Construction and Building Materials 132 (2017) 124–129

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Study on the heat-moisture transfer in concrete under real environment

Bongsuk Cho [a], Dongcheon Park [b,*], Jeongho Kim [c], Hitoshi Hamasaki [d]

[a] Environment Research Department, Research Institute of Industrial Science & Technology, Pohang City, Gyengbuk 790-330, Republic of Korea
[b] Department of Architecture and Ocean Space, Korea Maritime and Ocean University, Yeongdo-Ku, 606-791 Busan, Republic of Korea
[c] Dept of Civil & Env. Engineering, University of Connecticut, Storrs, CT 06269, USA
[d] Department of Architecture, Shibaura Institute of Technology, Koutoku 135-8548, Tokyo, Japan

## HIGHLIGHTS

- Temperature and humidity inside the concrete were measured.
- The surface temperature of the concrete was observed as higher by 6 °C during summers and lower by 2 °C during the winters.
- The inner temperature of the concrete was affected by temperature, solar radiation and radiation cooling.
- The temperature and humidity changes can be predicted by developing a FE coupling numerical analysis model.
- The temperature and humidity information of the concrete would contribute in the prediction of concrete's deterioration.

## ARTICLE INFO

*Article history:*
Received 26 October 2016
Received in revised form 22 November 2016
Accepted 24 November 2016

*Keywords:*
Concrete
Temperature
Relative humidity
FE coupling model
Natural environment

## ABSTRACT

Surplus water inside a concrete other than moisture that is used for hydration of the cement affects the physical properties of the concrete (modulus of elasticity, compressive strength, drying shrinkage, and creep) by drying. Changes in temperature and humidity inside a concrete has correlation with the movement speed and reaction rate of deterioration factors such as carbon dioxide and chloride ions. Though the prediction of temperature and humidity inside a concrete is an important research field, there are not enough research achievements about it due to difficulties in measurement. In this study, comparison was performed between temperature and relative humidity inside the concrete and meteorological data for exposure environment through measurement at the site for two years. Surface temperature of the concrete (depth 1 cm) was measured higher by 6 °C during the summers, while it was measured lower by 2 °C during the winters due to solar radiation, wind, and radiation cooling. As for relative humidity, change was large in the depth of 1 cm, while more than 85% was maintained in the depth of 10 cm. A heat-moisture coupling model was prepared using FEM for the test results. With the coupling model, temperature could be predicted with a high degree of accuracy. However, daily changes of the humidity could not be simulated with the model. It might be because ink bottle effect and hysteresis effect could not be reflected as a form developed from the macroscopic model based on the partial differential equation. Yet, the proposed model could predict average relative humidity changes capable of evaluating long-term durability evaluation.



## 1. Introduction

In concrete mixing, a considerable amount of water up to W/C = 60% is used to increase workability besides the water for the hydration reaction of cement. The moisture content distribution of surplus water after using it for hydration reaction is changed due to dryness as time passes. This moisture movement is closely related to a long-term behavior such as dry shrinkage or creep, compressive strength, elastic modulus [1–3], fire resistance (spalling) [4,5], and diffusion and reaction of durability-related deterioration [6].

In the current performance design of RC structure, advanced model is required to quantitatively identify the deterioration mechanism in a bid to predict residual life and establish a maintenance strategy. Included in the factors that reduce the durability of RC structure are neutralization, salt attack, alkali-aggregate reaction, and freezing damage. A combined deterioration is developed with surplus water as a medium which ultimately results in rebar

* Corresponding author.
*E-mail addresses:* chos8@rist.re.kr (B. Cho), dcpark@kmou.ac.kr (D. Park), jhkim@engr.uconn.edu (J. Kim), hamasaki@shibaura-it.ac.jp (H. Hamasaki).

http://dx.doi.org/10.1016/j.conbuildmat.2016.11.121
0950-0618/

corrosion and thus prediction of moisture or relative humidity is essential. Viewing the case of carbonation, diffusion coefficient of $CO_2$, and reaction factor of calcium hydroxide are heavily dependent on relative humidity [7].

Thus to predict the deterioration of concrete structure quantitatively, it is necessary to identify the environmental condition to which concrete structure is exposed and to ascertain the movement of the deterioration factor and reaction rate in relation to heat-moisture transfer properties. As concrete has hydrophilic property and a large specific area, most of them exist as absorption water and the moisture is dependent on surface tension, density, and viscosity in such porous material as concrete, directly affecting moisture movement rate. Among the factors that make the heat-moisture phenomenon complicated are hysteresis, resulting from the geometric structure of pores, and contact angle effect. For such reasons, moisture transfer mechanism is exceedingly complex to identify.

According to traditional moisture movement analysis method, concrete is considered a single assembly from a microscopic viewpoint. A nonlinear analysis using moisture diffusion coefficient with moisture content, or relative humidity calculated from the experiment as a parameter is a typical approach [8,9]. In the CEB-FIP (1990) model, the moisture diffusion coefficient to the isothermal condition was expressed as the function of the relative humidity of the pore. Bazant [10] proposed the equation considering the temperature effect in addition to the relative humidity of a pore. Since then, however, there have been especially few models that analyze the temperature and moisture movement together, making it difficult to predict temperature and relative humidity accurately.

The studies mostly performed a dry process at isothermal condition while in few cases using the environment to which the concrete is exposed (such as solar radiation, wind, and sky temperature as boundary condition and when the temperature and relative humidity only are used as boundary condition), accurate temperature and humidity in concrete can hardly be predicted. The studies on soil by Philip et al. [11–13]. in the 1950's served as the start point leading to the approach from microscopic viewpoint using physical absorption theory or condensation theory, which was further developed to the heat-moisture analysis of porous material.

It's intended to effectively incorporate the complex behaviors of external environment factors (including temperature, humidity, wind, solar radiation, and sky temperature) based on the macroscopic model aforementioned. A FE simulation model with coupled heat transfer and moisture diffusion was set up, and the accuracy of the model was verified using laboratory test data and temperature and humidity data by the depth of concrete specimen exposed to real environment.

## 2. Governed equation and finite element analysis of Heat-moisture coupled analysis

Heat transfer and moisture diffusion of concrete is represented by the function of material components, temperature, and relative humidity. The governed equation of heat-moisture transfer is expressed as follows. Heat transfer equation depending on temperature variation in concrete over time is shown in Eq. (1).

$$\rho C_T \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_T \frac{\partial T}{\partial x}\right) \tag{1}$$

Moisture transfer equation indicating the variation of HR is shown in Eq. (2).

$$\rho C_h \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(k_h \frac{\partial h}{\partial x}\right) \tag{2}$$

Initial condition is shown in Eq. (3) while air and concrete surface boundary conditions are demonstrated in Eqs. (4) and (5).

$$T(x)|t = 0 = T_0, h(x)|t = 0 = h_0 \tag{3}$$

$$k_T \frac{\partial T}{\partial x} + q_T = 0 \tag{4}$$

$$k_h \frac{\partial h}{\partial x} + q_h = 0 \tag{5}$$

$$q_T = q_{con\_T} + q_{sol} + q_{sky} + q_{evp} \tag{6}$$

$$q_h = q_{con\_h} \tag{7}$$

Here, $q_T$ is the sum of heat introduced to concrete surface, convective transfer $q_{con\_T}$, global solar radiation $q_{sol}$, sky radiation $q_{sky}$, and heat loss by evaporation heat $q_{evp}$, with $q_h$ being the moisture introduced. Convective heat transfer is in accordance with Newton's cooling law.

$$q_{con\_T} = h_c(T_{air} - T_s) \tag{8}$$

In this equation, $h_c$ is convective heat transfer coefficient which is dependent on concrete surface roughness and wind velocity [W/m$^2$K], $T_{air}$ is temperature [K], and $T_s$ is the temperature of concrete surface [K]. A net global solar radiation is the sum of the quantity of direct solar radiation and scattered solar radiation from sun disk which is reflected by atmospheric gas molecule, cloud, and dust. When global solar radiation per unit area of concrete surface and unit time is $S$ [W/m$^2$] and concrete absorption rate is $(1 - \alpha)$, it is estimated from Eq. (9).

$$q_{sol} = S(1 - \alpha) \tag{9}$$

In this equation, $\alpha$ is Albedo (reflectivity). Direction of net infrared radiation between the air and concrete surface is dependent temperature difference which is represented by Eq. (10).

$$q_{sky} = \varepsilon\sigma(T^4_{sky} - T^4_s) \tag{10}$$

Here, $\varepsilon$ is thermal emissivity, $\sigma$ is Stefan-Boltzmann (=$5.67 \times 10^{-8}$[W/m$^2$K]), $T_{sky}$ is sky temperature (representative temperature of the air, [K]), and $T_s$ is concrete surface temperature [K]. Emissivity is $0 \leqslant \varepsilon \leqslant 1$, which represents the relative scale of heat radiation of the black body. This value varies depending on material, surface temperature, and roughness. Evaporative latent hear of concrete surface is shown in Eq. (11).

$$q_{evp} = -(42.6 + 37.6\upsilon)(P_{cs} - hP_{ws}) \tag{11}$$

In this equation, $\upsilon$ is wind velocity [m/s], $P_{cs}$ is saturated vapor pressure of concrete surface [mmHg], $h$ is relative humidity [%], and $P_{ws}$ is saturated vapor pressure in air [mmHg]. $q_{con\_h}$ is the moisture on concrete surface, and relative humidity on concrete surface is affected by outer relative humidity. It's necessary to indicate the relationship between HR on concrete surface and outer HR through the boundary condition of humidity. Boundary condition on exposed surface is as follows.

$$q_{con\_h} = f(h_{en} - h_s) \tag{12}$$

In this equation, $f$ is surface modulus (m/s), $h_{en}$ is outer HR, and $h_s$ is HR on exposed surface. Bazant [10] introduced equivalent surface thickness concept which is represented by wind flow, surface roughness, temperature, and HR but it's difficult to accurately estimate the effect individually and in this study, it's represented by the function of $W/C$ referring to the study by Sakata and Kang. To solve the governed equation above, finite element method was used and concrete section was divided into 2D 4-node linear quadrilateral element while each node is represented by temperature and relative humidity.