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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.

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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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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:

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

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

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

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:

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

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

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

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:

$$T(t)=\begin{cases}T_P+T_b\cos\left(\frac{\pi}{t_a}t-\frac{t_a+t_{\min}}{t_a}\pi\right), & \text{Temperature-rise period}:\ t\in(t_{\min},t_{\min}+t_a)\\ T_P+T_b\cos\left(\frac{\pi}{24-t_a}t-\frac{t_a+t_{\min}}{24-t_a}\pi\right). & \text{Temperature-fall period}:\ t\in(t_{\min}+t_a,t_{\min}+24)\end{cases}\tag{8}$$

where T_p and T_b are the average temperature and temperature variation amplitude of the environment in °C, respectively; t_{min} is the time point of the lowest daily temperature in h; $T(t)$ is the air temperature in °C at time t; and t_a is the difference in time between the maximum and minimum temperatures in h.

Substituting Eq. (8) into Eq. (7), the RH model of the environment at time t is as follows:

$$\mathrm{RH}(t)=\frac{e}{e_{s0}\exp\left(\frac{L_V}{R_VT_0}\right)}\times\begin{cases}\exp\left[\frac{L_V}{R_V}\frac{1}{T_p+T_c\cos\left(\frac{\pi}{t_a}t-\frac{t_a+t_{\min}}{t_a}\pi\right)}\right], & t\in(t_{\min},t_{\min}+t_a)\\ \exp\left[\frac{L_V}{R_V}\frac{1}{T_p+T_c\cos\left(\frac{\pi}{24-t_a}t-\frac{t_a+t_{\min}}{24-t_a}\pi\right)}\right]. & t\in(t_{\min}+t_a,t_{\min}+24)\end{cases}\tag{9}$$

In most cases, it is difficult to directly obtain the water vapor pressure e, limiting the application of Eq. (9). Therefore, the RH model of the environment is simplified using a piecewise function.

As shown in Eq. (7), if the temperature is within the range of normal temperatures, an exponential function can be derived using a Taylor expansion, as shown in Eq. (10):

$$\mathrm{RH}(T)=\frac{e}{e_{s0}}\left(1+\frac{L_V}{R_VTT_0}(T_0-T)\right)\tag{10}$$

Similar to the piecewise function of temperature, a piecewise function for the RH model is derived as follows:

$$\mathrm{RH}(t)=\begin{cases}\mathrm{RH}_a+\mathrm{RH}_0\cos\left(\frac{\pi}{t_a}t-\frac{t_{\min}}{t_a}\pi\right), & \text{Humidity-fall period}:\ t\in(t_{\min}\leqslant t<t_{\min}+t_a)\\ \mathrm{RH}_a+\mathrm{RH}_0\cos\left(\frac{\pi}{24-t_a}t-\frac{t_{\min}+24}{24-t_a}\pi\right). & \text{Humidity-rise period}:\ t\in(t_{\min}+t_a\leqslant t<t_{\min}+24)\end{cases}\tag{11}$$

where RH_a and RH_0 are the average RH and the RH variation amplitude for the environment in%, which are easily derived from meteorological data, such as the characteristic RH values (e.g., maximum, minimum and average values) provided by a weather station.

Substituting Eq. (11) into Eq. (5), the WVD model of the environment is as follows:

$$\rho'_V(t)=\frac{\varepsilon e_s(T)}{R_dT}\times\begin{cases}\mathrm{RH}_a+\mathrm{RH}_0\cos\left(\frac{\pi}{t_a}t-\frac{t_{\min}}{t_a}\pi\right), & t\in(t_{\min}\leqslant t<t_{\min}+t_a)\\ \mathrm{RH}_a+\mathrm{RH}_0\cos\left(\frac{\pi}{24-t_a}t-\frac{t_{\min}+24}{24-t_a}\pi\right). & t\in(t_{\min}+t_a\leqslant t<t_{\min}+24)\end{cases}\tag{12}$$

2.2. The moisture model for the interior concrete

Water exists in the concrete pores as both liquid and vapor, endowing the micropores and the ink-bottle pores with a higher RH [14]. In general, liquid water still exists in the pores at low RH conditions. Based on the Kelvin formula shown in Eq. (13), the maximum pore radius can be calculated under different RH conditions [16] as follows:

$$\ln(\mathrm{RH})=\frac{2\gamma M_w}{R_eT\rho_lr}\tag{13}$$

where R_e is the ideal gas constant in J/(mol K), γ is the surface tension of liquid water in N/m, ρ_l is the density of liquid water in kg/m^3, and M_w is the molar mass of water in kg/mol.

As shown in Eq. (13), the saturation radius of the pore varies with the RH in the concrete. To maintain an equilibrium state, liquid water and water vapor can interchange via evaporation and condensation. Although the temperature gradient has only a slight effect on the moisture change in the concrete, in most cases, more liquid water exists in the pore than predicted by the theoretical calculations in Eq. (13). Consequently, the liquid water in the pore will be transformed into water vapor to sustain a slightly changing or unchanging equilibrium state in the short term. Moreover, the low porosity and closed pores of the concrete provide the microstructure with excellent permeability.

For these reasons, the RH of the interior concrete is assumed to be a linear function of time as follows:

$$\mathrm{RH}(t)=Kt+C\tag{14}$$

where K and C represent the curve-fitting constants.

Substituting Eq. (14) into Eq. (5), the WVD model of the interior concrete is as follows:

$$\rho'_V=(Kt+C)\frac{\varepsilon e_s(T)}{R_dT}\tag{15}$$

The temperature T of the interior concrete under sheltered conditions is determined as follows [17]:

$$T(x,t)=\begin{cases}T_p+T_be^{-x\sqrt{\frac{\pi}{2\alpha T}}}\cos\left(\frac{\pi}{t_a}t-\frac{t_a+t_{\min}}{t_a}\pi-x\sqrt{\frac{\pi}{2\alpha t_a}}\right) & t\in(t_{\min},t_{\min}+t_a)\\ T_p+T_be^{-x\sqrt{\frac{\pi}{2\alpha(24-T)}}}\cos\left(\frac{\pi}{24-t_a}t-\frac{t_a+t_{\min}}{24-t_a}\pi-x\sqrt{\frac{\pi}{2\alpha(24-t_a)}}\right) & t\in(t_{\min}+t_a,t_{\min}+24)\end{cases}\tag{16}$$

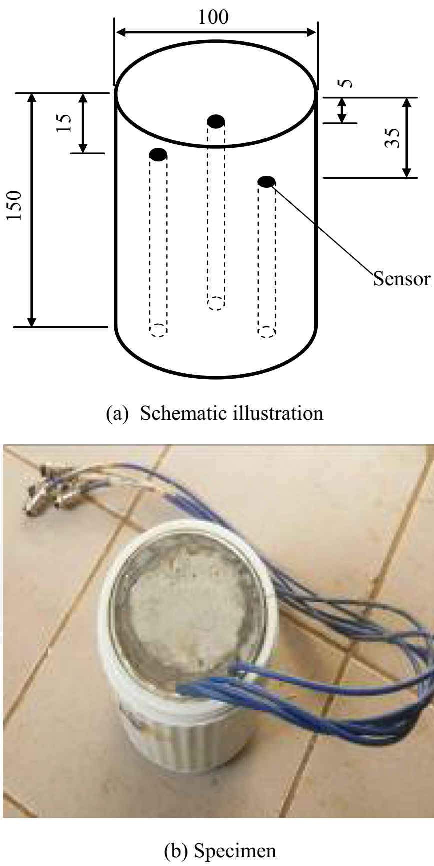


Fig. 1. Schematic illustration and specimen of concrete used for the humidity testing.

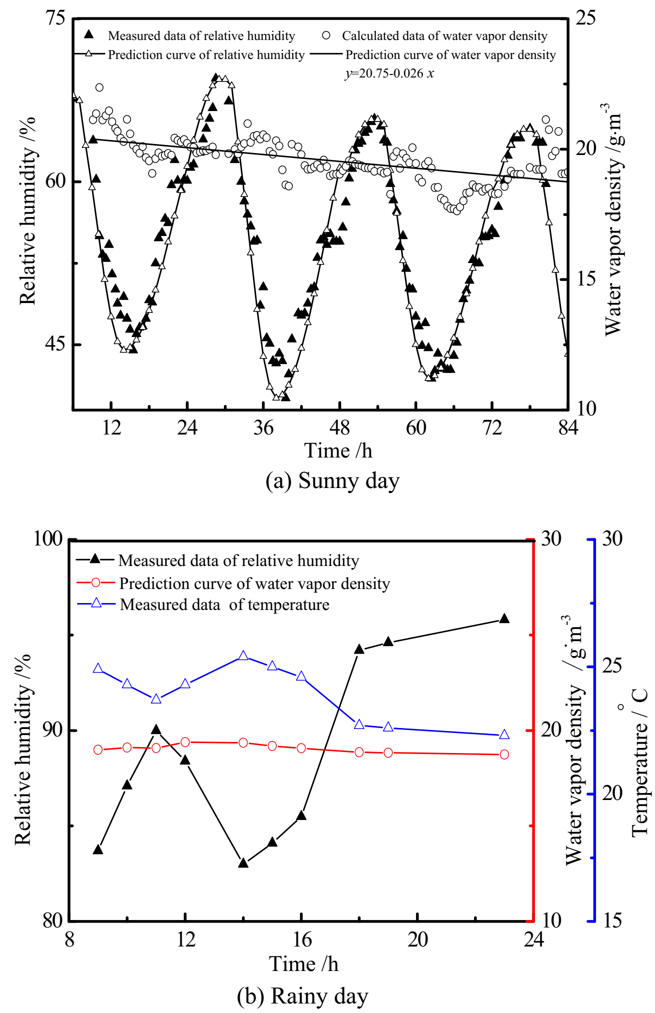


Fig. 2. Variation of RH and WVD in the environment (from August 19 to 20, 2011).

where $T(x,t)$ is the air temperature in °C in the interior concrete at depth x and time t; t_a is the time required to reach the maximum temperature from the minimum temperature in h; and α is the thermal diffusion coefficient in m^2/s.

3. Moisture variation in the external environment and the interior concrete

3.1. Experimental procedures

In this study, 42.5-grade ordinary Portland cement was used, following Chinese standards, with 0.48% Na_2O and 7.08% C_3A. Additionally, Class I fly ash and Class S95 slag were included as admixtures. The coarse aggregate used throughout this work consisted of crushed quartz limestone ranging from 5 mm to 20 mm in diameter, a water-reducing agent of the polycarboxylic series, local river sand with a fineness modulus of 2.9 and tap water. The mix proportions of the concrete for this experiment were cement: slag: fly ash: sand: gravel: water: water reducer = 375:85:35:720:1085:152:5 per cubic meter, and the measured compressive strength was 53 MPa at 28 days.

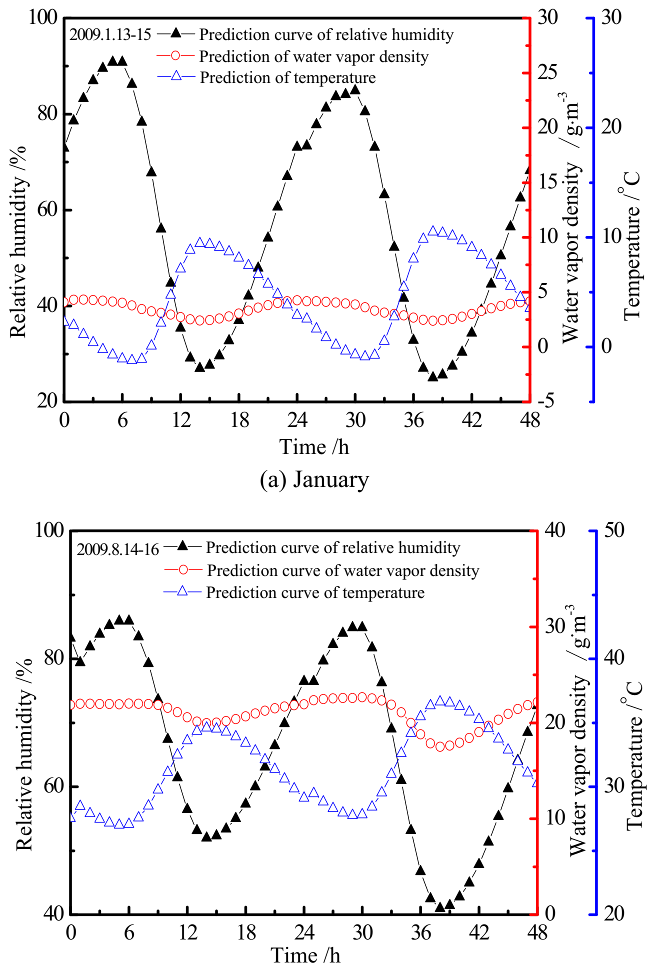
The standard concrete cubes (150 mm × 150 mm × 150 mm) were cast. After a standard 28-day curing, the cylindrical specimens, 100 mm in diameter × 150 mm in height, were pulled from the standard concrete cubes. Holes 10 mm in diameter were drilled in the cylindrical specimens with depths from the concrete surface of 5 mm, 15 mm and 35 mm. Temperature-humidity sensors were embedded in the holes and sealed with the same grade of concrete. Finally, the entire specimen was cast in a Dewar flask with the same grade of concrete. A schematic illustration of the concrete specimen used for the humidity testing is shown in Fig. 1.

Prior to the measurements, the specimens were placed in the environment for sufficient time to reach an equilibrium state. The specimens were then placed in the thermometer screen 1.5 m from the ground, and the humidity and temperature in the interior concrete were recorded in real-time. Moreover, the RH and temperature of the environment were monitored.

3.2. Variation of moisture in the external environment

The variations of the temperature and RH in the external environment were measured every half hour by temperature-humidity sensors, and the WVD values were calculated by Eq. (5) using the measured data. Fig. 2 shows the variations of the RH and the WVD in the natural external environment. As observed in Fig. 2, the measurement results show that the RH on sunny days exhibits periodic fluctuations caused by the diurnal cycle. The maximum fluctuation amplitude of the RH is approximately 35% with a 10 °C variation over an entire day, while the WVD shows only slight fluctuations (Fig. 2a). On rainy days, the RH varies within the range of 85–95%, fluctuating irregularly over the entire day; however, the WVD increases slightly at first and then decreases, plateauing to a constant value (Fig. 2b). The RH is a relative quantity, involving the coupled effect of the rainfall and temperature, giving rise to randomness and uncertainty. The

WVD is an absolute, temperature-independent quantity and thus presents perfect regularity on rainy days. This finding illustrates that the RH fluctuates with temperature and weather but the WVD is steady with respect to temperature changes. Fig. 2 also shows that the RH prediction curves agree well with the measured data, which confirms the rationality of the RH model proposed in this study.



(a) January

(b) August

Fig. 3. Variation of RH and WVD in January and August (2009).

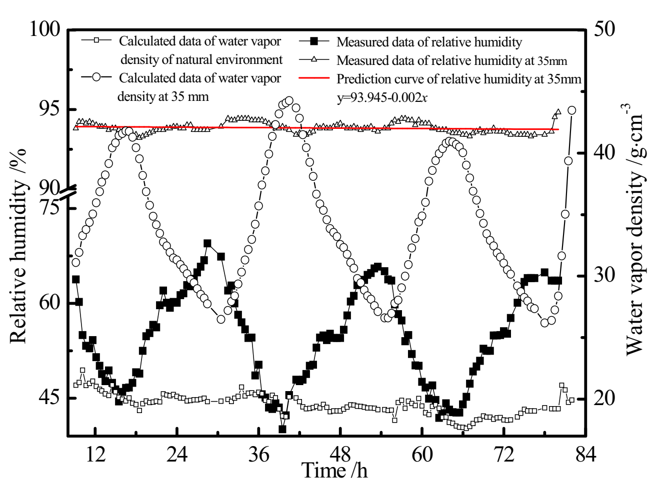


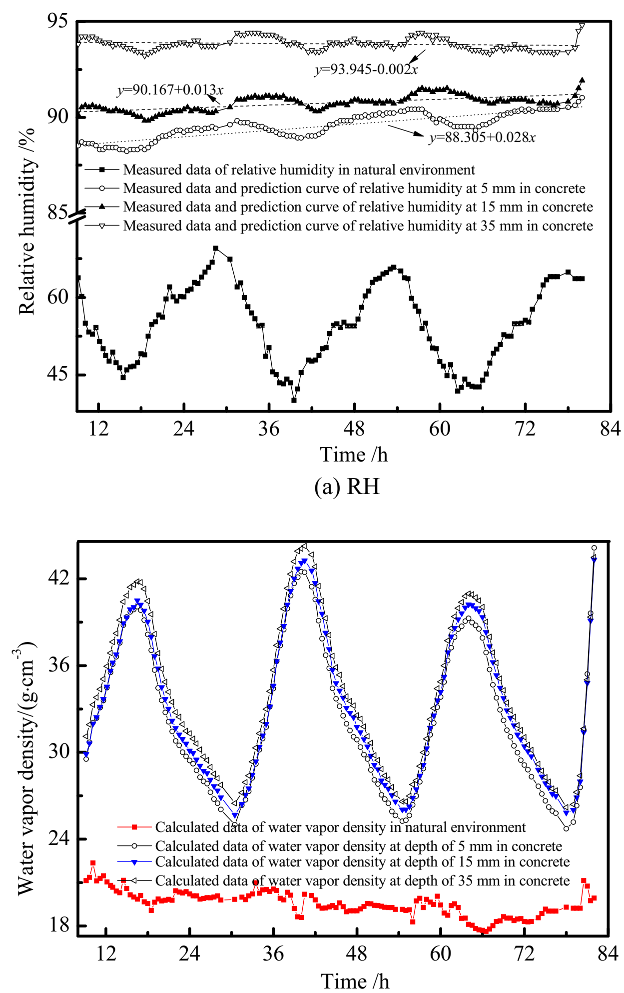
Fig. 4. Variation of the RH and the WVD at a depth of 35 mm in concrete (from August 16 to 19, 2011).

For this reason, we used the meteorological data provided by a local meteorological station to investigate the variation of the RH and WVD in different seasons. Fig. 3 shows the variations of the temperature, RH and WVD in January (winter) and August (summer). As mentioned above, the RH is more sensitive to the fluctuations in the diurnal cycle than the WVD is. The fluctuation ranges of the RH in January and August are approximately 30–90% and 40–90%, respectively, indicating that the RH changed little with the change in season. Unlike the RH, the WVD differs substantially between winter (approximately 3.5 ± 1 g/m^3) and summer (approximately 20 ± 2 g/m^3). The negligible variation of the WVD in the atmosphere may be attributed to the equilibrium between the evaporation, condensation and transmission among the ground, atmosphere and upper cloud layer.

The experimental results shown in Figs. 2 and 3 indicate that the RH is a relative quantity with relation to temperature; that is, it is sensitive to temperature but not the change in season. Therefore, the WVD based on the RH may be more convenient and precise for characterizing the moisture in quantitative model calculations and laboratory simulations for concrete structure durability research.

3.3. Variation of moisture in interior concrete

Fig. 4 shows the variations of the RH and WVD in the natural external environment and at a depth of 35 mm in the test



(a) RH

(b) WVD

Fig. 5. Variation of the RH and the WVD at different depths in concrete (2011.08.16–19).

specimen. As shown in Fig. 5, the variation of the moisture in the interior concrete differs from that in the natural environment. In Figs. 4 and 5, the variations of the temperature and RH were measured by temperature-humidity sensors, and the WVD calculated by Eq. (5) was based on the measured data. The WVD fluctuates periodically in the range 26–44 g/m^3, whereas the RH in the interior concrete is relatively steady and tends towards a constant value (approximately 94%). Because of the low permeability of concrete, the moisture transfers extremely slowly between the external environment and concrete interior. Comparatively speaking, the moisture content in the concrete interior varies with the change of the temperature and moisture gradient between the external environment and concrete interior. Because of the liquid water in the ink-bottle spaces of the interior concrete and the low moisture exchange, a dynamic self-equilibrium state between liquid water and water vapor may be realized in the interior concrete. Therefore, the moisture in the ink-bottle spaces of the concrete interior may be released and redistributed as condensed water via evaporation and condensation over time. Thus, the WVD in the concrete pores is a function of temperature and may fluctuate with time. The data in Fig. 4 also show that the theoretical curves of the RH agree well with the experimental data, indicating that the RH model used in this study predicts well the RH in the concrete interior.

The RH was measured in the external environment and at different depths (5 mm, 15 mm and 35 mm) in concrete, and the corresponding WVD was calculated using Eq. (5) and the measured RH data. Fig. 5 shows the variation of the RH and the WVD at different depths in the concrete. As mentioned above, the RH in the external environment fluctuates, whereas the RH in the concrete interior is fairly steady (Fig. 5a). The fluctuation range of the RH in the external environment is approximately 40–70%; however, the measured RH values, with variations, are approximately 89 ± 1%, 90.5 ± 0.5%, and 93 ± 0.25% at depths of 5 mm, 15 mm and 35 mm in concrete, respectively. The temperature variation triggers a change in the saturated water vapor pressure in air, but the liquid–gas phase transition in concrete micropores can occur via evaporation and condensation to reach local dynamic equilibria. The data also show that as the depth increases, the RH is higher and fluctuates less.

The data in Fig. 5b show that the WVD curves of the concrete interior at different depths also fluctuate periodically, but they differ significantly from the RH curves for the external environment. Compared with the RH curves in the external environment, the WVD curves are smoother and exhibit hystereses. The data indicate that as the depth from the specimen surface increases, the WVD fluctuates less and exhibits more hysteresis, which is less strongly influenced by the external environment.

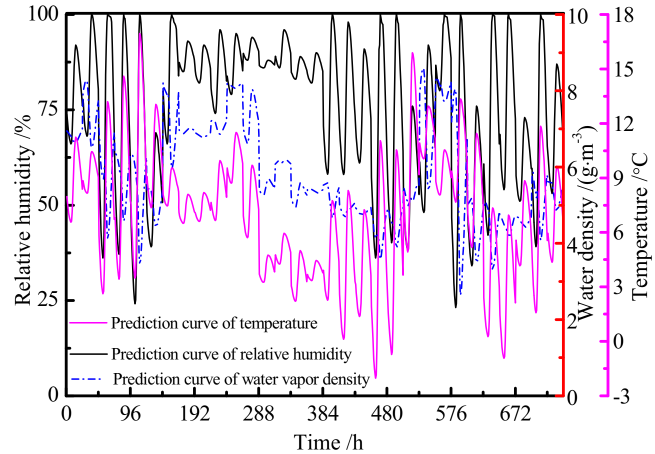


Fig. 6. Curves of temperature and moisture in December 2011.

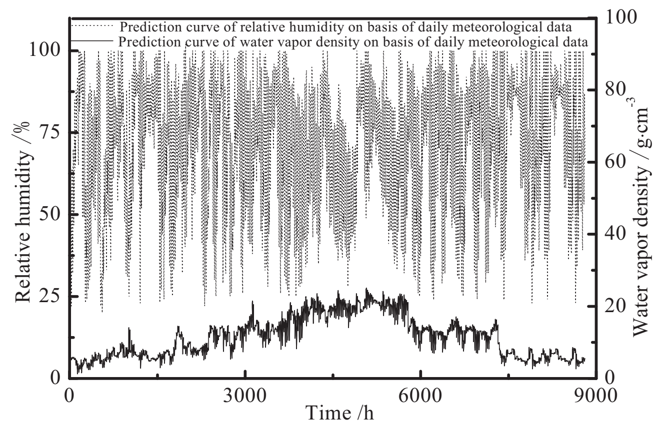


Fig. 7. Action spectrums of moisture in the outside environment (2011).

4. Action spectrums and response spectrums of moisture

In Section 3, the moisture variations in the external environment and interior concrete over the diurnal cycle were discussed. The moisture variations exhibit fluctuations and randomness. Therefore, the moisture variations should be simplified to form moisture action and response spectrums for monthly and annual periods. The action spectrums of moisture in the external

Table 1
Meteorological data for Changsha in December 2011.

Date	Rainfall/mm	Hours of sunshine/h	Average temperature/°C	Date	Rainfall/mm	Hours of sunshine/h	Average temperature/°C
1	1	0	8.9	16	0.2	0	3.9
2	4	0	9.3	17	0.7	5.5	5.0
3	0	7.2	7.9	18	0	3.2	4.2
4	0	7.1	9.0	19	0	3.9	4.3
5	0	9.5	10.2	20	0	7.6	4.5
6	Light rain	0	10.2	21	0	8.4	4.9
7	14.4	0	8.5	22	0	4.7	10.4
8	24.0	0	7.3	23	0.2	0	11.5
9	Light rain	0	7.4	24	3.4	0	9.3
10	7.9	0	8.3	25	Light rain	4.6	10.5
11	0.5	0	10.1	26	Light rain	0	8.3
12	2.7	0	7.7	27	6.4	7.2	3.8
13	21	0	4.0	28	0	4.3	3.0
14	0.5	0	5.1	29	Light rain	0	6.5
15	11.3	0	3.6	30	0	8.0	6.7

environment and the response spectrums of moisture in interior concrete are developed based on monthly and annual meteorological data. The verification details of moisture spectrums can be found in the author's thesis [18].

4.1. Action spectrums of moisture in the external environment

The action spectrums of moisture in the external environment are developed using a month of meteorological data provided by a local meteorological station. Table 1 shows the meteorological data for Changsha in December 2011. Fig. 6 shows the curves for the temperature, RH, and WVD in the external environment for the same month. The data in Fig. 6 and Table 1 show that the WVD fluctuates regularly, increasing during rainy weather and decreasing during sunny weather. The RH exhibits large irregular fluctuations, wherein it is difficult to identify the influence of weather. Hence, the WVD can better characterize the action of the moisture in the external environment.

The action spectrums of the moisture in the external environment were deduced on the basis of the annual temperature and moisture data in 2011, as shown in Fig. 7. The curves of the temperature and the RH were obtained from the daily meteorological data, and the WVD curve was calculated on the basis of the temperature and RH by Eq. (5). From Fig. 7, it can be seen that the RH and the WVD show different fluctuation trends: The WVD varies with the seasons, being lowest in the winter, highest in the summer, and moderate in the spring and in the autumn. However, the RH tends to fluctuate periodically, and the seasonal variations are difficult to describe. The difference between the RH spectrum and the WVD spectrum may result from the different forms of moisture present in the external environment. Consequently, the WVD spectrum may be more useful for quantitative comparisons, whereas the RH may be more useful for qualitative comparisons.

The data in Fig. 7 also show that the moisture action spectrum based on the meteorological data can be used to describe the annual tendency of the moisture in the environment, which may provide a novel method for simplifying the moisture curves in models and simulations for concrete durability research.

4.2. Response spectrums of moisture in interior concrete

Fig. 8 shows the response spectrums of the temperature, RH, and WVD at a depth of 35 mm in concrete, based on meteorological data from Changsha in August 2011. The WVD curve was calculated on the basis of Eq. (5). As mentioned above, the RH at a depth of 35 mm in concrete shows very small fluctuations, as observed in Fig. 5(a). Therefore, the RH in concrete was assumed to be constant, i.e., 94%, when calculating the WVD. The response spectrum for the WVD in concrete fluctuates periodically with time and temperature and thus may be useful for characterizing and quantifying moisture in interior concrete.

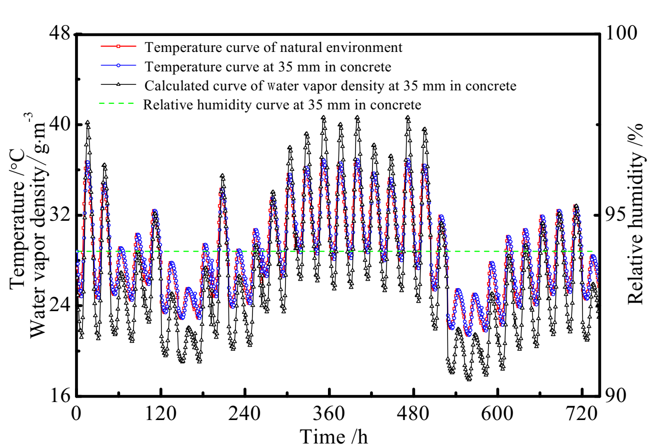


Fig. 8. Response spectrums of moisture in concrete (August, 2011).

Using a method similar to the above, the seasonal and annual moisture response spectrums are obtained, which provide a theoretical basis for the determination of the moisture for models and simulations for concrete structure durability research.

5. Conclusions

(1) A method for predicting the moisture of the external environment and the interior concrete was proposed based on the RH and the WVD concepts using meteorological data. The responses of the RH and the WVD in concrete were both measured and modeled.
(2) The RH and the WVD in both the external environment and the interior concrete show different characteristics as a result of the thermal conduction and permeability of concrete. The RH in the atmosphere fluctuates periodically with the diurnal cycle, whereas the WVD shows only slight fluctuations and a near-linear development. The WVD in interior concrete fluctuates periodically, whereas the RH is relatively steady and tends towards a constant beyond a critical depth.
(3) The action spectrum of the WVD in the external environment varies with the seasons, whereas the RH tends to fluctuate periodically, showing little difference with the change in seasons. The action spectrum of the WVD based on the meteorological data can be used to describe the annual tendency of moisture, which could provide a novel method for simplifying the moisture curve in models and simulations for concrete structure durability research.
(4) The response spectrum of the WVD in concrete fluctuates periodically with time and temperature, which may be useful for characterizing and quantifying moisture in interior concrete, thus providing a method to estimate the moisture in concrete.

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