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Concrete Structure and Protection of Steel Reinforcement

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Synopsis: The greatest threat to the durability of reinforced concrete structures is the reinforcement corrosion. The paper presents the importance of the concrete protective cover and the conditions causing the reinforcement corrosion under the action of chlorides and carbonic acid. Processes of absorption, diffusion and flow, i.e. of transport of media through concrete depend on the pore system and the amount of water in the pores.Physical laws describing the penetration of aggressive agents into concrete can serve as a basis for engineering calculations of reinforcement durability in the concrete as well as for the designing of the concrete cover. Physical laws and corresponding material parametars are briefly reviewed in the paper.
For engineering purposes, in calculating the durability, four typical tasks can be solved.
The processes of degradation depend on the pore system in the concrete structure, and the paper indicates some possible technological measures of structure modifications.

Keywords: Absorption; corrosion; cover; diffusion; durability; physical properties; porosity; reinforced concrete; structural design

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INTRODUCTION

The greatest threat to the durability of reinforced concrete structures often is the reinforcement corrosion. Conditions for the beginning of electrochemical process of corrosion appear, if concrete carbonatization causes the drop of pH value to below 9.5 i.e. if high alkalinity of pore water no longer presents a passive protection of the reinforcement. Reinforcement corrosion can also start if the amount of free chlorides in the concrete exceeds a critical value. There is no fixed critical value of the amount of chlor ions in the concrete to start reinforcement corrosion. It cannot be fixed because the total amount of chlorides determined by usual chemical analysis is not relevant. Corrosion is caused only by chemically free chlorides in the pore water, and they are difficult to determine. The risk to reinforcement corrosion at the same time also depends on the cement type and amount, concrete moisture, amount of alkalis and free lime and the kind and mechanical treatment of the steel reinforcement/1/. The whole problem of critical amount of chlorides in concrete is therefore an issue of risk-taking readiness, i.e. a probabilistic problem. For safety reasons the regulations usually determine the limit as 0.4 to 0.6 % chlor ions per cement mass.

It would be more suitable to use Page's classification /2/ for the reinforcement danger degree as:

slight risk		$Cl^- <$ 0.4% weight per cement mass
considerable risk	0.4 <	$Cl^- <$ 1.0% weight per cement mass
great risk		$Cl^- >$ 1.0% weight per cement mass

Some papers /1/, however, report on reinforced concrete structures where many times greater chloride concetration was found, without reinforcement corrosion.

Microclimatic conditions, heterogeneity of the micro structure and concrete quality essentially influence the corrosiveness of steel in concrete.

Penetraction of aggressive media into concrete depends on the pore structure and can be described by three processes: absorption (capillary suction), diffusion, and head flow. This paper describes the influences of pore system on the penetration processes of aggressive media into concrete and will point to possibilities of technological interventions in the structure of concrete. Each of the three processes of media penetrating the concrete can be defined by well-known physical laws, and mathematical connection can be found between the concentration of aggressive media per concrete depth and the potential service life of the structure. These relationships could serve as a basis for engineering computing the structure service life and designing the reinforcement protection. Four typical engineering tasks in design of concrete cover are presented.

STRUCTURE OF CONCRETE COVER

Processes of absorption, diffusion and flow, under external pressure .i.e. of transport of media through concrete depend on the pore system and the amount of water in the pores. Concrete contains pores ranging from centimetres to nanometres (Fig.1). Setzer /1/ has conveniently divided the pores according to their size and role in the transportation processes. These are voids from inadequate compaction or subsequent bleeding, speciffic pores due to aeration, capillary pores, and the minute gel pores. The great differences in pore size result in the structure of water and the water behaviour in the pores. For example, on the surface of the gel particles, water which is several molecules thick,due to the surface forces,has the density which is double to that in the capillaries or of free water in the voids.In the micropore area the dominant phenomena can be described only by physical laws of surface forces.The greater the pores,the greater the influence of macroscopic physical regularities,properties depending on the total volume of water in the pore,or on pore size. In larger pores,the influence of surface forces is smaller. In capillaries,this results in the well-known capillary suction and capillary elevation,and in the largest pores,the influence is negligible.In the largest pores,water transports only under head.

Gel pores, i.e. micro pores and mezo pores are constant ($\sim$ 28%) for the hydrated part of the cement stone, and their amount cannot be influenced. All other pores can be influenced by technological measures in the phase of mix design, compacting and curing (Fig.1).

In the interface area all kinds of oriented pores form /3/. This zone apparently presents the weakest part of the concrete structure, both concerning the mechanical properties and the durability. The pores between aggregate grains and cement stone are the ways of least resistance to the penetration of water and other media into concrete.

Aggregate pores have quite different character from pores in hydrated cement stone. Most aggregates have granular structure permeable to liquids. Their pores are usually much larger, and with the porosity of aggregates of about 1%, the rock permeability coefficient is approximately equal to that of cement stone of 50% porosity. On the aggregate grain surface, however, these pores are filled with cement stone of lower permeability. This may be the reasons why aggregate grains are not the main way for water and other media to penetration into concrete.

The quality of concrete depends very much on its surface layer known as concrete skin. Three skins of concrete can be defined /4 and 5/: cement (depth about 0.1 mm), mortar (depth about 4 mm) and concrete one (depth about 30 mm). Depth of the skins depends on the wall effect, sedimentation and seggregation, compacting method, and penetration and evaporation of water into the concrete and out of it. The consequences of these phenomena are variations of water /cement and aggregate/ cement ratios and increased porosity of the concrete surface layers.

These are the reasons why concrete skin in aggressive vironments should be improved. Each subsequent action on the concrete cover should include the removal of the cement or mortar skins. This practically means that in the preparation of the substrate, the surface layer of concrete 2-3 mm deep has to be removed.

PHYSICAL LAWS OF LIQUID AND GAS TRANSPORTATION IN CONCRETE

Penetration of media into concrete can be described by three processes: diffusion, absorption and head flow.

a) Diffusion

Transport of media through concrete due to chemical or moisture or temperature potential is diffusion, and for transient (not steady state) phenomena the process is described by Fick's second law

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \text{, where} \tag{1}$$

$\frac{\partial c}{\partial t}$ = concentration change in time

$\frac{\partial^2 c}{\partial x^2}$ = concentration change per cross-section

D = diffusion coefficient (m^2/s)

The most influencing gradient is that of the moisture concentration, but it is often in combination with gradients due to different solution concentrations or temperature differences as well.

Diffusion coefficient is a parameter of the material, but it is different for each media diffusing through the concrete. The passage of most media through concrete change the structure of the concrete, which in turn changes the diffusion coefficient. There are sugesstions on the dependence of diffsusion coefficient on humidity, but they are still unreliable for practical application. Prognoses on the basis of constant D give satisfactory results so far - no worse than those obtained by taking functionally changeable D.

There are good correlations between gas permeability coefficient according to Darcy and difussion coefficient /6/. Having data for D, Fick's diffusion equation can be solved numerically for actual boundary and initial conditions. For simple geometrical forms like those in Fig.2 /7/ the solutions are possible in closed form:

$$C_x = C_o \left(1 - \operatorname{erf} \frac{x}{\sqrt{2\, D.t}}\right) \quad (2)$$

b) Absorption

In capillary absorption, two phenomena are important: capillary pressure and the resistance to capillary flow. Both of these phenomena depend on the pore size diameter. In the water that rises in the capillary, subpressure appears (p_k). It is defined by the surface tension of the water (σ) and the wetting angle (δ) on the boundary of the liquid air and capillary wall. Laplace's equation for capillary pressure can be applied:

$$p_k = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{2\sigma \cos\delta}{r} \quad (3)$$

In expression (3), Laplace's equation is calculated for the capillary radius (r) and wetting angle /8/. If water is taken to completely wet the surface, equals zero. With this assumption, capillary elevation in concrete pores is calculated /1/ (Fig.3). In their final position capillary forces raising water are in balance with the water weight.

$$p_k = \rho \cdot g \cdot h$$

Actual capillary elevation greatly depends on the changeable geometry of the capillary pores and on whether the concrete is being wetted or dried /9/.

In order to obtain a balance of capillary forces and water column weight a certain time is necessary because water raising is resisted by friction against the walls.

Water absorption speed depends only on capillary porosity and is proportional to the capillary absorption coefficient A

$$q_a = \frac{A}{2} \frac{1}{\sqrt{t}} \quad (4)$$

Capillary absorption coefficient is determined experimentally /9/.

c) Flow under hydrostatic pressure

Water flow under external pressure is possible through capillary and larger pores (Fig.1). It is described by the Darcy's law

$$\frac{dq}{dt} = k \frac{h.A}{l} \qquad (5)$$

where

q - flow volume (m^3)
k - permeability coefficient for the considered medium (m/s)
h - pressure change on length l (m of water column)
A - area (m^2)
l - length (m)

During the water flow the pore size and the viscosity coefficient (η) radically change. It is a well know fact with concrete hydraulic structures, that most often water permeability decreases due to advanced hydration, concrete swelling, carbonatisation and capillary blocking in narrow places by water transported particles. Water permeability coefficient, therefore, is not a suitable parameter for concrete characterization. Standard tests can distinguish only very bad concrete from good concrete.

For flow of gasses, it is suitable to introduce specific permeability coefficient according to the Hagen-Poisuille equation:

$$K = \frac{k.\eta}{\rho .g} \quad (m^2)$$

Test of gas permeability, give a more reliable insight into the open and connected porosity of concrete. The influence of the kind of cement, w/c ratio and above all the curing of concrete on the gas permeability coefficient is very clearly illustrated by Fig.4. Badly cured concrete can have the coefficient of gas permeability which is 100 times greater than the normal one, which can result in halved service life. Methods are developed /11/ for testing the concrete gas permeability in laboratory and in situ. The gas permeability testing procedure is effectively used in determining the value of repair materials /12/. Good correlations are found between gas permeability of concrete and some other parameters for transport processes of media into concrete /11/.

COVER DESIGN

For engineering purpose, in calculating the durability and designing the structure regarding the corrosion protection of the reinforcement, four typical tasks (Fig.5) should be solved.

I. Diagnosis of the condition of the existing reinforced concrete structure. By testing samples taken from the structure, flow of aggressive media (Cl^-, CO_2 , etc.) per cover depth (c) and around the reinforcement is obtained. This and the actual age of the structure (t) serve as a basis to calculate the diffusion coefficient (D), absorption (A), permeability coefficient (k) and to forcast the structure service life (t).

II Calculation of permeability parameters D, A, k for the expected structure service life (t) and the given dimensions of the cover (c).

III. Designing the cover depth (c) for the expected structure service life and the given parameters D, A, k.

IV. Parameters D, A, k and the cover depth (c) are optimized for a given service life.

The real service life of numerous structures, especially bridges, industrial objects and some public objects is doubtlessly too short. On the other hand, in the design and the construction there is still no notion of the "designed service life" except for the wish for a structure to last "indefinitely". Beteween these two extremes, some minimum values of service life will soon have to be agreed upon, where routine checks and maintenance would enable the designed function of the structure.

The following proposal /13/ is a good example:

Structure	Expected service life (years)
Airport runways	30 - 50
Bridges (BS 5400)	120
Dams	50 - 100
Residiential buildings	60
Harbours	80
Factories	26 - 50
Offices, shops	50 - 100

In designing the service life, damage risk degree as a function of time can be shown in a simplified way in two characteristic phases by the scheme in Fig.6. Data on material parametars (D,A,k) are available from laboratory and in situ tests, hence practical calculations and evaluations of concrete cover are possible /14/. Designed depth of the concrete cover (c) can greatly exceed that common in present practice and existing regulations, especially in slender structures with greater spans. The depths of 70 and 80 mm are quoted as necessary /15/. A good substitute could be subsequently but timely applied thin layers of polymer modified cement mortars. With great adhesiveness such mortars have gas permeability which is about ten times smaller than that of concrete skin /12/.

If subsequent examinations of concrete structure show insufficient protective value of the concrete cover or some lower concentration of aggressive media in the concrete, the reinforcement in the concrete can be protected by means of additional layers of mortars based on portland cement with polymer admixtures, or only polymers, or polymer mortars. This is strengthening of concrete cover. Additional problems appear there: preparation and properties of the substrate, permeability properties of additional layer materials (selection), adhesion and compatibility and realkalisation.

Reinforcement cover saturated with aggressive media above the critical amount must be completely removed and replaced by a new one, which has adequate permeability properties. Special problems are similar to those strengthening the cover.

In both cases, correct diagnosis and categortization of the damage degreee as well as the selection of adequate repair measures are very important.

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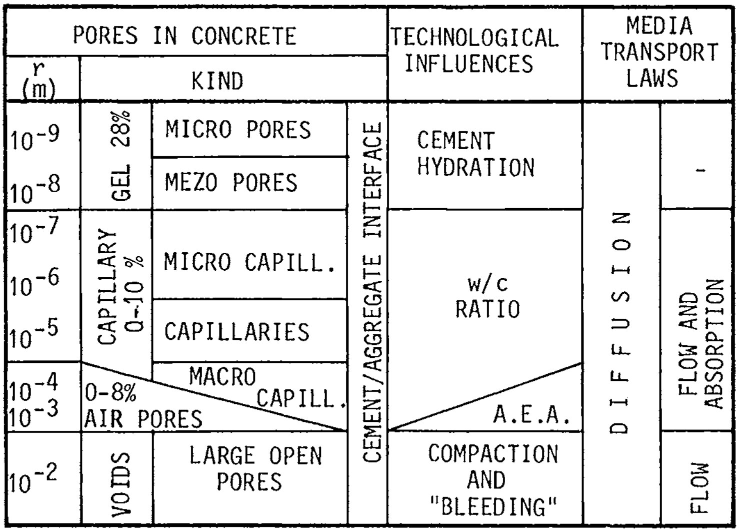

Fig. 1--Pore distribution and technological influences

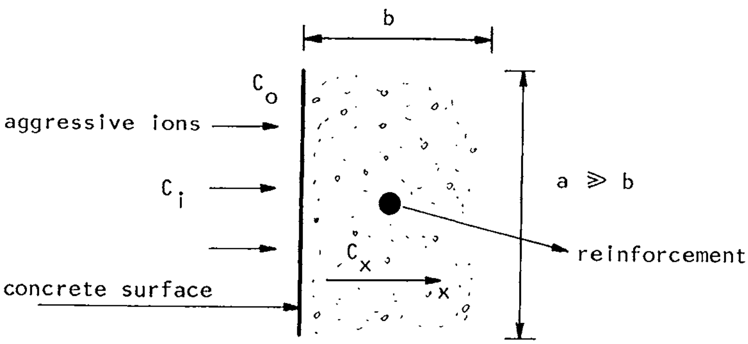

Fig. 2--Model of chloride ion transport into concrete