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USING SPONTANEOUS WATER IMBIBITION TO MEASURE THE EFFECTIVE PERMEABILITY OF BUILDING MATERIALS

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The present work is to introduce a new approach to measuring the effective permeability of building materials by using spontaneous water imbibition. A new linear relationship between water imbibition rate and the reciprocal of air recovery is derived and used as the basic theory to obtain the permeability information. The impact of buoyant-force change on the imbibition results is taken into consideration, which makes our results more accurate and reliable. The calculated effective permeabilities of three building materials, including limestone, concrete, and brick, are reasonably compared with permeability data in the literature.

KEY WORDS: *effective permeability, spontaneous water imbibition*

1. INTRODUCTION

Permeability is an important index of the durability of building materials. Several approaches to measuring the permeability of building materials have been proposed. For example, critical voltage of concrete at limited currents is used to evaluate the concrete permeability (Lu et al., 2000). Also, the permeability of concrete can be obtained by the conductivity of concrete when saturated with concentrated salt according to the Nernst-Einstein equation (Lu, 1997).

Spontaneous imbibition is the process during which the nonwetting fluid (air) in a porous medium is displaced by a wetting fluid (water) due to capillary forces. Li and Horne (2001) calculated the capillary pressure and effective permeability from spontaneous water imbibition data for sandstones. However, this work is the first time the effective permeability of building materials has been obtained from spontaneous imbibition.

2. THEORY

Based on Darcy's law and several assumptions, Li and Horne (2001) derived the following four equations:

$$Q_w = \frac{dN_{wt}}{dt} = a\frac{1}{\eta} - b \tag{1}$$

$$a = \frac{Ak_w(S_{wf} - S_{wi})}{\mu_w L} P_c \tag{2}$$

$$b = \frac{Ak_w}{\mu_w} \Delta\rho g \tag{3}$$

$$\eta = \frac{N_{wt}}{V_p} \tag{4}$$

where Q_w is the water imbibition rate; N_{wt} is the volume of water imbibed into the sample; t is imbibition time; η is the air recovery by water imbibition in terms of pore volume; A is the cross-section area of the sample; k_w is the effective permeability of water phase at a water saturation of wetting front S_{wf}; S_{wi} is the initial water saturation in the sample; P_c is the capillary pressure at S_{wf}; μ_w is the viscosity of water; L is the sample length; $\Delta\rho$ is the density difference between water and air; g is the acceleration due to gravity; and V_p is the pore volume of the sample.

According to Eq. (3), Li and Horne (2001) obtained the effective water permeability at the water saturation of S_{wf} as follows:

$$k_w = \frac{\mu_w}{A\Delta\rho g} b \tag{5}$$

In this study, the derivation process is similar to the studies of Li and Horne (2001) but with a little difference. They used the following equation as one of their basic equations:

$$v_w = -\frac{k_w}{\mu_w}\left(\frac{\partial p_w}{\partial x} + \rho_w g\right) \tag{6}$$

where v_w is the flowing velocity of water phase; p_w is the pressure of water phase at the position x; and ρ_w is the water density.

However, use of the + sign inside the parenthesis in Eq. (6) is disputable. Hassanizadeh (1993) used Eq. (7) to describe the Darcy velocity for the wetting phase in the research on the physics of two-phase flow. Considering simultaneous flow of two incompressible and immiscible fluid phases (water and oil) inside a porous medium, Hilfer (1998) presented the same equation as Eq. (7). Silin et al. (2009) conducted research on a vertical gas plume migration through a heterogeneous porous medium, which was similar to our imbibition experiments. In their research, they assumed that the carbon dioxide plume crossed a thick aquifer with uniform flow properties. According to their assumption on the vertical direction, a positive Darcy velocity means upward flow. Then they derived the same relationships between the Darcy velocities of gas and brine and their respective pressure gradients with Eq. (7) according to Darcy's law for two-phase flow.

$$v_w = -\frac{k_w}{\mu_w}\left(\frac{\partial p_w}{\partial x} - \rho_w g\right) \tag{7}$$

As a result, a new equation is derived to replace Eq. (1):

$$Q_w = \frac{dN_{wt}}{dt} = a\frac{1}{\eta} + b \tag{8}$$

where

$$b = \frac{Ak_w}{\mu_w}\rho_s g \tag{9}$$

and ρ_s denotes the sum of water and air densities. If we plot the water imbibition rate (Q_w) versus the reciprocal of air recovery ($1/\eta$), the intercept on the axis of water imbibition rate (b value) will be a positive value according to Eq. (8). We can then derive the equation of k_w from Eq. (9) as follows:

$$k_w = \frac{\mu_w}{A\rho_s g} b \tag{10}$$

This equation is used in this work to obtain the effective permeability k_w.

3. MATERIALS AND EXPERIMENTAL PROCEDURE

The following three types of building materials were used in this study: concrete, limestone, and red brick. All samples were cut into rectangular prisms and given a unique name. The properties and sources of these building materials are listed in Table 1.

After completing the porosity measurements, all sides (except top and bottom faces) of each sample were covered with quick-cure epoxy to avoid the water evaporation from the side surface of the samples during imbibition experiments. Each sample was oven dried at 60°C for at least 48 hours and then cooled to room temperature (22.5 ± 0.5°C) in a desiccator. During the imbibition experiment, the sample was suspended by a sample holder

TABLE 1: Sample properties and sources

Sample ID	Length (cm)	Width (cm)	Height (cm)	Porosity[a] (%)	Source[b]
Concrete 1	1.575	1.524	6.777	20.0	Home Depot
Concrete 2	1.766	1.713	1.579	19.7	Home Depot
Limestone	3.225	2.878	5.221	15.3	Cathedral Stone Products, Hanover Park, MD
Red brick	2.778	2.931	2.425	20.3	Triangle Brick Company, Durham, NC

[a]Porosity was determined by using the vacuum saturation method (RILEM Recommendations, 1984).
[b]From Sang Don Lee (USEPA, personal communication).

that was connected to a bottom-weighing electronic balance by a hook. A simplified schematic of the apparatus for the imbibition test is shown in Fig. 1. The sample was located inside an imbibition chamber with a water reservoir (a glass Petri dish) on its floor. Additional beakers of water were placed inside the chamber to keep the humidity inside the chamber constant at above 98%. The chamber position was vertically adjusted by a support jack below the chamber to make the sample submerged in water to about 1 mm depth to start the imbibition test. The balance automatically recorded the sample weight as frequently as once per second (Hu et al., 2001). The imbibition test was stopped by lowering the support jack and weighing the sampling weight after using a moist tissue to wipe off the excess water at the sample bottom. Imbibition experiments were repeated at least three times on the same sample for different experimental durations.

4. RESULTS AND DISCUSSION

4.1 Water Imbibition vs Time

We measured the water imbibition behavior of each building material sample. A typical imbibition curve is shown in Fig. 2 for limestone. The artificial weight gain produced by the buoyant-force change, which was caused by imbibition and evaporative losses, was corrected (Hu et al., 2001). The check weight, obtained directly by weighing the sample with the sample holder before and after each imbibition experiment, is consistent with the ultimate cumulative imbibition amount corrected by considering both evaporation and imbibition correction for the buoyant-force change (Fig. 2). It can be seen from Fig. 2 that the amount of water imbibed into the limestone sample reached the maximum value at about 250 min and the water imbibition rate became quite low after that time.

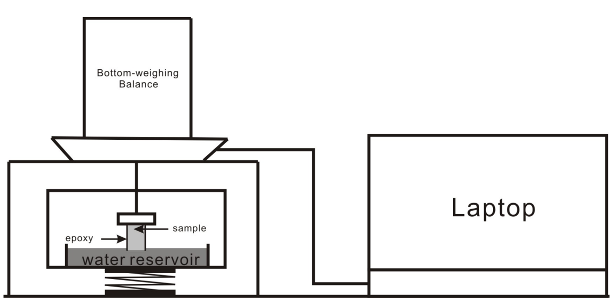

FIG. 1: Schematic of the apparatus for imbibition test.

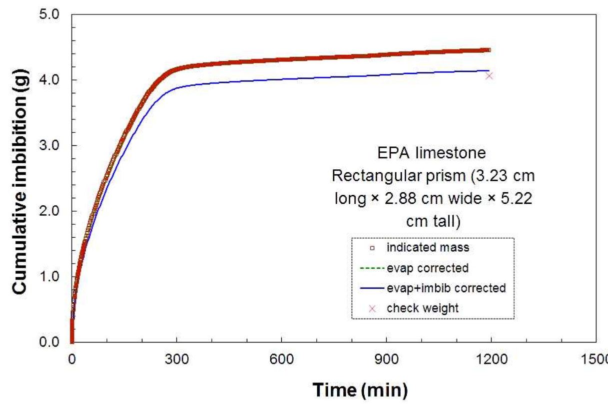

FIG. 2: Water imbibition into the limestone sample. Data for indicated mass from direct balance reading overlaps with these after evaporation correction because of the small evaporation amount.

4.2 Water Imbibition Rate vs the Reciprocal of the Air Recovery

Figure 3 shows that a linear relationship exists between the water imbibition rate and the reciprocal of the air recovery by water imbibition, and this linear relationship corresponds to the fast imbibition part (less than 250 min) shown in Fig. 2. The intercept (b value) on the axis of water imbibition rate is positive, which is consistent with Eq. (8) and the definition of b and proves that the use of Eq. (7) is appropriate in this work. The effective permeability can then be obtained from Eq. (10) and the results are listed in Table 2. The water saturation immediately behind the wetting front (i.e., effective porosity)

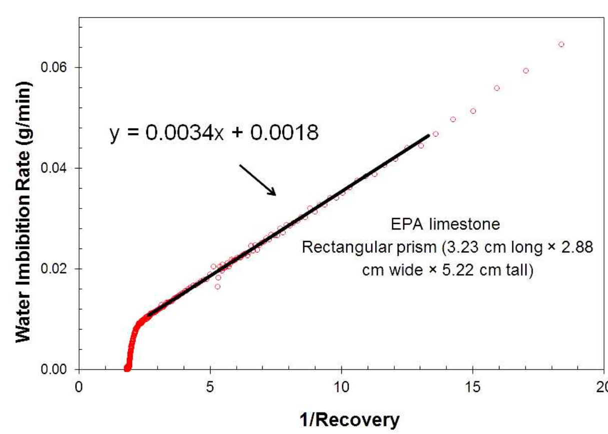

FIG. 3: Water imbibition rate vs the reciprocal of the air recovery.

TABLE 2: Result of effective permeability from spontaneous imbibition data.

Sample ID	***A*** **(cm^2)**	***b***^{a} **(cm^3/min)**	S_{wf}^a	$k_w^{a,b}$ **(md)**	***k*** **from references (md)**
Concrete 1	2.400	0.0011 $\pm$ 0.0006	0.99 $\pm$ 0.06	8.07 $\pm$ 4.17	10^{-2} – 10^{2c}
Concrete 2	3.025	0.0017 $\pm$ 0.0004	0.80 $\pm$ 0.06	9.60 $\pm$ 2.46	10^{-2} – 10^{2c}
Limestone	9.282	0.0026 $\pm$ 0.0008	0.55 $\pm$ 0.01	4.85 $\pm$ 1.48	2 – 27^d
Red brick	8.142	0.0311 $\pm$ 0.0072	0.73 $\pm$ 0.08	65.2 $\pm$ 15.0	6 – 39^e
ρ_g (at 20°C) = 1.2 kg/m^3; ρ_w (at 20°C) = 998.2 kg/m^3; g = 9.8 m/s^2; μ_w (at 20°C) = 1.002 (N S/m^2) $\times$ 10^{-3}.					

^{a} Average $\pm$ standard deviation for at least three replicate measurements.
^{b} Calculated according to Eq. (10).
^{c} From Picandet et al. (2009).
^{d} From Boving and Grathwohl (2001).
^{e} From Bentz et al. (2000).

ranges from 55 to 99% for these building materials. The k_w values, at the corresponding wetting front saturation, are similar to the reported absolute permeability (k) of (6–39) $\times$ 10^{-15} m^2 for brick (Bentz et al., 2000), (2–27) $\times$ 10^{-15} m^2 for limestone (Boving and Grathwohl, 2001), and (10^{-2}–10^2) $\times$ 10^{-15} m^2 for concrete (Picandet et al., 2009). Note that we are not aware of unsaturated effective permeability for these building materials, and even the absolute permeability values are very limited in the literature.

4.3 Discussion

The standard deviation for k_w shown in Table 2 is somewhat high and there are several possible factors to cause it. The initial state of the same sample may be slightly different in each imbibition experiment, although we tried to minimize this effect by treating samples similarly before and after each run. The permeability of the building materials used here is relatively low, which can also contribute to the fluctuations among permeability values for the same sample. The most likely factor is from the microscale sample heterogeneity, which is very sensitively reflected in the measured unsaturated effective permeability.

We could not obtain the permeability of asphalt concrete by using this method; one possible reason is the low porosity (2.2%) and the poor connectivity. This will be investigated in future work.

5. CONCLUSION

A new approach has been developed here to measure the effective permeability of unsaturated building materials from simple imbibition tests. The new derived linear relationship between water imbibition rate and the reciprocal of air recovery is corroborated by the results of imbibition experiments. The values we got here for permeability are in line with literature permeability results by using different approaches (e.g., mercury injection porosimetry). Considering the low permeability of these building materials and the factors mentioned above, the standard deviations for k_w are acceptable. This new method can be applied to materials with a relatively high porosity (e.g., >15% as tested in three materials in this work) and well-connected pore structure.

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