One and Two Dimensional Water Transport Predictions With Aid of Developed Moisture Measurement Technique and Experimental Investigations

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Abstract

In this study a moisture transport model is introduced in the forms of water vapor transport, described by Fick's diffusion, and liquid water transport, described by Darcy's law. In order to solve nonlinear differential equations of transport models, moisture storage has to be established. The transport models are evaluated by comparing with experiment results of concrete samples subjected to specific studied boundary conditions and measured by developed and traditional methods.

Keyword: Water transport, Moisture storage, Attenuation

1. Introduction

The use of concrete is widespread in the construction industry since it has a low cost and can be casted in various forms. However, concrete material can be deteriorated by environmental attacks. Most deterioration processes involve moisture transport [1], [2], [3] and the successful repair strategies can be accomplished by knowing water content [4]. Studies of moisture transport in concrete are focused on both moisture measurement techniques and mathematical modeling. In addition, the appropriate material characterization models should be deduced in order to solve nonlinear transport equations. Both of the moisture transport and the material characteristics models will be thereafter integrated in a simulation program in order to simulating behavior of moisture movement in building materials.

In this research the developed moisture transport and moisture storage models will be introduced. The liquid water transport model described by Darcy's law and water vapor transport model described by Fick's law are the two main components of the moisture transport model of concrete. The moisture storage model will be described by using Kuenzel's approach [5]. To evaluate the simulated results, the experiment investigations concerning to moisture measurement techniques for measuring moisture content and moisture distribution inside concrete specimens subjected to specified boundary conditions are conducted.

2. Moisture transport in concrete

2.1 Water vapor transport model

The water vapor transport in a pore system of porous building materials can be described by the sum of water vapor diffusion of gas phase, $\dot{m}_{d,diff}$, and the convection of gas flow, $\dot{m}_{d,conv}$ in consequence of partial water vapor partial pressure. From [6], the gradients of water vapor concentration and total pressure induce diffusion transport. Due to constant air pressure, the diffusion process caused by total pressure can be neglected. In addition, the diffusion caused by temperature gradient can also be neglected since this study deals only with isothermal transport. Therefore,

$$\begin{aligned} \dot{m}_{d,diff} &= -D_d \cdot \nabla C_d \\ &= -D_d \cdot \nabla \left(\frac{p_d}{R_d \cdot T} \right) \cdot \theta_d \approx \frac{-D_d}{R_d \cdot T} \cdot \nabla \, (p_d \; \theta_d) \end{aligned} \tag{1}$$

where $\dot{m}_{d,diff}$ is water vapour diffusion of gas phase in kg/m^{2}s, $\dot{m}_{d,conv}$ is convection of gas flow in kg/m^{2}s, R_d is the gas constant, T is temperature in K, p_d is water vapor partial pressure in Pa, and θ_d is water vapor in kg/m^3. In case of convective gas flow, the driving potential is pressure gradient ∇p_g in the gas phase, consisting of dry air and water vapor. K_g is the permeability coefficient of materials for water vapor. If there is a constant atmospheric pressure p_a in the pore system, this pressure is generally much larger than the water vapor partial pressure p_d , i.e., ∇p_g approaches zero. Consequently, the term $\dot{m}_{d,conv}$ in Equation (2) is near zero and neglected.

$$\dot{m}_{d,diff} = -\theta_d \cdot p_d \cdot K_g \cdot \nabla p_g \tag{2}$$

The total water vapor transport can be derived as:

$$\begin{aligned} \dot{m}_d &= \frac{D_d}{R_d \cdot T} \, (p_d \; \theta_d) \underbrace{-\theta_d \, p_d \, K_g \, \nabla p_g}_{\approx 0} \\ &= \frac{D_d}{R_d \cdot T} \nabla (p_d \theta_d) \end{aligned} \tag{3}$$

where $P_d = \varphi \cdot P_{d,sat}(T)$, $p_{d,satt}(T)$ is saturation water pressure at a given temperature, φ is relative humidity, D_d is $\frac{D_L(T,p_g)}{\mu}$, DL is diffusion coefficient of water vapor in m^2/s and is $2.3 \text{ x } 10^{-5} \; \frac{p_o}{p_L} \left(\frac{T}{273} \right)^{1.81}$, p_L is ambient atmospheric pressure in Pa, p_O is standard pressure in Pa ≈ 100KPa, and μ is water vapor diffusion resistance factor.

2.2 Water transport

The water transport equation can be described by the sum of diffusive and convective terms of water transport. As shown below, the first term is the diffusion of liquid water in a pore system. On a theoretical basis, the diffusion term of liquid water transport is considered in the vapor diffusion transport term since there is no measurement method which can isolate both transport processes from each other. Thus,

$$\begin{gathered}
\dot{m}_d = \underbrace{-D_w \nabla w}_{diffusive} \underbrace{- \theta_w \rho \frac{K_w}{\eta_w} \nabla p_k}_{convective} \\
\dot{m}_d = \underbrace{-D_w \rho_w \nabla \theta_w}_{\approx 0 \text{ and considered in } \dot{m}_d} - \theta_w \rho \frac{K_w}{\eta_w} \nabla p_k
\end{gathered} \tag{4}$$

where K_w is permeability in m^2 depending on water content (θ_w), η_w is viscosity of water Pa·s, ρ is density of water kg/m^3, and p_k is capillary pressure in Pa.

2.2.1 Water conductivity, K_w

According to Hagen-Poiseuille, the volumetric flow $\dot{V}k\ (r)$ in one particular capillary pore with radius (r) and capillary pressure gradient $\frac{\partial p_k}{\partial x_k}$ gives:

$$\dot{V}k = \frac{4\pi^4}{8\eta} \cdot \frac{\partial p_k}{\partial x_k} \tag{5}$$

Integrating over all ranges of volumetric flux (r_{min} to r_{max}) and considering the difference between pore model and real pore geometry by introducing tortousity $T(\theta)$, yields liquid water flux as:

$$\dot{m}_d = \left[\underbrace{-T(\theta) \cdot \frac{\rho}{8\eta} \int_{\theta min}^{\theta} r^2 (\theta) d\theta}_{K_w} \right] \cdot \frac{\partial p_k}{\partial x_k} \tag{6}$$

where θ and θ_{min} are water content and minimum water content in kg/m^3 respectively and , x_k is coordinate in m.

2.3 Moisture storage

In most moisture transport models, the relationship between moisture content and relative humidity or capillary pressure is a prerequisite, in order to solve differential equation as:

$$\dot{m}_d = \frac{-dw}{dp_k} \cdot \frac{dp_k}{dt} = \theta_w \rho \frac{K_w}{\eta_w} \nabla p_k \tag{7}$$

where dw/dp_k is the derivative of moisture storage function.

When porous building materials are in contact with moisture, the water molecules are physically bound to the surface of a pore system until subjected to equilibrium with ambient relative humidity [5], [7]. The equilibrium is described in terms of sorption isotherm curves which are composed of adsorption and desorption isotherms of concrete as denoted in Figure 1. In this research Kuenzel's approach is used to derive such a function. Thereafter, the $w(p_k)$ function will be obtained by applying the Kelvin equation to transform w-p_k relationship to w-p_k relationship.

Kuenzel [5] derived the simple formula to calculate this equilibrium as shown below

$$w = w_f \cdot \frac{(b - 1)\varphi}{b - \varphi} \qquad (8)$$

where w is equilibrium water content in kg/m^3, wf is free water saturation content in kg/m^3, b is an approximation factor which is always greater than 1, and φ is relative humidity. The factor (b) can be determined from substituting a numerical value of φ which equals 80%, and its corresponding moisture content into the equation.

The sorption isotherm calculated from Kuenzel's approach is shown in Fig. 1. By comparing between experimental results and Hansen [8], the calculated isotherm from this approach has value relatively near the desorption isotherm.

3. Simulation program

In this study the transport simulation program, ASTRa, which allows calculating coupled heat, moisture and ion transport in a pore system of building materials, is written in C language and developed under the Institute of Materials, Physics, and Chemistry of Buildings, Hamburg University of Technology. In the transport models in the ASTRa program, the thermodynamical principles are employed similarly to other transport programs. The thermodynamical differential equations, which consist of energy and mass balance equations, can be formulated. The calculation and simulation of coupled heat and moisture transport in building materials require the solution of these differential equations. The further details of applying previously described moisture transport and moisture storage models in ASTRa program are shown in [5], and used a solution method, i.e., finite volume can be found in [9].

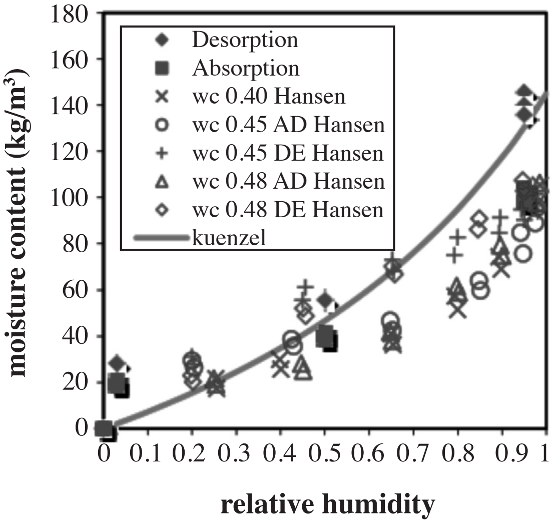

Fig. 1. Comparison between sorption isotherms obtained from Kuenzel's approach and results obtained from experiment and Hansen [8].

4. Experimental programs

This section is aimed to explain the details of developed moisture measurement methods and case study to compare with simulated results.

4.1 Moisture measurement method

Nowadays, there are several moisture measurement methods for determining moisture content in porous materials in a nondestructive way; for example, gamma-ray attenuation, nuclear magnetic resonance, and microwave methods, etc. For the microwave moisture measure method, [10] used a microwave moisture sensor system whose plane microwave field (frequency of 2.45GHz) was radiated by a planar antenna into a building material. It was found that the magnitude of microwave attenuation was influenced by the dielectric constant of the material and this constant was correlated with moisture content in a linear tendency. In this study the developed measurement technique was used to determine moisture content of the samples on the basis of moisture-dependent dielectric constant by applying a frequency of 3 to 10 MHz generated from a network analyzer and transmitted between 2 electrodes, as depicted in Fig. 2. The technique measured loss of signal between the 2 electrodes, and its relationship with moisture content can be observed at a frequency of 6.023 MHz.

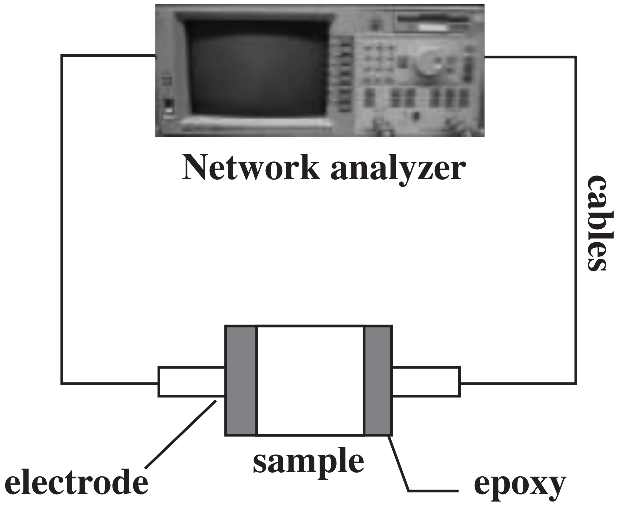

Fig. 2. Moisture measurement test configuration.

Considering Fig. 3, the relationship between water content and loss of signal can be described. In Fig. 3, if the sample has relative dielectric constant ε', the absolute dielectric constant is ε_0, the conductivity of sample equals σ, the area of electrode is A, the distance between electrode is d, and the frequency is ω, the electrical engineering admittance (inverse of impedance) can be formulated, y:

$$y = j\varpi\varepsilon_0\varepsilon'C' + G \longrightarrow y = j\varpi\varepsilon_0\varepsilon'\frac{A}{d} + \sigma\frac{A}{d} \tag{9}$$

where $\varepsilon_0\varepsilon'C'$ equals susceptance and G is conductance. Regrouping the above equation becomes:

$$y = j\varpi\varepsilon_0(\varepsilon' - j\frac{\sigma}{\varpi\varepsilon_0})\frac{A}{d} \tag{10}$$

where ε* is the complex dielectric constant, which equals $\varepsilon' - j\frac{\sigma}{\varpi\varepsilon_0}$. ε* can be written in simple form ε*= ε'- jε''. From Equation (10), it can be noticed that ω is known (applied frequency), and A, d, and ε0 are constant values. Hence, y depends only on ε*, which is equivalent to corresponding a measurement value, loss of signal or electrical current, and is influenced by water content of a sample.

The corresponding calibration results are shown in Fig. 4. The calibration tests were done on small concrete cubes (4x4x4 cm) with different moisture content. The x-axis represents the attenuation in decibels due to moisture content of samples. The y-axis represents the moisture content in %vol. of w/c 0.45 concrete cubes measured by drying wet sample in an oven, and calculating the weight difference between wet and dry weight, and dividing by the sample volume in m^3. By performing a regression analysis, the calibration equations can be derived, as shown in Equation (11). Therefore, on this basis, the water content of samples can be approximated.

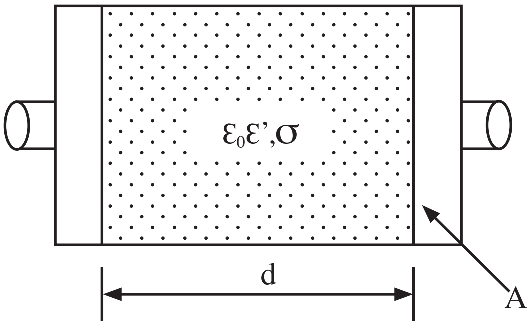

Fig. 3. Basic diagram used to explain relationship between water content and loss of signal.

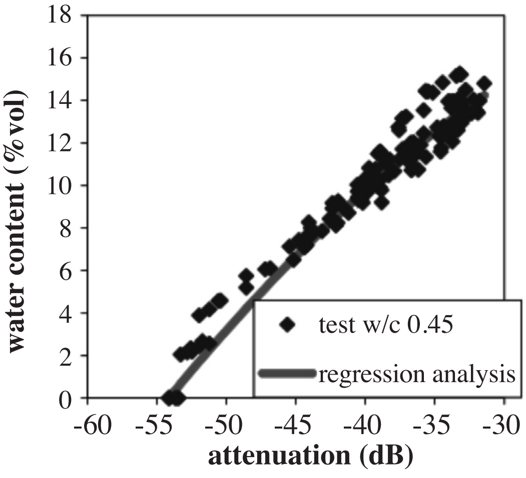

Fig. 4. Calibration curve of w/c 0.45 concrete.

$$w = 213.18 + (-0.065 . |At|^{2.02}) \tag{11}$$

where w is calculated water content, the parameter "At" is measured signal loss (attenuation) due to moisture content in the sample (y axis) in dB. From Figure 4, increased moisture content of the sample yields a decrease in signal loss in accordance with Equation (10).

4.2 Case study: water absorption and constant drying

The case study was designed to investigate moisture content of 4x4x15 cm concrete samples by a gravimetric method and attenuation method, subject to specific boundary conditions. In this case study, concrete samples (4x4x15 cm) with w/c 0.45 were dried at 105ºC to obtain the dry weight of samples. After drying, the electrodes were attached on 2 sides of samples by using conductive epoxy at five different positions, as shown in Fig. 5, to observe moisture profile inside the samples. Then the samples were coated with epoxy. One was coated on 2 surfaces to simulate 2-dimensional moisture transport. The other was coated on 4 surfaces of samples to simulate 1-dimensional moisture transport.

After that, the samples were allowed to uptake the water at one surface for 28 days. After 28 days, the samples were dried at 50% R.H., 23ºC in a controlled climate room for up to 56 days. For both cases of absorption and drying the moisture content was measured periodically up to 28 days. In addition, the samples were cut at 28 days and 56 days at five different positions. Each small proportion was dried at 105°C to obtain moisture content of samples.

The corresponding mix proportion of w/c 0.45 concrete is shown in Table 1

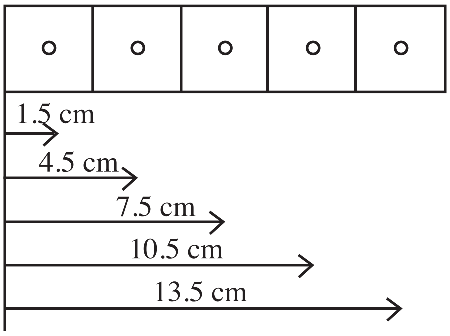

Fig. 5. Side view of tested concrete sample.

Table 1 Mix proportion of w/c 0.45 concrete per m^3.

Compositions	Description	Volume (litres)
cement	CEM I 42.5 R	113
additive	P40 MC admixture	1.78
	FK 99 MC admixture	3.10
gravel		359
sand		359
water		154
air		10

5. Results and discussions

The concrete prism samples 4x4x15 cm were subjected to a water reservoir at one surface. The top surfaces were in contact with laboratory and the other sides were coated according to 2-side or 4-side coating conditions. The ambient conditions were controlled and constant at 23°C and 50% relative humidity. At the beginning of the experiment, the initial water content of dry samples was approximately 5 kg/m^3. After 28 days, the test samples were dried at 50% relative humidity and 23°C.

Figs. 6 and 7 compare the experiment and simulated results of 2 and 4 side coated samples of w/c 0.45 concretes. In the figures, the gravimetric method was used by weighting the samples on a balance at a specific time and calculating the moisture content of a sample per m^3 of sample volume. All experimental results obtained by gravimetric and attenuation showed similar tendency. The samples absorbed water up to 28 days. However, the 2-side coated samples showed lower water absorption content. After 28 days the samples were removed from the water reservoir, and the drying period began. The experiment results showed a sharp drop of the curve as a result of simultaneous drying at the suction surface. The simulated results were represented by ASTRa as shown in the figures. It seemed that ASTRa well fit experimental results in the case of 2-side coated samples. Regarding to 4-side coated samples, ASTRa gave reasonable results.

The measured and calculated moisture distributions by attenuation and ASTRa of the w/c 0.45 concrete samples are shown in Figs. 8 and 9 from day 1 to day 56. At the beginning of water absorption at day 1, there were moisture fronts gradually penetrating through the samples from 1 to 28 days. The penetration was much faster if 4-side coated samples were considered, compared to 2-side coated samples. At 28 and 56 days the samples were split to investigate moisture distribution inside the sample as denoted as the cutting notation in Figs. 8 and 9. These results were correlated to measured results conducted by attenuation method. Regarding simulated results, the ASTRa program provided the same aspects.

After 28 day the samples were exposed to a relative humidity of 50% in a controlled climate room. The measured water contents by attenuation in Figs. 8 and 9 from 28 to 56 days gradually decreased and much decreased in the case of 2-side coated samples due to more exposed surfaces. Comparing between measured and calculated results, the reduction of water content due to drying calculated by ASTRa were lower than measured value.

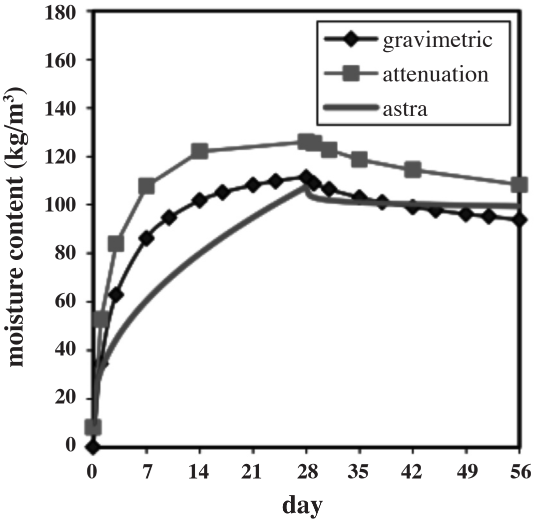

Fig. 6. Water content of 4 sides coated w/c 0.45 concrete subjected to water absorption and drying.

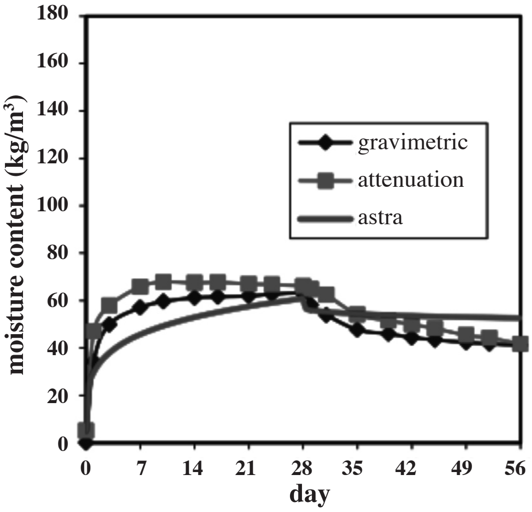

Fig. 7. Water content of 2-side coated w/c 0.45 concrete subjected to water absorption and drying.

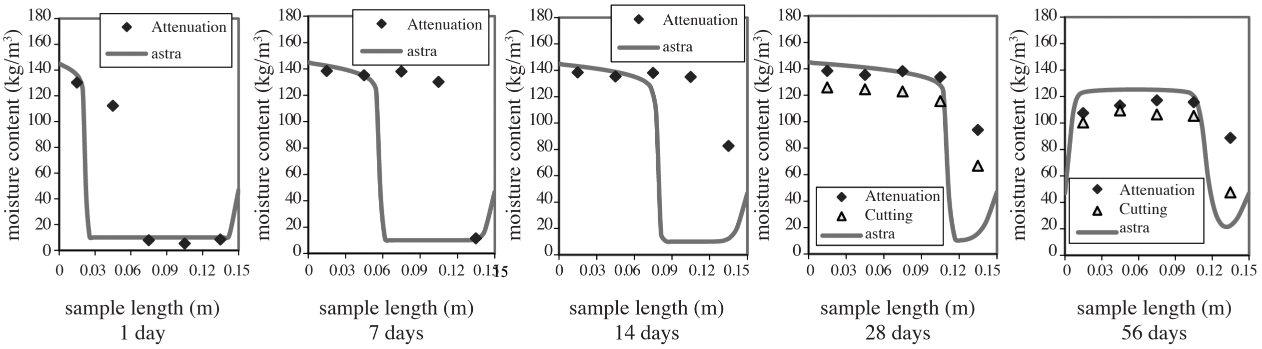

Fig. 8. Water content distribution in 4-side coated w/c 0.45 concrete samples.

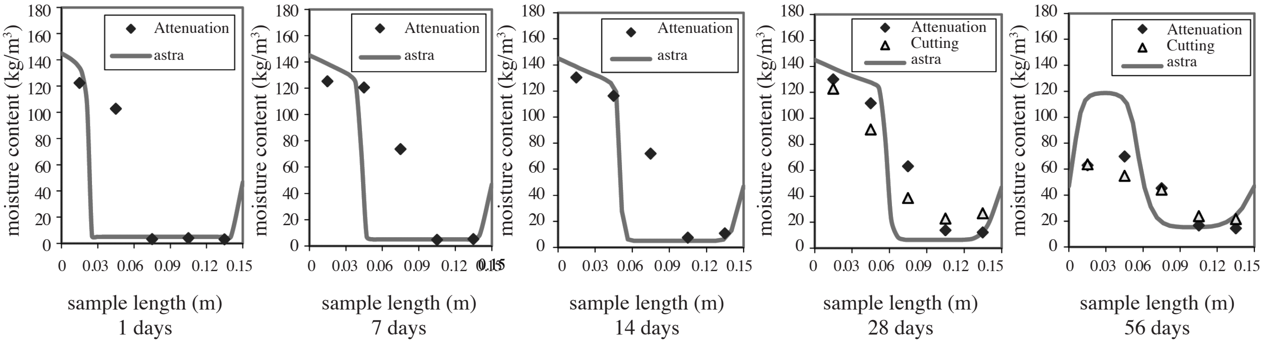

Fig. 9. Water content distribution in 2-side coated w/c 0.45 concrete samples.

6. Conclusions

There are two main components contained in this moisture transport model, i.e, a water vapor transport model described by Fick's diffusion, and a liquid water model described by Darcy's law. In solving the differential transport equations, the relationship defined as sorption isotherm is significant. The Kuenzel's approach is used to calculate the sorption isotherm in this study. To evaluate the transport models, the moisture content of concrete has to be determined experimentally, as measured by attenuation and gravimetric methods. Overall, the proposed models give acceptable simulated result compared with those measured values, however, a small discrepancy can be noticed. This is due to derivation of water conductivity function, Kw. As can be seen, the relationship between pore radius (r) and water content (θ) has to be determined in order to derive the Kw function. The traditional method used in this study to find this relationship is the mercury intrusion porosimetry (MIP) method. However, MIP measurement cannot measure all pore sizes according to the ink bottle pore effect. Therefore, This leads to less water content calculated from the simulation program than the measured water content. The developed moisture measurement technique also gives a satisfactory moisture content of concrete samples.

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