Corrosion of Building Materials

Prof. Dr. Andreas Gerdes

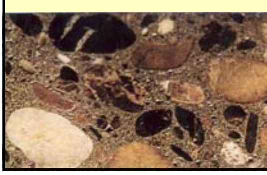
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Concrete and Mortar

Concrete and mortar is a mixture of...

- **Portland Cement**
- **Aggregates**
- **Water**
- **Admixtures**



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Aggregates I

Natural Aggregates	
Basalt	Mica
Gneiss	Opalit
Granite	Grauwacke
Quartz	Flint
Calcite	

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Aggregates

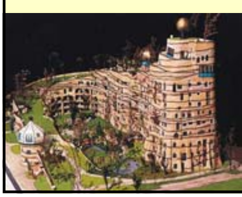
Industrial Aggregates
Bims
Blähton
Geblähte Schlacke
Geblähte Asche
Geblähtes Glas

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Aggregates III

Recycling-Aggregates
Excavation (Gotthard-tunnel)
FRANKA-Procedure
Crusher
Impact Mill

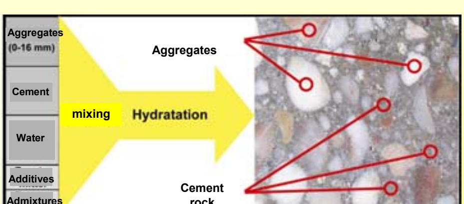


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

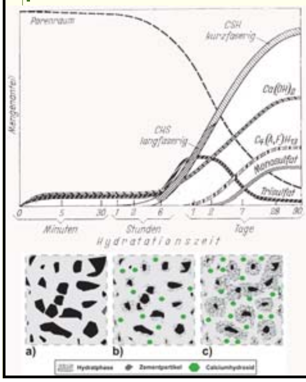
Properties of cement based materials

- Structure
- Chemical reactivity



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK



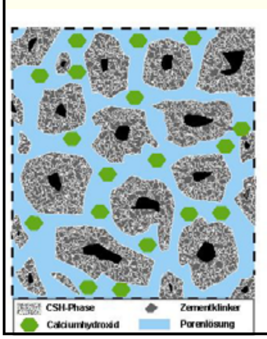
Structure build up due to hydration

- Formation of CSH-gel
- Decrease of pore volume
- Inclusion of calcium hydroxide in the pore volume / cement stone

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Structure of cement based materials

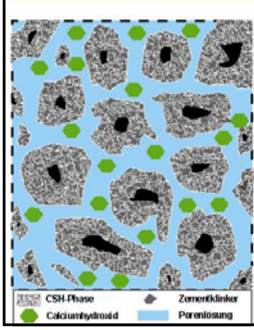


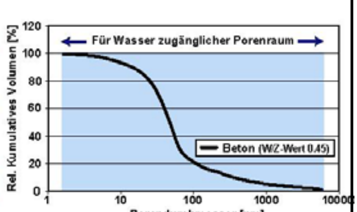
- Gel pores in CSH-Cluster
- Capillary pores between the Cluster

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Structure of cement based materials





Pore classification

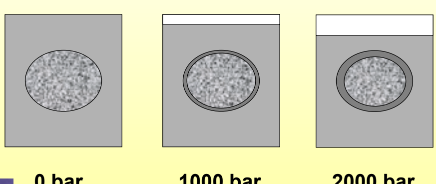
Concrete-techno-logical procedure	Pore type		Pore classification by Setzer	Pore classification by IUPAC
compacting	Compacting pores	Large pores	> 2 mm	-
Air entraining agents	Air pores	Micro-capillaries	50 µm – 2 mm	50 µm – 2 mm
W/C (water-cement-ratio)	Capillary pores	Capillaries	2 µm – 50 µm	2 µm – 50 µm
		Micro-capillaries	5 nm - 2 µm	5 nm - 2 µm
Hydration and type of cement	Gel pores	Mesopores	2 nm – 50 nm	2 nm – 50 nm
		Micropores	< 2 nm	< 2 nm

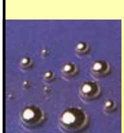
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft
FH Karlsruhe University of Applied Sciences Hochschule für Technik

Pore size and Pore size distribution

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft
FH Karlsruhe University of Applied Sciences Hochschule für Technik

Measuring of total porosity and pore size distribution by mercury pressure porosymetry

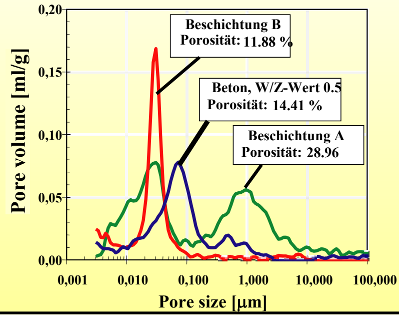




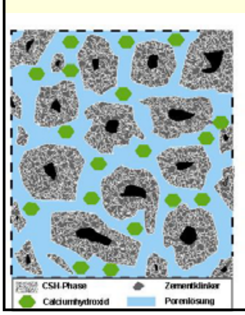
Pressure is increased step by step up to 350 MPa

- → **Total mercury content is equivalent to total porosity**
- → **With increasing pressure lower pore radii were filled**

Pore size distribution of cement based materials



Composition of the pore solution

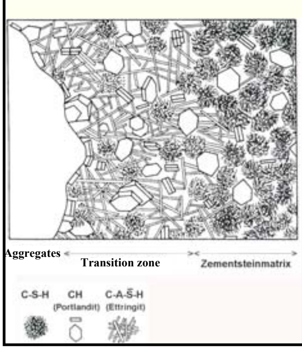


- Calcium hydroxide [$Ca(OH)_2$]
- Potassium hydroxide [KOH]
- Sodium hydroxide [NaOH]
- Calcium sulfate [$CaSO_4$]

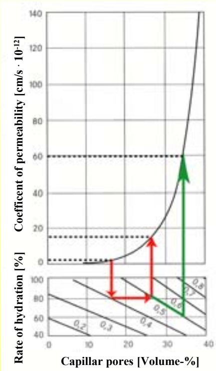
Saturated $Ca(OH)_2$-solution:
pH 12.3

Pore solution of cement rock:
pH 12.3 – 13.0

Microstructure of the phase boundary



1. The phase boundary between aggregate and cement rock is 3.5 times more porous than the cement rock
2. Structure of the interface
   - Duplex film (1 µm thick)
   - Crossover zone (approx. 50 µm thick)
3. Reasons for low strength
   - high porosity (high W/C-ratio)
   - Low crystalline bond of portlandite crystals
   - Hadley grains of hydration products



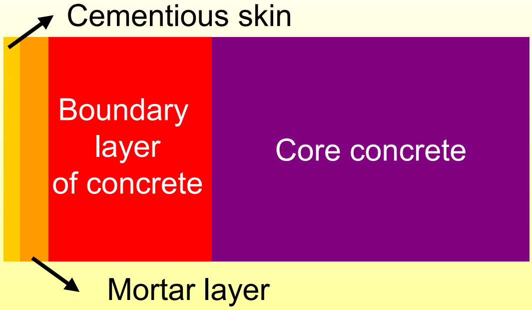
Permeability of cement based materials

Researches made by POWER's already made in the 1950's!!

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

The boundary layer of concrete

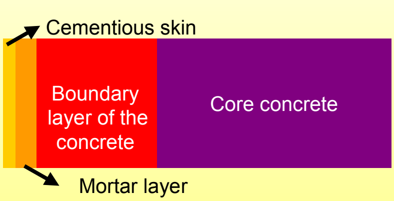


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Influencing factors on the permeability of the boundary layer

- **W/C-ratio**
- **Treatment after construction**
- **Used cement**



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Alkali-Silica-Reaction

1920 ➔ Verification of a reaction between aggregates and alkaline chemicals

1965 ➔ no danger in Germany
"Lachswehr"-bridge: built in 1965/66 , demolished in 1968

Mechanismen is well-known since the 1970's

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Alkali-Silica-Reaction (ASR)

1. Aggregate Reactivity
- Interferences in the grid structure
- Temperature
- Aggregate size
- pH-value of the solution

2. Influences on ASR
- Environment
  Temperature
  Humidity
- Amount and size of aggregates
- Permeability of the concrete
- Alkaline content of the cement
- Cement content

3. Counteractive measures
- Bond of alkaline content by puzzolanes
- Water repellent treatment

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

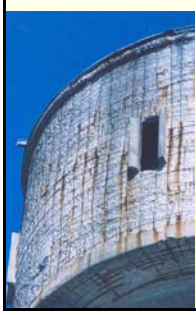
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage processes
Carbonation

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Carbonation of reinforced concrete



Brief historical abstract

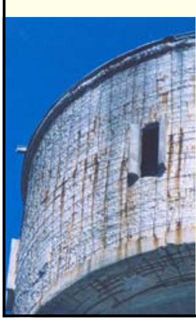
- **1879 Cement cover prevents iron from oxidizing (rust)**
- **1908 Realisation that the alkaline ambience prevents this corrosion**
- **1916 „Corrosion of highly importance because of security reasons "**
- **1919 1.5 cm cover concrete shall be enough to prevent corrosion of the reinforcement**

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Carbonation of reinforced concrete

The reaction of the CSH-phases with CO_2 is called CARBONATION



The $Ca(OH)_2$ (approx. 20 mass-%) which is build up by the hydration of cement and KOH & NaOH in the pore solution are responsible for the pH of approx. 12.3 to 13 of the concrete.

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2\ H_2O$$

Reasons for damages by carbonation

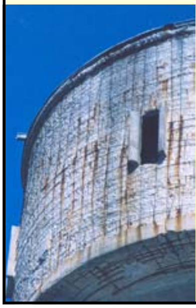
- Low cement content
- Minor dimension of cover concrete
- CO_2-content of the air
- Additional pollutants (NO, NO_2, NO_3)
- Insufficient manufacture of th concrete

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

FH Karlsruhe UNIVERSITY OF APPLIED SCIENCES HOCHSCHULE FÜR TECHNIK

Reaction steps of the carbonation

Carbonation is a coupled process: Transport & chemical reaction



1. Diffusion of CO_2 into the cement rock

2. Solution of CO_2 in the pore solution
$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow 2\,H^+ + CO_3^{2-}$

3. Reaction of $Ca(OH)_2$ with H_2CO_3
$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2\,H_2O$
Carbonation of the alkaline hydroxides
$2\,NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$
$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$

4. Decomposition of cement rock
$C_xSH_y + xCO_2 \rightarrow xCaCO_3 + SiO_2 \cdot y\,H_2O$

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

FH Karlsruhe UNIVERSITY OF APPLIED SCIENCES HOCHSCHULE FÜR TECHNIK

Consequences of carbonation

CARBONATION has positive & negative effects on reinforced concrete

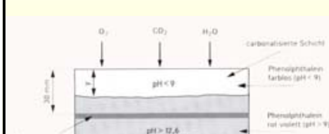
POSITIVE:
Increase in density of the concrete ($\Delta V=11\%$)

NEGATIVE:
Decomposition of the protective layer (approx. 50 nm) consisting of iron hydroxides and oxides on the surface of the reinforcement
$\rightarrow$ Corrosion of the reinforcement

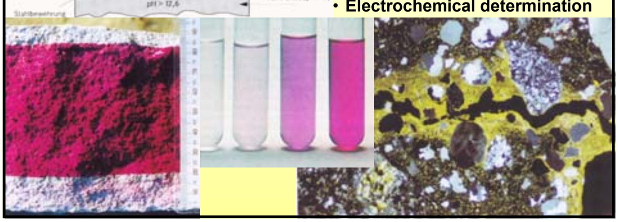
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

FH Karlsruhe UNIVERSITY OF APPLIED SCIENCES HOCHSCHULE FÜR TECHNIK

Determination of the depth of Carbonation



Carbonation depth can be measured by ...
- **Liquid indicators**
- **Microscopy**
- **Wet chemical measurement**
- **Electrochemical determination**



Calculation of carbonation depth

Carbonation is a diffusion controlled process:

1. Fick's law

$$\frac{dm}{dt} = D \cdot F \cdot \frac{dc}{dy}$$

Mass balance

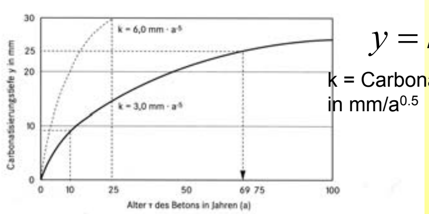
$$dm = m_0 \cdot F \cdot dy$$

m	**=**	CO_2 mass transported through the concrete surface [kg]
t	**=**	Time of admission [a]
D	**=**	Diffusion coefficient [m^2/s]
c	**=**	CO_2 concentration in the air and in the pore structure [kg/m^3]
y	**=**	Thickness of carbonated layer [m]
m_o	**=**	Absorbed CO_2mass per volume unit of concrete [kg]
F	**=**	Area of carbonating concrete [m^2]

Calculation of carbonation depth – √t-law

Solution of the diffusion equation:

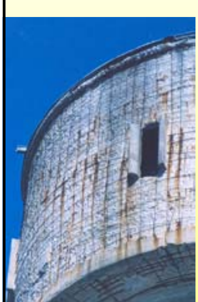
$$y = \sqrt{\frac{2 \cdot D \cdot c_0 \cdot}{m_0}} \cdot \sqrt{t}$$



$$y = k \cdot \sqrt{t}$$

k = Carbonation coefficient in $mm/a^{0.5}$

Factors affecting the depth of carbonation



- **Concentration of CO_2**
- **Humidity**
- **Concrete quality (W/C-ratio)**
- **Type of cement**
- **aftercare**
- **Aggregates, additives, admixtures**
- **Temperature**

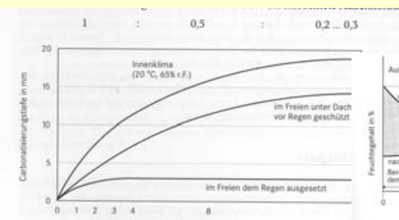
Factors affecting the depth of carbonation – CO_2-concentration

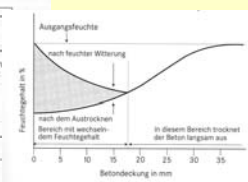
- **CO_2 content in air is approx. 0.03% and almost constant.**
- **Higher contents are a result of the type of use (e.g. basement garages or wine cellars)**

Factors affecting the depth of carbonation - Humidity

- High moisture content: lowers diffusion (D<<)
- Low moisture content: lowers reaction (RG <<)

➔ Optimal value lies between 60% and 80% rel. humidity



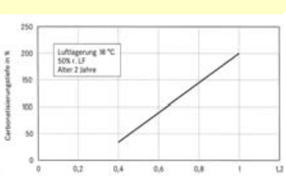


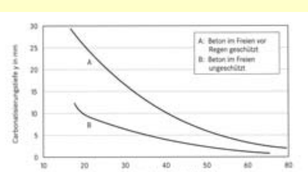
Factors affecting the depth of carbonation– W/C-ratio

- The Depth of carbonation is mainly determined by the permeability of the boundary concrete

➔W/C-ratio

Depending on the W/C-ratio different final depth of carbonation can be detected



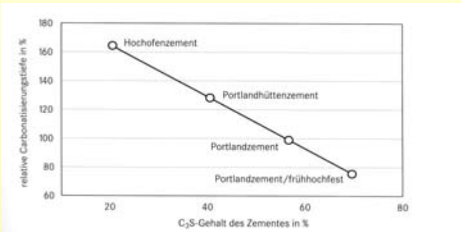


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors affecting the depth of carbonation– Type of cement

- Depending on the cement type different contents of $Ca(OH)_2$ were build up and structure of different density were formed



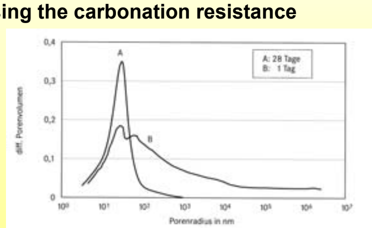
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors affecting the depth of carbonation - Aftercare

- Adequate aftercare forms a denser concrete boundary layer
- Aftercare by keeping in the formwork, covering with foils or water storage meadows, aftercare additives, spraying with water

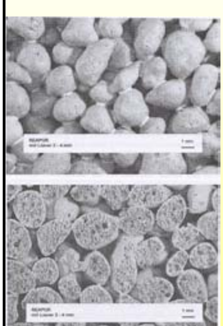
➔ **Increasing the carbonation resistance**



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors affecting the depth of carbonation – Aggregates, additives and admixtures



- Low weight aggregates (Perlite) result in an easier transport of water an CO_2
- Effect of admixtures is unexplained
- Additives form a denser concrete boundary layer; addition of up to 40% show no problem in the reaction with alkali

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Corrosion of the reinforcement

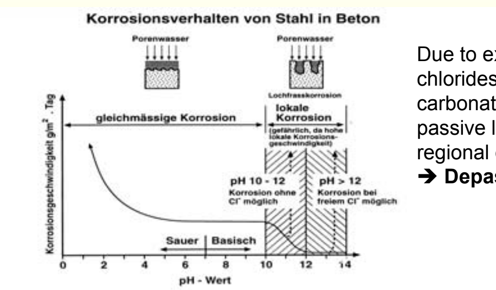
Contrary to steel kept at the atmosphere a thin PASSIVE LAYER is formed in high alkaline medium

➔ **Low speed of corrosion**

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Destabilisation of the passive layer



Das Korrosionsverhalten von Armierungsstahl in Abhängigkeit des pH-Werts sowie in Gegenwart von Chloridionen

Due to exposure of chlorides and carbonation the thin passive layer is regional destroyed

➔ **Depassivation**

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Corrosion of the reinforcement

Conditions for reinforcement corrosion

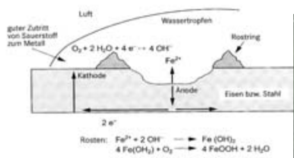
- **Availability of an electrolyte**
- **„Break-down“ of the passive layer**
- **Adequate oxygen supply**
- **Formation of local potentials**

Mechanism of reinforcement corrosion

The corrosion of the reinforcement is an electrochemical process

Electrochemical factors:

Anode:	$2\,Fe \rightarrow 2\,Fe^{2+} + 4\,e^-$
Cathode:	$O_2 + 2\,H_2O + 4e^- \rightarrow 4\,OH^-$
Total reaction:	$2\,Fe + O_2 + H_2O \rightarrow 2\,Fe(OH)_2$
Additional reactions:	$4\,Fe(OH)_2 + O2 \rightarrow 4\,FeOOH + 2\,H_2O$



Increase in volume leads to blasting of cover concrete

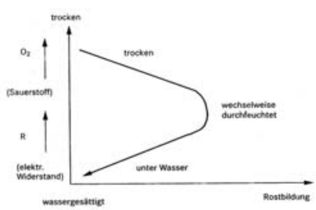
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Reinforcement corrosion – Affecting factors

The corrosion of the reinforcement is influenced by ...

- **Oxygen supply (concrete quality, moisture content)**
- **Electric resistance (moisture content, salt load)**
- **...**

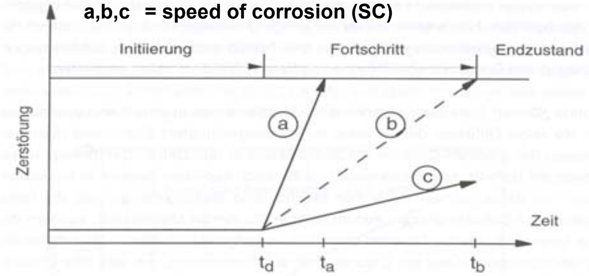


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Devolution of the corrosion

t_d	= point of depassivation
t_a, t_b	= reaching final state by SC
a,b,c	= speed of corrosion (SC)



Phase of Initiation

During the initiation phase aggressive compounds penetrate the boundary layer of concrete.

➔ The period of initiation is determined by:

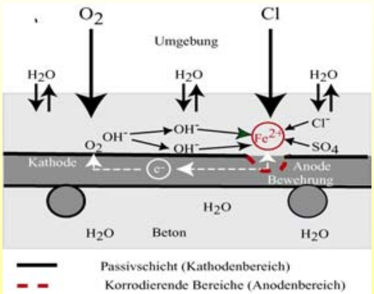
- **... Thickness of concrete cover**
- **... Penetration speed of pollutants**
- **... Concentration of pollutants**

➔ Calculation made by the civil engineer

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Speed of corrosion



Korrosionsmechanismus bei chlorid-belastetem Beton

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Characterising the process of corrosion

The process of corrosion can be expressed by the rate of degradation.

For example: 10-1000 µm per year

Methods to determine the corrosion

- Potential measurement ...
- Electrical resistance of the concrete
- Impedance measurement

... Allows fundamental evidence of

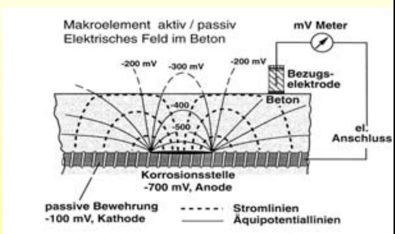
- Location and state of areas of corrosion
- Actual state of the corrosion of the reinforcement

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Corrosion potential of the reinforcement

Due to the current flow induced by the corrosion an electrical field is build up. The potential of the corrosion is representative for the actual state of the corrosion.



Prinzip der Potentialmessung auf der Betonoberfläche zum Auffinden korrodierender Bereiche der Bewehrung

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Phase II: Potential measurement

- After removal of the surface
- Up to 1000 m^2/d

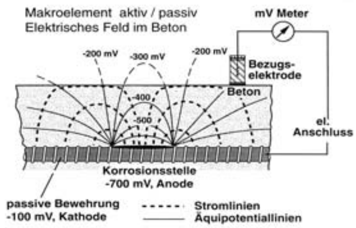
- In complex buildings
- Up to 1000 points/d

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Implementation of the measurement

- Connecting the $Cu/CuSO_4$-electrode with volt meter
- Connecting reinforcement with volt meter
- Measurement of the corrosion potential



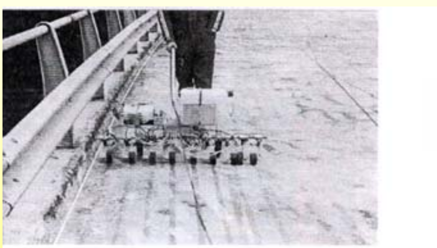
Prinzip der Potentialmessung auf der Betonoberfläche zum Auffinden korrodierender Bereiche der Bewehrung

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

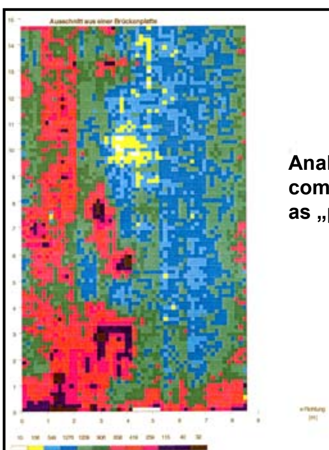
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Performance of the measurement

Large areas can be scanned by wheel-electrodes. The results are evaluated by computers.



Das im Rahmen des Forschungsprojekts entwickelte IBWK-Messystem für Potentialfeldmessungen mit acht Radelektroden im praktischen Einsatz



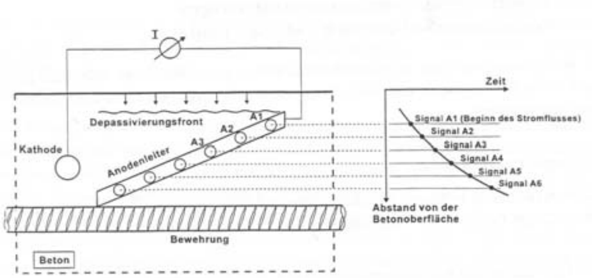
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Typical results

Analysis is performed by computers. The output is given as „potential mappings“.

Test probe for monitoring

Assembly of the test probes in very exposed concrete members.



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Condition analysis of a balcony plate

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

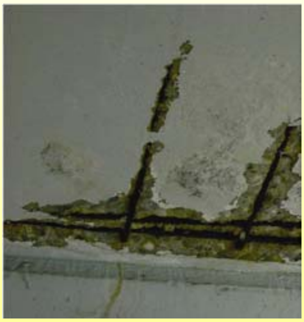
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Balcony – State of repair

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

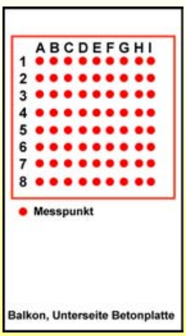
Balcony – State of repair



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

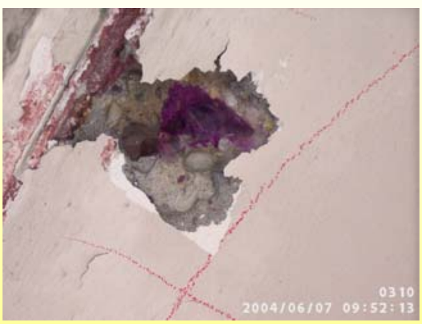
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

Adlerstrasse Nr. 38 - 5. OG										
Bewehrungsüberdeckung in mm										
A	B	C	D	E	F	G	H	I	Mittelwert	Standardabw.
19	23	12	25	33	25	31	29	10	23,0	8,0
9	11	27	12	18	24	21	7	5	14,9	7,9
15	18	21	21	28	25	11	-	-	19,9	5,8
18	20	14	8	9	14	18	8	-	13,6	4,8
18	20	14	8	9	14	18	8	-	13,6	4,8
10	8	8	7	13	14	16	22	-	12,3	5,1
9	9	12	29	13	30	28	9	-	17,4	9,8
9	8	5	9	7	22	30	32	11	14,8	10,4
		Mittelwert Bewehrungsüberdeckung/Standardabweichung:							16,2	7,1

Carbonatisierungstiefe			
Bohrkern 1	Bohrkern 2	Bohrkern 3	Mittelwert Carbonatisierungstiefe
15	20	12	15,7

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

Adlerstrasse Nr. 42 - 4. OG										
Bewehrungsüberdeckung in mm										
A	B	C	D	E	F	G	H	I	Mittelwert	Standardabw.
30	28	25	24	10	5	9	5	-	17,0	10,7
29	30	25	23	5	7	27	8	-	19,3	10,7
21	15	12	15	10	7	11	5	-	12,0	5,0
22	22	19	16	13	12	9	-	-	16,1	5,1
34	20	28	31	23	8	-	-	-	24,0	9,4
38	30	22	14	15	9	8	-	-	19,4	11,2
32	24	18	15	18	15	9	8	-	17,4	7,8
		Mittelwert Bewehrungsüberdeckung/Standardabweichung:							17,9	8,6

Carbonatisierungstiefe			
Bohrkern 1	Bohrkern 2	Bohrkern 3	Mittelwert Carbonatisierungstiefe

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

	Adlerstrasse Nr. 42 - 5. OG										
	Bewehrungsüberdeckung in mm										
Position	A	B	C	D	E	F	G	H	I	Mittelwert	Standardabw.
1	29	22	17	16	15	13	5	-	-	16,7	7,5
2	20	8	19	18	32	25	5	-	-	18,1	9,3
3	15	11	11	15	30	5	-	-	-	14,5	8,4
4	16	15	10	11	12	17	5	-	-	12,3	4,2
5	11	10	10	11	13	26	5	-	-	12,3	6,5
6	22	19	14	21	15	19	7	-	-	16,7	5,2
7	21	38	22	18	17	7	7	-	-	18,6	10,5
8											
			Mittelwert Bewehrungsüberdeckung/Standardabweichung:							15,6	7,4

Carbonatisierungstiefe			
Bohrkern 1	Bohrkern 2	Bohrkern 3	Mittelwert Carbonatisierungstiefe
2	10	5	5,7

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

	Steinsstrasse Nr. 19 - 4. OG										
	Bewehrungsüberdeckung in mm										
Position	A	B	C	D	E	F	G	H	I	Mittelwert	Standardabw.
1	37	28	17	19	20	5	5	-	-	18,7	11,6
2	32	30	22	20	15	8	5	5	-	17,1	10,7
3	37	36	24	31	29	22	16	-	-	27,9	7,6
4	40	37	30	14	12	16	14	-	-	23,3	12,0
5	39	32	17	11	21	19	7	-	-	20,9	11,3
6	43	42	41	39	38	27	7	5	-	30,3	15,8
7	32	23	11	5	9	7	5	7	9	12,4	9,8
8											
			Mittelwert Bewehrungsüberdeckung/Standardabweichung:							21,5	11,3

Carbonatisierungstiefe			
Bohrkern 1	Bohrkern 2	Bohrkern 3	Mittelwert Carbonatisierungstiefe
16	20	18	18,0

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Results of balcony analysis

	Steinstrasse Nr. 19 - 5. OG										
	Bewehrungsüberdeckung in mm										
Position	A	B	C	D	E	F	G	H	I	Mittelwert	Standardabw.
1	37	22	25	27	28	22	21	17	-	24,9	6,0
2	41	33	20	22	37	35	19	-	-	29,6	9,0
3	34	17	34	34	23	12	19	-	-	24,7	9,3
4	35	11	32	34	32	32	22	-	-	28,3	8,7
5	37	34	28	20	34	26	-	-	-	29,8	6,3
6	36	36	33	26	17	23	-	-	-	28,5	7,8
7											
8											
			Mittelwert Bewehrungsüberdeckung/Standardabweichung:							27,6	7,9

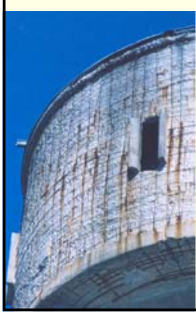
Carbonatisierungstiefe			
Bohrkern 1	Bohrkern 2	Bohrkern 3	Mittelwert Carbonatisierungstiefe
20	20	15	18,3

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Carbonation of reinforced concrete

The reaction of the CSH-phases with CO_2 is called CARBONATION



The $Ca(OH)_2$ (approx. 20 mass-%) which is build up by the hydration of cement and KOH & NaOH in the pore solution are responsible for the pH of approx. 12.3 to 13 of the concrete.

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2\ H_2O$$

Reasons for damages by carbonation

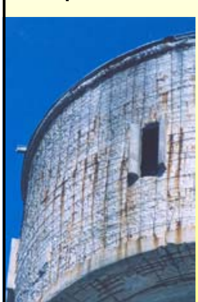
- Low cement content
- Minor dimension of cover concrete
- CO_2-content of the air
- Additional pollutants (NO, NO_2, NO_3)
- Insufficient manufacture of th concrete

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Reaction steps of the carbonation

**Carbonation is a coupled process:
Transport & chemical reaction**



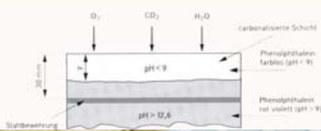
1. Diffusion of CO_2 into the cement rock

2. Solution of CO_2 in the pore solution
$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow 2\ H^+ + CO_3^{2-}$

3. Reaction of $Ca(OH)_2$ with H_2CO_3
$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2\ H_2O$
Carbonation of the alkaline hydroxides
$2\ NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$
$Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$

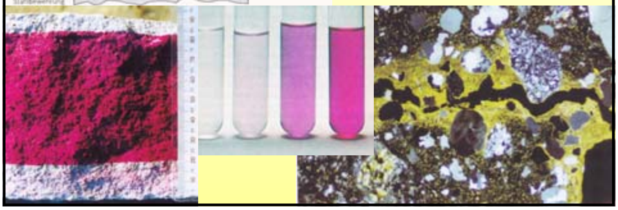
4. Decomposition of cement rock
$C_xSH_y + xCO_2 \rightarrow xCaCO_3 + SiO_2 \cdot y\ H_2O$

Determination of the depth of Carbonation



Carbonation depth can be measured by ...

- Liquid indicators
- Microscopy
- Wet chemical measurement
- Electrochemical determination



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Calculation of carbonation depth

Carbonation is a diffusion controlled process:

1. Fick's law

$$\frac{dm}{dt} = D \cdot F \cdot \frac{dc}{dy}$$

Mass balance

$$dm = m_0 \cdot F \cdot dy$$

m	**=**	CO_2 mass transported through the concrete surface [kg]
t	**=**	Time of admission [a]
D	**=**	Diffusion coefficient [m^2/s]
c	**=**	CO_2 concentration in the air and in the pore structure [kg/m^3]
y	**=**	Thickness of carbonated layer [m]
m_o	**=**	Absorbed CO_2 mass per volume unit of concrete [kg]
F	**=**	Area of carbonating concrete [m^2]

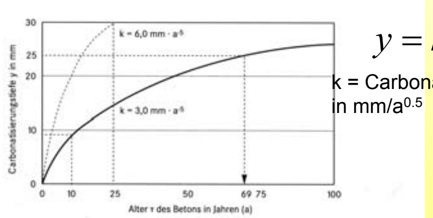
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Calculation of carbonation depth – √t-law

Solution of the diffusion equation:

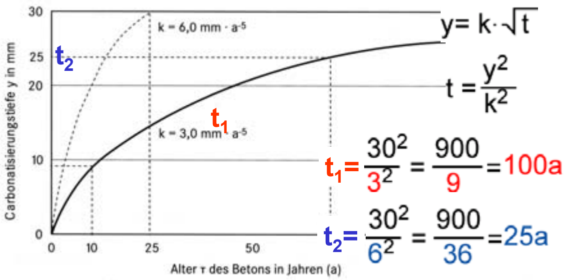
$$y = \sqrt{\frac{2 \cdot D \cdot c_0 \cdot}{m_0}} \cdot \sqrt{t}$$



$$y = k \cdot \sqrt{t}$$

k = Carbonation coefficient in $mm/a^{0.5}$

Calculation of the life span of a carbonating concrete member



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage mechanism

Sulfidation

Sulfate attack

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Sulfidation of concrete

Emissions (e.g. fuel) in the air are oxidised to SO_2 or SO_3. By reaction with rain „sulphurous acid“ and „sulphuric acid“ is formed

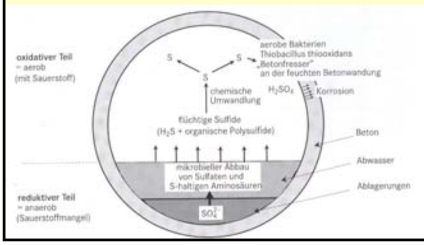
➔Reactions of these acids with cement rock form gypsum

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \cdot 2\,H_2O$$

But no high penetration depth ➔ surface near effect

Sulfidation of concrete

In presence of micro organisms gaseous sulfur compounds can also be formed which attack and destroy the concrete.

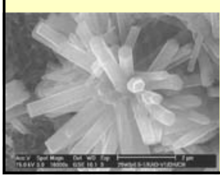


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Sulfate attack on concrete

-Important damage mechanism
-Known since 1877 (Michaelis)
- Structural damage due to the formation of complex compounds (3 $CaO \cdot Al_2O_3 \cdot 3\ CaSO_4 \cdot 32\ H_2O$)
- Damage event: 1890 in Magdeburg. Spring water with 2000 mg/l sulfate ➔ 8 cm expansion in 2 years

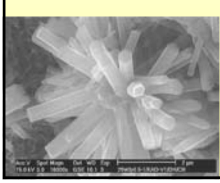


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Influence of sulfate – Attack through expansion

-Sulfate attack results in expansion
-Compounds of cement rock react together (**INTERNAL ATTACK**) or together with penetrating chemical agents (**OUTER ATTCK**)



Portland cement – Hydration of C_3A

Addition of water: $2C_3A + 21\,H \rightarrow C_4AH_{13} + C_2AH_8$
Conversion: $C_4AH_{13} + C_2AH_8 \rightarrow 2\,C_3AH_3 + 3\,CH$

- In absence of sulfate C_3A hydrates in thin plates (calciumaluminate- hydrates)
  ➔ **Result**: quick stiffening of the material

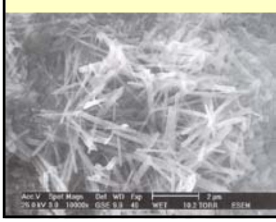
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Portland cement – Hydration of C_3A in presence of $CaSO_4$

Formation of ettringite

Addition of water: $C_3A + 3\,C\overline{S}H_2 + 26\,H \rightarrow C_3A{\cdot}3\,C\overline{S}{\cdot}\,32\,H$
ettringite



- In presence of gypsum the water-rich compound ettringite is formed
  ➔ **needle-structure**

Result: Decrease of the reactivity of the C_3A-Phase

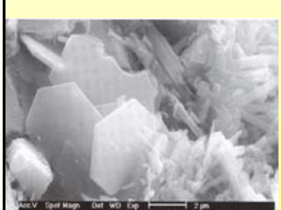
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Portland cement – Hydration of C_3A in presence of $CaSO_4$

Formation of monosulfate

Conversion: $C_3A{\cdot}3\,C\overline{S}{\cdot}H_{32} + 2\,C_3A\,H \rightarrow 3C_3A{\cdot}C\overline{S}{\cdot}\,H_{12}$
Monosulfat



- The layer get more porous and the reaction starts again.

Types of sulfate attack

Inner sulfate attack:

-Excessive gypsum content in Portland cement
-Cement mortar in contact with gypsum
(e.g. reconstruction of brickwork with mortars containing gypsum)

Outer sulfate attack:

-Sulfate containing waters and soils

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Inner/Outer attack – Reaction process

Inner sulfate attack:

-Comparative quick reaction
-Speed of reaction decreases by time

Outer sulfate attack:

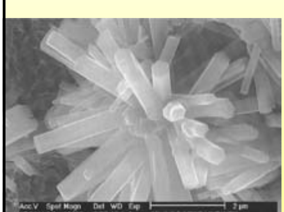
-Time-dependent because of transport process
-High sulfate concentration is necessary
-Speed of reaction increases
-Cation determines speed and amount of reaction too

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Properties of sulfate attack

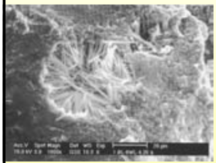
C_3A resp. calciumaluminate hydrates react with gypsum under formation of ettringite
➔ 8 times increase in mol volume

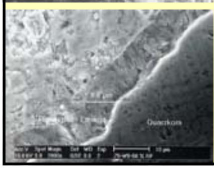


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Properties of sulfate attack





Formation of ettringite in pores and phase boundary layers

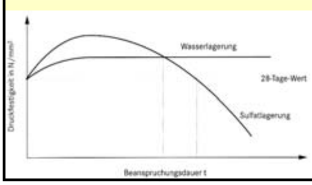
Reason:
Large pore area is accessible for precipitation products

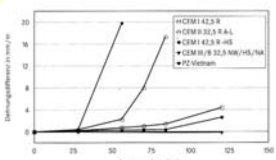
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Effect on concrete structure

- Formation of ettringite firstly results in higher strength
- Formation of micro cracks ➔ expansion!!
- Total demolition of the structure



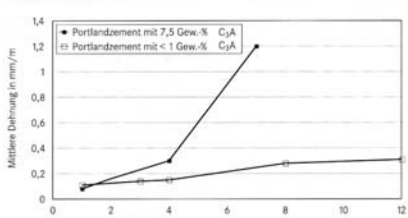


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors determining the sulfate resistance – C_3A-content

- Sulfate resistance is mainly depending on C_3A-content



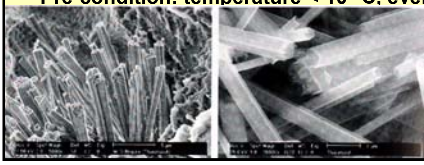
Additional factors:
Sulfate concentration
Temperature
pH-Value

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors determining the sulfate resistance – Low C_3A-content cements

- Even cements with low C_3A-content can be attacked by sulfate ➔ formation of thaumasite
- Mechanism:
- 1. Sulfate exposure to C_3A ➔ Ettringite (actuator)
- 2. CO_2/CO^{2-} (water) and SiO_2 (CSH-Gel) transform ettringite to THAUMASITE
- Pre-condition: temperature < 10 °C, even better < 5 °C

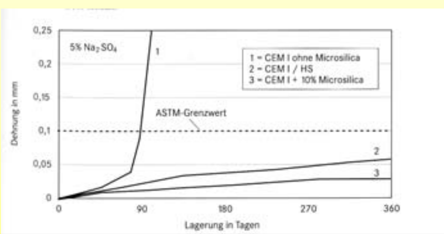


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Factors determining the sulfate resistance – Influence of additives

- Fly ash, sands und micro silica (Puzzolane) improve sulfate resistance ➔ higher density
- This effect is increased when C_3A-content decreases



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Type and Concentration of sulfate solution

- $(NH_4)_2SO_4 > MgSO_4 > Na_2SO_4 > CaSO_4$
- E.g. combination of dissolving and expanding attack
- Degree of attack depends on concentration (up to 10 000 mg/l)
  - ➔ up to 1000 mg/l: Formation of AFt und AFm
  - ➔ up to 1000 mg/l: Formation of gipsum

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Grenzwerte für die chemischen Merkmale der Expositionsklassen XA1–XA3 nach DIN EN 206-1

Chemisches Merkmal	Referenz-prüfverfahren	XA1	XA2	XA3
Grundwasser				
SO_4^{2-} mg/l in Wasser	EN 196-2	≥ 200 und ≤ 600	> 600 und ≤ 3000	> 3000 und ≤ 6000
pH-Wert	ISO 4316	≤ 6,5 und ≥ 5,5	< 5,5 und ≥ 4,5	< 4,5 und ≥ 4,0
CO_2 mg/l angreifend	PrEN 13577	≥ 15 und ≤ 40	> 40 und ≤ 100	> 100 bis zur Sättigung
NH_4^+ mg/l	ISO 7150-1 oder ISO 7150-2	≥ 15 und ≤ 30	> 30 und ≤ 60	> 60 und ≤ 100
Mg^{2+} mg/l	ISO 7980	≥ 300 und ≤ 1000	> 1000 und ≤ 3000	> 3000 bis zur Sättigung
Boden				
SO_4^{2-} mg/kg insgesamt [1)]	EN 196-2 [2)]	≥ 2000 und ≤ 3000 [3)]	> 3000 [3)] und ≤ 12.000	> 12.000 und ≤ 24.000
Säuregrad in ml/kg	DIN 4030-2	> 200 Baumann-Gully	in der Praxis nicht anzutreffen	

Critical value, defined by DIN EN 206-1

1) Tonböden mit einer Durchlässigkeit von weniger als 10^{-5} m/s dürfen in eine niedrigere Klasse eingestuft werden.

2) Das Prüfverfahren beschreibt die Auslaugung von SO_4^{2-} durch Salzsäure; Wasserauslaugung darf statt dessen angewandt werden, wenn am Ort der Verwendung des Betons Erfahrung hierfür vorhanden ist.

3) Falls die Gefahr der Anhäufung von Sulfationen im Beton – zurückzuführen auf wechselndes Trocknen und Durchfeuchten oder kapillares Saugen – besteht, ist der Grenzwert von 3000 mg/kg auf 2000 mg/kg zu vermindern.

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

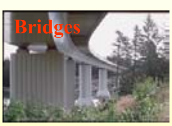
Influence of concrete quality on sulfate corrosion

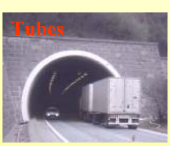
- Low W/C-ratio
- high Portland cement content ➔ Increase of sulfate resistance
- Low cement content
- Addition of puzzolanes

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Examples for highly endangered buildings





Beispiel: Beton für eine Kläranlage

		Belebungsbecken Sohle, Wände	Nachklärbecken Kronenbereich Laufbahn
Anforderungen		B 35 / Wasserundurchlässigkeit	
		hoher Frostwiderstand; hoher Widerstand gegen starken chemischen Angriff (1000 mg SO_4^{2-} /l im Grund-wasser/Baugrund)[1]	hoher Frost-Tausalz-Widerstand
Beton		Kiesbeton 0/32 mit Pumpförderung	
		Konsistenz KR	LP-Beton (ε = 5 ± 0,5 Vol.-%) Konsistenz KP
Zementart		CEM III/A 32,5-NW/NA	CEM I 32,5 R
Zementgehalt z	kg/m³	345	370
SFA f	kg/m³	50[1]	-
Wassergehalt w	kg/m³	180	170
w/z		0,52	0,46 < 0,50
$w/(z + 0{,}4f)$		0,49 < 0,50	-
Größtkorn	mm	32	32
Zuschlaggehalt g	kg/m³	1728	1710
Körnungen bei Sieblinie im Bereich AB	M.-%	0/2a = 34 2/8 = 18 8/16 = 24	16/32 = 24
Zusatzmittel		BV	BV, LP
Druckfestigkeit d = 28 / 56 Tage	N/mm²	42,8 / 50,2[2]	43,0 / -
Wassereindringtiefe e_{28}	mm	22 < 30	20 < 30
CDF-Test		-	Bestanden

[1] Nach RILI DAfStb 09/96 „Verwendung von Flugasche nach DIN EN 450 im Betonbau" gilt: $f / (z + f) \geq 0{,}10$ bei Einsatz von CEM III/A

[2] Vereinbartes Nachweisalter beim Beton mit CEM III/A ist d = 56 Tage

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Case study: concrete for waste water treatment plant

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Cement based materials in permanent contact with water

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Why are drinking water reservoirs coated?

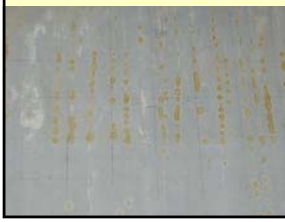
- Hygienic storing
- Repairing of entrapments (e.g. cracks)
- Abrasion layer against chemical and mechanical influences
- Easier cleaning
- appearance

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Corrosion of mineral materials

Characterisation of the damage
- Appearance
- Mechanical properties
- Chemical composition
- Kinetics

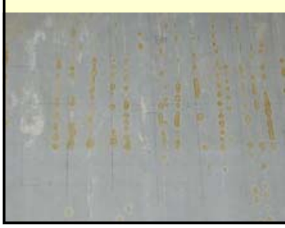


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage characterisation

Appearance
- Circular damage spots (diameter up to 5 cm)
- Often brown discoloration
- Often vertical, horizontal or orthogonal archetypes



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage characterisation

Mechanical properties
- Defect material is softened
- Material can be easy removed, e.g. by cleaning

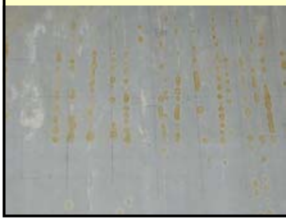
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage characterisation

Chemical composition

- $Ca(OH)_2$-content equals zero
- Increased $CaCO_3$-content



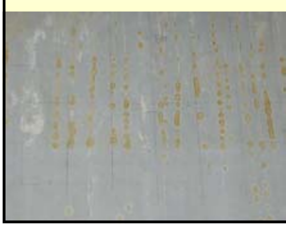
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Damage characterisation

Kinetic

- High speed and local increase in corrosion
- Damage appears already six month after application



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Possible causes for that damage

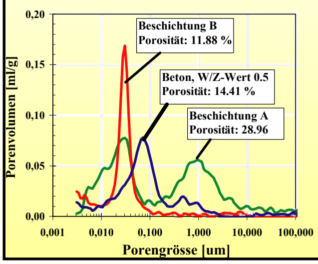
- **Water attacks chemically**
- **Microorganismn**
- **Acidic cleaners**
- **Hydrolysis of the cement based material**

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Mechanism of hydrolysis

1. Reaction step: <u>Ion-transport</u>
   - intake of HCO_3^--ions
   - export of Na^+, K^+ and Ca^{2+}-ions

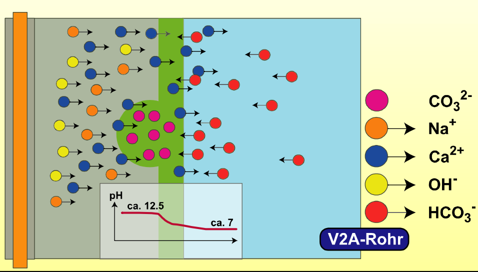


Mechanism
- **diffusion controlled**
- **transport resistance is structure dependent** (total porosity, content capillary pores)
- **accelerated by electric fields**

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Schematic demonstration: Hydrolysis of cement based materials

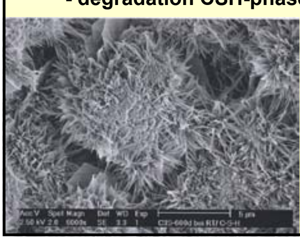


Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Hydrolysis mechanism

2. Reaction step: <u>chemical reaction</u>
   - pH-dependent transformation of HCO_3^- ions in CO_3^- ions
   - Precipitation of $CaCO_3$ by consuming $Ca(OH)_2$
   - degradation CSH-phases to SiO_2, Al_2O_3 and $CaCO_3$

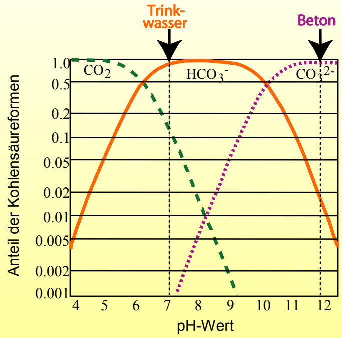


Hydrolysis is a coupled process of transport and chemical reaction

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

„Lime-carbonic acid“-balance



pH-Wert ca. 7:
es liegt praktisch HCO_3^- vor

pH-Wert ca. 12:
es liegt praktisch nur CO_3^{2-} vor

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Concept for quality insurance „Coatings for drinking water reservoirs“ in Switzerland

Tests:

1. Step: withdrawal of drilling core (Ø 50 mm)
2. Step : Determination of **layer thickness**
3. Step : Measurement of **total porosity** and **pore size distribution** (Hg-porosimetry)
4. Step: Determination of **calcium carbonate**- and **calcium hydroxide**-content

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

FH Karlsruhe
UNIVERSITY OF APPLIED SCIENCES
HOCHSCHULE FÜR TECHNIK

Concept for quality insurance „Coatings for drinking water reservoirs“ in Switzerland

Demands:

Layer thickness > 10 mm
Total porosity: < 15% (p=2500 bar)
1. Maximum in pore size distribution: < 0.1 µm
Chemical analysis: -