Permeability and Wicking Properties of Modal and Lyocell Woven Fabrics Used for Clothing

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ABSTRACT

In this study, air permeability, water vapor permeability and wicking properties of certain woven fabrics, which are important comfort properties for clothes and garments, have been investigated. The effects of raw material (modal, Lyocell), weave pattern (plain, 2/2 twill, 1/3 twill, 2/2 matt) and weft yarn density (18, 22, 26) on these properties have been analysed graphically and statistically.

The comfort characteristics of fabrics (permeability and wicking properties) are closely associated with the changes in their structural parameters: 2/2 matt and plain woven fabrics, where porosities are high, have better permeability and wicking properties. Increasing weft yarn density lead to decreases in porosity, resulting in decreased permeability and wicking properties. Increasing yarn twist increased the porosity of the fabrics. Lyocell fabrics showed improved permeability and wicking properties over modal fabrics due to Lyocell fibers' high percentage of fibrillary structure.

Keywords: plain weave, basic weaves, air permeability, water vapor permeability, wicking, permeability properties of fabrics

INTRODUCTION

Modern consumers consider comfort as one of the most important attributes in their purchase of textile and apparel products. Clothing comfort [1] is dependent upon the low stress mechanical, thermal and moisture transfer properties of the fabrics. There is general agreement that air and moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body, which is maintained by perspiring both in vapor and in liquid form.

Permeability properties of fabrics which such as air and water vapor permeability are directly related to fabric thickness. Permeability of fabrics depends on the amount and distribution of spaces in fabric structures. Water permeability of fabrics is related to fabric surface tension. On the other hand, water wicking of fabrics depends on the raw material used, and therefore is related to the chemical structure of fibers and capillary forces [2].

In recent years, the production of modal fibers, a special viscose fiber derived from beech wood and having high wet breaking strength, has becoming important. The cross section of modal is smoother than that of viscose and the molecular weight is higher than that of viscose. Lyocell fibers are directly regenerated from an organic solvent of cellulose. Their cross section is circular shape and their surface is smooth. Their handle is soft, mild and silky, so they are used for men and women's clothing [3].

A number of studies have been conducted on the air permeability, water vapor permeability and wicking properties of fabrics. Gorjanc and Bizjak [4] investigated the impact of the pre-finishing process (scouring/bleaching) on the comfort characteristics of pure cotton fabrics and of cotton fabrics with elastane in the weft direction in plain and twill weave. The results indicated that water vapor resistance decreased following pre-finishing of the fabrics. The decreases resulted from increases in warp yarn density and mass and decreases in thickness.

Varshney et al. [5] studied the effect of linear densities and profiles of 100% polyester and the other 67:33 Polyester/Viscose (P/V) blend micro denier fibers on the physiological properties of 2/1 twill fabrics woven with four different polyester fiber finenesses and four cross-sectional shapes (circular, scalloped oval, tetrakelion and trilobal). They found that use of non-circular polyester improved the wickability of water as well as the air and moisture permeability of the fabrics. Results showed that moisture absorption of viscose was an important factor in influencing the moisture and vapor transmission rate of the P/V-blended fabrics.

Das et al. [6] studied the air permeability, water vapor permeability, in-plane wicking and vertical wicking of PV-blended fabrics. PV-blended yarns of varying blend proportion, yarn count and twist levels were used for fabric manufacture. Most of the moisture transmission characteristics were significantly influenced by blend ratios, count and twist levels at 95% confidence levels.

Ogulata and Mezarcioz [7] studied the air permeability of 100% cotton and 97/3 cotton/lycra woven fabrics. They found that the permeability and pore size are strongly related.

Çay and Tarakçıoğlu [8] investigated the effects of the fabric structure on vacuum drying efficiency. Thirty woven fabrics with different porosities were dried by vacuum extraction, and it was found that the lower the porosity the lower the air permeability.

Das et al. [9] studied the characteristics of plain-woven fabric produced from cotton–acrylic high-bulk yarns. Thermal resistance, air permeability and moisture vapor transmission of fabrics woven with high-bulk yarns were higher than that of 100% cotton fabric.

Mazloumpour et al. [10] examined the wicking of water in plain woven fabric samples with different weft yarn counts, density, and type of fiber in blend yarns. The average wicking rise of water decreased with increasing weft yarn density. The wicking of water along the cotton–polyester blend weft yarn was higher than 100% cotton weft yarn samples.

Komisarczyk et al. [11] studied liquid transport through a double-layer knitted fabric and a sateen woven fabric, both made from hydrophilic and hydrophobic fibers (cotton, viscose and polypropylene). They observed that during the initial stage, only a part of the hydrophobic layer was filled. Moisture collected between the fibers and existing channels transported the moisture to the hydrophilic layer, where it accumulated.

Sarıcam [12] applied correlation analysis, two sided independent t-test analysis and ANOVA tests to determine the relationship between the production parameters and comfort characteristics (absorption, vertical and transfer wicking and drying) of knitted fabrics. She found that tension and elastane composition affect the comfort characteristics by changing the porosity, thickness and the pathways within the fabric.

Kwon et al. [13] applied four different concentrations of fluorocarbon finish agents to lyocell 100% (L), PET 100% (P), and 50%/50% PET/lyocell blend (PL) fabrics in order to develop breathable, antistatic, superhydrophobic PET/lyocell fabrics. Water repellency tests were performed to evaluate the wettability and hydrophobicity of treated fabrics. The air permeability of L was considerably higher than that of P or P/L, probably due to the lower fabric density of L (55×41 in cm^2) over those of P (67×47 in cm2) and P/L (67×39 in cm^2). For the same reason, P/L showed relatively higher air permeability than P.

This paper discusses the influence of the yarn and fabric structural parameters, such as raw material, weave pattern and weft density on the moisture related comfort characteristics of the modal and Lyocell fabrics used for clothing. The air permeability, water vapor permeability and wicking properties of woven fabrics were tested and analysed by means of graphic plots of data obtained, analysis of variance and t tests.

THEORETICAL

Since textiles are discontinuous materials, being produced from macroscopic sub-elements such as fibers and filaments, they have void spaces or pores and therefore finite porosities [14]. Hseih [15] defines porosity as

$$\varepsilon = 1 - \frac{\rho_a}{\rho_b} \tag{1}$$

where ρ_a is the fabric density (g/cm^3), ρ_b is the fiber density (g/cm^3) and ε is the porosity. Fabric density is calculated by dividing the fabric weight per unit area by the fabric thickness.

The pores of a fabric can be classified as pores between the yarns or pores between the fibers (micro voids) within the yarns. The dimensions of the pores between the yarns are directly affected by the yarn density and yarn thickness. By the increasing the yarn density, the dimensions of the pores become smaller, thus the permeability decreases [16], [17]. The dimensions of pores within the yarns between the fibers (micro voids) are generally affected by fiber fineness, yarn count, yarn twist and crimp, and the deformation and flattening of the yarns. For loose fabrics, air mainly passes through the pores between the yarns due to the large pore dimensions; however, a dominant air flow through the yarns between the fibers can occur in the case of dense fabrics that have very small pores between the yarns [18]. The resistance of dense fabrics to air is very high, so air passes through all the voids. Depending to the fabric structure, great variation on the amount of the air flow and the air flow paths are possible.

On the other hand, water vapor can pass through textile fabrics by different processes [19], [20] namely: (1) diffusion of the water vapor through the fabric; (2) absorption, transmission and desorption of the water vapor by the fibers; (3) adsorption and migration of the water vapor along the fiber surface; and (4) transmission of water vapor by forced convection. Liquid moisture transmission is determined mainly by type of fiber; yarn structure such as arrangement of the fibers, pore size, effective capillary pore distribution in the yarn packing density; and fabric structure such as size and number of the capillary paths through the fabric. The speed of water transport in the capillaries is reduced by the presence of randomly arranged fibers in the yarn. With an increase in the packing coefficient of the yarn, the fibers are forced closer to each other, introducing a greater number of capillaries with smaller diameter, which are likely to promote liquid flow. The tortuosity of the pores has a great influence on the wicking process. The capillary rise at a specific time will be faster in a porous medium with larger pore size. However, the higher initial wicking through the capillaries with larger diameter is overtaken with time by the capillaries with smaller diameter.

EXPERIMENTAL

Materials

In this research, 24 types of clothing woven fabric samples were produced in-house using a CCI automatic sample rapier loom (Evergreen 8900, Taiwan). Nm 34/1 staple fiber of Modal and Lyocell yarns in white colour were used. The twist of modal yarns is 714 t/m and the twist of Lyocell yarns is 808 t/m. Weave patterns are shown in *Figure 1*. The properties of fabrics are given in *Table I*.

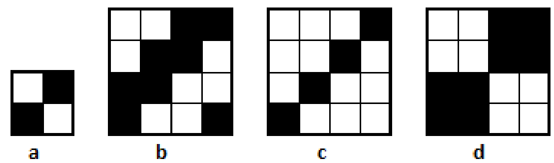

FIGURE 1. Weave patterns used in experimental: a) Plain weave, b) 2/2 twill weave, c) 1/3 twill, d) 2/2 matt.

Weave patterns and weft densities of fabric samples are shown in *Table I*. The letter in the fabric codes represents the raw material of the yarns, the number represents weave patterns and weft densities used. These are square unit weaves, so the number of each warp and weft yarn interlacing is equal. The weave interlacing coefficient, defined by Galcerán [21] has been calculated by;

$$KL = \frac{i}{w_1 \times w_2} \quad (2)$$

where i is the number of interlacing points in weave repeat, w_1 is the number of ends in weave repeat w_2 is the number of picks in weave repeat. Porosities of the fabric samples were calculated by Eq. (1).

TABLE I. Specifications of the fabrics.

Fabric Code	Raw Material	Weave	Warp Setting (cm-1)	Weft Setting (cm-1)	The weave interlacing coefficient	Thickness (mm)	Mass per Unit Area (g/m^2)	Porosity (ε)
A1	100% Modal	Plain	24	14	1	0.29	129.3	0.27
A2	100% Modal	Plain		18		0.31	142.9	0.25
A3	100% Modal	Plain		22		0.33	156.5	0.22
A4	100% Modal	2/2 Twill	32	18	0.5	0.35	162.7	0.24
A5	100% Modal	2/2 Twill		22		0.36	175.7	0.2
A6	100% Modal	2/2 Twill		26		0.37	188.8	0.16
A7	100% Modal	1/3 Twill	32	18	0.5	0.33	155.3	0.23
A8	100% Modal	1/3 Twill		22		0.34	167.8	0.2
A9	100% Modal	1/3 Twill		26		0.35	180.2	0.15
A10	100% Modal	2/2 Matt	32	18	0.5	0.35	159.8	0.25
A11	100% Modal	2/2 Matt		22		0.36	172.5	0.22
A12	100% Modal	2/2 Matt		26		0.38	185.3	0.19
B1	100% Lyocell	Plain	32	14	1	0.3	131	0.27
B2	100% Lyocell	Plain		18		0.32	144.8	0.25
B3	%100 Lyocell	Plain		22		0.34	158.6	0.22
B4	%100 Lyocell	2/2 Twill	32	18	0.5	0.31	138.5	0.26
B5	%100 Lyocell	2/2 Twill		22		0.33	151.7	0.23
B6	%100 Lyocell	2/2 Twill		26		0.34	164.9	0.19
B7	%100 Lyocell	1/3 Twill	32	18	0.5	0.29	132.2	0.25
B8	%100 Lyocell	1/3 Twill		22		0.31	144.8	0.22
B9	%100 Lyocell	1/3 Twill		26		0.32	157.4	0.18
B10	%100 Lyocell	2/2 Matt	32	18	0.5	0.31	136	0.27
B11	%100 Lyocell	2/2 Matt		22		0.33	148.9	0.24
B12	%100 Lyocell	2/2 Matt		26		0.34	161.9	0.21

Test Facilities and Conditions

Water vapor permeability tests were conducted on the fabrics in-house in the Chemical Testing Laboratory. Air permeability tests were conducted on the fabrics in-house in the Physical Testing Laboratory. The fabric samples were conditioned at standard atmosphere conditions (20 ± 2ºC, 65% ± 2% relative humidity) for 24 hours prior to testing.

Yarn Sizing and De-sizing

The yarns lacked tensile strength, therefore; they are sized. Synthetic sizing liquors were prepared in-house. Ensize TX11 5% was used for sizing. Wachs 2% sizing agent was added to all size recipes. Size liquors were heated to 80°C and scoured at 80°C 20 minutes. The temperature of the sizing chamber was set to 80°C, and the temperature of the heating chamber was set to 86°C during sizing process. These conditions were used for sizing all samples. After weaving, all fabrics were de-sized for 20 minutes at 60°C to eliminate the possibility of the sizing agents influencing test results.

Air Permeability Test

Air permeability was measured in accordance with ASTM D737-04 [22], by the Tex-Test air permeability tester (FX3300, Switzerland). The air permeability is expressed as the quantity of air in cubic centimeters passing through a square centimeter of fabric per second ($cm^3/sec \cdot cm^2$). The air permeability tests were done at a test pressure drop of 100 Pa (20 cm^2 test area). The average of five measurements was used for comparison.

Water Vapor Permeability Test

Water vapor permeability of fabric samples was determined using an SDL Atlas instrument (M261, USA) according to ISO 14596 [23]. A test specimen was sealed over the open mouth of a test dish which contains water, and the assembly was placed in a controlled atmosphere. After establishing equilibrium water vapor pressure gradient across the sample, successive weighings of the assembled dish were made and the water vapor permeation through the specimen was determined. The water vapor permeability (WVP) in $g/m^2/day$ was calculated by the equation;

$$WVP = \frac{24 \times M}{A \times t} \quad (3)$$

where M is the loss in mass of the assembly over the time period t (in g), t is the time between successive weighings of the assembly in hours, A is the area of exposed test specimen (equal to the internal area of the test dish (in m^2)). In this case A = 0.0054113m^2

Wicking Test

Wicking behaviour of fabric samples was determined according to DIN 53924 [24]. Five specimens were cut along the warp and weft directions respectively to dimensions of 200 mm × 25 mm and suspended in a reservoir of 1% K_2CrO_4 with their bottom ends at a depth of 30 mm into the water. The height of the solution raised was measured and recorded in terms of mm after 60 seconds.

Macroscopic Analysis

Microscopic images were taken with an IVYMEN Stereomicroscope. The total magnification of the image is 100X.

Statistical Evaluation

Wicking test results were evaluated statistically by ANOVA according the General Linear Model with a SPSS 15.0 software package. In order to analyse the effect of weave and weft density, multivariate analysis was made for the two groups of fabrics: one including fabrics woven with modal fibers the other including fabrics woven with Lyocell fabrics. Significance degrees (p), which were obtained from ANOVA, were compared with significance level (α) of 0.05. Effects having a significance degree of less than 0.05 were interpreted as statistically important.

The effect of raw material on wicking height, air and water vapor permeability of fabrics were evaluated by t tests for modal-Lyocell fabrics. The effect of test direction on wicking height of fabrics was evaluated by t tests for modal-Lyocell fabrics in the warp and weft directions. The t tests were done using MATLAB 6.5 with significance level (α) of 0.05. A hypothesis of h_0 determined that averages were equal. If h, the calculated value, was equal to 1, h_0 would be ignored and the difference between the wicking test results is statistically important.

RESULTS AND DISCUSSION

Air Permeability Test Results

Air permeability of modal and Lyocell fabrics are shown in *Figure 2* and *Figure 3*, respectively. From the figures, it is observed that the air permeability of fabric samples changes according to raw material, weave pattern and weft density. Air permeability of Lyocell fabrics are higher than those of modal fabrics. This is due to the fact that although calculated porosities of Lyocell fabrics are almost the same as those of modal fabrics, the porosities of Lyocell fabrics are larger than those of modal fabrics when observed microscopically. Because Lyocell yarns have higher twist than the modal yarns, the structure of Lyocell yarn is denser than Modal yarn and the volume of air in Lyocell yarn decreases. Samples A10, A11, A12, which are 2/2 matt weave, and samples A1, A2, A3, which plain weave have better air permeability properties than samples A4, A5, A6 which are 2/2 twill weave and the samples A7, A8, A9 which are 1/3 twill weave. This is due to the fact he plain weave fabrics have the highest weave interlacing coefficient and thus higher porosity. Although the matt weave has the same interlacing coefficient as the 2/2 twill and 1/3 twill weaves, the floating pairs of matt weaves get close to each other, increasing the porosity of the matt weave. The air permeability of the 1/3 twill woven fabric samples are higher than those of 2/2 twill woven fabric samples, even though they have the same weave interlacing coefficient. This is probably due to the fact that in 1/3 twill weave there are weft yarn floats passing over three warp yarns. These longer yarn floats move away from each other easily under the air pressure applied during the air permeability test, effectively increasing the porosity of 1/3 twill fabric increased. When air permeability values are compared within ternary groups of (A1, A2, A3), (A4, A5, A6), (A7, A8, A9), (A10, A11, A12) the air permeability of the fabrics decreases within each group, as shown in *Figure 1* and *Figure 2*, due to the increase of the weft yarn density. This is due to the fact that within each ternary group, fabric density is increasing, thus decreasing pore size. This relationship is also valid for the Lyocell fabric samples. The standard deviation of modal and Lyocell fabric samples decreased when the air permeability of fabrics decreased.

The variance analysis showed that both the effects of weave and weft density on air permeability of the modal and Lyocell fabrics are statistically significant, with p-values of (0.001) and (0.023) respectively. The results of the t-test confirmed that the air permeability changed as a function of the raw material, having the h-values of (1) for the modal-Lyocell fabrics. Significant differences are also indicated by the fact that the error bars in graphs do not overlap.

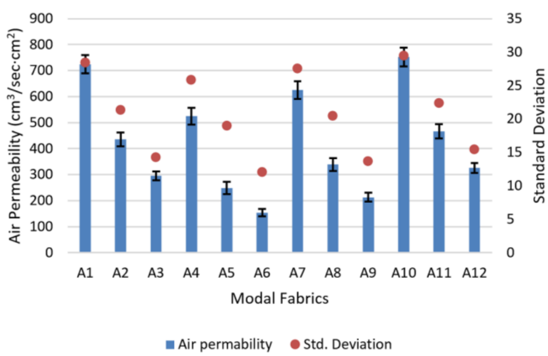

FIGURE 2. Air permeability of modal fabric samples.

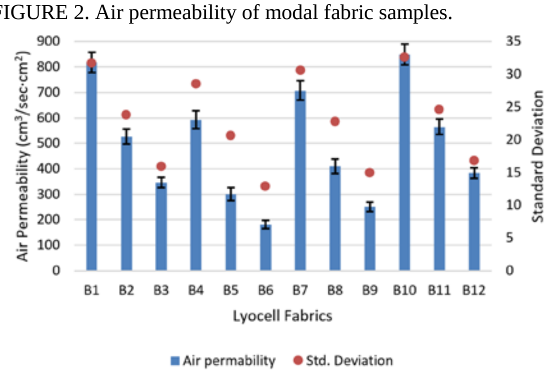

FIGURE 3. Air permeability of Lyocell fabric samples.

Water Vapor Permeability Test Results

Water vapor permeability of modal and Lyocell fabrics are shown in *Figure 4* and *Figure 5*, respectively. From the figures, it is seen that the water vapor permeability of fabric samples change according to raw material, weave pattern and weft density. Lyocell fabrics have better water vapor permeability properties than modal fabrics. This is because the porosities of Lyocell fabrics are larger than those of modal fabrics and the fact that bonding between fibrils in Lyocell fibers is weak, resulting easier fibrillation and a higher percentage of fibrillar structure than modal fibers [3]. Therefore, water molecules diffuse more readily into Lyocell fibers. Water vapor permeability of samples A10, A11, A12, which are 2/2 matt weave and samples A1, A2, A3, which are plain weave, are higher than those of the samples A7, A8, A9, which are 1/3 twill weave and samples A4, A5, A6 which are 2/2 twill weave. As explained for air permeability test results, Matt and plain woven fabrics have larger porosities than 2/2 twill and 1/3 twill weaves. Although the weave interlacing coefficients of 2/2 twill and 1/3 twill weaves are equal, the 2/2 twill woven fabric samples have better water vapor permeability properties than 1/3 twill woven fabric samples. This is due to the fact that in 1/3 twill weave there are weft yarn floats passing over three warp yarns, therefore warp yarn density will increase and the porosity of 1/3 twill weave will decrease. When ternary groups (A1, A2, A3), (A4, A5, A6), (A7, A8, A9), (A10, A11, A12) are compared, the water vapor permeability of the fabrics decreases within each group, as shown in *Figure 3* and *Figure 4*, due to the increase of the weft yarn density. A larger amount of liquid mass can be retained in larger pores, which facilitates the diffusion process from the inner layer to the outer layer. This relationship is also valid for the Lyocell fabric samples. Modal fabric samples A3, A6, A9 and A12, which have lowest water vapor permeability values, also showed the lowest standard deviation values. Similarly, the standard deviation of B3, B6, B9 and B12 (Lyocell samples with lowest water vapor permeability) were the lowest.

From the results of ANOVA, it can be concluded that the effects of weave and weft density on the water vapor permeability of modal and Lyocell fabrics are statistically important at the significance level of 0.05, with p-values of (0.001) and (0.02) respectively. From the results of t tests, it can be concluded that raw material affected the water vapor permeability of fabric samples statistically ($\alpha = 0.05$), with h-values of (1) for the modal-Lyocell fabrics. Significant differences are also indicated by the fact that the error bars in graphs do not overlap.

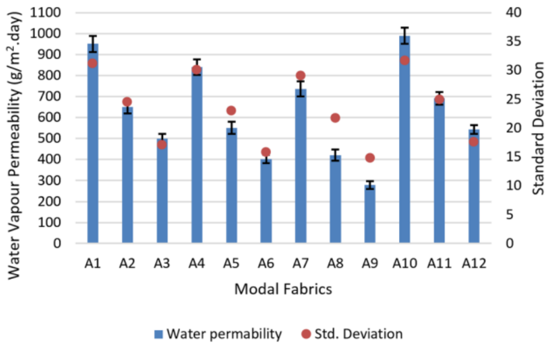

FIGURE 4. Water vapor permeability of modal fabric samples.

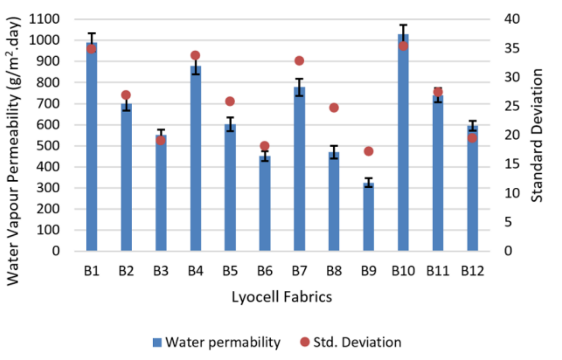

FIGURE 5. Water vapor permeability of Lyocell fabric samples.

Wicking Test Results

Figure 6 and *Figure 7* show the wicking heights of modal fabrics in the warp and weft direction respectively. *Figure 8* and *Figure 9* show those of Lyocell fabrics in warp and weft direction respectively. From the figures, it is observed that the wicking heights of fabric samples change as a function of raw material, weave pattern and weft density both in warp and weft directions. Wicking heights of the Lyocell fabrics are higher than those of modal fabrics because the Lyocell fibers contain higher percentage of fibrillar structure than modal fibers [3], so water molecules diffuse more readily. The 1/3 twill woven fabrics show highest wicking heights. This is due to the fact that in the 1/3 twill woven fabrics, weft yarns float over three warp yarns. With warp yarns passing under three weft yarns, the yarns will crimp less, and flat yarns have less resistance to the rise of a solution. On the other hand, plain woven fabric has the lowest wicking height. This is because in a plain weave, each yarn goes over and under the intersecting yarn, resulting in higher crimp. More pressure is applied to yarns at the intersecting points and interlacing areas, thus reducing the wicking height. Although the matt woven fabric has an equal average float length of yarn, its wicking height is lower than 2/2 and 1/3 twill woven fabrics. This is because the interlacing and intersection order is similar to that of plain weave, reducing the wicking height of matt woven fabric. The fabrics woven with higher weft settings had lower wicking heights than the fabrics woven with lower weft settings. This is due to the fact that when the weft setting increases the porosity of the fabrics will decrease. This result may be explained using the mechanism of the wicking, which is based on the capillary flow of the liquid. It is known that the flow of liquid through textile materials is the result of fiber-liquid molecular attraction at the surface of the fiber materials [15], which in turn is determined by the surface tension, effective capillary pathways and pore distribution [25]. Wicking of fabrics, except those woven using lowest weft setting, is lower in the warp than in the weft direction. As the weft density increases, the warp yarn will crimp more, reducing the wicking height in warp direction. These relationships are also valid for the Lyocell fabric samples.

While standard deviation of A4 was the highest within the wicking in warp direction, standard deviation of A10 was the lowest within the wicking in warp direction. Modal fabric samples A6 has the highest standard deviation of wicking in weft direction, whereas; samples A4 and A12 have the lowest standard deviation of wicking in weft direction. While standard deviation of B8 was the highest within the wicking in weft direction, standard deviation of B3 was the lowest within the wicking in weft direction. Lyocell fabric samples B4 has the highest standard deviation of wicking in weft direction, whereas; sample B10 has the lowest standard deviation of wicking in weft direction.

The variance analysis showed that both the effects of weave and weft density on wicking height of the modal and Lyocell fabrics are statistically significant in both the warp and weft directions, with p-values of (0.000), (0.021) and (0,001), (0,032) respectively. The results of independent t-test confirmed that the wicking height changed with the raw material and test direction, with h-values of (1) for both the modal-Lyocell fabrics and in warp-weft directions. Significant differences are also indicated by the fact that the error bars in graphs do not overlap.

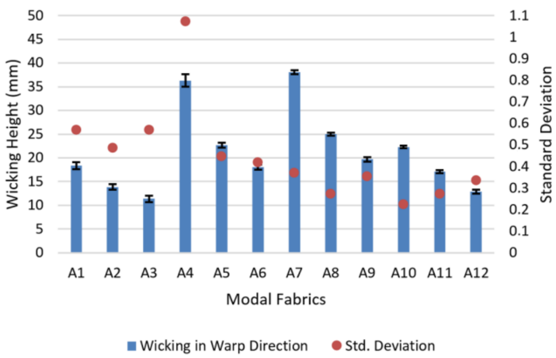

FIGURE 6. Wicking behaviour of modal fabric samples in warp direction.

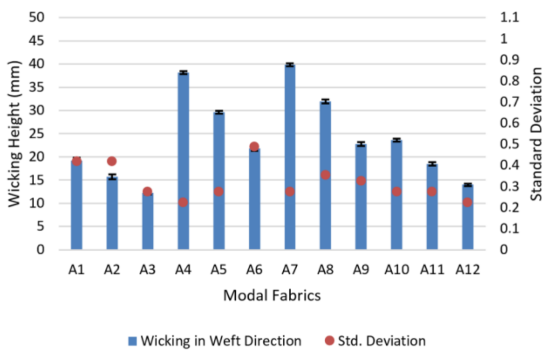

FIGURE 7. Wicking behaviour of modal fabric samples in weft direction.

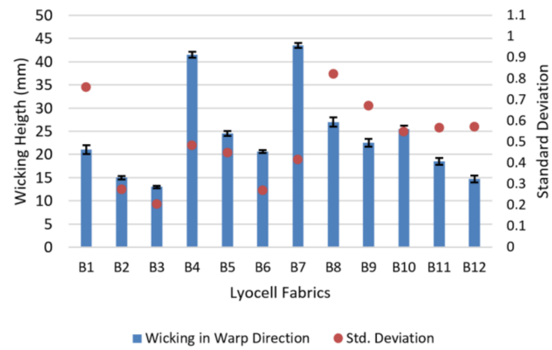

FIGURE 8. Wicking behaviour of Lyocell fabric samples in warp direction.

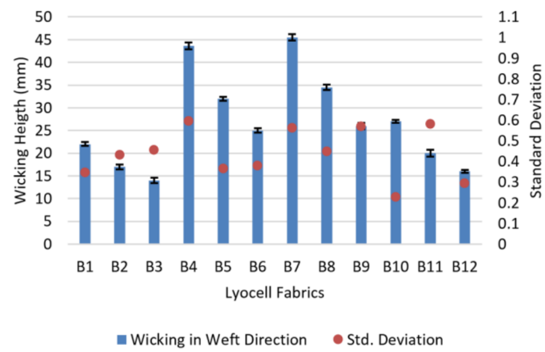

FIGURE 9. Wicking behaviour of Lyocell fabric samples in weft direction.

The stereomicroscopic observation images of modal and Lyocell fabrics are given in *Figure 10* and *Figure 11* respectively.

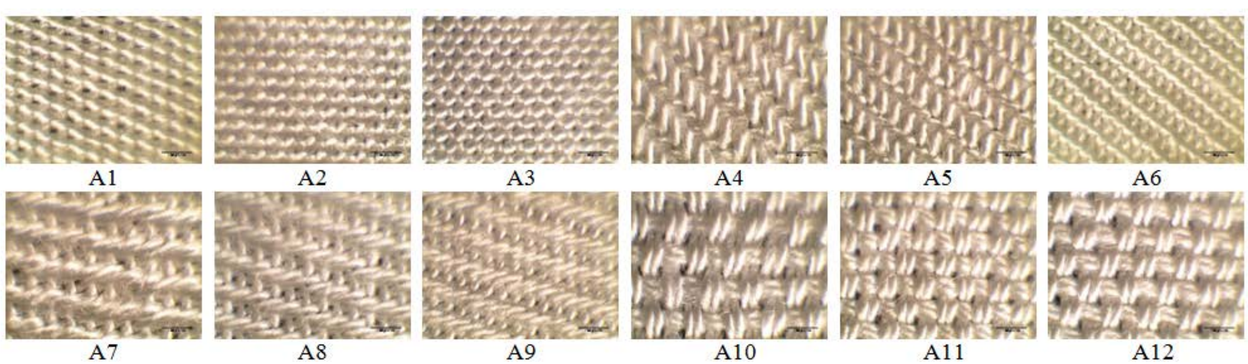

FIGURE 10. The stereomicroscopic observation images of modal fabrics (magnification of 100×).

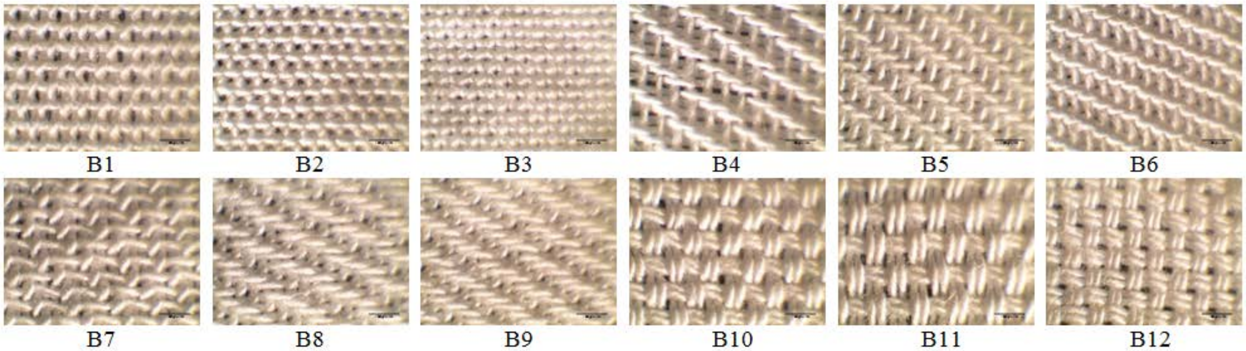

FIGURE 11. The stereomicroscopic observation images of Lyocell fabrics (magnification of 100×).

CONCLUSION

Depending on fabric structure, great variations in the amount of air and water vapor flow as well as air and water vapor flow paths were observed. The permeability and pore size are strongly related to each other. If a fabric has very high porosity, it can be assumed that it is highly permeable. So the factors that affect the porosity such as weave pattern, weft density, raw material and yarn twist, also affect the permeability of fabrics. Increasing the weave interlacing coefficient, which indicates the density of interlacing points increased the porosity of fabrics, and thus increases the air and water vapor permeability. Long lengths of weft yarn floats in 1/3 twill increased air permeability but decreased water vapor permeability. When the number of yarns per unit area is increased, the number of pores between the yarns decreases. During the air and water vapor flow, air and water vapor passes mainly between the yarns for loose fabrics and cannot penetrate the capillary voids within the yarns. If the yarn twist increases, the density of yarn will increase, the volume of air in yarn will decrease, and the porosity of fabric will increase.

The weave interlacing coefficient, which indicates the density of binding yarn crimp, affects the wicking height of fabric samples. The plain weave, with the highest interlacing coefficient, has the lowest wicking height. The wicking height of 1/3 twill woven fabric, with longer yarn floats and less crimped yarns, is the highest. Increase in weft yarn density leads to a decrease in porosity, due to increased warp yarn crimp and therefore a decrease in wicking height.

Lyocell fabrics have high air permeability, water vapor permeability and wicking height values due to their high percentage of fibrillar structure. In conclusion, 2/2 matt and plain Lyocell fabrics are more convenient for indoor and outdoor performance activities.

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REFERENCES

[1] Li, Y.; The Science of Clothing Comfort; *Textile Progress* 2001, 31(1/2), 1-135.

[2] Başer, G.; *Technique and Art of Weaving* Vol.1; Punto Publishing: İzmir, 2004 (in Turkish).

[3] Morton, W.E.; Hearle, J.W.S.; *Physical Properties of Textile Fibres*; Woodhead Publishing Limited: Cambridge, 2008.

[4] Gorjanc, D.S.; Bizjak, M.; Impact of Pre-Finishing Process on Comfort Characteristics of Stretchable Cotton Fabric; *Journal of Engineered Fibers and Fabrics* 2015, 10(3), 57-68.

[5] Varshney, R.K.; Kothari, V.K.; Dhamija, S.; A Study on Thermophysiological Comfort Properties of Fabrics in Relation to Constituent Fibre Fineness and Cross-Sectional Shapes; *The Journal of the Textile Institute* 2010, 101(6), 495-505.

[6] Das, B.; Das, A.; Kothari, V.K.; Fangueiro, R.; de Araújo, M.; Studies on Moisture Transmission Properties of PV-Blended Fabrics; *The Journal of the Textile Institute* 2009, 100(7), 588-597.

[7] Ogulata, R.T.; Mezarcioz, S.M.; Total Porosity, Theoretical Analysis, and Prediction of the Air Permeability of Woven Fabrics; *Journal of the Textile Institute* 2012, 103(6), 654-661.

[8] Çay, A.; Tarakçioğlu, I.; Relation between Fabric Porosity and Vacuum Extraction Efficiency: Energy Issues; *Journal of the Textile Institute* 2008, 99(6), 499-504.

[9] Das, A.; Kothari, V.K.; Balaji, M.; Studies on Cotton-Acrylic Bulked Yarns and Fabrics. Part II: Fabric Characteristics; *Journal of the Textile Institute* 2007, 98(4), 363-376.

[10] Mazloumpour, M.; Rahmani, F.; Ansari, N.; Nosrati, H.; Rezaei, A.H.; Study of Wicking Behavior of Water on Woven Fabric Using Magnetic Induction Technique; *Journal of the Textile Institute* 2011, 102(7), 559-567.
[11] Komisarczyk, A.; Dziworska, G.; Krucinska, I.; Michalak, M.; Strzembosz, W.; Kaflak, A.; Kaluza, M.; Visualisation of Liquid Flow Phenomena in Textiles Applied as a Wound Dressing; *AUTEX Research Journal* 2013, 13(4), 141-149.
[12] Saricam, C.; Absorption, Wicking and Drying Characteristics of Compression Garments; *Journal of Engineered Fibers and Fabrics* 2015, 10(3), 146-154.
[13] Kwon, S.O.; Park, C.H.; Kim, J.; Breathable, Antistatic and Superhydrophobic PET/Lyocell Fabric; *Journal of Engineered Fibers and Fabrics* 2015, 10(3), 46-56.
[14] Rebenfeld, L.; Miller B.; Using Liquid Flow to Quantify the Pore Structure of Fibrous Materials; *Journal of the Textile Institute* 1995, 86(2), 241-251.
[15] Hseih, Y. L.; Liquid Transport in Fabric Structures; *Textile Research Journal* 1995, 65(5), 299-307.
[16] Brown, J.J.; Rusca, R. A.; Effect of Fabric Structure on Fabric Properties; *Textile Research Journal* 1955, 25, 472-476.
[17] Clayton, F. H.; The Measurement of the Air Permeability of Fabrics; *Journal of the Textile Institute* 1935, 26, 71-86.
[18] Backer, S.; The Relationship Between the Structural Geometry of a Textile Fabric and Its Physical Properties, Part 4: Interstice Geometry and Air Permeability; *Textile Research Journal* 1951, 65(1), 703-714.
[19] Das, B.; Das, A.; Kothari, V.K.; Fanguiero, A.; de Araújo, M.; Moisture Transmission through Texts, Part-I: Process Involved in Moisture Transmission and the Factors at Play; *AUTEX Research Journal* 2007, 7(2), 100-110.
[20] Slater, K.; Comfort Properties of Textiles; *Textile Progress* 1977, 9(4), 21-29.
[21] Galceran, V.; *Weaving Technology*; Technical University of Catalonia: Terrassa, 1962 (in Spanish).
[22] ASTM D737-04; Standard Test Method for Air Permeability of Textile Fabrics 2012.
[23] ISO 14596; Textiles - Measurement of Water Vapor Permeability of Textiles for the Purpose of Quality Control 2004.
[24] DIN 53924; Testing of textiles - Velocity of Soaking Water of Textile Fabrics (Method by Determining the Rising Height) 1997.
[25] Zhu, Q.; Li, Y.; Effects of Pore Size Distribution and Fiber Diameter on the Coupled Heat and Liquid Moisture Transfer in Porous Textiles; *International Journal of Heat and Mass Transfer* 2003; 46, 5099-6111.

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