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Durability of Concrete — a Measurable Quantity?

Durabilité du béton — quantité mesurable?

Die Dauerhaftigkeit von Beton — Eine messbare Grösse?

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SUMMARY

The durability of concrete depends primarily on the resistance of the concrete against the ingress of aggressive substances. Though the transport of such substances may follow different mechanisms, it is investigated if a single parameter, the air permeability of concrete is suitable to characterize concrete durability in a general way. A simple test method to determine this parameter is presented. The effect of water-cement ratio and curing on progress of carbonation and rate of capillary suction can be described with this parameter, however, not the influence of type of cement.

RÉSUMÉ

La durabilité du béton dépend de la résistance du béton à la pénétration de substances agressives. Bien que le transport de telles substances puisse se produire selon des mécanismes différents, nous avons examiné si un seul paramètre, le coefficient de la perméabilité à l'air du béton est apte à caractériser généralement la durabilité du béton. Une méthode d'essai simple pour la détermination du paramètre est présentée. A l'aide de cette valeur, il est possible de décrire l'influence du rapport eau/ciment et de la cure sur le progrès de la carbonatation et sur la succion capillaire, mais il n'est pourtant pas possible de mettre en évidence l'influence du type du ciment.

ZUSAMMENFASSUNG

Die Dauerhaftigkeit von Beton wird von seinem Widerstand gegen das Eindringen aggressiver Substanzen bestimmt. Obwohl der Transport solcher Substanzen nach verschiedenen Mechanismen erfolgt, wird untersucht, ob nur ein Parameter, der Permeabilitätskoeffizient des Betons für Luft geeignet ist, die Dauerhaftigkeit von Beton allgemein zu charakterisieren. Es wird ein einfaches Prüfverfahren zur Bestimmung dieses Parameters vorgestellt. Der Einfluss des Wasserzementwerts und der Nachbehandlung auf die Karbonatisierung und auf das kapillare Saugen können mit diesem Parameter beschrieben werden, nicht jedoch der Einfluss der Zementart.

1. INTRODUCTION

The durability of concrete structures depends both on the resistance of the concrete against physical and chemical attack and on its ability to protect embedded steel reinforcement against corrosion. So far, concrete quality is evaluated primarily on the basis of the compressive strength of standard companion specimens. However, irrespective of differences between the concrete in a structure and in a companion specimen, the parameters controlling strength are not identical to those controlling durability. Furthermore, the compressive strength e.g. of a cube depicts an average property of the entire cross-section whereas durability is governed primarily by the properties of the surface near region of a section exposed to an aggressive environment.

Therefore, certain requirements regarding concrete composition as well as type and quality of concrete making materials are specified in most national and international codes in order to ascertain a sufficient durability of the finished concrete structure. However, concrete composition can be controlled reliably only at the mixer, and with a few exceptions a rapid analysis of the composition of fresh concrete still constitutes an unsolved problem [1].

If we can measure the potential strength of a particular concrete, why can't we measure its potential durability? One reason is that "durability" is a collective term for the resistance against a variety of physical and chemical attacks, whose intensity may vary with time. Thus durability always has to be related to a point in time or to the design life of a structure.

However, also "strength" is not a unique property and varies with time. Nevertheless some mostly empirical relations between the compressive strength of a standard specimen and tensile strength, strength under multiaxial states of stress, sustained load and fatigue strength etc. have been derived, are reasonably reliable and widely accepted.

Though there exists no cube test for concrete durability microstructural and other physical properties of concrete may be used to describe the potential durability of a particular concrete.

2. MICROSTRUCTURAL ASPECTS

Though concrete consists of two major phases, the hydrated cement paste and the aggregates, mechanical properties as well as the durability of concrete are governed primarily but not exclusively by the hydrated cement paste. HCP consists primarily of calcium silicate hydrates, calcium hydroxide, calcium aluminate hydrates and residues of unhydrated cement. Additional compounds which exist in smaller quantities such as calcium sulfates, potassium and sodium hydroxides may play a significant role for the durability of concrete.

The hydrated cement paste contains a system of small gel pores and partially continuous capillary pores. Particularly the capillary pores allow the ingress of water or aggressive media so that the most decisive characteristic of durable concrete is a dense pore structure i.e. a low total porosity and pore diameters as small as possible.

The total volume and the diameters of capillary pores decrease with decreasing water-cement-ratio and increasing degree of hydration which in turn depends on the duration of curing and on the age of the concrete [2]. This can be seen from Figs. 1 and 2 which show the size distribution of capillary pores from approx. 5 to 10^5 nm as determined by mercury intrusion porosimetry. With decreasing water-cement-ratio and increasing duration of curing the total capillary porosity decreases, and the pore size distribution shifts to smaller sizes. As a result the hydrated cement paste exhibits a denser structure. This reflects itself in the air permeability of concrete which decreases with decreasing water-cement-ratio and increasing duration of curing as will be shown in chapter 8.

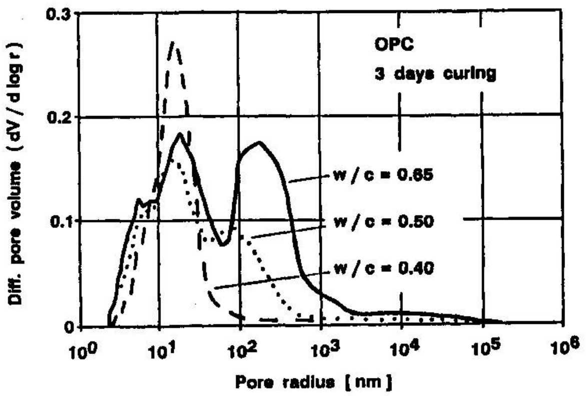

Fig. 1 Effect of water-cement ratio on pore size distribution of hydrated cement paste; ordinary portland cement (OPC); duration of curing: 3 days [3]

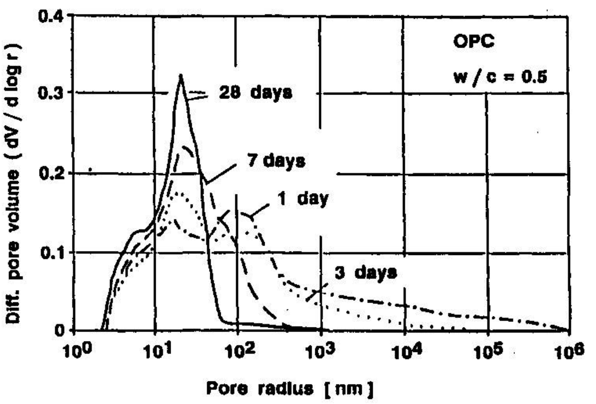

Fig. 2 Effect of duration of curing on pore size distribution of hydrated cement paste; ordinary portland cement OPC; water-cement-ratio = 0.50 [3]

Normal weight aggregates generally have a much lower porosity than the hydrated cement paste and, therefore, play no decisive role for the permeability of a concrete. Though most aggregates are chemically inert some minerals may react with compounds of the hydrated cement paste resulting in concrete deterioration.

The microstructure of the aggregate-cement paste interface generally has a higher porosity and a larger proportion of calcium hydroxide. In addition, microcracks may form at the interface resulting in a higher permeability of concretes compared to that of hydrated cement pastes.

3. SOME MECHANISMS OF PHYSICAL AND CHEMICAL ATTACK OF CONCRETE

The microstructure of concrete may be altered by a variety of external influences which often but not always lead to concrete deterioration. References describing these mechanisms are given e.g. in [2; 3].

Concrete whose pore system is critically water saturated will eventually be destroyed by freezing and thawing. Concrete shows a high resistance to freezing and thawing if the aggregates are frost resistant, if the amount of freezable water in the concrete is low i.e. if the capillary porosity is low and if the paste contains a system of entrained air voids characterized by a spacing factor <0.20 mm. Such concretes rarely reach a critical degree of saturation. Though the chemical effects of most deicing agents are minor they strengthen the effects of freezing and thawing by increasing the degree saturation and the number of actual freezing and thawing cycles.

Various chemicals such as acids or salt solutions may desolve some compounds of the hydrated cement paste. Chemical reactions may also result in a volume increase of the hydrated cement paste and thus cause disruption of the concrete e.g. if sulfate solutions from the ground water penetrate the concrete and react with the calcium aluminates of the cement to form ettringite.

Some concrete aggregates may contain silicate minerals such as opals or chalcedonites which are partially amorphous and may react with the sodium and potassium hydroxides of the hydrated cement paste. The reaction products form a gel which swells if water is available. As a consequence the concrete may be destroyed due to the swelling pressure.

In all cases of chemical and physical attack the ingress of water into the concrete plays a major role. Therefore, in addition to other measures such as air entrainment or the proper choice of cements, the concrete is the more durable the denser its pore structure.

4. MECHANISMS OF DEPASSIVATION OF STEEL EMBEDDED IN CONCRETE

It is well known that steel embedded in concrete does not corrode even if oxygen and an electrolyte are present. A passive layer is formed on the steel surface in the environment provided by the concrete which is characterized by a pH-value of the pore solution of approx. 12.6. However, under certain circumstances this passive layer may be destroyed resulting in corrosion of the steel.

Many of the durability problems encountered in reinforced concrete structures are caused by carbonation of the concrete. Carbondioxide which occurs in the open air in amounts of approx. 0.03 percent by volume penetrates the dry concrete through the capillary pores and reacts with the calcium hydroxide of the hydrated cement paste and to some extent with calcium silicate hydrates. Calcium carbonate is formed, and the pH-value of the pore solution decreases to values between 8 and 9 so that the passive layer is no longer stable. Carbonation is not necessarily detremental to the mechanical properties of the concrete. Of particular significance in this context is the observation that for concretes made of portland cement carbonation may densify the pore structure, whereas in the case of concretes made of slag cements with a high slag content coarsening of the pore system may occur [2], [4].

Carbonation of the surface near regions of concrete cannot be avoided, however, the rate of carbonation can be kept so low that the carbonation front does not reach the level of reinforcement even after centuries, provided the concrete cover is sufficiently thick.

The progress of carbonation with time can be described on the basis of Fick's first law with sufficient accuracy by eq. 1 [e.g.3]:

$$d_c = \sqrt{2\, D_c \cdot \frac{C_a}{C_c} \cdot t} \qquad (1)$$

where d_c = depth of carbonation [m]
t = duration of carbonation [sec]
D_c = diffusion coefficient of CO_2 through carbonated concrete [m^2/sec]
C_a = concentration of CO_2 in the air [g/m^3]
C_c = amount of CO_2 required for complete carbonation of a unit mass of the concrete [g/m^3].

The term C_c depends on the type of cement as well as on the presence of pozzolans or additions. The diffusion coefficient D_c is controlled primarily by the pore structure and by the moisture content of the concrete. As the relative humidity approaches 100 percent, D_c approaches zero and carbonation seizes. The rate of carbonation is the lower, the lower the capillary porosity of the concrete.

Even if the pH-value of the concrete is high the passive layer on the surface of an embedded steel bar may be locally destroyed by chloride ions penetrating the concrete e.g. by means of sodium chloride solutions used as deicing agents. The prediction of depth of penetration of chloride ions into concrete is difficult because the concentration of chloride ions on the concrete surface is not a constant and because both diffusion and capillary suction may take part in the transport of chloride ions [e.g. 5]. Also the type of cement influences the rate of penetration of chlorides since different types of cement have different binding capacities of chloride ions. Nevertheless, the general rule that dense concrete enhances concrete durability still applies.

5. TEST METHODS TO EVALUATE CONCRETE DURABILITY

Mostly phenomenological test procedures have been developed to estimate the probable behavior of a particular concrete in a given aggressive environment.

Various test methods are described in national and international specifications to determine the freeze-thaw resistance of concrete. In most instances concrete specimens are exposed to cyclic freezing and thawing in water. A decrease in dynamic modulus of elasticity of the concrete or the loss of weight or volume due to surface deterioration of the samples after a given number of freezing and thawing cycles is taken as a measure of the frost resistance of the concrete. Since in such experiments the degree of saturation of the concrete is not a constant but increases with time every concrete will eventually be destroyed once a critical degree of saturation is reached. Therefore, a test method proposed by Fagerlund appears to be the most objective [6]; [7]:

Different concrete specimens of the same mix are brought to different degrees of saturation and exposed to freezing and thawing cycles in a sealed condition. Thus a critical degree of saturation S_{crit} resulting in severe damage after a few freeze-thaw cycles is determined. In additional experiments the uptake of water by capillary suction S_{cap} is determined. Capillary suction-time relationships exhibit two distinct phases: the initial phase during which the water rises up to the top face of the concrete specimen and the second phase during which additional pores such as air voids gradually become water filled. It is the second phase which is of particular significance for the frost resistance of concrete. According to Fagerlund frost resistance F is defined as $F = S_{crit} - S_{cap}$. Thus F depends on the duration of exposure to capillary suction.

To estimate the resistance of concrete against chemical attack generally mortar or concrete samples are placed in solutions of various concentrations. Mostly weight change, change in dynamic modulus of elasticity or length and volume change are taken as relative measures of the resistance of a particular concrete against chemical attack. Deterioration may be accelerated by testing at elevated temperatures. However, the temperature dependence of the various deterioration processes is not well known, and different deterioration mechanisms may take place in different temperature regimes.

The measurement of depth of carbonation using phenolphtaleine as an indicator is well established. However, at least several months are required to estimate the resistance of a particular concrete against carbonation. The use of higher CO_2-concentrations results in an acceleration of carbonation. However, the structure of a concrete after carbonation at e.g. 3 percent CO_2 differs substantially from the structure of a concrete carbonated at 0.03 percent CO_2 [2].

6. TRANSPORT OF LIQUIDS AND GASES IN CONCRETE

The take-up of moisture in the concrete may occur either by permeation of liquid water under an external pressure, by capillary suction of water or by diffusion of water vapor.

Permeation of water through a porous body under a constant pressure gradient is generally described by Darcy's law:

$$Q = K_w \cdot \frac{h}{l} \cdot A \cdot t \qquad (2)$$

where Q = volume of water $[m^3]$ flowing during time t [sec]
$\frac{h}{l}$ = hydraulic gradient in terms of hydraulic head [m/m]
A = penetrated area
K_w = coefficient of permeability of water [m/sec]

The rise of the water level by capillary suction can be expressed in terms of the diameter of the capillaries. However, in hydrated cement paste the pore diameters vary over a range of several orders of magnitude so that capillary suction cannot be expressed on the basis of theoretical considerations. It may be approximated by the following empirical relation [3]:

$$\frac{w}{w_1} = \left(\frac{t}{t_1}\right)^n \tag{3}$$

where w = water absorption at time t
w_1 = water absorption after 1 h
t = time
t_1 = 1 h
n = exponent

For a steady state the transport of water vapor by diffusion can be described by Fick's first law of diffusion. However, in most practical cases a steady state is not reached. Therefore, for transient phenomena Fick's second law of diffusion has to be applied where the diffusion coefficient depends on the moisture concentration:

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left[D(H)\frac{\partial H}{\partial x}\right] \tag{4}$$

where H = internal relative humidity at location x
D = Diffusion coefficient [m^2/sec] at relative humidity H

The penetration of gases into concrete by permeation may be expressed by:

$$V = K_v \frac{A}{T}\frac{(p_1 - p_2)}{} \cdot \frac{p^*}{p} \cdot t \tag{5}$$

where V = Volume of gas [m^3] flowing during time t [sec]
$p_1 - p_2$ = pressure difference [N/m^2]
p^* = $p_2 + 0{,}5\ (p_1 - p_2)$
p = local pressure at which V is observed [N/m^2]
l = thickness of member [m]
η = viscosity of the gas [$Nsec/m^2$]
K_v = coefficient of gas permeability [m^2]

The transport of gases by diffusion can be described sufficiently well by Fick's first law. Eq. 1 is an example for the diffusion of CO_2.

From these relations it follows that there is no single materials characteristic to describe the resistance of concrete against the ingress of various aggressive substances. Further research is needed to establish relations e.g. between permeation and diffusion of air and diffusion or capillary suction of water or of aggressive solutions. Nevertheless, an attempt will be made to correlate some durability characteristics with a single concrete parameter, the characteristic air permeability K_{AC} of a concrete disc of given dimensions and age cured and stored in a prescribed way.

7. CONCRETE AIR PERMEABILITY-TEST METHOD

Schönlin developed a test procedure to determine the air permeability of a concrete disc, thickness 40 mm, diameter 150 mm as shown in Fig. 3 [4]; [8]. The concrete sample is cast directly into a rubber ring and is subsequently cured for 7 days, unless the duration of curing is the variable, and then stored in a constant environment of 20°C, 65 percent RH up to the time of testing at an age of 56 days.

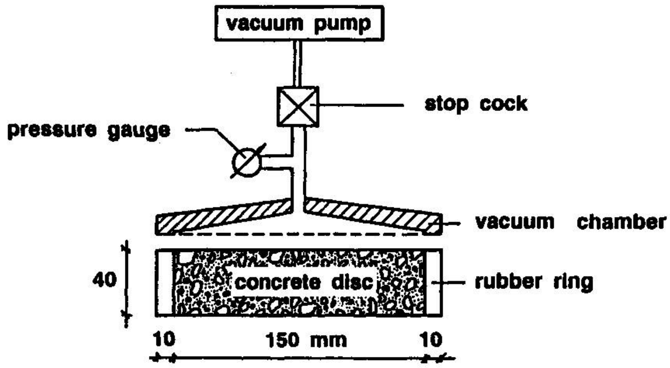

Fig. 3 Apparatus to determine concrete air permeability [3]; [8]

For the test a suction device is placed on one side of the specimen. A vacuum is generated in the space between the specimen and the instrument. After evacuation a stop cock between the vacuum pump and the instrument is closed. The pressure inside the instrument gradually increases and can be read from a pressure gage. A time t_o is taken at the instant the pressure reaches a value of p_o = 20 mbar. The time t_1 corresponds to the time after which p_1 = 50 mbar. The coefficient of permeability of the concrete disc can be calculated from eq. 6 which follows from eq. 5 neglecting the influence of the pressure p and not taking into account the viscosity of air.

$$K_{AC} = \frac{(p_1 - p_o) \cdot V_s}{(t_1 - t_o)\left(p_a - \frac{p_1 + p_o}{2}\right)} \cdot \frac{l}{A} \tag{6}$$

where
K_{AC} = characteristic air permeability [m^2/sec]
p_1, p_o = pressure inside the suction device at the end and at the beginning of the experiment, respectively
$t_1 - t_o$ = duration of experiment
V_s = Volume of interior of suction device
p_a = atmospheric pressure
l = thickness of the specimen
A = cross-section of the specimen

No special measures are needed to attach the apparatus to the specimen. An experiment takes from a few minutes upt to 60 minutes for very dense concretes. Since the test result depends on the moisture content of the concrete the dimensions as well as the curing and storage conditions have to be kept constant. A similar device has been developed to measure the permeability of the concrete skin of a structure [3]; [9].

8. CONCRETE AIR PERMEABILITY - TEST RESULTS

8.1 Effect of water-cement-ratio and duration of curing

Fig. 4 shows the influence of duration of curing on K_{AC} for concretes made of ordinary portland cement with different water-cement-ratios. Reductions of the water-cement-ratio or an increase of the duration of curing may lead to a reduction of K_{AC} by more than one order of magnitude.

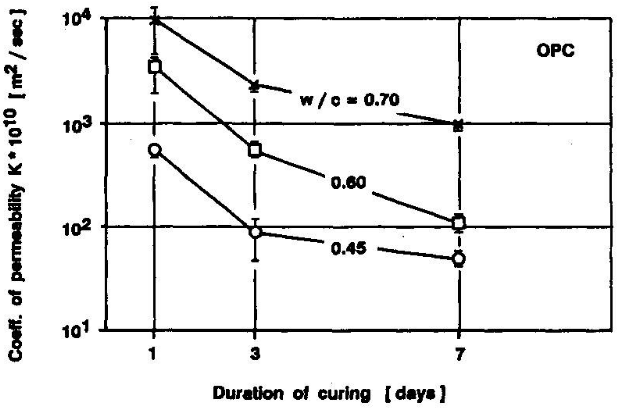

Fig. 4 Effect of duration of curing and water-cement ratio on air permeability of concrete; ordinary portland cement (OPC) [3]

Tests on concretes made of different types of cement with and without additions and cured at different temperatures demonstrated the well known fact that cements containing blast furnace slag or pulverized fuel ash need longer curing periods - other parameters being equal - to reach a certain impermeability [3].

8.2 Permeability and microstructure

There exists a unique relation between the air permeability of the surface near region of a concrete section and microstructural parameters e.g. as given in Figs. 1 and 2 which is independent of type of cement, water-cement-ratio and curing. For further details refer to [3]; [4]; [8].

8.3 Permeability and carbonation

Concrete cubes 150 by 150 by 150 mm, cement content 300 and 360 kg/m^3, respectively, were made of the following types of cement: ordinary portland cement (OPC) with additions of pulverized fly ash (FA) such that 0; 20; 30 or 40 percent of the weight of cement were replaced by FA, and portland blast furnace slag cements (PBFSC) with a slag content of 35 percent and of 65 percent, respectively. Water-cement-ratios of 0.45; 0.60 and 0.70 were employed, and the specimens were cured for 1; 3 or 7 days. After 1 year of storage in air with 0.03 percent CO_2, 65 percent rel. humidity and 20°C the depth of carbonation was determined. For further details refer to [3].

Fig. 5 shows for some of the concretes tested the relation between the square of the depth of carbonation d_c^2 after 1 year and the permeability coefficients K_{AC} on a double logarithmic scale. Two distinct relations exist, one for the concretes made of slag cements with 65 percent slag (PBFSC), the other for the concretes made of portland cement (OPC) with 0 and 20 percent FA replacement and slag cements with 35 percent slag. For the concretes with 30 or 40 percent FA replacement the depth of carbonation for a given permeability K_{AC} increased with increasing FA content.

Eq. 1 in chapter 4 describes the progress of carbonation with time as a function of the diffusion coefficient of carbondioxide through carbonated concrete.

In [10] it is shown that there exists a linear relationship between the logarithms of the diffusion coefficient and of the permeability coefficient of oxygen in non-carbonated concrete. Therefore, it is assumed in the following that a general relation exists also between D_c as defined in eq. 1 and the characteristic permeability coefficient K_{AC}:

$$\frac{D_c}{D_{co}} = \left(\frac{K_{AC}}{K_{ACo}}\right)^m \tag{7}$$

where D_{co}, K_{ACo} = dimensional coefficients

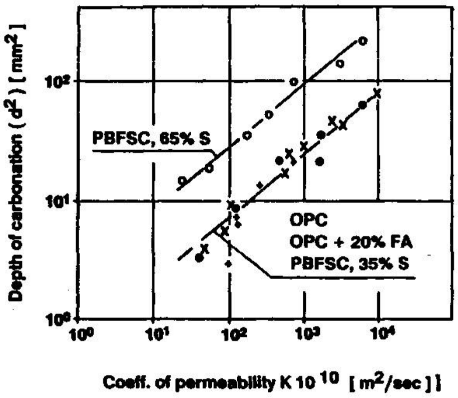

Fig. 5 Air permeability of concrete and depth of carbonation after 1 year at 65 percent rel. humidity and 20° C [3]

From eqs. 1 and 7 the following relation between depth of carbonation d_c at time t for a concrete with a characteristic permeability K_{AC} can be deduced:

$$d_c = d_{co}\sqrt{\left(\frac{K_{AC}}{K_{ACo}}\right)^m \cdot \frac{t}{t_o}} \tag{8}$$

The depth of carbonation d_c of concretes with different values of K_{AC} exposed to certain environmental conditions after an exposure time $t = t_o$ can be expressed as follows:

$$\log d_c^2 = \log d_{co}^2 + m \cdot \log \frac{K_{AC}}{K_{ACo}} \tag{9}$$

Such relations can be determined from the experimental results presented in Fig. 5 for t_o = 1 year. Apparently, these results closely follow eq. 9. The power m in eqs. 7 through 9 is given by the slope of the streight lines in Fig. 6. It is independent of the type of cement, m = 0.5. If we set K_{AC} = 1, $\log d_{co}^2$ is given by the intersect of the streight lines with the $\log d_c^2$-axis:

$\log d_{co}^2$ = -0.15 for OPC, OPC + 20 % FA and PBFSC, 35 % S

and $\log d_{co}^2$ = +0.45 for PBFSC, 65 % S

The most significant conclusion to be drawn from these experiments is the observation that for given environmental conditions and a given type of cement there exists a unique relation between the characteristic air permeability K_{AC} and the progress of carbonation which is independent of water-cement ratio, curing and cement content within the range investigated. The reasons why d_{co} depends on the type of cement may be twofold: C_c in eq. 1 i.e. the amount of CO_2 required to carbonate the concrete is influenced by the type of cement. Furthermore, carbonation itself alters the pore structure of HCP differently depending on the type of cement [2].

It has to be pointed out that the applicability of eq. 8 to carbonation of concrete in a structure still has to be verified by long term observations of concrete with a known K_{AC} under natural exposure conditions. This is particularly true for the values of d_{co} given above which are valid only for the controlled laboratory environment prevailing during these experiments.

8.4 Permeability and capillary suction

The uptake of water by capillary suction was determined on the same concrete discs, thickness 40 mm, diameter 150 mm, which were used to measure the characteristic air permeability. Concretes made with different types of cement, water-cement-ratios, and durations of curing were investigated. For further details refer to [3]. Immediately after the determination of K_{AC} the specimens were brought into contact with a water bath, and the uptake of water was measured. The results closely followed eq. 3.

It was found that there exists a linear increase of w_1 in eq. 3, the water absorption after 1 hour, with the logarithm of K_{AC}. The relation between the power n in eq. 3 and K_{AC} is given in Fig. 6. Only for rather permeable concretes values of n = 0.5 as reported in [6], [7] were observed. For a given value of K_{AC} concretes made of slag cement with 65 percent slag show a significantly lower value of n and thus absorb water by capillary suction at a slower rate than portland cement concretes. For very low values of K_{AC} the relations between n and K_{AC} approach a horizontal slope. This may be due to differences in the transport of moisture and of air in porous media, a phenomenon which should be studied in more detail in the future.

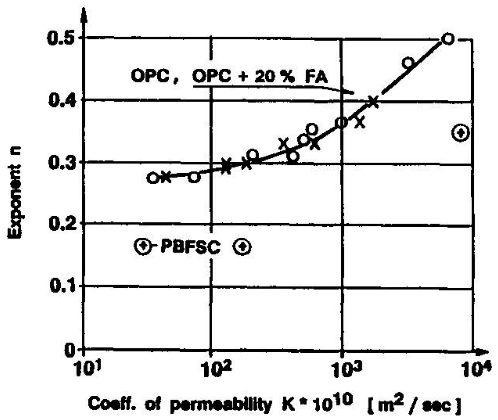

Fig. 6 Air permeability of concrete and rate of water absorption [3]

In these studies only the initial phase of water absorption by capillary suction as referred to in chapter 5 has been observed. So far it is not known if also the point of transition from the first to the second phase and the second phase itself can be described in terms of K_{AC}.

8.5 Permeability and other concrete durability properties

There is no doubt that a reduction in concrete permeability leads to an enhanced frost resistance of the concrete. This is supported by test results described in [3]. However, it is unlikely that a unique relation exists between the critical degree of saturation as defined in chapter 5 and K_{AC}. In particular the effects of air entrainment will not reflect themselves in the characteristic air permeability.

Other parameters being equal concrete resistance to chemical attack will increase as K_{AC} decreases. However, the chemical composition of the cement paste i.e. the type of cement used will in many instances have a dominating effect.

The same is true for the resistance of concrete to chloride penetration. Though in [3] a close relation between depth of penetration of chloride ions due to capillary suction and K_{AC} was found the effect of the binding capacity of the concrete and thus type and amount of cement and additions will be the dominating parameters.

9. CONCLUSIONS

- A characteristic air permeability coefficient K_{AC} of a standard concrete specimen which has been cured and preconditioned in a standardized way can be determined rapidly and reliably with the test procedure developed by Schönlin.

- The characteristic air permeability coefficient K_{AC} correlates well with the progress of carbonation under laboratory conditions. Effects of water-cement ratio and curing reflect themselves in K_{AC}. However, if cements containing larger amounts of components other than portland cement clinker such as pulverized fly ash or slag are used the relation between depth of carbonation and K_{AC} is no longer unique.

- Other parameters being equal concretes absorb water by capillary suction the slower the lower K_{AC}. Consequently they show a higher resistance to freezing and thawing, to chemical attack and to the pentration of chloride ions than concretes with a higher K_{AC}. But other microstructural and chemical aspects which do not reflect themselves in K_{AC} such as air-entrainment or composition of the cement may be of equal significance.

- Thus, concrete air permeability K_{AC} is not the unique parameter to describe concrete durability, and it is unlikely that such a parameter exists. Nevertheless, it is advantageous to characterize concrete not only in terms of its standard compressive strength but also in terms of K_{AC} since together with a knowledge of the type of cement it reveals the effects of several technological parameters such as composition and curing on the potential durability of a particular concrete.

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Influence of Material Properties on the Durability of Structures

Influence des caractéristiques des matériaux sur la durabilité des structures

Einfluss von Materialeigenschaften auf die Dauerhaftigkeit von Bauwerken

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SUMMARY

The influence of material properties on the durability of structures is an integrated part of the interaction between environmental aggressivity and the resistance of the structure. Durability is treated in a Service Life concept depending on level of modelling of deterioration mechanisms. The Service Life achieved depends on initial decisions, codes and standards and on Management and Maintenance Systems employed. CEB-FIP Model Code 1990 is the first Service Life Code and helps bridge the communication gap between material scientists and structural engineers.

RÉSUMÉ

L'influence des caractéristiques des matériaux sur la durabilité des constructions est une partie intégrante de l'interaction entre l'aggressivité du milieu ambiant et la résistance de la structure. La durabilité est traitée dans le concept Durée de vie dépendant du niveau de détail de la modélisation des mécanismes de détérioration. La Durée de vie dépend des décisions initiales, des codes et des normes et des systèmes de gestion et de maintenance utilisés. Le Code Modèle CEB-FIP 1990 est le premier code de Durée de vie, et permet de rétablir le dialogue entre les spécialistes de la science des matériaux et les ingénieurs civils.

ZUSAMMENFASSUNG

Der Einfluss von Materialeigenschaften auf die Dauerhaftigkeit von Bauwerken ist Bestandteil der Wechselwirkung zwischen der Aggressivität der Umwelt und der Widerstandsfähigkeif des Bauwerks. Die Dauerhaftigkeit wird in einem Nutzungsdauer-Konzept behandelt, welches vom Niveau des Modells für den Alterungsprozess abhängt. Die erreichte Nutzungsdauer ihrerseits hängt ab von anfangs getroffenen Entscheidungen, von Vorschriften und Normen und von den angewandten Verwaltungs- und Unterhaltungssystemen. Der CEB-FIP Model Code 1990 (Mustervorschrift) ist die erste Vorschrift zur Nutzungsdauer, und hilft die Verständigungslücke zwischen Materialforschern und Bauingenieuren zu überbrücken.

0. INTRODUCTION

The influence of material properties on the durability of structures is an integrated part of the overall interaction between the

- aggressivity of the environment, and the
- resistance against premature degradation as provided by the structure.

The environmental aggressivity is determined by the

- moisture availability
- temperature level
- type and amount of aggressive substance in gaseous or dissolved form,

and the concentrations, variations and gradiants of these parametres on a micro-environmental scale determined very locally by the interaction between the environment and the stucture.

The resistance of a structure against premature degradation, when exposed to an aggressive environment, is determined by the combined effect of the

- structural design and layout as fixed by the architect and the engineer,
- building material, or combination of the chosen materials,
- quality of execution, determining if the in-situ material properties are obtained including their variability,
- development of material properties with time, as determined by the physico-chemical micro-environment and type, level and frequency of maintenance performed.

0.1 Building Materials

The most widely used building materials are concrete, steel, wood and masonry, and the aggressivity of an environment differs considerably, depending on which building material that is being employed in the structure.

Our traditional approach in constructing and maintaining buildings differs surprisingly, depending on the chosen building material. In crude form this means that

- **Masonry** is chosen for wall-type structures in compression and is in general considered to be a robust low-maintenance material mainly because of its inorganic nature resembling stone. Its sensitivity to salt bursting caused by crystal growth in a polluted environment, sensitivity to moisture accumulation and freeze-thaw action often comes as a surprise, though these mechanisms are well-known to material scientists.
- **Wood** is a very versatile material, but its organic nature has led to the acceptance, that exposed structures very early need a regular maintenance and supplementary protection in the form of paint and impregnation.
- **Steel** is a high performance refined material threatened only by rusting, so regular re-painting will ensure a long term durability.
- **Concrete** is a unique material due to its as believed very simple production out of domestic materials, and due to its formability. The development of reinforced and prestressed concrete has created an ideal interaction between steel and concrete judged from a load carrying and a

durability point of view. The inorganic nature and the strength levels of concrete, make users believe that this material in all respects is superior to natural stone, and to constitute maintenance-free structures.

The errors in these simplistic characteristics are painfully evident, looking at the durability problems arising in many areas all over the world.

The structural engineer and the user have forgotten the thermodynamic instability inherently associated with these highly energy containing, worked materials. However, the physicists and chemists (material scientists) have had a clear mind on these durability problems for more than a century. This raises the questions:

- Why does this serious knowledge gap prevail today?
- How do we overcome the problems?
- Will theses problems last into the next century?
- Who should lead the way - those who mainly know the answers (material scientists) or those who have realized their own ignorance and ask the questions (structural engineers)?

1. SERVICE LIFE OF STRUCTURES

The natural ageing of building materials renders the concept of "Durable Structures" non-operational in practice because it leaves the questions "How durable?" and "Durable for how long?" unanswered. By considering the associated time scale, a "Service Life Concept" evolves which is directly applicable by the structural engineer when handling design of new structures and when assessing the residual service life of existing structures (1).

These considerations have led to the definition of the Service Life of a structure, as being the time for which the structure satisfies the imposed functional requirements, without needing unforeseen or excessive costs for maintenance and repair.

In this way durability is not merely a technical problem of relevance mainly to the engineer and the scientist, but becomes a combined technical and economic problem, which directly reflects the interest of the user and the owner (2).

1.1 Technical, Economic and Functional Service Life

The Technical Service Life depends on the performance of the materials and the structure in time, when exposed to a given environment.

The Economic and Functional Service Life depends on the economic demands in time, to ensure safe and satisfactory use of the structure.

The Economic and Functional Service Life of structures is a political instrument in the overall economic optimization of costs for creating a structure and keeping it in operation. The required minimum quality of a structure may reflect:

- the condition of structural and non-structural elements,
- the load carrying capacity, or safety, of the structure,

- the geometric restraints such as clearances, construction depths, etc.,
- the aesthetical qualities of the ageing structure.

Political decisions may influence the imposed requirements with respect to

- the safety level required
- the design loads and required clearances (room heights, bridge clearance, etc.)
- the acceptable appearance.

Changes in such requirements will simultaneously change the corresponding residual Economic and Functional Service Life, although the Technical Service Life is kept unaltered. In practice it would be optimal, if the Technical Service Life is longer than or equal to the Economic and Functional Service Life.

The Service Life Concept allows individual design policies to be pursued for each structure, based on an economic sub-optimization of the economy of each individual owner. From society's point of view this will soon become an unacceptable situation, why some uniformity must be ensured. This is mainly achieved through Codes and Regulations which may be tailored such as to ensure a reasonable uniformity in the safety and the serviceability of similar structures over the years, i.e. ensure an acceptable service life of the structures viewed from the point of view of society.

2. CONCRETE STRUCTURES - A LONG TERM CHALLENGE

Out of the previously mentioned four main building materials, concrete and concrete structures, including reinforced and prestressed structures, present probably the most complicated set of problems with respect to the durability and service life of structures.

Concrete is a conglomerate of many different inorganic materials bound together by several types of cementiteous and pozzolanic materials. The size of each particle is several orders of magnitude larger than the individual particles in other materials such as steel, and each particle (aggregate) is in itself a complicated component.

The production of concrete, and the execution of concrete structures, follows very simple procedures compared to the procedures in other structural technologies such as in the airplane, nuclear and electronic industry. Therefore, the influence of workmanship and the conditions of execution has a very pronounced influence on the quality of the outcome of the process.

2.1 "Lab-crete" and "real-crete"

The hardened concrete achieved on site very often differs substantially from the specified concrete, and when quality is to be verified, specially cast and cured cylinders or cubes are produced, and tested for strength. The sometimes humorous differentiation between "lab-crete", representing performance test specimens and specimens for research, and "real-crete", representing the in-situ concrete, is a serious matter when evaluating the durability of structures. A service life design having a reasonable degree of reliability will have to be based on in-situ measurements of the decisive parametres for durability as determined from the deterioration mechanisms which threaten the structures.

The variability of in-situ concrete quality is even more pronounced, when the hardening and curing conditions are taken into account. If the curing does not control the moisture exchange between hardening concrete and the environment, the surface layer - or skin - of concrete will exhibit early micro-cracking and even plastic shrinkage cracking, due to drying out, or may be harmfully porous due to excessive water uptake during the curing process. Similarly, the temperature levels and temperature differences between the newly cast concrete and the surrounding air, or between new and old concrete across a construction joint must be kept below specified values to avoid the early age cracking which will once and for all open up the concrete for penetrating aggressive agents including water.

2.2 Strength versus durability

The traditional 28 day strength requirement for concrete has been a simple and operational means of verifying the strength requirements. With the growing concern for durability, this parameter is not sufficient to reveal the durability characteristics of concrete. Much more involved testing is required in order to clarify if a concrete will be durable in a structure exposed to certain aggressive environments.

2.2.1 Testing for durability

Nearly all deterioration mechanisms depend on some type of aggressive media entering from the surrounding environment through the surface of the concrete and penetrating into the concrete. The one most important substance promoting deterioration is water. In fact only mechanical damage and temperature differences may cause damage without the governing influence of water.

The important rate-determining parameter then becomes the rate of penetration of aggressive substance including water. The permeability and the diffusivity of the concrete becomes decisive, and especially the conditions of the outer concrete layer, i.e. the skin of the concrete, or possibly the concrete cover will be a main controlling factor in the rate of deterioration.

There is no tradition for designing concrete with low permeability nor any well established test methods to verify the permeability of structural concrete. The permeability also differs for the same concrete, depending on the penetrating medium such as gaseous substance (CO_2), water, and chlorides dissolved in water. New concrete mix designs are currently being developed to cope with the service life requirements.

The one well established parameter controlling the permeability and diffusivity of concrete is the W/C-ratio. A very low W/C-ratio, usually achieved by introducing plasticising or superplasticising admixtures, will enhance the durability. Penetration of chlorides is a main governing risk with respect to corrosion of reinforcement. However, pozzolanic admixtures develop their properties at very different rates. Microsilica usually reacts very quickly, and the effect is obtained after just a few days. Contrary to this flyash reacts very slowly, and the effect is usually not traceable at the classical 28 days testing age. After 3 months a considerable improvement in permeability and diffusivity e.g. in connection with chloride penetration, is observed, but the effect may still improve after 1-2 years. Consequently the age at which veryfying tests shall be performed is very difficult to fix, and the 28 days testing age with respect to concrete strength cannot uncritically be maintained when the effects on durability are considered. This has further implications when performing pre-production trials and production controls, as the test results are not available until long after production has started or corrective interventions have become very difficult.

2.3 Hazards

Due to the usual progression of deterioration from the surface inwards and due to the composite nature of concrete structures, where concrete is combined with reinforcement, deterioration may have different consequences.

The corresponding hazards may be graded as follows (3):

- local hazards, where the surface of the structure slowly disintegrates and spalls due to cracking of the concrete (freeze/thaw action, Alkali-Silica Reactions etc.) or due to corrosion of the reinforcement. This creates serious hazards for users and bypassers risking being hit by falling debries. In the initial stage of development this does not cause noticeable reductions in overall load carrying capacity, stability and safety of the structure.
- global hazards,where damage has developed to such an extend that the structural integrity, stability and safety is reduced, and parts of or the whole structure may collapse or otherwise become unfit for use.

In this respect the warning associated with initial cracking, miscolouring and spalls are valuable signals of distress which should not be left unattended.

2.4 Concrete is expected to crack

It should be recalled, that concrete structures by virtue of their designed load uptaking mechanics are expected to develop load induced cracks with limited crack widths. For this reason cracking in concrete structures shall not à priori be considered signs of deterioration or malfunction.

3. DETERIORATION MODELLING

In order to understand the mechanisms of deterioration it is essential that physico-chemical models are available explaining how degradation occurs and clarifies which parametres are governing the process. This knowledge is a prerequisite in order to:

- perform a rational assessment into the damage type and the rate of development,
- select correct interventions and remedial measures and avoid aggravating the ongoing degradation, - the latter point unfortunately often being the case when incorrect remedial measures are being employed,
- avoid premature deterioration to develop in future structures,
- perform relevant maintenance during the operation of structures.

Decisions on these aspects are usually taken by structural engineers whereas the deteriorating processes are occurring within the micro-structure of the materials. The problem thus contains an inherent conflict between the level of modelling being directly or indirectly employed.

3.1 Micro, mesa or macro level of modelling

The deep insight into materials behaviour is represented by the materials scientist who naturally bases his models on micro-level materials science models whereas the structural engineer takes decisions based on his understanding of the problem which incorporates macro-level modelling or structural engineering models.

If these two basically different levels of modelling are not fully clarified in the information transfer between the structural engineer and the materials scientist, misunderstandings will occur. They will not speak the same language, and the so called communication gaps develops. The intermediate, or mesa-level modelling, performed by the materials engineer is an attempt to help bridging the main communication gap between micro-level and macro-level approaches.

However, it should be clear, that models on each level have the same degree of validity and are all indispensable. I.e. micro-level models are not necessarily more correct, or better than macro-level models.

3.2 Modelling, credibility and education

The tasks of the scientists and the engineers are to ensure compatibility between models on different levels treating the same phenomena. This is maybe the area most neglected in modern materials science and materials engineering; a communication problem that may well continue to create the most serious conflicts in the building and construction sector, including repair and rehabilitation.

The situation may well remain so well into the next century, if our engineering educational system is not changed. This represents the most serious dilemma of our profession in our relations to society and is contributing to our growing credibility problem. The lack of interdisciplinary understanding (and mutual respect) among engineers makes it especially difficult to cope with the durability problems of our structures, because these problems encompass all the disciplines of the engineer such as

- structural design, statics and mathematics,
- materials and their degradation,
- heat and moisture insulation,
- climatic conditions,
- execution and maintenance,
- repair and strengthening.

Information must be received and transferred between the different levels of detailing. This highlights the true need for a professional and rational interdisciplinary scientifically based engineering curriculum, - a true poly-technical education (4).

4. EXISTING STRUCTURES

4.1 Operation and maintenance strategies

Recent years growing durability problems with part of the existing buildings and structures have emphasized the need to follow a rational operation and maintenance strategy in the upkeep of structures.

These problems have grown to levels where the traditional approach of repairing damaged structures and attempting to bring them back near to initial quality will be exorbitantly expensive. Completely new ways of handling these problems on both structural level, and safety and reliability level have been sought. In the intermediate say 10 years with unclear maintenance and repair strategies the size of the problems have been close to getting out of hand, especially what concerns problems associated to concrete structures, because major parts of concrete problems are rather new and the total number of concrete structures is very large.

Today we have realized the following needs

- Repairs do not necessarily have to re-install initial or near initial quality and performance, a sufficient target quality of the repaired structure must be determined.
- From a service life concept point of view the economic optimization will often lead to the conclusion that repair and upgrading is not optimal, and a decision of non-repair together with an intensified inspection and maintenance routine, e.g. including monitoring, may well be the optimal solution. I.e. degenerate under control.
- The traditional visual inspections of structures may tend to maximize maintenance costs instead of the minimizing effect sought. The reason being that interventions are not made until an active or rapidly propagating deterioration mechanism is in progress. Preventive maintenance is thus not applicable or is of very little value.
- Deterioration mechanisms threatening our building materials in the structures must be clarified, and the main governing - and influenceable parameters must be identified in order to allow for a repair procedure which can slow down or stop an ongoing deterioration.
- Inspection procedures - also so-called superficial inspections - should include on-site testing to determine the degree of break-down of inherent protective effects in the structure. For concrete structures this means determining the current state with regard to e.g. carbonation depth, chloride penetration, electro-chemical potentials, depth of deleterious reactions, residual bar diameter etc.
- Preventive maintenance performed before the onset of rapid propagation of deterioration will be a very cost-effective way of prolonging the service life of structures. This leads to a need to make users and owners of structures much more conscious of the long term economic benefits of such interventions. This task is difficult from a political and psychological point of view, because maintenance activities must be performed on an otherwise intact structure showing no visual signs of distress.
- In order to keep track of the condition of structures and their time-dependent developments, rational management systems should be employed.

Thus the management of structures becomes a major task in the overall optimization of costs and technical efforts in the upkeep of structures (5).

4.2 Structures Management and Maintenance Systems

Structures Management and Maintenance Systems thus performs a rational and systematic administration of structures aiming at:

- maintaining an acceptable performance of each structure
- ensuring an optimum economic service-life of each individual structure.

In doing this, the following factors shall be considered:

- safety, local as well as global,
- current construction and repair technology,
- economic constraints,
- aesthetics,
- social and political aspects.

It shall be noted, that the road and bridge sector has been the forerunners with respect to combined Bridge Management and Maintenance Systems. Much value can be gained by profiting from experience from this field (6).

5. DESIGN OF NEW STRUCTURES

5.1 Codes and standards

Codes and standards constitute the legal technical basis for structural design and execution. They represent the requirements of society towards safety and serviceability in the complex task of creating structures. Thereby codes and standards constitute the most important structural design pre-requisites, and will remain to do so in a foreseeable future. Codes often incorporate centuries of invaluable national or regional experience. As such they may, however, at times be regarded as obstacles towards introducing new technologies.

Recent years' rapid technological development coinciding with the growing awareness to consider the long term durability of structures present a challenge to code writers. Future generations of codes shall focus on formulating basic principles of long term validity and allow freedom and openness in specifying means of fulfilling these principles. Only so can they be sufficiently flexible to profit from new technological achievements and accomodate new techniques without loosing the valuable parts of accumulated experience.

Concrete is - and will continue to be - our most important building material and ongoing international concrete code-writing activities will strongly influence the civil and structural engineering profession and may well set milestones for the code developments for other materials.

5.2 CEB-FIP Model Code 1990

CEB is, in cooperation with FIP, currently preparing a new Model Code for Concrete Structures for the 90'ies, MC 90. The Model Code attempts to incorporate service life design concepts in an operational code-like format penetrating all relevant aspects of safety and serviceability. By avoiding that service life aspects constitute a separate limit state, but are integrated into sections of Ultimate Limit State and Serviceability Limit States, a harmonic evolution of the Model Code is ensured. The Model Code is further supported by a separate Design Guide: "CEB -Guide to Durable Concrete Structures" (7).

MC 90 thus leads towards a new generation of structural Codes of Practice being prepared for concrete structures, but being conceptually adaptable to codes for other building materials. This represents the internationalization of design concepts which is leading to ongoing harmonization of codes and standards, e.g. as represented by the Eurocodes and Euronorms of the European Community and by the Comecon Codes of the CMEA countries in Eastern Europe.

This valuable achievement can be attributed mainly to the year-long international professional cooperation within private organizations like IABSE, FIP, RILEM and CEB.

5.2.1 Service Life Requirements in CEB-FIP Model Code 1990

The basic requirements in the Draft CEB-FIP Model Code 1990 currently under discussion are (8):

"Concrete structures shall be designed, constructed and operated in such a way that, under the expected environmental influences, they maintain their safety, serviceability and acceptable appearance during an explicit or implicit period of time without requiring unforeseen high costs for maintenance and repair".

In order to fulfil these requirements the Draft - Model Code focus on the whole building process. It is assumed that durability problems only can be avoided if adequate and coordinated efforts are imposed upon all persons involved and upon all phases in the process of defining, planning, building and using the structure until the end of its expected lifetime.

The whole process of creating structures and keeping them in satisfactory use and service requires cooperation between the following four parties:

- The owner, by defining his present and foreseen future demands and wishes.
- The designers (engineers and architects) by preparing design specifications (including quality control schemes) and conditions.
- The contractor who will try to follow these intentions in his construction works. Most commonly also subcontractors are involved.
- The user, who will normally be responsible for the maintenance of the structure during the period of use.

Any of these four parties may - by their actions or lack of actions -contribute to any unsatisfactory state of durability of the structure and thus cause a reduction of the service life. Also interactions between two parties may cause faults which can have an adverse effect on durability and service life.

5.2.2 Decisions on design life and exposure class

The selection of design life and of exposure class constitute the two most important decisions with respect to the resulting long term durability and appearance of the structure.

The required service life should be obtained without relying on special protections needing frequent maintenance or redoing. However, in cases of especially aggressive environments special protective measures may be foreseen.

5.2.3 Service Life Design Strategy

The design strategy should consider possible measures protecting the structure against premature deterioration. A set of appropriate measures (one or more) shall be combined to ensure that the required service life is obtained with a sufficiently high probability.

Protective measures may be established by, i.a.:

- the selected structural form,
- the concrete composition, including special additions or admixtures,
- the reinforcement detailing including cover,
- a special skin concrete quality, including skin reinforcement,
- limiting or avoiding crack development and crack widths by prestressing,
- additional protective measures such as tanking, membranes or coatings, including coating of reinforcement,
- specified inspection and maintenance procedures during in-service operation of the structure, including monitoring procedures,
- special active protective measures such as cathodic protection or warning systems.

A service life design may profit from a multitude of protective measures cooperating simultaneously to ensure the required service life with an acceptable level of reliability.

This design strategy is considered a Multistage Protection Strategy which leaves the selection of individual protective measures to the designer.

6. RESEARCH, DEVELOPMENT AND EDUCATION

The durability problems facing the structural engineer has lead to a dilemma in the research community.

It is a well established procedure in research, that complicated problems are split into more easily defined part-problems. These part-problems are then solved one by one, and the results combined to constitute the answers to the initial and more complicated problems.

However, the durability problems - especially in the field of concrete structures - have proven to be so interdependent that splitting may result in misleading conclusions. The interdisciplinary problems relate partly to macro-level and partly to micro-level problems including physical, chemical, electro-chemical and even biological processes, which complicate the problem solving process even further.

In this connection it should be recalled, that the durability problems in so-called more advanced technologies like the aircraft, space and nuclear industries are faced with only one major problem of durability, being the development and growth of cracks (3). In this way the assessment and maintenance activities are reduces to - crudely speaking - a simple analysis, track recording, and management of crack propagation.

The complexity of the durability problems are in reality shaking the established scientific schooling, and a new multidisciplinary approach must evolve from the turmoil.

Part of the problems may also be related back to our basic education in which two simplifications distort part of our spontaneous understanding of the problems:

- we think in linear scales, both in geometric terms and in time,
- we think in deterministic events.

For reasons above, we are faced with a communication gap between engineers and everyday people not trained in a technical approach to problems.

The technical community should therefore concentrate more effort in presenting and explaining the problems of durability and service life considerations - and the uncertainties associated with our answers - to the users and owners of the structures, including lawyers, politicians and other decision makers. Education is needed on all levels!

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