ON THE CAPILLARITY OF CONCRETE

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The kinetics of water absorption in concrete can be described approximately by three coefficients, m, k and ε_e. In the article a simple method for determination of those coefficients is suggested. Experimental results indicate relatively well-defined relations between the capillary porosity and the coefficients m and k. Thus, all capillary constants can be evaluated theoretically once the cement content, the w/c-ratio and the degree of hydration are known. The effect of the initial moisture condition of the concrete can also be evaluated theoretically. Experiments confirm that the air-voids in concrete have very little effect on the absorption process.
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1.   ELEMENTARY THEORETICAL BACKGROUND

Consider an unsaturated, porous specimen sucking water from a free water surface, either vertically or horizontally, FIG 1. The effect of gravitation and hydraulic head are omitted. The specimen is supposed to have been in moisture equilibrium before the suction started.

The relation between the depth of penetration z (m) and time t (s) counted from the start of suction is approximately

$$t = m \cdot z^2 \tag{1}$$

where m is the "resistance to water penetration" (s/m^2). Thus, the rate of the penetration of the water-front is successively reduced. Eq (1) is somewhat simplified since no consideration is taken to phenomena such as adsorption and capillary condensation ahead the water front or drag forces caused by the displaced air. The equation is a good approximation, however, as long as the specimen is not too thick ($\le$ 50 mm for concrete) and not too moist when the suction starts.

The value of m is only a function of the pore structure but not of the total porosity; the smaller the pores, the slower the water penetration and hence the larger the value of m. Theoretically, m should also be, to some extent, affected by the initial moisture content.
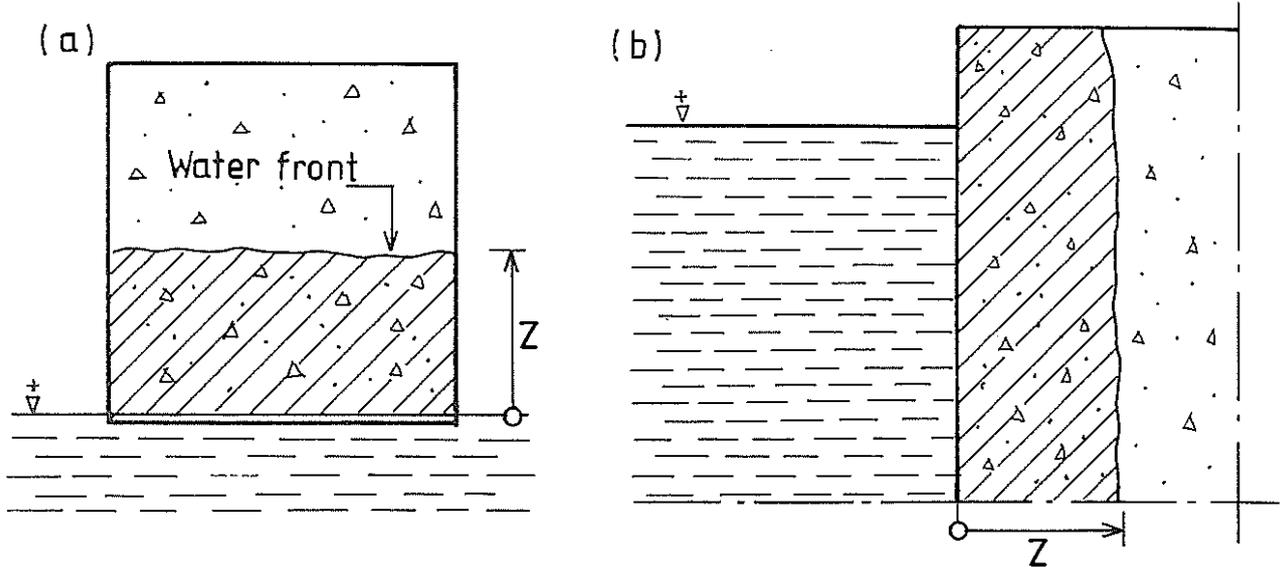
FIG 1. Capillary suction.
(a) Vertically (b) Horizontally

The total amount of water that is taken up per unit suction surface after time t is

$$W_a = 1000 \cdot \varepsilon_e \cdot z \quad (kg/m^2) \qquad (2)$$

where 1000 is the density of water (kg/m^2) and ε_e is the porosity that is available for water filling - "the effective porosity" (m^3/m^3). Combination of eq (1) and (2) yields

$$W = \frac{1000 \cdot \varepsilon_e}{\sqrt{m}} \cdot \sqrt{t} \qquad (3)$$

or

$$W_a = k \cdot \sqrt{t} \qquad (4)$$

where k is the <u>coefficient of capillary absorption</u> $(kg/m^2 \cdot s^{\frac{1}{2}})$.

The effective porosity ε_e is

$$\varepsilon_e = \varepsilon - \varepsilon_w - \varepsilon_i \qquad (5)$$

where ε is the total porosity and ε_w is the porosity that was water-filled already when the suction started. ε_i is the "inert porosity", i.e. the amount of pores that cannot be water-filled by capillary suction. For a concrete with non-porous aggregate ε_i is approximately equal to the total "air content"; see below.

k can now be written

$$k = \frac{1000 \cdot \varepsilon_e}{\sqrt{m}} = \frac{1000(\varepsilon - \varepsilon_w - \varepsilon_i)}{\sqrt{m}} \qquad (6)$$

The value of k is therefore a function of the total porosity, of the moisture state before suction started and of the pore structure, the influence of which is expressed in terms of the coefficients ε_i and m.

The rate of water absorption q_a (kg/m^2 · s) is obtained by derivation of eq (4).

$$q_a = \frac{k}{2} \cdot \frac{1}{\sqrt{t}} \qquad (7)$$

The whole capillary absorption process can thus be approximately described by the three coefficients m, k and ε_e.

2.   TEST METHOD FOR CAPILLARITY

A thin concrete or cement paste slice (20-30 mm) is conditioned to moisture equilibrium. The normal conditioning climate should be 50% RH free of CO_2 but other climates are of course also possible. The suction surface should normally be sawn and be free from carbonation and other "contaminations".

The slice is placed with one flat surface touching a free water surface, or placed on a "coarse-porous" sponge that is kept saturated. The vessel with water and specimen(s) is covered by a (transparent) impermeable lid so that evaporation from the specimen is hindered.

The slice is weighed at suitable intervals; e.g. 1/12; 1/6; 1/4; 1/2; 1; 2; 3; 4; 6; 24; 48; 72; 96 etc hours counted from the start of the test. The suction surface is wiped with a moist sponge before weighing.

A curve according to FIG 2 is obtained if the time axis is in square root scale. The nick-point between stages 1 and 2 corresponds to the point when the advancing water front has just reached the upper surface of the specimen. Thus, stage 1 corresponds to the water-filling of all initially empty gel and capillary pores while stage 2 corresponds to the gradual filling of the inert pores or air-voids by an air-dissolution-diffusion process /1/. Only the first stage is considered here. The second stage is of great interest in conjunction with frost resistance /1/.

Theoretically, if the specimen acted as a single capillary the change-over from stage 1 to stage 2 should be abrupt, but in reality there is often a "rounded" transition from the steep line during stage 1 to the levelled line during stage 2, se FIG 2. The reason for this is that the material has a certain pore size distribution leading to different rates of penetration along
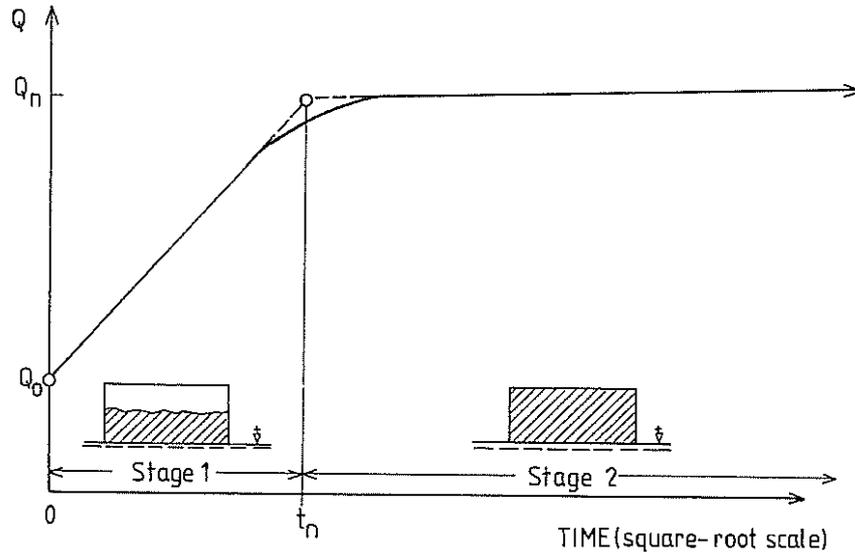
FIG 2. A typical water absorption curve obtained in a capillarity test.

different "paths". This effect is, however, not as great as could be expected due to bifurcations between individual paths.

The nick-point is defined as the intersection of the two extrapolated lines.

The coefficients m and k and the effective porosity ε_e can now be easily calculated from the "nick-point absorption", $Q_n - Q_o$ (kg), and the "nick-point time", t_n (s); c.f. eq (1) and (4).

$$m = \frac{t_n}{h^2} \tag{8}$$

$$k = \frac{Q_n - Q_o}{\sqrt{t_n}} \cdot \frac{1}{A} \tag{9}$$

where Q_n is the specimens weight at the nick-point and Q_o is the initial weight. h and A are the specimen thickness (m) and the suction area (m^2) respectively.

The effective porosity ε_e is

$$\varepsilon_e = \frac{Q_n - Q_o}{A \cdot h \cdot 1000} \tag{10}$$

3.   SOME EXPERIMENTAL RESULTS - EFFECT OF CEMENT CONTENT,
        W/C-RATIO AND MATURITY

A limited study comprising 9 cement mortars with 3 w/c-ratios
(0.42, 0.64, 0.70), each of which with three different air
contents, has been carried out with the method described above.
The test was done at four different mortar ages; 5, 12, 26 and 89
days.

The specimens had a suction area of 4 x 16 cm^2 and a thickness of
about 1.8 cm. They were made by cutting a normal cement mortar
prism 4 x 4 x 16 cm^2 into two halves. The specimens were stored
in water until the ages stated above when they were transferred
to a room kept at about 50% RH. Thus, a certain but small hydra-
tion could take place even after the specimens were taken out of
water. The real degree of hydration at the time of test is,
however, known. It was determined on accompanying specimens
stored in exactly the same manner as the suction specimens. The
degree of hydration was measured in the conventional way by
igniting specimens at $+1000^{\circ}C$ after an initial drying to equi-
librium at $+105^{\circ}C$ /2/. Corrections were made for the loss on
ignition of the aggregate and of the unhydrated cement. The
amount of chemically bound water at full hydration ($\alpha = 1$) is
supposed to be 25% of the cement weight.

The capillary porosity $\varepsilon_{c,p}$ of the cement paste phase was then
calculated by the following formula /3/.

$$\varepsilon_{c,p} = \frac{w/c - 0.39\alpha}{0.32 + w/c} \quad (m^3/m^3)$$ (11)

where w/c is the water/cement ratio and α is the degree of
hydration.

Values of the coefficient m_{50} valid for a pre-conditioning at 50%
RH were calculated by eq (8) and are plotted versus $\varepsilon_{c,p}$ in FIG
3. There is a relatively well-defined linear relationship.

$$m_{50} = 11(1 - 2 \cdot \varepsilon_{c,p}) \cdot 10^7 \quad (s/m^2)$$ (12)

Thus, for mature pastes with 80% degree of hydration it is valid

$$m'_{50} = 11(1 - 2 \cdot \frac{w/c - 0.31}{0.32 + w/c}) \cdot 10^7$$ (12')

An extrapolation of eq (12') gives $m'_{50} = 0$ for w/c = 0.94. This
is of course not correct which indicates that the relation m -
$\varepsilon_{c,p}$ is non-linear for high values of $\varepsilon_{c,p}$.

It is very interesting to note that the air pores have no sub-
stantial effect on the absorption process. Thus they are true
inert pores; other examples of the good agreement between the
air-void volume and the inert porosity is seen below; FIG 9.

The initial moisture state corresponded to a state where all
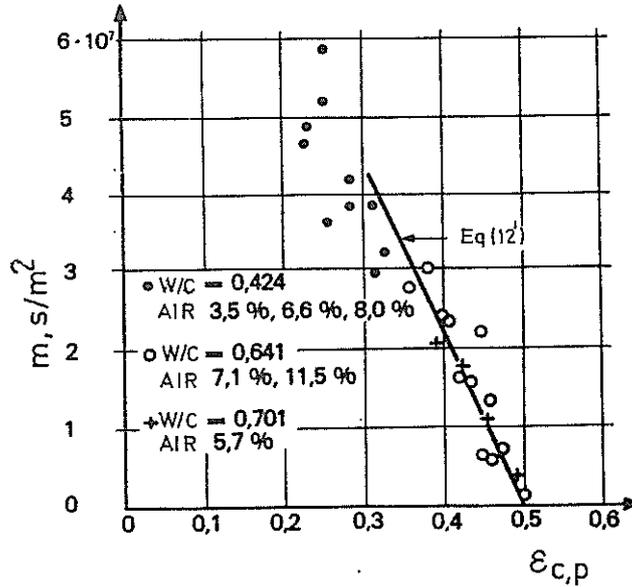capillary pores were air-filled while the largest portion of the

FIG 3. The resistance to water absorption versus the capillary porosity of the cement paste phase, eq (12).

gel pores was water-filled. Therefore it was mainly the capillary pores that became water-filled during the test.

The coefficient of capillary absorption $k_{c,p}$ of a cement paste conditioned to a state where only the gel pores are water-filled is according to eq (6) and (12).

$$k_{c,p} = \frac{1000 \cdot \varepsilon_{c,p}}{\{11(1-2\cdot\varepsilon_{c,p})\cdot 10^7\}^{\frac{1}{2}}} = \frac{\varepsilon_{c,p}}{10.5(1-2\cdot\varepsilon_{c,p})^{\frac{1}{2}}} \quad (13)$$

This equation is plotted in FIG 4.

The relation $k_{c,p} - \varepsilon_{c,p}$ can be expressed

$$k_{c,p} = 0.34 \cdot \varepsilon_{c,p}^{1.5} \quad (14)$$

The capillary porosity of a concrete $\varepsilon_{c,c}$ can be expressed

$$\varepsilon_{c,c} = \frac{C}{1000} (w/c - 0.39\alpha) \quad (15)$$

where C is the cement content in kg/m^3.

Thus, the coefficient of capillary absorption $k_{c,c}$ of a concrete pre-conditioned to a state where only the gel pores are water-filled is

$$k_{c,c} = \frac{1000 \cdot \varepsilon_{c,c}}{\sqrt{m}} = C \cdot \frac{w/c - 0.39\alpha}{\sqrt{m}} \quad (16)$$
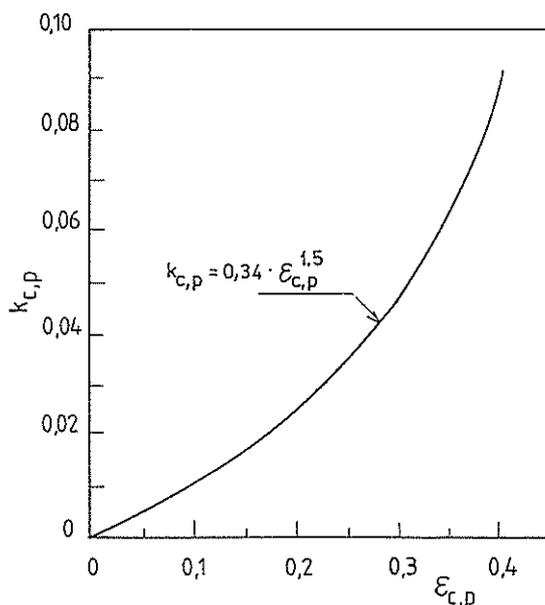
FIG 4. The coefficient of capillary absorption of
cement paste pre-dried to a state where only the
gel pores are water-filled, versus the capillary
porosity.

where m is given by eq (12). (m is the same for cement pastes,
cement mortars and concretes under the condition that the cement
paste properties are the same and the aggregate is non-porous.)

For 80% hydration it is valid

$$k_{c,c} = C \; \frac{w/c - 0.31}{\sqrt{m'}} \tag{16'}$$

where m' is given by eq (12').

4.   ESTIMATED EFFECT OF THE INITIAL MOISTURE CONTENT

4.1   The coefficient m is supposed to be constant

The value of m is as a first approximation supposed to be un-
affected by the initial moisture state. This is not an altogether
unreasonable assumption since the rate of capillary rise is to a
great extent determined by the coarsest portion of the pore
system which becomes water-filled only at very high relative
humidities. Then eq (12) and (12') should be valid for all
initial moisture states.

The effective porosity is

$$\varepsilon_{e,c} = C(w/c - 0.19a) - \varepsilon_{w,c} \tag{17}$$

where the first term is the total porosity exclusive of air
pores. $\varepsilon_{w,c}$ is a function of the conditioning climate and can be
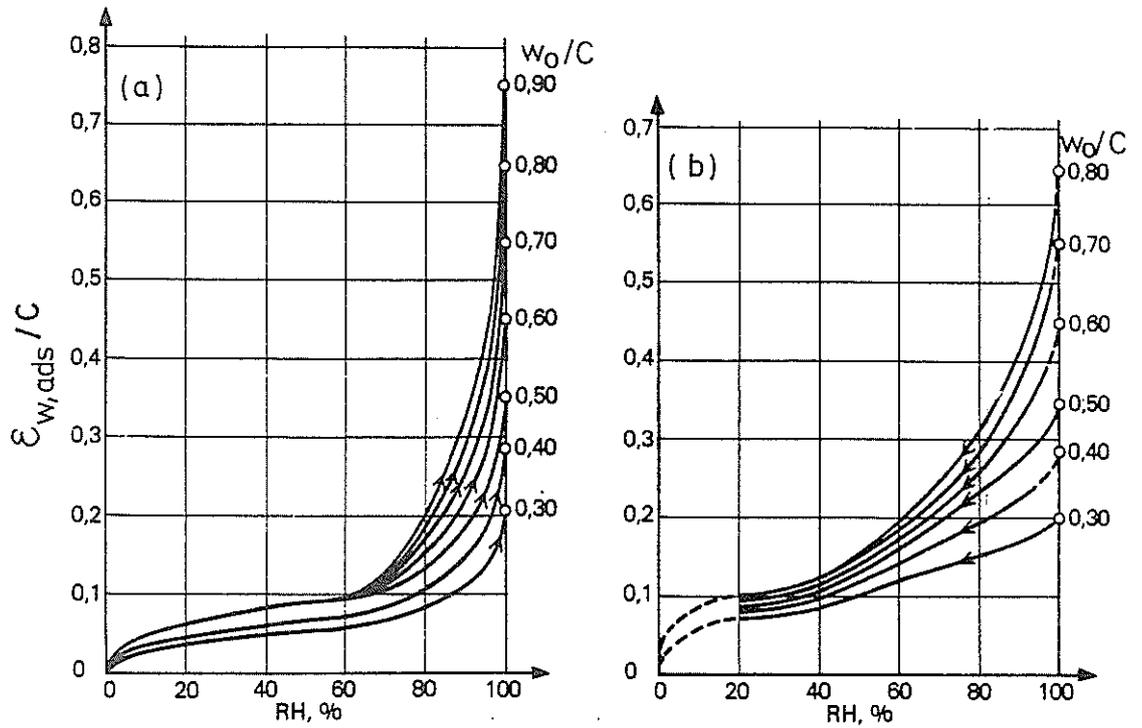
FIG 5. Sorption isotherms for mature cement
pastes.
(a) adsorption isotherms /7/
(b) desorption isotherms /8/

estimated on basis of the sorption isotherms of cement paste.
Isotherms for well-cured pastes are shown in FIG 5.

For well-cured concretes <u>pre-dried</u> to 90% RH the following
relation is valid, FIG 5a.

$$\varepsilon_{w,des90,c} \cong 0.52 \cdot w/c \cdot C \tag{18}$$

For the same concrete <u>pre-moistened</u> to 90% RH it is instead
valid, FIG 5b.

$$\varepsilon_{w,ads90,c} \cong 0.39 \, w/c \cdot C \tag{19}$$

Similar relations can be derived for other RH's and other degrees
of hydration /7, 8/.

Then, the coefficients of capillary absorption are

$$k'_{des90,c} \cong C \cdot \frac{0.48w/c - 0.15}{\sqrt{m'}} \tag{20}$$

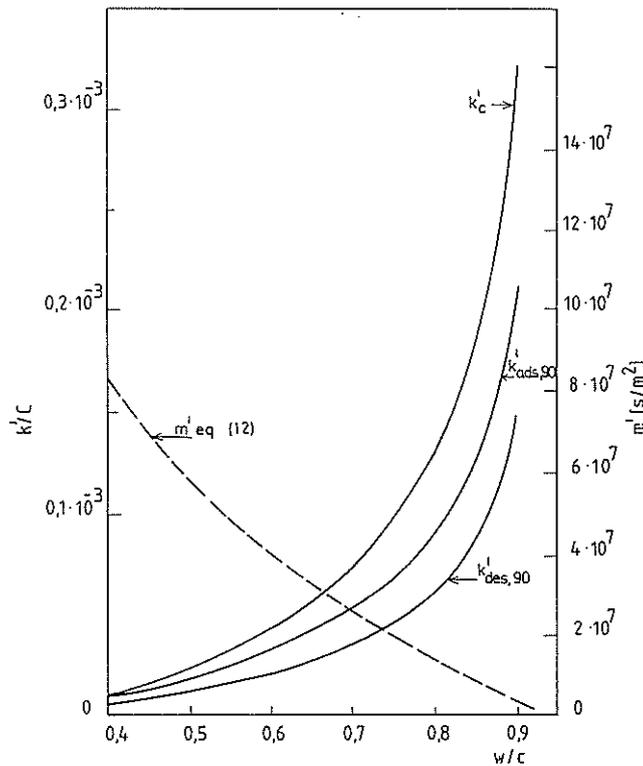$$k'_{ads90,c} \cong C \cdot \frac{0.61w/c - 0.15}{\sqrt{m'}} \tag{21}$$

FIG 6. Relations between the w/c-ratio and the coefficient of capillary absorption for different pre-conditioning climates (α = 80%). The coefficient m is supposed to be unaffected by the initial moisture condition.

where m' is calculated by eq (12').

The relations (16'), (20) and (21) are plotted in FIG 6.

It is interesting to note that the coefficient of absorption k is even more sensitive to changes in the w/c-ratio than is the resistance to water penetration m. This effect is partly eliminated in the real case since the cement content of concrete goes up with decreasing w/c-ratio. For concretes therefore the following relation is approximately valid for all initial moisture contents.

$$k' \cong A \cdot (\frac{w}{c})^2 \qquad (22)$$

where A is a constant that depends on the initial moisture content when suction starts. This equation is derived directly from the curves in FIG 6 assuming a normal relationship between w/c-ratio and cement content.

The rate of water absorption is, therefore, approximately proportional to the square of the w/c-ratio as are so many other types of flow processes in concrete.

4.2 The coefficient m is supposed to be a function of the initial moisture content

As a second approximation m is supposed to be inversely proportional to the effective porosity. Hence

$$m = \frac{B}{\varepsilon_e} \tag{23}$$

For $\varepsilon_e = 0$ there will be an infinitely slow capillary rise.

The constant B can be evaluated by inserting m_{50} from eq (12) and $\varepsilon_{c,p}$ from eq (11) in the equation. This is not altogether correct since $\varepsilon_{c,p}$ is a bit smaller than $\varepsilon_{50,p}$ corresponding to 50% RH (see below).

Eq (23) will then be

$$m = \frac{11 \cdot 10^7 (1 - 2 \cdot \varepsilon_{c,p}) \cdot \varepsilon_{c,p}}{\varepsilon_e} \tag{24}$$

This expression should be inserted in the equations of type (20) and (21) at which $\varepsilon_{c,p}$ is given by eq (11) for $\alpha = 0.80$ and ε_e is given by eq (17).
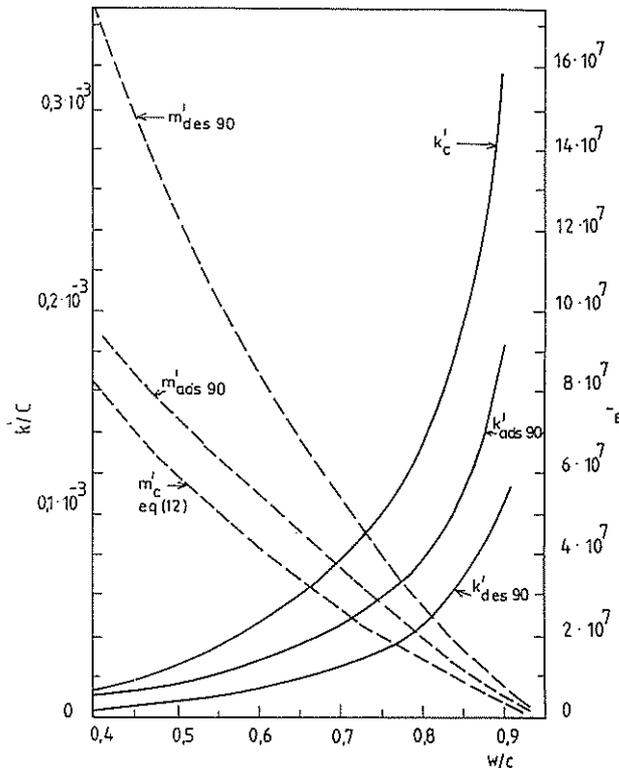

FIG 7. Relation between the w/c-ratio and the coefficient of capillary absorption for different pre-conditioning climates ($\alpha = 80\%$).
The coefficient m is supposed to be inversely proportional to the effective porosity.

The new relations m', $k'_{des90,c}$ and $k'_{ads90,c}$ are plotted in FIG 7. The effect on k and thus on the rate of water absorption of a variable value of m is not dramatically large. The value of m itself is, however, very much influenced by the initial moisture condition.

5.   EFFECT OF THE CEMENT TYPE

A study of the potential frost resistance of slag cement concrete has been performed /4/. This included a study of the water absorption properties using the method described above.

The air content varied between 2% and 8%. The w/c-ratio was the same in all concretes. The concretes had a hydration corresponding to 91 days of wet curing when the test started. The specimens were pre-dried at +50°C during 1 week before the test.

Some results are shown in FIG 8.

The resistance to water penetration increases with the slag content indicating that the concrete becomes more impervious.

The effective porosity is about the same in all concretes. Therefore, the coefficient of capillarity goes down with increasing slag content.
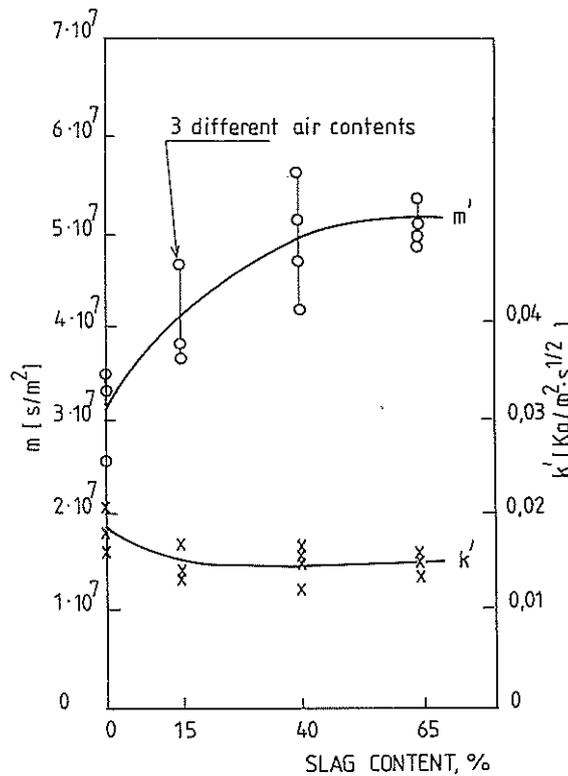

FIG 8. The effect of the slag content of the cement on the capillary properties of concrete.

6. THE INERT POROSITY AND ITS EFFECTS

Water that is sucked into a porous solid will entrap air in such cavities that are completely surrounded by a more fine-porous substance that provides bifurcations or channels that link opposite parts of the cavity. The process is described in /5/. If the entrapped bubble is small enough it will collapse almost immediately due to the over-pressure created by the enclosing water menisci. If the bubble is big ($\geq$ 1 µm), however, it will stay air-filled for quite a long time until all its air has been dissolved in the pore water. Thus, such big pores do not take part in the capillary absorption process; they are inert.

For concrete the inert porosity corresponds to the so called air pore volume. Such pores are isolated and they are larger than 5 to 10 µm and will therefore stay air-filled in the absorption process /1/.

The good agreement between the inert porosity and the air pore volume is seen in FIG 9 showing results from the tests of slag cements (FIG 8). ε_a is the air porosity of the hardened concrete; ε_i is the air-filled or inert porosity when the nick-point is reached during the water absorption test, i.e. when all pores except the inert ones have become water-filled; FIG 2. The agreement between ε_a and ε_i is almost perfect.

One cannot exclude, however, that the inert pores have a certain effect on the absorption process. They might, for instance,
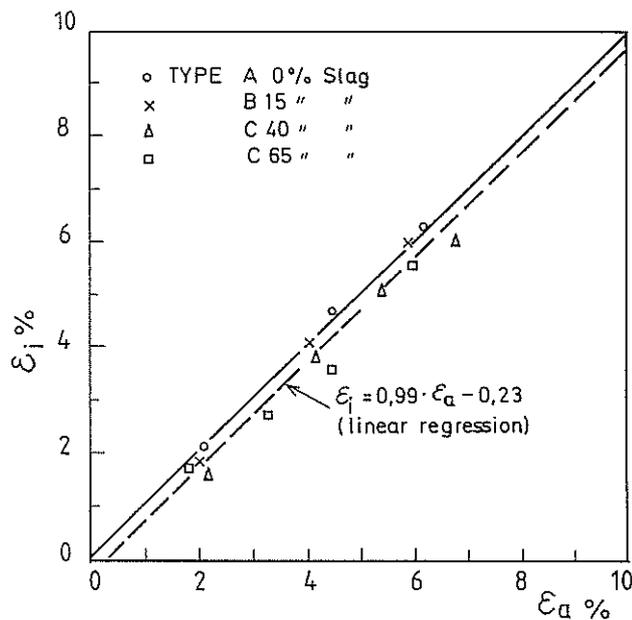

FIG 9. Relation between the air content of the hardened concrete ε_a and the observed inert porosity at the nick-point absorption ε_i. (The same concrete as in FIG 8.)

increase the "tortuosity"; i.e. increase the effective migration length of the water front that is penetrating the specimen. Eq (1) should then be written

$$t = m_o \cdot (\beta \cdot Z)^2 = m \cdot Z^2 \qquad (1')$$

where m_o is a fictive value valid for a case where there is no tortuosity and β is the tortuosity factor expressing the ratio between the real migration length of the water front and the vertical distance between the water front and the free water surface.

The coefficient m should then, theoretically, be a function of the amount of inert pores since the factor β should increase with increasing inert porosity forcing the water front to constantly change its direction.

$$m = m_o \cdot f(\varepsilon_i) \qquad (25)$$

The results in FIG 3 indicate no significant effect of the inert pores. Results from the slag cement tests are plotted in FIG 10. One can distinguish a tendency towards higher values of m' with increasing air porosity, especially when this becomes high. The results are, however, very limited and do not allow any more general conclusions as regards the effect of inert pores on the kinetics of the water absorption process.
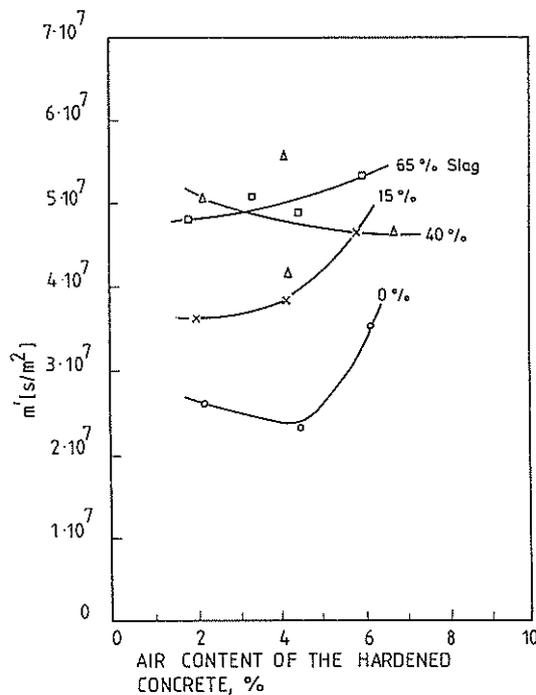

FIG 10. Relation between the coefficient m' and the air content of the hardened concrete. (The same concretes as in FIG 8.)

7.   COMPARISON WITH THE POWERS AND BROWNYARD EXPERIMENTS /6/

Powers and Brownyard /6/ made a limited study of the capillarity of four cement mortars with the w/c-ratios 0.33 and 0.45.

They defined a "coefficient of absorptivity" K_a according to

$$\frac{q}{A} = \sqrt{K_a \cdot t} \tag{26}$$

where q is the water absorption in cm^3, A is the suction area in cm^2 and t is in seconds. Thus, K_a differs from the coefficient of water absorption k defined by eq (4). The relation between these two coefficients are

$$k = 10\sqrt{K_a} \tag{27}$$

The specimens were stored at 50% RH for 6 to 7 months before the test. The authors found that the plot q/A versus $t^{\frac{1}{2}}$ was completely linear during the first hour. Thus, stage 1 in FIG 2 was observed and it was used for evaluating the value of k_{50} which is the coefficient of capillarity that is evidently valid for the well-cured specimens pre-conditioned at 50% RH.

The results are plotted in FIG 11a versus the capillary porosity of the cement paste phase; eq (11). Before plotting, the measured k-values have been adjusted to be valid for the cement paste phase (the aggregate was non-porous) by applying the following equation.

$$k_{50,p} = \frac{k_{50,m}}{V_p} \tag{28}$$

where $k_{50,p}$ and $k_{50,m}$ are valid for cement paste and cement mortar respectively and V_p is the fractional volume of cement paste.

The following relation between k' and the capillary porosity is valid; see FIG 11a.

$$k'_{50,p} = 0.006 + 0.28 \cdot \varepsilon_{c,p}^{1.40} \tag{29}$$

This equation is very similar to eq (14) that was derived on basis of my own experiments. The equation and the figure, however, indicate a small absorptivity even when $\varepsilon_{c,p} = 0$. The reason for this is that a larger pore volume than the capillary pore volume defined by eq (11) was empty when the suction test started. Those pores became water-filled in the test and did therefore contribute to the k_p-value. It can be shown /7/ that 50% RH corresponds to a water-filled porosity of about (see FIG 5a):

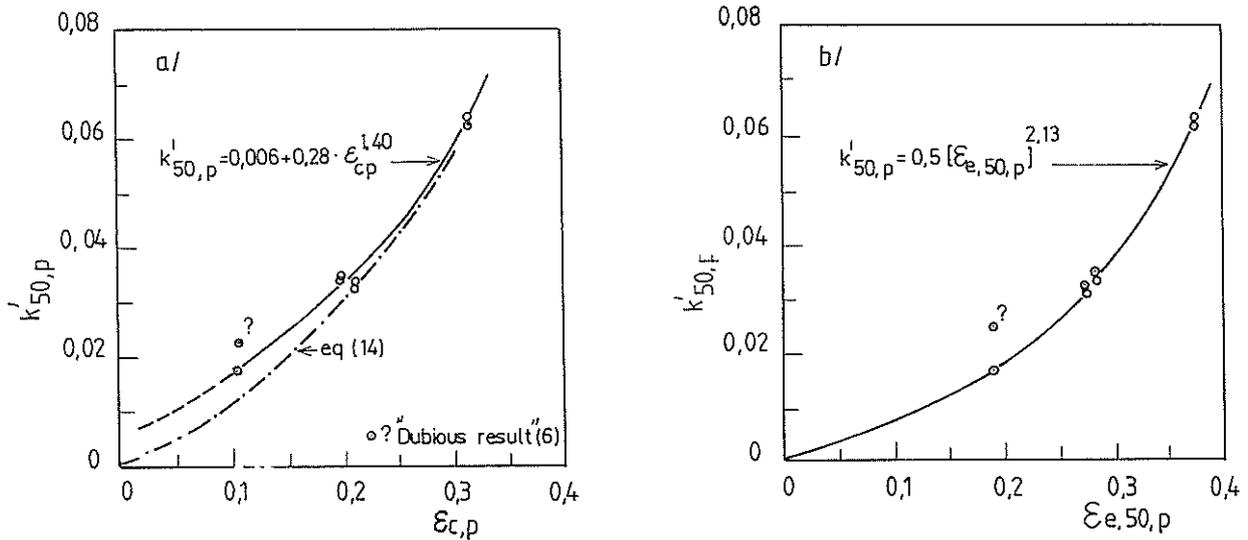$$\varepsilon_{w,50,p} = \frac{0.117\alpha}{0.32 + w/c} \tag{30}$$

FIG 11. Powers' and Brownyard's /6/ experiments.
The coefficient of capillarity of the hardened
paste conditioned to 50% RH as function of the
cement paste porosity defined in two different
ways.

Thus, according to eq (17), the effective porosity in the <u>paste</u>
when the test started was

$$\varepsilon_{e,50,p} = \frac{w/c - 0.31\alpha}{0.32 + w/c} \tag{31}$$

In FIG 11b the measured k_p-values have been plotted versus
$\varepsilon_{e,50,p}$. The following curve describes the results very well.

$$k'_{50,p} = 0.5 \cdot (\varepsilon_{e,50,p})^{2.13} \tag{32}$$

Hence, the rate of water absorption is approximately proportional
to the square of that porosity that is available to water absorp-
tion, c.f. eq (22).

Unfortunately the authors did not measure the rate of capillary
rise. The coefficient m can, however, be calculated by the
following equation that is derived from eq (6).

$$m' = (\frac{1000 \cdot \varepsilon_{e,50,p}}{k'_{50,p}})^2 \tag{33}$$

m'-values calculated by eq (33) are plotted versus the capillary
porosity in FIG 12. The results fall on one relatively well-
defined curve. The equation (12) comprising my own results -
section 3.1 - is also shown and is in good agreement with the
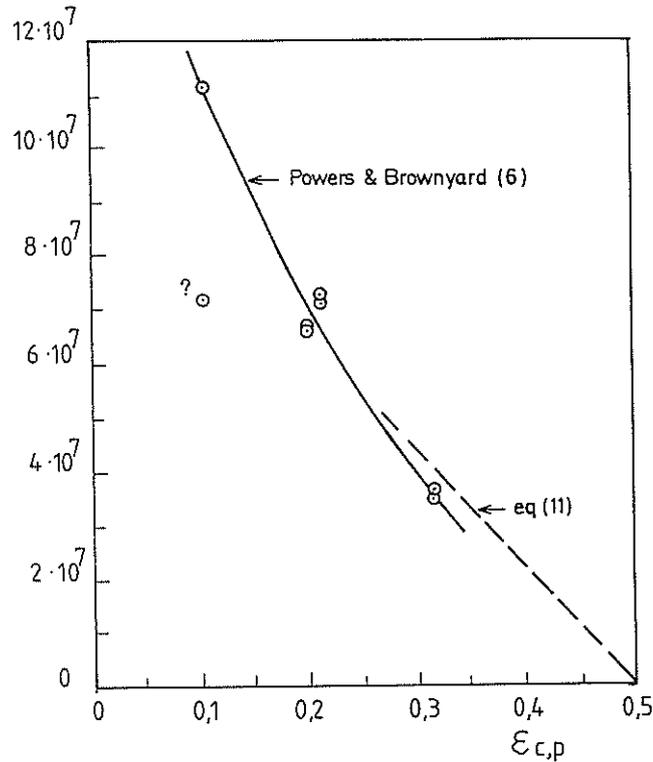results of Powers and Brownyard.

FIG 12. Experimental relation between the resis-
tance to water penetration, m, and the capillary
porosity of the cement paste.

8.   INTERRELATION BETWEEN THE CAPILLARITY AND THE WATER
            VAPOUR DIFFUSIVITY

The water vapour transfer – or moisture transfer – through
concrete can always be described by

$$q = -K \cdot \frac{dp}{dx} \qquad (34)$$

where q is the moisture flux in $kg/m^2 \cdot s$, dp/dx is the water
vapour pressure gradient in Pa/m and K is a coefficient of
moisture diffusivity having the dimension $kg/m \cdot Pa \cdot s$. K will
not be a constant, however, but will increase considerably with
increasing RH. Thus, in order to use eq (34) one must consider
this variation in K which must, therefore, be determined experi-
mentally for many values of RH. In the low and medium high range
of RH the simple wet-cup method could be used /8/. This method
is, however, unsuitable for the very high RH range (< 95%) due to
the great problems of maintaining for long time the high tempe-
rature constancy that is required in order to avoid condensation
in the specimen.

An attempt will be made to theoretically calculate the moisture
diffusivity K at RH ≅ 100% on basis of capillarity data. It is
supposed that capillary suction is a diffusion process.

The moisture flow at capillary suction can be described by eq (7). It can also be expressed as a diffusion process as in eq (34).

$$q = -K_{100} \cdot \frac{dp}{dz} \tag{35}$$

where K_{100} is the moisture diffusivity at 100% RH and dp/dz (Pa/m) is a linear vapour pressure gradient which is, in the actual case, the difference between the vapour pressure over a flat water surface and the vapour pressure over the water menisci at the water surface.

Thus, it is valid

$$\frac{dp}{dz} = -\frac{A}{Z} \tag{36}$$

where z is the capillary rise at time t and A is a constant that expresses the "suction force" at capillary suction; i.e. A is a measure of the mean curvature of the water menisci at the water front. Kelvin's law gives

$$A = p_o \{1 - \exp(-\frac{\sigma M}{\rho RT} \cdot \frac{2}{r})\} \tag{37}$$

where p_o is the saturation vapour pressure (2338Pa at $+20^{\circ}$C), σ is the surface tension between water and air (0.0756 N/m), M is the molecular weight of water (18 kg/kmole), ρ is the density of water (1000 kg/m^3), R is the gas constant (8314 J/degree $\cdot$ kmole), T is the absolute temperature and r is the mean radius of curvature of the menisci.

Combination of eq (7), (35) and (36) gives

$$K_{100} = \frac{k}{2} \cdot \frac{1}{t^{\frac{1}{2}}} \cdot \frac{z}{A} \tag{38}$$

The resistance to water penetration m is defined by eq (1) which inserted in eq (38) gives

$$K_{100} = \frac{k}{2} \cdot \frac{1}{m^{\frac{1}{2}}} \cdot \frac{1}{A} \tag{39}$$

In order to obtain a value for the "suction" A it is supposed that the mean radius of curvature of the menisci is 0.05 μm and that the suction experiment was done at $+20^{\circ}$C.

Then, it is valid

$$A = 51.7 \text{ Pa}$$

Insertion into eq (39) yields

$$K_{100} = \frac{k}{2} \cdot \frac{1}{m^{\frac{1}{2}}} \cdot \frac{1}{51.7} \tag{40}$$

Thus, the diffusivity at RH = 100% could be expressed in terms of the two "capillary coefficients" k and m.

Theoretically K_{100} should be valid for RH = 100% on one side and RH = 98% on the other side of the specimen since the meniscus radius 0.05 µm corresponds to 98% RH.

Above - eq (12), (13) - it was shown that for cement pastes conditioned to a state where only the gel pores are water-filled the following relations are approximately valid.

$$k_c = \frac{1000 \cdot \varepsilon_{c,p}}{m^{\frac{1}{2}}} \qquad (13')$$

$$m_c = (1 - 2 \cdot \varepsilon_{c,p}) \cdot 11 \cdot 10^7 \qquad (12')$$

where $\varepsilon_{c,p}$ is the capillary porosity of the cement paste defined by eq (11).

Thus, eq (40) is transformed to

$$K_{100} \cong \frac{1000 \cdot \varepsilon_{c,p}}{2} \cdot \frac{1}{(1-2 \cdot \varepsilon_{c,p}) \cdot 11 \cdot 10^7} \cdot \frac{1}{51.7} \qquad (41)$$

This equation is plotted in FIG 13. It gives very high diffusivities. It must, however, be remembered that there are very few
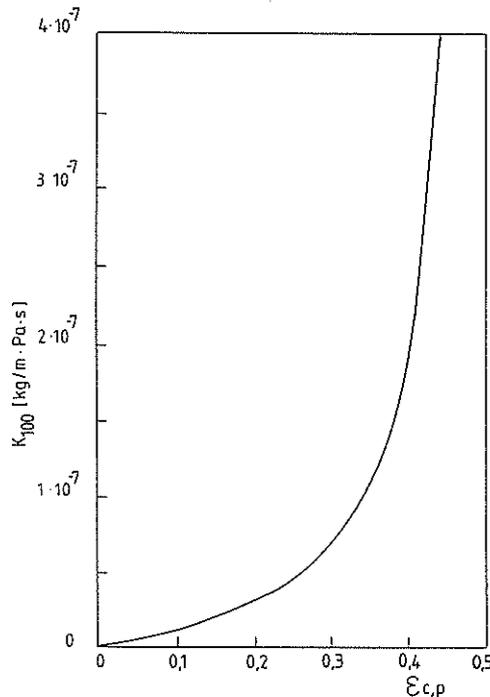
FIG 13. The moisture diffusivity at 98-100% RH as function of the capillary porosity of the cement paste; eq (41).

occations when diffusion at such high values of RH as 99-100% is
of importance. Already after a very short period of diffusion the
material is either completely saturated at which moisture flow
ceases completely due to lack of driving gradient or its RH falls
to values with more moderate diffusivities (but higher gra-
dients).

For calculations of the "micro"-redistribution of moisture in
very wet concrete due to short-term temperature gradients etc.
one must, however, use realistic diffusivities. Then the values
given by eq (40) or (41) might be applicable /9/.

9.   SUMMARY

Capillarity is described by three coefficients, the "resistance
to water penetration", m, the "coefficient of capillary absorp-
tion", k, and the "effective porosity", ε_e. Their interrelation
is given by eq (6). m depends on the pore structure while k and
ε_e depend also on the initial moisture state before water uptake
and on the porosity.

The paper describes a simple method for determination of those
coefficients; FIG 2, eq (8), (9).

The method has been applied to cement mortars and concretes. m
was found to be a simple function of the capillary porosity; eq
(12), FIG 3. It is, as a first approximation, supposed to be
unaffected by the initial moisture condition. k on the other hand
depends on this. Hence, in order to calculate k one must also
know how much water the concrete contains initially or to which
RH it has been pre-conditioned. Then, the moisture content is
given by the sorption isotherm; FIG 5. Some examples of the value
of k for mature concrete are given in FIG 6.

The air pores in the concrete seem to take no part in the ab-
sorption process; they are "inert", see FIG 9.

The result of a limited study from 1948 made by Powers and
Brownyard has been analyzed. The agreement with the new results
is excellent; FIG 11 and 12.

A theoretical relation between the capillarity coefficients and
the water vapour diffusivity at high values of RH is derived.

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