Concrete for geotechnical engineering

Author: Prof. Dr. habil. Heinz Konietzky
(TU Bergakademie Freiberg, Geotechnical Institute)

Editor: Prof. Dr.-Ing. habil. Heinz Konietzky Layout: Angela Griebsch
TU Bergakademie Freiberg, Institut für Geotechnik, Gustav-Zeuner-Straße 1, 09599 Freiberg • sekr_fm@ifgt.tu-freiberg.de

1 Introduction

Concrete is a basic material in geotechnical engineering and is used in two different forms:

- as flowable concrete (e.g. in-situ concrete or shotcrete, Fig. 1)
- as prefabricated solid construction part (Fig. 2)

Concrete is a composite material, which consists of the following ingredients: cement, mineral admixtures, aggregates, water and chemical admixtures. Concrete is a brittle material with medium to high compressive strength, but low tensile strength. Therefore, concrete is often reinforced by steel or geosynthetic bars or fibres. The components must be properly mixed, placed and cured to obtain the desired concrete quality and properties, respectively.

Design (dimensioning) of concrete structures is based on Eurocode 2 (see Fig. 3). However, for geotechnical applications Eurocode 7 & 8 might be also consulted and for mixed structures depending on the used material Eurocode 3 to 9 might also be of relevance.

Most important properties and requirements on concrete and cement are summarised in Tab. 1. In addition shrinkage and creep behaviour should be considered.

Fig. 1: Flowable concrete applications (left: shotcrete, right: pumped concrete; company material)

Fig. 2: Pre-cast concrete (examples: company material)

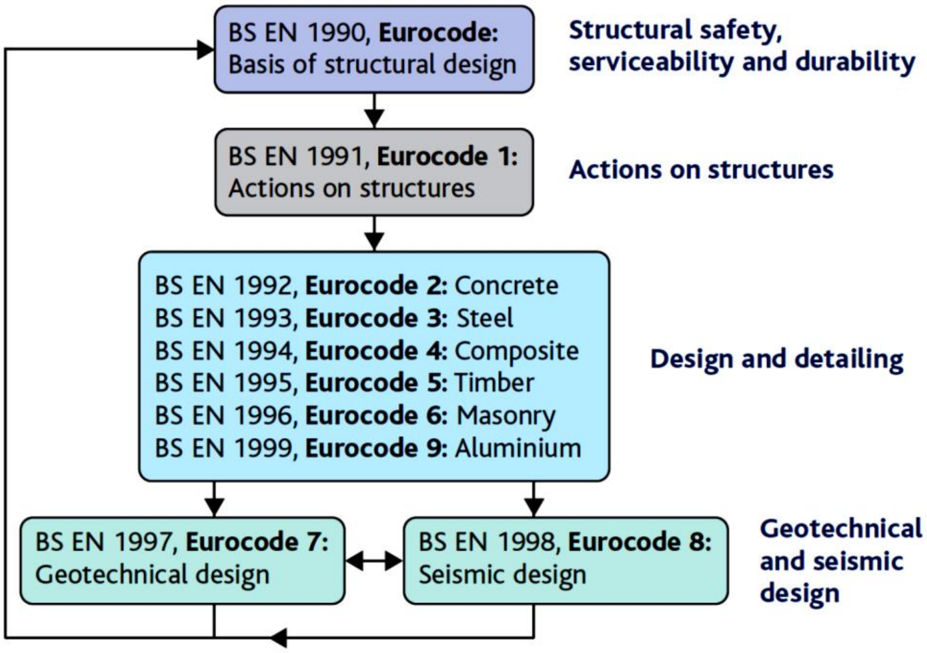


Fig. 3: Eurocode system (Bond et al. 2006)

Tab. 1: Characteristics and requirements on cement and concrete (Sybertz & Thielen, 2006)

Eigenschaft / *Property*	**Anforderung / *Requirement*** Unmittelbare Leistungsmerkmale *Performance characteristics*	Beschreibende Kenngrößen *Descriptive characteristics*	
Verarbeitbarkeit / *Workability* – Wasseranspruch / *water requirement* (Normsteife) / *(standard consistency)* – Erstarren / *setting*	(x) x		**Zement / *Cement*** } Grenzwert / *Limit*
Festigkeit / *Strength* – Anfangsfestigkeit / *early strength* – 28-Tage-Druckfestigkeit / *28-day strength*	 x	x	} Festigkeitsklassen *Strength classes* [32,5; 42,5; 52,5 (N,R)]
Raumbeständigkeit / *Soundness* – Kalktreiben / *lime expansion* – Sulfattreiben / *sulphate expansion* – Magnesiumtreiben / *magnesia expansion*		x x x	} Grenzwerte / *Limits*
Chloride / *Chlorides*	x		
Verarbeitbarkeit / *Workability* – Konsistenz / *consistency*	x		**Beton / *Concrete*** } Erstprüfung / *Initial testing*
Festigkeit / *Strenght* – 28-Tage-Druckfestigkeit / *28-day-strength*	x		
Dauerhaftigkeit / *Durability* – Schutz der Bewehrung / *Protection of reinforcement* • Carbonatisierung / *carbonation* • Chlorideindringen / *penetration of chloride* – Frostwiderstand / *Frost resistance* • ohne Tausalz / *without de-icing salt* • mit Tausalz / *with de-icing salt* – Chemischer Widerstand / *Chemical resistance*		 x x x x x	} Zusammensetzung *Composition* • max w/z / *w/c* • min z/c • Zementart / *Cement types* etc.

2 Cement

According to the cement type the following classification is used according to DIN EN 197-1:

- CEM I Portland cement (general purpose)
- CEM II Portland composite cement (sulphate resisting)
- CEM III Blast furnace cement (high early strength)
- CEM IV Pozzolanic cement (low hydration heat)
- CEM V Composite cement (severe sulfate resistance)

The main constituents of the cement are:

- Portland cement clinker
- Granulated blastfurnace slag
- Natural pozzolana (trass)
- Burnt shale
- Siliceous fly ash
- limestone

Tab. 2 illustrates the composition of the most common cement types. Hints how to choose the appropriate cement type according to exposure and construction type is given in Tab. 3.

Tab. 2: Characteristics/ requirements on cement and concrete (Sybertz & Thielen, 2006)

Zementart / Cement type				Hauptbestandteile / Main constituents						Neben-bestandteile Minor additional constituents [2]
Hauptart Main type	Benennung / Designation	Kurz-zeichen Notation (neu / new)	Kurz-zeichen Notation (alt / old)	Portland-zement-klinker Portland cement clinker K	Hütten-sand Granulated blast-furnace slag S	Natür-liches Puzzolan Natural pozzolana P	Kiesel-säurereiche Flugasche Siliceous fly ash V	Gebrannter Schiefer Burnt shale T	Kalkstein Limestone L	
CEM I	Portlandzement Portland cement	CEM I	PZ	95 – 100	–	–	–	–	–	0 – 5
CEM II	Portlandhüttenzement Portland-slag cement	CEM II/A-S	EPZ	80 – 94	6 – 20	–	–	–	–	0 – 5
		CEM II/B-S		65 – 79	21 – 35	–	–	–	–	0 – 5
	Portlandpuzzolanzement Portland-pozzolana cement	CEM II/A-P	TrZ	80 – 94	–	6 – 20	–	–	–	0 – 5
		CEM II/B-P		65 – 79	–	21 – 35	–	–	–	0 – 5
	Portlandflugaschezement Portland-fly ash cement	CEM II/A-V	FAZ	80 – 94	–	–	6 – 20	–	–	0 – 5
	Portlandölschieferzement Portland-oil shale cement	CEM II/A-T	PÖZ	80 – 94	–	–	–	6 – 20	–	0 – 5
		CEM II/B-T		65 – 79	–	–	–	21 – 35	–	0 – 5
	Portlandkalksteinzement Portland-limestone cement	CEM II/A-L	PKZ	80 – 94	–	–	–	–	6 – 20	0 – 5
	Portlandflugaschehüttenzement Portland-fly ash-slag cement	CEM II/B-SV	FAHZ	65 – 79	10 – 20	–	10 – 20	–	–	0 – 5
CEM III	Hochofenzement Blastfurnace cement	CEM III/A	HOZ	35 – 64	36 – 65	–	–	–	–	0 – 5
		CEM III/B		20 – 34	66 – 80	–	–	–	–	0 – 5

Tab. 3: Application rules for cement according to DIN EN 197-1 and DIN 1164

✖ gültiger Anwendungsbereich / *valid area of application* ❍ nach DIN 1045-2 nicht anwendbar / *cannot be used in accordance with DIN 1045-2*		Zemente nach / *cements complying with* DIN EN 197-1 und / *and* DIN 1164								
		CEM I	CEM II				CEM III		CEM IV	CEM V
Bauteil / Bauwerk *component / structure*	Bemessungsrelevante Expositionsklassen *exposure classes relevant to the design*		S T D A-LL	V[5] A-L[6] P/Q	B-LL B-L A-M A-W	B-M B-W	A/B	C[2]	A/B	A/B
Unbewehrter Beton *unreinforced concrete*	X0	✖	✖	✖	✖	✖	✖	✖	✖	✖
Frostgeschützte Bauteile (innen oder im Wasser) *components protected from frost (interior or in water)*	XC1-XC4	✖	✖	✖	✖	❍ [1]	✖	❍ [1]	❍ [1]	❍ [1]
Außenbauteile, Wasserbauwerke *exterior components, hydraulic engineering structures*	XC, XF1, XF3	✖	✖	✖	❍	❍	✖	❍	❍	❍
Außenbauteile unter Taumitteleinwirkung *exterior components exposed to de-icing agents*	XC, XD, XF2, XF4	✖	✖	❍	❍	❍	✖ [3) 4)]	❍	❍	❍
Meeresbauwerke *maritime structures*	XC, XS, XF2, XF4	✖	✖	❍	❍	❍	✖ [3) 4)]	❍	❍	❍
Chemischer Angriff[7] *chemical attack*[7]	XA	✖	✖	✖	❍	❍	✖	❍	❍	❍
Verkehrsflächen *traffic surfaces*	XF4, XM	✖ [9]	✖ [8) 9)]		❍	❍	✖ [3) 4) 8) 9)]	❍	❍	❍
Verschleiß ohne Frost *wear without frost*	XM	✖	✖	✖	❍	❍	✖	❍	❍	❍

1) Verwendung bei Expositionsklasse XC2 erlaubt
2) Verwendung bei Expositionsklasse XD2 und XS2 erlaubt
3) bei Expositionsklasse XF4: Nur CEM III/A der Festigkeitsklasse ≥ 42,5 oder ≥ 32,5 R mit einem Hüttensandanteil ≤ 50 M.-%
4) bei Expositionsklasse XF4: CEM III/B darf nur für die folgenden Anwendungsfälle verwendet werden:
   a) Meerwasserbauteile: w/z ≤ 0,45; Mindestfestigkeitsklasse C35/45 und z ≥ 340 kg/m³
   b) Räumerlaufbahnen w/z ≤ 0,35; Mindestfestigkeitsklasse C40/50 und z ≥ 360 kg/m³; Beachtung von DIN 19569
   Auf Luftporen kann in beiden Fällen verzichtet werden.
5) CEM II/B – V für Verwendung bei Expositionsklasse XF3 nicht erlaubt
6) Verwendung bei Expositionsklasse XF1 und XF3 nicht erlaubt
7) Bei chemischem Angriff durch Sulfat (ausgenommen bei Meerwasser) muss oberhalb der Expositionsklasse XA1 Zement mit hohem Sulfatwiderstand (HS-Zement) verwendet werden. Zur Herstellung von sulfatwiderstandsfähigem Beton darf bei einem Sulfatgehalt des angreifenden Wassers von SO_4^{2-} ≤ 1 500 mg/l anstelle von HS-Zement eine Mischung aus Zement und Flugasche verwendet werden.
8) Für Betonfahrbahndecken nach ZTV Beton-StB in Abstimmung mit dem Auftraggeber (Hochofenzement nur CEM III/A mindestens der Festigkeitsklasse 42,5)
9) Für Betonfahrbahndecken nach ZTV Beton-StB Gesamtalkaligehalt Na_2O-Äquivalent ≤ 1,0 M.-%

1) Use for exposure class XC2 permitted
2) Use for exposure classes XD2 and XS2 permitted
3) For exposure class XF4: only CEM III/A of the strength classes ≥ 42,5 or ≥ 32,5 R containing ≤ 50 % by mass blastfurnace slag
4) For exposure class XF4: CEM III/B may only be used for the following applications:
   a) Sea water components: w/c ≤ 0.45; minimum strength class C35/45 and c ≥ 340 kg/m³
   b) Track for rotating scraper bridge, w/c ≤ 0.35; minimum strength class C40/50 and c ≥ 360 kg/m³; note DIN 19569
   Air voids can be dispensed with in both cases.
5) CEM 11/B-V not permitted for use with exposure class XF3
6) Use not permitted for exposure classes XF1 and XF3
7) For chemical attack by sulfate (except in sea water) highly sulfate resisting cement must be used above exposure class XA 1. A mixture of cement and fly ash may be used instead of highly sulfate resisting cement for producing sulfate resisting concrete where the corrosive water has a sulfate content of SO_4^{2-} ≤ 1500 mg/l
8) For concrete carriageway surfaces complying with ZTV Beton-StB with the agreement of the client (only CEM III/A blastfurnace cement at least of 42,5 strength class)
9) For concrete carriageway surfaces complying with ZTV Beton-StB, total alkali content Na_2O-equivalent ≤ 1.0 % by mass

3 Concrete strength

Concrete is classified according to its uniaxial compressive strength, e.g. C20/25 means concrete with UCS of 20 MPa (f_{ck}) and 25 MPa ($f_{ck,cube}$), respectively. UCS is measured either by using cylindrical samples (300 mm length and 150 mm diameter - f_{ck}) or cubic samples with edge length of 150 mm ($f_{ck,cube}$). In both cases the curing time is 28 days. Beyond C50/60 the concrete is called high-strength concrete. The off concrete develops during the hydration process. Exemplary, Fig. 4 illustrates the strength development during the hydration process.

In general the strength after 28 days of curing is used as reference. The strength classification according to DIN EN 206-1 and DIN 1045-2 is based on the 28-day-strength. After 28 days the strength has reached nearly the final value (100 %). After 7 days the strength has reached about 20 % to 60 % of the final values depending on concrete type. The hydration process is also influenced by the environmental conditions (e.g. temperature, humidity).

The strength of concrete is influenced by ballast parameters (grain size, shape and strength), the bonding between cement matrix and ballast grains and of course the cement matrix itself (hydration degree, porosity, w/z-value, cement type).

Tab. 4: Strength classes for concrete according to EN 1992-1-1: 2010

Strength classes for concrete															Analytical relation / Explanation
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	2.8
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck} + 8$ (MPa)
f_{ctm} (MPa)	1.6	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.1	4.2	4.4	4.6	4.8	5.0	$f_{ctm} = 0.30 \times f_{ck}^{(\frac{2}{3})} \leq$ C50/60 $f_{ctm} = 2.12\ln(1 + (\frac{f_{cm}}{10})) >$ C50/60
$f_{ctk,0.05}$ (MPa)	1.1	1.3	1.5	1.8	2.0	2.2	2.5	2.7	2.9	3.0	3.1	3.2	3.4	3.5	$f_{ctk,0.05} = 0.7 \times f_{ctm}$ 5% fractile
$f_{ctk,0.95}$ (MPa)	2.0	2.5	2.9	3.3	3.8	4.2	4.6	4.9	5.3	5.5	5.7	6.0	6.3	6.6	$f_{ctk,0.95} = 1.3 \times f_{ctm}$ 95% fractile
E_{cm} (GPa)	27	29	30	31	33	34	35	36	37	38	39	41	42	44	$E_{cm} = 22\left[\left(\frac{f_{cm}}{10}\right)\right]^{0.3}$ (f_{cm} in MPa)
ε_{c1} ($^0/_{00}$)	1.8	1.9	2.0	2.1	2.2	2.25	2.3	2.4	2.45	2.5	2.6	2.7	2.8	2.8	See Figure 3.2 $\varepsilon_{c1}(^0/_{00}) = 0.7 f_{cm}^{0.31} \leq 2.8$
ε_{cu1} ($^0/_{00}$)	3.5									3.2	3.0	2.8	2.8	2.8	See Figure 3.2 for $f_{ck} \geq 50$ MPa $\varepsilon_{cu1}(^0/_{00}) = 2.8 + 27[\frac{98 - f_{cm}}{100}]$
ε_{c2} ($^0/_{00}$)	2.0									2.2	2.3	2.4	2.5	2.6	See Figure 3.2 for $f_{ck} \geq 50$ MPa $\varepsilon_{c2}(^0/_{00}) = 2.0 + 0.085(f_{ck} - 50)^{0.53}$
ε_{cu2} ($^0/_{00}$)	3.5									3.1	2.9	2.7	2.6	6.6	See Figure 3.2 for $f_{ck} \geq 50$ MPa $\varepsilon_{cu2}(^0/_{00}) = 2.6 + 35[(90 - f_{ck})/100]^4$
n	2.0									1.75	1.6	1.45	1.4	1.4	for $f_{ck} \geq 50$ MPa $n = 1.4 + 23.4[(90 - f_{ck})/100]^4$
ε_{c3} ($^0/_{00}$)	1.75									1.8	1.9	2.0	2.2	2.3	See Figure 3.4 for $f_{ck} \geq 50$ MPa $\varepsilon_{c3}(^0/_{00}) = 1.75 + 0.55[(f_{ck} - 50)/40]$
ε_{cu3} ($^0/_{00}$)	3.5									3.1	2.9	2.7	2.6	2.6	See Figure 3.4 for $f_{ck} \geq 50$ MPa $\varepsilon_{cu3}(^0/_{00}) = 2.0 + 35[(90 - f_{ck})/100]^4$

An overview about the evolution of early-age properties of concrete is provided by Nehdi & Sollmann (2011).

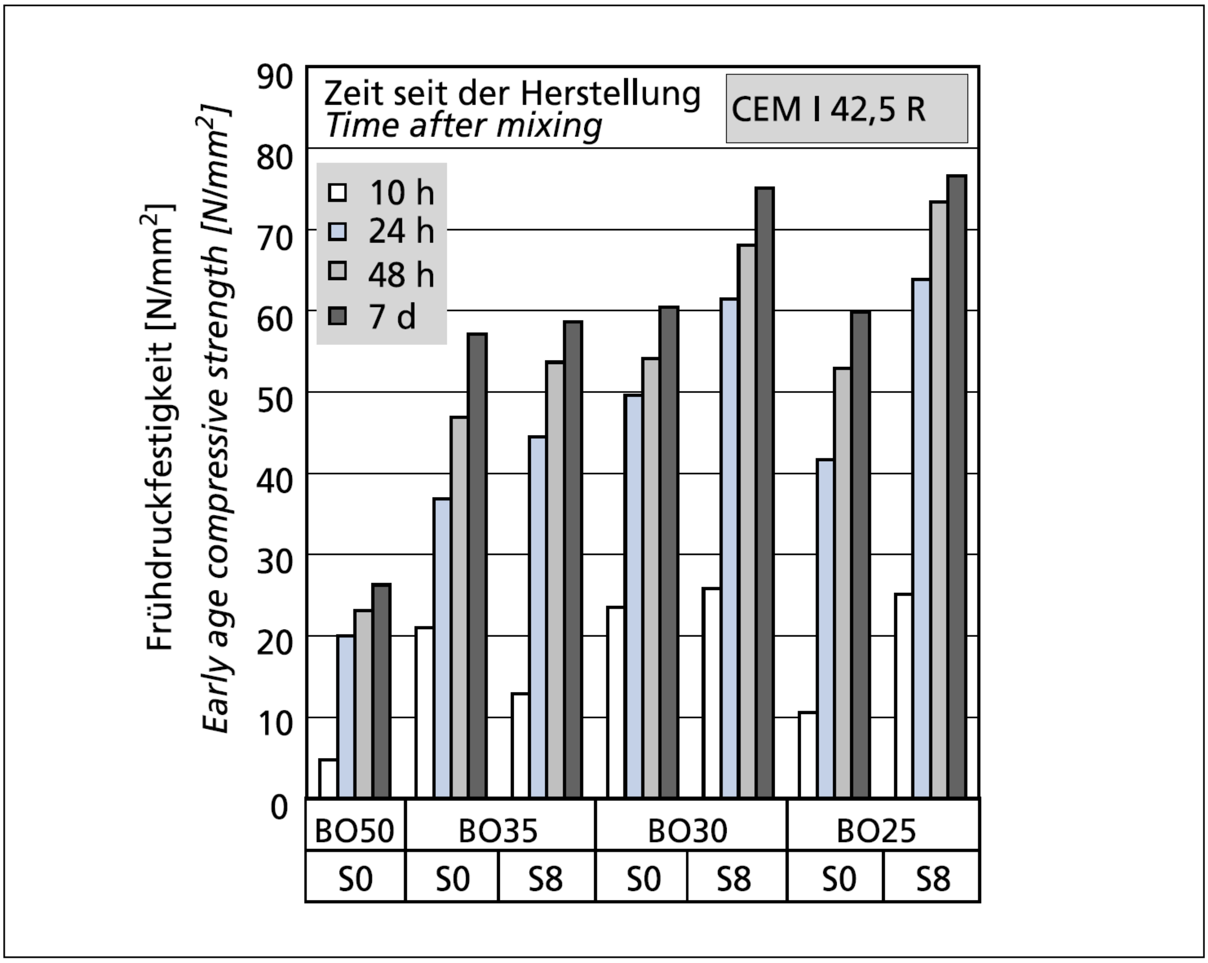


Fig. 4: Strength evolution of several high strength concretes versus time (Alonso 2003)

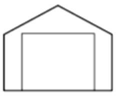
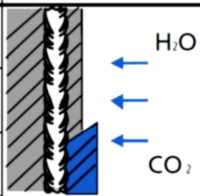
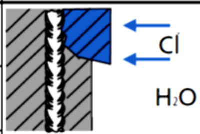
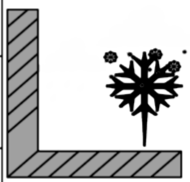
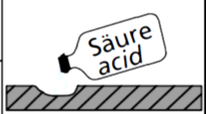
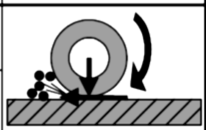
4 Exposure classes

Durable concrete constructions need the consideration of the environmental impact to these constructions. Tab. 5 shows the exposure classes according to EC2.

Tab.5: Exposure classes for concrete according to EC2

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion attack		
XC0	For concrete without reinforcement or embedded metal: all exposure except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside building with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within the exposure class XC2
3 Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete components exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
4 Corrosion induced by chlorides from sea water		
XS1	Exposed to airborne salt but not in direct contact to sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/Thaw attack		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and air-borne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agents or sea water	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zone of marine structures exposed to freezing
6 Chemical attack		
XA1	Slightly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA2	Moderately aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA3	Highly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water

Tab.6: Exposure classes and corresponding concrete technology measures (Grube & Kerkhoff, 2003) (max w/z = max. water/cement ratio; min. z = minumim content of cement in kg/m^3; T = de-icing salt)

Expositionsklassen (Umwelteinwirkungen, „Angriffe") *Exposure classes (environmental effects, "attacks")*				Betontechnische Maßnahmen („Widerstände") *Concrete technology measures ("resistances")*		
Klassenbez. *class designation*		Einwirkung und Beanspruchung *effect and stress*		Max. w/z *max. w/c*	Min. z *min. c*	f_{ck}, cube *f_{ck}, cube*
XO		 kein Angriff *no attack*	kein Betonangriff *no concrete attack*	keine Anforderung *no requirement*	keine Anforderung *no requirement*	C8/10 *C8/10*
XC	1	 H_2O CO_2 Carbonatisierung *carbonation*	trocken *dry*	0,75	240	C16/20
	2		ständig nass *constantly wet*	0,75	240	C16/20
	3		mäßig feucht *moderately moist*	0,65	260	C20/25
	4		nass / trocken *wet / dry*	0,60	280	C25/30
XD/ XS	1	 Cl H_2O Chlorid *chloride*	mäßig feucht moderately moist	0,55	300	C30/37
	2		ständig nass *constantly wet*	0,50	320	C35/45
	3		nass / trocken *wet / dry*	0,45	320	C35/45
XF	1	 Frost /+ Salz *freeze-thaw /+ salt*	mäßige Wassers. o. T. *moderate water saturation (o.T.)*	0,60	280	C25/30
	2		mäßige Wassers. m. T. *moderate water saturation (m.T.)*	0,55 + LP 0,50	300 320	C25/30 C35/45
	3		hohe Wassers. o. T. *high water saturation (o.T.)*	0,55 + LP 0,50	300 320	C25/30 C35/45
	4		hohe Wassers. m. T. *high water saturation (m.T.)*	0,50 + LP	320	C30/37
XA	1	 Chem. Angriff *chemical attack*	schwach angreifend *weakly corrosive*	0,60	280	C25/30
	2		mäßig angreifend *moderately corrosive*	0,50	320	C35/45
	3		stark angreifend *strongly corrosive*	0,45	320	C35/45
XM	1	 Verschleiß *wear*	mäßiger Verschleiß *moderate wear*	0,55	300	C30/37
	2		starker Verschleiß *severe wear*	0,45	320	C35/45
	3		sehr starker Verschleiß *very severe wear*	0,45	320	C35/45

According to Grube & Kerkhoff (2003) the exposure scenarios can be described as follows (see also Tab. 5 and 6):

> *"XC1 relates to the corrosion-promoting action for reinforcing steel in dry interior spaces, XC2 in components in non-corrosive water, XC3 in moist spaces like indoor swimming pools and XC4 in external components directly exposed to rain. Components in the XD and XS exposure classes are exposed to the action of chloride through de-icing salt (XD) or seawater (XS), specifically from spray (XD1 / XS1), in continuous contact with salt-containing water (XD2 / XS2) and alternating contact with salt solution and drying out (XD3 / XS3). Further effects on the concrete itself relate to components exposed to freeze-thaw (XF1 – XF4) with moderate and high water saturation and with and without de-icing salt. The grade of attack during concrete corrosion by chemical attack (XA1 – XA3) is classified in accordance with the definitions in DIN 4030. In Germany there is also the wear exposure class which regulates moderate (XM1), strong (XM2) and very strong (XM3)."*

5 Hydration process

The basic chemical elements of cement are: Ca, Si, Al, Fe and O_2. They occur mainly as CaO, Al_2O_3, SiO_2 and Fe_2O_3. During burning limestone and clay at temperatures between 1400 °C and 1600 °C the cement compounds are produced (clinker). The main components of the clinker are:

- Alite ($3CaO \cdot SiO_2$) chemical abbr.: C_3S
- Belite ($2CaO \cdot SiO_2$) chemical abbr.: C_2S:
- Tricalcium aluminate($3CaO \cdot Al_2O_3$) chemical abbr.: C_3A
- Brownmillerite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$) chemical abbr.: C_4AF

During the hydration process itself the clinker components react with water and produce cement pastes like Calcium hydroxide, Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate, Calcium Trisulfoaluminate Hydrate, Calcium Monosulfoaluminate etc. Fig. 5 and 6 illustrate the hydration process.

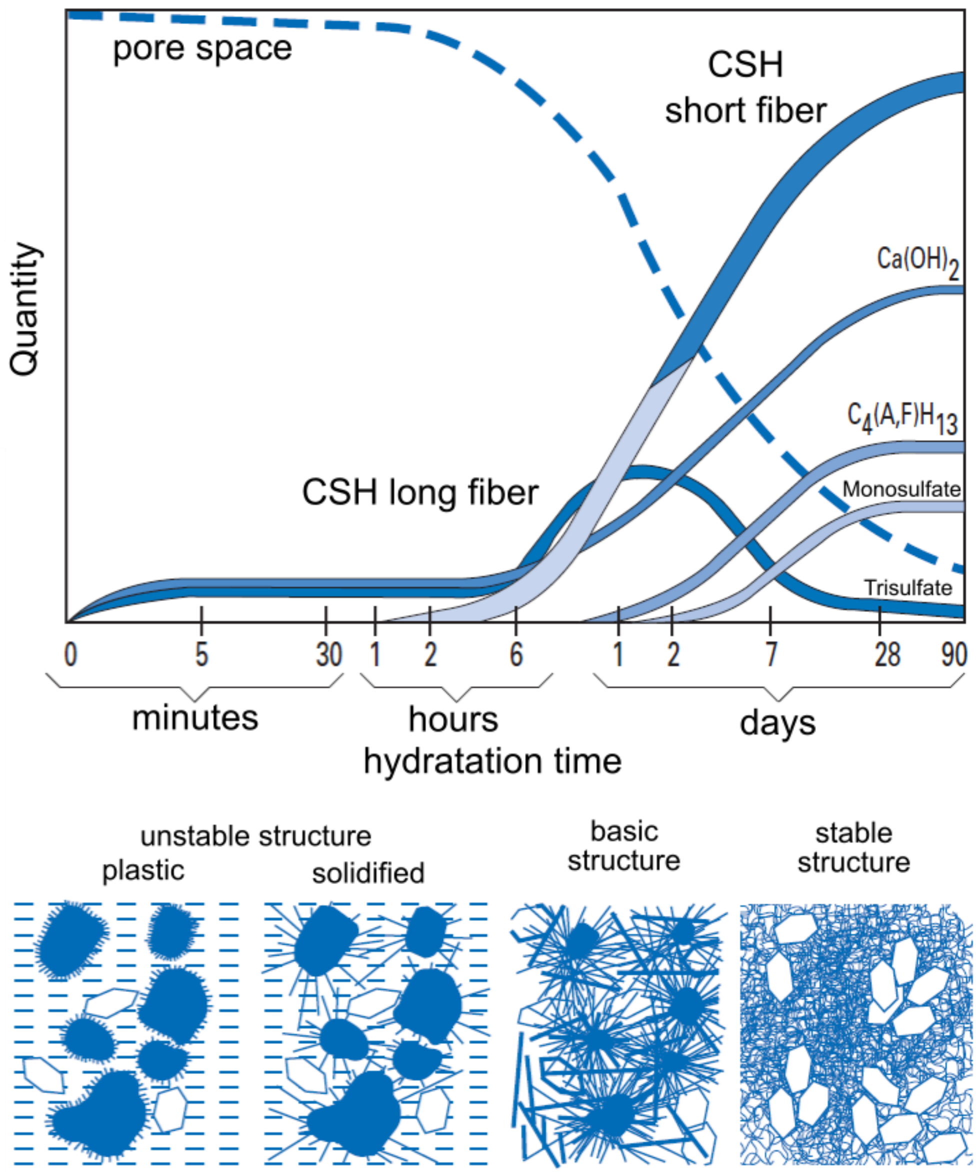


Fig. 5: Illustration of principles of hydration process (modified after VDZ, 2002)

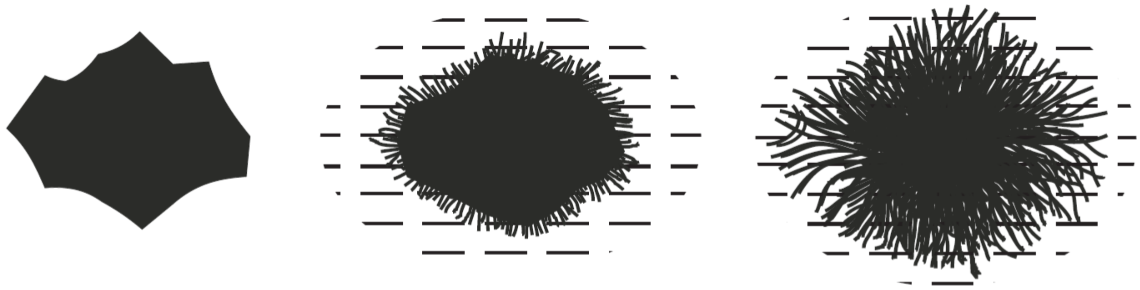


Fig. 6: Schematic view of hydration of cement grain (modified after VDZ, 2002)

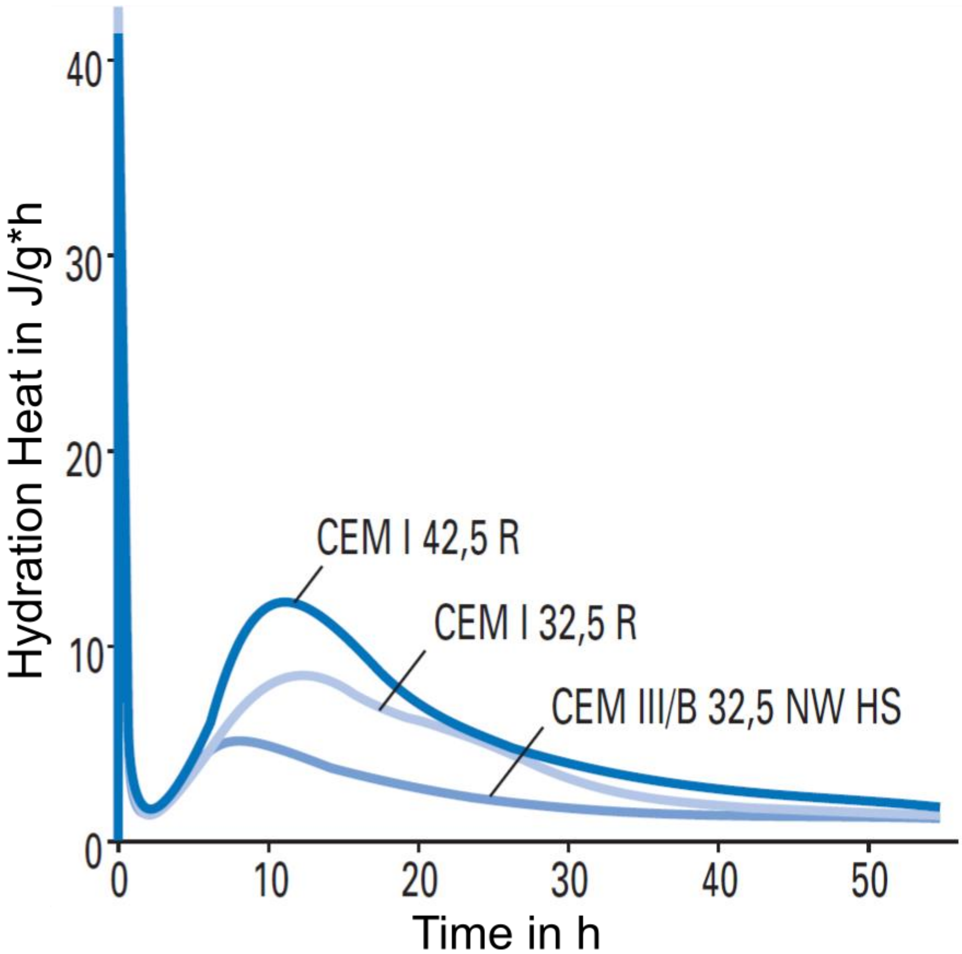


Fig. 7: Development of hydration heat vs. time (modified after VDZ, 2002)

During the hydration process significant amount of heat is generated. Fig. 7 shows the heat generation versus time during the hydration process for different types of cement.

6 Shrinkage and creep

Shrinkage means a decrease of volume during the hydration process incl. loss of water by evaporation:

$Volume_{water} + Volume_{cement} > Volume_{concrete}$

The following forms of shrinkage can be distinguished, see for instance Sahinagic-Isovic (2012), Kawano (2012) or Kovler & Zhutovsky (2006):

- Plastic shrinkage (drying of fresh concrete surface)
- Chemical shrinkage (chemical binding of water)
- Autogenous shrinkage or hydration shrinkage (self-desiccation of pores of non-hydrated cement)
- Drying shrinkage (water evaporation from capillaries – see Fig. 8)
- Thermal shrinkage (due to temperature change during hydration process)
- Carbonation shrinkage (due to chemical reactions between cement and carbon dioxide)

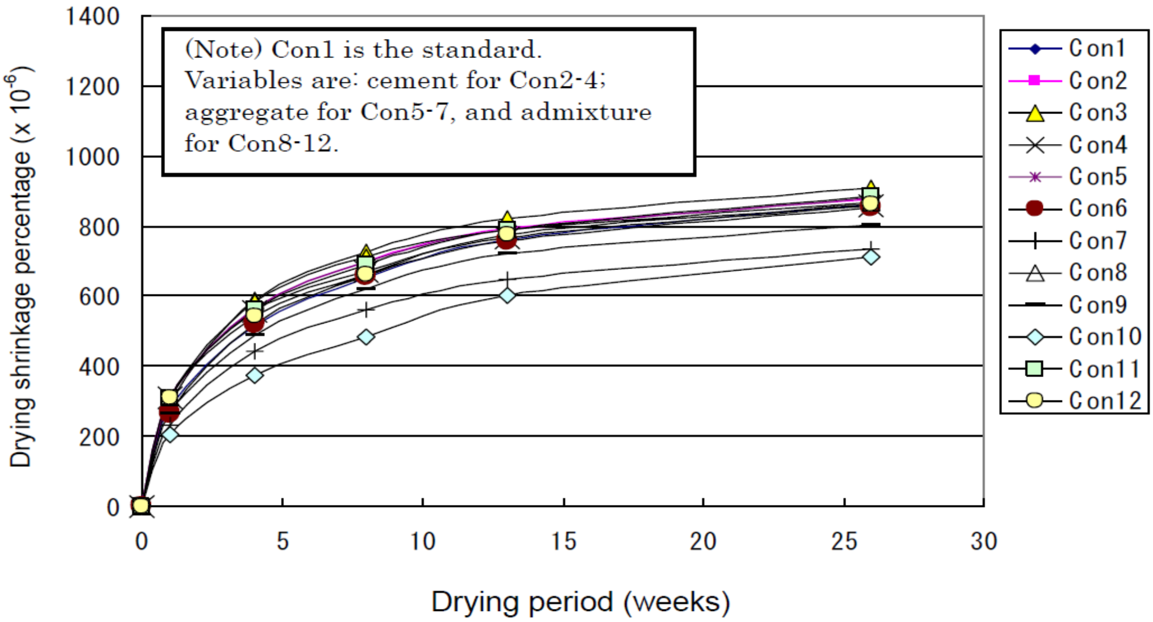


Fig. 8: Drying concrete of different type of concrete (Kawano et al. 2012)

7 Numerical simulation

Depending on task and scale (see Fig. 9) quite different modelling approaches are used covering:

- continuum based or discontinuum based
- pure mechanical or coupled
- static or dynamic (incl. cyclic)
- deterministic or stochastic

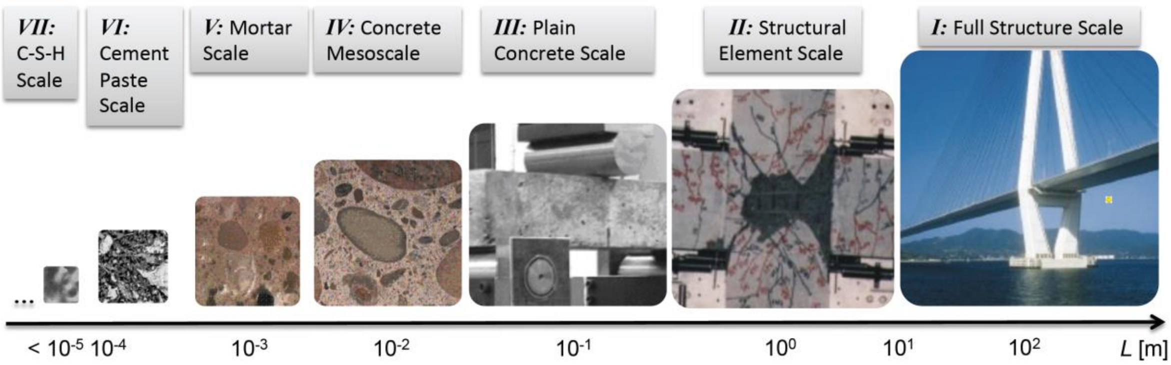


Fig. 9: Length scales for concrete simulation (Cusatis et al. 2014)

A typical stochastic modelling procedure to simulate time-dependent reliability contains the following steps (see for instance Wan-Wendner, 2018):

(1) development of a mechanical model with aging and damaging effects

(2) determination of stochastic input-parameters

(3) generation of *n* realizations via sampling method (e.g. LHS)

(4) analysis of all *n* realizations for *m* points in time

(5) Statistical evaluation of response quantities

(6) Reliability and life cycle performance assessment based on PFFs of actions and obtained CDFs of structural response for any *m* points in time

(7) Sensitivity analysis

The following example (see also Konietzky et al. 2001) illustrates a typical approach to simulate the hydration process including strength and stiffness evolution. The procedure contains 5 steps:

(1) Calculation of equivalent concrete age t_e on the basis of actual temperature T and thermal time t:

$$t_e = \sum_{t=0}^{t} e^{\frac{E_A}{R}\left(\frac{1}{293}-\frac{1}{T}\right)} \cdot \Delta t$$

(2) Determination of degree of hydration α on the basis of the equivalent concrete age:

$$\alpha = e^{-\left(\ln\left(1+\frac{t_e}{t_1}\right)\right)^b}$$

(3) Determination of the actual hydration heat q_t based on the change of the degree of hydration per thermal time step Δt:

$$q_t = Q^{\max} \cdot C \cdot \frac{\Delta\alpha}{\Delta t} \quad \text{with} \quad Q^{\max} = \frac{\Delta T \cdot c_c \cdot \rho}{C}$$

(4) Determination of actual temperature using the thermal constitutive law taken into account the corresponding hydration heat

(5) Adjustment of strength and stiffness parameters according to the actual degree of hydration

$$E = E_{\text{cte}} \cdot \left(\frac{\alpha - \alpha_0}{1-\alpha_0}\right)^a \qquad \sigma_{\text{D}} = 0.85 \cdot \left(\frac{f_{\text{cte}}}{c} \cdot \frac{\alpha - \alpha_0}{1-\alpha_0}\right) \qquad \sigma_Z = f_{\text{cte}} \cdot \left(\frac{\alpha - \alpha_0}{1-\alpha_0}\right)$$

Using the following notation:

E_A:	activation energy
C_c:	specific heat
R:	universal gas constant
t:	thermal time
t_e:	equivalent concrete age
T:	temperature
q:	heat release
Q^{max}:	maximum heat production
C, b, t_1, a, α_0	cement constants
E_{cte}:	Young`s modulus after complete hydration
f_{cte}:	uniaxial tensile strength after complete hydration
E:	Young`s modulus
σ_D:	uniaxial compressive strength
σ_Z:	uniaxial tensile strength

Based on the values of uniaxial compressive and tensile strength corresponding parameters for the Drucker-Prager elasto-plastic constitutive law can be derived. Exemplary, Fig. 10 to 12 document a calibration or rather validation process for a specific type of concrete, by comparing simulation results with lab test results (Konietzky et al. 2001).

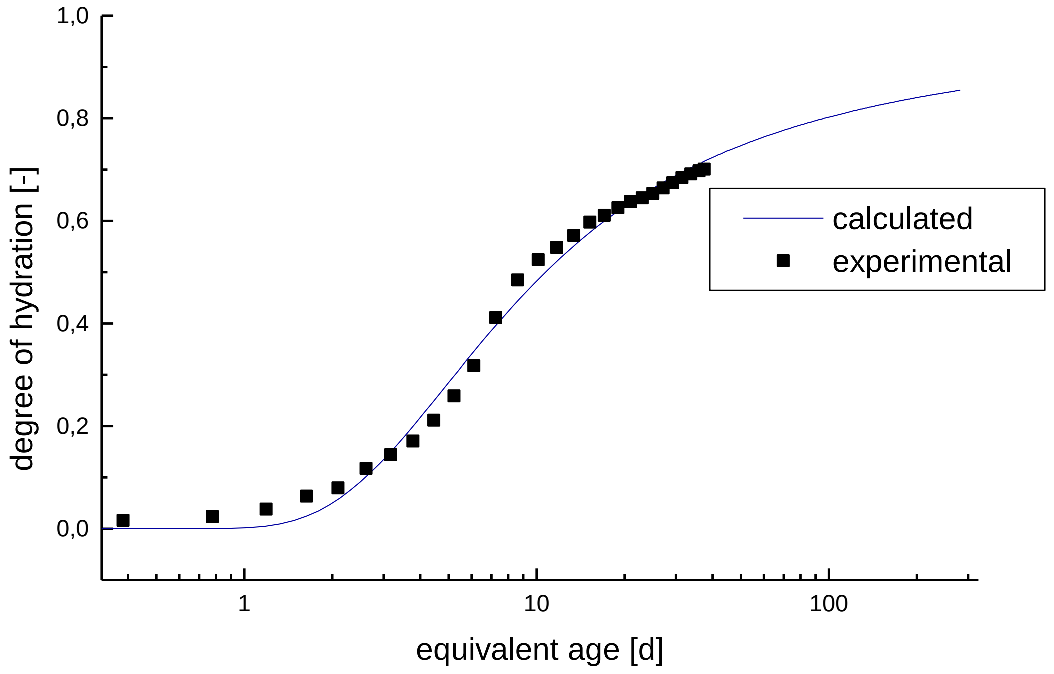


Fig. 10: Evolution of degree of hydration vs. equivalent concrete age

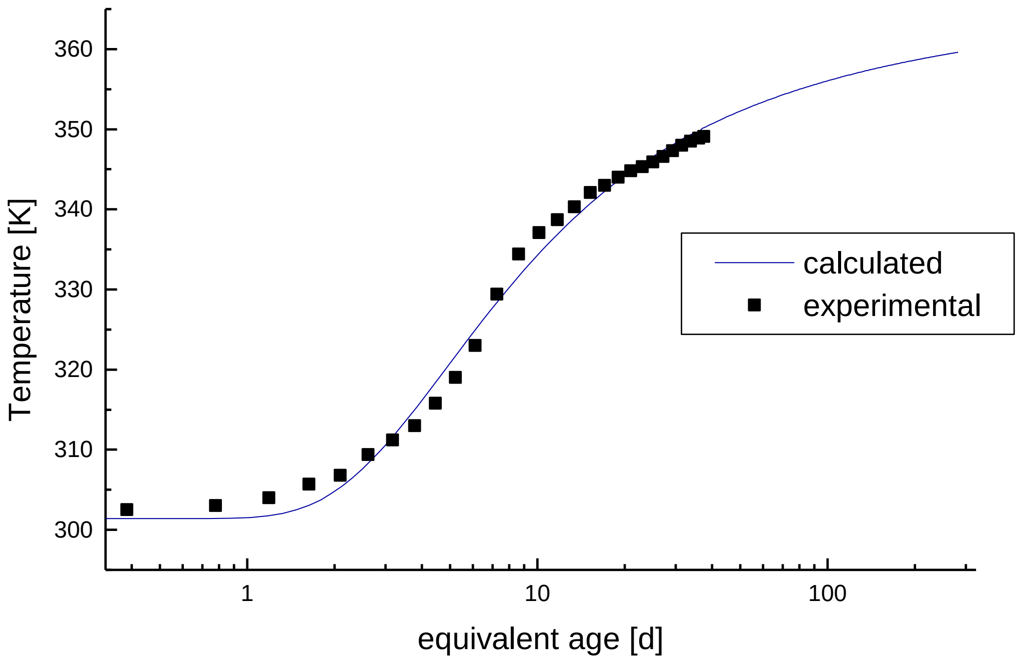


Fig. 11: Evolution of temperature vs. equivalent concrete age

Figures 13 and 14 show an application (concrete wall on a slab). The slab is initialized with 278 K, the concrete wall with 283 K. The temperature at the outer boundary of the wall is fixed to 280 K.

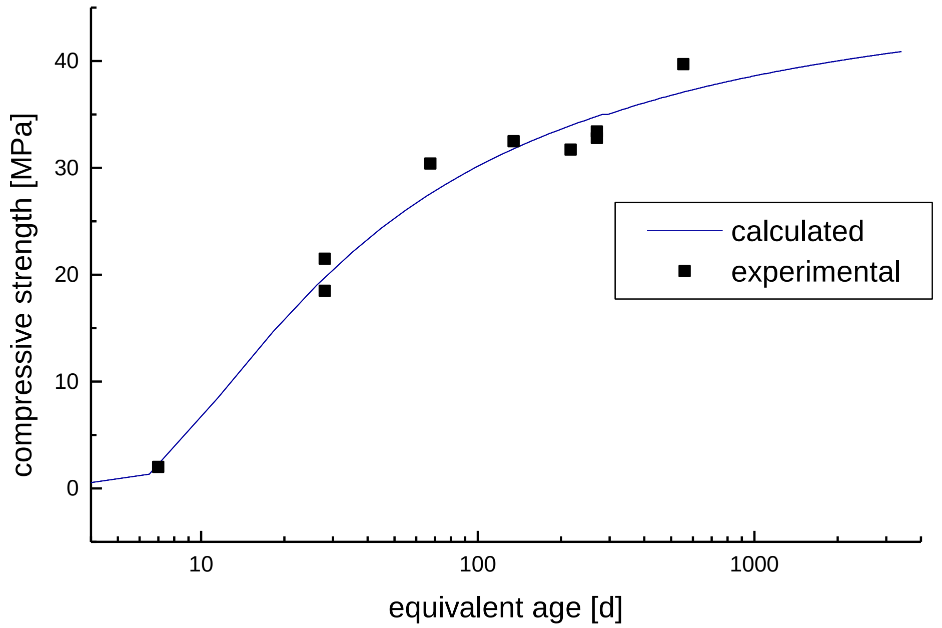


Fig. 12: Evolution of uniaxial compressive strength vs. equivalent concrete age

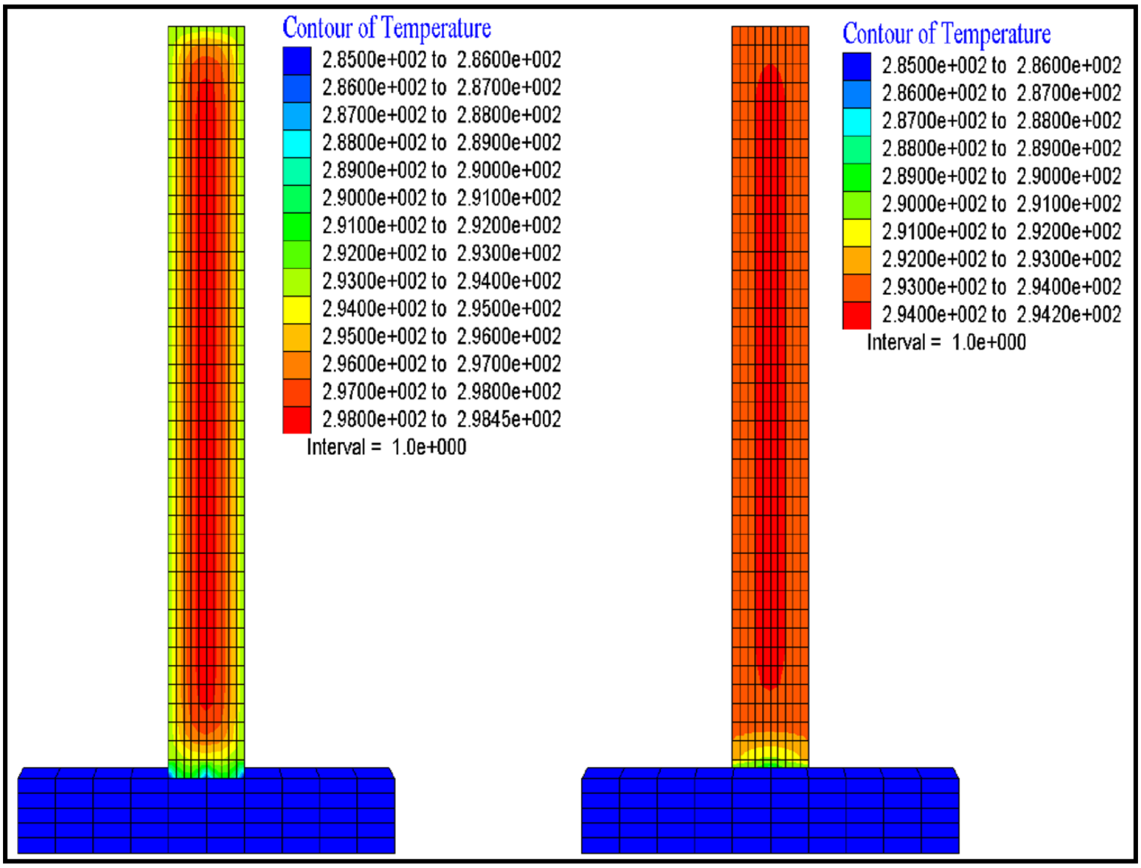


Fig. 13: Temperature [K] distribution in concrete (Left: after 24 hours, right: after 72 hours)

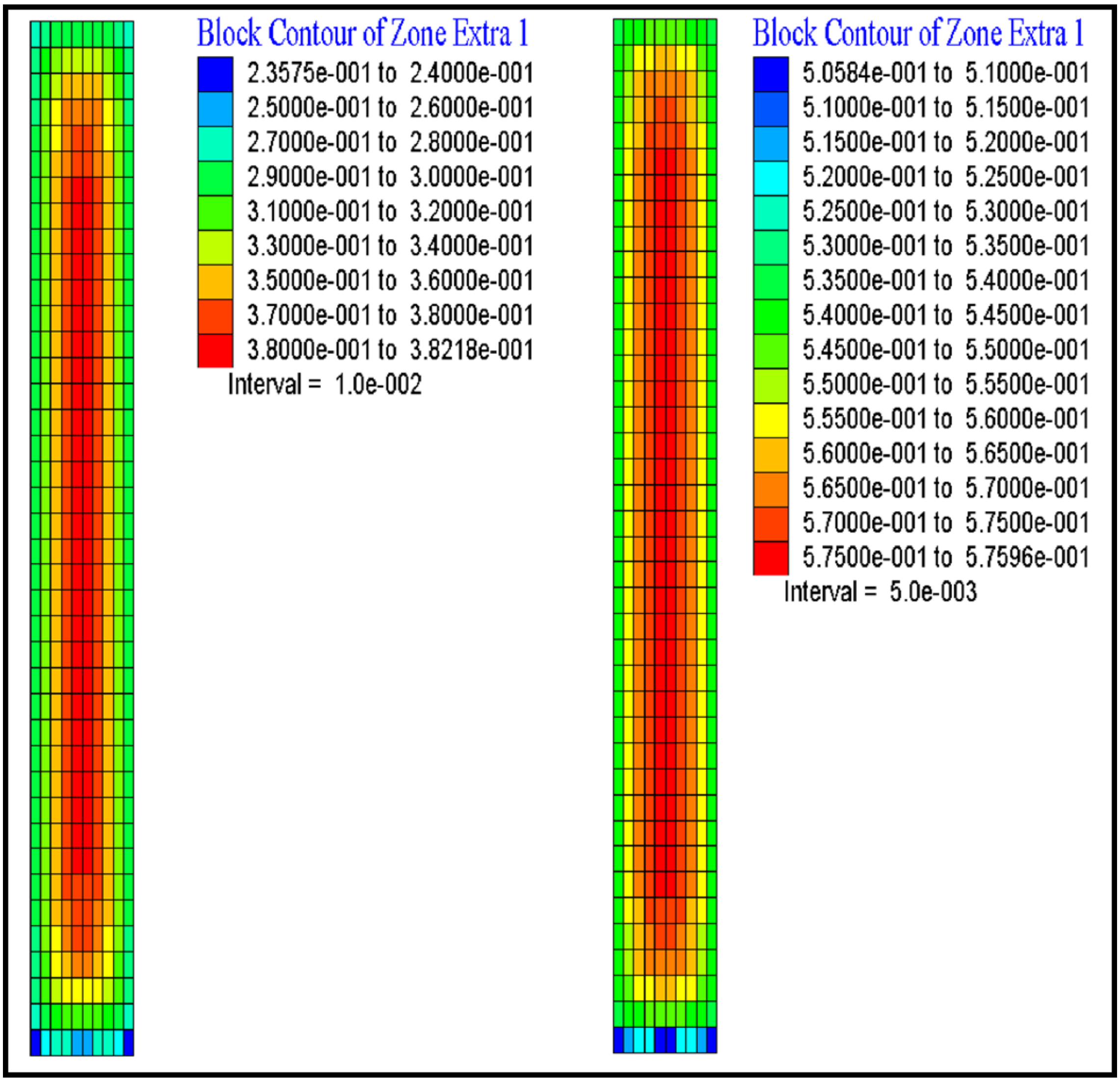


Fig. 14: Degree of hydration in concrete (left: after 24 hours, right: after 72 hours)

8 Concrete admixtures

Concrete admixtures or additives are chemical or mineral based ingredients to improve certain properties, to reduce costs and to increase productivity. The most common additives are:

- Shrinkage reducing additives
  - Reduces short- and long-term shrinkage incl. shrinkage cracking
- Superplasticizers
  - Improves the workability by high slump
- Corrosion inhibiting additives
  - Reduces corrosion in steel-reinforced concretes
  - Reduces maintenance costs
- Accelerator additives
  - Reduces setting time
  - Increases rate of strength development
  - Especially important for low temperature environment
- Water reducing additives
  - Creates desired slump with lower water-cement ratio
  - Creates desired strength with lower water-cement ratio
  - Helps to place concrete under difficult conditions
- Air entrainment additives
  - Increases freeze-thaw durability
  - Increases workability
- Self-retarding additives
  - Slow-down chemical reactions during hydration
  - Reduces water consumption
  - Reduces temperature effects
  - Eliminates cold joints
  - Resists cracking due to deflections

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