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The effect of fibre swelling on fluid flow in cotton fabrics: An experimental study

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Abstract:
Design of hygiene products such as sanitary napkins, diapers, etc. is heavily dependent on the liquid absorption performance of fabrics. As fibres swell upon liquid absorption, their liquid absorption performance changes. Understanding the flow through porous media under swelling conditions has important implications for product design and has yet to be elucidated fully. The goal of our research was to study the effect of fibre swelling experimentally. Cotton is selected as the test fabric as it is commonly used in most hygiene applications. Under swelling conditions, the effect of swelling on individual fibres, porosity, permeability, and performance of the cotton fabric is analysed. Findings showed that upon water absorption, the fibre diameter increased by 10%, porosity decreased by 11%, and permeability decreased by 60% under fully swollen conditions. The porosity reduction is also predicted analytically using the data obtained from the fibre swelling measurements. In contrast, predictions of commonly used analytical models showed only a 30% reduction in the porosity. To correct this, two new correction factors to account for effects of inter-fibre interactions on the total swelling rate of fabric are proposed. The performance measures of cotton samples under swelling conditions indicated that advancement of the flow front on the lower face was more dominant than the upper face of the sample possibly related to gravity. These experimental data improve our understanding of wicking flow which can help to improve the design of hygiene products and to develop more realistic computational fluid dynamics models.

1. Introduction

A wide variety of properties are used to design new hygiene products. The product developers have to optimise a set of characteristics such as shape, absorption potential, breathability, durability, cost, etc. Pure cotton or cotton blends with polyester are among commonly used materials in absorbent fabrics. All these hygiene products are linked by the same basic criterion that they must be absorbent structures first and foremost; nevertheless, they differ from one another due to the amount and characteristics of the fluids that they absorb.

Liquid absorption within porous media is influenced by a variety properties such as pore diameter, surface treatment, swelling potential, and structural properties, such as porosity, permeability, pore structure, and pore size distribution (Xiao et al., 2019, 2022). Also, absorption is dependent on liquid properties such as surface tension and viscosity. The structural properties of the fibrous porous media highly affects the liquid absorption process, i.e., porosity is the most important property in determining absorption capacity (Dhiman and Chattopadhyay, 2021). Swelling, on the other hand, has a considerable effect on the permeability and porosity of the fabrics. Swelling reduces pore size which results in a reduction in permeability due to increased flow resistance. As a result, the swelling effect leads to an error in the predictions of the wicking performance of the porous media if the changes in porosity and permeability are not considered (Masoodi

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and Pillai, 2010, 2012). Depending upon the applications, different aspects of wicking flow become important, such as mass/volume of absorbed liquid within porous media, the rate of flow front propagation and so forth (Zarandi and Pillai, 2021). Hence determining changes in these properties of the fabrics plays a key role in designing products and modelling the flow through fabrics (Salokhe et al., 2021).

A variety of experimental work focuses on the performance of fabrics, such as wettability tests, vertical and horizontal wicking tests, horizontal spreading tests, moisture management, and forced flow tests. All these tests are used to predict the absorption and transport properties of woven fabrics. Wettability and vertical wicking tests are the most common methods used for testing fabrics (Tang et al., 2017). The permeability testing of fabrics is studied by a few researchers. Oğulata and Mavruz (2020) proposed an analytical model to determine the permeability and porosity of knitted fabric and conducted a series of permeability tests with an air permeability tester for a constant pressure drop of 100 Pa. Xiao et al. (2012) focused their work on the prediction of dynamic permeability. A series of experiments were done using an arrangement similar to an air permeability tester. The experimental results revealed that dynamic permeability was larger than the static permeability for loose textiles. Patanaik and Anandjiwala (2009) conducted falling-head permeability tests on non-woven flax fabrics and measured their pore size by a capillary flow porometer. The obtained results for velocity were then compared with a developed numerical model based on Finite Element Method. Huang and Qian (2007, 2008) compared different test methods to measure the water vapour permeability of fabrics. The main objective of the work was to determine the thermal comfort properties of clothing systems. Their results from the upright cup method, inverted cup method, dynamic moisture permeation cell method, etc. were compared with a newly proposed method. Most of the work related to permeability testing of fabrics is focused on air permeability testing to determine the comfort and air-breathing characteristics. Some have studied the moisture absorption and wicking performance of the fabrics, but there is a gap in knowledge of actual permeability of these fabrics.

There are few studies on swelling measurements reported in the literature. Moore et al. (2016) investigated the swelling of cotton in water. The study included the microscopic investigation of changes in the cross-section of raw cotton fibres as a result of swelling. Also, their work included study of the changes in the circularity of a single fibre as a result of swelling. They found that for a single raw fibre, the percentage change in the circularity ranged from 3.1% to 10.1% for mature and immature cotton fibres. The study focused on the swelling performance of raw cotton fibres; hence, it may not be useful to predict the porosity or permeability changes for woven cotton fabrics. A few investigators, however, reported the prediction of changes in permeability as a result of fibre swelling. Masoodi and Pillai (2012) experimentally characterised the effect of swelling on jute fibres under different test liquids. The swelling of jute fibres was examined under the microscope to capture the changes in the fibre diameter. Based on this work, Masoodi et al. (2012) estimated the changes in the volumetric porosity and permeability using analytical models. Further, to measure the changes in the permeability experimentally, a constant volume flow test setup was developed and changes in the inlet pressure analysed to predict real-time permeability changes. Later it was observed that over shorter times, the models based on estimated porosity and permeability changes showed good agreement with experimental results, but over longer times, the associated error increased. Similar work was done by Francucci et al. (2010) by considering the humidity absorption. All these studies investigated natural or conventional fibres used in composite materials. Also, limited data are available describing the changes in porosity as a result of swelling. Further, very few studies have focused on the swelling measurement of cotton fabrics; the majority of such studies are focused on the reaction of cotton fibres with different chemicals. Cuissinat and Navard (2006) analysed the behaviour of cotton cellulose fibres in water mixtures to observe swelling and dissolution mechanisms such as ballooning. Remadevi et al. (2017) investigated the swelling of cotton fibres as a result of treatments with aqueous glycine solutions. They analysed the effect of glycine solution treatments and their influence on the regain properties and cross-section morphology of cotton fibres. Their analysis included factors such as the effect of pH values of a solution on ribbon width, cross-sectional area, and moisture regain.

In summary, the majority of experimental studies that have been done in terms of performance testing of fabrics were based on standard testing methods or on air permeameter equipment etc. Further, reviewed literature shows that the majority of studies focused on the testing of the fabrics to determine the fundamental factors that contribute to comport, and were focused on moisture absorption only. Although the main aim of these tests was to determine the transport properties of the fabric, mostly the permeability measurement was excluded. Another important factor is the swelling measurement of fabrics; yet few experimental studies are available measuring the swelling of fabrics. These studies measured changes in fibre diameter and permeability as a result of swelling action. However, the measurement of real time changes in porosity was mostly neglected. Also, the available analytical models to predict the changes in the porosity assume of presence of single fibre within fabric matrix and they neglect the effects of other fibres within matrix. Hence, it is essential to study the swelling behaviour of fabrics to estimate the consequent effects on their performance.

The present study aimed to measure fabric transport properties in rigid and swelling conditions, critical data for designing hygiene products. Here, in this study a method to measure the changes in the porosity as a result of fibre swelling is proposed. Also, to account for effects of other fibres in matrix, the correction factors for existing analytical models are proposed in this study. Further, the flow front advancement was measured on the upper and the lower surface of the thick fabric samples. Analysis of these performance parameters is important for designing or optimising hygiene products where liquid absorption and retention is the main goal. Furthermore, study of flow front propagation in swelling conditions is

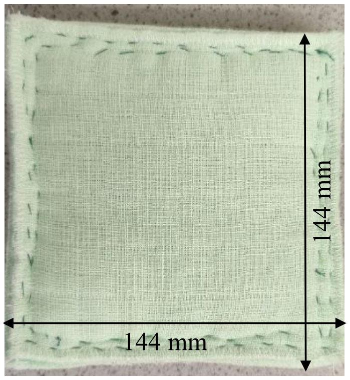

Fig. 1. Samples made of cotton fabric used for the experiments. (a) Top view of test sample, (b) lateral view of test sample made by stacking of nine machine sewed sheets.

necessary to modify the design, shape, or size of the products (White, 2003; Ajmeri and Ajmeri, 2016; Hoffmann et al., 2020).

2. Experimental details

2.1 Material details and sample preparation

The cotton fabric used in this study was selected based on the scope of this study, the design of hygiene products. Hence, muslin squares (used as nappies for baby care products) made up of 100% cotton were selected for study. As specified by the manufacturer, these fabrics are woven using extra-long staple cotton that provides a tight weaving pattern and better absorbency. To create a final test sample, several pieces of cotton fabric sheet were cut to a size of 144 mm × 144 mm and sewn together using a machine sewing process to form a single "Machine-Sewed Piece". Nine of these pieces were then stacked and hand-sewn together, resulting in a sample with a thickness of 25 mm. The sewing lines compressed the sample near the edges, but it remained uniform and isotropic in other areas as shown in Fig. 1.

2.2 Measurement of fibre diameter

To measure the changes in the diameter, the method described by Masoodi et al. (2012) was adopted. The swelling of individual fibres was analysed using the Nikon metallurgical microscope eclipse lv150N at a magnification of 100×, along with the live recording camera to examine the cotton fabric behaviour due to water absorption. The microscope was calibrated within a range of 3 μm as specified by the manufacturer.

Several 150 mm cotton fibres samples/slides were prepared by securing both ends using a suitable adhesive strip. The diameters of fibre at the different locations were recorded in the dry state, taken as pre-swelled diameter (D_o). Once this was measured, the samples were exposed to the water. The process was recorded for a total of 1 minute. Once recorded, the photographs were taken every 1 or 2 seconds. The diameters (D) were then measured at different time values and compared with the pre-swelled diameter to see any change. The process was repeated 5 times. Finally, the results were extracted in terms of relative changes in diameter (D/D_o) with time.

2.3 Measurement of porosity

For this study, the porosity was measured for rigid and swelling conditions. The porosity in rigid conditions is measured by imbibition method (Sandoval et al., 2017). Further, the porosity was measured under swelling conditions using an approach described in Section 2.2.

2.3.1 Measurement of porosity in rigid conditions

The saturation (or imbibition) method as described in Anovitz and Cole (2015) was employed. The sample was first weighed before saturation with a wetting liquid. Once this was done, the sample was submerged in the container with oil (i.e., a liquid that induces no swelling). The weight of the sample was determined after removing the excess quantity of oil. The weight of absorbed liquid/oil was determined by calculating the difference between the weight of the sample in dry and wet conditions. The porosity was calculated using the following formula.

$$\phi_o = \frac{W_s - W_d}{\rho_o V_s} \tag{1}$$

where ϕ_o is initial porosity, ρ_o is the density of the oil, V_s is the volume, W_s and W_d are weight of sample in saturated (s) and dry (d) conditions.

2.3.2 Measurement of the rate of porosity change in swelling conditions

The measurement of porosity reduction in swelling conditions was done using the same microscope as that of fibre diameter measurement. Several samples of the cotton fabric cell (24 mm × 24 mm) were pasted on the slide with their all ends secured using the adhesive. The whole wetting process was recorded, and photographs were taken every second. The images are then characterised (Fig. 2) and a respected pore area was obtained for each time. The process was repeated 5 times. Also, according to Masoodi et al. (2012), one can estimate the rate of porosity change based on the data obtained

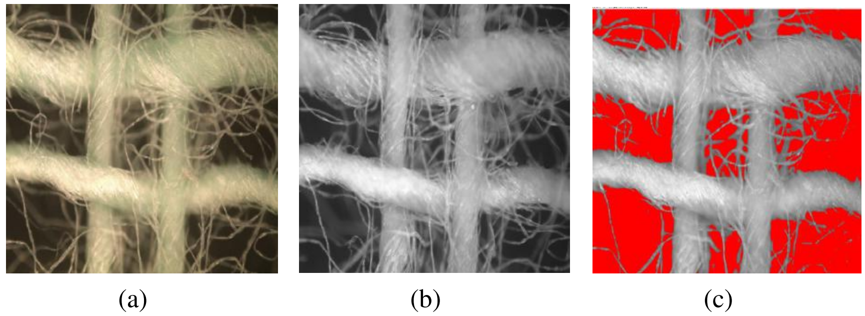

Fig. 2. Characterization process of the image to calculate the pore area: (a) original image, (b) black and white image, and (c) pore area tracking.

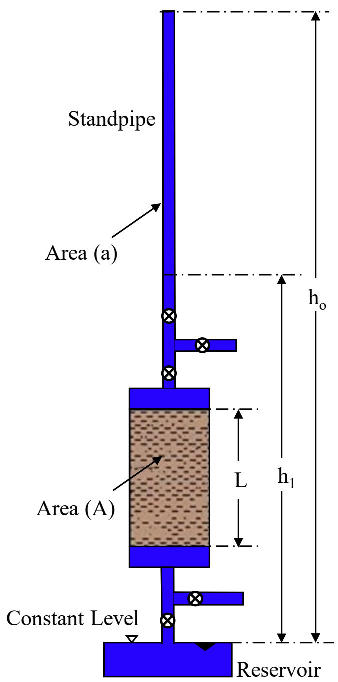

Fig. 3. Schematic view of the falling head permeability test system.

for relative changes in fibre diameter. The following equation can be used to predict the porosity reduction in fibrous porous media (Masoodi et al., 2012).

$$\phi = 1 - (1 - \phi_o)\left(\frac{D}{D_o}\right)^2 \tag{2}$$

where ϕ is final porosity of fabric. Finally, the relative changes in the porosity are plotted against the time which is explained in the results section.

2.4 Measurement of permeability

2.4.1 Falling head permeability tests

For this study, the permeability of the sample was measured in both rigid and swelling conditions. The falling head permeability test is an effective and simple method to determine the permeability of porous materials. A schematic of the in-house built testing setup is shown in Fig. 3.

The setup consisted of the acrylic mould box, 145 mm×145 mm×25 mm in size. The vertical pipe of internal diameter 22.5 mm along with the valve was fitted on the top and bottom of the mould. For the permeability measurement in rigid conditions, oil was used as the test liquid whereas for the swelling conditions, water was used. The tube was first filled with test liquid (oil/water) and made to flow through the sample of cross-section A to reach the steady state. Once a steady state was reached, the time was recorded for the different values of head differences, and rigid permeability was calculated using the following expression:

$$K_o = \frac{a}{A}\frac{L}{t}\frac{\rho g}{\mu}\ln\frac{h_0}{h_1} \tag{3}$$

where A is the cross-section area of the sample, a is the cross-section area of the tube, L is the thickness of the sample, h_0 and h_1 are the initial and final liquid column heights, ρ is density of liquid, μ is viscosity of liquid, and t is time. Further, the real time changes in the permeability were estimated using the analytical model proposed by Masoodi and Pillai (2010, 2012). This model gives the permeability as a function of time once the data related to the porosity reduction is known (Masoodi and Pillai, 2010). The analytical model is given by:

$$K = K_o\left(\frac{\phi}{\phi_o}\right)^3 \frac{1-\phi_o}{1-\phi} \tag{4}$$

where K_o is the initial permeability and K is permeability in swelling.

2.5 Water absorption test

To test the performance of the cotton fabric, a simple water absorption test setup was developed as shown in Fig. 4. The test setup was similar to the constant head permeability test where a constant head of water was maintained at the reservoir.

A red food colouring was mixed in the water so that the flow front advancement could be tracked easily. To record the flow front advancement accurately, the upper and lower faces of the sample holder were engraved with the predefined flow front locations. Further, the whole process was recorded from top and bottom using two cameras. The recording time of both cameras was synced to avoid any errors in the measurements. The main purpose of this test was to obtain the data of flow front advancement in swelling conditions which is useful whi-

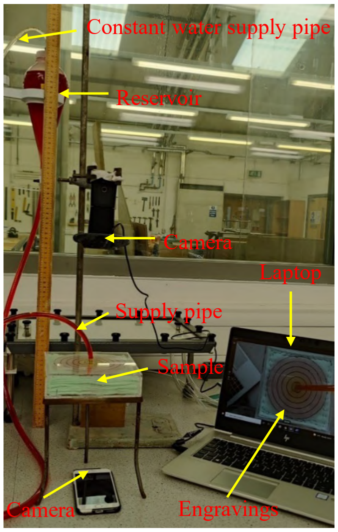

Fig. 4. The setup to test the water absorption performance of the fabrics.

le designing the hygiene products. The obtained flow front locations were plotted against the time, which is explained in the results section.

3. Results and discussion

3.1 Fibre diameter measurement

Fig. 5 shows the evolution of the average fibre diameter of cotton when exposed to water. It demonstrates that when fibres were unrestricted, they swelled up to 10%. From Fig. 5, it is clear that the maximum swelling of cotton fibre occurred within a shorter period of time due to its super absorbency. The α-cellulose content of a typical cotton fibre ranges from 88.0% to 96.5% (Moore et al., 2016). The polar group on the cellulose molecule attracts water molecules by hydrogen bonding, resulting in moisture build-up in the cell wall and fibre swelling. The predictions related to the changes in the diameter of cotton fibre could be useful while predicting the porosity and permeability changes analytically; such predictions would help engineers to design and optimise the products made up of cellulose-based fabrics. Based on the obtained results, the expression that predicts the changes in cotton fibre diameter when exposed to water is given as:

$$\frac{D}{D_o} = 1.125 - 0.125\mathrm{e}^{-0.183t} \tag{5}$$

3.2 Porosity measurement

The prepared samples as described in the previous section were used for the porosity measurement in rigid conditions. The weight of the sample in the dry and saturated state was recorded for each test and the porosity was calculated using Eq. (1). The five different tests were conducted to measure the porosity to report the results with a confidence level of 95%. Finally, the average porosity was found to be 0.88. The capillary pressure was also measured for sample. A vertical wicking test method was used to measure the capillary pressure. The final wicking height of the waterfront was used

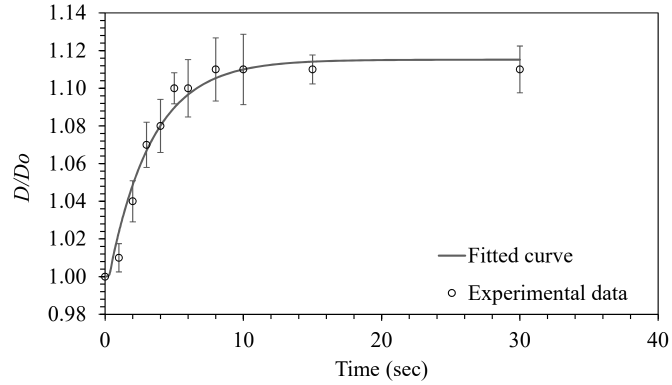

Fig. 5. Swelling of cotton fibres in water: the current averaged diameter of the fibres is $D_o = 0.000272$ m; the error bars show the confidence interval of 95%.

to calculate the hydrostatic pressure, which is equivalent to that of capillary pressure. The test was repeated five times. The obtained value for capillary pressure was 1,412 Pa. Further, the porosity measurement was done in swelling conditions. Fig. 6(a) shows the reduction in the porosity as a result of swelling when exposed to water. It shows that the porosity reduction was around 11%. It was observed that porosity reduction was dominant for 6 seconds; after that it became almost constant. Based on the obtained results for porosity reduction, a fitted expression that predicts the reduction in porosity when exposed to water is given by:

$$\frac{\phi}{\phi_o} = 0.0012t^2 + 0.0234t + 1 \tag{6}$$

Also, the porosity reduction was predicted analytically by using Eq. (2). The predictions showed that the total reduction in porosity was around 30%. The reason behind this difference in both predictions is the analytical model assumes that the fibre swells independently, whereas in reality due to a dense network of fibres, there are restrictions on the space between fibres. To account for these effects, the correction factor C_n ($n = 1$ or 2) is proposed (see Eq. (7)). The obtained experimental results are compared with analytical predictions to propose new correction factors. Finally, using the regression analysis, two correction factors (C_1 and C_2) are proposed, which are given by Eqs. (8) and (9), respectively.

$$\phi = 1 - (1 - \phi_o)\left(\frac{D}{D_o}\right)^2 C_n \tag{7}$$

$$C_1 = a\left(\frac{\phi}{\phi_o}\right)^{2-b} \tag{8}$$

$$C_2 = \frac{\phi}{\phi_o} e^{a\left(b - \frac{\phi}{\phi_o}\right)} \tag{9}$$

The proposed correction factors have fitting constants a and b whose values are optimised. The type of functions for the correction factors was selected based on the nature of the graph. Table 1 shows the values of constants a and b for each correction factor.

Fig. 6(b) shows a comparison between experimental and modified analytical predictions using proposed correction fac-

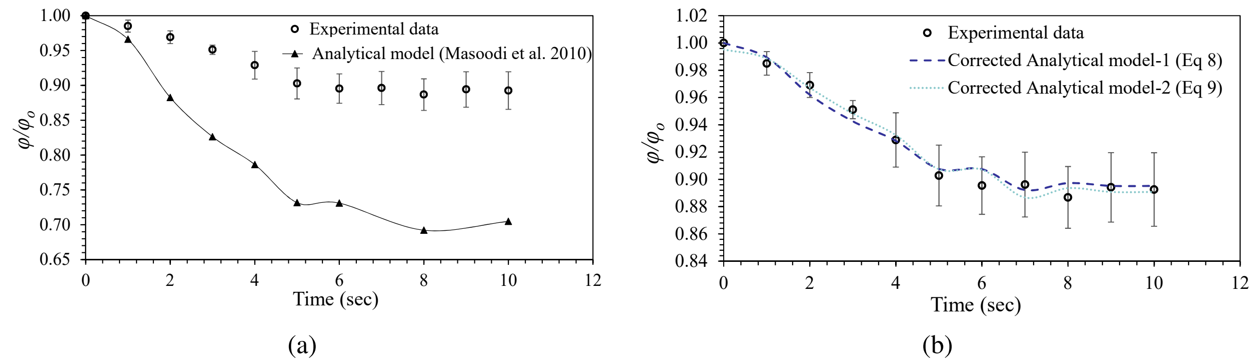

Fig. 6. Swelling of the unit cell of cotton fabric in water: the current averaged initial porosity (ε_o) of unit cell is ε_o = 0.4359; the error bars show 95% confidence intervals. (a) Predictions of porosity reduction based on analytical model from Masoodi et al. (2010), (b) comparison between experimental and modified analytical predictions with proposed correction factors.

Table 1. Values of the constants a and b for the correction factors.

Correction factor	a	b
C_1	1	0.67
C_2	0.997	0.82

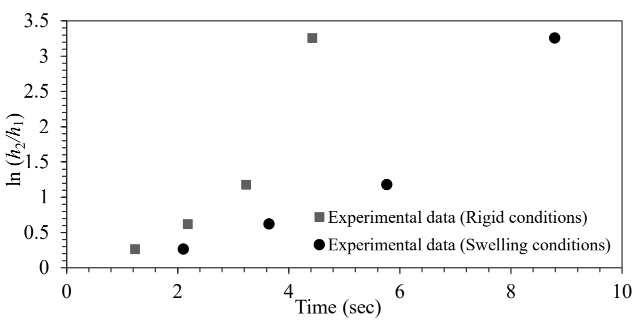

Fig. 7. Permeability coefficients at different height of liquid for rigid and swelling conditions.

tors (Eqs. (8) and (9)). It can be seen that analytical predictions from Eq. (7) were in good agreement with the experimental predictions. This demonstrates the applicability of such correction factors in analytical models to account for the effects that were not taken into consideration, such as fibre interactions etc.

3.3 Permeability measurement

Swelling of fibre causes variation in local permeability due to changes in local porosity and pore size. The permeability of the sample before swelling is called rigid or initial permeability K_o. To measure the rigid permeability, the falling head permeability test was used. Fig. 7 shows the evolution of ln (h_2/h_1) with time for both rigid and swelling conditions. To calculate the averaged permeability, the slope of ln (h_1/h_2) versus time was equated with Eq. (3). Hence, the obtained value of rigid permeability was 3.961×10^{-11} m^2. Oil was used as a test liquid to measure permeability in rigid conditions. The same procedure was repeated for the permeability measurement in swelling conditions. For this case, water was used as test liquid and the corresponding value of permeability was 1.5507×10^{-11} m^2. For each case (rigid and swelling), new samples were used. It can be seen that the permeability of the sample was reduced by almost 60.85%. Note that this permeability value refers to a fully saturated condition of the sample.

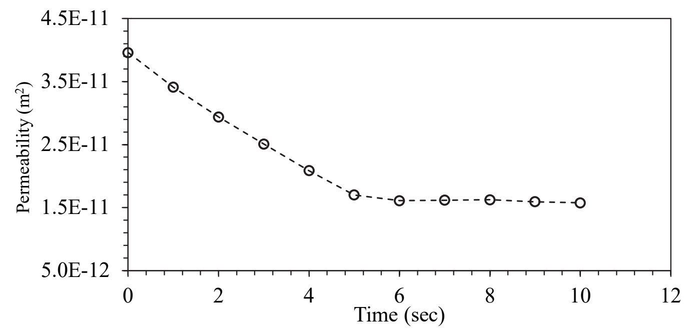

Fig. 8. Analytical predictions of the permeability reduction with time based on Eq. (4) using Kozeny Carman model from Masoodi and Pillai (2010).

Fig. 8 shows the analytical predictions for variation of the permeability with time. Eq. (4) was used to predict permeability changes based on the data obtained for the relative porosity changes. It can be seen from Fig. 8 that the permeability sharply declined till 6 seconds and became constant. According to the analytical model, permeability was reduced by 60.35%, which was close to the permeability of sample under a fully saturated (with water) condition. To predict permeability changes, the values of initial permeability and porosity were taken as 3.961×10^{-11} m^2 and 0.8801.

3.4 Water absorption test

Fig. 9 shows the obtained flow front locations for the water absorption test. The test was conducted for two cases of 52 and 130 cm of constant inlet water head. Fig. 9 shows the evolution of the flow front locations with time. The advancement of the flow front is shown for the upper and lower faces of the sample. The graph shows the flow front advancement was

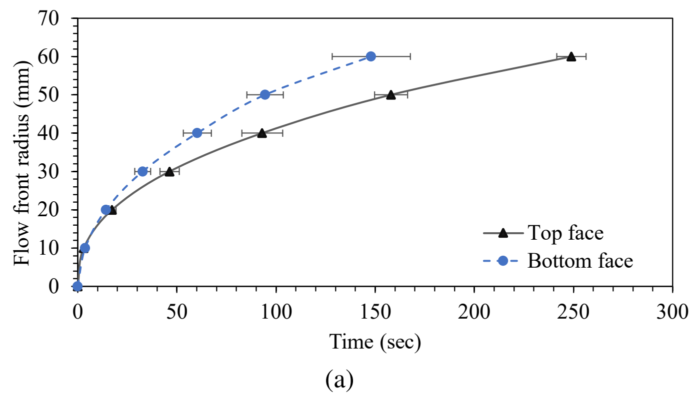

Fig. 9. The experimental observation of water flow front locations on top and bottom faces of sample: (a) inlet water head 52 cm, (b) inlet water head 130 cm.

more dominant on the bottom face of the sample than the top face. The reason behind this could be the effect of gravity on liquid front propagation. As the capillary forces along with the gravity and in flow force are in the same direction, the liquid absorption in the downward direction becomes dominant causing the faster flow on the bottom face. It is evident from Fig. 9 that changes in water head have an impact on the advancement of the flow front. When comparing Figs. 9(a) and 9(b), it is observed that an increase in inlet pressure head accelerates the flow front advancement on the top and bottom face of the sample. In the case of a 132 cm water head, the flow front advancement on both faces is faster than that of 52 cm water head case. Also, it is observed that, during the initial stages of the experiment with a 132 cm water head, the advancement of the flow front was primarily dominated on the top face. It was observed that errors were larger in the case of the bottom face flow front advancement than that of the top face.

The reason behind this could be related to the variation in the stacking pressure between each fibric pieces. Ideally, it should be uniform for each layer. However, in this case, the fibric pieces were stacked together through the hand-sewing process. Hence, the resulting distribution of pressure within the sample may not be uniform. It is expected that for machine sewed samples, this error may reduce. Also, the samples were dried and reused for some tests; it was observed that the size of samples after reuse changed slightly, which could be a reason behind the errors. Note that these results are the averaged values of five experiments and error bars are 95% confidence intervals.

4. Summary and conclusion

In this study, the swelling of cotton fibres in water was analysed. To study the effect of swelling, the changes in the fibre diameter, porosity and permeability were experimentally investigated. The swelling of cotton fibres caused porosity and permeability of fabric samples to decrease. Finally, the water absorption test was conducted for two water heads to analyse the absorbency of fabrics.

Thick fabric samples were made by stacking overlocked pieces of cotton fabric. Changes in the diameter of cotton fibre upon absorption of water was first analysed using microscopic images. It was seen that the fibres swelled quickly upon application of water. It was observed that the cotton swelled about 11% when exposed to water. One fitting equation was found to capture the changes in the fibre diameter. The initial porosity in the rigid conditions was measured by the imbibition method. The oil was used as a test liquid as it does not typically cause swelling in the fibres. The obtained porosity was 0.8801 for the sample. Further, the changes in the porosity were recorded using microscopic images at different time values. These changes were then characterised by a novel method that allowed us to track the changes in the pore area of the unit cell of a fabric. The several slides of accurately cut unit cells were prepared and placed under the microscope and the water absorption process was recorded. Further, using an image characterisation method, the changes in pore area of unit cell were tracked. It was observed that the swelling action reduced the porosity by 12%. Finally, an equation predicting the porosity as a function of time was proposed. The obtained experimental results were then compared with predictions from a modified analytical model that used data from fibre diameter measurement. To account for the effects of other fibres in fabric matrix, two correction factors were proposed to modify an existing analytical equation. As a result, the predictions from the modified analytical model improved.

The permeability of the prepared samples was measured using the falling head permeability measurement technique. It was seen that the permeability of samples decreased by 60.85% under fully swollen conditions. The changes in the permeability were also predicted analytically based on the data obtained for relative porosity reduction. The predictions showed similar permeability reduction as that of the experimental results. Finally, the water absorption test was performed to analyse the performance of the fabric under swelling conditions. To do so, a simple test setup was developed that maintained the water reservoir at a constant level and recorded the absorption process with camera arrangements on top and bottom. The liquid absorption performance of fabric was tested for the two different values of the water heads (i.e., 52 cm and

130 cm). As a result, the effect of changes in the water head was seen on the flow front advancement on the upper and lower face of the sample. It was also observed that gravity considerably affected the water absorption behaviour of the fabric, causing faster flow front propagation on the lower face of the sample.

These findings related to the liquid absorption performance of the fabrics under swelling conditions are useful in the hygiene industries where the design of products is mainly based on the liquid absorption performance.

Conflict of interest

The authors declare no competing interest.

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