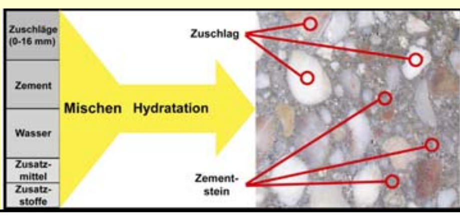
Durability and Restoration of Concrete Structures

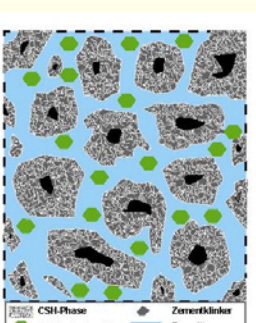
Prof. Dr. Andreas Gerdes

Properties of cement based materials

- Structure
- Chemical reactivity

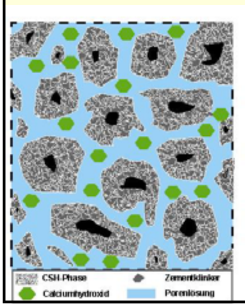


The structure of a cement based material



- Gel pores in CSH-clusters
- Capillary pores in between clusters

Formation of the pore dilution

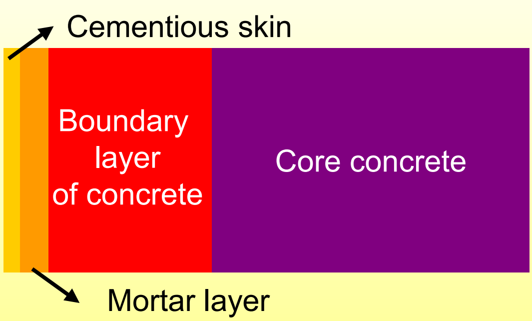


- Calciumhydroxide [$Ca(OH)_2$]
- Kaliumhydroxide [KOH]
- Natriumhydroxid [NaOH]
- Calciumsulfat [$CaSO_4$]

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

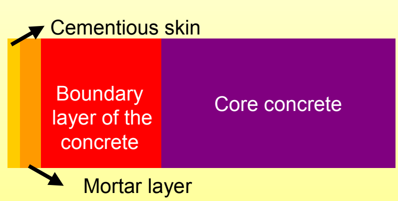
Pore dilution of cement stone:
pH 12.3 – 13.0

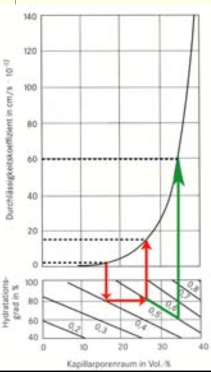
The boundary layer of concrete



Influencing factors on the permeability of the boundary layer

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



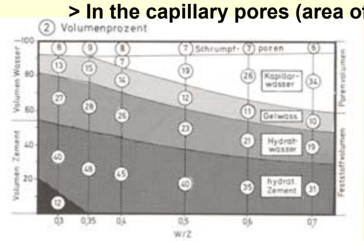


Permeability of cement based materials

The analysis undertaken by POWER's are existing already are originated from the 1950`s.

Influence of the W/C-ratio on the pore structure

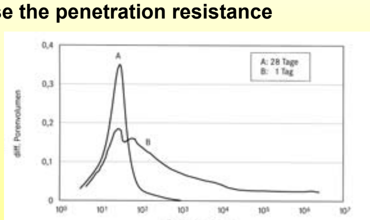
- **After hydration water is bounded in different forms in the structure.**
  - **> Chemically**
  - **> Adsorbed in gel pores**
  - **> In the capillary pores (area of transport processes)**



Influence of treatment after construction on the structure of the pores

- Sufficient treatment increases the density of the boundary layer.
  - •The treatment is enabled by using, transparent slides, mats for storing water, water spray, treatment agents and finally concrete remains in formwork.

➔ **Increase the penetration resistance**



Impregnation of cement based materials

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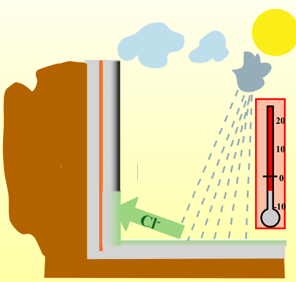
Environmental impacts on concrete structures



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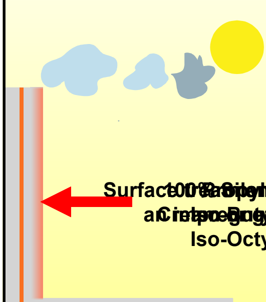
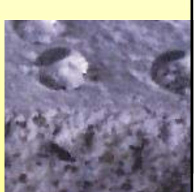
Surface impregnation of a structure



Iso-Octyltriethoxysilane



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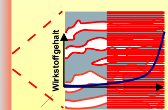
Performance of a impregnation



The Performance of a impregnation is depending on ...

- The penetration
- Potency at the boundary layer

i.e. from the potency profile

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What factors do have influence on the durability of impregnation?

potency=
transport + chemical
reactivity chemical
reactivity...
... of silanes

penetration
+ potency
= potency profile

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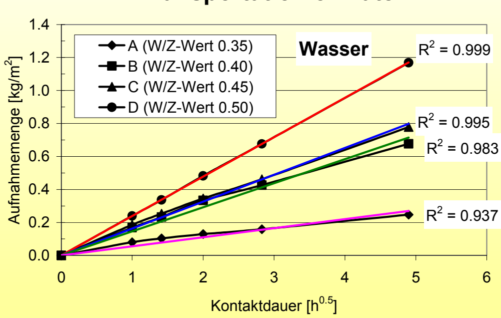
Transportation of water



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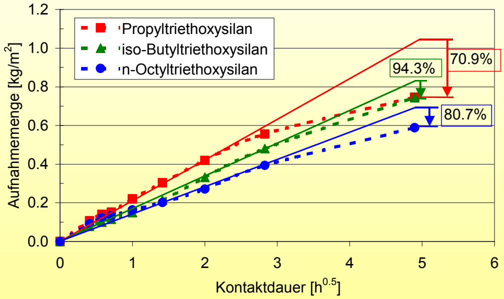
Transportation of organosilicon compounds



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Applications for impregnations

- Grounding near coatings
- Bridges and tunnels

- protection of offshore-buildings

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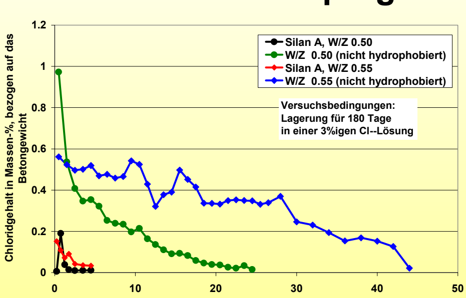
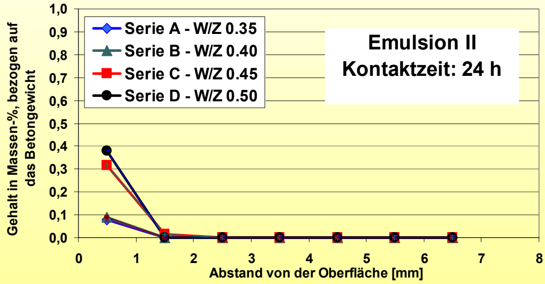
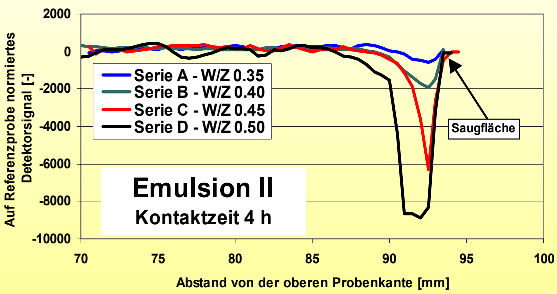
Effectiveness of an impregnation



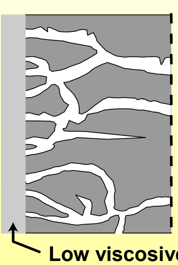
Types of the used solvent – potency profile



Types of the used solvent – fluid profile



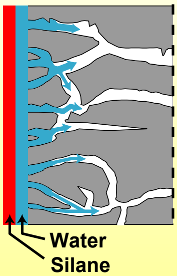
Type of the used solvent – breaking the emulsion



The low viscosive emulsion is applied on the surface.
➔ Absorption caused by capillarity

Low viscosive aqueous emulsion

Type of the used solvent – breaking the emulsion



Influencing factors on the breaking of a emulsion:

- Presence of cations
- pH-value
- Filtration
- Absorption
- Impact of organic compounds

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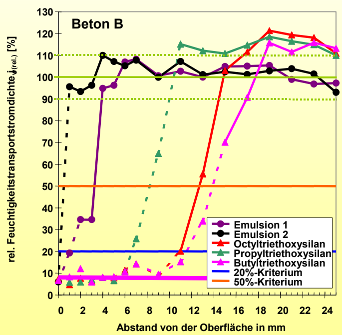
Criteria of effectiveness that are used in praxis



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Quality control of an impregnation

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Determination of potency profiles

1. Taking drilling cores
2. Impregnation
3. Testing the water absorption behaviour
4. Re-conditioning
5. Milling
6. Analysis

$$A_W = \frac{m_W}{F \cdot \sqrt{t}}$$

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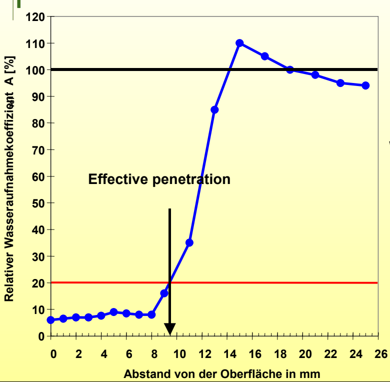

Water absorption behaviour of an impregnation

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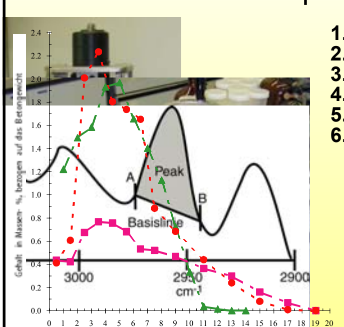
Determination of potency profiles



1. Taking drilling cores
2. Milling
3. Mixing with KBr
4. Making KBr-tablets
5. FT-IR-Spectroscopy
6. Analysis

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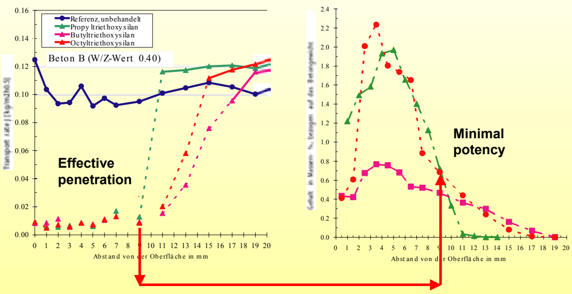
Determination of a minimal potency



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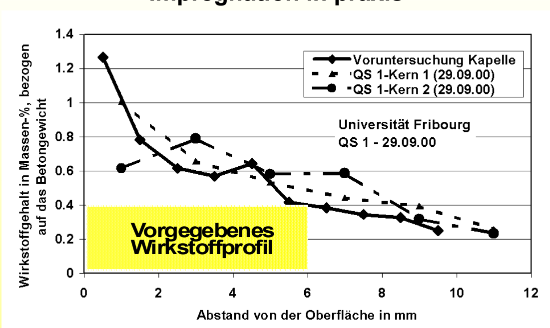
Impregnation in praxis



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Planning repair works

Repair works of a reinforced concrete structure

- Condition analysis
- Project planning
- Construction
- Quality control and maintenance

Task of a condition analysis

Recording the condition of the building regarding:

- Causes for damages
- Measurement of damages
- Temporally development of damages

Preconditions for planning phase:

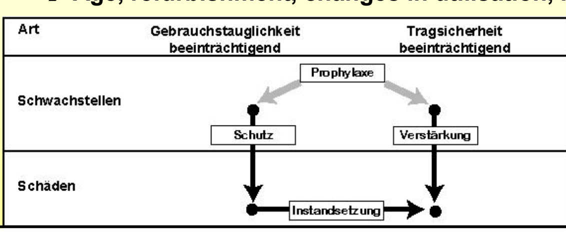
- Economical choice of the rehabilitation works
- High accuracy in calculating the costs of rehabilitation works

Concept for the condition analysis

Reason: Observation by the owner

1. Step:

- Recoding important data of the building
  ➔ Age, refurbishment, changes in utilisation, ...



Concept for the condition analysis

- Used materials (z.B. type of concrete)
- Location of the building
- Type and scale of utilisation
- Scope (area)
- Accessibility (e.g. scaffolding)
- Danger (health and safety)
- Construction (weak points)
- Aspects regarding energy recovery (e.g. isolation)
- Aesthetic aspects (shape, colour)

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Scope of the condition analysis

- Phase I: Visual appraisal (photos/drawings)
- Phase II: Analysis of the building on site
- Phase III: Laboratory Analysis

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Phase I: Visual appraisal

Documentation

- Cracks and pictures of cracking
- Leaking splices
- Spalling
- Inhomogeneous concrete
- Applied repair work
- Paintworks
- blowhole
- Natural cover
- Water (e.g. water from penetration)
- Pollution and scum's

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Phase I: Visual appraisal

From this the following can be derived:

- Stability problems
- Risk for brittle fracture
- Inroad of the building
- Deformation
- Cracking
- Falling Items

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Phase II: Measurement on site

Adhesive tensile strength

Grid-cut-testing

Natural cover
Cracking line
Spalling
Blowhole

Measurement with
→ measuring stick

Inhomogeneous concrete → Geologists hammer

paintwork
→ Adhesive tensile tools
→ Grid-cut-testing

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Phase II: Measurement of concrete

Compression strength → Schmidt-hammer
Adhesive tensile strength → Adhesive tensile testing tools
Carbonation depth → Taking drilling cores
Moisture content → Moisture measurement tools
Water absorption → Karsten-tube
Chloride penetration → „Silver nitrate/Chromate-test“

Phase II: Measurement of reinforcement

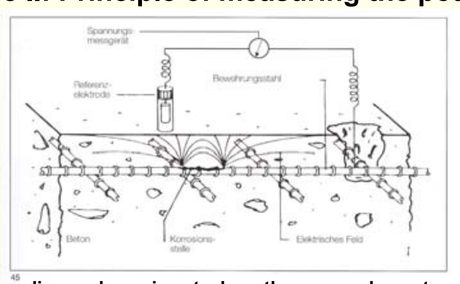
Position of the reinforcement ➔ Tool for searching the reinforcement

Condition of the corrosion ➔ Measuring the field of potential

The corrosion condition comprises:
Position and scope of the corrosion area

Supplemented by:
➔ Chloride distribution
➔ Carbonation
➔ Moisture distribution

Phase II: Principle of measuring the potential

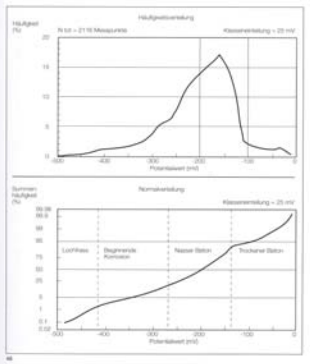


- Corroding and passive steel are the macro elements
- Caused by the elec. current an electrical field is originated
- An electrode is used for referencing
  ➔ Measurement of the potential <u>field</u> and <u>position</u>

Phase II: Types for potential measurement

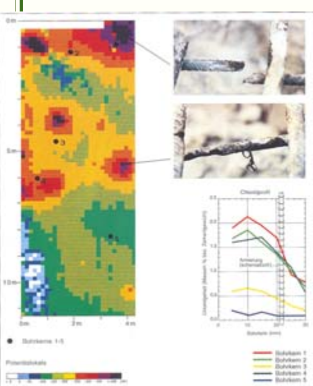
- Removal of pavement
- Up to 1000 m^2/d

- At complex buildings
- Up to 1000 points/d



Phase II: Measurement of the potential – Statically analysis

Classification of different conditions of the reinforcement



Phase II: Measurement of the potential – Measurement of a road surface

Phase III: Laboratory analysis

Laboratory analysis is supplementing the results of phases I and II

- **Mechanical properties** (Strength, E-Module)
- **Physical properties** (Porosity, water absorption)
- **Chemical properties** (Chloride-content, Carbonation)
- **Analysis of the structure** (Disruption, air pores)
- ...

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Appraisal of the condition data

Appraisal of the gathered data regarding:

- Scope and reason of the damages
- Weak points
- Development of damages (regarding time)
- Safety of the building
- Example carbonation

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Repair works of a concrete facade

Carbonation

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Project planning of repair works carbonation

The task of project planning is to develop different steps to carry out work and to eliminate weak points.

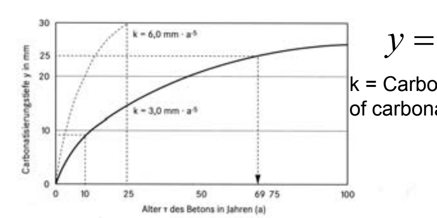
➔Avoid damages in future

➔Decision on the maintenance that is needed

Calculation of carbonation depth – √t-law

Solution of the equation for diffusion:

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



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

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

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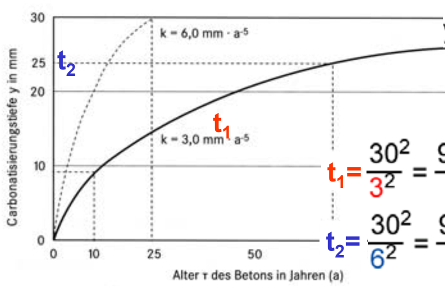
Calculation of the expected life span of a carbonating concrete structure



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

$$t = \frac{y^2}{k^2}$$

$$t_1 = \frac{30^2}{3^2} = \frac{900}{9} = 100a$$

$$t_2 = \frac{30^2}{6^2} = \frac{900}{36} = 25a$$

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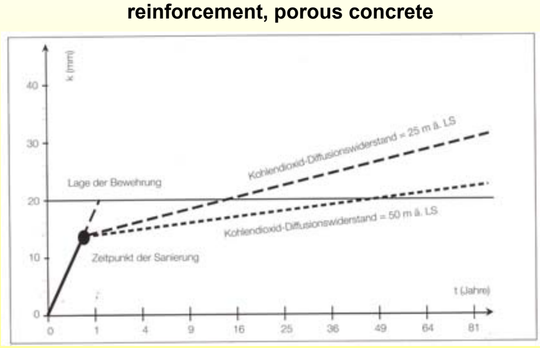
Case Study 1: Carbonation front < concrete cover of the reinforcement, porous concrete



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Carbonation - Planning of restoration measures

- **Coating of the concrete surface with a polymer coating with a high resistance against CO_2-diffusion**

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Calculation of diffusion resistances of concrete against CO_2

- The permeability of concrete against CO_2 is described analogously to the diffusion of water vapour.
- Additionally the so called μ-value, factor for diffusion resistance or the resistance factor is defined.
- The μ-Value gives information, about how much higher the resistance value compared to inactive air layer is.
- The μ-Value according to it´s definition is 1.

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Diffusion resistance of CO_2 for different materials

Werkstoff	Eigenschaften		μ-Wert
Leichtbeton	Gute Qualität		200
Normalbeton	Schlechte Qualität		150
	Mittlere Qualität		250
	Gute Qualität		350
Silicatfarbe			20 000
Dispersionsfarbe	Hoch gefüllt		5 000
	Weichelastisch		1 000 000
Epoxidharzmörtel			100 000 – 1 000 000
Acrylharzlösung	Pigmentiert		2 000 000

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Calculation of the diffusion-equivalent air film thickness R

$$\mu_{CO2} \cdot s = R$$

s = film thickness [m]
R = diffusion-equivalent thickness of the air film

Example:
μ-value for concrete, good quality: **300**
Thickness of concrete s : **15** mm

$$300 \cdot 0.015 \text{ m} = \underline{4.5 \text{ m}}$$

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Impact of an impregnation on carbonation

$$\mu_{CO2} \cdot s = R$$

Example:
μ-value of concrete: 360, thickness s: 25 mm

$$R = 360 \cdot 0.025 \text{ m} = \underline{\mathbf{9.0 \text{ m}}}$$

By determining the carbonation depth a life span of **62.5** years has been calculated.

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Impact of an impregnation on carbonation

Impregnation zone: ${}^{S}\mu_{CO2} \cdot {}^{S}s = {}^{S}R$
Concrete zone: ${}^{B}\mu_{CO2} \cdot {}^{B}s = {}^{B}R$

The factors of diffusion resistance ${}^{x}\mathbf{R}$ are add together

Impregnation Zone: $270 \cdot 0.002$ m = 0.54 m
Concrete zone: $360 \cdot 0.023$ m = 8.28 m
Total resistance: 0.54 m + 8.28 m = <u>8.82 m</u>

Caused by impregnation the diffusion-equivalent air film is reduced by 0.18 to 8.82 m.

Calculation of the life span

9 m diffusion-equivalent air film R result in a life span of **62.5a**.
What is the life span with a air film thickness of **8.82 m ?a**.

$$\frac{62.5 \cdot 8.8}{9} = t$$

Using the new air film thickness causes, according to the calculation, a reduction of the life span by 1.25 years.

➔ But by now no serious data are available that bring evidence!!

Reduction of Carbonation

The reduction is reached because of a very high diffusion- resistance value.

➔ That in turn minimizes the speed of carbonation!!

Reduction of carbonation : ${}^{C}\mu_{CO2} \cdot {}^{C}s = {}^{C}R$

Concrete zone: ${}^{B}\mu_{CO2} \cdot {}^{B}s = {}^{B}R$

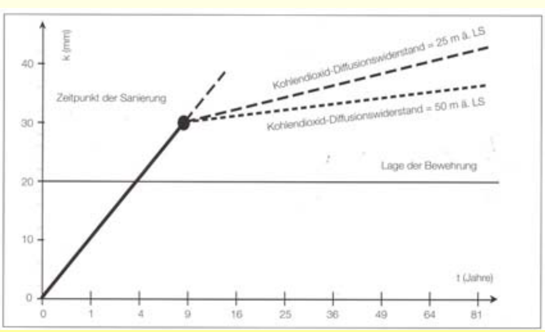
Impregnated zone: 2 000 000 · 75·10^{-6} m = 150 m

Concrete zone: 360 · 0.025 = 9.00 m

Total resistance: 150 m + 9.00 m = 159 m

The life span increases from 62.5 a to 1104 a.

Case Study 2: Carbonation front > concrete cover for the reinforcement



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Project planning of repair works carbonation

- Removing the cover concrete
- Uncovering the reinforcement
- Covering the reinforcement
- Repair works using shotcrete

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Dismantling of concrete

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Basics of high water pressure spraying (HWS)

Principle:
A water-jet with a very high speed is produced by pushing water through a valve.
(Pressure: many 100 up to 1000 bar)

➔ High kinetically energy

Basics of the HWS – Calculation of the kinetically energy

Example: Pressure of 2000 bar

$$v = \sqrt{\frac{2E_w}{\rho}\left(1 - e^{\frac{-p}{E_w}}\right)}$$

➔ E_w = E-module of water ($4.07 \cdot 10^9$ N/m^2)

➔ ρ = Water density ($1.07 \cdot 10^3$ kg/m^3)

➔ At 2000 bar: 600 m/s (by friction: 570 m/s)

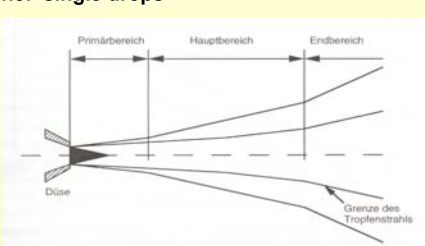
Basics of the HWS – Calculation of the kinetically energy

Example: Pressure of 2000 bar

$$p_{Stau} = \frac{1}{2} \cdot \rho \cdot v^2$$

Basics of HWS – Structure of the water-jet

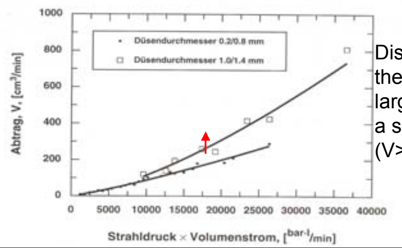
Prime zone: Conic, same speed as leaving the valve
length 0.24 · diameter valve
Main zone: Speed profile (length: 2-3 times of the prime zo.)
End zone: single drops



Basics of HWS – Water pressure and volume current

- Material dismantling > with p>, because v becomes larger
- Material dismantling > with V>, because the hydro-dynamic pressure becomes larger

➔Dismantling rate is f from the dismantling performance = p · V



Dismantling rate at the same performance larger valve and at a smaller pressure (V>>)

Basics of HWS – dismantling mechanism

- **Jet leads to a high p-gradient at the surface**
- **Tensile strength causes cracks**
- **Hydrostatic and hydrodynamic pressure leads to further cracking**
- **Contamination of micro and macro cracks**
- **Existing cracks are the starting point**
- **Additional effects: Shearing stress, friction and cavitation**

➔ Impact pressure

Basics of HWS – Application in construction

< 1 mm: Cleaning of the surface
1-3 mm: Keying
> 3 mm: Dismantling

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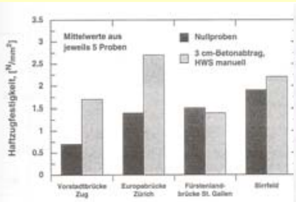
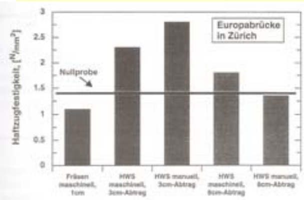
Basics of HWS – Advantages

1. Increase of the adhesive tensile strength of the subsurface.
2. HWS leads to a less valuable damages in comparison to other techniques.





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Basics of HWS – Advantages

1. Increasing of the adhesive tensile strength of the subsurface
2. HWS load to a less valuable damages in comparison to other techniques

HWS - Less delamination

Milling - Cracking

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Basics of HWS – Application

Parameters as...
- Water pressure
- Amount of water
- Valve diameter

...determine the treatment depth

Large degradation rate: p <<, Amount of water >>
Small degradation rate : p >>, Amount of water <<

HWS- Geringe Ablösung

Cement based coatings

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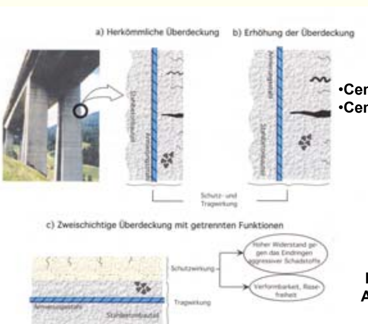
Concepts



- Cement based coating (30 mm)
- Cement based coating (80 mm)

Double layer coating and
And separation of function

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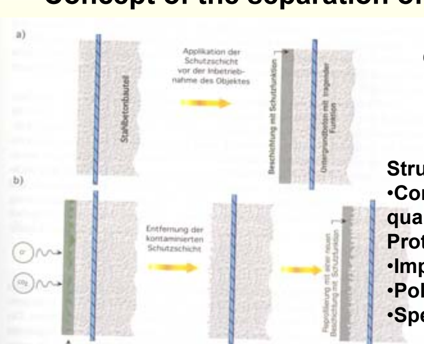
Concept of the separation of the tasks



Parameters:
Compression strength?
Durability?

Structure function :
- Concrete in large quantities

Protection function:
- Impregnation
- Polymer coating
- Special mortar

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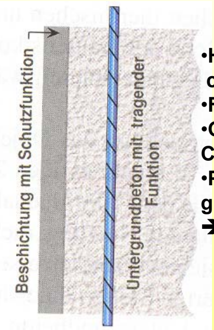
Demands on the protection function



- High resistance against aggressive chemicals (Cl^-, SO_4^{2-}, CO_2)
- Freeze-and thaw-salt-resistance
- Good bond to the subsurface (No Cracking, crack bridging)
- Protection against thermal and hygric gradients

➔ Control of the functionality (e.g. using sensors)

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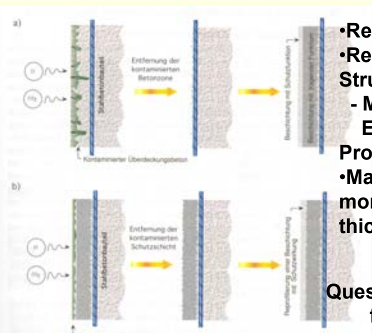
Concept for repair works



- Removing concrete
- Repair works

Structure function:
- Mortar with adjusted E-module

Protection function:
- Mass-impregnated mortar (approx. 20 mm thick)

Question: coating systems free from cracking

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Demands on a coating system

Experiences from practise show:

A durable coating system and a sustainable subsurface do not guarantee the durability of the coating/substrate.

➔Both properties of the system underlie inner and/or outer strains ➔ deformations

➔If deformations do differ hindrances do rise.

➔Result: failure of the coating if the load limit is transgressed

Demands of a coating system - Appraisal

The ability of a material of a system to take hindrances and loads is determined by:

- Elastic deformation E
- Fracture energy G_f
- Ability to creep J

Meaning of different impacts:
Physical impacts ➔ large
Mechanical impacts ➔ small
Chemical impacts ➔ avoidable

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Tension- and deformation analysis

According to a numerical model, that describes

- Endogenous Shrinkage
- Shrinkage caused by drying
- Creep
- Appearance of cracking

... using non-linear fracture mechanics, the relevant material parameters are described that are crucial for cracking of a coating

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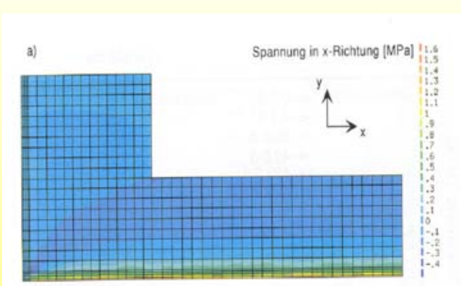
Finite-element-net of a concrete structure

Tension distribution after 123 days drying



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Risk reduction of cracking and delamination

Using the numeric model, the following material parameters have been identified:

- Hygric alternatively thermal Extension coefficient
- Fracture energy
- E-Module
- Appearance of cracking

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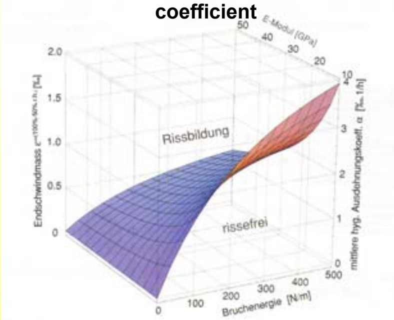
Risk for cracking as function of the fracture energy, the E-module, final material shrinkage and the hygric extension-coefficient



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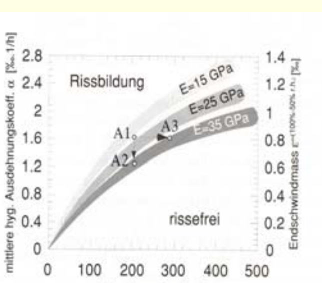
Two - Dimensional illustration of the risk for cracking

Point A1 hast to be shifted from the critical zone (cracking) to the safe zone (no cracking).



Possibility:

a) Reducing the material shrinkage (A2)
   ➔ **PC-content smaller**

b) Increasing the fracture energy (A3)
   ➔ **Increase fibres**

c) Reduction of the E-Module to 15 Gpa)
   ➔ **Other aggregates**

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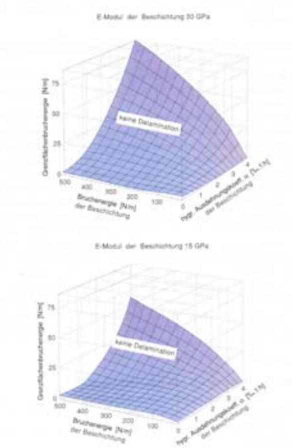
Delamination of coatings

For the dissolution of the coatings (delaminate) the following parameters play a major role:
- Strength in between the boundary layer
- Fracture energy near to the boundary zone

It is essential:

At a high **fractural energy** and **hygric strain**, but a weak strength in between the **boundary layer,** it is more likely that the coating dissolutes than the coating strains.



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Delamination of coatings

High mechanical strength and fracture energy of the subsurface can be reached by:
- **Sufficient roughness of the subsurface**
- **Application of primer (polymers)**

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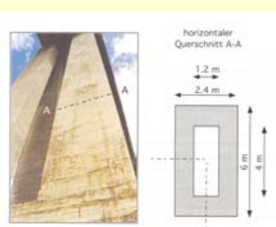
Case study: Repair works of a 25 year old concrete bridge



Alternatives for repair works:

a) Fibre-reinforced mortar with a max. aggregate size of 3 mm and a W/C-ratio of 0.38. Thickness of the layer that amounts 60 mm.

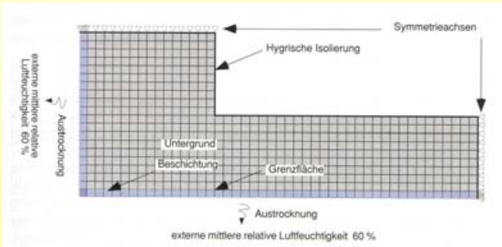
b) Concrete with a max. aggregate size of 8 mm and a W/C-Ratio of 0.36. The thickness of the layer that amounts 70 mm.

c) Shortcrete with a max. aggregate size of 8 mm and W/C-ratio of 0.38. The thickness that amounts 55 mm. Finally impregnated mortar with a layer thickness of von 5-10 mm.

Finite-Element-Net of a fourth of a column

Presumption:

a) From symmetry only a fourth of the column is chosen
b) Outer surface at 60% rel. humidity
c) Inner surface is sealed



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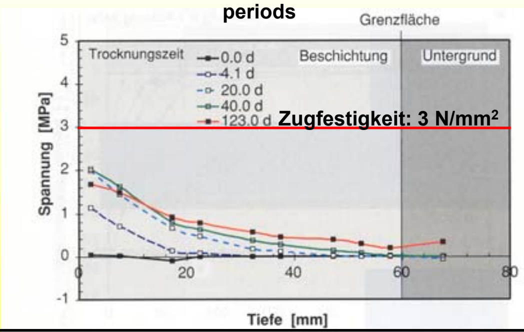
System A:
Tension distribution in x-direction at different drying periods



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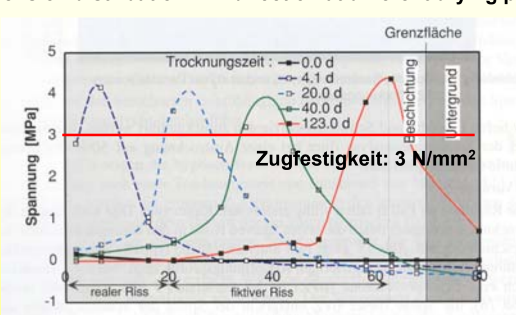
System B:
Tension distribution in x-direction at different drying periods



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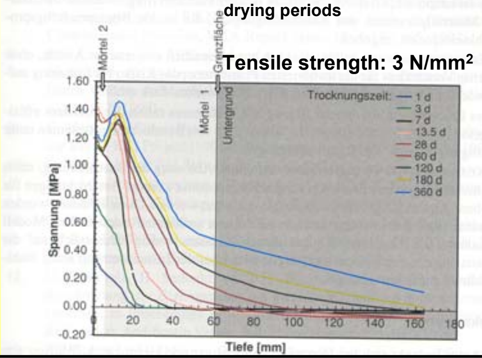
System C: tension distribution in x-direction at different drying periods

Tensile strength: 3 N/mm²



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Quality Control

Compressive strength	➔ Schmidt-hammer
Adhesive tensile strength	➔ Adhesive tensile testing tools
Water absorption	➔ Karsten's-tube
paintwork	➔ Adhesive tensile testing tool
	➔ Grid-cut-testing

Adhesive tensile strength

Grid-cut-testing

Karsten's tube