Moisture Fixation and Moisture Transfer in Concrete

J.-E. Jonasson
Swedish Cement and Concrete Research Institute, Royal Institute of Technology, S-100 44 Stockholm, Sweden

Abstract

Different ways of formulating the basic equation for moisture transfer in concrete are discussed. Thereby, a phenomenological model expressed in terms of vapour pressures seems to be most feasible. This model is based only on material features, which means that necessary model parameters can be determined according to separate tests on concrete.

The presented model requires proper description of inclinations in sorption isotherms. In this paper a way of decucting such curves is presented for concrete made of Portland cement, both in desorption and absorption conditions.

Finally, calculated characteristic cumulative pore volumes associated to sorption isotherms are shown. The pore size distribution is aimed to be used in the future for instance to describe the influence of concrete age on transportation coefficients.

1. Introduction

The need for prediction of moisture state in engineering application is very extensive. A great deal of theoretical and experimental research work has been carried out in this field. But still quite realistic models for prediction of moisture transfer do not exist.

Moisture transportation in concrete was first modelled as a linear diffusion problem, see studies in connection with shrinkage by Picket /1/. More recent diffusion models use non-linear transportation coefficients, see for instance Pihlajavaara /2/, Bazant et al /3/, Nilsson /4/, and Sakata /5/. However, necessary parameters in these models do not reflect material features for concrete in all cases. The aim of this paper is to present the fundamentals of a diffusion model, where these disadvantages are eliminated.

2. Model for moisture transfer in concrete

From a phenomenological point of view, for instance when interpreting vapour permeabilities according to tests by the cup method as in /4/, and even for physical reasons at lower humidities /3/ the moisture flux is preferably expressed in gradients of vapour pressure as

$$J = - K_p \cdot \text{grad } p \qquad (1)$$

where J is the water flux (kg/m^2s), K_p is the vapour permeability (kg/Pa m s), and p is the vapour pressure in the pores (Pa).

For normal weight concrete a reasonable approximation seems to be, see chapter 3, that sorption curves exist all the way up to completely wet condition at atmospheric air pressure in the surroundings. Hereby, different moisture state parameters (water content, capillary tension, temperature) are directly related to the vapour pressure. From this it follows that Eq. (1) may be applied in the whole moisture range. In very high temperature ranges it has been specially applied by Bazant et al /6/.

One must notice that Eq. (1) is not describing the real physical mechanisms of moisture transportation, which is believed to contain 1) vapour diffusion, 2) surface layer diffusion, and 3) capillary flow, see for instance Kiessl /7/, Kohonen /8/, and Huang et al /9/. These mechanisms are evidently in most cases acting, in different proportions depending on humidity, at the same time. From experiments it seems impossible to distinguish between real mechanisms. As values for K_p in Eq. (1) are possible to determine experimentally by the cup method, K_p is a real material parameter from a phenomenological point of view. However, the notation vapour permeability must in respect to mechanisms be interpreted as a formal permeability.

For simplicity, in the sequel only constant temperature will be treated. The extension to variable temperature is then straight-forward. At constant temperature Eq. (1) may be reformulated in terms of the relative humidity as

$$J = - K_\phi \cdot \text{grad}\ \phi \qquad (2)$$

where $\phi = p/p_s(T)$ is the relative pore humidity, p_s is the partial vapour pressure (Pa) at saturation and temperature level T (K), and $K_\phi = K_p \cdot p_s(T)$ is the "humidity" permeability (kg/m^2 s).

The law of conservation of masses yields

$$\frac{\partial w}{\partial t} = - \text{div}(J) \qquad (3)$$

where w is the water content (kg/m^3), and t is the time (s).

Insertion of Eq. (2) into Eq. (3) leads to the so called diffusion equation

$$\frac{\partial w}{\partial t} = \text{div}(K_\phi \cdot \text{grad}\ \phi) \qquad (4)$$

The water content of concrete is in a usual manner divided into two parts

$$w = w_e + w_n \qquad (5)$$

where w_e is the evaporable water content (kg/m^3), and w_n is the non-evaporable water content (kg/m^3).

The basic assumption of the existence of sorption isotherms for normal weight concrete means that the evaporable water content (w_e) and the moisture capacity ($\partial w_e/\partial \phi$) can always be treated as functions of the vapour pressure and the temperature (or functions of the relative humidity at constant temperature).

A direct insertion of Eq. (5) into Eq. (4) yields a "mixed" formulation of the diffusion equation as

$$\frac{\partial w_e}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} + \frac{\partial w_n}{\partial t} = \text{div}(K_\phi \cdot \text{grad}\ \phi) \qquad (6)$$

Eq. (6) is formally expressed in terms of the relative humidity (ϕ) (corresponds to the vapour pressure at variable temperature) with three material parameters, namely 1) moisture capacity ($\partial w_e/\partial \phi$), 2) rate of chemical binding of water ($\partial w_n/\partial t$), and 3) humidity permeability (K_ϕ).

The diffusion equation may also be formulated in other ways. A strict formulation in terms of the water content leads to

$$\frac{\partial w_e}{\partial t} + \frac{\partial w_n}{\partial t} = \mathrm{div}\left(K_\phi \cdot \frac{\partial \phi}{\partial w_e} \cdot \frac{1}{1 + \frac{\partial w_n}{\partial w_e}} \cdot \mathrm{grad}(w_e + w_n)\right) \qquad (7)$$

A strict formulation of the diffusion equation in terms of the humidity yields

$$\frac{\partial \phi}{\partial t} - \frac{\partial \phi_o}{\partial t} = \frac{\partial \phi}{\partial w_e} \cdot \mathrm{div}(K_\phi \cdot \mathrm{grad}\ \phi) \qquad (8)$$

where ϕ_o is the humidity due to self-desiccation at sealed conditions.

The Eqs. (6), (7), and (8) are equivalent formulations of the diffusion equation based on Eq. (2). The formulation according to Eq. (7) is not advisable for computing, because the term $1/(1+\partial w_n/\partial w_e)$ may cause numerical problems as $\partial w_n/\partial w_e$ approaches -1 at sealed conditions for hydrating concrete. The Eqs. (6) and (8) are from a numerical point of view almost identical, but Eq. (6) is preferable for hydrating concrete since the term $\partial w_n/\partial t$ is more easily connected to material behaviour than the drop of the humidity value due to self-desiccation. The drop of the humidity may be obtained as a consequence when applying Eq. (6) to sealed conditions. For mature concrete all three formulations are in principle identical.

However, the Eqs. (7) and (8) have in the past been approximated as

$$\frac{\partial w_e}{\partial t} + \frac{\partial w_n}{\partial t} = \mathrm{div}(D_w \cdot \mathrm{grad}\ w_e) \qquad (9)$$

and

$$\frac{\partial \phi}{\partial t} - \frac{\partial \phi_o}{\partial t} = \mathrm{div}(D_\phi \cdot \mathrm{grad}\ \phi) \qquad (10)$$

where D_w is the diffusivity (m^2/s) with respect to water content, and D_ϕ is the diffusivity (m^2/s) with respect to relative humidity. These diffusivities are not indentical. Neither of them is a real material parameter except in special cases, such as nonhydrating concrete without gradients in non-evaporable water content in Eq. (9), and constant moisture capacity in Eq. (10). The Eq. (9) has been used for instance by Nilsson /4/ and Sakata /5/, and Eq. (10) has been used by Bazant et al /3/ and Jonasson /10/.

One advantage of the Eqs. (9) and (10) is that only two model parameters are needed before numerical treatment, either $\partial w_n/\partial t$ and D_w or $\partial \phi_o/\partial t$ and D_ϕ , while Eq. (6) requires three parameters. Especially, sorption isotherms must be explicity expressed to enable the use of Eq. (6). Such functions are presented in chapter 3. The more complicated calculations involved in the use of Eq. (6) are probably counterbalanced by the use of real material parameters. Hereby, extrapolations at trial applications outside a certain test range could be more justified.

3. Sorption isotherms

Sorption isotherms for concrete, mortar or cement paste made of Portland cement have been established in accordance with

$$\frac{w_e}{C} = \left(\frac{w_e}{C}\right)_{gel} + \left(\frac{w_e}{C}\right)_{cap} \qquad (11)$$

where w_e is the evaporable water content (kg/m^3), C is the cement content (kg/m^3), the index gel indicates gel pores, and the index cap indicates capillary pores. Eq. (11) relates to the same lines as the model of paste structure given by Powers and Brownyard /11/ and Powers /13/.

In absorption, $(w_e/C)_{gel}$ denotes the so called gel isotherm (Powers et al /11/), see FIG 1. Furthermore, in desorption a "gel isotherm" has been introduced in FIG 1, where the corresponding inclinations or moisture capacities are also shown.

The water content in the capillary pores is expressed by

$$\left(\frac{w_e}{C}\right)_{cap} = \gamma_c \cdot \frac{w_{cap}}{C} \qquad (12)$$

where γ_c is the capillary filling factor ($0 \leq \gamma_c \leq 1$), see FIG 2, and w_{cap} is the water content (kg/m^3) at completely filled capillary pores, expressed as

$$\frac{w_{cap}}{C} = \frac{w_o}{C} - 0.385 \cdot \alpha \qquad (13)$$

where w_o is the initial water content (kg/m^3), and α is the degree of hydration, and w_o/C is the water-cement ratio.

The total water content at saturation is expressed by

$$\frac{w_s}{C} = \frac{w_o}{C} - 0.175 \cdot \alpha \qquad (14)$$

where w_s is the total water content (kg/m^3) at saturation. The Eq. (14) is describing the case when all the gel and capillary pores are completely filled with water, and when all the air pores are filled only with air.

To be able to apply Eq. (12), the capillary filling factor must be known. In FIG 2 the values at some distinct humidity levels, namely at $\phi = 0.20$, 0.45, 0.75, and 0.98, respectively, are shown. These values are dependent on the capillary pore volume ratio, δ_c, indicating the relative volume of capillary pores, expressed as

$$\delta_c = \frac{w_{cap}}{w_s} = \frac{\frac{w_o}{C} - 0.385 \cdot \alpha}{\frac{w_o}{C} - 0.175 \cdot \alpha} \qquad (15)$$

On humidity levels between the distinct values of FIG 2, analytical splines, suitable for computer calculations, have been established. They are not given here. In hand calculations, readings of FIG 1 and FIG 2 are sufficient. For computer purposes, all curves of FIG 1 are also expressed in analytical form.

An example of comparisons between calculated and measured desorption curves on concrete /4/ are shown in FIG 3. In FIG 4 comparisons based on absorption tests on cement paste /11/ are shown.

One application of calculated isotherms and moisture capacities at the water-cement ratio 0.6 is given in FIGs 5 - 8. As can be seen from FIG 6 and FIG 8 the inclinations of the sorption curves are far away from constant values. This indicates that the adaption diffusivities (D_ϕ) when using Eq. (10) are not real material parameters. At a completely wet state ($\phi = 1$) the inclination of the sorption curves according to the model presented here have finite values. So, here it is possible, in case of normal weight concrete at atmospheric pressure, to use sorption curves all the way up to complete saturation.

4. Characteristic pore structure

The sorption isotherms are related to the pore structure of the cement paste. In studying the topic of moisture in concrete, the pore structure, or a sufficient characteristic pore structure, must be known to make it possible, in a material sence, to take into account the influence of age on the transportation coefficients. The dispergation effect of some admixtures is also believed to be properly expressed by use of pore size distributions.

Different models exist for the translation between sorption curves and the pore structure. Here, a modified BET-theory according to Hillerborg /12/ has been chosen. This model is applied on cylindrical pores. As the desorption and absorption curves differ, they imply different characteristic pore size distributions. To overcome this problem, the characteristic pore structure has been calculated at the average water content. One example of calculated characteristic cumulative pore volume at the water-cement ratio of 0.6 is shown in FIG 9. It can there be seen that hydrating cement, as expected, gives increase in finer pores and less total porosity.

5. Future work

The area of moisture transfer and moisture effects in concrete is one part of a research project in progress at the Swedish Cement and Concrete Research Institute. The future work will be concentrated on descriptions of the necessary material parameters, see chapter 2. Test procedures are planned to be focused on the effect of moisture on the hydration rate, i.e. the evaluation of the factor β_ϕ in Eq. (16). This topic has not been studied experimentally since the work of Powers in 1948 /14/. Usually, the hydration rate, $d\alpha/dt$, is expressed as

$$\frac{d\alpha}{dt} = a_o(\alpha) \cdot \beta_T \cdot \beta_\phi \cdot \beta_\Delta \qquad (16)$$

where $a_o(\alpha)$ is the reference function for a certain cement type (1/s), β_T is the temperature rate factor, β_ϕ is the moisture rate factor, and β_Δ is the admixture rate factor.

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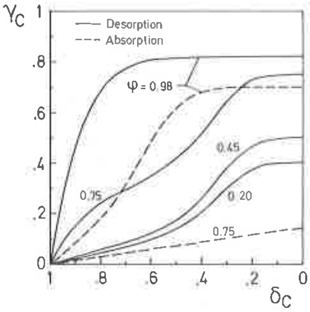

FIG 2. Capillary filling factor for desportion and absorption at some distinct humidities, see Eq. (12).

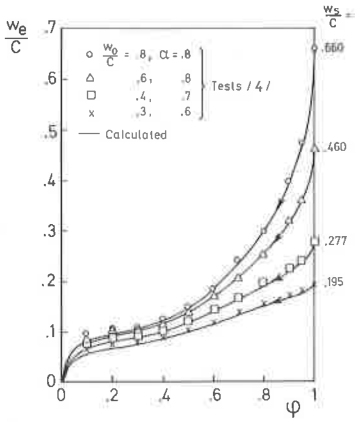

FIG 3. Comparison between calculated and measured /4/ desorption curves for concrete.

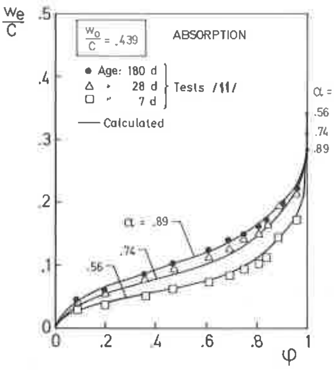

FIG 4. Comparison between calculated and measured /11/ absorption curves for cement paste.

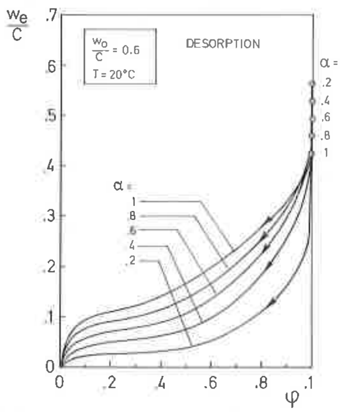

FIG 5. Calculated desorption isotherms for water-cement ratio 0.6 at different degrees of hydration.

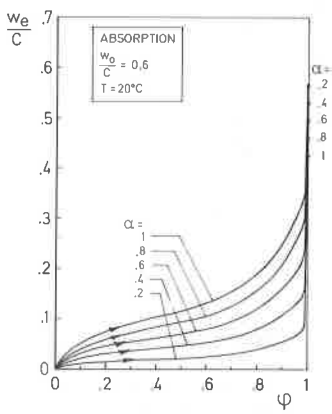

FIG 7. Calculated absorption isotherms for water-cement ratio 0.6 at different degrees of hydration.

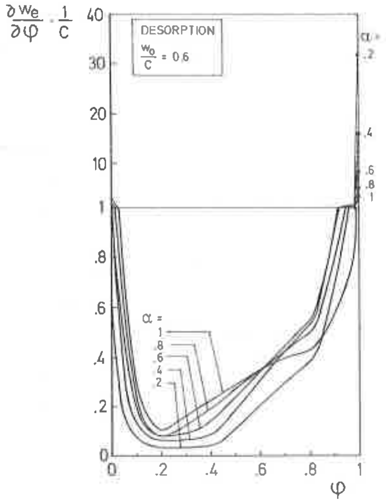

FIG 6. Calculated moisture capacities at desorption for water-cement ratio 0.6 at different degrees of hydration.

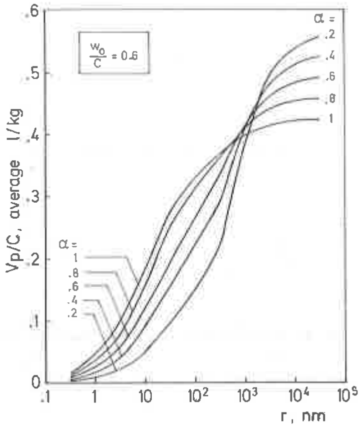

FIG 9. Calculated characteristic cumulative pore volume for water-cement ratio 0.6 at different degrees of hydration.

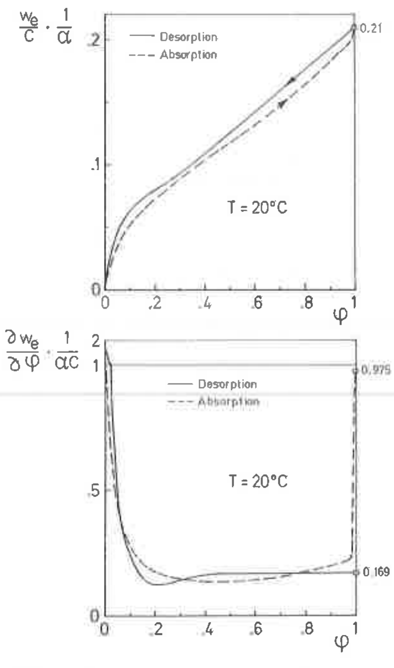

FIG 1. Absorption and desorption isotherms and associated moisture capacities for water fixed in gel pores of hardened paste.

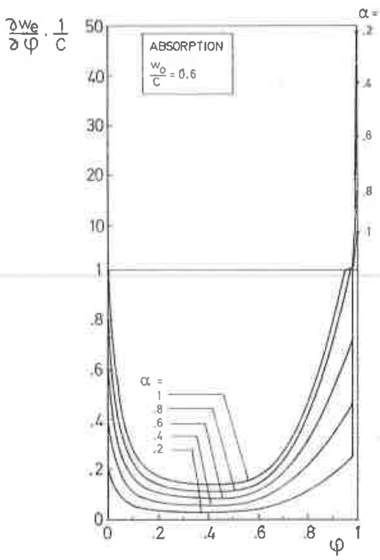

FIG 8. Calculated moisture capacities at absorption for water-cement ratio 0.6 at different degrees of hydration.