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.
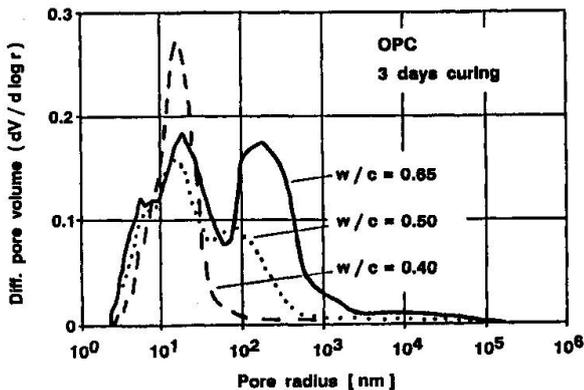
Fig. 1   Effect of water-cement ratio on pore size distribution of hydrated cement paste; ordinary portland cement (OPC); duration of curing: 3 days [3]
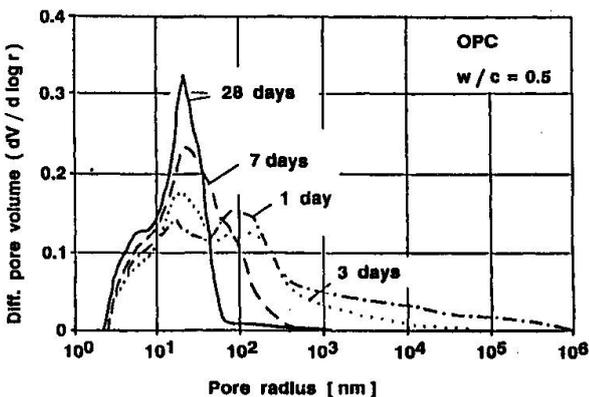
Fig. 2   Effect of duration of curing on pore size distribution of hydrated cement paste; ordinary portland cement OPC; water-cement-ratio = 0.50 [3]

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 detrimental 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]:

$$d_c = \sqrt{2 \, D_c \cdot \frac{C_a}{C_c} \cdot t}$$
(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 rela-
tionships 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 con-
crete against chemical attack. Deterioration may be accelerated by testing at
elevated temperatures. However, the temperature dependence of the various dete-
rioration 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 sub-
stantially 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:

$$Q = K_w \cdot \frac{h}{l} \cdot A \cdot t \tag{2}$$

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]:

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

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:

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

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:

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

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.
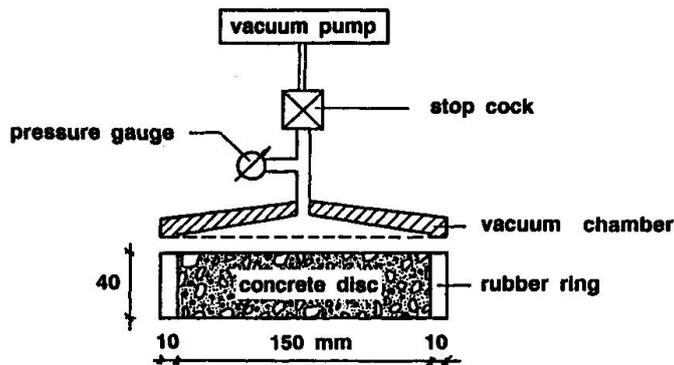
Fig. 3   Apparatus to deter-
         mine concrete air
         permeability [3]; [8]

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_0 is taken at the instant the pressure reaches a value of p_0 = 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.

$$K_{AC} = \frac{(p_1 - p_0) \cdot V_s}{(t_1 - t_0)\,(p_a - \frac{p_1 + p_0}{2})} \cdot \frac{1}{A}$$

(6)

where K_{AC} = characteristic air permeability [m^2/sec]
        p_1, p_0 = pressure inside the suction device at the
                 end and at the beginning of the experiment, respectively
        $t_1 - t_0$ = duration of experiment
        V_s = Volume of interior of suction device
        p_a = atmospheric pressure
        1 = 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 re-
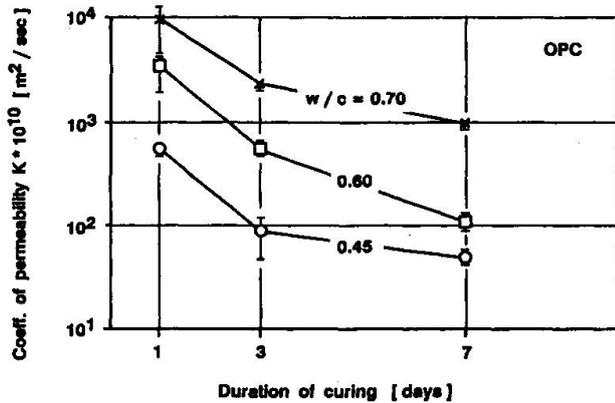duction of K_{AC} by more than one order of magnitude.

Fig. 4 Effect of duration of
curing and water-cement
ratio on air permeabil-
ity of concrete; ordi-
nary 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 ce-
ments 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, re-
spectively, were made of the following types of cement: ordinary portland ce-
ment (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, re-
spectively. 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$_c$ 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} in-
creased with increasing FA content.

Eq. 1 in chapter 4 describes the progress of carbonation with time as a func-
tion 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

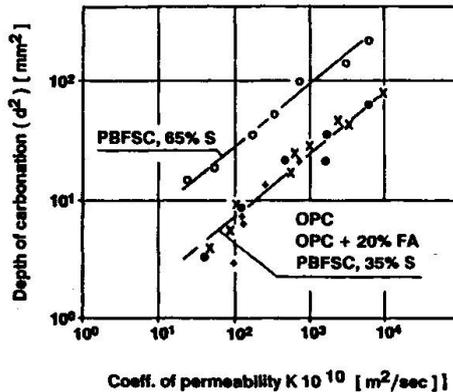Coeff. of permeability K 10 ^{10} [m²/sec]]

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:

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

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

The most significant conclusion to be drawn from these experiments is the ob-

servation 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.
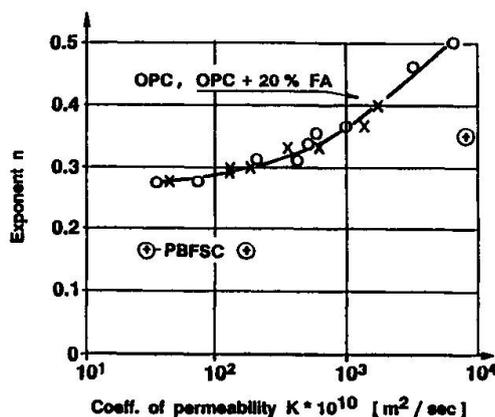

Fig. 6   Air permeability of concrete and rate of water absorption [3]

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.

10. REFERENCES

1.   NÄGELE E., HILSDORF H.K., Die Frischbetonanalyse auf der Baustelle. Beton, Heft 4, 1980.

2.   BIER Th.A., Karbonatisierung und Realkalisierung von Zementstein und Beton.
     Schriftenreihe des Instituts für Massivbau und Baustofftechnologie, Univer-
     sität Karlsruhe, Heft 4, 1988.

3.   SCHÖNLIN K., Permeabilität als Kennwert der Dauerhaftigkeit von Beton.
     Schriftenreihe des Instituts für Massivbau und Baustofftechnologie, Uni-
     versität Karlsruhe, Heft 8, 1989.

4.   KROPP J., Karbonatisierung und Transportvorgänge in Zementstein. Disserta-
     tion, Universität Karlsruhe, 1983.

5.   P. JUNGWIRTH, W. BEYER, P. GRÜBL, Dauerhafte Betonbauwerke, Substanzerhal-
     tung und Schadensvermeidung in Forschung und Praxis. Beton-Verlag, Düssel-
     dorf, 1986, pp. 167.

6.   FAGERLUND G., The critical degree of saturation method of assessing the
     freeze-thaw resistance of concrete. Prepared on behalf of RILEM Committee
     4DC, Matériaux et Constructions, Vol. 10, 1977, pp. 217.

7.   FAGERLUND G., The international cooperative test of the critical degree of
     saturation method of assessing the freeze-thaw resistance of concrete.
     Matériaux et Constructions, Vol. 10, 1977, pp. 231.

8.   K. SCHÖNLIN, H.K. HILSDORF, The potential durability of concrete.
     IV European Ready Mixed Concrete Organisation Congress, Stavanger 1989.

9.   K. SCHÖNLIN, H.K. HILSDORF, Evaluation of the effectiveness of curing of
     concrete structures. Concrete Durability, Katharine and Bryant Mather In-
     ternational Conference, American Concrete Institute SP-100, 1987, pp. 207.

10. LAWRENCE C.D., Transport of oxygene through concrete. The British Ceramic
     Society Meeting - Chemistry and chemically related properties of cement.
     Imperial College, London, 1984.

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