Drying of Fluid Saturated Porous Materials by Electroosmosis

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Abstract

Electroosmosis is generated by the relative displacement of an electrolytic fluid with respect to solid surfaces under application of an electric field. The induced flow can assist in drying wet porous materials such as masonry used in buildings. In this work, the effectiveness of electroosmotic water transport induced by the application of a constant voltage across a wet porous sample is studied. A quantitative evaluation of water content is then performed at three different positions of the sample using a capacitive sensor. From the measured capacitance, the change of the dielectric constant of the wet sample over time is deduced. A model is then used to estimate the water content from the dielectric constant of the sample. It is seen that under application of constant voltages, the water content of the wet porous sample at the position close to the positive electrode decreases drastically. However, the water content remains almost constant in the middle of the sample and at a position close to the negative electrode. The reason is that water is pushed from the positive electrode to the negative electrode under application of electric field. Therefore, the water content becomes almost saturated right after applying a voltage across the sample. The results suggest that the electroosmotic technique can be applied to the drying of wet walls of buildings, and to stone and earth masonry structures, especially in cases where traditional techniques have not been able to solve the problems. Additionally, it is shown that our use of capacitive sensors is a technique that could be used to monitor the water content in wet porous materials.

Keywords: rising damp; capillary; masonry; electroosmosis
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1. Introduction

The existence of water in buildings and masonry structures is generally one of the most common issues influencing architectural heritage. The water may be present for various reasons including accident, wind driven rain, flooding, and rising damp from the ground [1-3]. The existence of rising damp creates a bad ambiance in buildings. It also enhances damaging processes such as the degradation of building materials, the loss of thermal resistance of building walls, and the decrease in the mechanical performance of the masonry [4-6].

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Several methods have been presented to limit rising damp. One method, a mechanical one, consists in the insertion of an impermeable layer in building walls. Another method, a chemical one, consists in drilling holes at the horizontal base of walls and filling those holes with chemical products. Additionally, another method is based on electroosmosis in porous materials. The application of an electric field on porous media can generate a motion of water in pores and that effect is called electroosmosis. Electroosmosis is related to the electrical double layer at interfaces between solid surfaces and water.

The effectiveness of the electroosmotic technique is still controversial in the literature. For example, Bertolini *et al*. [7] concluded that the chances of applying the electroosmotic technique effectively in drying damp masonry are extremely low. However, some authors state positive results on potential applications of this technique [8, 9]. Especially, Stanley and McFeat-Smith [10] have applied the electroosmotic technique using multi-pulse sequencing in the field for removing water from building walls. The results show that electroosmosis is a good method of driving moisture out of concrete and other masonry structures. In the literature, quantitative results on the variation of humidity over time under electroosmosis are scarce and sometimes unsatisfactory [7]. For example, Nevertheless, Ottosen and Rorig-Dalgaard [8] evaluated the change of water content in a brick under an electric field by cutting the brick into several pieces with a hammer. The water content was then measured as weight loss in each piece. However, the cutting itself may have changed the water content of each piece of the brick due to friction. Besides that, the porosity in each piece may not have been the same. Consequently, the assessment of water content in that work may have been less than accurate. Similarly, Ivliev [9] evaluated the variation of the water content by weight loss measurement after a given period of time.

In this work, electroosmotic water transport is obtained by applying an electric field to a sandstone sample. A quantitative evaluation of water content is then performed at three different positions of the sample using a capacitive sensor. We use the Texas Instruments FDC1004 integrated capacitance sensor. From the variation of the measured capacitance, the change of the dielectric constant of the wet sample over time is deduced. A model is then used to estimate the water content from the dielectric constant. The change of water content with position along the sample at a given applied voltage is used to evaluate the effectiveness of electroosmotic technique in drying wet porous materials.

2. Materials and Methods

2.1 Electroosmosis in porous media

Porous materials are created by solid grains. When solid grain surfaces contact with water, the surfaces become electrically charged [11]. This leads to the charge distribution termed the electrical double layer (EDL) at the water-solid interface (Figure 1). The EDL consists of the Stern layer where ions are immobile, and the diffuse layer where ions are free to move [11]. The zeta potential (ζ) is the potential at the shear plane in the diffuse layer separating the mobile liquid from the liquid that is attached to solid surfaces (Figure 1). The zeta potential depends on mineral compositions of porous materials, properties of fluid, pH, temperature, etc. [12, 13].

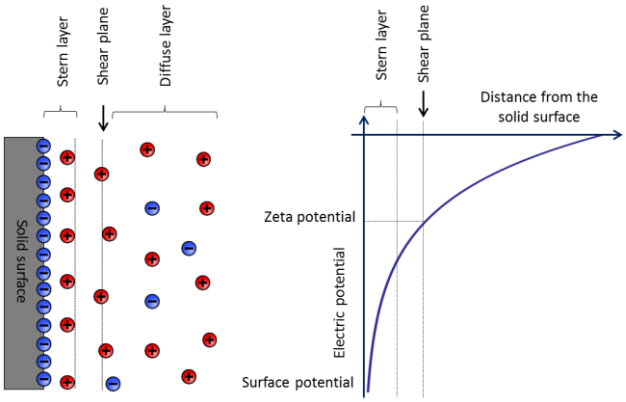

Figure 1. Stern model for the charge and electric potential distribution in the EDL [14, 15]

Electroosmosis was first performed by Reuss for a clay-sand-water mixture [16]. When an electric field is setup parallel to walls of capillary tubes, ions in the EDL suffer an electrical force and move, which creates a fluid movement in the capillary. That effect is called electroosmosis (Figure 2). A porous material can be conceptualized as a bundle of parallel capillaries of the radius a with zeta potential ζ. The volume flow rate in a capillary under application of an electric field E is given by Gad-el-Hak [17]:

$$q = \frac{\varepsilon\varepsilon_o|\zeta|.E.\pi.a^2}{\eta} = \frac{\varepsilon\varepsilon_o|\zeta|.V.\pi.a^2}{L.\eta} \quad (1)$$

where ε is the relative fluid permittivity, ε_o is the dielectric permittivity in vacuum, ζ is the zeta potential, η is the dynamic fluid viscosity, V is applied voltage across the porous material and L is the length of the capillary.

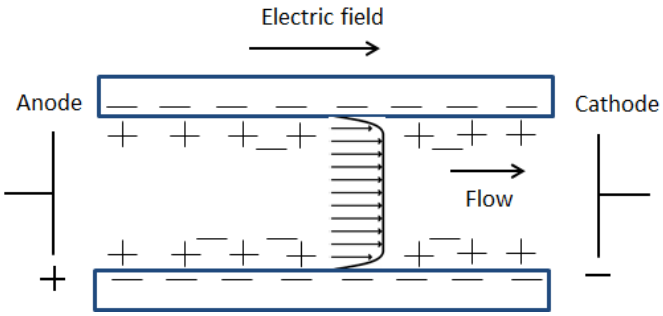

Figure 2. Electroosmotic flow in a capillary tube

Equation (1) indicates that the fluid flow through a capillary is proportional to the zeta potential, the applied electric field, and the capillary size. It should be noted that besides the main electroosmotic mechanism during the drying process, there may also be other mechanisms contributing to water movement in porous media such as diffusion, gravity, external pressure difference, capillary action and convection. Different models are available in the literature for the drying process of porous media [18].

2.2 Dielectric constant in water saturated porous media

A porous material consists of three components: water, air and solid grains. Its dielectric constant (ε_r) is dependent on the dielectric constant and relative volume of each component. The dielectric constants of air and solid grains are normally considered unchanging. Namely, ε_r of air is taken as 1 and ε_r of solid grains is taken between 2 to 10. Those values are much smaller than that of pure water ε_w= 80.2 at 20ºC [19]. Therefore, any change of the amount of water in porous materials will cause change of the ε_r. The ε_r of water-filled porous media is very sensitive to the water content and weakly sensitive to solid particle-specific parameters such as grain radius, mineral composition of solid grain, solid density, and temperature [20]. Consequently, the dielectric constant deduced from capacitance measurements is a good indicator of water content. There have been several empirical equations proposed that relate the ε_r of a porous material to the water content θ_l. For example, one is provided for a Caen stone in the range $0 < \theta_l < 39$ % [21]:

$$\varepsilon_r = 2.1 + 24.1\theta_l \tag{2}$$

Due to the similarity in mineral composition, type of porous media (consolidated rock) and type of liquid (water) of the Caen stone sample and the rock sample used in this work, Eq. (2) will later be used to quantitatively estimate the water content from the ε_r of the porous sample in this work.

2.3 Experiments

To assess the variation of water content in fluid saturated porous media, we use an experimental setup as shown in Figure 3. A porous sample is a slab of Berea sandstone (10 cm×5 cm×3 cm). The porosity of the sample is measured as 25% by a simple method described in Thanh *et al*. [22]. The fluid used to saturate the porous sample is tap water. The electrical conductivity and pH of the water as measured are0.73 mS/cm and 7.3, respectively. The sample is first dried in an oven at 105ºC for 24 h, cooled down to room temperature, and filled with water using the setup shown in Figure 4.

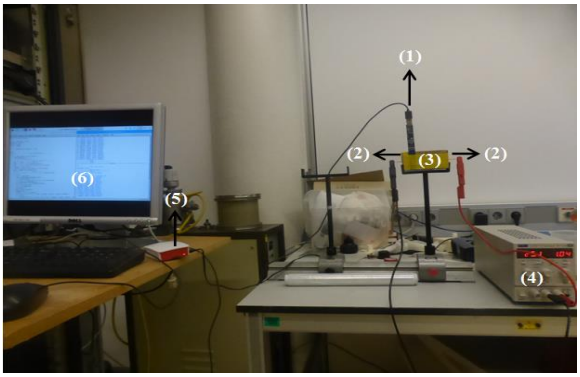

Figure 3. Experimental setup for electroosmotic measurements
(1) Capacitance sensor, (2) Copper electrodes, (3) Porous sample, (4) DC power supply, (5) Raspberry Pi used for data collection, (6) Monitor

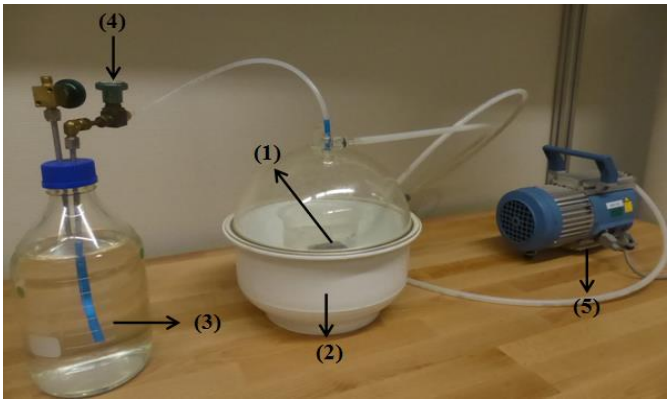

Figure 4. Experimental setup used to saturate porous samples
(1) Porous sample, (2) Desiccator, (3) Tap water container, (4) Valve, (5) Vacuum pump

The sample is taken out of the water bath and scrubbed with wet tissue paper. The water content of the wet sample is then measured as 20 % (by weighing the wet and dry samples). The sample is put in place as shown in the experimental setup (Figure 3). Copper electrodes are placed against the ends of the porous sample and fixed. The electrodes have a surface area of 5 cm x 3 cm and they are connected to a power supply (Aim-TTi PLH250-P). Constant voltages of 25V and 12.5V are selected in this work because those values are enough to observe the effect in porous bricks as stated in Ottosen and Rorig-Dalgaard [8] (50 V/23 cm) and to disregard air bubbles generated at two copper electrodes and electrode processes. To decrease the resistance between the brick and the electrodes, steel wool is used. The sample, steel wool and electrodes are wrapped carefully with plastic film during measurement in order to minimize evaporation. The electrical current (I) through the sample is measured by an Ampere meter in the power supply. The result shows that electrical current decreases over time and becomes stable after a certain amount of time. For example, at the beginning of the application of 25 V across the sample, the current is measured to beI_{i} = 1.3 mA and the stable value is measured to be I_{f} = 0.1 mA after 30 hours. This observation is the same as that inferred from the work of Ivliev [9], in which it was shown that the specific resistivity of porous medium increases over time under application of an electric field. The reason for the increase of specific resistivity of the sample may be that there is electrolysis at the anode and the cathode under applied voltage. These electrode reactions produce ions and gas at both electrodes. These reactions induce a low pH at the anode, a high pH at the cathode, and a decrease in electrical conductivity of fluid. Additionally, water redistribution along the sample under an applied voltage may lead to an increase of the specific resistivity.

To quantitatively evaluate the variation of water content over time at a given position on the sample, capacitance measurements are performed with the capacitive sensor (FDC1004) obtained from Texas Instruments. The sensor is pressed against the plastic-wrapped sample at three different positions as shown in Figure 3 (the sensor is not directly in contact with the wet sample).

Before carrying out the capacitance measurements under applied voltages across the sample, reference experiments are also performed. The first reference used for capacitance measurement is with the sensor in air without contact with the sample. The second one used for the capacitance measurement is with the sensor in contact with the dry sample. The third one is with the sensor in contact with the wet sample but without applied electric field.

The experiment is run on a Raspberry Pi (Figure 3), which uses Python as the programming language. Based on the code of the Python program that is not shown in this work, we are able to set the number of data points and the time between two consecutive data points in a way we want to. The measured data are recorded and saved into .csv files on the Raspberry Pi. The .csv files are then transferred to a computer to be analyzed by Matlab.

3. Results and Discussion

The variation of capacitance with time in the reference experiments is shown in Figure 5. The results show that the capacitance in the cases of the sensor in air and the sensor in contact with the dry sample do not vary over time. It means the lab conditions (humidity, temperature, etc.) that may affect the capacitance are stable. In the case of the sensor being in contact with the wet sample without an applied electric field, the capacitance slightly decreases at the beginning (for around an hour) and then becomes nearly constant over time. Hence, the water content does not change over time under gravity when the wet sample is placed in the setup. The reason is that water is held onto rock particles by adhesion or by capillary force for the fine rock samples, as mentioned in Harter and Rollins [23].

Figure 6 shows the variation of the capacitance with time under application of a constant voltage of 25 V across the wet sample for 35 h when the sensor is placed next to the positive electrode. As expected, the capacitance of the sensor and therefore the water content

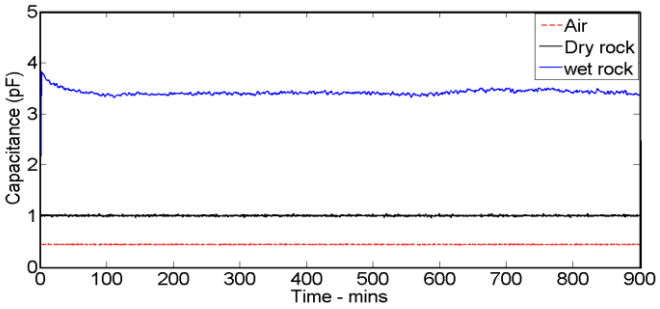

Figure 5. Variation of the capacitance with time (15 h) for the reference experiments

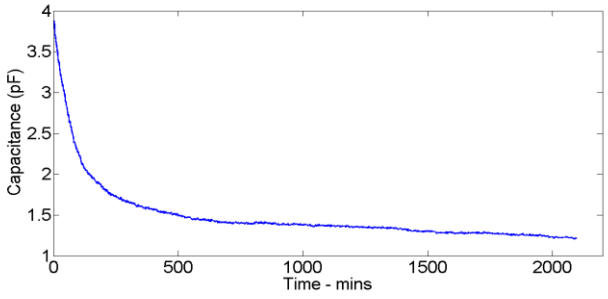

Figure 6. Variation of the capacitance with time in 35 h under an applied voltage of 25 V when the sensor is placed next to the positive electrode

decreases over time. The rate of decrease of the capacitance for around the first four hours is much higher than that for the next 30 h. This can be inferred from the time constants obtained by exponential fitting and is shown in Figure 6. On average, the relative change of the capacitance in 35 h $\Delta C/C$ and therefore the relative change of the dielectric constant of the wet sample $\Delta\varepsilon_r/\varepsilon_r$is approximately 69% (the area A and distance d between two plates of the capacitor do not vary). From Eq. (2), it is deduced that the water content of the sample decreases by around 69%.

To estimate the time to push water out of a capillary (the capillary is assumed to be fully occupied by water) under application of a voltage of 25 V, equation (1) is used:

$$t = \frac{Volume_{capillary}}{q} = \frac{\pi a^2 L}{q} = \frac{\eta L^2}{\varepsilon\varepsilon_o|\zeta|\pi V} \tag{3}$$

Where L is the length of the sample of 0.1 m, V is taken as 25 V, $|\zeta|$ is approximately taken as 0.04 V for the tap water-rock system [24]. Therefore, the time to get a stable water content is calculated to be 50 hours and this number is in agreement with that observed in this work (35 h).

Figure 7 shows the variation of the capacitance with time under application of a constant voltage of 25 V when the sensor is placed at the middle of the sample and next to the negative electrode, respectively. It is seen that the capacitance of the sensor slightly decreases with time for the middle position. In particular, the capacitance barely changes over time at the negative electrode position. That observation can be explained by the fact that under application of anelectric field, water is pushed from the positive electrode to negative electrode. Therefore, water content becomes almost saturated right after applying an electric field at the position close to the negative electrode. The total loss of water in the sample wrapped by the plastic film after 40 hexperiments is measured as around 2 %.

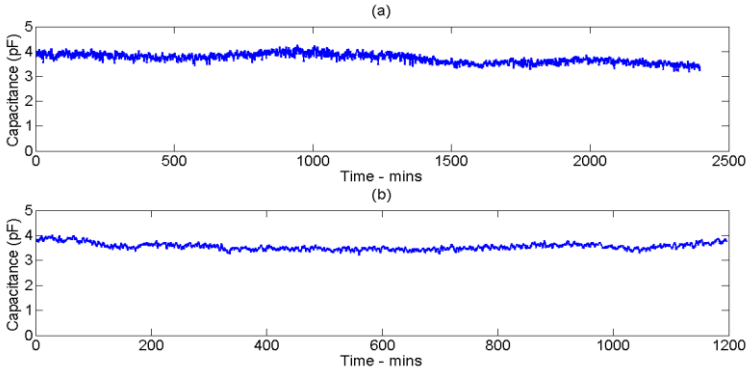

Figure 7. Variation of the capacitance with time under a constant voltage of 25 V when the sensor is placed at the middle of the sample (a) and next to the negative electrode (b)

Figure 8 shows the variation of capacitance with time under application of a constant voltage of 12.5 V when the sensor is placed next to the positive electrode. For the same argument mentioned above, it is seen that the water content of the sample decreases by around 28% in this case. This value is significantly smaller than that of the 25 V voltage application.

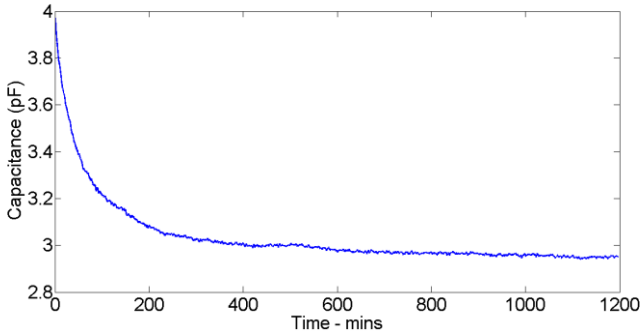

Figure 8. Variation of capacitance with time for 20 hours under a constant voltage of 12.5 V when the sensor is placed next to the positive electrode.

Similarly, the time to get stable water content is calculated to be 25 h and this value is in the same range as that observed in Figure 8 (around 20 h).

The results show that techniques based on electroosmosis might be effective in drying wet buildings, and stone and earth masonry structures. Thus, the concept of water movement in porous material by applying a voltage is effective and is consistent with the observations of others [8-10]. Based on the findings of this work, it can be inferred that the effectiveness of the electroosmotic technique in the drying of wet porous materials is proportional to the applied voltage. However, if the applied voltage exceeds a certain value, there will be electrolysis and therefore air bubbles at the electrodes. Generated air bubbles may block the water movement in rock capillaries and affect the electroosmotic technique. Hence, further studies to determine the optimal voltages as well as the distance between electrodes for wet porous media need to be carried out.

4. Conclusions

In this work, electroosmotic water transport is obtained by applying a voltage across aporous sample. A quantitative evaluation of water content is then performed at three different positions of the sample using a capacitive sensor. We use the Texas Instruments FDC1004 integrated capacitance sensor. It is a low cost, digital high precision sensor that operates at low power and is easily interfaced toa data collecting microcomputer. From the variation of the measured capacitance, the change of the ε_r of the water filled sample over time is deduced. A model is then used to estimate the water content from the ε_r of the sample. The results show that under application of constant voltages of 25 V and 12.5 V, the water content of the wet porous sample at the position close to the positive electrode decreases drastically by around 69 % and 28 %, respectively. However, the water content remains almost constant in the middle of the sample and at a position close to the negative electrode. The reason is that water is pushed from the positive electrode to the negative electrode under application of an electric field. Therefore, water content becomes almost saturated right after applying the electric field in the middle of the sample and atthe position close to the negative electrode. The results suggest that the electroosmotic technique can be applied in the drying of moisture in buildings, and in stone and earth masonry structures. Additionally, it is shown that our use of capacitive sensors is a promising technique for monitoring the water content in wet porous materials.

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