A New Method for Paper Porosity Estimation

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ABSTRACT

A method is proposed for estimating the porosity of paper by comparing the electric current passing through a wax-printed channel patterned on the paper surface with that passing through a hollow PDMS channel. To ensure the accuracy of the estimation results, the paper channel is sandwiched between two flat polydimethylsiloxane (PDMS) plates in order to minimize evaporation losses and to emulate the surface condition of the hollow PDMS channel used for reference purposes. a good agreement is observed between the estimated values of the paper porosity and the porosity values determined from the basis weight and thickness data provided by the paper manufacturer. The proposed method provides a low-cost and effective means of evaluating candidate materials for microfluidic paper-based analytical devices (μPADs).

Keywords: porosity, paper-based microfluidic devices

1 INTRODUCTION

Paper is a common material with many everyday applications. However, in addition to its normal uses, it has recently attracted growing interest as a detection substrate due to its high specific surface area, which allows fluid to flow through the paper under the effects of capillary action alone without the need for an external driving force. One of the earliest μPADs was that presented by Martinez et al.[1], in which well-defined millimeter-scale channels were created on hydrophilic paper by patterning the paper with hydrophobic photoresist "walls". In a typical μPAD assay, the μPAD is rinsed or impregnated with reagent and is then spotted with the sample of interest. The resulting reaction between the sample and reagent is detected and analyzed using some form of colorimetric method. Among these various factors, the porosity plays a particularly important role in determining the volume of reagent required and the capillary flow rate. Consequently, effective methods for measuring the porosity of paper are essential in selecting appropriate substrate materials for μPAD devices.

The porosity of paper is generally evaluated using simple weighing [2] or volume methods [3] in which the porosity is analyzed by gauging the difference in weight or volume of the sample relative to that of a reference sample with known porosity. In the present study, the porosity of paper samples is evaluated by measuring the electric current passing through a millimeter-scale channel patterned on the paper surface. In developing the proposed method, it is speculated that the ion flow through the channel is obstructed by the papers fibers and the paper porosity can therefore be evaluated by measuring the current drop relative to that through a hollow (100% porosity) channel of the same cross-sectional area. The feasibility of the proposed method is demonstrated by measuring the porosities of three different paper samples (Whatman filter paper, Grade 1, Grade 2 and Grade 5) and then comparing the estimated results with those calculated based on the paper properties reported by the manufacturer.

2 PRINCIPLE

For an electric current flowing in a microchannel, the total current comprises the contributions of three different phenomena, namely (1) bulk part, which causes the ions in the bulk solution to eletrophoreticly move in the channel; (2) the Stern layer, which is affected by the electric field; and (3) electroosmotic flow, which causes the ions near the surface to drag the surrounding solution. The governing equations for these currents are:

$$I_{total} = I_{bulk} + I_{Stern} + I_{EOF} = K_{bulk}V + K_{Stern}V + K_{EOF}V \quad (1)$$

$$K_{bulk} = \frac{2wC_{\infty}}{l}\int_0^{\frac{h}{2}}\left[\Lambda_+ \exp\left(-\frac{F\Psi}{RT}\right) + \Lambda_- \exp\left(\frac{F\Psi}{RT}\right)\right]dy = K_{bulk}^{\infty} + \frac{2w\lambda_{bulk}}{l}\left[\int_0^{\frac{h}{2}} cosh\left(\frac{F\Psi}{RT}\right)dy - \frac{h}{2}\right] \quad (2)$$

$$K_{Stern} = \frac{2(h+w)}{l}\lambda_{Stern} \quad (3)$$

$$K_{EOF} = \frac{\int_A \rho_e u_{eo} dA}{(-\Delta\Phi)} = \frac{2w\varepsilon^2\varepsilon_0^2}{\mu l}\left(\frac{RT\kappa}{zF}\right)^2\left[\int_0^{\frac{h}{2}}\cosh\left(\frac{zF\Psi}{RT}\right)dy - \frac{h}{2}\cosh\left(\frac{zF\Psi_0}{RT}\right)\right], \quad (4)$$

where w is the width of the channel, l is the length of the channel, C_{∞} is the molar concentration of the electrolyte solution, h is the height of the channel, ʌ is the molar conductivity, F is the Faraday constant, R is the gas constant, Ψ is the electrical field potential, and λ is the conductivity of the solution. As shown in Eqs. (2) ~ (4), all three electrical conductance terms depend on the cross-sectional area of the channel (w x h).

For the currents flowing through two identical channels of the same cross-sectional area should be the same. However, in the case of paper channels considered in the

present study, the ion flow through the channel is obstructed by the paper fibers, where the number of these fibers increases with a decreasing porosity. Consequently, the measured current flow is less than that in a 100% porosity (i.e., hollow) channel with the same cross-sectional area. Thus, taking a hollow PDMS channel for reference purposes, the porosity of the paper channel can be estimated.

2.1 Fabrication of PDMS Hollow Channel

In all of the tests, the channels (PDMS and paper) were filled with 10^{-3} M potassium chloride (KCl) electrolyte solution. In conventional PDMS fabrication processes, the required structure is patterned on a silicon wafer using a photolithography technique involving photoresist deposition followed by selective UV exposure. However, such a process is needlessly complex for the simple hollow structure required in the present study. Thus, an alternative approach was employed (see Fig. 1), in which a copper plate with a length of 25 mm was attached to a glass substrate using double-sided tape and a PDMS solution (Sylgard 184A and Sylgard 184B, Sil-More Industrial Ltd USA, mixed in a ratio of 10:1 under vacuum conditions to remove bubbles) was then poured over the plate such that it was completely covered. (Note that the copper plate and double-sided tape had overall dimensions of 1.8 mm x 0.15 mm (width x height), giving a cross-sectional area of 0.27 mm2.) The substrate was placed on a hot plate at 55℃ for 24 hours and the cured PDMS structure was then mechanically peeled from the mold Two holes were punched at either end of the channel to serve as reservoirs and an oxygen plasma treatment process was then performed to change the PDMS channel wall property from hydrophobic to hydrophilic. Finally, the PDMS channel was bonded to a blank PDMS substrate to complete the device.

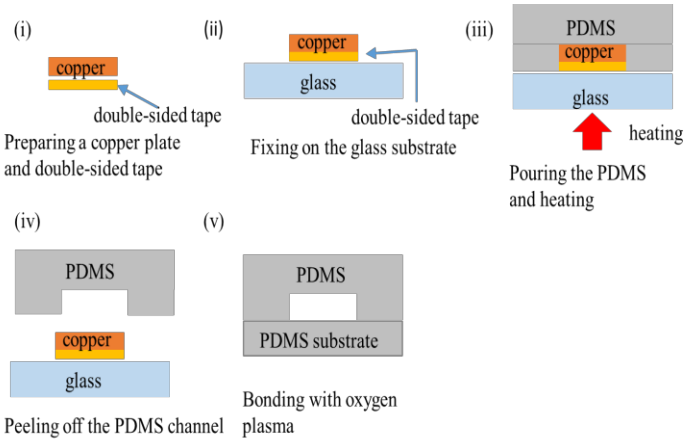
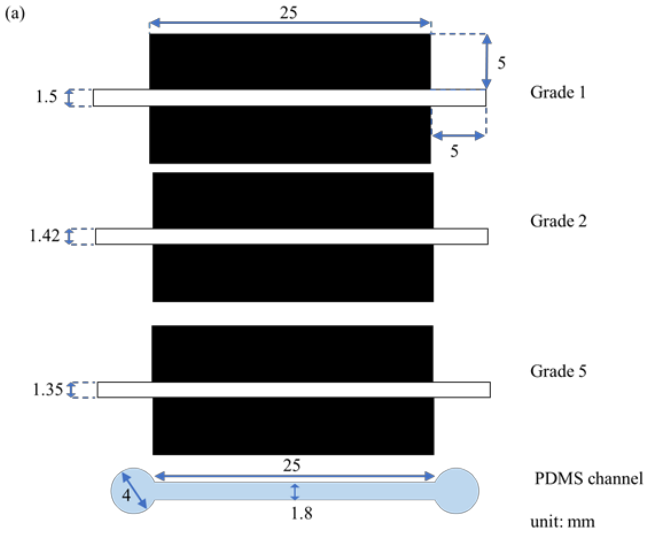


Fig.1. Overview of PDMS hollow channel fabrication process.

2.2 Design and Fabrication of Paper Channels

According to the supplier's specification, the Grade 1, Grade 2 and Grade 5 paper samples had thicknesses of 0.18, 0.19 and 0.2 mm, respectively. Thus, to achieve the same cross-sectional area as the PDMS hollow channel (0.27 mm^2), the channel widths for the three samples were specified as 1.5, 1.42 and 1.35 mm, respectively (see Fig. 2). The channels were produced using a wax-printing process followed by heating at a temperature of 155 ℃ for 90 s to ensure the penetration of the wax through the entire paper thickness. The dimensions of the channel were confirmed using ImageJ. The design values of the channel width were then adjusted (and the wax printing process repeated) to take account of the wax diffusion distance during the heating and solidification processes



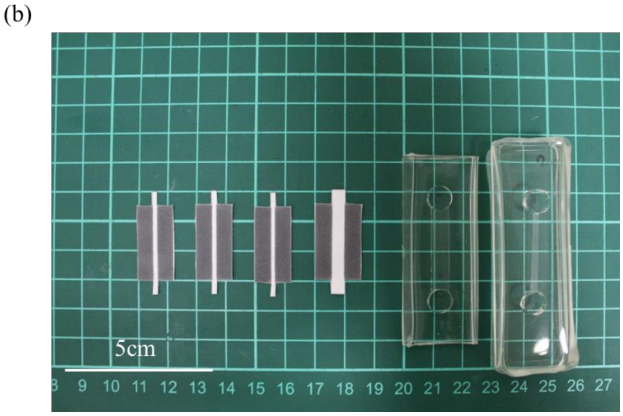


Fig.2. (a) Dimensions of paper channels (upper) and PDMS hollow channel (lower), (b) fabricated paper channels and PDMS hollow channel.

2.3 Experimental Setup

The source meter was set in the bias voltage mode and voltages of 10, 20, 30, 40 and 50 V, respectively, were applied across the channel. For each value of the applied voltage, the current was measured only for the first 10 s. Figure 3 shows the setup used to measure the current flowing through the paper channels. The experimental procedure was identical to that used for the PDMS hollow channel other than the electrolyte "injection "process. More specifically, while the electrolyte solution was physically injected into the reservoirs of the PDMS channel, for the paper channels, the ends of the channel were simply placed in two reservoirs and the electrolyte was then allowed to fill the channel naturally under the effects of capillary forces. The paper channels were fixed between the two PDMS plates using double-sided tape. (Note that the tape was replaced after each experiment).

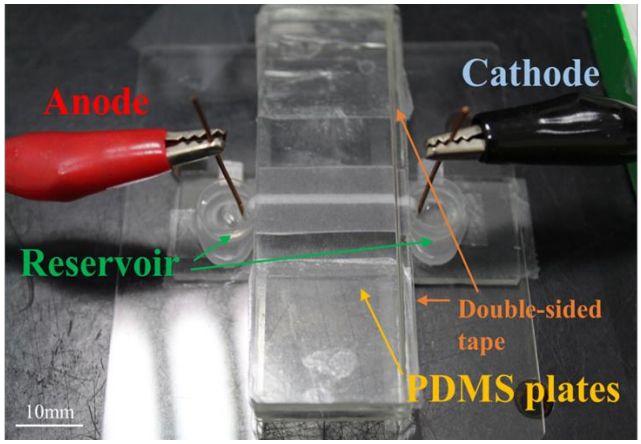


Fig.3. Use of double-sided tape to fix PDMS plates and paper channel.

3 RESULTS AND DISCUSSION

In general, the porosity (also known as the pore volume fraction) of a porous medium is defined as the ratio of the void volume (V_v) to the total volume (V_t). For the case of paper, the porosity can be derived as

$$\varepsilon = 1 - \frac{bw_0}{\rho_{cel}\tau_p} \quad (5)$$

where ε is the pore volume fraction, bw_0 is the basis weight of the paper (i.e., the ratio of the mass of the paper to the top face area), ρ_{cel} is the density of cellulose (1540 kg m^{-3}), and τ_p is the thickness of the paper. Using the data provided by the supplier, the three paper samples considered in the present study were found to have the porosity values shown in Table 1.

Table 1. Properties of Whatman qualitative paper.

Paper Type	Basis Weight (g/m^2)	Thickness (mm)	Porosity
Whatman Grade 1	88	0.18	0.683
Whatman Grade 2	103	0.19	0.648
Whatman Grade 5	98	0.2	0.682

To avoid the void compression problem, the current paper channels were fixed between the two PDMS plates using double-sided tape rather than clips. (Note that the tape was replaced after each experiment). Figure 4 shows the measured values of the current obtained for each channel under each applied voltage. The corresponding results for the estimated porosity are shown in Fig. 5 and Table 2. It is seen that the Grade 1 and Grade 5 samples have very similar porosities. Moreover, both samples have a higher porosity than the Grade 2 sample. In other words, the tendencies of the estimated porosity values are consistent with those shown in Table 1 ased on the manufacturer's specification. In addition, it is seen that all three estimated porosity values are in good agreement with the actual pore volume fraction value. Finally, it is noted that the porosity estimates are insensitive to the magnitude of the applied voltage. For example, the estimated porosity values vary by no more than 0.683, 0.648 and 0.682 for the Grade 1, 2 and 5 samples as the electric field is increased from 4 to 20 V/cm.

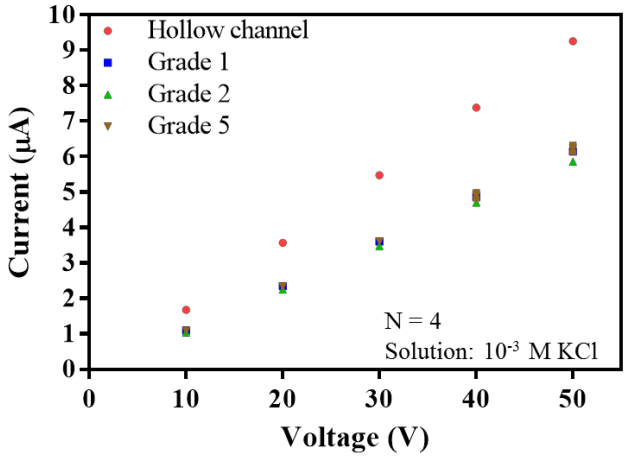


Fig.4. Electric current in paper channels fixed between two PDMS plates using double-sided tape.

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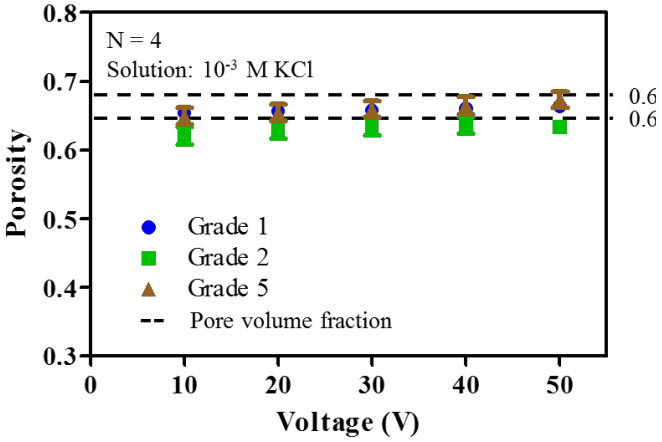

Fig.5. Estimated porosity values for paper channels fixed between two PDMS plates using double-sided tape.

Table 2. Comparison of estimated and actual pore volume fraction results for paper channels fixed between two PDMS plates using double-sided tape

	Whatman Grade 1	Whatman Grade 2	Whatman Grade 5
4 V/cm	0.654 ±0.006	0.621 ±0.013	0.650 ±0.013
8 V/cm	0.657 ±0.003	0.631 ±0.014	0.655 ±0.013
12 V/cm	0.658 ±0.002	0.635 ±0.014	0.660 ±0.013
16 V/cm	0.660 ±0.003	0.636 ±0.012	0.665 ±0.013
20 V/cm	0.664 ±0.002	0.633 ±0.001	0.673 ±0.012
Pore Volume Fraction	0.683	0.648	0.682

4 CONCLUSION

This study has presented a new method for estimating the porosity of paper by measuring the electric current passing through a wax-defined channel printed on the paper surface. In particular, the porosity is estimated by dividing the measured current value by that obtained for a hollow PDMS channel of the same cross-sectional area. The validity of the proposed method has been demonstrated by comparing the estimated porosity values for three paper samples (Whatman qualitative filter paper Grades 1, 2, and 5) with the values calculated in accordance with the supplier's specification. It has been observed that when the paper channels are taped between two PDMS plates in order to minimize evaporation effects and to approximate the channel surface condition in the reference PDMS hollow channel, the estimated porosity values are within 3% of the calculated values. In addition, it has been shown that the estimated porosity values are insensitive to the electric field intensity over the range of E = 4 ~ 20 V/cm. Thus, the proposed method provides an effective and low-power technique for evaluating the feasibility of different paper substrates for μPAD applications.

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