Prediction of Free Shrinkage Strain Related to Internal Moisture Loss

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Abstract:*Drying shrinkage in concrete, which is caused by drying and the associated decrease in moisture content, is one of the most important parameters which affects the performance of concrete structures. Therefore, it is necessary to develop experimental and mathematical models that describe the mechanisms of drying shrinkage and damage build up in concrete. The main objective of this research is the development of a computational model and an experimental method for evaluation of concrete free shrinkage strain based on the internal moisture changes. For this purpose and for modeling of moisture losses in concrete members a computational program based on finite element approach and the modified version of Fick's second law in which the process of diffusion and convection due to water movement are taken into account, is developed. Also the modified SDB moisture meter was used to measure the internal moisture changes in concrete. Based on the obtained results, calculated humidity is in good agreement with measured data when modified Fick's second law with diffusion coefficient from Bazant method were used, and are very reasonable for determining the moisture gradient. Also, the predicted value of shrinkage strain from the proposed method is in good agreement with measured data and also the established relationship can be used for determine the distribution of shrinkage strains in concrete members.*

Keywords: *shrinkage, moisture loss, diffusivity, humidity, water vapor.*

1. Introduction

Drying shrinkage in concrete structures is even more critical in the Persian gulf region because of the sever environment characterized by adverse climatic condition, typified by the large fluctuations in diurnal and seasonal humidity and temperature regimes with the relative humidity ranging from 40 to 100% and the temperature varying as much as 30? C over a period of 24 hours. These sudden and continuous variation in humidity and temperature creates cycles of expansion/contraction in concrete which induces shrinkage and thermal stresses leading to cracking in concrete members [1].

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Drying shrinkage in concrete is due to drying and the associated decrease in moisture content. Therefore, it is necessary to estimate the moisture loss as accurately as possible in order to study drying shrinkage in concrete members. Correct prediction of concrete drying shrinkage inevitably requires understanding of the concrete moisture content and its variation. It is generally accepted that drying shrinkage is caused by capillary tension, solid surface tension, and withdrawal of hindered adsorbed water and interlayer water movement from the cement gel [2].

The water movement within concrete which occurs during the whole lifetime of concrete, is more complex than other porous materials [3] because a very wide range of pore structures are present in cement paste and pore structures change with time [4]. In the simplest case, it occurs through the drying process of the material, when concrete is submitted to a lower environmental relative humidity than its internal one. In this case, the vapor pressure of the water remaining in the region losing water decreases progressively with the moisture content. It is this tendency of the vapor pressure to equalize that causes the slow drift of moisture toward the drying surface. Therefore, the drying process starts at the surface that is exposed to drying and gradually penetrates into the concrete [3]. This phenomenon affects the surface zone of many civil engineering structures. Moreover, these processes are also often combined with other mass transport processes or with chemical reactions that occur in non saturated conditions, such as carbonation or penetration of chloride ions. All of these facts point out the basic need to understand perfectly and to be able to forecast moisture transfers and the drying process in particular [5].

Many papers have been written on moisture diffusion as it relates to the drying of concrete. Pickett [6] derived the theoretical expressions for deformations and distribution of shrinkage stresses in concrete beams and slabs which occur during the course of drying. He used an analytical approach for the solution of the boundary value problem governing the diffusion of moisture. According to Pickett research, the flow of water could be expressed by the diffusion equation if the vapor pressure of water in the concrete is proportional to the moisture content, and the permeability is independent of the moisture content. In addition, if the shrinkage tendency of each elemental volume were linearly related to the moisture content, then the unrestrained shrinkage could also be expressed by the diffusion equation.

Bazant and Najjar discussed the drying of concrete as a nonlinear diffusion problem [7,8] and used Ficks 2nd Law to express the loss of water from cement paste and concrete. Also, Sakata [9] studied the time-dependent phenomenon of moisture diffusion and distribution of water in concrete using the nonlinear diffusion theory. The finite element technique was used to solve the nonlinear moisture diffusion equation and the diffusion coefficient was determined as a function of moisture content at each time step by the experiment. Sakata showed that the diffusion coefficient was strongly dependent on the relative moisture content at the beginning of drying and the moisture loss rate is almost linearly related to the shrinkage strain.

2. Research significance

The scope of this study is to develop a computational model and an experimental method to evaluate the moisture loss and relative volumetric changes in concrete members. To this end, in addition to the numerical analysis, an experimental procedure was carried out to determine internal humidity changes and associated drying shrinkage in concrete specimens.

3. Finite element analysis for evaluation of moisture loss

The moisture flux (J) in concrete is proportional to the gradient of the humidity (Eq. 1):

$$J = -K.grad(C) \tag{1}$$

In equation 1, K is the permeability and C is humidity. Moisture flux in concrete can be expressed using two different ways [10]. It can be defined in terms of the free water content gradient or in terms of the pore relative humidity gradient (Eq. 2):

$$J_m = -K_w\left(\frac{\partial W_e}{\partial x} + \frac{\partial W_e}{\partial y}\right) \quad \& \quad J_m = -K_c\left(\frac{\partial C}{\partial x} + \frac{\partial C}{\partial y}\right) \tag{2}$$

Where, J_m (m/s) is the moisture flux, K_w (m2/s) is the moisture diffusion coefficient, w_e is the evaporable water content, K_c is the humidity diffusion coefficient and C is the pore relative humidity at x and y. Coefficients K_w and K_c have different physical meanings and therefore take different values for given moisture flux J_m [10].

According to Bazant and Najjar [7,8] the use of Fick's diffusion laws in terms of w_e will cause erroneous results when hydration proceeds, since the distribution of evaporable water becomes non-uniform with time. Therefore, the pore relative humidity C instead of the water content w_e has been used as the field variable describing moisture movement in concrete [10].

The mass conservation equations corresponding to Eq. 2 is given by Eq. 3, where both the progress of cement hydration and heat diffusion are taken into account in characterizing moisture transport [10]:

$$\frac{\partial W_e}{\partial C}\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(K_c\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_c\frac{\partial C}{\partial y}\right)+\frac{\partial h_s}{\partial t}+K\frac{\partial T}{\partial t}-GC+Q \qquad (3)$$

Where, $\frac{\partial h_s}{\partial t}$ is pore relative humidity variation due to self-desiccation and *K* is hygrothermic coefficient (1/ºC) and $\partial T/\partial t$ is the variation of temperature over time. For normal concrete, the drop in humidity, *C*, due to self-desiccation is known to be quite small and can be neglected as an approximation even if hydration has not yet terminated [8]. Furthermore, the effect of heat in moisture transport can also be ignored, since the contribution of this term has appeared to be rather small for a normal range of temperatures [8]. Thus the equation governing moisture transport in concrete is reduced to:

$$\frac{\partial W_e}{\partial C}\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(K_c\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_c\frac{\partial C}{\partial y}\right)-GC+Q \qquad (4)$$

where $\partial w_e/\partial C$ is the moisture capacity, which represents the slope of the equilibrium adsorption isotherm. Employing the Galerkin weighted residual method for solution of the above differential equation (Eq.4) yields to [1]:

$$\{R^e\}=-\int W_i(x,y)\left\{\frac{\partial}{\partial x}\left[Kc\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[Kc\frac{\partial c}{\partial y}\right]-GC+Q-\frac{\partial C}{\partial t}\right\}d\Omega$$

(5)

Where $W_i(x,y)$ is a weighting function and Ω represents the domain of the problem. The final form of Eq. 5, after extension, calculation and simplification using finite element approach, is converted to:

$$[K]\{ø\}+[L]\{ø`\}=\{F\} \qquad (6)$$

Where [K] represents the moisture diffusivity matrix, [L] the moisture velocity matrix, {F} the external moisture flow vector, {ø} the nodal moisture content and {ø`} the rate of change of nodal moisture content. Equation 6 represents a system of linear first-order differential equations in the time domain. In order to obtain a numerical solution, equation 6 was integrated in time domain by means of a finite-difference approximation [11]. The final form of equation 6, using finite-difference method, is converted to:

$$([L]+\theta\Delta t[K])(ø)_{t+\Delta t} = ([L]-(1-\theta)\Delta t[K])(ø)_t + \Delta t\{F\} \qquad (7)$$

Where θ is a parameter ranging from 0 to 1 and Δt denotes a time increment. Equation 7 evaluates physical quantities at time t+Δt as a function of quantities at the previous time step.

3.1. Humidity diffusion coefficient

The moisture diffusion coefficient is dependent on several factors. In the Bazant and Najjar method, K_c depends on the level of pore relative humidity *C*, temperature T and degree of hydration, according to equation 8:

$$K_c = K_{cref}F_1(C)F_2(T)F_3(t_e) \qquad (8)$$

Where K_{cerf} is the humidity diffusion coefficient (*m²/s*) determined at some specified reference condition. In the Sakata method [9], the equation 9 is used as a humidity diffusion coefficient:

$$k_c(C)=k_0+a\left(\frac{C}{1-C}\right)^b \qquad (9)$$

Where, K_0 is the diffusivity at *C=0* % and *a,b* are regression parameters. In this research tree different methods were used for diffusion coefficient (The linear humidity diffusion coefficient, the Bazant and Najar method and Sakata formula).

4. Relationship between shrinkage strain and relative humidity

The relationship between drying shrinkage and pore relative humidity at each location of concrete is necessary to estimate the differential drying shrinkage. As is well known, drying shrinkage may be approximately proportional to the loss of water from concrete [12, 13, 14, 15,…]. According to this and based on experimental findings, shrinkage as a material property can be described by the following incremental relation:

$$\varepsilon_{sh} = k_{sh} f(h) \tag{11}$$

where k_{sh} is the shrinkage coefficient and f is function of pore relative humidity. However, in this research and according to proposed model [16], the drying shrinkage is taken as proportional to the pore relative humidity variation in which the shrinkage coefficient not constant and is function of humidity (Eq.11).

$$\varepsilon_{sh}(t) = k_{sh}(h)(1-h) \tag{12}$$

5. Analytical and experimental program

The purpose of this research is evaluation of humidity changes and associated shrinkage strain in concrete. For this purpose a computational method for calculation of drying shrinkage was suggested, in which the process of diffusion and convection due to water movement were taken into account. According to the equation 7, a finite element code was developed for computing the time-dependent moisture loss. This program handles two dimensional moisture diffusion through concrete members.

In experimental program, the moisture content and drying shrinkage strain was measured in cube, slab and cylindrical specimens at various positions by using the embedded *SDB* moisture meters [17], and the strain gauges. Also, these forms were used in the analytical program to calculate the internal moisture gradient.

As mentioned above, to monitor the internal humidity changes modified *SDB* moisture meter [17] was used. The SDB sensor consists of mortar cub (10*10*10mm) containing two stainless steel plates which were drilled in center (fig. 1).

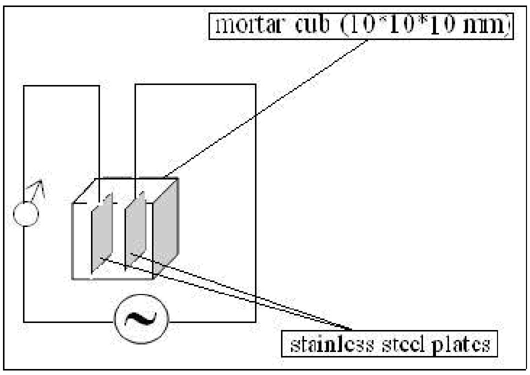

Fig.1 Modified SDB moisture meters.

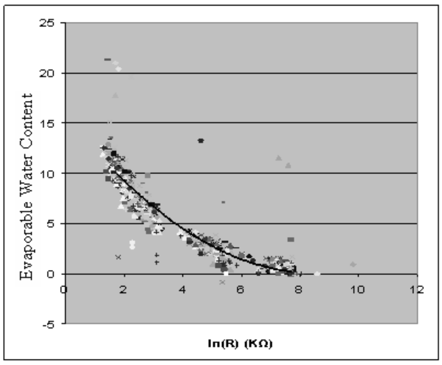

Fig. 2 The calibration curve of moisture meters.

The mortar mixture proportion has been designed in such a way that gives the same adsorption kinetic as testing concrete. It permits to assure a close link of the equilibrium humidity between moisture meter and concrete specimen during the tests [17].

The *SDB* sensors were cast in a batch. Following removal from the moulds, the moisture meters have been stored in lime water for seven days. After this, they were autoclaved in saturated steam at $P=20$ bar for about 2 days. The moisture meter autoclaving could minimize the ageing effects (according to *XRD* analysis, the hydration process was considerably accelerated and pore structure was stabilize in autoclaved samples). Electrical resistance was used to calibrate the moisture meters. The calibration curve of moisture meters is illustrated in figure 2.

6. Results and discussion

For the one – dimensional moisture diffusion problem, the predicted values using linear and nonlinear moisture diffusion theory and also

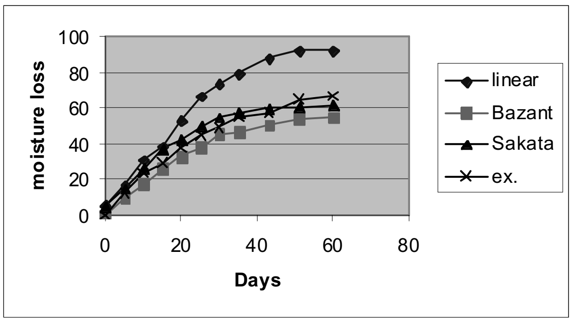

Fig. 3 Experimental and predicted values of moisture loss.

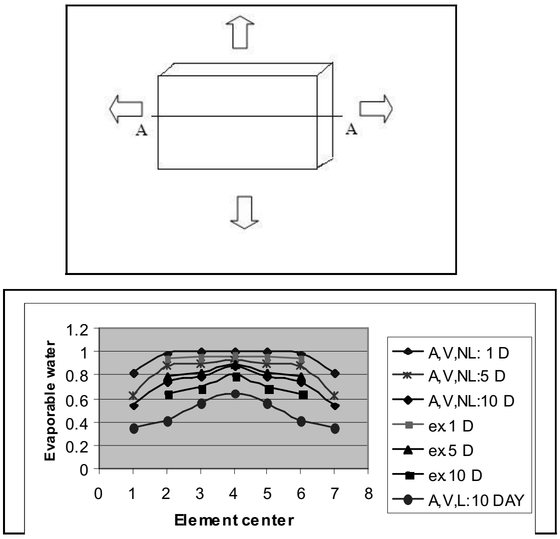

Fig. 4 Experimental and predicted values of moisture loss in A-A

values obtained from the experiment (center point of the specimen with 60*20*20 size), with respect to drying time are summarized in figure 3. For the linear case k was 0.1175, and for the nonlinear state of moisture diffusion coefficient, Bazant (12) and Sakata (4) models were used.

According to figure 3, the prediction of moisture loss using moisture dependent diffusivity (Bazan and sakata method) is found to be more accurate than using a constant diffusivity.

Distributions of moisture in across of a slab (60*60*10 cm) with moisture flow just in two directions (a slab with boundary conditions resulting from figure 2) are shown in figure 4. Like the one dimensional state, the prediction of moisture loss using moisture dependent diffusivity is found to be more accurate than using a constant diffusivity.

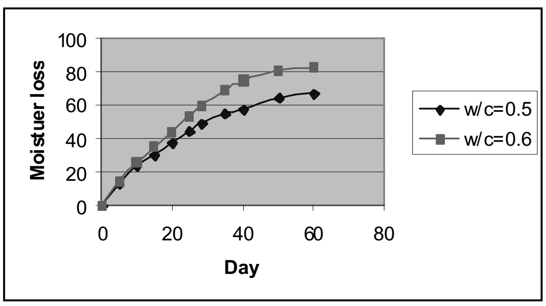

Fig. 6 The w/c ratio effect on moisture loss.

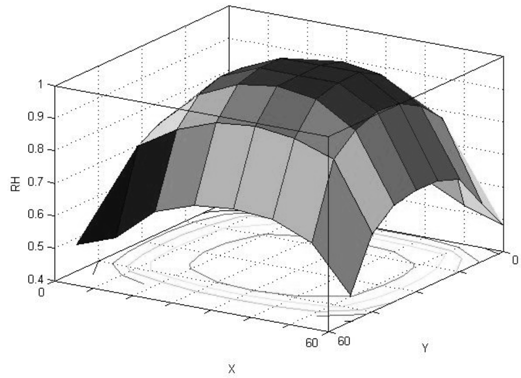

Fig. 5 The contour lines and distribution of moisture content in the slab (after 10 day).

The contour lines and distribution of moisture content after 10 days with boundary condition illustrated in figure 4, are shown in figure 5.

In figure 6, the *w/c* variation effect on the moisture loss over the time is illustrated. According to this, although the moisture loss rate is approximate constant, the amount of moisture loss increases with increasing the *w/c* ratio.

The distribution of humidity in the 60x60x10 slab is shown in figure 7a at 20 and 150 ages. Also drying shrinkage strains obtained from the experiments and predicted from the proposed method (Eq. 6) are plotted against the drying time in figure 7b.

It can be inferred from figure 7 that the shrinkage strains increase rapidly during the initial period. Also, the distribution of shrinkage strain is non-uniform. The maximum value of shrinkage strain was obtained near the edges of slab and the minimum value measured and calculated at the symmetry axes.

Also, according to equation 7 and proposed model (Eq. 12, [16]), distribution of shrinkage strain along the x axis is not constant. In the figure 8 the predicted values along the x axis from the slab (fig 7) are shown.

In figure 9, the measured data and predicted shrinkage strains from equation 12 and ACI209 standard model in cylindrical specimen are shown.

According to figure 9, distribution of shrinkage strain is non-uniform in the section of cylinder. Shrinkage strain increases from the center (415 x10-6) to drying surface (586x10-6). In this case the distribution of shrinkage strain along any axis parallel to x is constant.

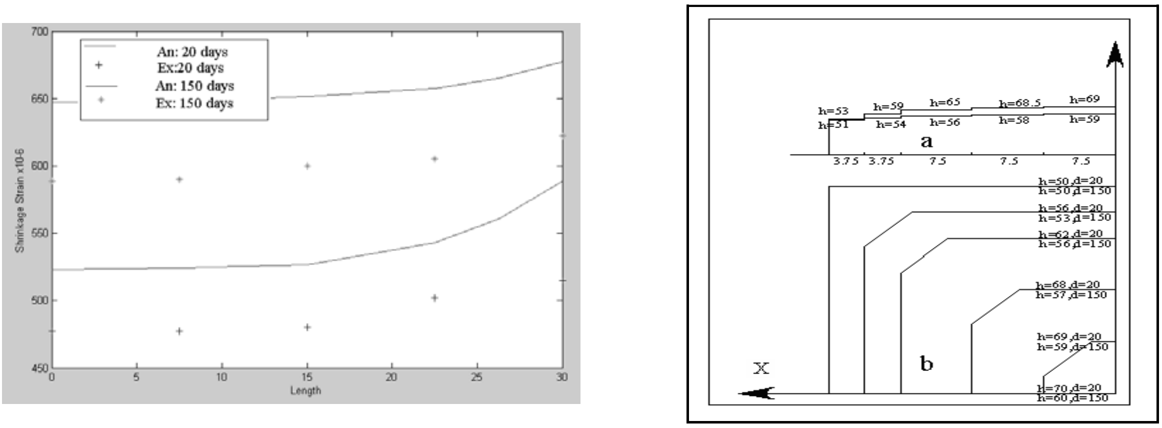

Fig. 7 (a) Humidity distribution in slab, (b) Experimental and predicted values of shrinkage strain.

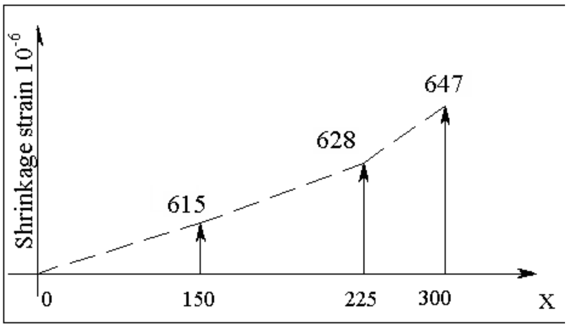

Fig. 8 The distribution of shrinkage strain along the x axis.

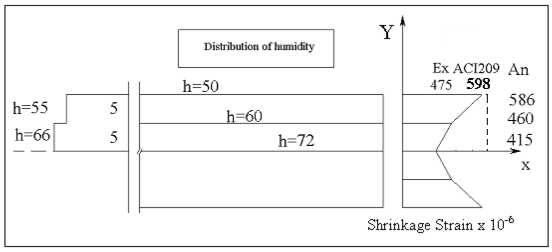

Fig. 9 Distribution of shrinkage strain in cylindrical specimen.

In figure 10, the predicted shrinkage strains from equation 12, ACI209 standard code and the results obtained directly from the experiments (in 40x20x20 cube) are shown.

According to this figure there is a good agreement between predicted and measured values. Also, the distribution of shrinkage strains is non-uniform and increases from the main axes to the surface portion in contact with outside air.

7. Summary and Conclusion

In this research, a computational model based on finite element method and an experimental method for predicting the moisture loss and relative volumetric changes in concrete members were developed, and the obtained results are summarized as follows:

- Moisture loss is highly nonlinear with respect to the diffusivity coefficient (Kc) which depends on the moisture content (C) especially in higher relative humidity.
- According to the evaporable water content measured at various positions of concrete by using the embedded SDB moisture meters, it seems that the technique using the embedded SDB moisture meters is suitable for measuring the internal water content and humidity changes.
- The change in moisture content near the free surface of concrete is rapid, but at points slightly deeper inside, the change is slow.
- The good agreement between analytical values obtained from proposed method and tests results shows that the proposed method is suitable to estimate the drying shrinkage strain.
- The distribution of shrinkage strain in concrete members is non-uniform. The maximum value of shrinkage strain was obtained near the

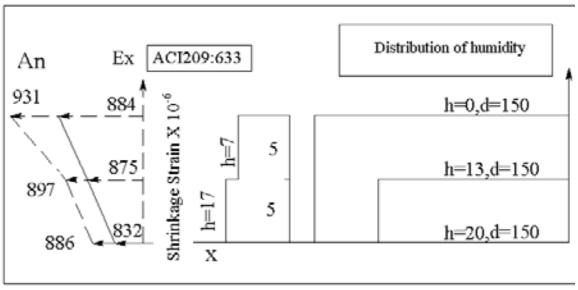

Fig. 10 Distribution of shrinkage strain (An: analytical, Ex: experimental, d: days)

edges and the minimum value measured and calculated at the symmetry axes. Also, the distribution of shrinkage strain along the symmetry axis was not constant.

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