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Full Length Research Paper

Internal relative humidity distribution in concrete considering self-desiccation at early ages

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The internal relative humidity (RH) and humidity gradients in concrete at early ages have significant influence upon the properties of concrete, where exists, great discrepancy among the test results under different methods. By comparing and analyzing the common measuring methods of the RH in concrete, a newly developed measuring method will be introduced in this study, which could measure the internal RH in cement-based materials accurately, conveniently and digitally. The changing laws of the internal RH in concrete at early ages were discussed. And the numerical simulation of the internal RH was carried out, using the calculated parameters appropriately. The results indicate that the measuring results under the newly developed system was more accurate than that by the predrilled-hole method, while the external environment does not have any effect on the measured results obtained by using the new measurement system. There exist obvious humidity gradients in concrete. In concrete with low water/cement ratio, self-desiccation considerably influence on internal RH distribution. The finite element analysis results from moisture diffusion theory were in good agreement with experimental results.

Key words: Concrete, low water-cement ratio, admixtures, early ages, internal relative humidity, a new measurement system, self-desiccation, finite element analysis.

INTRODUCTION

Cracking is detrimental to the serviceability, durability, and the aesthetic quality of concrete structures. A major driving force behind cracking is the early-age drying shrinkage. Drying shrinkage stresses may cause significant micro cracking and macro cracking. And it may further results in the development of internal relative humidity (RH) gradients in concrete (Grasley et al., 2006). The determination of RH in concrete is the premise to calculate the drying shrinkage stresses (Grasley et al., 2006), and the coefficient of thermal dilation (CTD) of concrete is a function of the RH in concrete (Kolver and Zhutovsky, 2006; Grasley and Lange, 2007).

The humidity sensor is often used when measuring the internal RH in concrete. However, it is difficult to measure in practice. Nowadays, the measuring of internal RH in concrete is a universally acknowledged problem (Jiang et al., 2005). As the number of research projects incorporating IRH measurements in concrete increased substantially in recent years, researchers have warned of potential problems that may be encountered when measuring the internal RH in concrete.

Loukili et al. (1999), Yang (1999) and Andrade et al. (1999) all used RH probes to measure the internal relative humidity in concrete. Loukili (1999) used a probe to measure autogenous RH change of a sealed specimen. A single probe was inserted into a port within a sealed, hardened concrete specimen, and was not removed until the end of the test. However, the experiments by Yang (1999) and Andrade et al. (1999) required the removal of the instrument between measurements, a procedure that exposed a serious limitation of capacitive probes. Andrade et al. (1999) pointed out that after placing the probe in a new measurement hole, it could take more than 24 h for the measurements to stabilize at RH > 90%. Parrot (1988) also acknowledged the slow response of capacitive

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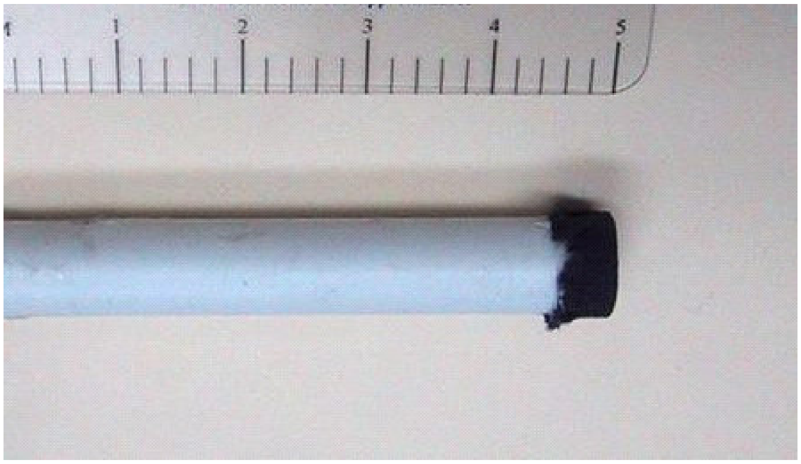

Figure 1. RH sensor packaged for embedding in concrete.

probes at high relative humidity. This problem may be even worse when placed in high-performance concrete (HPC) where the denser microstructure slows the diffusion of moisture to the surface of the concrete in measurement cavity (Persson, 1997). Another event that can lead to erroneous RH measurements in concrete occurs when the temperature of the air inside the measurement cavity is different from the temperature within the concrete. Jensen and Hansen (1999) believed that a difference in temperature of 1℃ between the sensor and the concrete material could yield an error of approximately 6% RH.

It is noteworthy that the concrete specimens of above experiments were mostly hardened concrete. However, numerous engineering cases indicate that the cracking of modern concrete structures happened at early ages (Bentz, 2008). So, the research on changing laws of internal RH in concrete at early ages has significant meaning for monitoring the cracking situation of concrete structures.

Compared with temperature field in concrete, the simulation of internal RH in concrete is rather difficult. Besides the nonlinearity of mathematical model, it mainly results in the difficulty to determine calculated parameters. For example, the diffusion coefficient of moisture in concrete take changes with internal RH (Bazant, 1972).

By comparing and analyzing on common measuring methods of the internal RH in concrete, a newly developed measuring method will be introduced in this study, which could measure the RH in cement-based materials accurately, conveniently and digitally. The changing laws of the internal RH in concrete at early ages were discussed, followed by the numerical simulation of the internal RH distribution, using the calculated parameters appropriately. It has great significance for researching shrinkage characteristic of concrete and predicting drying shrinkage stresses at early ages.

A NEW MEASUREMENT SYSTEM

A new measurement system of the internal RH in concrete was introduced in this paper. This system can be used in measuring RH, both in hardened and the early age concrete. There are several kinds of sensors to measure the internal RH in concrete, dew point and capacitive type of humidity sensors are often used in the measurement. The dew point type has advantage of high measuring accuracy, while its cost is high. The cost of capacitive type is low and its size is small. Especially, the small size of the capacitive type of humidity sensor reduces the required cavity volume, allowing measurement of the internal RH at an exact location or depth, the small volume also lowers the time to equilibration. Considering the above factors, the humidity sensors used in new measure system are capacitive type of humidity sensors made in Switzerland (SHT7X, 6 mm×20 mm). The accuracy of the sensors is reported by the manufacturer to be ±2% RH, between 10 and 90%, and ranges up to ±4% at 100% RH.

The sensor is encased in sleeve with a cap, making it capable of being embedded in concrete. The cap was made by a film, which allowed vapor transmission while preventing the penetration of liquid moisture and ions that could invoke erroneous measurements. Vapor pressure equilibration will occur between the sensor tube and the concrete pore structure in contact with the cap. The caps may be secured to the plastic tubes using gel-type superglue or other adhesive. The adhesive tube will avoid any contamination due to the evaporation. The packaged sensor should be placed in the environment of 20 to 30℃ and relative humidity above 74% for 48 h. The small packaged sensor, prepared for embedding in concrete, is shown in Figure 1.

Table 1. Mix proportions of concrete (kg/m^3).

OPC	Water	Sand	Aggregate	PFA	GGBS	Expansive agent	Water reducing agent
415	155	650	1100	30	40	10	7.5

Data transmitted digitally from the sensors is collected by a computer through a serial connection. By using the developed software to control the data collection hardware, the measurements are allowed to be taken from many sensors at prescribed intervals. For low water/cement ratio mixtures, the moisture in the large capillary pores may be consumed before the sensor can equilibrate to the internal RH. As a result, the measured RH may never reach the maximum internal RH of the material before self-desiccation initiates (that is, 97 to 98%). This may require that sensors be preconditioned to a high RH prior to embedment. The sensors can be stored in a sealed container above distilled water to precondition, and then, inserted rapidly into the tubes immediately, prior to casting.

The new system overcomes many drawbacks of alternative approaches. A major disadvantage of capacitive sensors is that, the capacitance in sensor lead-wires may make calibration of capacitive sensors difficult, and may negatively jeopardize the accurate measurement. The capacitive sensor in the new measurement system does not suffer from this limitation. The analog signal will be converted to a digital output on the sensor itself.

The embeddable internal RH measurement system has the following advantages; digital signal avoids negative effects of lead-wire capacitance; small size means a small cavity of air equilibrates before accurate results are obtained; embeddable packaging allows measurements to be initiated at casting; cost-saving for throw-away embedment applications; computerized data-acquisition; temperature measured on same printed circuit board as RH.

EXPERIMENTAL PROGRAM

The internal RH in concrete at early ages was measured by new measurement system and traditional measure system (predrilled-hole method). The property of new measurement system was analyzed, and the changing laws of the internal RH in concrete are studied.

Materials and mix proportions

In this experiment, 42.5 ordinary Portland cement (OPC) based on Chinese standards was used. The mineral admixtures of pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) were also used. The water/cement ratio (w/c) was 0.37, and the water/binder ratio was 0.32. River sand was used as fine aggregate and crushed granite gravel, passing the 19-mm sieve was used as coarse aggregate. Detailed mix proportions of concrete specimens are given in Table 1.

Specimen preparation and RH measurement method

The dimension of specimens for one-face drying used in two RH measurement methods was both 150×150×150 mm. The number used in this experiment was two, which marked as A and B respectively. Except the drying surface, the other five surfaces were sealed with epoxy resin sealant with the thickness of 2 mm which would guarantee that moisture diffusion conducts uniaxially during drying process. When it exceeds 24 h, the specimens were demoded.

The internal RH in specimen A was measured by newly developed system. Internal RH sensors were embedded in fresh concrete specimen using small plastic tubes with caps. The tubes were inserted to various depths such as the measurements were being taken at depths of 5, 90 and 120 mm from the drying surfaces. The detail of testing set is shown in Figure 2. The sensors were marked H1, H2 and H3 respectively.

The internal RH in specimen B was measured by predrilled-hole method. After drilling a hole at 75 mm distance from the drying surface, plastic sleeve was placed at the location. The RH probe was inserted with a rubber plug in the plastic sleeve. The RH was measured as soon as the equilibrium between the concrete and the air in the plastic sleeve was obtained. The sensor was marked H4.

RESULTS AND DISCUSSION

The results of internal RH measured by two methods are shown in Figure 3. The H4 curve was the data obtained by predrilled-hole method. Its curve had large volatility, this indicates the measurement results was influenced seriously by surroundings, while the curves H1 to H3 obtained by newly developed system were stable. By comparing the results obtained by two measurement methods, the results measured by the newly developed system were found more accurate than that by predrilled-hole method. For newly developed system, it takes little time for the measurement to stabilize.

Figure 3 also shows the internal RH at the distance of 5, 90 and 120 mm from exposed surface. The internal RH differed significantly according to the depth from the exposed surface, and the change of RH was greater at the depth close to exposed surface than at an inner region of the concrete. The RH decrement at distance of 6 mm is higher than those at the distances of 90 and 120 mm. The RH gradient was existed obviously. Under the environment with average temperature of 22°C and humidity of 40±5%, the RH at 5 mm from surface kept decreasing at the early ages, its value decreased down to 72.4% at 21 days, while the RH in the inner region of the concrete decreased slowly down to 95.3% at 21 days.

Parrot (1988) presented a formula for the prediction of moisture profiles throughout drying concrete made with water/cement ratios 0.40 to 0.60:

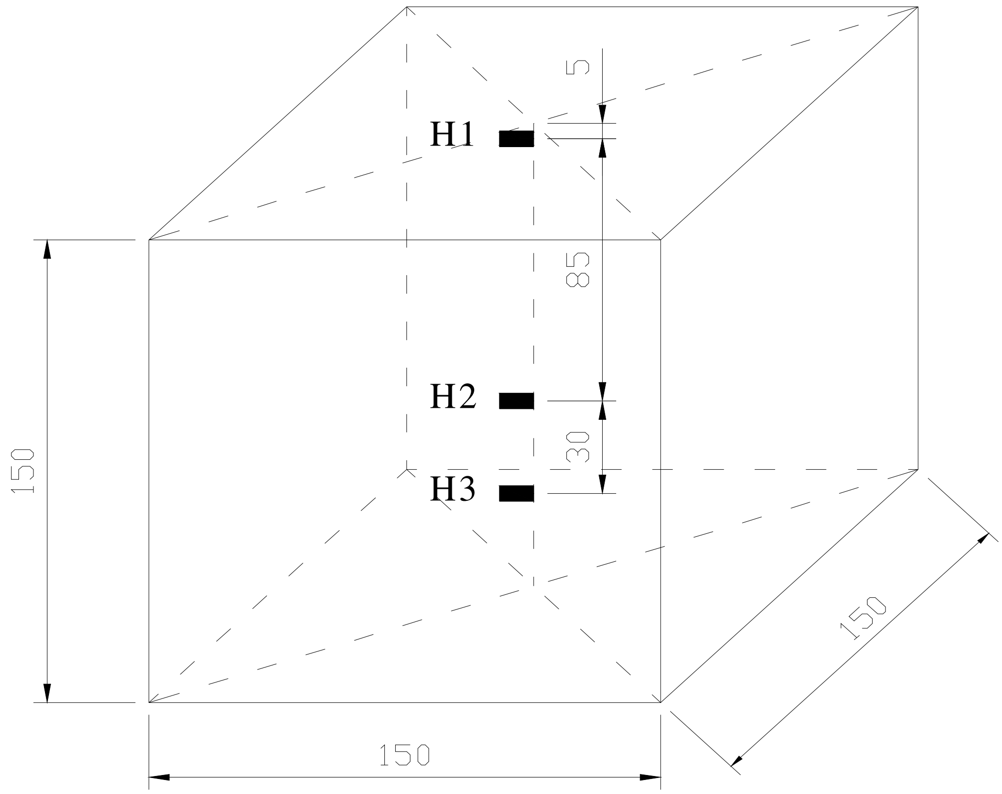

Figure 2. Dimensions and sensor position of specimens for RH measurement (mm).

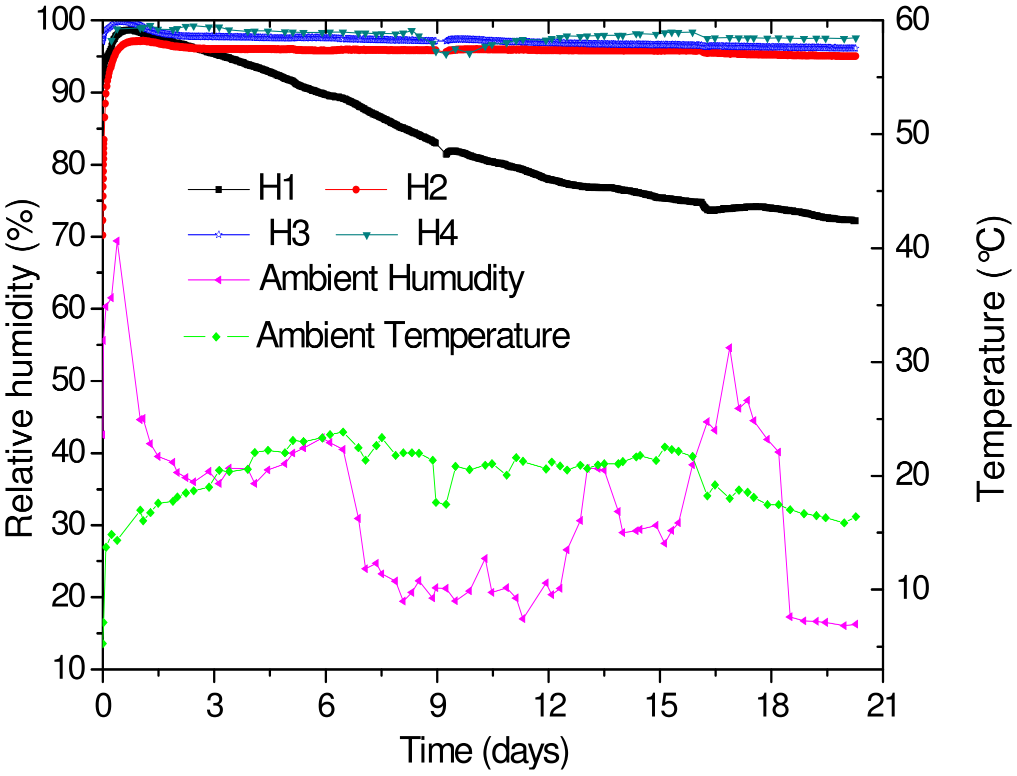

Figure 3. The internal RH distribution in concrete at early ages.

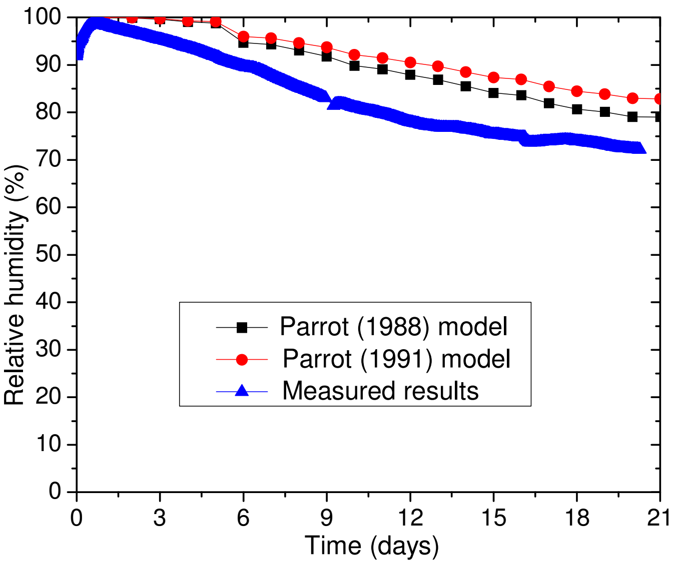

Figure 4. Calculated RH values compared to experimental values.

$$RH = RHA + (100 - RHA) \times f(t)$$
$$f(t) = 1/(1 + t/b)$$
$$b = d^X (Y - e)(w - Z)/W \tag{1}$$

where RH is the predicted relative humidity (%), RHA is the ambient relative humidity, t is the drying time (days), d is the depth from drying surface (mm), e is the OPC replaced by PFA or GGBFS (%), and w is the water/binder ratio. W, X, Y and Z are constants. Parrot then assigned values to the four parameters, such that $W = 8$, $X = 1.35$, $Y = 70$ and $Z = 0.19$.

Parrot (1991) presented another formula for the prediction of moisture profiles throughout drying concrete made with water/cement ratios 0.40 to 0.83:

$$f(t) = e^{-kT} \tag{2}$$

where $k = 0.8 - 0.14T + 0.01T^2$, and $T = t/t_{1/2}$. The values of k diminishes from 0.8 to 0.4 as T changes from 0 to 4.

The values of $t_{1/2}$ that were used to normalize the drying time were plotted against the depth d from the exposed surface, Parrot found the plots to be bilinear. The relationship between drying time and d could be represented by the equations

$$t_{1/2} = 10jd \text{ for } t_{1/2} < 414 days \tag{3a}$$

$$t_{1/2} = 3jd + 290 \text{ for } t_{1/2} \geq 414 days \tag{3b}$$

where j = 1.00, 0.56 and 0.56 for OPC, PFA and GGBS concrete respectively.

Figure 4 shows the comparison between the measured and calculated results of Parrot (1988, 1991) models for RH at 5 mm distance from exposed surface. It indicates that both models are not suitable for predicting the internal RH in concrete with low w/c and mineral admixtures at different distances due to the moisture diffusion. As stated earlier, the prediction models are just suitable for concrete or paste with high w/c that has higher porosity and more free water than concrete with low w/c and consequently the effect of self-desiccation on its internal RH change is little. For the adding of PFA and GBFS, the moisture diffusion would decrease and it mainly lies in that, mineral admixtures make the microstructure of paste denser, and porosity changes as well, thus its diffusion coefficient becomes smaller. These results correspond well with the results presented in other literature (Jiang et al., 2006; Kim and Lee, 1999). It indicates that, when the internal RH changing laws of concrete with w/c number higher than 0.4 resulting from moisture diffusion is predicted, or calculated, self-desiccation shall be taken into consideration and new internal RH changing laws of concrete with low w/c shall be established.

NUMERICAL MODELING OF INTERNAL RH IN CONCRETE

If concrete is exposed to ambient air at early ages, water movement takes place due to the moisture diffusion. Therefore, the moisture distribution of a cross-section becomes non-uniform. In addition, self-desiccation in concrete occurs due to hydration of cement. Therefore, the valuation of relative humidity in young concrete is a result of both moisture diffusion and self desiccation. The self-desiccation phenomenon is especially significant in low water/cement ratio concrete at early ages.

The rates of moisture diffusion and self-desiccation are mainly dependent on material properties of the concrete, such as water/cement ratio and microstructure of concrete, and the outer drying conditions. Assuming that the inner variation of relative humidity due to self-desiccation in drying specimens is the same as that in sealed specimens, the total variation of internal relative humidity can be represented in Equation (4) as:

$$\Delta h = \Delta h_d + \Delta h_s \tag{4}$$

where Δh is the total internal variation of relative humidity, Δh_d is the variation of relative humidity due to

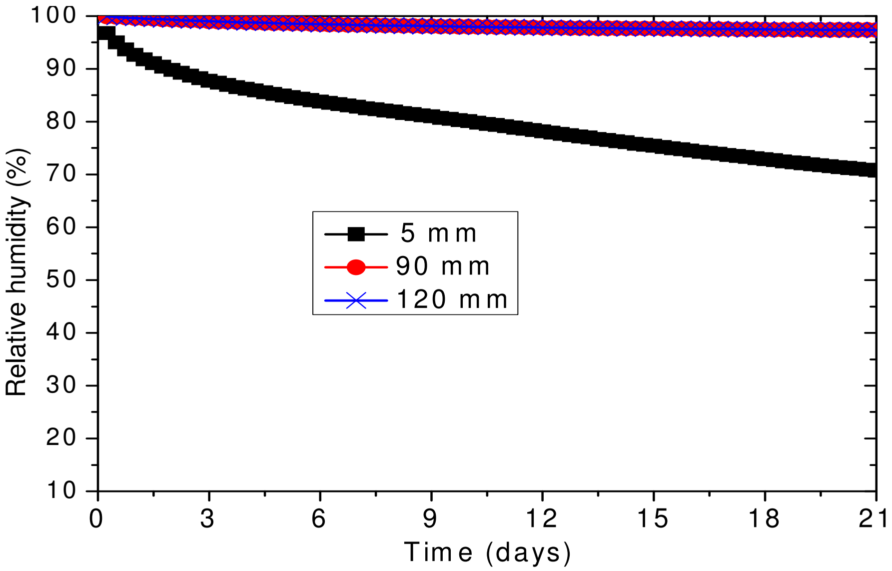

Figure 5. The calculated results of internal RH at measured points.

moisture diffusion at each location, and Δh_s is the variation of relative humidity due to self-desiccation.

From moisture diffusion theory, the following equation can be obtained (Akita et al., 1997):

$$\frac{\partial h}{\partial t} = div\left(D\left(h_s, h, w/c\right) gradh\right) + \frac{\partial h_s}{\partial t} \tag{5}$$

where D denotes the moisture diffusion coefficient. Bazant (1972) derived the formula to calculate the moisture diffusion coefficient, which is expressed as a function of the pore relative humidity as seen in Equation (7):

$$D(h) = D_l\left(\alpha + \frac{1-\alpha}{1+\left[(1-h)/(1-h_c)\right]^n}\right) \tag{6}$$

where D_l is the maximum of $D(h)$ for $h=1.0$, $\alpha = D_0/D_1$, D_0 is the minimum of $D(h)$ for $h=0.0$, h_c is the pore relative humidity at $D(h)=0.5D_1$, and n is an exponent. $\alpha = 0.05$, $h_c = 0.80$, and $n=15$ are approximately assumed (Yuan and Wang, 2002).

As the boundary condition of moisture, it is necessary to correlate the surface moisture with the humidity of the environmental atmosphere. On the exposed surface S, the boundary condition is shown in Equation (8):

$$D\left(\frac{\partial h}{\partial n}\right)_s = f\left(h_{en} - h_s\right) \tag{7}$$

where f is the surface factor, h_{en} is the environmental humidity, and h_s is the relative humidity on the exposed surface.

Bazant (1972) dealt with this problem by assuming an additional thickness to the specimen (that is, the equivalent surface thickness). Comparing analytical results with experimental ones, Merikallio et al. (1996) reported that, the value of the equivalent surface thickness is 0.75 mm.

Numerical modeling of the internal RH in concrete at early ages was carried out by finite element software ANSYS. The calculated results for measured points are shown in Figure 5. According to Figure 5, it illustrated that the measured values correspond well with the prediction, the calculated values of RH at 5 mm from the exposed surface at 21 days was 71.6%, the measured value is 71.6%, the relative error is 0.7%, showing finite element method can be applied into simulating the changing laws of the IRH in different concrete members.

Conclusions

A newly developed measurement system for measuring internal RH in concrete at early ages is introduced in this paper, the changing laws of internal RH in concrete at early ages were studied and the finite element analysis of internal RH was carried out by using the software ANSYS. The following results can be obtained:

i) The measuring results by newly developed system were found more accurate than that by method of predrilled. The external environment had no effect on the measured results obtained by the new measurement system and the results measured by newly developed system, approached the real RH in concrete very quickly.

ii) The RH near the surface of the specimen decreased quickly, while the RH in center of the specimen decreased slowly; the moisture contents, d, unevenly distributed through the various height of the specimen; there exists obvious humidity gradients in concrete.

iii) Parrot's change laws of internal relative humidity in concrete with w/c no higher than 0.4 and mineral admixtures due to moisture diffusion considering self-desiccation are different from those in concrete with higher w/c ratio. And new internal RH changing laws of concrete with w/c no higher than 0.4 shall be established.

iv) The analytical results obtained by moisture diffusion theory were in good agreement with experimental results. It seems that moisture distribution in concrete was also well predicted by moisture diffusion theory in concrete exposed to the ambient air at early ages.

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