

Capillary rise kinetics on woven fabrics – Experimental and theoretical studies

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Kinetics study of vertical water capillary rise on woven fabrics has been studied. Experiments are performed at $20 \pm 2^\circ\text{C}$ and $65 \pm 2\%$ RH by using a CCD camera and an electronic microbalance. A mathematical model is developed in order to interpret the experimental data in terms of diffusion parameters of water molecules on the porous materials and the height attained at equilibrium. The results show that the theoretical predictions are in reasonable agreement with experimental data with higher correlation coefficients. It is also found that kinetic parameters and the height of water attained at equilibrium are influenced by the composition (type of fibre) and the structure of the woven fabrics. It is concluded that the wicking ability is strongly enhanced with the decrease of the weft count (yarns/cm) and in the presence of higher float length of the weft yarns in the woven structure as in the case of satin 8/5. The sorption ability of the cotton fabrics has also been studied by using measurements of the mass of water absorbed by the textile. The results indicate that the satin structure, which is the less tightened one, has the best sorption ability.

Keywords: Capillary rise, Diffusion parameters, Mathematical model, Sorption ability, Woven fabric

1 Introduction

Moisture and liquid transport in woven or knitted fabrics are important factors affecting physiological comfort¹⁻⁴. The kinetic of moisture and liquid transport away from the skin surface allows the comfort or the discomfort of the wearers. So, it is very important to understand the liquid transport mechanism.

Also, all textiles chemical processes, such as pretreatment, dyeing, printing and finishing, are mostly carried out in aqueous solutions and thus require several dozen gallons of water. The optimization of water consumption in all industrial textile wet processing can be done through the study of the liquid water transport along fabrics by controlling both capillary penetration and sorption kinetics.

Liquid transport mechanisms include water diffusion and capillary wicking. Wicking is the spontaneous flow of a liquid in a porous media. Capillary flow through textile materials and liquid adsorption into textile fabrics have been extensively investigated in the literature⁵⁻¹². For example, the phenomenon of penetration of liquid into cylindrical

capillary has been initiated by Lucas¹³ and Washburn¹⁴. They showed that a liquid of viscosity ' η ' rises in a vertical tube of radius ' r ' according to the following law:

$$h(t) = \sqrt{Dt} \quad \dots (1)$$

where h is the height of liquid rise into the tube; and D , the capillary rate coefficient. This coefficient is related at the same time to the capillary radius, the surface properties and viscosity of the liquid according to following equation :

$$D = \frac{r \gamma \cos\theta}{2 \eta} \quad \dots (2)$$

where η is the viscosity of the liquid; γ , the surface tension of the liquid; and θ , the contact angle between the liquid and the inside surface of the capillary.

Among the extensive research in the field of liquid transport, textile yarns are treated as porous media. The yarn is considered as assemblies of vertical capillary tubes of radius r , the liquid flow through which can be modeled by Lucas–Washburn kinetics law^{6,9,15-18}. Indeed, Washburn's theory assumes the model as a bundle of cylindrical capillaries. Capillary radius ' r ' is equal to mean or equivalent pore radius.

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The Lucas-Washburn approach is very useful. However, the main deficiency of this law is the fact that it can be applied as long as gravity forces are negligible, which means that, it is applicable only for short experimental time when the height attained by the liquid is very smaller than the height at equilibrium. That's why this law must be corrected. These discrepancies were partly overcome by many researchers^{19,21}. In previous works^{20, 21}, we have studied the capillary flow in cotton and polyester fabrics using a generalized Lucas-Washburn equation, which was applicable for short and long experimental time, as shown below.

$$h\dot{h} = \frac{D}{2} \left[1 - \frac{h}{h_e} \right] \quad \dots (3)$$

where h_e is the height of liquid rise into the fabric at equilibrium.

Many techniques were used to study experimentally the vertical capillary flow in textiles. The first one consists of observing the liquid rise in textile structure using a colored liquid^{22,23}. Many researchers^{15,16,20,21} developed another method based on the analysis of CCD images taken during the capillary rise of colored liquid in textiles. It has been demonstrated that the addition of the dye changes the liquid properties and modifies its velocity. Moreover, the kinetics of water can be more important than those of the dye, and the results found can be erroneous.

In this study, attempts have been made to develop a mathematical model for predicting the complete profile of vertical wicking through woven fabrics considering different influencing parameters, i.e. composition and structure. By using the developed model and the ameliorated experimental system, we can also determine the diffusion parameters and the height attained by the water at equilibrium without the addition of the dye. The sorption ability of the woven fabrics is also considered.

2 Materials and Methods

The experimental setup used in this study is composed of a device assuring the vertical suspension of fabric-surface on the liquid and a lighting system (UV lamp). The textile is maintained vertically in the warp direction, maintaining the same conditions of the continuous dyeing where the fabric is fed in open width. In the developed apparatus, lab jack is used to hoist the liquid reservoir containing the water (Fig. 1). The image of the liquid rising in the textile is received

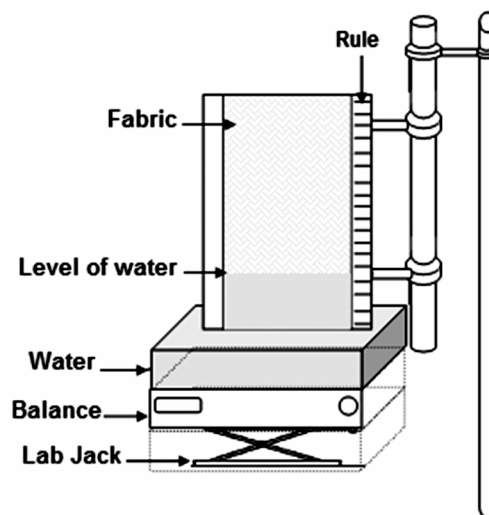


Fig. 1—Experimental device assuring vertical suspension of fabric

by the CCD camera, which is then smoothed on a visualization screen at different time interval ' t '. Then, the height attained by the liquid is evaluated (every 2 min) directly from the image. The use of UV lamp gives a good resolution and quality of images without addition of a dye.

A series of experiments is conducted on woven fabrics varying the construction parameters and composition. The characteristics of the tested woven fabrics are presented in the Table 1.

All tested fabrics were treated for 15 min at 65°C with a solution containing 5 mL/L of biolase PCL, 2.5 mL/L of wetting agent and 1 mL/L of acetic acid. This desizing treatment is realized to remove the warp sizes that were applied to yarns prior to weaving. After that, to remove the waxes and oils attached to greige fabrics that interfere with material hydrophilicity, we realized a scouring treatment by running fabrics in a bath containing 1.5% of caustic soda, 0.2% of surfactant and 0.1% of sequestrant at 100°C for 20 min.

3 Results and Discussion

3.1 Experimental Data

The height attained by the water raised along tested fabrics is determined. For this, three compositions (cotton, viscose and polyester 'PES'), three different structures (plain, twill and satin) and three different weft counts (15, 17 and 20) were employed. The experiments were conducted under the same conditions (temp. = 20±2°C and RH = 65±2%). The dimension of the dry sample used in our experiments

was 25 cm × 35 cm. The results of the experimental data are reported in Fig. 2, which show the evolution of the liquid height along the textile fabrics as a function of time.

As shown in Fig. 2, the lowest height attained by the water at the same time (*t*) is detected for the viscose fabric. This can be explained by the fact that the viscose has the lowest degree of crystallinity (40-50%) among the other. A great number of amorphous regions mean that viscose has good sorption ability, and more available hydroxyl groups in the amorphous regions are capable of binding water.

The highest height attained by water was detected for the polyester fabric. This result is expected since polyester has the highest crystallinity (80-90%), and a tiny number of amorphous regions which leads to poor sorption ability.

Figure 2 also shows the effect of weft count on capillary rise of water. As the weft count increases the capillary height decreases. The 20 yarns/cm weft count has the lowest height as compared to the 17 yarns/cm and 15 yarns/cm weft count respectively. It can also be seen that the capillary rise of water is influenced by the weave structure. The plain structure, which is the more tightened one, has the lowest height attained by the water as compared to the twill and satin respectively.

3.2 Mathematical Models

Figure 2 shows that the curve of the experimental data of cotton woven fabric (plain structure) has a positive slope but this slope decreases with time and attains zero at full saturation. In this case, the uptake process of water sorption in knitted fabrics could be

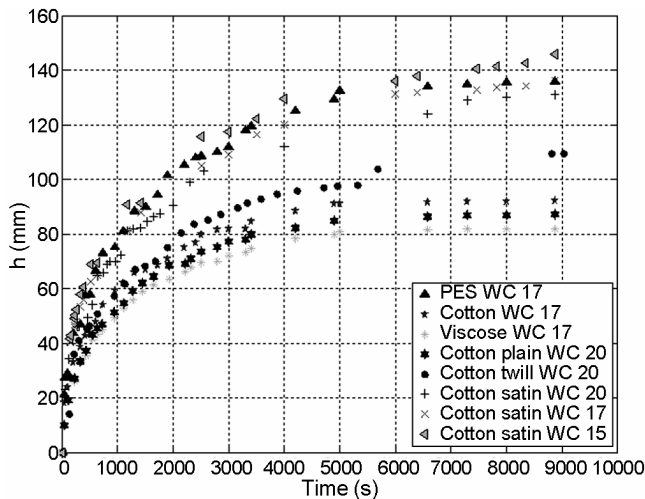


Fig. 2—Experimental results of capillary rise

divided into two steps, namely the rapid phase and the slow phase.

Hence, in order to study and interpret the capillary kinetics of water molecules in woven fabrics, the experimental height attained by water raised in fabrics at each time is fitted in the double-exponential model (DEM) proposed by Wilczak *et al.*²⁴ to describe lead and copper adsorption onto activated carbon. Wilczak *et al.*²⁴ used this model to determine the mass adsorbed at equilibrium and to study the kinetics of adsorption. They used the model, as defined below:

$$q_t = q_e - a \exp(-K_1 t) - b \exp(-K_2 t) \quad \dots (4)$$

where q_e is the amount of sorbed metal at equilibrium; K_1 and K_2 , the diffusion parameters (min^{-1}) controlling the mechanism.

In order to interpret capillary rise of water molecules in cotton fabrics, the experimental data of the height attained by the water absorbed onto fabric at each time were curve fitted using MatLab software (Matrix Laboratory) according to the modified double-exponential function. In fact, we replace in Eq. (4) the quantity of sorbed metal at equilibrium by the height attained at equilibrium. So, the mathematical model proposed in this study is shown below:

$$h_t = h_e - a \exp(-K_1 t) - b \exp(-K_2 t) \quad \dots (5)$$

In this case, the uptake process of water capillary rise on woven fabrics could be divided into two steps, viz rapid phase and slow phase. Hence, in Eq. (5), K_1 (s^{-1}) and K_2 (s^{-1}) are the diffusion parameters of the rapid step and the slow step respectively; and h_e is the height attained by the water at equilibrium (saturation of fabric).

As shown in Fig. 3 (a), the DEM presented by the solid line fits well with the experimental data with higher correlation coefficients (> 0.98). Indeed, the DEM fitting curve is composed of two exponential terms which represent a fast process [$a \exp(-K_1 t)$] and a slow process [$b \exp(-K_2 t)$] respectively. The best fit kinetics parameters (h_e , a , b , K_1 , and K_2) corresponding to the higher correlation coefficient (R^2) and the lower SSE values are given automatically by the software. Utilizing these given parameters and equations, the fitted curve can deconvoluted according to the model into a fast process associated with capillary height ($h_1=a$) and a slow process associated with capillary height ($h_2=b$). A representative example of capillary rise in the cotton plain 20 woven fabric is presented in Fig. 3. In this

case, the capillary height at equilibrium (h_e) is found to be equal to 87.69 mm, the diffusion parameters K_1 (s^{-1}) and K_2 (s^{-1}) are equal to $0.0066 s^{-1}$ and $0.000585 s^{-1}$ respectively. We observe that $K_1 \gg K_2$, which means that the rapid process can be assumed to be negligible on the overall capillary kinetics. Then, the exponential term associated with the slow processes and the DEM equations have the same appearance and they are almost confounded [Fig. 3 (b)]. So, the DEM equation can thus be simplified as shown below.

$$h_t = h_e - h_e \exp(-K_2 t) \quad \dots (6)$$

Equation (6) can be rearranged in its linear form, as shown below:

$$\ln(h_e - h_t) = \ln h_e - K_2 t \quad \dots (7)$$

To explain this phenomenon, we must analyze correctly the fabric structure. So, it is clear that the woven fabric contains following three porosity scales in which the water molecules can be diffused (accessible pores through which the flow of the liquid takes place):

- (i) Macro pores — vacuums between yarns in the structure;
- (ii) Meso pores — vacuums between fibers in the yarns;
- (iii) Micro pores — accessible sites of amorphous regions.

Indeed, the water can only enter the cotton fibre in its amorphous region, as the inter polymer spaces in the crystalline regions are too small for the water molecules. Therefore, a trace amount of adsorbed water on the surface of crystalline region is almost

negligible, and hence the amount of absorbed water in fibres, also called the bound water, almost totally relies on the accessible sorption sites of amorphous regions.

Based on the theoretical study of the capillary rise in fabric structure [Fig. 3 (b)], it can be concluded that the liquid is diffused, initially in the macro and meso pores which are responsible for the diffusion during the short time [the fast process indicated in Fig. 3(b)]. Then, after saturation of the macro and meso pores, the water diffusion takes place in the micro pores which are responsible for the long time diffusion.

The second goal of this study is to calculate the sorption ability values for all the fabrics which can provide information about the sum of the macro, meso and micro pores values. From the knowledge of weight of liquid trapped in fabrics and thickness of fabrics, the sorption ability values ‘SA’ are calculated for each fabric using the following equation:

$$SA = \frac{W_v}{F_v} = \frac{M_w}{\rho_w \times (L_F \times Wd_F \times T_F)} \quad \dots (8)$$

where W_v is the water volume; F_v , the fabric volume; M_w , the liquid mass absorbed by fabric; ρ_w , the density of water; L_F , the length of fabric; Wd_F , the width of fabric; and T_F , the thickness of fabric.

3.3 Analysis of Capillary Kinetics using DEM Equation

Influence of Composition

To study the effect of composition on capillary kinetics, experiments were performed on fabrics prepared from natural, regenerated and synthetic

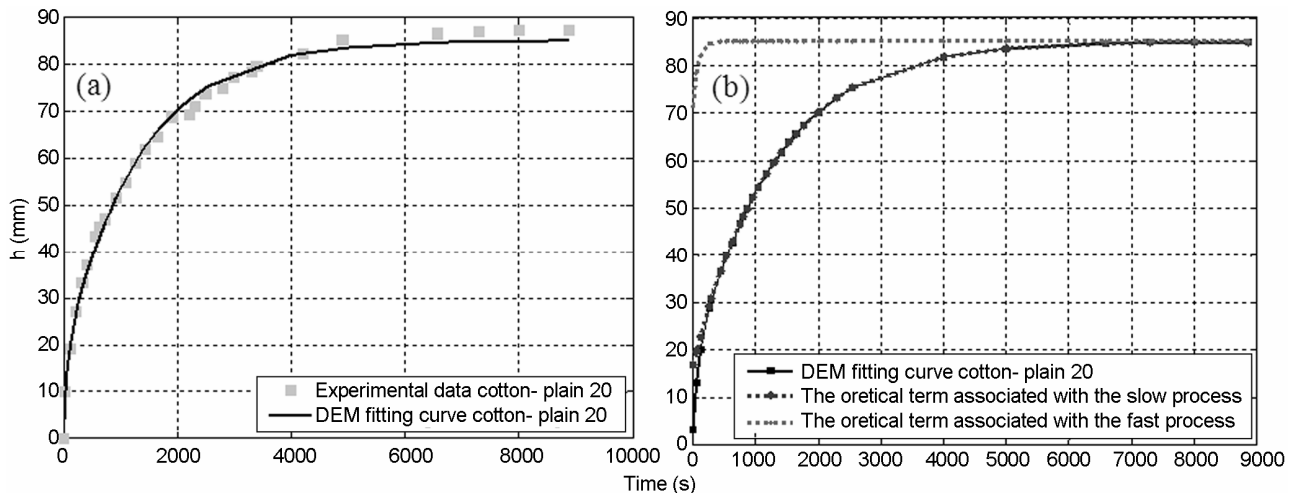


Fig. 3—(a) DEM fitting curve of experimental data of plain 20 cotton fabric; and (b) fitted curves showing slow and the fast processes

Table 1—Characteristics of tested woven fabrics

Sample	Composition	Weave structure	Wefts count yarns cm	Warps count yarns/cm	Crimp of weft	Thickness mm
1	Cotton	8-H/5 satin	15	24	1.10	0.54
2	Cotton	8-H/5 satin	17	24	1.12	0.62
3	Cotton	8-H/5 satin	20	24	1.15	0.65
4	Cotton	Twill 1/3	20	24	1.57	0.73
5	Cotton	Plain	20	24	1.69	0.79
6	Cotton	Plain	17	24	1.62	0.74
7	Viscose	Plain	17	24	1.45	0.72
8	PES	Plain	17	24	1.66	0.78

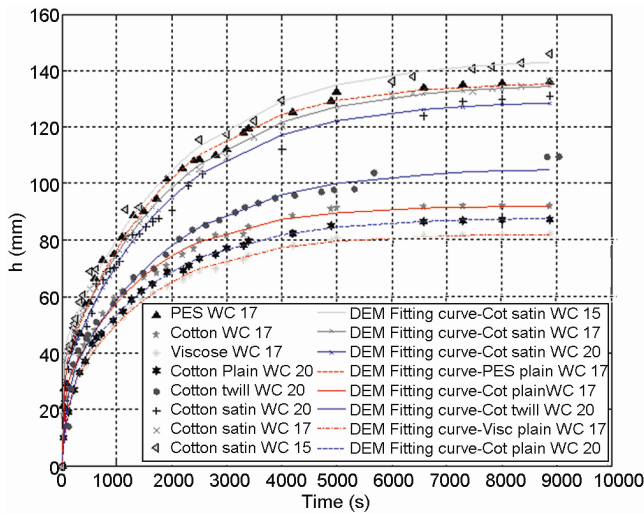


Fig. 4—DEM fitting curves of experimental data

fibres. Description of the experimental woven fabrics used in this section is provided in Table 1 (Samples 6 - 8). The result of DEM fitting curves of experimental data of capillary rise in different fabrics are presented in Fig. 4. The correlation coefficients R^2 , the capillary height at equilibrium (h_e), and the values of double-exponential model rate parameters K_1 and K_2 were obtained and listed in Table 2.

Based on the R^2 values (> 0.99 in all cases) as shown in Table 2, we observed that experimental data are well correlated to the DEM equation for the three tested fabrics. It can also be observed that ' K_1 ' is greater than ' K_2 ' for the three fabrics structure tested. Moreover, it can be seen that the theoretical values of the capillary height at equilibrium ' h_e ' (saturation of fabric) determined from the DEM are approximately equal to the sum of h_1 and h_2 .

Table 2 shows that Samples 6-8 strongly differ from each other in the capillary height at equilibrium ' h_e ' as well as in the diffusion parameters ' K_1 ' and ' K_2 '.

Table 2—Influence of composition on double exponential model parameters

Sample	h_e , mm	$a=h_1$	$b=h_2$	K_1 , min^{-1}	K_2 , min^{-1}	R^2
Cotton	92.58	25.75	65.21	0.0199	0.000630	0.9959
Viscose	82.13	22.13	59.74	0.0112	0.000629	0.9983
PES	135.9	33.54	102.80	0.0291	0.000552	0.9960

Because of hydrophobic character of polyester, the water does not penetrate into fibre pores and the capillary height at equilibrium in the Sample 8 is higher than in both Samples 6 and 7. In contrast to polyester, viscose fibre has a good ability to absorb water which can penetrate into fibre pores. Thus, the polyester woven fabric is associated with higher capillary height at equilibrium followed by the viscose woven fabric and the cotton woven fabric respectively.

In woven fabric experiments, we can say that initially in the fast process, the capillary diffusion takes place in the macro and meso-pores (pores between yarns in the woven structure and pores between fibres in the yarn respectively) and then, in the slow process it takes place in the micro-pores (pores intra fibres). So, the macro and meso-pores are responsible for the diffusion during the short experimental time (in the beginning of the experiment) and the micro-pores are responsible for the diffusion during the long experimental time diffusion. Also, in contrast to polyester, during impregnation viscose and cotton swell and consequently the size of the macro-pores and meso-pores in viscose and cotton fabrics decreases. These reasons explain the easy penetration of the liquids and the high capillary kinetic ' K_1 ' in polyester fabric at the fast process. Then, at the slow process when the liquid penetrates the micro-pores, the capillary kinetic ' K_2 ' in viscose and cotton fabric becomes higher than in polyester fabric.

Table 3—Influence of woven structure on the double exponential model parameters

Sample	h_e , mm	$a=h_1$	$b=h_2$	K_1 , min ⁻¹	K_2 , min ⁻¹	R ²
Satin 15	143.5	41.04	102.9	0.0199	0.000498	0.9967
Satin 17	135.7	38.25	97.67	0.0171	0.000485	0.9985
Satin 20	130.4	35.48	95.39	0.0169	0.000483	0.9944
Twill 20	105.6	28.24	79.53	0.0088	0.000502	0.9893
Plain 20	87.69	24.41	61.68	0.0066	0.000585	0.9989

Table 4—Sorption ability of the tested samples

Sample	Composition	Weave structure	M_w , g	$\rho_w \times (L_F \times Wd_F \times T_F)$	Sorption ability
1	Cotton	Satin 15	26.820	47.250	0.5676
3	Cotton	Satin 20	29.890	56.875	0.5255
4	Cotton	Twill 20	33.150	63.875	0.5189
5	Cotton	Plain 20	35.260	69.125	0.5100

Influence of Woven Structure and Weft Count

Characteristics of the fabrics used to assess the effect of the woven structure and weft count on capillary kinetics are summarized in Table 1 (Samples 1-5). The results of DEM fitting curves of experimental data of capillary rise in different woven structures and in different weft counts are presented in Fig. 4. The correlation coefficients R², the capillary height at equilibrium (h_e), and the values of capillary kinetic parameters K_1 and K_2 are listed in Table 3.

As mentioned before, it is clear from the results presented in Table 3 that the experimental data are well correlated to the DEM equation for the five tested fabrics and ' K_1 ' is found to be greater than ' K_2 ' for all tested fabrics.

As known earlier, increasing number of weft yarn/cm results in a tightly woven structure, and consequently the porous rate of the woven structure decreases. As a consequence, the order of the capillary height at equilibrium is as follow:

Weft count of 15 yarns/cm > weft count of 17 yarns/cm > weft count of 20 yarns/cm.

Also, the plain fabric is characterized by the higher intersections between warp and weft yarns in the woven structure. However, the satin weave fabric is characterized by the higher float length of the weft yarns in the woven structure. As a result, satin fabric has the highest capillary height at equilibrium followed by the twill and the plain fabrics respectively.

As the weft count per centimeter increases and the structure is more tightened, the capillary kinetic coefficient K_1 for rapid step decreases. In contrast, the capillary kinetic coefficient at the slow process increases. This can be explained by increasing the quantity of cellulose materials in these fabric types.

3.4 Determination of Sorption Ability

We also determined the sorption ability values using the Eq. 9. This method requires the measurement of the mass of the raised liquid at equilibrium. For this reason, the fabric is attached to a sensitive electronic balance (AND GX-2000 precision balance) with an accuracy of 0.01 g (Fig. 1). The balance has the capability of recording the weight of the absorbed water (g) versus time (s) with its special software (RsCom program of WinCT data communication software Version 2.40 compatible with Windows, Window 95, 98 & NT). The experimental values of the mass of water absorbed at equilibrium by the cotton fabrics are reported in Table 4. Finally, the sorption ability values of all tested cotton fabrics are calculated using the measured values of the amount of liquid retained by fabrics after wicking experiments (Table 4).

As the weft count increases, the sorption ability of the fabric decreases. The 20 yarns/cm weft count has the lowest sorption ability as compared to the 15 yarns/cm weft count. It can also be seen that the sorption ability of the fabric is influenced by the weave structure. The plain structure, which is the more tightened one, has the lowest sorption ability as compared to the twill and satin respectively.

4 Conclusion

It is observed that there are significant variations in the capillary height at equilibrium and the capillary kinetics coefficients K_1 and K_2 between different weft count (15, 17 and 20) and structure (plain, twill and satin) of fabrics by changing the form and the size of the pore responsible for the migration of the water molecules. The weft count of 15 yarns/cm

demonstrates the best wicking ability. It has the highest values of the height at equilibrium and the kinetic parameters (h_e , K_1 and K_2) followed by the weft count of 17 and then the weft count of 20 respectively. Also, the satin structure shows better wickability than twill and plain structures.

The composition has also a significant influence on the capillary kinetics because there is a great difference between the hydrophilicity of natural (cotton), artificial (viscose) and synthetic fibres (polyester). It is for this reason, the polyester shows a good wicking ability.

The study on determination of sorption ability shows that it is influenced by both the weft count and the weave structure of fabrics. The 15 yarns/cm weft count shows a good sorption ability as compared to the 20 yarns/cm weft count. However, the plain structure, which is the more tightened one, has the lowest sorption ability as compared to the twill and satin respectively.

References

- 1 Laughlin R & Davies J, *Text Res J*, 31 (1961) 904.
- 2 Hollies N, Kassinger S, Barbara W & Herman B, *Text Res J*, 27 (1957) 8.
- 3 Yan Z, Huaping W, Chuanxiong Z & Yuchua C C, *J Materials Sci*, 42 (2007) 8035.
- 4 Wu H Y, Zhang W & Li J, *Fibres Text Eastern Eur*, 15 (2009) 46.
- 5 Bivainyte A & Mikucioniene D, *Fibres Text Eastern Eur*, 19 (2011) 64.
- 6 Doakhan S, Ravandi S A H, Gharehaghaji A & Mortazavi S M, *Iranian Polym J*, 16 (2007) 397.
- 7 Das B, Das A, Kothari V K & Fanguero R J, *J Text Inst*, 102 (2011) 957.
- 8 Amico S & Lekakou C, *Composites: Part A*, 31 (2000) 1331.
- 9 Sharabaty T, Biguenet F, Dupuis D & Viallier P, *Indian J Fibre Text Res*, 33 (2008) 419.
- 10 Fayala F, Hamdaoui M & Ben Nasrallah S, *J Porous Media*, 11 (3) (2008) 231.
- 11 Hamdaoui M, Fayala F & Ben Nasrallah S, *AUTEX Res J*, 8 (2) (2008) 44.
- 12 Hamdaoui M, Achour N S & Ben Nasrallah S, *J Eng Fibers Fabrics*, 9 (1) (2014) 101.
- 13 Lucas R, *Kolloid Zeitschrift*, 23 (1918) 15.
- 14 Washburn E W, *Phys Rev*, 17 (1921) 273.
- 15 Perwuelz A, Mondon P & Cazé C, *Text Res J*, 70 (2000) 333.
- 16 Perwuelz A, Casetta M & Cazé C, *Polym Testing*, 20 (2001) 553.
- 17 Zhong W, Ding X & Tang Z L, *Text Res J*, 71 (2001) 762.
- 18 Kamath Y K, Hornby S B, Weigmann H D & Wilde M F, *Text Res J*, 64 (1994) 33.
- 19 Sénécot J M, *Thèse Université de Haute Alsace*, (2002).
- 20 Hamdaoui M, Fayala F & Ben Nasrallah S, *J Porous Media*, 9(4) (2006) 381.
- 21 Hamdaoui M, Fayala F & Ben Nasrallah S, *J Appl Polym Sci*, 104 (2007) 3050.
- 22 Kawase T, Sekoguchi S, Fujii T & Mingawa M, *Text Res J*, 56 (1986 a) 409.
- 23 Kawase T, Sekoguchi S, Fujii T & Mingawa M, *Text Res J*, 56 (1986 b) 617.
- 24 Wilczak A & Keinath T M, *Water Environ Res*, 65 (1993) 238.