Construction and Building Materials 102 (2016) 76–83

Contents lists available at ScienceDirect

Construction and Building Materials

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

Quantitative moisture model of interior concrete in structures exposed to natural weather

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HIGHLIGHTS

- Water vapor density is used as a novel variable to quantify the moisture content.
- A quantitative moisture model is proposed to predict the humidity variation.
- The moisture variations in the environment and concrete are measured and modeled.
- The moisture in the environment and concrete shows different characteristic.
- Water vapor density fluctuates periodically in the interior concrete.

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 25 August 2015
Accepted 15 October 2015

Keywords:
Concrete
Moisture
Natural environment
Spectrum
Response

ABSTRACT

The moisture in interior concrete is the primary factor directly influencing the deterioration phenomena of concrete structures. In this study, a method for predicting the moisture of the natural environment and the interior concrete was proposed based on the relative humidity (RH) and water vapor density (WVD) concepts using meteorological data. The variations of the moisture in the environment and the interior concrete were measured and modeled. After experimental validation, the moisture model was extended to investigate the action spectrum of humidity in the environment and the reaction spectrum of moisture in the interior concrete based on monthly and annual meteorological data. The results show that the characteristics of the RH and WVD differ from one another in both the environment and the interior concrete as a result of the intrinsic properties of the concrete. In the atmosphere, the RH fluctuates periodically with the diurnal cycle, whereas the WVD shows only slight fluctuations. In the interior concrete, the WVD fluctuates periodically, whereas the RH is relatively steady and tends towards a constant beyond a critical depth. Thus, it is proposed that the WVD, supported by the RH, be used to quantitatively characterize the moisture and the RH be used to qualitatively characterize the moisture.

1. Introduction

Currently, the durability design and assessment of concrete structures is shifting from a prescriptive to a performance-based approach. In this research and design environment, the quantitative analysis and detailed modeling of the deterioration mechanisms in concrete structures require further study [1]. It is essential to accurately predict the moisture content of concrete for various environmental conditions for use as an input in the durability design and assessment of concrete structures. This importance stems from the fact that concrete deterioration phenomena, such as carbonation, attack by chloride or sulfate, freezing or thawing, and the corrosion of rebar in concrete, are mostly caused by mass transfer from the moisture [2–4], and the moisture level significantly affects the rates of the transfers and reactions involved in the deterioration [5].

Extensive research has been conducted on the effect of moisture on the deterioration of concrete structures. The results of these studies show that the rate of structural deterioration, such as concrete carbonation, chloride diffusion, and the corrosion of rebars in concrete, depends strongly on the micro-environment in the interior concrete; meanwhile, deterioration predictions based directly on the natural climate environment are inaccurate. The temperature and humidity in the interior structural concrete are significantly different from those of the atmosphere, but the micro-environment of interior concrete is obviously dependent on both the natural climate and the intrinsic properties of the concrete [6–9]. Baroghel-Bouny et al. [10] investigated the equilibrium and transfer moisture properties of concretes using isothermal

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http://dx.doi.org/10.1016/j.conbuildmat.2015.10.073
0950-0618/

desorption and adsorption experiments and then described the time evolution of the moisture profiles. Xin et al. [11] proposed a method for determining the diffusion coefficient of hardening concrete by measuring the pore relative humidity (RH) profiles using inverse nonlinear diffusion analysis. Yuan et al. [12,13] constructed climate temperature and RH action spectrums and relative reaction spectrums in the interior of concrete based on experimental results and the extreme difference dissection method. Ryu et al. [1] studied the effect of simulated environmental conditions on the internal RH and relative moisture content distribution of concrete. The electrode method and humidity sensors were used to elucidate the effects of cyclic daily changes in the environmental conditions (temperature and RH) and rainfall on the internal RH and relative moisture content distribution within exposed concrete. The results shown that external temperature/RH changes only changed the internal RH and relative moisture distribution in the surface region of the concrete; the moisture content was found to decrease extremely slowly farther from the surface.

The previous studies have shown that it is essential to develop a quantitative moisture model of interior concrete to accurately predict deterioration phenomena. However, these studies also show that this is a complex problem. It is well known that variations of the RH in the natural external environment can affect the moisture content in the concrete, but both the temperature and the RH in the atmosphere differ from those in the interior concrete because of the thermal conduction and permeability of the concrete. In addition, the RH in the natural environment fluctuates both annually (by season) and over shorter periods (daily). The short-term fluctuations are more important when considering the deterioration factors associated with moisture transfer. The time-dependency, randomness, and regional variation of the RH in the natural environment and the hysteresis of the moisture in the interior concrete all contribute to the complicated behavior of the moisture in the concrete, hampering accurate predictions. Therefore, it is not found the simplify quantitative moisture model of interior concrete in structures exposed to the natural weather. The existing literatures focus on mainly transfer moisture properties of concretes and the interior reaction tests of structure concrete subjected to simulating simply the natural environment. It is still very difficult to acquire effectively the quantitative moisture in the interior concrete exposed to the natural weather in the prediction and simulating of structure deterioration.

To address this problem, this paper presents a quantitative moisture model of interior concrete based on the concepts of RH and water vapor density (WVD) using meteorological data. First, a quantitative moisture model based on the RH and WVD, i.e., the absolute humidity concept, is built using daily meteorological data. Second, the variation of moisture in the external environment and that in the interior concrete are measured and modeled. After experimental validation, the moisture model is extended to investigate the action spectrum of humidity in the external environment and the reaction spectrum of moisture in the interior concrete based on monthly and annual meteorological data. Except otherwise defined and instructions, the intrinsic properties of studied sample were considered as an constant and their effect on moisture change in concrete weren't involved in this study.

2. Quantitative moisture model of the climate and the interior concrete

It is well known that moisture can be described by the RH and WVD. The RH is defined as the ratio of the partial vapor pressure to the saturated vapor pressure and is primarily a function of temperature. The RH and WVD are closely related but have different meanings. In this study, the moisture model is based on the conventional RH and WVD using meteorological data to characterize the action spectrum of the humidity in the external environment and the reaction spectrum of moisture in the interior concrete.

2.1. The humidity model for the external environment

The saturated water vapor pressure is usually calculated from such equations as the Goff–Gratch, Wexler–Greenspan and Clausius–Clapeyron equations [14]. The Clausius–Clapeyron equation integrates the function of water vapor pressure with respect to temperature, volume, and the thermal effect and then fits the equation to represent the phase equilibrium, shown in Eq. (1) as follows:

$$\frac{de_s(T)}{dT} = \frac{L_V e_s(T)}{R_V T^2} \tag{1}$$

where T is the absolute temperature in K, $e_s(T)$ is the saturated vapor pressure of the liquid level at T in Pa, R_v is the specific gas constant of water vapor in J/(kg K), and L_V is the heat of evaporation of liquid water in kJ/mol.

When the proposed model is applied over the temperature range of 273–373 K, L_V may be considered temperature-independent. Eq. (1) is transformed as follows:

$$e_s(T) = e_{s0} \exp\left[\frac{L_V}{R_V}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \tag{2}$$

where e_{s0} and T_0 are the reference pressure and reference temperature, respectively.

Substituting Eq. (2) into the WVD formula expressed in Eq. (3), the WVD formula described by Eq. (5) is then solved simultaneously by incorporating the RH formula shown in Eq. (4) as follows:

$$\rho_V = \frac{e_s(T)}{R_V T} = \frac{\varepsilon e_s(T)}{R_d T} \tag{3}$$

$$\rho'_V = \mathrm{RH}\rho_V \tag{4}$$

$$\rho'_V = \mathrm{RH}\frac{\varepsilon e_s(T)}{R_d T} \tag{5}$$

where ρ_V is the saturation WVD of air in kg/m^3, ρ'_V is the WVD of air at the corresponding RH in kg/m^3, R_d is the specific gas constant of dry air in J/(kg K), and ε is the molar mass ratio of water vapor and dry air, with a recommended value of 0.622.

The RH of the air in the external environment can also be determined via Eq. (6), as follows:

$$\mathrm{RH} = \frac{e}{e_s(T)} \tag{6}$$

Substituting Eq. (2) into Eq. (6) relates the RH and the temperature as follows:

$$\mathrm{RH} = \frac{e}{e_{s0}} \exp\left[\frac{L_V}{R_V}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{7}$$

where e is the corresponding water vapor pressure at temperature T in Pa. When no-rainfall days and severe weather occur, the WVD in air tends toward a quasi-equilibrium state, which means that the water vapor pressure e, the heat of evaporation of liquid water L_V, and the specific gas constant of water vapor R_v are all constant.

It is well known that the temperature can be described using sine or cosine curves [15]. The temperature action models of the environment under sheltered conditions were derived in another study, with the following results: