# Water and the hygro-thermal characteristics of hardened concrete

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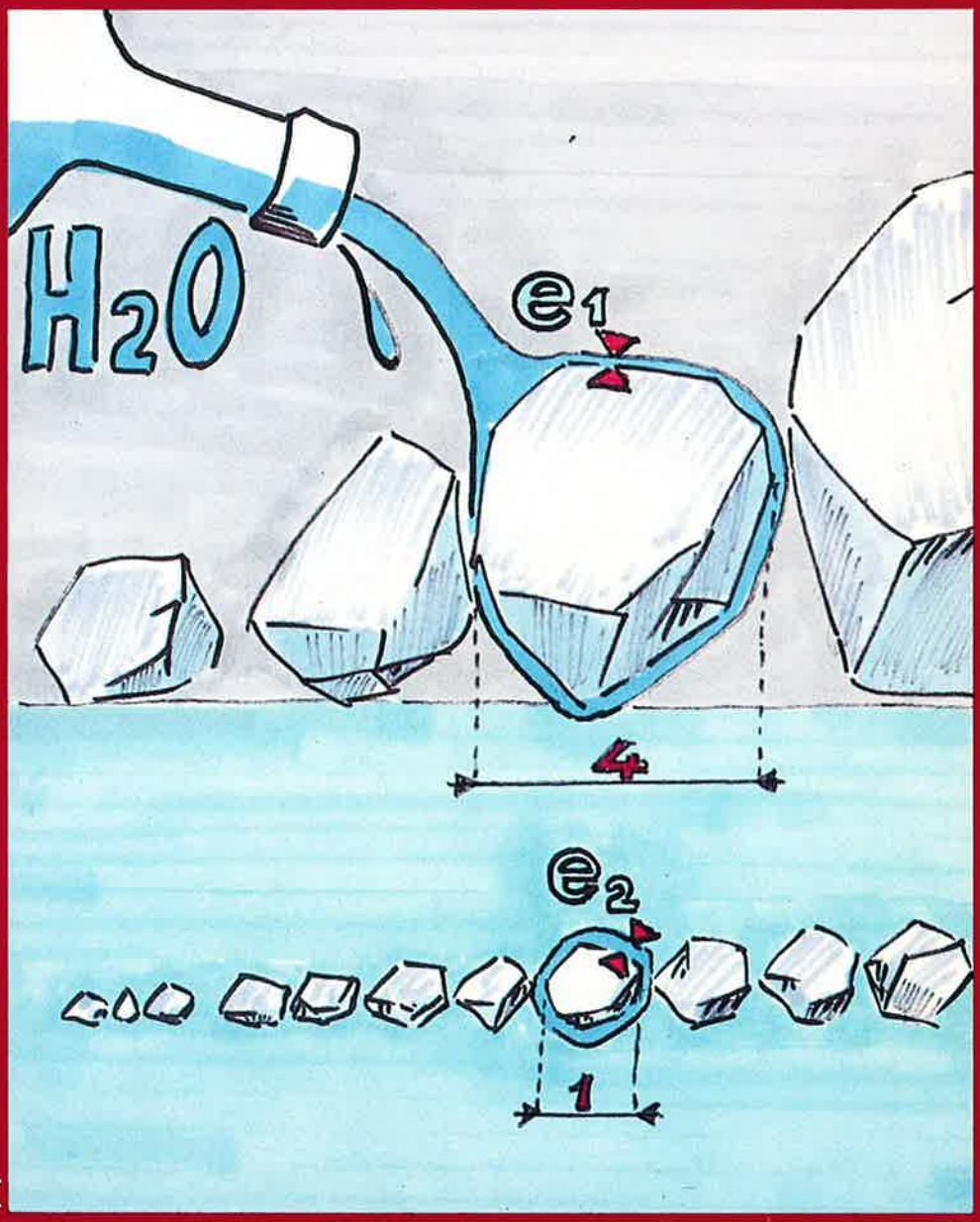
# LE BETON ET L'EAU

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# SOMMAIRE

# WATER AND THE HYGRO-THERMAL CHARACTERISTICS OF HARDENED CONCRETE

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## I. INTRODUCTION

The moisture conditions of concrete are of decisive importance for most phenomena in concrete, such as the rate of hydration, carbonation, alkali-aggregate reactions, reinforcement corrosion and the durability of surface coverings. Consequently it is essential to be able to predict, describe and measure the moisture conditions and the moisture changes in a concrete structure when dealing with various phenomena.

## II. SIGNIFICANCE OF MOISTURE

### 2.1 THE PARTICIPATION OF MOISTURE IN PRINCIPLE

Water participates in many phenomena that lead to a deterioration in one way or another. The participation can vary considerably. To a certain extent the moisture content can act as a plain volume effect by simply occupying space, but generally the absorption of water means an increase in pressure, the pore water pressure. This naturally influences the dimensional changes and the micro-cracking.

Water is a solvent for the gases and ions taking part in a deterioration and also a transport media for dissolved gases and ions. The flow of water is affected by the moisture conditions in such a way that moisture diffuses at lower humidities and flows in the liquid phase at higher humidities. This means a time effect on a deterioration where water is needed. The flow of water of course causes an increasing transport of dissolved substances but where ions are concerned the moisture flow as diffusion at lower humidities is a "capillary break", i.e. an obstacle to such a transport. That is also what happens when no moisture flow takes place and the flow of ions as diffusion in water is prevented at lower humidities when no continuous liquid phase is present. Increasing humidity means an increasing number of paths for such a flow.

The effect of humidity on the flow of gases in a moist material is the reverse. If no continuous gas phase exists the flow rate is drastically decreased due to the much slower rate of diffusion in water than in air, about $10^4$ to $10^5$ times less.

These different ways of moisture affecting various processes act singly or together in many cases of deterioration of concrete or materials combined with concrete. The moisture dependence of a total process can possibly be explained and estimated by dividing the mechanism into parts, as given above, and determine their effect.

However a quantitative estimate is difficult to make as a critical moisture condition is not only a matter of mechanism but is in principle also a material property, that should be measured.

## 2.2 SOME EXAMPLES OF CRITICAL MOISTURE CONDITIONS

Alkali-silica reactions (ASR) are greatly affected by moisture in many ways. For the reaction to take place water acts as a solvent and transport media of alkalies. There is a critical moisture condition at about 80 - 85% relative humidity (RH) below which the reaction rate is very slow and no damages due to ASR occur, cf Fig. 1. /1/.

Around 90% RH there is a maximum and close to 100% RH a lot of reactions occur but no damage will follow. The viscosity of the produced gel decreases when the humidity increases. The gel becomes more fluid and penetrates the surrounding cement matrix without causing any expansion.

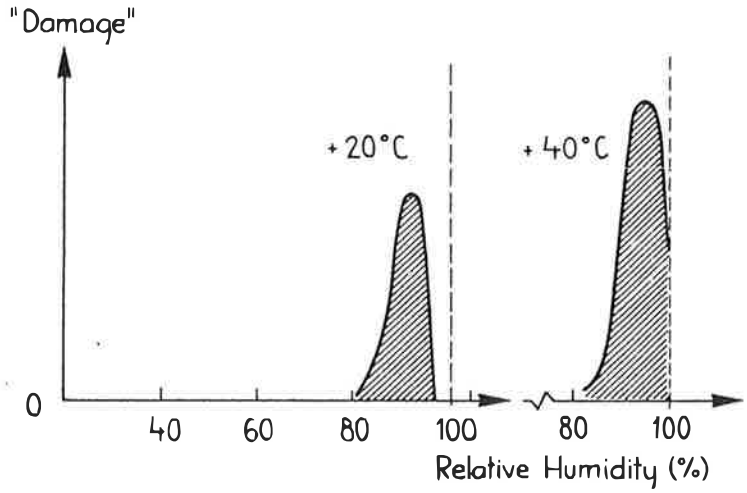


Fig. 1. The pessimum effect of moisture, in principle, at room temperature and elevated temperature /1/.

Moisture also has a decisive effect when it comes to carbonation and lime efflorescence, cf Fig.2 /2/ /3/. If the carbonation proceeds in a moisture condition over 80% RH, the carbonation is almost complete and only a small amount of calcium-ions is available and can leak out to the surface. Consequently lime efflorescence is avoided. If, however, carbonation occurs in a drier concrete we know that the rate of carbonation is high but there will be calcium-ions left unreacted close to the surface and a drop of water at the surface will cause efflorescence.

The effect of moisture on reinforcement corrosion, initiated by carbon dioxide, is also of decisive importance, /4/. Below 80% RH the rate of corrosion

is very low due to the impaired contact between anode and cathode surfaces since no continuous liquid path exists in the concrete. The rate of corrosion is also very low at humidities close to 100% RH when the pore system is almost saturated with water. This means an obstacle to the oxygen-supply to the cathode and consequently a limiting effect on the corrosion reaction.

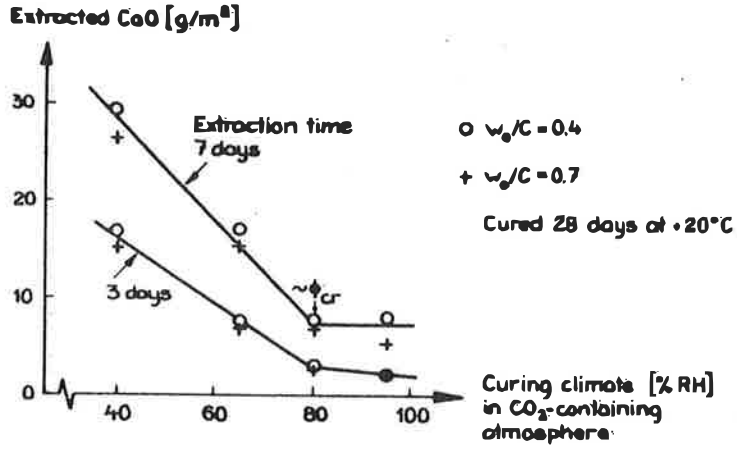


Fig. 2. Amount of lime extracted by water for cement mortars carbonated in different climates; data from Samuelsson (1977) /2/.

## III. GENERAL DESCRIPTION OF HYGRO-THERMAL BEHAVIOUR

To describe the hygro-thermal behaviour of hardened concrete, i.e. the moisture and temperature changes, the laws of mass and energy conservation are used. The equation for conservation of energy is

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (\lambda \frac{\partial T}{\partial x}) + h \qquad \ldots(1)$$

where $\rho c$ ($J/m^3k$) is the product of density and specific heat capacity for the concrete material. It is a function of the moisture content and the concrete composition.

The heat flow is described with the thermal conductivity, $\lambda$, (W/mk), and gradient in temperature T(K). The last term h($W/m^3$) describes the generated heat per time and volume unit. This term is of major importance in hardening concrete where it describes the heat evolution from the reaction between the cement and the water.

The term h is, however, not always negligible in hardened concrete. For accurate descriptions of the temperature conditions close to the surface the heat of evaporation has to be taken into consideration.

The equation for conservation of mass is

$$\frac{\partial w_e}{\partial t} = - \frac{\partial q_m}{\partial x} - \frac{\partial w_n}{\partial t} \qquad \ldots(2)$$

where $w_e$ and $w_n$ are the evaporable and non-evaporable water content ($kg/m^3$) and $q_m$ is the moisture flow ($kg/m^2 \cdot s$).

This equation is precise and contains no essential assumptions. The last term is rather simple. It describes the rate of hydration which depends on the type of cement, cement content, temperature, humidity etc. When carbonation occurs the last term should be taken into consideration when describing the liberation of water in the carbonation reaction.

The moisture flow $q_m$ is however more difficult to express accurately and this is where assumptions and simplifications are necessary as the mechanism of moisture flow in a porous material is extremely complicated. In the case of concrete it is, if possible, even more complicated as concrete is a heterogeneous material with a highly variable composition. Furthermore the properties, of a given composition, change with the degree of hydration.

To solve the above equation boundary conditions have to be expressed. In order to do this the sorption isotherm is invaluable as it gives the equilibrium conditions towards which the material is striving. It is of course also a function of composition and age.

The material properties needed for the description of moisture in concrete are consequently:

- o rate of hydration
- o sorption isotherm
- o moisture flow coefficients

expressed as functions of composition and age as well as of moisture and temperature conditions.

Many solutions to the equation (2) have been published with different degrees of simplification of the equation and the material properties e.g. excluding hydration, assuming the sorption isotherm is a straight line or using constant moisture flow coefficients. However, all the simplifications whera made, due to lack of knowledge about the material properties mentioned above. These properties may be called the "hygro-thermal characteristics" that describe the behaviour of concrete.

Since the heat transfer in concrete is very rapid, compared to moisture transfer, the following presentation will only deal with isothermal conditions. Temperature differences in concrete equalize very rapidly and temperature gradients in a hardened concrete have a very short life. The hygro-thermal behaviour of a hardened concrete may consequently be described fairly accurately in most cases by assuming isothermal conditions and taking the temperature level into account.

For hardening concrete the conditions are completely different.

## IV. HYDRATION AND SELF-DESSICCATION

### 4.1 INTRODUCTION

The fixation of the chemically bound water to the cement, i.e. the cement hydration, plays a significant role when dealing with moisture effects in concrete. It is of great importance to know the rate of hydration in different conditions because of the direct effect on the moisture content, according to eq. (2), and consequently also on the moisture flow . The degree of hydration is however also an essential quality when describing different moisture properties of the material in question, e.g. sorption isotherm and moisture flow coefficients.

The hydration taking place for instance before the drying begins, reduces the physically bound water and consequently the amount of water to be removed. The initial conditions, i.e. the moisture content at the start of drying, are given as follows:

$$w_{eo} = w_o + \Delta w - w_n \qquad \ldots(3)$$

where $\Delta w$ is any additional water during curing. The "internal drying" is known as self-dessiccation and is also naturally continuous during external drying. The decrease in evaporable water content according to eq. (3) is usually assumed to be equally distributed in a cross-section, but as additional water or air is supplied from the surface there should be a rise in the water or air content close to the surface.

The progress and rate of hydration depend on the type and make of the cement used and has to be known or determined. The hydration of the cement is however affected by the concrete composition, mainly $w_o/C$ as is well-known, the temperature and moisture conditions in each point of the concrete.

The rate of hydration increases with an increase in $w_o/C$. For water-cement ratios less than 0.4 the hydration stops at degrees of hydration less than 1 when the capillary porosity is zero, and there is no space left for additional hydration products.

### 4.2 EFFECT OF TEMPERATURE

The effect of temperature can be estimated approximately by using the maturity factor /5/

$$M = \int_o^t (\theta + 10)\, dt \quad (\text{days } ^oC) \qquad \ldots(3:2)$$

where dt is the curing time at a curing temperature of $\theta$ $^oC$. At a constant temperature $\theta$ the progress of hydration can be estimated from the hydration at $+20^oC$ by

$$w_n(t_\theta) = w_n(t_{20}^{eq}) \qquad \ldots(3:3)$$

where the equivalent curing time at +20°C is given as follows

$$t_{20}^{eq} = t_{\theta} \frac{\theta+10}{30} = \frac{M}{30} \qquad \ldots(3:4)$$

in Fig. 3. /2/ data from /6/ are used together with $t_{20}^{eq}$ as a parameter.

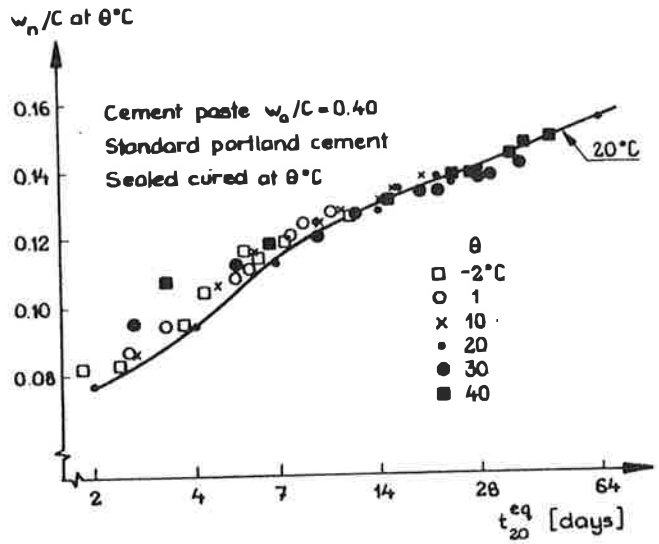


Fig. 3. Progress of hydration at different temperatures with "equivalent age at +20°C" as a parameter. Data from Danielsson (1966) /2/.

## 4.3 EFFECT OF MOISTURE CONDITIONS

The effect of the moisture conditions on the process of hydration is quantatively less known. Powers /7/ determined the progress of hydration of a dry cement stored in climates of different relative humidity with the result shown in Fig. 4.

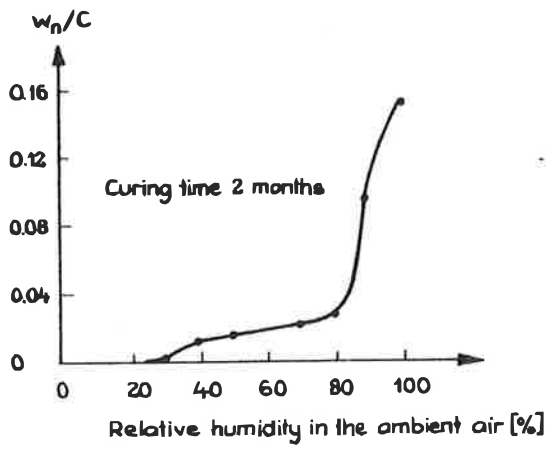


Fig. 4. Effect of storing climate on the progress of hydration for a dry cement, acc. to Powers (1947) /7/.

This example shows that the hydration almost stops at humidities below 80% relative humidity. The rate of hydration is very low for humidities below 0.80 but a progress is measured for humidities as low as 0.40. Measurements of the decrease in humidity under sealed conditions, i.e. self-dessiccation, also indicate a negligible rate of hydration at a humidity of about 0.80 cf. /8/.

## V. MOISTURE FIXATION, SORPTION ISOTHERMS

### 5.1 INTRODUCTION

Knowing the way in which the evaporable water in concrete is fixated under different conditions is essential for several reasons. The sorption isotherm gives information regarding the moisture content at the surface of a material and thereby the moisture content towards which the concrete strives. The sorption isotherm is also necessary to judge the moisture load arising at a tight surface layer applied when the concrete has a certain moisture content. Furthermore the sorption isotherm is a great help when translating moisture flow coefficients from one way of description to another.

In a porous material the water is fixated at different energy levels. The chemically bound water has reacted with the material and is present as hydroxide or crystal water, when the water has kept its original molecular shape and is fixated with covalent bonds or hydrogen bonds as hydrate.

Physically bound water can be fixated in several ways. Zeolitic or interlayer water is firmly bound between different layers in the crystal structure but is not chemically bound. Dependent on the drying method used, some of it might however be included in the non-evaporable water, $w_n$.

Adsorbed water is fixated by van der Waal-forces to the surface of the pores and the force depends on the distance to the surface, i.e. the first molecular layer is the most firmly bound. The thickness of the adsorbed water layer increases with an increasing pore humidity and is approximately 10 Å at 90% RH. As the adsorbed water is fixated to the walls of the pores, the amount of adsorbed water is proportional to their total surface, that is the specific surface when expressed per weight unit.

Capillary condensed water is fixated by curved surfaces of water, meniscus, arising in the pores due to surface tension. Over these water surfaces the water vapour pressure at saturation is lower than on a plane surface, i.e. the vapour pressure at saturation is reached and condensation occurs at a pore humidity $\phi$ less than 1. The connection between the pore humidity and the radius of the curvature, r, is given in the Kelvin-equation. For a partly filled cylindrical pore this is as follows:

$$\ln \phi = - \frac{2\sigma V_m}{r RT} \qquad \ldots(4)$$

where the surface tension of water is $\sigma \cong 0.074$ N/m and the molar volume of water is $V_m \cong 0.018$ $m^3$/k mole. The radius is generally assumed to be equal to

the radius of the pore reduced by the thickness of the adsorbate. The Kelvin equation with this assumption is shown in Fig. 5.

For a material with known porosity and pore-size distribution, the amount of fixated water at a certain humidity can be estimated by using eq. (4).

The pressure of the pore water, $P_w$ (Pa), is given in Thomson's formula

$$P_w = \frac{RT}{V_m} \ln \phi = -\frac{2\sigma}{r} \qquad \ldots(5)$$

In small pores the pore water pressure reaches very high negative values (tension), cf. TABLE I.

| Pore radius Å ($10^{-10}$m) | Relative humidity (-) | Pore water pressure (MPa) |
|---|---|---|
| 20 | 0.6 | -69 |
| 50 | 0.8 | -30 |
| 100 | 0.9 | -14 |
| 200 | 0.95 | - 7 |
| 540 | 0.98 | - 3 |

TABLE I : Connections between pore radius, relative humidity and pore water pressure at + 20 °C.

In this case the amount of physically bound water is treated as the evaporable water when drying at 105°C and usually determined as the moisture ratio u but expressed as moisture content per unit volume

$$w_e = \frac{\text{weight of water evaporable at } 105^\circ\text{C}}{\text{total volume of the material}} \ (\text{kg/m}^3)$$

The connection between moisture content or moisture ratio and relative humidity or pore humidity at equilibrium is called the sorption isotherm. In Fig. 6. a

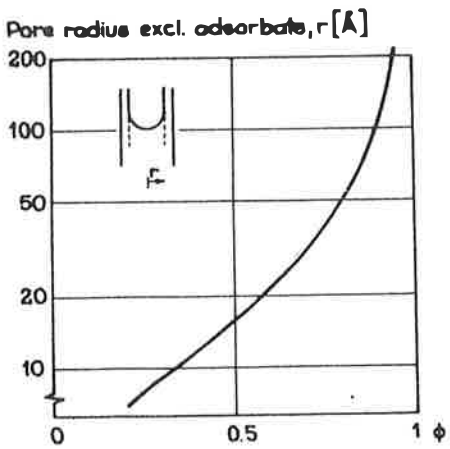


Fig 5 Size of water-filled pores as a function of pore humidity at desorption, Kelvin-equation at 293 K.

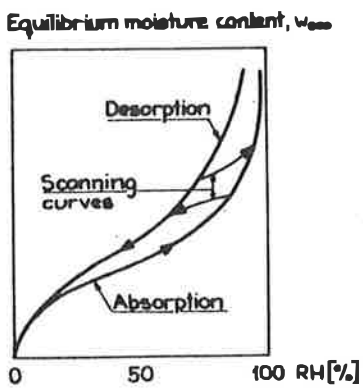


Fig. 6 Sorption isotherm in principle.

sorption isotherm is shown in principle with hysteresis between the absorption and desorption isotherms, i.e. the difference in equilibrium moisture content during drying and wetting respectively.

The moisture capacity is defined as the slope of the sorption isotherm for the moisture content in question, i.e. $(\partial w_{e\infty}/\partial\phi)_w$.

The hygro-thermal coefficient is defined as the slope of a curve with the humidity as a function of temperature at constant moisture content, i.e. $(\partial\phi/\partial T)_w$.

## 5.2 SORPTION ISOTHERMS FOR CONCRETE

As concrete is used with highly variable compositions and hardens continuously, its properties are changed with composition and age. This is also valid for the sorption isotherm. As the sorption isotherm has an upper limit of about 98% RH and the pores that become filled with water are very small, cf. Fig. 5, only the changes in composition of the cement paste in concrete will be considered. The pores added when making concrete, e.g. separation voids, are of far greater size and contain no water at 98% RH. By knowing the sorption isotherm as a function of water-cement ratio and degree of hydration for cement paste it should be possible to calculate the sorption isotherm for any concrete with non-porous aggregate.

For applications in practice it is the desorption isotherms that are interesting. Concrete surfaces that have been dried and then rewetted will follow a scanning curve close to the desorption isotherm. The absorption isotherm has almost no practical application.

Desorption isotherms for hardened concrete with different water-cement ratios are shown in Fig. 7. These curves are valid for fairly well cured concrete, aged for more than half a year.

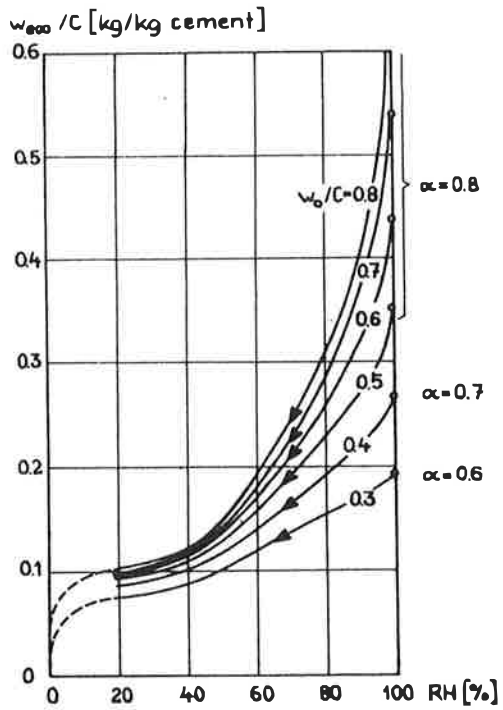


Fig. 7 Desorption isotherms for different water-cement ratios. Degrees of hydration 0.6 - 0.8 /2/.

Knowledge concerning the desorption isotherms at lower ages is still far from complete. A reasonable estimation for practical applications can however be achieved by interpolating in Fig. 7 at humidities less than or equal to 45% RH, i.e. using a "gel-isotherm" at desorption, independent of $w_o/C$, with an equilibrium moisture content at 45% RH of

$$\frac{w_e}{C} (\phi = 0.45) \cong 0.15\ \alpha \qquad \ldots(6)$$

The equilibrium moisture content at 100% RH can be estimated from the assumption that all gel and capillary pores are saturated.

$$\frac{W_e}{C} (\phi = 1.00) \cong \frac{w_o}{C} - 0.19\ \alpha \qquad \ldots(7)$$

Between the two points at 45 and 100% RH the desorption isotherm can be drawn with the aid of the curves in Fig. 7. The accuracy will of course be limited with such a method.

The desorption isotherms derived in this way and from Fig. 7 do not cover all concrete compositions. Some recent measurements /9/ indicate a dispersion effect of admixtures and additives in modern concrete that increases the equilibrium moisture contents, i.e. causes a finer capillary pore system.

## VI. MOISTURE FLOW

### 6.1 MECHANISMS AND DESCRIPTION

In a porous material moisture is transported from the wetter part to the drier part. The transport takes place either in the vapour phase or in the liquid phase or a combination of the two. The direction of the moisture flow is determined by the state of the water at the different points.

Many ways of describing the state of moisture have been used and are being used, the most common being the temperature in combination with the water vapour content, vapour pressure, moisture content, moisture ratio or pore humidity. In rare cases the pressure of the water is used. In some cases different descriptions are used at different humidity intervals to separate the vapour flow from the liquid flow, but since it is usually a combination, such a separation is very difficult, and completely unnecessary under isothermal conditions. The coefficients used in one method of describing the moisture flow can easily be converted to another. Moisture transport coefficients expressed in most ways can be translated into the desired one.

Moisture transport in concrete, as in other porous materials, takes place mainly as the diffusion of water vapour in airfilled pores with the vapour pressure or content as the driving force and as capillary suction in water-

filled pores with the pore-water pressure as the driving force, cf. eq. (5). Due to the pore structure, it is practically always a combination of these two, and only one gradient is usually used to describe the moisture transport under isothermal conditions, as the vapour flow can be expressed in the same way as the liquid flow and vice versa.

When the moisture flow is described as a diffusion, cf. eq. (8), the flow coefficient k (kg/m•Pa•s) is called the "water-vapour permeability".

$$q_m = - k \frac{\partial p}{\partial x} \qquad \ldots(8)$$

This equation may very well describe the total moisture flow in isothermal conditions according to that which is stated above. Then the coefficient k is not a constant but varies with the moisture content of the pores. In these circumstances the total flow may of course also be described as if it was a capillary suction.

At the moment when it is not possible to measure the pore-water pressure, and sorption isotherms expressed in this quantity do not exist, capillary suction is usually described with the evaporable moisture content $w_e$ as the driving force. In one dimension the description of the total flow becomes

$$q_m = - D \frac{\partial w_e}{\partial x} \quad (kg/m^2 \cdot s) \qquad \ldots(9)$$

where the coefficient D ($m^2/s$) is called the diffusivity, which is certainly not a constant but a function of the local climatic conditions, composition and age etc.

This way of expressing moisture transport has chiefly two limitations. It cannot be used accurately for a combination of drying and wetting with hysteresis as moisture might flow from a lower to a higher moisture content in such a case. Under a temperature gradient vapour flow and capillary suction can take place in different directions and a way of separating them becomes necessary. It is however only in very special cases that greater temperature differences occur within the type of concrete structures dealt with here.

## 6.2 EFFECT OF MOISTURE CONDITIONS

Flow coefficients expressed as water vapour permeabilities vary with the moisture conditions in pores as seen in Fig. 8. The permeability increases very much at higher humidities.

The shape of the curves may be explained in the following way. As the capillary pores are smaller at low water-cement ratios, a continuous liquid phase is present at lower humidities. The moisture flow between the capillary pores must however pass through very narrow gel pores and the water vapour permeability is consequently still rather low even at higher humidities. At higher water-cement ratios the communication between the capillary pores is better. This of course leads to increasing permeability by increasing $w_o/C$ at low

humidities, where the moisture flow mainly takes place in a vapour phase. At higher humidities the capillary flow becomes dominating and the permeability increases very rapidly at a high $w_o/C$ once a continuous liquid phase has been formed.

When expressing the moisture transport with a gradient in moisture content, according to eq. 9, the moisture dependence of the diffusivity can be obtained from the water vapour permeability by dividing this by the moisture capacity. By using the moisture capacities in Fig. 7, the diffusivities corresponding to vapour permeabilities in Fig. 8 are obtained with results as shown in Fig. 9.

The characteristic for these diffusivities is a maximum at about 20% RH due to the slope of the desorption isotherm, cf. Fig. 7, low diffusivities in an intermediate interval and a new maximum at higher humidities, more pronounced in high water-cement ratios.

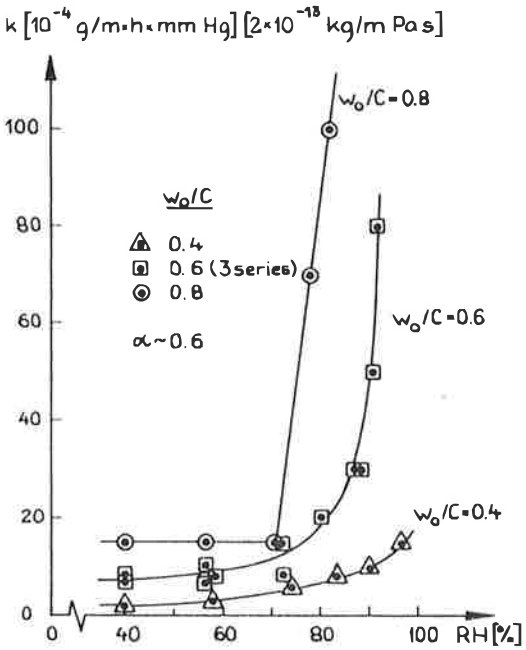


Fig. 8. Water vapour permeabilities as functions of pore humidity for cement mortars of different water-cement ratios /2/.

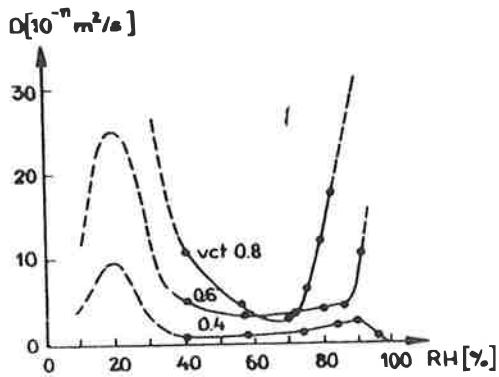


Fig. 9. Diffusivities as functions of humidity /2/.

As seen in Fig. 8 and 9, there is a lack of knowledge regarding very high humidities for high water-cement ratios. The water-vapour permeability and the diffusivity are difficult to obtain close to 100 % RH.

## 6.3 EFFECT OF COMPOSITION AND AGE

Naturally the water-cement ratio is found to have a crucial effect on the rate of the moisture transport, even if a gradient in the evaporable water content does not represent the same driving force of different $w_o/C$. No other factor investigated is of equivalent importance. The effect is shown in Fig. 10 /2/.

The air content of cement mortars has proved to be of great importance to the rate of drying. In many cases the effect of the air content conceals the effect of other factors in the composition, besides the water-cement ratio /2/.

The effect of air content on the diffusivity is shown in Fig. 11. A simple composite model /2/ can explain the effect as the vapour permeability

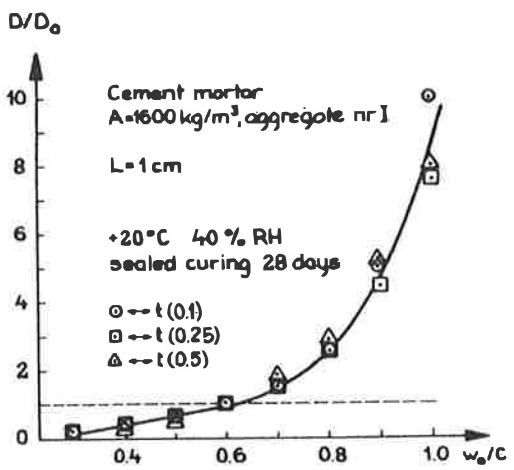


Fig. 10. Effect of water-cement ratio on the diffusivity of cement mortars /2/.

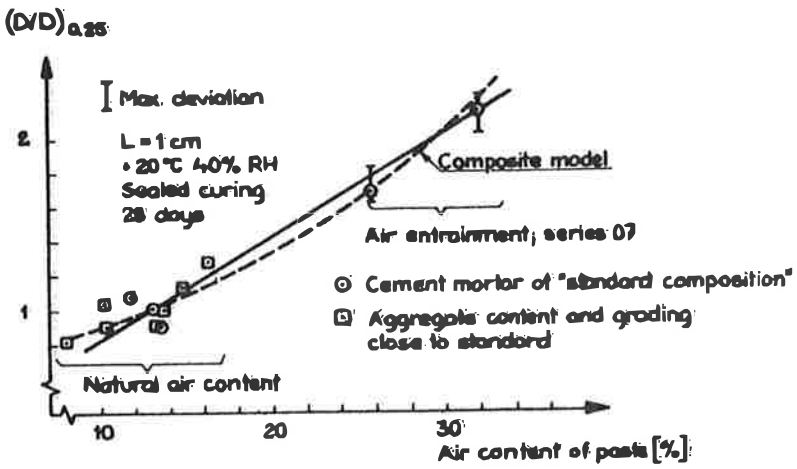


Fig. 11. Effect of air content of the "paste" on the diffusivity of cement mortars /2/.

of air is much higher than that of the paste; approximately 100 times greater. The agreement is obviously rather good and the effect of air may be interpreted entirely as a volume effect with the moisture flow finding its way through air voids where the resistance is much less than in the rest of the paste.

The main effect of aggregate content and gradation is found to be that of aggregate size expressed in terms of modulus of fineness. The diffusivity for concrete with larger stones is to the order of 1.5 - 2.5 $D_o$.

The main cause of the effect of increasing amounts of larger grains is probably the separation voids which appear under the stones, perhaps together with cracks, acting to some extent in the same way as entrained air.

Of course the age of the concrete is of essential importance to the rate of moisture flow due to a continuous densification when the concrete hardens. Few measurements exist and a comparison between a young concrete and a concrete some years old is rare. The effect of age is a factor of 10 - 50 between an age of one day and one month /2/.

The rate of moisture flow is of course also influenced by other factors. The temperature plays an important role. Close to the surface of a concrete structure the moisture flow is influenced by a different aggregate gradation (smaller size), micro-cracks, carbonation /10/ etc. To describe the hygro-thermal behaviour of the part close to the surface is consequently very difficult at the present state of knowledge.

## VII. APPLICATION : DRYING

With the aid of the hygro-thermal characteristics presented in the preceding chapters, most cases of moisture changes in hardened concrete may be described fairly accurately as long as one is close to isothermal conditions. The lack of knowledge described above of course limits the possible applications to some extent and additional information is required in certain cases, e.g. when describing capillary suction.

One important application is described below; drying of concrete structures and the effect of various factors on the drying process.

### 7.1 DRYING OF CONCRETE STRUCTURES

Since the drying of concrete proceeds very slowly, excess moisture is present in a concrete structure for a very long period of time, usually several years. Consequently a sufficient part of the excess moisture must be dried out before materials sensitive to moisture are combined with the concrete. The remaining amount of excess moisture must be allowed to remain in the structure for perhaps a couple of years without causing any damage. The problem that arises is therefore that of being able to state the drying-times required under different conditions to dry out a sufficient smount of the excess moisture. In accomplishing this, profound knowledge is required regarding the moisture properties of concrete and combined materials described in the previous chapters.

The drying starts when the climate around the concrete allows evaporation to take place, i.e. at equal temperatures when the relative humidity is less than 100%. The drying proceeds as a combination of a moisture flow inside the material up to the surface and an evaporation at the surface.

The description of the drying process is found by solving equation (2), the law of mass conservation, with initial conditions according to eq (3) and boundary conditions given by the surrounding climate and the sorption isotherm.

Analytical solutions to such a problem may be found if the flow coefficients are assumed constant. If the knowledge about the hygro-thermal behaviour is to be used to a somewhat greater extent, then computer calculations must be used to solve such non-linear problems.

Such solutions have been calculated in a number of cases to show the effect of various factors /2/. In TABLE II the results of several calculations are shown as drying times required to obtain an average moisture content corresponding to different relative humidities.

## 7.2 EFFECT OF VARIOUS FACTORS

The concrete strength influences the required drying time very much. A higher cement content (and low $w_o/C$) functions in two ways. The available amount of excess moisture is decreased and the rate of moisture flow is decreased. The total effect will be a shorter required drying time when the cement content is increased. For a concrete with a strength of 15 MPa the required drying time will be twice that of a concrete with strength 25 MPa. Observe that most of the effect will be lost if the concrete hardens in contact with water.

The frequently used rule, that a doubling of the slab-thickness means four times the drying time, is not quite valid for hardening concrete, due to the effect of hydration.

A concrete older than one month at the start of drying, dries more rapidly with large slab thicknesses, proportionately, due to the self-dessiccation that proceeded to a greater extent in the thicker slab. For a younger concrete, with slab thicknesses less than 15 cm, the greater moisture flow capacity at the beginning of the drying has a major effect and the drying is very rapid. With slab thicknesses greater than 15 cm the age at the start of drying is of less significance.

In TABLE II the effects of other factors are also shown . The surrounding climate naturally has an effect on the drying process. The possibility of drying downwards through a heat insulation depends on the water-vapour permeability of the heat insulation and the direction of the heat flow. A permeable insulation and a substrate that is somewhat colder than the concrete structure will reduce the required drying time due to additional drying downwards.

TABLE II Required drying time for excess moisture in a concrete structure.

**BASIC CASE**

- cubic strength of concrete 25 MPa
- drying prevented downwards
- thickness L = 100 mm
- age of concrete 1 month
- cured under a plastic sheet
- required dryness: 90% RH
- drying climate: +20°C, 40% RH

REQUIRED TIME FOR DRYING [60 DAYS]

Correction factors to account for different concrete properties or drying conditions:

**CONCRETE STRENGTH (MPa)**

| 15 | 25 | 25 air | 40 | 40 air |
|---|---|---|---|---|
| [2] | [1] | [0.5] | [0.5-0.6] | [0.3] |

- correction factors are not valid when water curing or rain and water has increased the initial moisture content
- "air" = the air content has been increased from 2% to 8%

**AGE**

When the age of concrete is one week at the beginning of drying, the following correction factors may be applied

- slab thickness < 150 mm [0.7]
- slab thickness > 150 mm [1]

**DRYING CONDITIONS**

| Relative humidity | 20-50% | 60% | 80% |
|---|---|---|---|
| | [1] | [1.2] | [1.5] |
| Temperature | 10°C | 20°C | 30°C |
| | [1.3-1.4] | [1] | [0.6-0.7] |

**SLAB THICKNESS L (mm)**

| 60 | 80 | 100 | 120 | 140 | 160 | 200 |
|---|---|---|---|---|---|---|
| [0.4] | [0.7] | [1.0] | [1.4] | [1.8] | [2.3] | [3.3] |

- the correction factors correspond to drying in one direction
- if drying occurs to both directions L = half of the slab thickness
- the factors are valid for concrete strength 25 MPa

**MATERIAL UNDER THE SLAB**

| 50 mm of polystyrene | 150 mm of lightweight aggregate | 50 mm of mineral wool |
|---|---|---|
| [0.9-1.0] | [0.7-0.8] | [0.6-0.7] |

- no plastic sheet between the concrete and insulation
- temperature difference of > 2°C over the heat insulation

**REQUIRED DRYNESS**

| RH = 90% | 80% | 70% |
|---|---|---|
| [1] | [3-4] | [6-8] |

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