AN ANALYTICAL METHOD OF MOISTURE TRANSFER WITHIN CONCRETE DUE TO DRYING

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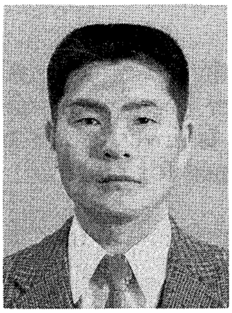

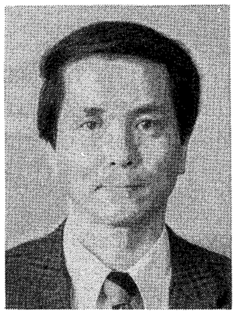

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Moisture transfer within concrete during drying is analyzed using a non-linear diffusion equation. The overall analysis procedure is established by comparing numerical results with experiments for a wide range of concrete mix proportions. Coefficient values needed in the analysis are also described for a wide range of water-cement ratios and certain characteristics of these coefficients are discussed on the basis of the numerical results. In addition, the effects of evaporative heat loss on water transfer are considered by an analysis of simultaneous heat and moisture transfers. Results show that the effect is negligible when drying takes place at room temperature and humidity.

Keywords: moisture transfer, concrete, drying, diffusion

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1. INTRODUCTION

Moisture transfer within concrete during drying causes shrinkage and cracks. Since it is difficult to observe moisture transfer within real concrete structures, an analytical prediction method, based on an appropriate theory, is required. Although linear diffusion equations were initially applied to moisture transfer, Bazant et al. [1] demonstrated that a non-linear equation was necessary because the coefficient of diffusion varies widely with water content. Sakata et al. [2] proposed a method of obtaining the coefficient from experimental values of water content by using Bolztmann's transformation [3].

In a previous paper [4], the authors applied the same method as Sakata et al. not only to drying, but also to moisture absorption and water absorption within the mortar. In this paper, the drying process of concrete is investigated both by experiment and analysis based on the previous results obtained for mortar.

Three issues are raised for previous researches on moisture transfer within concrete. The first is whether a diffusion equation is suitable for the analysis. This point has not been fully discussed in spite of its fundamental importance. The second is the need to clarify the variation of diffusion coefficient and other factors with concrete mix proportion, because those are essential to carrying out an analysis. So far, there is no research that elucidates the variation of all coefficients and other factors necessary in the analysis. The third issue is that there has been insufficient discussions of the consistency between experimental results and analysis and of the reliability of experimental results.

In this paper, these three issues are discussed or clarified on the basis of experimental results considered to be the most reliable. This allows us to establish a complete procedure for the analysis of moisture transfer within concrete during the drying process. In addition, three-dimensional heat and water transfer is analyzed and the effects of evaporative heat loss are clarified. A prismatic specimen dried from six faces is also analyzed using a three-dimensional model in order to examine the applicability of the present procedure.

2. EXPERIMENT

In order to know moisture transfer, the variation in water content at each point in a concrete specimen was measured in this research. The definition of relative water content (explained in 3.1) was 100% for a water-saturated state in a water curing pool and 0% for the oven-dried state at 105 °C. The water content at each point was obtained by splitting the specimen and comparing the weight difference of each piece between before and after oven drying. This procedure is considered to be the most direct and reliable method in spite of its three faults: it only gives the average water content in each piece; different specimens are observed each time; and many specimens are required.

Table 1 Mix proportions of specimens for one-face drying and obtaining equilibrium water content

Mix No.	W/C (%)	s/a (%)	Unit weight (kg/m³) C	W	S	G
(1)	50	43	360	180	757	1003
(2)	60	43	300	180	778	1031
(3)	70	43	257	180	792	1050
(4)	50	43	300	150	810	1074
(5)	70	43	300	210	745	987
(6)	30	43	600	180	667	883
(7)	100	43	180	180	825	1092

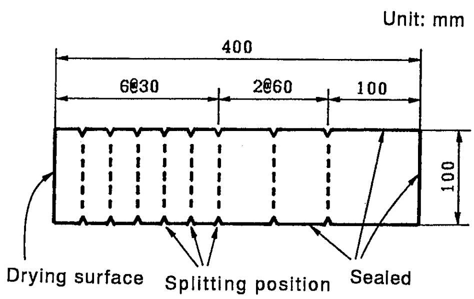

Fig.1 One-face drying specimen

The specimens were made with normal Portland cement, river aggregate (specific gravity: 2.54, maximum size: 20 mm) and river sand (specific gravity: 2.53). They were cured for 28 days. The drying atmosphere was chosen to be 20 °C and 60% relative humidity.

Three types of experiment were carried out. The first was one-face drying to observe the water content profiles under one-dimensional moisture transfer. Second was six-face drying to observe the weight decrease of a specimen over a wide range of mix proportions. Finally, an experiment to observe equilibrium water content for several atmospheric humidity was carried out.

The mix proportion of specimens for one-face drying experiments is shown in Table 1 as number (1)-(5). The specimens were 10×10×40 cm prisms, and they were notched in preparation for later splitting as shown in Fig. 1. In order to produce one-dimensional moisture transfer, five of the faces except one 10×10 cm face were sealed with plastic film and paraffin. Sealing effect was confirmed by making a control specimen with all faces sealed; it suffered a weight loss of only 0.2 g over 8 weeks.

For specimens drying through all six faces, 30 mix proportions were used. The variables in the mix proportions are shown in Table 2. The mix proportions of the specimens used to obtain equilibrium water content are numbers (1), (3), (6), and (7) in Table 1. The specimens were sliced into 1.5 cm thick sections from the 10×10×40 cm prisms, and dried in a desiccater under various conditions of relative humidity. In order to produce the atmosphere of a certain relative humidity, sulfuric acid having concentration given in Table 3 was placed in the desiccater with the drying specimens. Weight change was used to judge whether equilibrium had been achieved or not at each relative humidity. Equilibrium was supposed to have been reached six weeks after setup because no further change in weight could be observed.

Table 2 Mix proportion variables for six-face drying specimens

Water-cement ratio W/C (%)	30,35,40,45,50 55,60,70,100
Volumetric aggregate ratio Va (%)	60,65,70,75
Sand percentage s/a (%)	46
Maximum size of aggregate (mm)	20

Table 3 Relative humidity and correlated sulfuric acid concentration

Relative humidity (%)	Sulfuric acid concentration (%)
0	95.6
20	57.9
40	47.8
60	38.4
80	26.1

3. ANALYSIS

3.1 Differential Equation of Simultaneous Moisture and Heat Transfer

As in the previous paper, relative water content R is defined as follows in order to determine independently on mix proportion:

$$R = \psi / \psi_s \times 100 \tag{1}$$

where ψ (%) represents water content and ψ_s (%) water content in the saturated state.

The basic equations are the simultaneous non-linear diffusion equations when heat transfer is considered as well as moisture transfer [5]:

$$\frac{\partial R}{\partial t} = \nabla(D\nabla R) \tag{2}$$

$$\rho C_c \frac{\partial T}{\partial t} = \lambda \nabla^2 T + Q\frac{\partial R}{\partial t} \tag{3}$$

where t: time (s); ∇: differential operator; D: diffusion coefficient (m^2/s); ρ: density of concrete (kg/m^3); C_c: specific heat of concrete ($J \cdot kg^{-1} \cdot K^{-1}$); T: temperature (K); λ: thermal conductivity of concrete ($W \cdot m^{-1} \cdot K^{-1}$); and Q: evaporation heat of water (J/kg).

The second term on the right-hand side of Eq. (3) represents the latent heat used in evaporation. In a precise analysis of simultaneous moisture and heat transfer, moisture transfer caused by temperature gradient (the Soret effect) and heat transfer caused by water content gradient (the Dufour effect) must be considered. However, they are not considered in this analysis because such effects are known to be negligibly small under normal conditions [6]. Thus, only two effects are considered: temperature variation caused by evaporative heat loss and fall in evaporation rate caused by temperature drop on the drying surface.

In the case of drying from the saturated state, the basic equations are solved under the initial conditions:

$$R(x,y,z) = 100 \quad (4)$$
$$T(x,y,z) = T_0 \quad (5)$$

and the boundary conditions:

$$D\frac{\partial R}{\partial n} + \alpha_m(H_s - H_0) = 0 \quad (6)$$
$$\lambda\frac{\partial T}{\partial n} = \alpha_c(T - T_0) + q \quad (7)$$

where T_0: ambient temperature (K), n: normal vector to the drying surface, α_m: surface factor (m/s), α_c: heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), H_s and H_0: relative humidity of drying surface and atmosphere (%), q: latent heat of evaporation (W/m^2).

3.2 Equilibrium Water Content

In order to analyze moisture transfer within concrete using diffusion equations, the relation between water content and relative humidity must be known. Since water in concrete is usually in equilibrium with the vapor pressure at any particular point, the water content is determined according to relative humidity. Curves expressing this relation are called isotherms. Few isotherms have been reported so far, since it takes a long time to obtain each equilibrium by experiment.

The isotherms obtained from the present experiments are shown in Fig.2. It can be seen that relative water content depends not only on the relative humidity but also on the mix proportion of the concrete. Isotherms were determined from the experimental results by the following procedure.

First, the relative water content R is assumed to be a function of two variables H and γ (γ expresses the water-cement ratio, W/C). The function is assumed to be a perfect polynomial as follow.

$$R = a_1 + a_2H + a_3\gamma + a_4H^2 + a_5H\gamma + a_6\gamma^2 + a_7H^3 + a_8H^2\gamma + a_9H\gamma^2 + a_{10}\gamma^3 \quad (8)$$

The undefined constants a_1-a_{10} are determined from two conditions: R=100% when H=100% for arbitrary γ, and the curved surface expressed by Eq. (8) becomes the least squares approximation to the experimental data. The final values of these constants are shown in Table 4 and the final isotherms are also shown in Fig. 2.

3.3 Surface Factor

The surface factor is needed for boundary condition (6). Vapor diffusion from the drying surface is thought to depend on capillary pores open to the surface, except in the initial stage when the whole surface is wetted. Since this implies that the surface

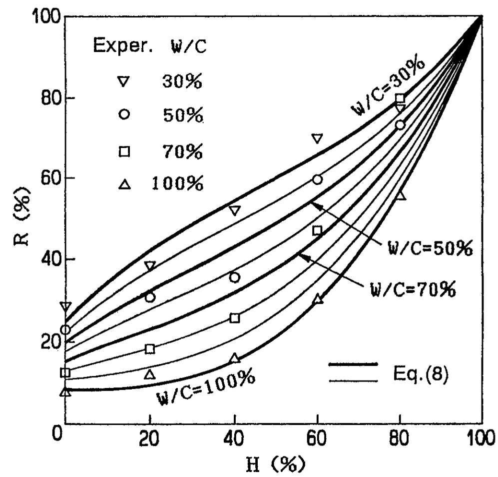

Fig.2 Isotherms

Table 4 Constants in Eq.(8)

Constant	Value	Constant	Value
a_1	33.4	a_6	4.22×10^{-4}
a_2	1.46	a_7	7.73×10^{-5}
a_3	-0.287	a_8	1.74×10^{-4}
a_4	-1.58×10^{-2}	a_9	-4.22×10^{-6}
a_5	-1.45×10^{-2}	a_{10}	0

factor depends also on mix proportion, it is determined by trial and error so as to match analytical values of weight decrease with the experimental data in the early stage. Because, the influence of surface factor on weight decrease is significant in the initial stage but rapidly becomes small as time passes.

Surface factors, initial water amounts and weight decreases during the first hour are shown in Table 5 for mix proportions (1) to (5). Initial water amount means the water contained in a specimen initially, which is obtained from the weight difference between the saturated state and the oven dried state. Since relative water content equals to the percentage of water amount against the initial water amount, a larger surface factor results in more weight loss when the initial water amount is the same. In fact, this can be seen by comparing the mix proportions (1) and (3) in Table 5.

3.4 Diffusion Coefficient

As Sakata et al. have indicated, the diffusion coefficient can be obtained from experimental values of water content using Boltzmann's transformation. If the moisture transfer obeys the diffusion equation in one-dimensional drying, then the relation between water content and the variable

$$\eta = \frac{x}{2\sqrt{t}} \tag{9}$$

is expressed by a certain curve. The example for mix proportion (1) in Fig.3 demonstrates this, though there is some scatter in the experimental data. This result is common to the other mix proportions. It indicates that the drying process can be described by diffusion equation and that Boltzmann's transformation is applicable to an analysis of the process.

Table 5 Surface factors and others

Mix proportion	(1)	(2)	(3)	(4)	(5)
Surface factor α_m (cm/day)	4.7	4.4	5.8	6.4	7.3
Weight decrease (g)	1	1.1	1.4	1	1.6
Initial water amount (g)	756	735	754	643	786

Table 6 Constants in Eq.(11) and others

Mix	a	b	f	η_1	D_1
(1)	0.059	0.36	0.0044	3.3	4.1
(2)	0.058	0.34	0.0042	3.4	4.3
(3)	0.107	0.44	0.0041	4.7	8.3
(4)	0.091	0.4	0.004	4.4	7.1
(5)	0.084	0.39	0.004	4.2	6.6

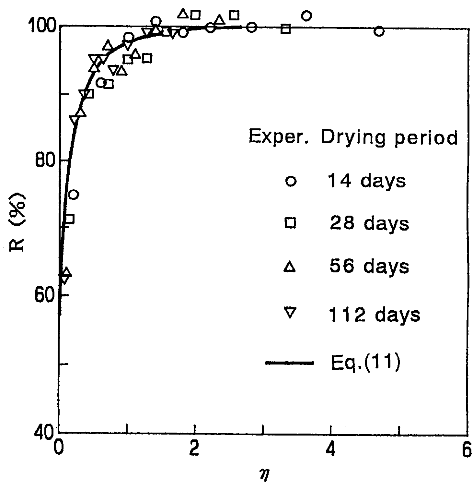

Fig.3 Relationship between η and R

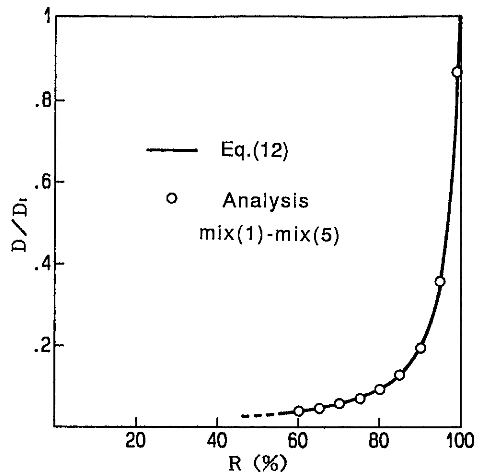

Fig.4 Relationship between R and D/D_1

From this curve, the diffusion coefficient for an arbitrary relative water content r can be derived by

$$D_{R=r} = 2\left(\frac{d\eta}{dR}\right)_{R=r} \int_r^{100} \eta dR \tag{10}$$

In order to calculate D from Eq. (10), R is expressed by the following hyperbola

$$R = 100\left\{1 + f - a/(\eta + b)^2\right\} \tag{11}$$

where a, b, and f are constants and determined as described in the previous paper. Table 6 shows these constants for the five mix proportions actually analyzed. If D_1 denotes D when R=100%, Figure 4 shows the calculated D/D_1. The curve in the figure is expressed by the following formula

$$D/D_1 = 1/\{29(1 - R/100) + 1\}^{1.4} \tag{12}$$

It can be seen that diffusion coefficient largely depends on water content; it decreases to almost 1/20 when relative water content decreases from 100% to 60%. This implies that a linear diffusion equation is not appropriate to the analysis and that a non-linear diffusion equation must be adopted.

No difference among the five curves obtained from the mix proportions (1)-(5) can be recognized in the same figure. This means that formula (12) can be commonly applied to these mix proportions. Namely, the relation between D/D_1 and R is independent of mix proportion, though the relation between D and R depends on it. Thus, the dependence of diffusion coefficient on mix proportion appears only in D_1, demonstrating the wide variation shown in Table 6.

4. INFLUENCE OF EVAPORATION HEAT ON MOISTURE TRANSFER

4.1 Simultaneous Moisture and Heat Transfer

In the moisture transfer process, heat transfer also takes place because of evaporative heat loss. This transfer of heat is neglected in conventional analysis, though the validity of doing so is not fully confirmed as yet. Thus we studied the influence of heat transfer and evaporation heat on moisture transfer through analysis.

During simultaneous moisture and heat transfer, one-face drying does not necessarily mean one-dimensional transfer, since the temperature drop caused by evaporation induces a lateral heat flow from the side faces. Thus, the three-dimensional model shown in Fig. 5 is adopted for analysis, modeling 1/8 of a specimen from symmetry. The sectional subdivision is common to all sections, and the subdivisions are made smaller towards a drying face or side faces. The material constants adopted in this analytical model are shown in Table 7. The numerical model is established using the control volume method [7]. Time integration was performed by the perfect implicit method, and the time interval adopted was 6 minutes.

Moisture transfer in concrete is understood to consist of capillary water flow when the water content is high and vapor diffusion when it is low. Water becomes vapor during the transfer process, resulting a much more complex process. In this study, the latent heat spent in converting water to vapor is dealt with as follows. Latent heat is not considered in the specimen until the relative water content decreases to 95%, since it is reported that capillary water flow switches to vapor diffusion at a relative water content of 90-95% [8]. After reaching 95%, the second term on the right-hand side of Eq.(3) is accounted in proportion to water content decrease. All water aside from that already evaporated in the specimen is assumed to reach the drying surface in liquid form. Concerning this water, evaporation heat at the drying surface is given by Eq.(7). At the five faces aside from the drying surface, only the first term of Eq.(7) is necessary, because no water can evaporate there.

Table 7 Material constants

Concrete	Heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)	5.41
	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1.34
	Density (kg/m^3)	2300
	Specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)	1.05
Water	Evaporation heat (kJ/kg)	2448
	Relative water content at which capillary flow switches to vapor diffusion (%)	95

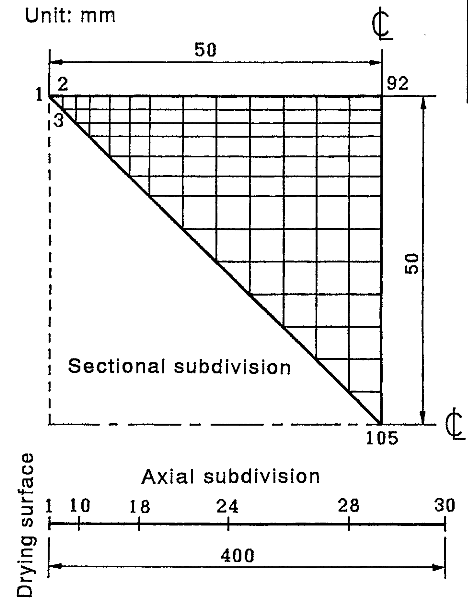

Fig.5 Subdivision for three-dimensional analysis

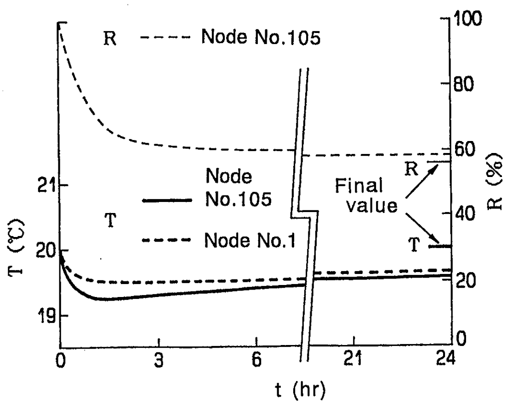

Fig.6 Temperature and relative water content at drying surface

4.2 Three-Dimensional Effects in One-Face Drying

Figure 6 shows analytical histories of temperature and relative water content at the center (node No.105 in Fig. 5) and a corner (node No.1) of the drying surface in the case of mix proportion (1). It can be seen that the temperature drop due to evaporation heat is a maximum of 0.8°C after about 1 hour, and thereafter the temperature gradually approaches ambient. The relative water content rapidly decreases and reaches approximate equilibrium with atmospheric humidity in about two hours. Final values in the figure show atmospheric temperature and the relative water content in equilibrium with atmospheric humidity, a situation reached after a sufficiently long time.

The temperature of the drying surface is lower at the center than at a corner, and the difference is at most 0.2 °C. The relative water content at the drying surface is large at center, because the temperature drop causes the decrease of evaporation. Since the difference between water content at the center and a corner is at most 0.9%, it cannot be recognized and only the water content at the center is shown in Fig. 6. These results show that the three-dimensional effects of lateral heat flow caused by evaporative heat loss are actually negligible for one-face drying under experimental conditions.

4.3 Effect of Evaporation Heat

In order to clarify the influence of evaporation heat, the one-dimensional transfer of moisture without heat transfer was also analyzed. In this case, it is simply necessary to solve Eq.(2) under initial condition (4) and boundary condition (6). Results show that evaporation is greater and relative water content is at most 2.4% smaller than in the previous result, because there is no temperature drop at the drying surface. However, this difference is only at the drying surface. The difference at inner part of 4 mm from the surface is only 0.1%. Concerning weight decrease, the difference in both results is always less than 0.1 g.

Consequently, the influence of evaporation heat can be neglected for typical levels of precision, when the object of analysis is moisture transfer. Since the results are the same for other mix proportions, the influence of evaporation does not depend on mix proportion. However, it must be mentioned that this conclusion is only appropriate to temperature conditions of around 20 °C, since all the physical constants adopted in this analysis are at that temperature.

5. DEPENDENCE OF COEFFICIENTS ON MIX PROPORTION

Unless the necessary coefficients and factors are known for all mix proportions, moisture transfer within concrete cannot actually be analyzed. It is known that water in concrete is located in the pores and that the pore structure is strongly affected by the water-cement ratio [9]. Thus, variations in coefficients and factors with water-cement ratio are clarified by comparing experimental results with the analytical results. Only moisture transfer is considered, since it is known from the previous section that the influence of heat transfer can be neglected under the experimental conditions.

5.1 Analysis of Six-Face Drying

In order to analyze six-face drying, the difference in diffusion coefficients in the casting direction and perpendicular to the casting direction must be known. For this purpose, a $10\times10\times40$ cm prism was divided into four $10\times10\times10$ cm specimens. Case 1 specimens were sealed except for two side faces and case 2 specimens were also sealed except for the cast plane and the bottom plane. The weight decreases of these specimens were observed, with the drying faces vertically in both cases in order to ensure the same drying conditions.

Figure 7 shows the results concerning mix proportions (1) and (3). For both mix proportions, the differences between the two cases are negligible, though case 1 shows a somewhat bigger weight decrease. This means that concrete can be thought

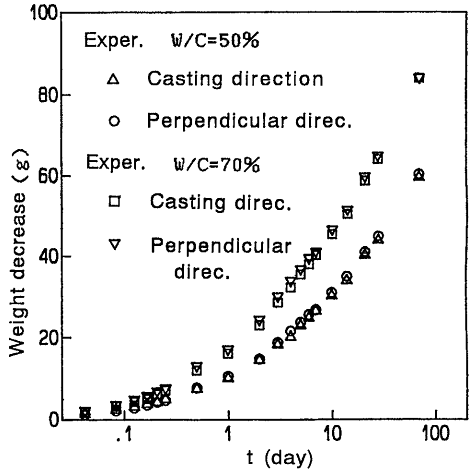

Fig.7 Weight decrease for direction of drying

Table 8 Dependence of weight decrease on α_m

Time		1hr	3hrs	6hrs	12hrs	1day	3days	7days	14days	28days	56days	112days
Weight decrease (g)	α_m=4.7cm/day	1.03	1.88	2.59	3.57	4.97	8.49	12.91	18.23	25.77	36.44	51.54
	α_m=2.3cm/day	0.62	1.47	2.26	3.31	4.74	8.3	12.74	18.07	25.61	36.29	51.4
Difference (g)		0.41	0.41	0.33	0.26	0.23	0.19	0.17	0.16	0.16	0.15	0.14
Rate of difference (%)		39.8	21.8	12.7	7.3	4.6	2.2	1.3	0.9	0.6	0.4	0.3

of as an isotropic material as regards moisture transfer, since no difference in behavior between the direction of the cast plane and its perpendicular can be recognized.

It is known that the surface factor of heat transfer in the horizontal plane is a half of that in the vertical plane [10]. However, it is not clear that the surface factor of moisture transfer exhibits the same characteristics. Even if it becomes a half, it is not a problem in the case that the influence on the analytical results is small enough to be neglected. If this can be confirmed, the same factor can be used in both vertical and horizontal planes.

Table 8 shows the weight decrease for a one-face drying specimen (1) for α_m=4.7cm/day (base value) and α_m of half this value. The weight decrease is roughly proportional to the surface factor in the initial stage, then becoming small as time passes. Even if the surface factor is half, the difference is only 2.2% of the base value after three days, and can be neglected. Thus the analytical model can be 1/16 of the specimen from a consideration of symmetry, since difference in surface factors between vertical and horizontal faces can be neglected. Consequently, a model half that shown in Fig. 5 can be used.

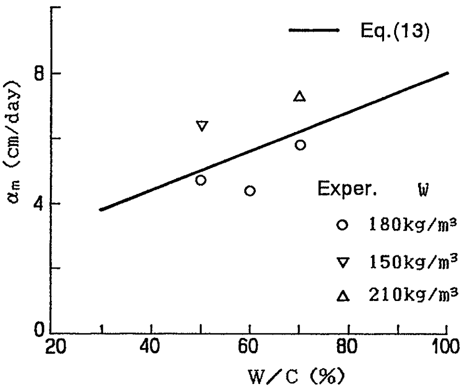

Fig.8 Relationship between W/C and α_m

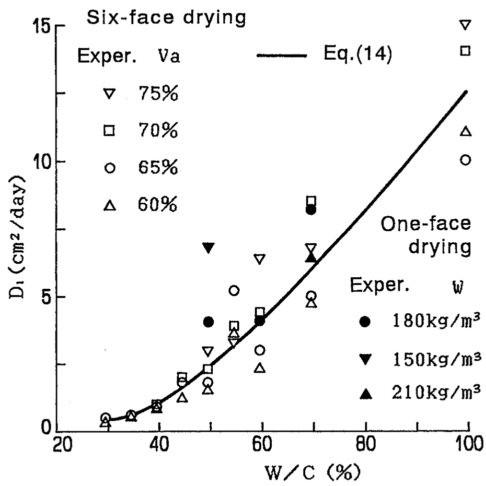

Fig.9 Relationship between W/C and D_1

5.2 Surface Factor

The relation between surface factor and water-cement ratio shown in Table 5 is graphically illustrated in Fig. 8. From Sakata et al's linear relation between them, the following formula can be derived from the experimental results:

$$\alpha_m = 0.06\gamma + 2 \tag{13}$$

5.3 Diffusion Coefficient

Both D_1 obtained from six-face drying and from one-face drying already shown in Table 6 are illustrated in Fig. 9. In the analytical process for six-faces drying, Eq.(12) and Eq.(13) were assumed to be applicable to the range W/C=30%-100%. D_1 was determined so that the experimental and analytical weight decreases coincided with each other.

Figure 9 shows that the smaller volumetric aggregate ratio is, the smaller D_1 is when W/C is the same. It might accept the validity of the analytical procedure that the relation between D_1 and W/C is almost same in both case of one-face drying and six-face drying. The curve expressing the relation in the figure is the following:

$$D_1 = 230/\gamma + 0.25\gamma - 14.7 \tag{14}$$

Figure 9 shows that D_1 varies to some extent according to volumetric aggregate ratio even for the same water-cement ratio. The prediction errors due to the error in D_1 on analytical values of weight decrease in six-face drying is shown in Fig. 10. In this figure, weight decrease is expressed as a ratio to initial water amount;

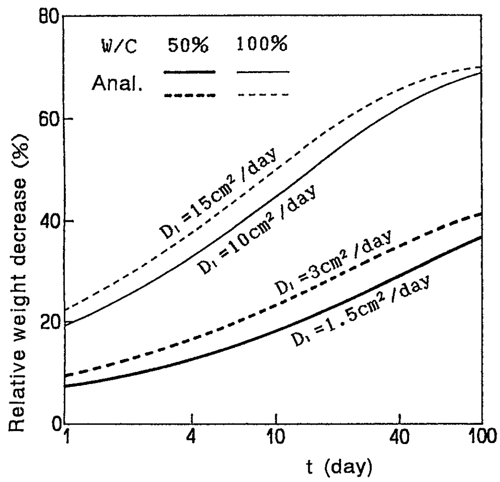

Fig.10 Dependence of weight decrease on D_1 for six-face drying

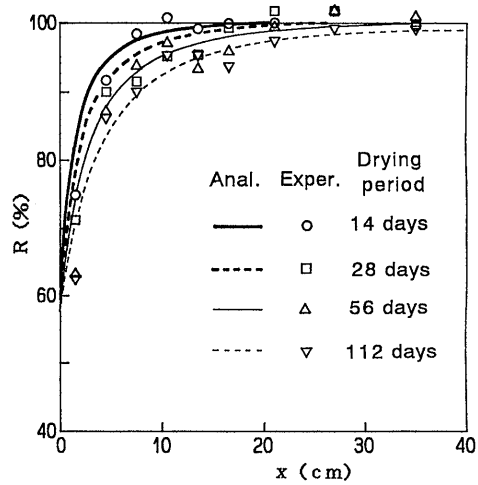

Fig.11 Profiles of relative water content for one-face drying

namely, it is a relative weight decrease. Four analytical results are illustrated for W/C=50% and 100% and for both the upper limit and lower limit of D_1 from the experiment. It might be mentioned that the analytical cases are upper and lower limits, though the error of weight decrease due to the error of D_1 is not small enough to be neglected. Thus, it is considered that analytical error is not so great in general, even if D_1 is determined from Eq.(14).

6. DISCUSSION OF VALIDITY OF ANALYTICAL PROCEDURE

6.1 One-Face Drying

Figure 11 shows experimental and analytical relative water contents for one-face drying in the case of mix proportion (1). The observed data exhibit some scatter, and some of the data exceed 100% in relative water content. The reasons for this scatter are considered to be that the thickness and the coarse aggregate ratio of each split piece varies. However, the experiments can be considered reliable, since the overall distributions are appropriate in space and time in spite of the scatter. One reason for accepting the validity of the analytical procedure is that the analytical results appropriately match the experimental variations in relative water content in space and time.

Figure 12 shows the experimental and analytical weight decreases for mix proportions (1) and (3). The data are averages of three specimens, and the differences among the individual observations are at most 1.3 g, demonstrating the

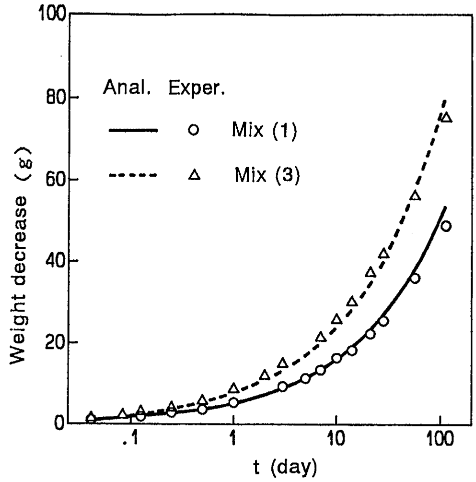

Fig.12 Weight decrease for one-face drying

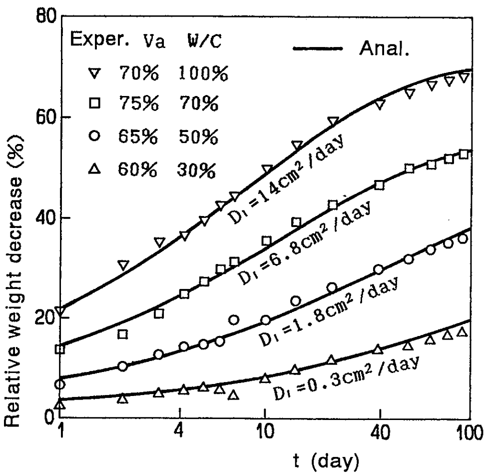

Fig.13 Weight decrease for six-face drying

accuracy of the experiment. It can also be seen that the experimental and analytical results agree closely up to 112 days. Of course, the diffusion coefficient was chosen so as to match the analytical weight decrease with the experimental values. However, a further measure of the validity of the analytical procedure might be that coincidence is obtained over the whole period.

6.2 Six-Face Drying

Figure 13 shows the histories of relative weight decrease for six-face drying. It can be seen that experimental and analytical results almost agree at every time and for every mix proportion. This indicates that Eq.(12), representing the D-R curve obtained from one-face drying, can be applied to the analysis of six-face drying. This good agreement is also considered one reason to accept the validity of the analytical procedure. Figure 13 also shows that the variations in water-cement ratio greatly affect the weight decrease. This reason is considered that the factor having most influence on weight decrease is the relative water content at the drying surface obtained from the isotherm (Fig. 2).

7. CONCLUDING REMARKS

In order to establish an analytical method for moisture transfer within concrete due to drying, and in order to provide actual data for the analysis of concrete with any mix proportion, experimental and analytical studies were performed. The following conclusions were reached.

(1) The validity of a non-linear diffusion equation to moisture transfer is considered to be confirmed on the basis of various evidence: Boltzmann's transformation can be successfully applied; diffusion coefficients consistent with experimental results coincide for one-face drying and six-face drying; experimental and analytical weight decreases coincide for both types of drying; and experimental and analytical relative water content profiles almost coincide for one-face drying.

(2) All of the coefficient, factor and relationship needed in the analysis were obtained from the experiments: the relation between equilibrium water content and surrounding humidity in Fig. 2; the surface factor in Fig. 8; and the diffusion coefficient in Fig. 9.

(3) As regards equilibrium water content, surface factor, and diffusion coefficient, the following points are clarified:
a) The relation between water content and relative humidity is greatly affected by mix proportion and this has a great influence on analytical results.
b) Expressed in terms of D/D_1, the diffusion coefficient can be written as Eq.(12) independently of mix proportion.
c) The diffusion coefficient decreases to 1/20 when the water content decreases from the saturated state to an intermediate state. This indicates that a linear diffusion equation cannot be applied to moisture transfer.
d) D_1 varies widely according to W/C, and the relationship between them obtained from one-face drying and six-face drying are almost coincide.
e) For the same W/C, D_1 tends to become large when the unit water weight is small or the volumetric aggregate ratio is large.
f) The influence of surface factor on analytical water content or weight decrease is small except in the initial stage of drying.

(4) If the mix proportion of the concrete and the atmospheric conditions are known, the water content distribution can be analyzed. The procedure is as follows.
a) D_1 corresponding to W/C of the concrete is determined from Eq.(14).
b) D/D_1 is determined from Eq.(12), and then D is obtained for any relative water content.
c) The surface factor α_m corresponding to W/C is determined from Eq.(13).
d) The non-linear diffusion equation (2) is solved under initial condition (4) and boundary condition (6). The relationship between H and R necessary for the boundary condition is obtained from Eq.(8) and Table 4.

(5) As far as one-face drying under normal conditions is concerned, three-dimensional effects induced by lateral heat flows caused by evaporative heat loss are small. Also, the influence of evaporative heat loss on water content and weight decrease is negligible.

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