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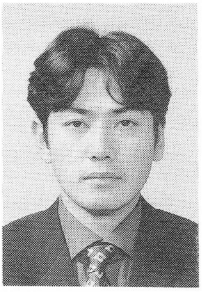
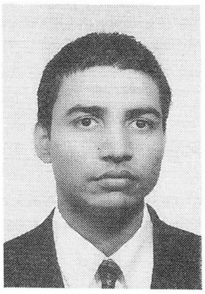
MODELING OF PORE WATER CONTENT IN CONCRETE UNDER GENERIC DRYING-WETTING CONDITIONS

(Translation from Proceedings of JSCE, No.564/V-35, March 1997)



Tetsuya ISHIDA



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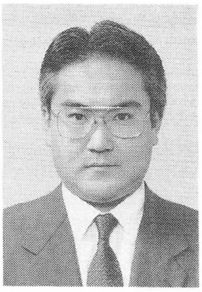

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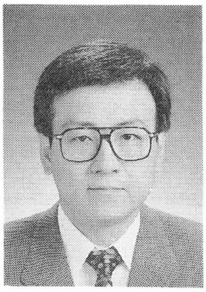

Koichi MAEKAWA

In this paper, the authors propose an analytical model for the hysteresis behavior of moisture isotherms in concrete. The microstructure of concrete is approximated in terms of a porosity distribution to which the proposed analytical model is applied to predict concrete water content under variable environmental conditions. The proposed model is formed based upon the physical phenomenon observed in porous media called as the inkbottle effect. The model is able to predict the water content in concrete under general drying-wetting conditions satisfactorily.

Keywords: *Pore structure, Isotherm, Hysteresis, Inkbottle effect, Durability*

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1. INTRODUCTION

A porous material like concrete contains a certain amount of water within its pores in a normal environment. Most of the deterioration mechanisms that affect reinforced concrete structures, such as cracking due to drying shrinkage, carbonation, corrosion, and sulfate attack, are related to this water content and its migration. It is therefore essential to predict the water content in concrete under any environmental condition in order to develop rational and quantitative durability assessment for concrete structures. The principal objective of this work is to develop an analytical model for predicting the water content, and this will be achieved by summing up the moisture content of all pores, which have a broad distribution of radii.

In the design stage of RC structures, the main focus has in the past been addressed to the limit state as it relates to structural safety. In fact, owing to the development of enhanced constitutive laws for reinforced concrete [1], it is now possible to numerically predict the structural response as well as mechanical states of constituent elements in both time and space under the effect of any external mechanical action. A similar kind of evaluation method for durability performance was proposed by the JSCE in 1989. The crucial point of this original proposal was that it gave a numerical score to overall durability performance by assigning certain durability values. It has been noted, however, that this scoring procedure is still at a primitive stage and uses simplified empirical formula, so further research and development are required to make durability design more versatile and trustworthy [2].

The durability performance of conventional concrete is dependent on the construction method used (and especially on the quality of the concreting work), and this makes it difficult to establish an approach based on performance evaluations. This problem, however, has mostly been solved by self-compacting high performance concrete (HPC) [3]. HPC overcomes the uncertainties introduced by human error and yields a reliable structural concrete. In other words, with the development of self-compacting HPC, the uniformity of in-site concrete mixture can be guaranteed. Thus, for modeling of concrete performance achieved in the following stage, we can set the initial condition the same as that of the laboratory tests.

Against this background, the ultimate goal of this paper is to establish an analytical system for durability evaluation, similar to the generic structural analysis method now established in the field of structural engineering. In this paper, the authors focus on the development of an analytical model able to predict water content under any environment condition, since water content is crucial to the qualitative evaluation of each deterioration factor. Since RC structures in a real environment are exposed to complicated drying-wetting cycles, it is very important to establish a water content evaluation scheme that can be applied to any ambient condition.

Moisture in the pores of cementitous materials can be present in both liquid and vapor forms. Usually, the volumetric content and thermodynamic characteristics of these two phases of moisture dispersed in capillary and gel pores are determined by Kelvin's equation, which expresses the thermodynamic equilibrium between liquid water and vapor [4][5]. In this approach, the equilibrium is assumed to be perfectly reversible under various environmental conditions, such as phases of drying and wetting. Here, it is experimentally known that the water content in concrete varies with drying and wetting, even if exposed to the same relative humidity [6][7]. This phenomenon is called hysteresis and has been explained by various mechanisms, such as the inkbottle effect, or the irreversibility of adsorption and desorption of water molecules by the micropore structure [8]. However, no rational and quantitative method of expressing this irreversibility for the practical evaluation of moisture content in a porous body exists. In this paper, we attempt to model the path-dependence of water content in concrete under any drying-wetting conditions, considering mainly the inkbottle effect.

2. COMPUTATIONAL MODEL OF WATER CONTENT IN CONCRETE

2.1 The porosity distribution function [4]

Cement paste is a porous medium containing pores of various sizes and configurations. In this paper, we consider only those pores that contribute to moisture transport, and subdivide the overall micropore structure into three basic components, i.e., capillary, gel, and interlayer pores. The total porosity distribution function $\phi(r)$ is obtained by considering the coupling of hydration, moisture transport, and pore structure formation models as [4][9][15],

$$\phi(r)=\phi_{cp}V_{cp}(r)+\phi_{gl}V_{gl}(r)+\phi_{lr} \tag{1}$$

where, r : pore radius, ϕ_{lr} : interlayer porosity, ϕ_{gl} : gel porosity, and ϕ_{cp} : capillary porosity. $V_{cp}(r)$ and $V_{gl}(r)$ represent the fractional pore volume of capillary and gel pores in the distribution, respectively (Fig.1).

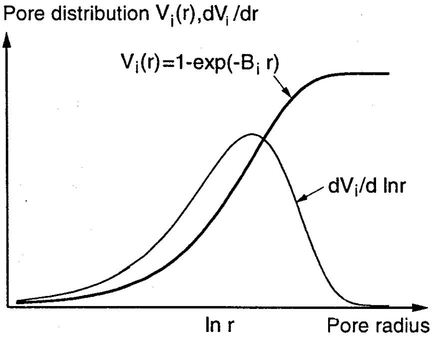


Fig.1 Definition of the porosity distribution function

$$V_i(r)=1-\exp(-B_i r) \quad (0\le V_i(r)\le 1) \tag{2}$$

$$dV_i=B_i r\exp(-B_i r)d\ln r \tag{3}$$

where, B_i is the porosity distribution parameter of pore i, and can be obtained once the surface areas and relevant porosity of the gel and capillary components are computed.

The porosity distribution function $\phi(r)$ is mathematically expressed as a linear summation of interlayer porosity ϕ_{lr}, gel porosity distribution $\phi_{gl}V_{gl}(r)$, and capillary porosity distribution $\phi_{cp}V_{cp}(r)$. The use of this porosity distribution function means it is easily applicable to a model in which different physical characteristics are assumed for various sizes of pores.

2.2 Moisture profile in capillary and gel pores

a) Thermodynamic equilibrium of liquid and vapor phases

Under equilibrium conditions, the moisture content of a porous medium is dependent on the ambient relative humidity. This is because, for a given relative humidity, a certain group of pores whose radii is smaller than the specific radius at which a liquid-vapor interface forms are completely filled with water, whereas larger pores remain empty or partially saturated. Considering local thermodynamic and interface equilibrium in a porous medium, the pore radius r_s at which an interface between liquid and vapor is created can be determined by Kelvin's equation as [4] [5],

$$\ln\left(\frac{P_v}{P_{vO}}\right)=-\frac{2\gamma M_w}{RT\rho_L}\frac{1}{r_s} \tag{4}$$

where, P_v : partial vapor pressure [Pa], P_{vO} : saturated vapor pressure [Pa], γ : surface tension of liquid water [N/m], M_w : molecular mass of water [kg/mol], R : universal gas constant [J/mol.K], T : absolute temperature of the vapor-liquid system [K], and ρ_L : density of liquid water [kg/m^3].

If the porosity distribution of the micropore structure is known, the amount of water present in pores under a given ambient relative humidity can be obtained from Eq. (4) since, to satisfy the equilibrium conditions, all pores with radii smaller than r_s would be completely filled whereas other pores would be empty (Fig.2).

b) Adsorbed phases of liquid water

The above assumption based on Kelvin's equation is generally made in predicting the moisture state in concrete. However, Eq. (4) is not enough to fully describe the moisture state, since it cannot explain the adsorption of water molecules in micropores. In this paper, we consider this adsorption of liquid water by using the B.E.T. theory. This theory describes the adsorption mechanisms of molecules on a plane surface of infinite radius. A modification of the original theory to take into account the shape effect of pores was proposed by Hillerborg [10]. With this model, the thickness, t_a [m] of the adsorbed layer in micropores is given as (Fig. 3),

$$t_a = \frac{0.525\times10^{-8}RH}{\left(1-RH/RH_m\right)\left(1-RH/RH_m+15RH\right)} \qquad (5)$$

where, RH : relative humidity, and RH_m : humidity required to fully saturate the pore. If we assume a cylindrical pore shape, then from Kelvin's equation and Fig. 3, RH_m is obtained as,

$$RH_m = \exp\left(\frac{-\gamma M}{\rho_L RT r_1}\right) \qquad (6)$$

where $r_1 = r - t_a$ is the actual interface radius and is smaller than the actual pore radius. As the relative humidity inside a pore increases, the thickness of the adsorbed layer increases.

In this paper, we consider both the condensed and adsorbed phases of liquid water. Using modified B.E.T. model to take into account adsorption implies that an equilibrated interface between liquid and vapor is created in a pore of radius r_c, which is larger than the pore radius r_s as determined by Eq. (2). In other words, pores with radii smaller than r_c are completely saturated, whereas larger pores are partially or completely saturated depending on the drying- wetting history.

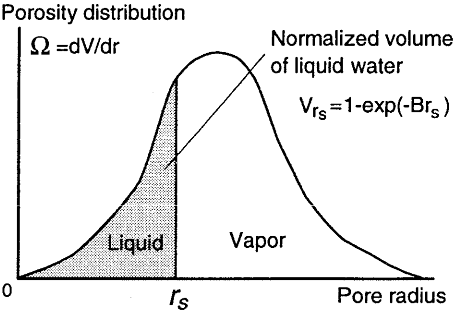


Fig.2 Moisture phase in pore structures

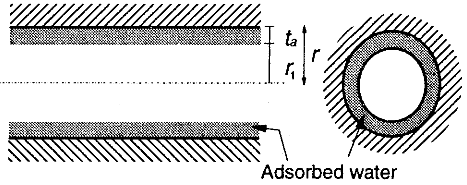


Fig.3 Adsorption phenomena in an ideal pore

2.3 Hysteretic behavior of isotherm

The thermodynamic equilibrium expressed by Kelvin's equation and the adsorption model based on modified B.E.T. theory can determine the only one path for a moisture isotherm under drying-wetting conditions. In actual cases, however, the adsorption and desorption curves of typical isotherms are seen to follow different paths. This is true not only in concrete, but also in other porous media. This irreversibility of isothermal paths of water content in concrete under cyclic drying-wetting conditions is illustrated in Fig. 4. All desorption curves lie above the corresponding adsorption curves, and hysteresis loops can be observed. Here, we will focus mainly on the inkbottle effect, which is most likely to cause this type of hysteresis behavior in porous media.

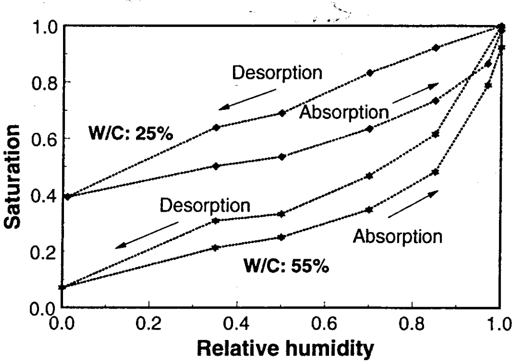


Fig.4 Irreversibility of moisture isotherms of typical mortars

Owing to the complex geometrical characteristics of a random microstructure in cementitous materials, pores shaped like inkbottles exists. These form when pores of different radii come into contact. Figure 5 is schematic representation of the hysteresis moisture isotherm for a single pore, as derived from water entrapped by the inkbottle effect. Consider a small pore with external openings at each end. For the sake of simplicity, water adsorbed on the pore wall will be neglected from the following discussion. During the wetting stage (*a*→*b*→*c*), as the relative humidity increases, liquid water gradually condenses in the pore, as governed by the thermodynamic equilibrium. On the other hand, during drying (*d*→e→*f*), vaporization of liquid takes place from the larger pore space. However, at point *e* in Fig. 5, the larger pore volume in the middle is confined by the smaller pore openings, and moisture cannot be lost. Therefore, the isotherm of a single pore would follow the hesteresis behavior shown in Fig. 5. In this paper, the water entrapped in each pore by the inkbottle effect is assumed to give rise to macroscopic hysteresis behavior of moisture in the concrete under drying-wetting conditions.

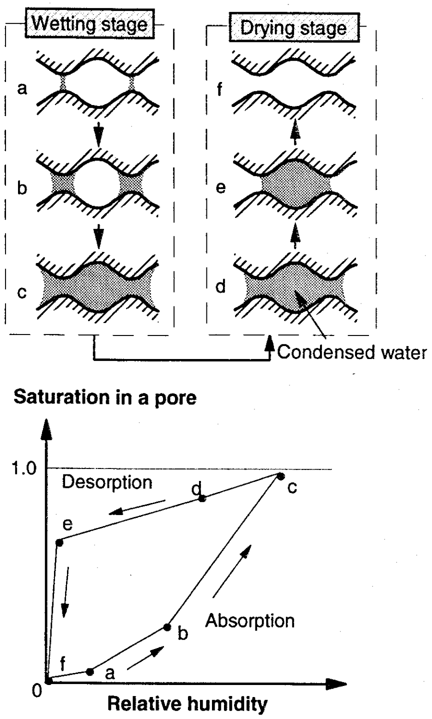


Fig.5 Hysteresis behavior in a pore

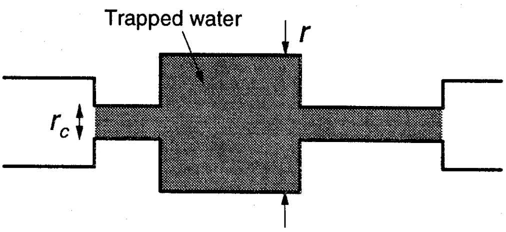
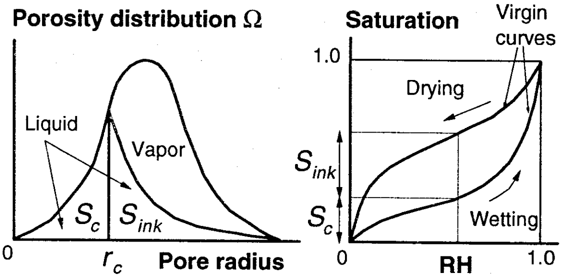


Fig.6 Inkbottle effect in an idealized pore



Wetting stage : $S_{total} = S_c$ **Drying stage :** $S_{total} = S_c + S_{ink}$

Fig.7 Moisture distribution in pore structure under drying-wetting conditions

Figure 6 shows a schematic representation of the inkbottle model used in this paper. We consider all pores to be cylindrical. To express the inkbottle pore structure, we introduce the simplest possible geometrical characteristic model, which is linearly connected cylinders of different radii. In this pore system, during drying, we can expect some additional trapped water in pores whose radius r is larger than r_c, as long as the connecting pores remain saturated. To express the hysteresis, this entrapped water should be included in the total water content.

2.4 Primary drying-wetting loops of the moisture isotherm

a) Wetting stage

First of all, we consider the virgin wetting curve on the moisture isotherm. In this case, absorption starts with the porous medium in a completely dried state, and saturation monotonically increases, as the relative humidity rises (Fig. 7).

At any location during this stage, pores of radius smaller than r_c are completely saturated under equilibrium conditions, whereas larger pores would contain moisture in the adsorbed phase only, which is neglected here for the sake of brevity. Therefore, the total saturation S_{total} of the pore distribution can be obtained by integrating the individual micropore saturation over the entire porosity distribution function as,

$$S_{total} = \int_0^{r_c} \Omega dr = \int_0^{r_c} dV = 1 - \exp(-Br_c) = S_c \tag{7}$$

where, $\Omega = dV/dr$ is the derivative of the normalized volumetric porosity function V with respect to radius r. The function V, which defines the porosity distribution of gel and capillary pores, is expressed as V=1-exp(-Br) (eq. (2), (3)). To calculate the total water content in a cementitous material, the state of water in both gel and capillary pores should be considered. However, in this discussion of the moisture isotherm model, we will use the basic porosity distribution function V=1-exp (-Br) for the sake of simplicity, instead of using a total porosity distribution function that combines the gel and capillary pores.

b) Drying stage

Next, we consider the virgin drying curve, where monotonic drying starts from a completely saturated state (Fig. 7). As already mentioned, the virgin drying curve of a moisture isotherm is always higher than the corresponding wetting curve. In this case, the water entrapped due to the inkbottle effect must be added to the water content. In the above inkbottle model, we assume that water in a pore of radius r ($r > r_c$) is completely preserved. This assumption means the total fractional volume of that pore, connected to a pore whose radius is less than r_c, is equal to the amount of the additional trapped water.

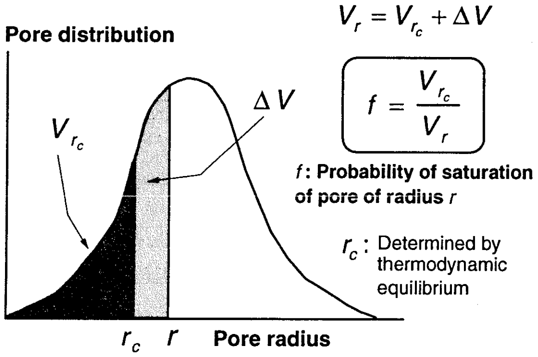


Fig.8 Definition of probability f of entrapment of water in a pore

Here, we define a probability parameter f to take into account the geometric characteristics of connections between pores of different radii. This parameter denotes the probability that a pore of radius r will be connected only to pores of radius less than r_c. In other words, as already mentioned, this parameter is the probability of water entrapment in a pore of radius r that is larger than pores of radii r_c. Obviously, this probability depends on the chance of an intersection between the larger pore and the smaller completely filled pores. In its simplest form, we take this probability to be proportional to the ratio of the volume of completely saturated pores and the volume of pores up to radius r. Based on this discussion, a mathematical definition of f can be obtained as,

$$f = \frac{V_{r_c}}{V_r} \qquad (0 \le f \le 1) \tag{8}$$

where, V_{rc} : the volume of pores of radius up to r_c, which is in fact the volume of fully saturated pores, and V_r : the volume of pores of radius up to r. This probability parameter f is based on the concept that the geometric connection between pores is perfectly random. Moreover, as a material parameter expressing macroscopic random pore structures, the pore volume using this model might have a clear physical meaning and validity. It should also noted that parameter f vanishes at unit saturation value, where the drying and wetting curves meet.

Based on the above discussion, the saturation of pores S_{ink} due to the inkbottle effect could be obtained from information on the probability parameter f and porosity distribution function. This is done by summing up the most probable degree of saturation of all pores of radius greater than r_c, over the porosity distribution from pore radius r_c to infinity. Mathematically,

$$S_{ink} = \sum_{r=r_c}^{\infty} f \cdot \Omega \cdot \Delta r = \int_{r_c}^{\infty} f dV = -S_c \ln(S_c) \tag{9}$$

where, S_c is the saturation due to the condensed liquid water in all pores of radius less than r_c and, in fact, is saturation on the virgin wetting curve. It should be noted, that $-S_c\ln(S_c)$, is always positive, thus matching the observation that the drying curve is always higher than the adsorption curve. It is also important to note that, as shown in Eq. (9), this analytical solution does not depend on assumptions regarding the mathematical description of porosity distributions. Thus this equation can be applied to an arbitrary porous model, and will provide an estimate of the trapped water as long as S_c or the virgin wetting history of the porous medium is known.

Finally, total saturation under virgin drying conditions can be obtained by simply adding S_{ink} to S_c as,

$$S_{total} = S_c + S_{ink} = S_c[1 - \ln(S_c)] \tag{10}$$

2.5 Scanning curves of the moisture isotherm

The previous section described a computational model for a quantitative representation of moisture behavior in concrete under virgin wetting-drying conditions. However, actual concrete structures are often exposed to variable environmental conditions, and virgin loops are not sufficient for predictions in such cases. Therefore we need to extend the application of this concept to account for arbitrary environmental conditions, such as complex cyclic wetting-drying. As with the virgin wetting and drying situations, we discuss two cases which cover all possible scenarios of drying-wetting paths. These paths on the isotherm are expressed by scanning/inner curves.

a) From wetting to drying

Figure 9 schematically illustrates the moisture state in concrete exposed to drying conditions after some initial period of wetting. During the monotonous wetting phase, the adsorption curve is similar to the virgin wetting curve (Fig. 9, $h \rightarrow i \rightarrow j$). However, when the relative humidity decreases again, the desorption curve cannot be assumed to return along the virgin curve, but rather it traces an inner scanning drying curve as $j \rightarrow k \rightarrow l$. For these scanning drying curves, the inkbottle model is applied as in the earlier virgin drying case and the saturation owing to the inkbottle effect S_{ink} can be obtained as,

$$S_{ink} = \int_{r_c}^{r_{\max}} f dV = S_c\left[\ln\left(S_{r_{\max}}\right) - \ln\left(S_c\right)\right] \qquad (11)$$

where, r_{max}: pore radius of the largest pores which experienced complete saturation in the wetting history of the porous medium, and S_{rmax} : peak saturation experienced by the porous medium in its

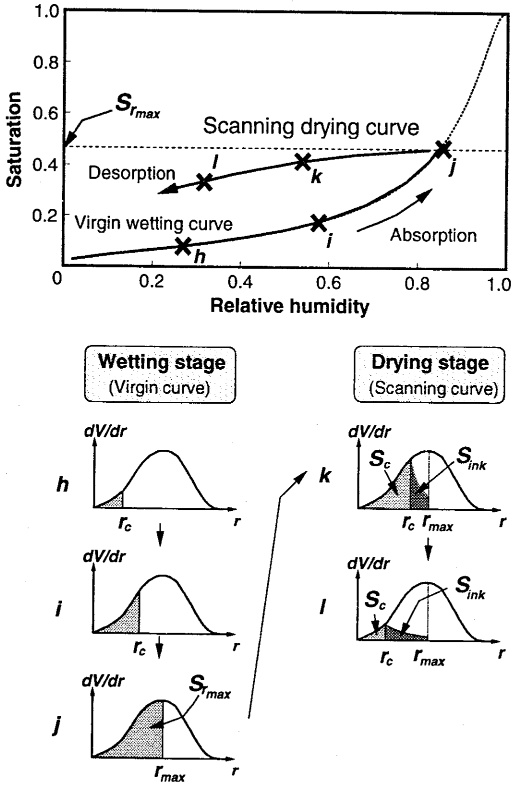


Fig.9 Scanning curves for a porous medium initially completely dry

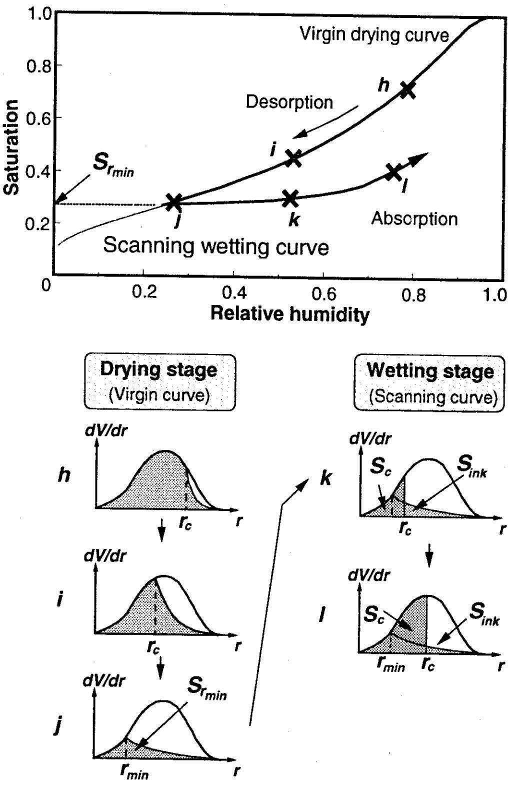


Fig.10 Scanning curves for a porous medium initially fully wet

wetting history. In fact, r_{max} is the radius of pores corresponding to the saturation state S_{rmax} of the porous medium (Fig. 9, point *j*). In Eq.11, the summation used to obtain the amount of trapped water is carried out till r_{max}, since pores whose radius is greater than r_{max} have never experienced complete saturation in their wetting history. Thus, the total saturation as a sum of the usual condensed and entrapped water is obtained as,

$$S_{total} = S_c + S_{ink} = S_c\left[1 + \ln\left(S_{r_{\max}}\right) - \ln\left(S_c\right)\right] \tag{12}$$

In the inner loops, absorption and desorption processes are assumed to be reversible so that the inner scanning curves follow a similar path. Moreover, in the drying-wetting history if wetting proceeds such that r_c exceeds r_{max}, then the adsorption path will return to the virgin wetting loop. We have assumed this reversibility for the inner loops primarily to obtain a closed-form analytical solution of the hysteresis model. Of course, based on the inkbottle concept discussed earlier, it is possible to trace exact hysteresis behavior for the inner loops. However, this would require keeping track of all turning points in the drying-wetting history and would thus limit the practical applicability of the model.

b) From drying to wetting

As with the previous case, during the first period of drying, saturation would decrease along the virgin drying loop (Fig.10, *h*→*i*→*j*). However, when the ambient relative humidity increases, a scanning absorption loop would be formed and moisture would gradually return as it filled up the smaller pores (Fig.10, *j*→*k*→*l*). In this case, also, the total saturation is the summation of S_c and S_{ink}. At this stage, S_{ink} means the entrapped water left after the initial drying stage, and is expressed as,

$$S_{ink} = \int_{r_c}^{\infty} \frac{S_{r_{\min}}}{V} dV = -S_{r_{\min}} \ln\left(S_c\right) \tag{13}$$

where, r_{min} : pore radius of the smallest pores which experienced emptying in the drying history and S_{rmin} : minimum saturation of the porous medium in its wet-dry history (Fig. 10, point *j*). The integration in the case is carried out from pore radius r_c, since all pores below r_c would be completely saturated. The total water content is computed as,

$$S_{total} = S_c + S_{ink} = S_c - S_{r_{\min}} \ln\left(S_c\right) \tag{14}$$

The scanning curves of absorption and desorption paths are assumed to be similar for the reasons explained earlier. As drying proceeds such that r_c becomes smaller than r_{min}, the desorption path will again return to the virgin drying loop.

2.5 Hysteresis behavior of moisture in interlayer pores

A C-S-H grain formed by hydration is known to have a layer structure [11][12]. In this research, we will treat the water existing between the layers of this structure as interlayer water. The mechanical behavior of interlayer water is quite different from that of gel and capillary water, since it is restrained by strong surface forces and some is chemically combined [6][12]. For this reason, we distinguish between this and other water components, and consider its specific hysteresis behavior separately.

The process by which water is removed from such layers is different from its re-entry during adsorption, thus accounting for the hysteresis. During drying, it has been experimentally shown that interlayer water loss occurs

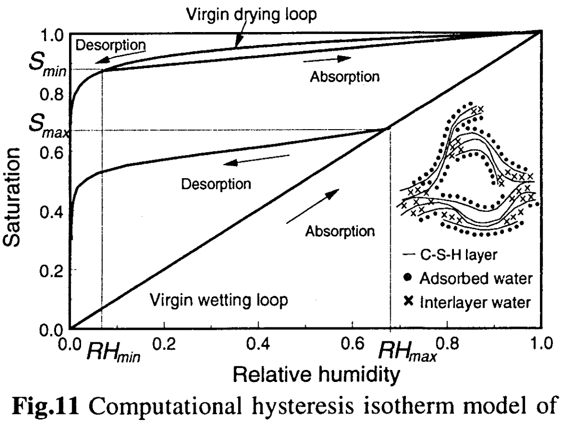


Fig.11 Computational hysteresis isotherm model of interlayer component

gradually between 30% to 10% RH, and that further removal occurs when the RH is less than 10% [6]. On the other hand, during the wetting process, re-entry of interlayer water takes place gradually as the relative humidity increases. During wetting, therefore, we assume that interlayer saturation S_{lr} is a linear function of relative humidity. Based on this understanding, the hysteresis functions of interlayer moisture are assumed to be (Fig. 11),

$$S_{lr} = RH \quad \text{Virgin wetting loop} \quad (15)$$

$$S_{lr} = RH^{0.05} \quad \text{Virgin drying loop} \quad (16)$$

$$S_{lr} = S_{\max} \cdot RH^{0.05} \quad \text{Scanning curve, initially fully dried} \quad (17)$$

$$S_{lr} = \frac{S_{\min} - 1}{RH_{\min} - 1}(RH - 1) + 1 \quad \text{Scanning curve, initially fully wet} \quad (18)$$

where, S_{max} : peak saturation experienced by the porous medium in its wetting history, S_{min} : minimum saturation of the porous medium in its drying history, and RH_{min} : minimum relative humidity experienced in its drying history. The proposed relationship between saturation and relative humidity was not derived theoretically, but was empirically obtained from experimental results. This is because the exact thermodynamic behavior associated with these processes is not clearly understood. However, by using the above relationships, the interlayer water can be predicted more reasonably.

3. Verifications

3.1 Computational scheme

An analytical study of the hysteresis behavior of moisture isotherms was implemented using the proposed isotherm model. The model is able to express the moisture state in a porous material, once the micro-structure and exposure environment history are given. Therefore, it is possible to predict the water content of a concrete structure for arbitrary conditions by combining the hydration and micropore structure development process with the isotherm model.

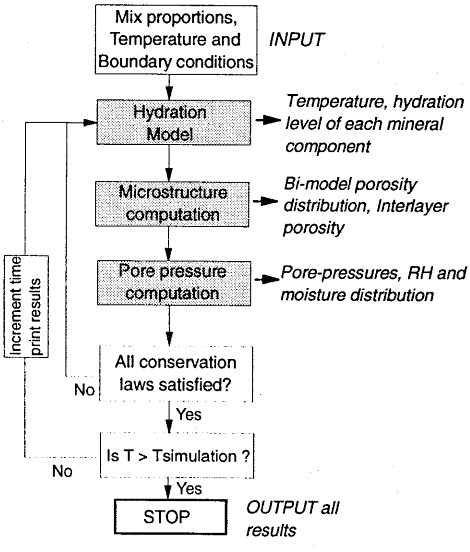


Fig.12 Coupled 3D-FEM scheme of solution for hydration moisture transport and structure formation problem in concrete

The analytical code **DuCOM** has been established for the purpose of evaluating the material properties of concrete at a young age. This code considers the inter-relationships between hydration, moisture transport, and micro-pore structure development [9][15]. An outline of the overall computational scheme is shown Fig.12. The inputs required in this scheme are mix proportion, powder material characteristic, casting temperature, the geometry of the target structure, and the boundary conditions to which the structure will be exposed during its life cycle. First of all, using the multi-component hydration model, solutions to the temperature, degree of hydration, and amount of chemically combined water are obtained [13][14]. Once this information related to the hydration process is obtained, the geometry of the pores is determined by the pore structure development model. The resulting porosity and pore distributions are used to evaluate moisture conductivity. Using the moisture transport model, which considers both vapor and liquid transports, the pore pressures, relative humidity, and moisture distribution can be obtained [5][16]. In calculating the pore pressures, the governing equation is the mass balance of moisture and this should be satisfied. In this scheme, the moisture consumed by the hydration process is included in the mass balance equation. This inter-dependency makes it possible to couple the early-age hydration problem dynamically, and also makes it possible to consider the hydration process under any curing and environmental conditions. As for the heat transfer process, by applying the

Table.1 Mix proportion of mortar specimens

Case	W/C	Mix unit weight [kg/m^3]			
		W	S	Lime	C$^{1)}$
I	0.25	266	1036		1064
II	0.55	382	1036		694
III	0.325	247	738	40	1191
IV	0.253	289	1144		917

1) Medium heat portland cement

thermodynamic energy conservation, the temperature distribution can be obtained. Based on the above, **DuCOM** can give solutions for the various material properties in 3D space and the time domain. The proposed isotherm is the moisture transport model in the program. Given the micropore structure, and the experienced environmental history, we can predict the water content for arbitrary environmental conditions, including complex cyclic drying-wetting conditions.

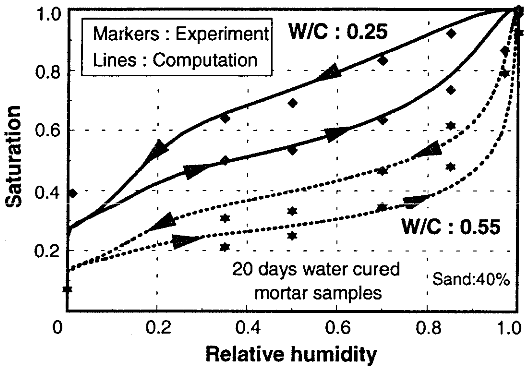


Fig.13 Experimental and computed isotherms for different mortars

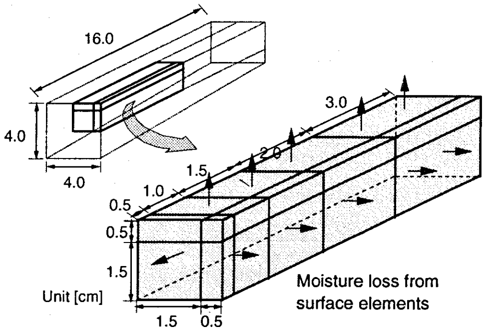


Fig.14 Mesh layout for FEM analysis

3.1 Computational scheme

a) Hysteresis behavior on moisture isotherm

To verify the proposed isotherm model, we carried out tests on mortar specimens, which are easier to produce than concrete specimens. If natural aggregates of low porosity were used, moisture could be assumed to exist only in the paste matrix, so mortar specimens can be substituted for concrete since moisture transport between aggregate and paste is negligible. Obviously, if high-porosity aggregates such as lightweight aggregates were used in the concrete mix, the moisture profiles of mortar and concrete would be different. The roles and significance of these components, i.e., aggregates and the interfaces between aggregate and matrix, to the moisture transport process have been discussed in the past by some of the authors [5]. By combining the moisture transport processes in these components using the concept of local moisture transfer, overall moisture transport behavior can be obtained.

The first case is a study of the hysteresis behavior of moisture isotherms under drying-wetting conditions. The mix proportions of the mortar specimens in this work are shown in Table.1 (Cases I and II). In the experiment, after one day of sealed curing, the specimens were immersed in water for 20 days. After the curing period, the specimens were broken into several smaller pieces (about 1 cm^3 each) and kept in a humidity and temperature control chamber. The relative humidity inside the chamber was gradually decreased in several steps, with each step held constant for more than two days. After that, the samples were freeze dried and again exposed to increasing humidity in several steps with each step held for about two days. Weight measurements were taken at the end of each step to obtain the water-content and isotherm loops. The saturation S of the experimental specimens is calculated as follows,

$$S = \frac{W_{sample} - W_{oven}}{W_{wet} - W_{oven}} \qquad (19)$$

where, W_{sample}: measured sample weight, W_{oven}: oven-dried weight in 110℃ chamber, and W_{wet}: wet weight.

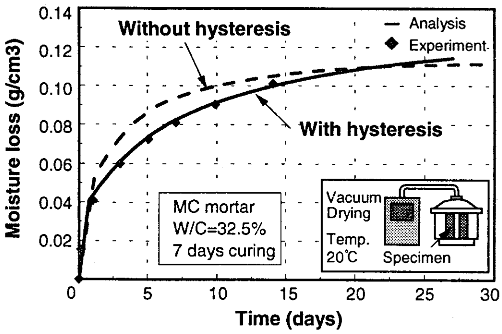


Fig.15a Moisture loss behavior under vacuum drying

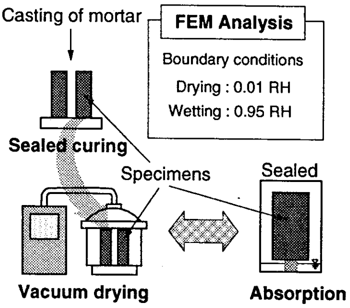


Fig.16a Schematic representation of drying-wetting experiments and computation scheme

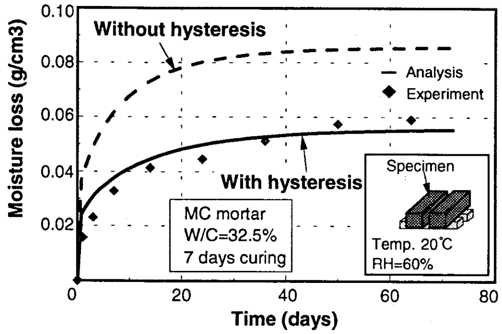


Fig.15b Moisture loss behavior under 60%RH drying

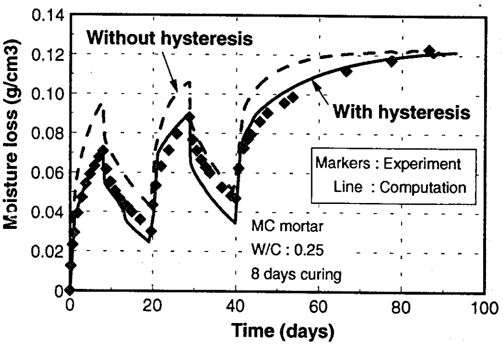


Fig.16b A comparison of the computed and measured moisture loss data for cyclic dry-wet conditions

The curing conditions and exposure conditions were input as the boundary conditions of the target structures in 3D-FEM analysis. All of the input values corresponded to the experimental conditions. In the analysis, the boundary condition for freeze drying was taken as 0.005RH. The computed saturation of the specimens can be obtained as,

$$S = \frac{\phi_{cp} \cdot S_{cp} + \phi_{gl} \cdot S_{gl} + \phi_{lr} \cdot S_{lr}}{\phi_{total}} \tag{20}$$

where, ϕ_{cp}: capillary porosity, ϕ_{gl}: gel porosity, ϕ_{lr}: interlayer porosity, ϕ_{total}: total porosity ($=\phi_{cp} + \phi_{gl} + \phi_{lr}$), S_{cp}: saturation of capillary pore, S_{gl}: saturation of gel pore, and S_{lr}: saturation of interlayer pore.

Computations were performed to predict the moisture isotherms of mortar samples for different W/C cases with time under cyclic drying-wetting conditions (Fig. 13). If only thermodynamic equilibrium is considered, it is impossible to treat the wetting path and the drying path separately.

b) Weight loss behavior under monotonic drying condition

When concrete is exposed to drying conditions, the relative humidity within pore structure will decrease due to the gradient in RH between ambient conditions and the concrete interior, and this results in fall in the saturation of pores. The observed total weight loss would be the summation of the reduction in saturation of each pores. Therefore, a suitable isotherm model is needed to accurately predict the rate of moisture loss and the amount of weight loss. In the experiment, the water-to-powder ratio was 32.5% and the size of the mortar specimens was 4×4×16[cm] (Table.1, Case III). After 7days of sealed curing, the specimens were exposed to both vacuum drying (Fig.15a) and 60%RH drying (Fig.15b), and the change in weight with time was measured [4]. In the vacuum drying test, specimens were dried in a glass desiccator of 20 [l] capacity connected to a vacuum pump with a pumping speed of about 50 [l/min]. In the analysis, for convenience of computation, this vacuum state was taken to be 1% humidity. The mesh used for FE analysis is shown in Fig.14. The macroscopic weight loss behavior is the summation of the moisture behavior in each element. The computational results are shown Fig.15. For comparison, we analyzed two cases: one using the proposed model and the other without the proposed model. The computed results show reasonable agreement in terms of not only the rate of moisture loss, but also the absolute amount of moisture loss. Especially, under 60% drying conditions, it is difficult to predict the amount of moisture loss because the difference between the wetting and drying loops on the isotherm is large in this case.

c) Moisture state under cyclic drying-wetting condition

The final case is the simulation of the moisture state of mortar specimens under cyclic drying-wetting conditions. The test specimens used in this case had a W/C of 25.3% in their mix proportion (Table.1, Case IV), and after 7 days of sealed curing, specimens were put taken to the extremes of the cyclic conditions: vacuum drying followed by exposure to near 100% humidity. In the computations, these states were taken as 1% humidity during drying and 95% humidity during wetting (Fig.16a). Reasonable agreement was obtained as regards weight loss. The use of hysteresis models in the adsorption isotherms clearly improves agreement with experimental results.

4. Conclusions

An analytical model for computing moisture isotherms of concrete in consideration of the inkbottle effect is proposed. It appears that the model is applicable to cementitious microstructures, since it is based on the geometrical characteristics of a random pore-structure. By using this model as a part of moisture transport model, the moisture conditions of concrete under any ambient level of relative humidity can be predicted. Computed results show that the simulated isotherms and weight loss behavior of mortar under repeated drying-wetting conditions have reasonable agreement with the experimental data.

Acknowledgement

The authors wish to thank Professor Hajime OKAMURA (University of Tokyo) for his valuable suggestions during the course of this study. We would also like to thank Associate Professor Takumi SHIMOMURA (Nagaoka University of Technology) for kindly providing the experimental data. This study was financially supported by grant-in-aid for scientific research No.06555125 from the ministry of education of the Japanese government.

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