論文 Simulation of Drying Shrinkage under Cyclic Ambient Humidity Condition

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ABSTRACT: Drying shrinkage of concrete specimens subject to a cyclic ambient humidity condition is simulated by employing axisymmetric finite element modeling and the concept of fictitious layer at the drying surface. The difference in shrinkage behavior for constant and cyclic ambient humidity as well as the effect of specimen size are discussed.
KEYWORDS: drying shrinkage, cyclic humidity change, simulation, modeling, concrete

1. INTRODUCTION

Variations of environmental factors, such as temperature, humidity, wind speed, etc. are commonly considered to give significant influences on the drying shrinkage strain behavior of concrete. Some experimental and analytical works have been done to understand and predict the influence of these factors on drying shrinkage strains using real environmental conditions, such as the work of Fattuhi and Al-Khaiat [1] and that of Torrenti *et al.* [2] which concern drying shrinkage response due to real climate conditions. While a comprehensive approach by taking into account as many environmental factors as possible is always rendered necessary for an appropriate shrinkage prediction, this approach requires that the influence of each factor on drying shrinkage be thoroughly understood. When humidity factor is concerned, one of the important problems which still need to be addressed, and therefore become the topic of the present work, is the influence of cyclic environmental humidity condition on the drying shrinkage behavior of concrete.

It is generally expected that the average shrinkage strain subject to a cyclic ambient humidity condition is close to that due to constant ambient humidity of the mean of the cyclic humidity values, however some experimental data seem to contradict it. The experiment done by Muller *et al.* [3], for example, shows that the shrinkage strain due to a cyclic ambient humidity condition is smaller than that due to a constant ambient humidity. In this work a numerical investigation is performed to study shrinkage behavior under constant as well as cyclic ambient humidity condition using axisymmetric finite element modeling. Based on the simulation results, the effect of specimen size and cyclic humidity period on shrinkage behavior is discussed.

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2. MODEL OF DRYING SHRINKAGE

2.1 MOISTURE DIFFUSION

An internal moisture flow assuming a nonlinear diffusion process in which the diffusivity D is dependent on the local relative humidity h is used in the modeling, as given in Eq. 1. The accuracy of this assumption has been confirmed by simulation studies[4] for various experimental results.

$$\nabla(D(h)\nabla h) = \frac{\partial h}{\partial t} \tag{1}$$

In this model, the humidity-dependent diffusivity D is represented by a tri-linear model, as shown in **Fig.1**, simplifying the continuous function model[4]. The diffusivity D is constant (D_2) for the local relative humidity range between 1.0 and h_2 = 0.98. Then it decreases linearly as the local humidity decreases to h_1. At lower local relative humidity ($h<h_1$), the diffusivity assumes a constant value of $D_1 = 0.15D_2$.

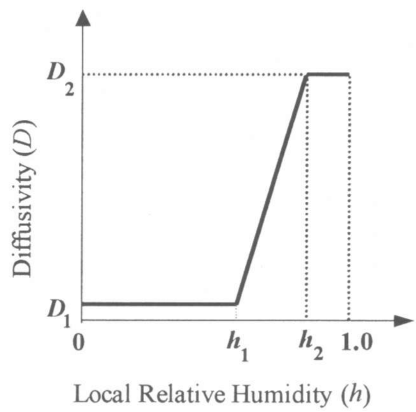

Fig.1 Humidity dependence of diffusivity

In this model it is also considered that there is a thin fictitious layer with thickness T connecting the surface of a specimen to the ambient air. It is assumed that moisture diffuses linearly in this layer so that a linear diffusion equation with diffusivity D_{fl} is used. In order to model the difference between the drying and wetting phases, D_{fl} is also considered to be proportionally dependent on the ambient humidity, as given in Eq. 2,

$$D_{fl} = Ch_a \tag{2}$$

where h_a is the ambient relative humidity and C is a proportional constant. At the interface between the fictitious layer and the ambient air, a fixed boundary condition is applied. This layer is conceived to regulate the rate of moisture inflow and outflow which in this model is assumed to be dependent on the ambient relative humidity. It has been confirmed through preliminary simulation that almost the same simulation results can be obtained using proper values of film coefficient and a convective boundary condition.

2.2 DRYING SHRINKAGE STRAIN

For strain calculation, a linear relationship between an incremental local relative humidity Δh and the corresponding incremental change of shrinkage strain $\Delta\varepsilon$ is assumed, as given in Eq. 3, based on the experimental observation[4],

$$\Delta\varepsilon_i = \alpha_{sh}\Delta h \tag{3}$$

where index i is used to stand for r, θ, z components and α_{sh} is a proportional constant.

2.3 MECHANICAL PROPERTIES

For stress calculation which takes into account the effect of creep, the following effective modulus E_{eff} is used.

$$E_{eff}(t,t_o) = \frac{E(t_o)}{1+\phi(t,t_o)} \tag{4}$$

where E is the modulus of elasticity, ϕ is the creep coefficient and is considered a constant for the current simulation, t stands for the current concrete age in days and t_o for the age of concrete at the start of drying. For simplicity the creep Poisson's ratio ν_{cr} is considered the same as the elastic Poisson's ratio ν.

3. NUMERICAL SIMULATION

3.1 AXISYMMETRIC FINITE ELEMENT MODELING

The model of shrinkage in the previous section is implemented into finite element modeling for numerical simulation. A four-node isoparametric axisymmetric linear element is considered appropriate to model the moisture flow of cylindrical and ring-type concrete specimens with surface drying. The same element is used to model the fictitious layer. The thickness of the fictitious layer T is set constant throughout the drying surface of the specimen. The incremental change in local relative humidity Δh is introduced to the finite element equation as incremental equivalent nodal forces.

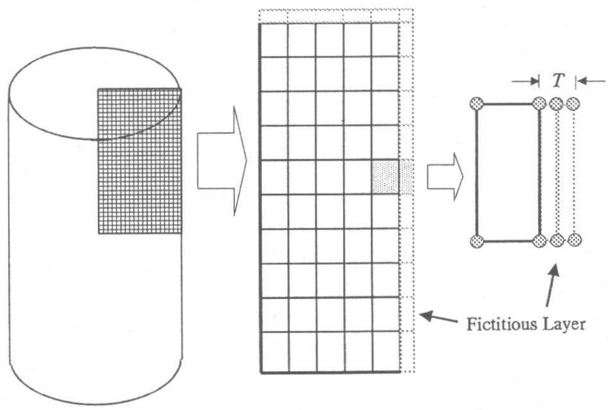

Fig.2 Discretization of specimen and fictitious layer

The schematic finite element representation of a cylindrical specimen and the fictitious layer is shown in **Fig.2**. The fictitious layer is represented by two layers of axisymmetric elements over its thickness. A fixed boundary condition is applied on the external surface of the fictitious layer.

The Euler backward scheme is used for time integration. The integration of the element diffusivity and stiffness matrices employs 2-point Gaussian numerical integration scheme.

3.2 SIMULATION OF EXPERIMENTAL DATA

The experimental data to be simulated are that of Muller *et al.*[3] and that of Al-Alusi *et al.* [5]. The mix proportions of the specimens and the drying conditions of the experiments are shown in **Table 1**.

Table 1 Experiments for cyclic humidity

Case	Experiment	Mix proportion (by weight) water/cement/sand/gravel	Age at drying t_0	Humidity condition (Range and period)
1	Muller *et al.*	0.55/1/2.85/3.15	8 days	90-40%RH, 14 days
2	Al-Alusi *et al.*	0.58/1/2/0	21 days	100-50%RH, 28 days

(a) Muller's experimental data

In Muller's experiment, cylindrical specimens with the diameter (d) to height (h) ratio d/h = 50 mm/200 mm (Case 1a) and d/h = 100 mm/300 mm (Case 1b) are allowed to dry after curing in water at 20°C for 8 days after demolding. The specimens were then exposed to either a constant ambient humidity of 65% RH or a cyclic ambient humidity. For the cyclic humidity experiment, the cycle started with 90% RH for 7 days then was followed by 40% RH for 7 days. The temperature was kept constant at 20°C and strain measurements were done at the drying surface. The modulus of elasticity at the beginning of drying was measured as 29840 N/mm^2.

Table 2 Parameters used in simulation

Case	D_2 (cm^2/day)	h_l	C (cm^2/day)	T (mm)	α_{sh}	ϕ	ν
1	0.6	0.5	0.015	1.0	1.5x10^{-3}	2.5	0.2
2	1.5	0.6	0.25	1.0	3.0x10^{-3}	1.5	0.2

A 2.5 mm x 2.5 mm element size is used to discretize specimens. The size of the fictitious layer element is 0.5 mm x 2.5 mm. Since there is no sealed surface in this experiment, the fictitious layer is applied to the entire surface of the specimen. The time step Δt is 0.5 day.

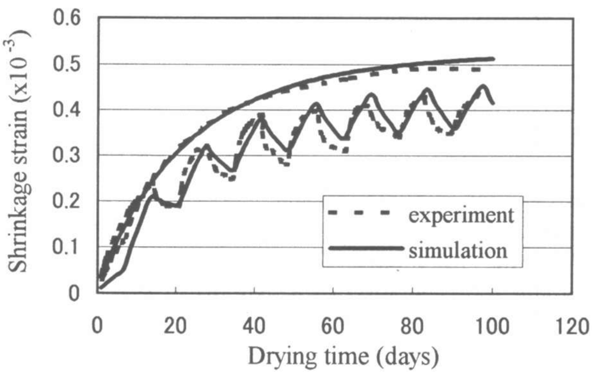

Fig.3 Simulation for Case 1a

The simulation results are shown in **Fig.3** and **4**. For both figures, the thick shady lines indicate experimental data, and the thin solid lines indicate simulation results. Smooth curves correspond to constant ambient humidity, and wavy curves correspond to cyclic ambient humidity. It is shown in the figures that the shrinking behavior and the magnitude for the constant humidity case are closely predicted. The general shrinking and swelling behavior for the cyclic humidity case, as well as the strain amplitude are also closely predicted using the parameters given for Case 1 in **Table 2**. It is confirmed that as shown by the experimental data, the simulations also predict that shrinkage strain due to constant ambient humidity is larger than that due to cyclic ambient humidity for a cyclic period of 14 days. The shrinkage strains in the early phase of drying, especially in the first 14 days, are shown to be generally higher than the simulation results. This is probably partly due to chemically induced shrinkage and mostly due to strain recovery after significant swelling during curing in water. Both physical processes are not yet considered in the present modeling.

The effect of size on shrinkage as observed in the experimental data is that specimens of larger size give smaller shrinkage strain and smaller strain amplitude. This effect is also shown by the simulation curves very closely. The simulations for these two cases (Case 1a and 1b) are performed using the same values of model parameters, as shown in **Table 2**. This result indicates that the effect of size has been represented properly in the present model.

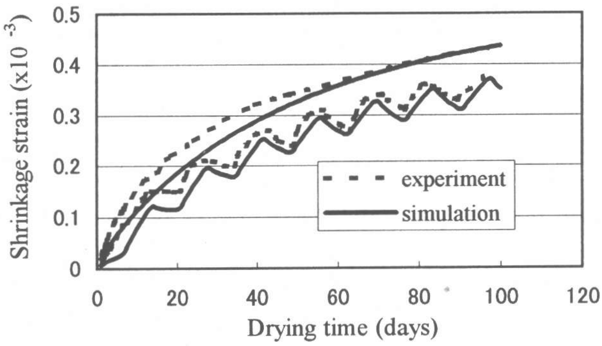

Fig.4 Simulation for Case 1b

(b) Al-Alusi's experimental data

Al-Alusi's experiment uses hollow mortar cylinders of 5 in. internal diameter, 6 in. external diameter and 40 in. length (Case 2). The specimens were cured at 100% RH and 22.8°C constant temperature for 21 days. The specimens were then exposed to either a constant ambient humidity of 50% RH or a cyclic ambient humidity. For the cyclic experiment, the cycle started with exposing the specimens to drying of 50% RH environment for 14 days, then was followed by 100% RH environment for 14 days. For simulation, the element size used is 2.54 mm x 4.23 mm, whereas for fictitious layer elements, the size is 0.5 mm x 4.23 mm. Since the top and bottom surfaces are sealed, and both the internal surface and the external surface are exposed to the ambient condition, the fictitious layer elements are applied to the drying internal and external surfaces only. The time step Δt is 0.25 day. The measured modulus of elasticity at the beginning of drying is 23566 N/mm^2.

Using the parameter values given for Case 2 in **Table 2**, the simulation results give generally close agreement for constant as well as cyclic ambient humidity cases, as shown in **Fig.5**. For the drying phase in the cyclic case, the simulation result predicts the general increasing curve and the strain magnitude closely. For the wetting phase, however, the experiment shows large increasing residual shrinkage strain with time, whereas the simulation gives much lower residual shrinkage strain. This difference between experimental data and simulation results is considered to be due to the influences of other physical and chemical factors not included in the present model. It is also observed that the decrease rate of shrinkage strain in the wetting phase is much larger in the experiment than in the simulation result. Although the conditions are not the same as those of Case 1, this result implies the necessity of more investigation in the modeling of both drying and wetting phases.

A simulation is also performed under a constant ambient humidity of 75% RH. As also shown in **Fig.5**, the magnitude of shrinkage strain is close to the average strain for the case of cyclic ambient humidity. Assuming that the simulation curve closely predicts the actual shrinkage strain, and considering the opposite behavior shown by Muller's experiment, it seems likely that whether or not the strain due to a constant ambient humidity be close to the average strain due to cyclic ambient humidity is influenced by the cyclic period. The smaller the cyclic period is, the larger is the difference between the strain due to constant humidity and the average of the strain due to cyclic ambient humidity. Therefore, for the prediction of shrinkage strain under a real environmental humidity condition, even short-period humidity variations, like daily variations, may give a significant influence on the shrinkage behavior.

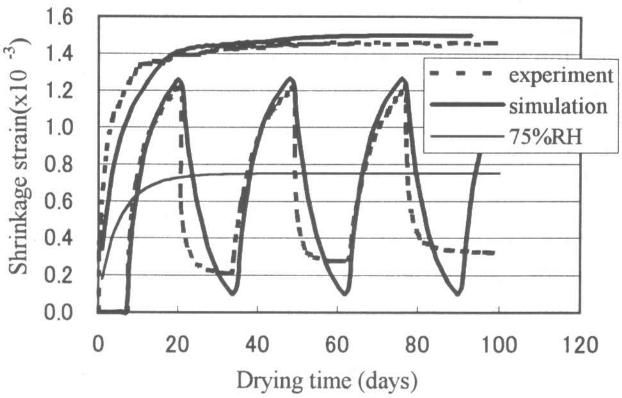

Fig.5 Simulation for Case 2

4. CONCLUSIONS

The general shrinkage behavior under constant and cyclic environmental humidity can be predicted by a numerical model with the tri-linear diffusivity model and the fictitious surface layer concept. The effect of size on the shrinkage of cylindrical specimens can be considered properly by employing the axisymmetric modeling.

The experimental data and the simulation results indicate that environmental humidity variations having shorter periods seem to give greater influence on the average magnitude of shrinkage strain.

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