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Durability in Design, Detailing and Construction

Chemical and physical effects on the durability of concrete structures

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1 General

Today, the main criteria for durability are well understood, agreed upon, and reflected in most specifications and codes [1],[2]. Improved durability of structures requires both, knowledge of materials and experience in execution. The fields which have to be mastered are improved materials characteristics, architectural and structural design, process of execution, inspection techniques and maintenance procedures.

Planning and execution must meet quality assurance requirements. Quality assurance covers technology as well as organization: The construction company, the local branch, the building site, the client and the architect need to be involved in every total project. Schematised approaches to service life design are not considered reliable in practice.

Concerning these specific items, the Teach-In is subdivided into the following main sections:

1. Theoretical Background (Hillemeier), 2. Design (Pakvor), 3. Execution (Limsuwan), 4. Curing (Müller), 5. Examples (Dillman).

2 Influences on durability

Durability of concrete structures is mainly controlled by transportation processes of heat, moisture and chemical substances and by physical, chemical and biological corrosion as type and rate of degradation processes of concrete and steel.

Dominant factors for durability of structures are water and the transport mechanisms of water and gases within pores and cracks. Planning and design must aim to minimize negative effects of water attack.

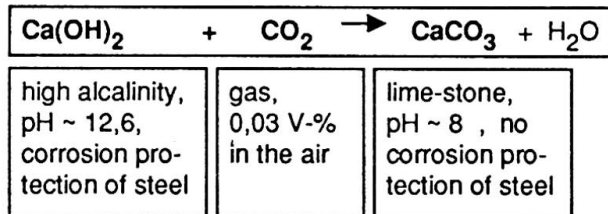
3 Necessity of dense and durable concrete

Concrete consists of two major phases: cement paste and aggregate. The mechanical as well as the durability properties of concrete are determined above all by the cement paste.

Cement and water react with each other to form the fibrous and very finely interlocking cement gel. The cement needs only a portion of the mixing water for its hydration. Water that is not used by the cement evaporates, leaving capillary pores behind that runs through the cement paste like veins. It is obvious that a high water content and insufficient curing increases the evaporation and thus the number of capillary pores breaking through to the surface of the concrete. Acidic gases invade the concrete through these pores and react with the alkaline elements of the hydrated cement.

3.1 Concrete attack mechanisms

Carbonization. Carbon dioxide (CO_2) in the air changes alkaline calcium hydroxide into neutral limestone and thus prevents the rust protection of the steel reinforcement:



Chloride attack. The permeability of concrete facilitates the entry of chlorides. This, in turn, makes the destructive chloride corrosion possible. It is well known that the presence of significant levels of free chloride ions (0,4 M-% of cement Cl combined with Friedel-salt $\text{C}_3\text{A} \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$) causes disruption of the protective passivating, thin film of gamma ferric oxide which forms on steel embedded in concrete by virtue of the high alkalinity of the concrete pore water.

The objective is therefore to limit chloride levels in the concrete mix constituents to as low a level as possible and to provide a dense concrete of low permeability to reduce the intrusion of chloride ions from external sources.

Sulphate attack. High concentrations of sulphate ions, particularly of magnesium sulphate, attack concrete. This attack involves the formation of calcium sulphate (CaSO_4 - gypsum) and calcium trisulphoaluminate within the cement matrix by reaction of the sulphate ions with the cement constituents, calcium hydroxide and tricalcium aluminate (C_3A) respectively. These reactions are expansive, which can weaken the concrete and cause cracking and breakdown of the concrete core.

Acid attack involves, initially, the softening of the cement matrix by the removal of calcium oxide leaving only hydrated silica and alumina. Strong acids may even dissolve silica and alumina hydrates.

The mechanism and kinetics of dissolution of the cement matrix and soluble aggregates in concrete subject to carbonic acid attack are complex. In the first instance, it is necessary to establish whether a water is undersaturated with carbonate, contains free carbon dioxide and is aggressive to concrete, or is oversaturated with carbonate acid and can deposit calcium carbonate.

From the point of view of a permanent contact of water with a concrete surface the state of undersaturation of water with respect to calcium carbonate is important. A simple technique exists to establish the



undersaturation state of a water, commonly called the marble test, which is used by hydrochemists. The test is specified in DIN 4030. [3]

To summarize, the key elements determining the durability of concrete are:

1. low water/cement ratio and sufficient cement content so that the cement particles are densely packed.
2. intensive curing in order to keep the water required for the chemical reaction from evaporating. Both are prerequisites for a
3. good quality concrete cover for the steel reinforcement.

The well-known relationship concerning Power's theory according to which the percentage volume of capillary pores decreases by reducing the water/cement ratio leads to the major requirement for durable concrete:

Limitation of the volume of pores in hydrated cement

$$V_K = c / \gamma_W \cdot (w / c - 0,36 \cdot m)$$

where

V_K Capillary pores in the cement paste [dm³]

c cement content [kg]

w/c water cement ratio

γ_W density of water [kg/dm³]

m maturity of cement paste, degree of hydration
 $m \sim 0,17 \ln(d)+0,18$ (for Portland cement, at 20 °C)

d age of cement paste in days

An intensive curing must make sure that the cement has enough water available for the hydration process which will serve to minimize the capillary pores. During the planning and design phase quality assurance (QA) measures have to be involved to actually realize the specific requirements for a dense concrete. ISO standards 29000 to 29004 represent the relevant quality assurance measures.

3.2 Concrete resistance properties

Permeability is influenced by the pore structure of the cement paste. For a characterization of the relevant pore structure with regard to the transport of substances into and within porous building materials, two parameters are of importance:

- relevant porosity, and
- pore size distribution.

Relevant porosity means pores which are interconnected so far that a transport of liquids or gases and/or the exchange of dissolved substances is possible. At the same time, the relevant porosity

corresponds to the maximum reversible water content and, in the case of cement paste, lies in the region of between 20 and 30 per cent.

The pore size distribution influences particularly the type and the rate of transport mechanisms and binding mechanisms in respect of water. The size of pores in the cement paste covers a range of several orders of magnitude. According to origin and characteristics, the pores are described as:

- compaction pores
- air pores
- capillary pores
- gelpores.

Expressed in more general terms, the following classification appears to be convenient:

- micropores (10⁻¹⁰ to 10⁻⁷ m in diameter), gel pores
- capillary pores (10⁻⁷ to 10⁻⁴ m)
- macropores (10⁻⁴ to 10⁻² m), compaction pores + air pores

Free surfaces of solids exhibit a surplus of energy due to a lack of binding components to the adjacent molecules. This energy is called surface energy. In the pores of the cement paste surface energy causes the water vapour molecules within the pores to adsorb to the pore surface (adsorption), the thickness of the water film thereby depending on the degree of humidity within the pores.

Due to the fact that the ratio between the surface area and the volume of the pores increases with decreasing pore radius, the rate of the water quantity adsorbed relatively to the pore volume will also increase until, at a certain limit value of the pore radius, the pore is completely filled with water. This process is called capillary condensation. The limit value of the pore diameter primarily depends on the water content of the air within the pore which, in the case of constant conditions, is proportional to the humidity of the air surrounding the concrete. (Fig. 1)

Any transport processes of gases, water, or substances dissolved in water are diffusion processes in respect to the ambient conditions.

Diffusion processes are induced by the tendency of equilibrating differences in concentrations. The driving forces for diffusion are therefore differences in concentrations.

Carbon dioxide diffuses into concrete due to a chemical reaction with CO₂ developing at the pore walls in the concrete, which causes the concentration within the pores to be reduced. This applies equally to oxygen when it is consumed during corrosion of the reinforcement.[1]

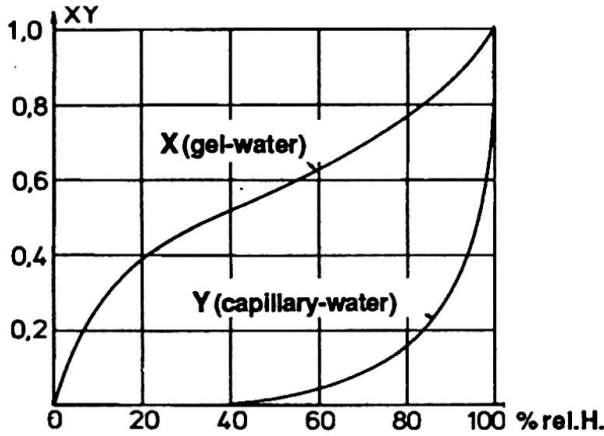


Fig. 1 Sorption-isothermes (Powers)

In the case of continuously immersed structures, large quantities of water may, under unfavourable conditions, be transported. A continuous transport of water will develop when water is allowed to evaporate at the concrete surfaces exposed to the air. The intensity of this water transport depends on the following three variables:

- evaporation
- capillary suction
- hydraulic pressure.

With the water, dissolved agents (carbonate, chloride, sulphate, etc.) will be transported. However, these agents are left behind in the concrete in the region of evaporation where they are likely to arrive at considerable concentrations. Efflorescence phenomena may also be due to this effect: the agents first dissolved are caused to crystallize at the concrete surfaces.

In concrete the expansive forces due to salt crystallization near the surface only cause minor problems, of importance is the chemical effect of the increased concentration of aggressive substance. However, in other porous materials such as sandstone, marble, masonry, etc., bursting and scaling due to salt crystallization is a serious cause of deterioration. This mechanism results in rapid deterioration of sculptures, monuments, etc. exposed to aggressive environments.

3.3 Cracking of Concrete

Cracking of concrete will occur whenever the tensile strain to which concrete is subjected exceeds the tensile strain capacity.

The tensile strain capacity of concrete reaches a nearly constant limit value of about 0,15 ‰ approximately after the 7 th day of age. This ultimate value is nearly the same for all types of concrete. The minimum ultimate tensile strain of about 0,05 ‰ is found in the concrete age between 6 hours and one day.

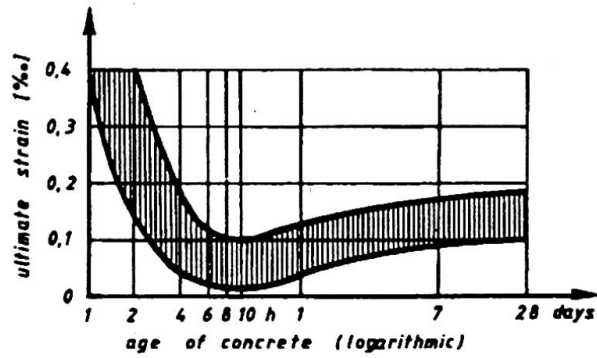


Fig. 2 Ultimate tensile strain of concrete depending upon age. [1]

As Fig. 2 shows young concrete is especially prone to cracking. Within the transition phase leading from fresh ("green") to hardened ("young") concrete, a critical period with very low tensile strength and a very low deformability is observed.

To consider whether a concrete may get cracked the different types of local deformations have to be added and compared to the ultimate tensile strain rate. Influences causing local strains which lead to tensile stresses if the movements are restrained are:

- drying shrinkage
- contraction due to temperature change
- externally imposed loading and/or deformation conditions
- expansion of material embedded within the concrete, (corrosion of reinforcement, alkali aggregate reaction,...)

Shrinkage can be assessed analogous to temperature change ΔT . The applicable range tends from 10 to 45 degrees Celsius, depending on the environmental conditions. Cracking occurs if $\epsilon \sim 0,5 \cdot 10^{-5} \cdot (\Delta T_{Temp.} + \Delta T_{Shrink.})$ exceeds the ultimate tensile strain.

The temperature distribution in the cross section of a structural element has generally to be analysed with the equation for non-stationary heat conductivity:

$$dT/dt = \lambda \rho c \cdot d^2T/dx^2$$

In most cases it will be possible to transform the model of consideration to a one dimensional problem.

4 Corrosion of reinforcement

The corrosion process can be separated into two single processes, the cathodic and the anodic process.

The anodic process is the real dissolution of iron. Positively charged iron ions pass into solution:





The surplus electrons in the steel will combine at the cathode with water and oxygen to form hydroxyl ions.

Cathodic process: $2e^- + 1/2 O_2 + H_2O \rightarrow 2(OH)^-$

After some intermediate stages, the iron and hydroxide ions will combine to form rust which, at least theoretically, can be written as Fe_2O_3 . Water is only necessary to enable the electrolytic process to take place.

The highest corrosion rate will occur in concrete surface layers, subjected to highly changing wetting and drying conditions.

At the steel surface, anodically and cathodically acting areas may be situated either close together (micro-cell corrosion) or at locally separated places (macro-cell corrosion) even over relatively great distances. Consequently, corrosion may occur in areas of the structure where the direct access of oxygen to the surface of the reinforcement is impeded.

5 10 rules for durable concrete [4]

1. Select high quality materials

- Cement: Select high strength, moderate C_3A (5-8 %), moderate alkali content, uniform quality.
- Aggregates: Check soundness and impurities, control content of fines < 0,30 mm to ensure stability at high slump, uniform grading.
- Admixtures: Select efficient water reducers (superplasticizers), air entrainers at high slump benefit by modified batching process, check air spacing factor (<0,2 mm) and specific surface for frost resistance.

2. Get mix proportions right

- w/c ratio < 0,50 is imperative.
- Cement content > 380 kg/m³ gives high "self healing" ability in cracks and joints.
- Stable mix at high slump requires selected grading of sand and efficient superplasticizers.
- Small dosage (< 5%) of CSF (condensed silica fume) benefits strength and stability, large dosage impairs constructability.
- Full scale site trials are essential before mix is chosen.

3. Employ modern automatic batching plants

- Batch type and batching procedure affects obtained properties.
- Select optimum batching procedure.
- Print-out of each batch (100% control).

4. Develop sound work procedures beforehand

- Think concreting before steel fixing. Ensure back up of plant and materials.
- Do trials or mock-ups if in doubt.

5. Compact the concrete generously

- Revibrate top layer for increased strength and elimination of voids under embedded items. (Revibration is an added bonus in slipforming).
- Make sure the concrete cover to the rebars is fully compacted

6. Ensure adequate cover to rebars

- Min. 50 mm cover to main reinforcement.
- Quality of cover is as important as thickness.
- Deficient cover is made up by cement-based coating (for 30-50 mm cover) or epoxy coating (for 30 mm cover).

7. Pay attention to construction joints

- Remove laitance (surface retarder and water jet are efficient on large areas).
- Apply rich mix against joint. Vibrate thoroughly.

8. Make allowances for temperature

- Avoid excessive temperature differences across sections. Temperature rise in thick sections can generally be expected as 12°C/100 kg cement.
- Initial temperature can be efficiently reduced by ice flakes as part replacement of mixing water (8 kg/m³ ice gives 1°C Temp. reduction).

9. Keep design simple

- Generous sections are easier to pour.
- Rounded and smooth surfaces discourage surface decay.
- Avoid sudden changes in geometry.
- Larger rebars take less space.

10. Use trained and skilled operators

- Only the operators performing the work can efficiently and continuously affect the quality of what is being produced.

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