source: VDZ

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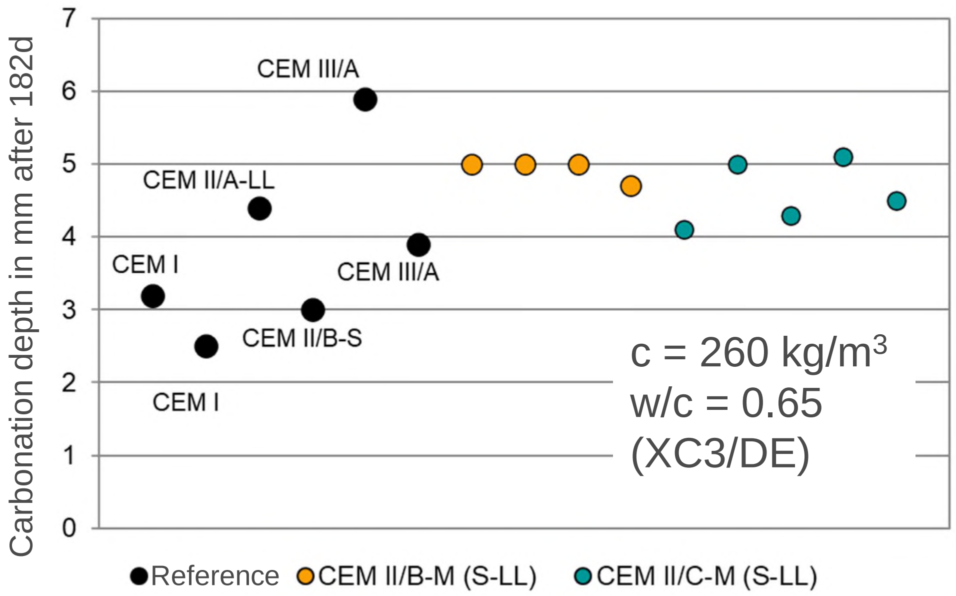

No differentiation by cement type within the same exposure

- Portland cement CEM I (≥ 94 % clinker)
- Slag cement CEM II/B-S (≥ 65 % clinker)
- Limestone cements CEM II/A-LL (≥ 80 % clinker)
- Slag cements CEM III/A (~ 35-50 % clinker)

Source: VDZ

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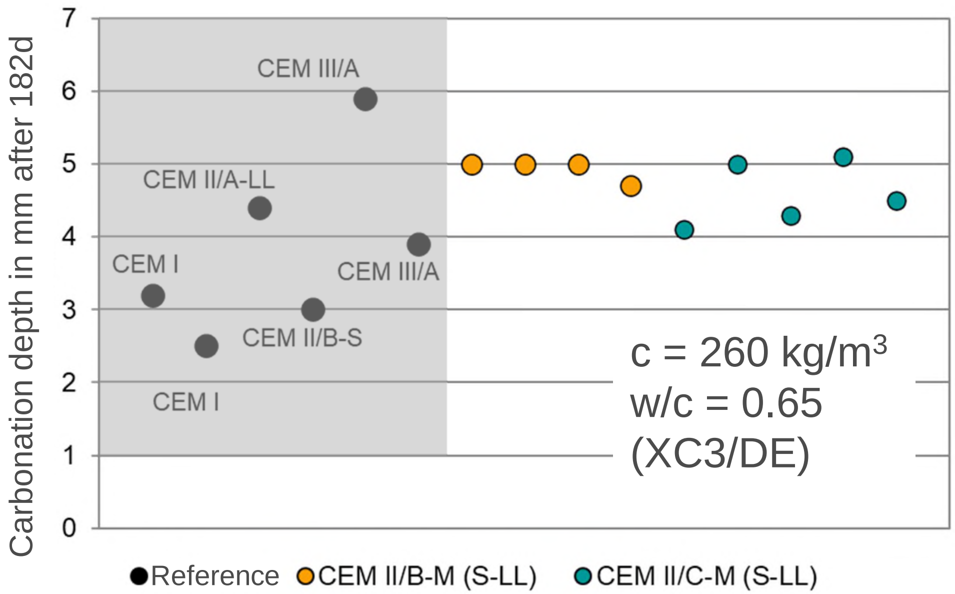

Well-tried and proven cements

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Carbonation of concrete with different cements

vdz

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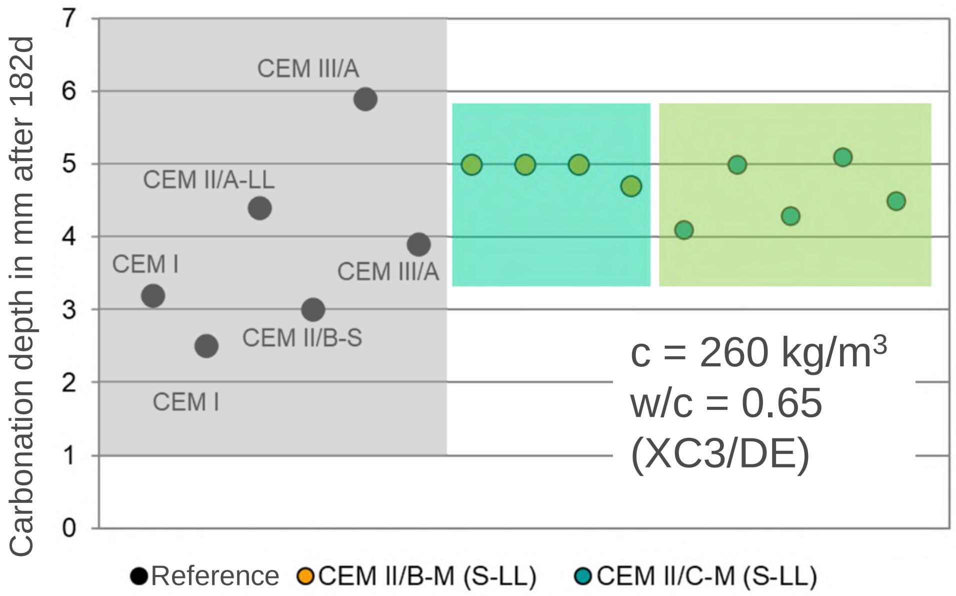


New cements CEM II-M comparable with well-tried and proven cements

No differentiation by cement type within the same exposure

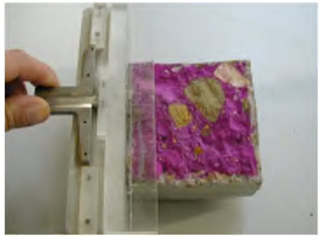
- Portland cement CEM I (≥ 94 % clinker)
- Slag cement CEM II/B-S (≥ 65 % clinker)
- Limestone cements CEM II/A-LL (≥ 80 % clinker)
- Slag cements CEM III/A (~ 35-50 % clinker)
- Ternary cements CEM II/B-M with ≥ 65 % clinker, ≤ 20 % limestone and slag
- Ternary cements CEM II/C-M with ≥ 50 % clinker, ≤ 20 % limestone and slag

Source: VDZ

Introduction of new low carbon cement types

1

Lab Performance



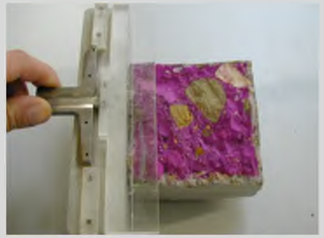
Deemed-to-satisfy

compare with well-tried and proven cements

Structure

2

Lab Performance



Modeling

e. g. acc. to fib Model code

Structure

Performance-based approach

Exposure Resistance Classes: Example Carbonation

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ERC	Exposure class (Carbonation)							
	XC1		XC2		XC3		XC4	
	Design service life (years)							
	50	100	50	100	50	100	50	100
XRC 0,5	10	10	10	10	10	10	10	10
XRC 1	10	10	10	10	10	15	10	15
XRC 2	10	15	10	15	15	25	15	25
XRC 3	10	15	15	20	20	30	20	30
XRC 4	10	20	15	25	25	35	25	40
XRC 5	15	25	20	30	25	45	30	45
XRC 6	15	25	25	35	35	55	40	55
XRC 7	15	30	25	40	40	60	45	60

NOTE 1 The designation of XRC classes for resistance against corrosion induced by carbonation is derived from the carbonation depth [mm] (characteristic value 90 % fractile) assumed to be obtained after 50 years under reference conditions (400 ppm CO_2 in a constant 65 %-RH environment and at 20 °C). XRC has the dimension of a carbonation rate [mm/√(years)].

NOTE 2 The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least Execution Class 2 and Curing Class 2.

NOTE 3 The minimum covers can be increased by an additional safety element $\Delta_{cdur,\gamma}$ considering special requirements (e.g. more extreme environmental conditions).

Increase in the minimum concrete cover in mm due to decrease in carbonation resistance

Definition of the carbonation behavior under reference conditions

Source: Eurocode 2: Design of concrete structures - Part 1-1: General rules - Rules for buildings, bridges and civil engineering structures - DRAFT FprEN 1992-1-1:2023

Exposure Resistance Classes: Example Carbonation

ERC	Exposure class (Carbonation)							
	XC1		XC2		XC3		XC4	
	Design service life (years)							
	50	100	50	100	50	100	50	100
XRC 0,5	10	10	10	10	10	10	10	10
XRC 1	10	10	10	10	10	15	10	15
XRC 2	10	15	10	15	15	25	15	25
XRC 3	10	15	15	20	20	30	20	30
XRC 4	10	20	15	25	25	35	25	40
XRC 5	15	25	20	30	25	45	30	45
XRC 6	15	25	25	35	35	55	40	55
XRC 7	15	30	25	40	40	60	45	60

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Optimization regards

- **concrete performance**
- **concrete cover**
- **service life**

Increase in the minimum concrete cover in mm due to decrease in carbonation resistance

Definition of the carbonation behavior under reference conditions

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Example for a data-base on carbonation (n = 362)

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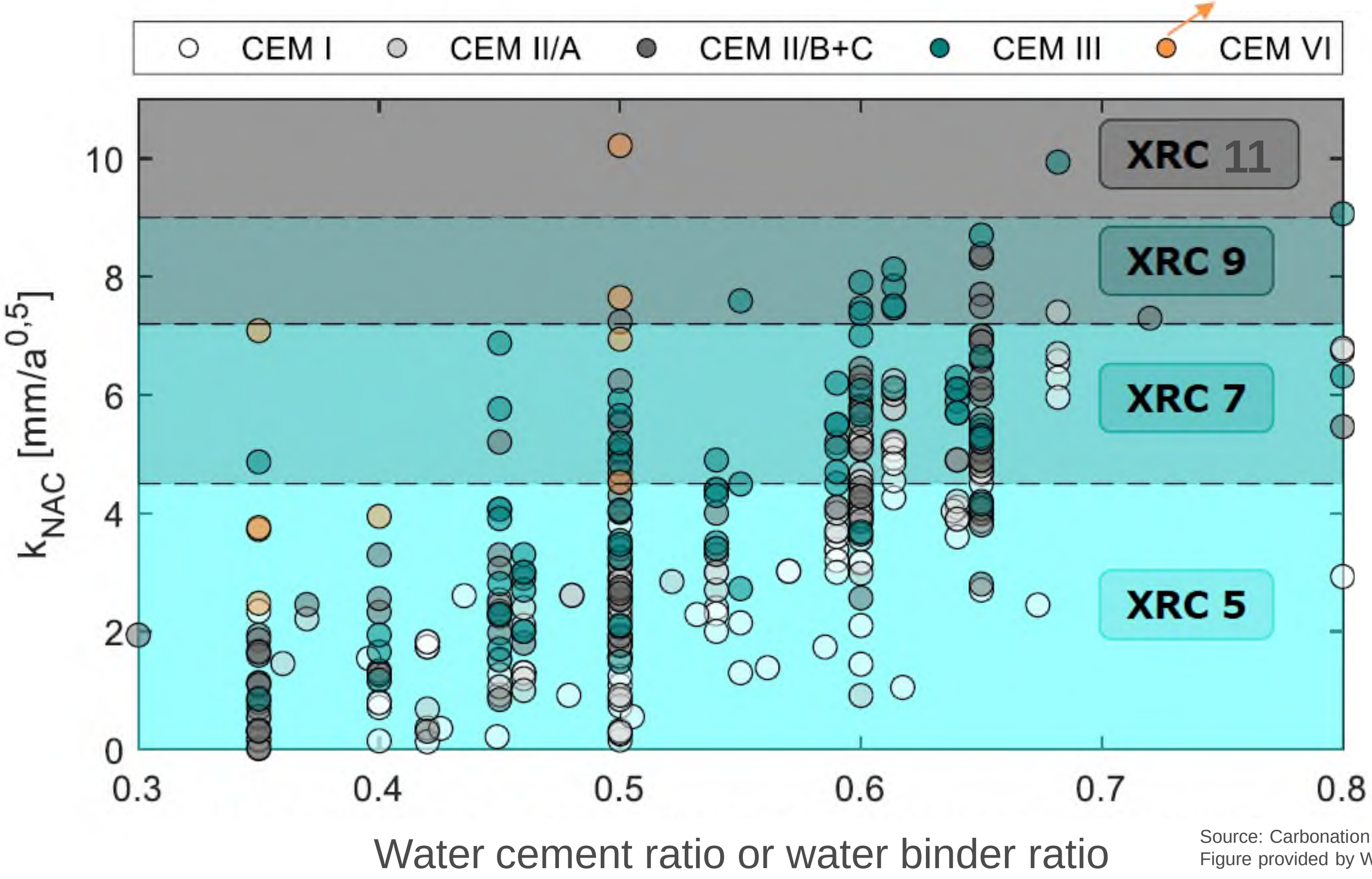
Lab cements only (two projects)



- CEM VI = Blended cements with min. 35 % clinker
- CEM III = Slag cements with min. 35/20 % clinker
- CEM II/C = Blended cements with min. 50 % clinker
- CEM II/B = Blended cements with min. 65 % clinker
- CEM II/A = Blended cements with min. 80 % clinker
- CEM I = Portland cement

decreasing clinker content

Source: Carbonation data-base compiled by the German committee of reinforced concrete
Figure provided by Wibke Hermerschmidt

Example for a data-base on carbonation (n = 362)

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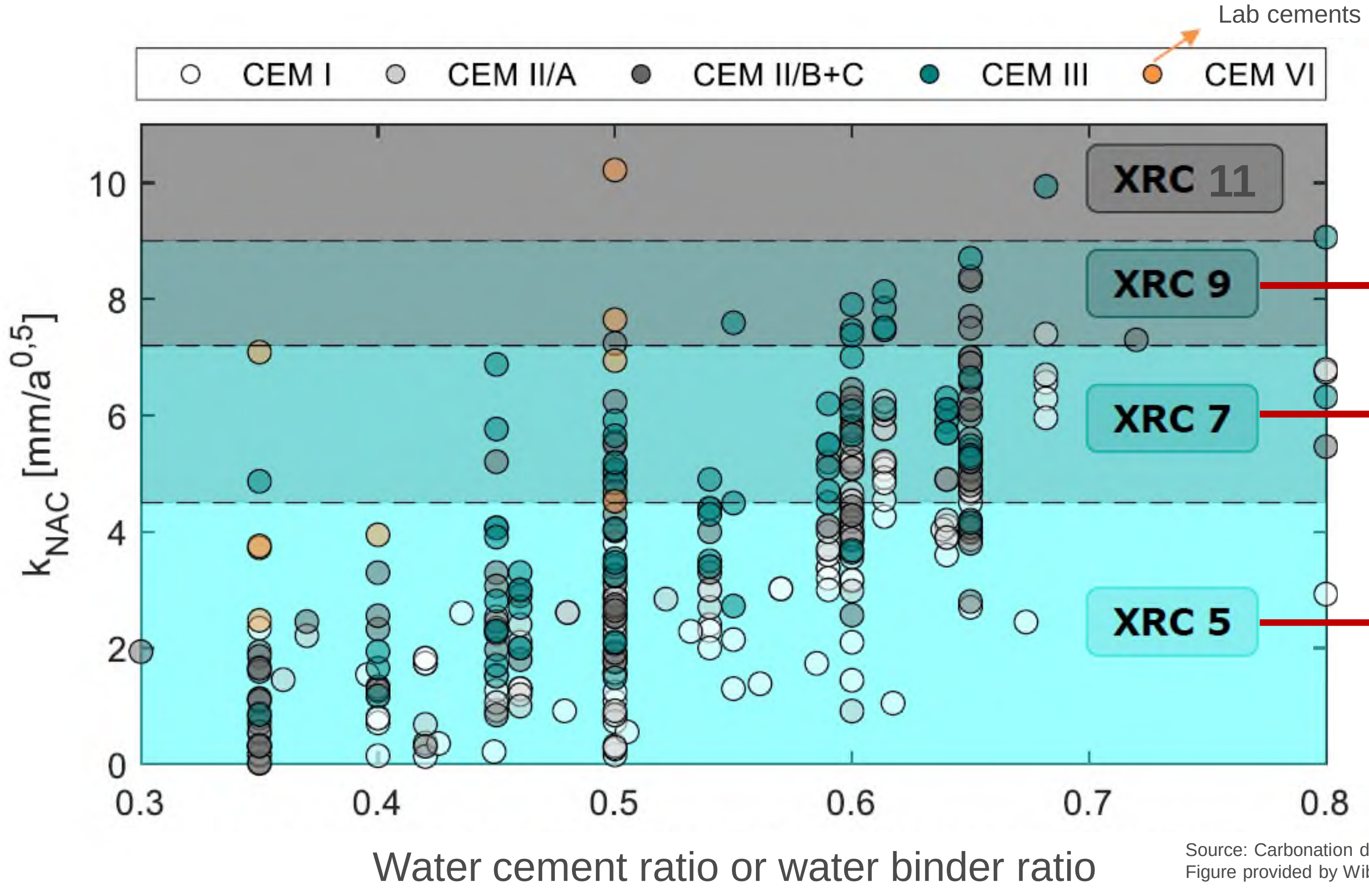


$c_{min,dur}$ = 35 mm

$c_{min,dur}$ = 30 mm

$c_{min,dur}$ = 25 mm

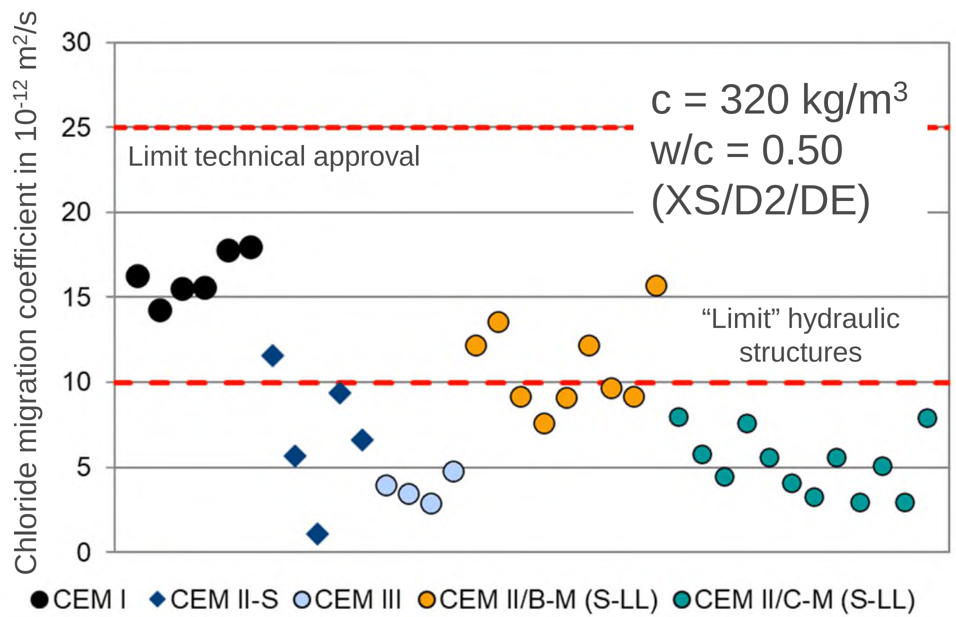
$c_{min,dur}$ = 15 mm

XC4 (DE) and 50 years with curing class 3

Source: Carbonation data-base compiled by the German committee of reinforced concrete
Figure provided by Wibke Hermerschmidt

Durability performance of concrete with different cements

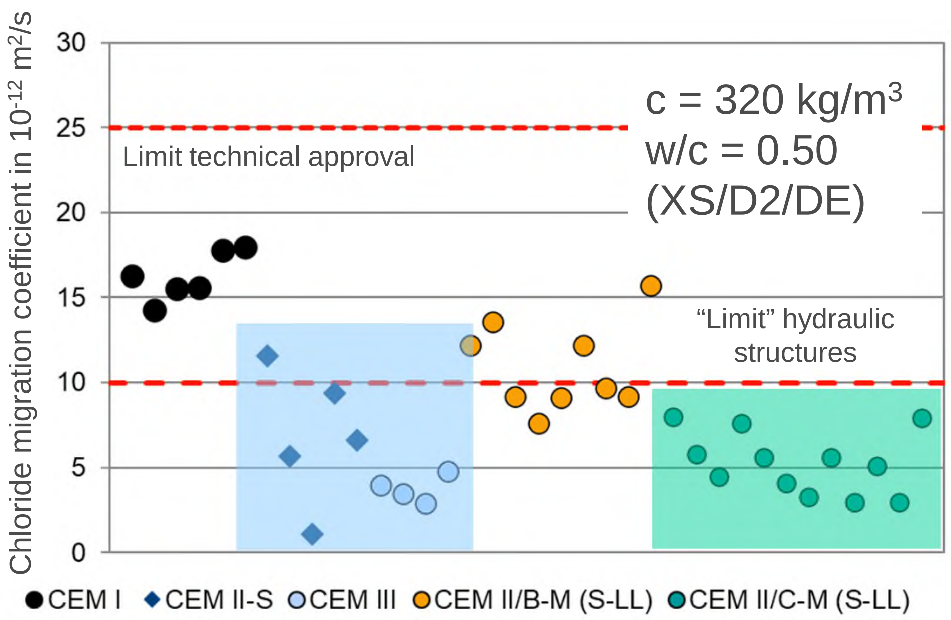
Chloride migration coefficient



Source: VDZ

Durability performance of concrete with different cements

Chloride migration coefficient



High resistance with slag or fly ash (calcined clay)

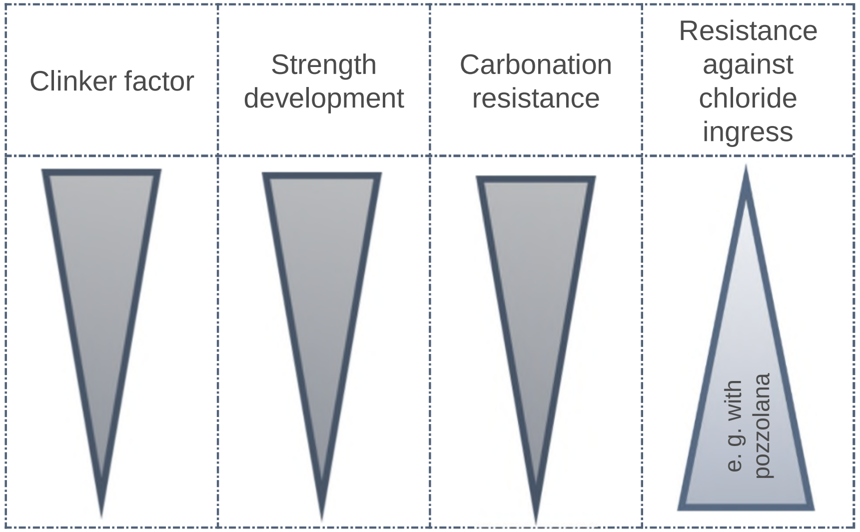
Source: VDZ

Low-Clinker Cements

Opportunities and Challenges for their Deployment

- The reduction of the clinker factor depends on the availability of materials that can replace clinker
- Clinker efficient cement can contain besides clinker
  - Pozzolana / Fly ash / Slag
  - Unburned limestone
  - Calcined/activated clay
  - Recycled (concrete) fines
  - others
- The clinker content and the type and amount of other constituents are to some extent influencing several properties of cement, mortar and concrete in different ways.
- Reduction of the clinker factor may not jeopardize the performance of mortar and concrete. Grinding will become more important e. g. to accelerate early strength development.
- The clinker factor (%) to be continuously reduced in the coming years (e. g. Germany)

2024	2030	2050
67	63	53



- In order that all stakeholders develop confidence in clinker-reduced cements and concretes, a comprehensive database should be obtained.
- This database and subsequent deemed-to-satisfy rules or performance indicators should take into consideration specific ambient (e. g. relative humidity) and building conditions (min concrete cover)

Thank you for your attention.

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