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Moisture and thermal management properties of woven and knitted tri-layer fabrics

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In this study, bamboo charcoal, lyocell, bamboo and micro polyester yarns have been used to enhance the moisture and thermal management properties of the functional fabrics. Two tri-layer fabrics are developed by using both knitted and woven structures. These fabrics are then evaluated for the comfort characteristics, such as water vapour permeability, thermal conductivity, water absorption, wicking, drying rate and spreading rate. The results reveal that the tri-layer weft knitted fabrics possess exceptionally good functional characteristics, such as air permeability, water vapour permeability, transverse wicking and drying rate, due to their structural factors as compared to the woven tri-layer fabrics. The woven tri-layer fabric possesses higher thermal conductivity, water absorption and vertical wicking than the knitted structure. The effects of fibre content on the properties of tri-layer fabrics are also found to be significant. The tri-layer fabric made of bamboo charcoal/micro polyester/lyocell exhibits higher air permeability, water vapour permeability, thermal conductivity, wicking tendency and faster drying rate. In the case of tri-layer fabric made of bamboo/ micro polyester/lyocell combination, the water absorption, verticle wicking, transverse wicking and spreading areas are found to be high.

Keywords: Bamboo charcoal, Lyocell, Micro polyester, Moisture management properties, Thermal conductivity, Tri-layer fabric

1 Introduction

Fabrics are rarely worn as a single layer in garments and several comfort properties are altered with layering/spacing. Layering of fabrics which are likely to be used as garments when worn together has major effects on properties such as permeability to air and water vapour, thermal resistance, and thermal conductance[1]. The moisture content of a single layer fabric is not only dependent on the material properties of that particular layer, but also on the properties of neighbouring layers or even of the whole combination. The overall moisture distribution in multilayer protective clothing can be influenced by using defined combinations of hydrophilic and hydrophobic textile layers[2]. Much research work has been carried out to analyze the functional properties of layered fabrics. Behera *et al*.[3] produced bi-layer interlock knitted structures using 100% polypropylene and 100% cotton spun yarn and studied the transmission behaviours of air, water and heat in order to assess their suitability for sportswear. Sharabaty *et al*.[4] studied the wettability characteristics of polyester, cotton and multilayered polyester/cotton fabrics to manage human perspiration and found that wicking coefficient of multilayered fabrics is better than cotton fabrics.

Field sensor is a very popular high performance fabric from Toray, which employs a multilayer structure that not only absorbs perspiration quickly but also transports it up to the outer layer of the fabric very rapidly using the principle of capillary action. It is composed of coarser denier yarn on the inside surface (in direct contact with the skin), and fine denier hydrophobic polyester yarn in a mesh construction on the outer surface to accelerate quick evaporation of sweat[5]. Another multi-layered fabric developed using high-tech polyester yarns with specially designed ‘W’ shape cross-section speeds up fabrics ability to transport water away from the skin[6].

Four types of special fibres like lyocell, bamboo charcoal, bamboo and micro polyester were selected to develop multilayer fabrics. Previous research work on these fibres suggests that they possess certain functional qualities, which make them suitable for next-to-skin applications in different areas like sportswear, bed linens and protective clothing. Thomas and Christian[7] evaluated the skin compatibility of commercially available lyocell textiles in patients suffering from atopic dermatitis or

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psoriasis in an everyday situation and concluded that from dermatological point of view, these textiles can be recommended not only for healthy subjects but also for people with sensitive skin or even patients with skin diseases, like atopic dermatitis or psoriasis. Heinrich *et al*.[8] analyzed the comfort properties of single layered and double layered fabrics made of lyocell/ polyester blended yarns in the face of the fabric and polyester as the skin contact layer**.** From the experimental results the authors concluded that lyocell can be used effectively for the development of high performance sportswear, provided that the fabric is carefully designed to maximize the contribution of the lyocell to the performance of the fabric.

Ramachandran and Senthilkumar[9] stated that the comfort properties of polyester microfibre fabric are more in terms of wicking when compared with micro polyester /cotton blends and pure polyester non-micro fibre fabrics. Other researchers[10] highlighted that bamboo fibre is characterized by its good hygroscopicity, permeability, soft feel, and both anti-bacterial and deodorizing in nature. Since the cross-section of the bamboo fibre is filled with various micro-gaps and micro-holes; it has much better moisture absorption, ventilation and an excellent wicking ability that pulls moisture away from the skin so that it can evaporate. Bamboo owns a unique anti-bacterial and bacteriostatic bio-agent named 'bamboo kun' which gives the inherent antimicrobial property to the bamboo fibre[11].

Polyester based bamboo charcoal fibre is produced by imbuing in polyester master batch with about 50% bamboo charcoal[12,13]. Since the bamboo charcoal fibre contains activated carbon, which is efficient in adsorbing odourous volatile micro-organism, thereby reducing the odour and growth of micro-organisms, it is used in hospital textiles for reduction of microbial growth and adsorption of wound odour[14]. The unique properties of bamboo charcoal include uniform composition, high porosity, anti-bacterial & anti-fungal properties, breathability, thermal regulation**,** odour control**,** absorption and emission of far infrared energy, preventing static electricity buildup and good wash durability[15]. As the bamboo charcoal particles are embedded in the fibre rather than simply coated on the surface, these fabrics are washable without reducing the effectiveness of the special qualities of charcoal powder, even after 50 washes[16]. Thenmozhi *et al*.[17] analyzed cotton, bamboo / cotton and bamboo charcoal bed linens for their suitability as hospital textiles by applying anti-microbial and blood repellant finish and found that the anti-microbial activity, blood repellency and odour resistance are higher for bamboo charcoal fabrics than bamboo /cotton union fabrics or cotton fabrics.

This research work deals with design and development of multi-layered knitted and woven fabrics for functional applications and analyses of their comfort characteristics. Tri-layered knitted and woven fabrics were developed using different fibres, such as lyocell, bamboo charcoal, bamboo and micro polyester in different combinations.

2 Materials and Methods

To enhance the moisture and thermal transmission properties of functional textiles, four types of tri-layer fabrics were produced from special fibres like lyocell (30 Ne), bamboo charcoal (30 Ne), bamboo (30 Ne) and micro polyester (32 Ne) in two different combinations. Tri-layer knitted and woven fabrics were produced in two fibre combinations such as bamboo charcoal/micropolyester/lyocell and bamboo/ micro polyester /lyocell.

In bamboo charcoal/micro polyester/lyocell combination fabric, the top layer contains bamboo charcoal yarn in warp direction and lyocell yarn in the weft direction. Lyocell is introduced in the weft direction to ensure maximum moisture spreading along the width of the fabric so that the moisture is transferred away from the human body in case of bed linen applications. The bottom layer is made of lyocell to ensure rapid absorption of water from the inner layer and faster drying. The connecting layer is made of micro polyester warp which interweaves with the face and back weft alternatively, assisting in moisture transfer from the inner layer to the outer layer. Micro polyester with high wicking ability acts as an efficient medium to transfer moisture from the inner layer to the outer layer. In the bamboo / micro polyester / lyocell combination fabric, bamboo yarn is used in the top layer and lyocell yarn in the bottom layer. The connecting layer is made of micro polyester warp. The fibre composition of the different types of multi layered fabrics produced are listed below:

(i) Knitted fabric 1 (BC/L/MP) made of bamboo/ charcoal (top layer), micro polyester (connecting layer) and lyocell (bottom layer).

(ii) Knitted fabric 2 (B/L/MP) made of bamboo (top layer), micro polyester (connecting layer) and lyocell (bottom layer).

(iii) Woven fabric 1 (BC/L/MP) made of bamboo/ charcoal (top layer), micro polyester (connecting layer) and lyocell (bottom layer).

(iv) Woven fabric 2 (B/L/MP) made of bamboo (top layer), micro polyester (connecting layer) and lyocell (bottom layer).

Weft knitting machine with two sets of needles has the ability to create two individual layers of fabric that are held together by tucks. Such a fabric was referred to as a double-faced fabric, also called as tri-layer fabric. Sequence of operation in knitting tri-layer fabric is given in Fig. 1 (a). The tri-layer fabric was knitted using 72 feeders, 18 gauge, 32 inch diameter double jersey weft knitting machine. The tri-layer woven fabric was produced in a sample loom using three warp sheets and two types of weft yarns. The weave structure is given in the Fig. 1 (b).

2.1 Testing Procedure

All the tri-layer fabrics produced were tested for their fabric properties such as fabric strength and elongation[18], water vapour permeability (BS 7209 - 1990) and water spreading rate[19] using standard testing methods. The physical properties of the fabrics such as fabric sett, fabric weight per unit area, fabric thickness and the tensile properties were measured for all the fabric samples. The air permeability of the fabric was measured in cm^3/cm^2/s using air permeometer at an air pressure of 100 Pa using ASTM D737 (1996) test standard. Thermal conductivity was measured using Lee's Disc method[20]. Rate of water absorption in transverse direction was determined by measuring the mass of water taken up by the fabric from a horizontal pan of water[21]. Vertical wicking for both warp and weft directions for a specified time was also measured as per the standard (BS 4554 -1970) method. Quick drying capability of the fabric was evaluated by its drying rate as per ASTM D 4935-99[22]. The rate of moisture vapour diffusion through the fabric is determined according to the simple dish method, similar to ASTM E96-80. The ability of the fabric to absorb water is measured by absorption rate and spreading action as per AATCC 79:2000 standard.

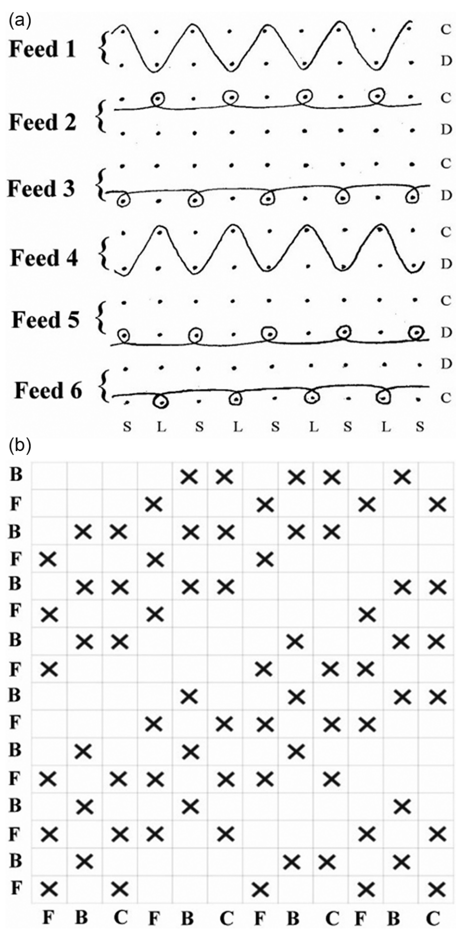

Fig. 1—(a)Knitting sequence of Ttri-layer fabric, and (b) weave structure of tri-layer woven fabric

3 Results and Discussion

The four tri-layer fabrics produced were tested for fabric parameters and the findings are listed below:

(i) BC/L/MP knitted fabric— 15.74 wales/inch, 9.5 courses/inch, 306 g/m^2 fabric weight, 0.73 cm fabric thickness, 63 kgf bursting strength. BC/L/MP woven fabric— 27 ends/inch, 20 picks/inch, 162 g/m^2 fabric weight, 0.60 cm fabric thickness, 130 kgf warp strength, 24.7% warp elongation, 80 kgf weft strength and 28.7% weft elongation.

(ii) B/L/MP knitted fabric— 15.74 wales/inch, 9.5 courses/inch, 248 g/m^2 fabric weight, 0.75 cm fabric thickness, 55 kgf bursting strength. B/L/MP woven fabric— 27 ends /inch, 20 picks/inch, 174 g/m^2 fabric weight, 0.53 cm fabrics thickness, 193 kgf warp strength, 23.9% warp elongation, 100 kgf weft strength and 33.8% weft elongation.

3.1 Air Permeability

The air permeability values of the tri-layer fabrics are as follows: BC/L/MP – 80 cm^3/cm^2/s (knit) & 30 cm^3/cm^2/s (woven) and B/L/MP - 76 cm^3/cm^2/s (knit) & 25 cm^3/cm^2/s (woven). It is observed that the bamboo charcoal/lyocell/micro polyester tri-layer fabrics are having higher air permeability (y-value) as compared to other similar fabrics, which may be due the presence of countless small cavities and highly porous nature of bamboo charcoal. Presence of ultra fine charcoal particles also creates micro spaces inside the yarn structure, thus enhancing air passage through fabric. Since bamboo and lyocell have more uniform and smooth structure which leads to more compact structure of yarn and fabric, the lyocell and bamboo contents lead to decreased air permeability than the previous one. Compared to woven tri-layer fabrics, knitted fabrics have higher air permeability, which might be attributed to the loop structure and higher porosity of the knitted fabrics.

3.2 Thermal Conductivity of Multilayered Fabrics

The thermal conductivity values of multilayered fabrics are found to be as follows: BC/L/MP – 0.036 W/mk^{-1} (knit) & 0.042 W/mk^{-1} (woven) and B/L/MP - 0.031 W/mk^{-1} (knit) & 0.033 W/mk^{-1} (woven). The thermal characteristics of the fabric depends on the entrapped air and type of fibre in the fabric. Milenkovic *et al.*[23] proved that fabric thickness, enclosed still air and external air movement are the major factors that affect the heat transfer through a fabric. The results indicate that the thermal conductivity of the bamboo charcoal and lyocell tri-layered fabrics is found to exhibit higher value than bamboo cotton tri-layer fabrics (both woven and knitted). Out of the two bamboo charcoal tri-layer fabrics, the woven tri-layer fabric made of bamboo charcoal/lyocell combination has higher thermal conductivity values than the knitted structure. This may be due to the presence of more number of charcoal ultra fine particles which are good conductors of heat. However, the effect of structural difference is also inevitable. The amount of fibre in the unit area increases and the amount of air layer decreases as the weight increases[24]. Morris[25] presented a study on thermal properties of textiles, and concluded that their thermal conductivity increases with density, and based on his observation when two fabrics are of equal thickness, the one with lower density shows the greater thermal insulation. The thermal conductivity values of fibres are higher than that of the entrapped air[18]. So, heavier fabrics that contain less still air have higher thermal conductivity values. In this case, the woven fabric structures are comparatively denser than the knit structure, thereby having the higher thermal conductivity.

3.3 Water Vapour Permeability of Multilayered Fabrics

The amount of water vapour passing through the multi-layered fabrics is found to be as follows: BC/L/MP - 2585 $g/cm^2/day$ (knit) & 2280 $g/cm^2/day$ (woven) and B/L/MP - 2560 $g/cm^2/day$ (knit) & 2200 $g/cm^2/day$ (woven). The highest water vapour permeability is observed in case of knitted structures for both bamboo charcoal tri-layer fabrics and bamboo lyocell tri-layer fabrics. This may be attributed to the highly porous nature of knitted structure than the similar woven structure. The higher fibre density (fabric cover comparatively) in woven fabric may be the main reason for the reduced water vapour permeability. These results are also supported by Das and Kothari[26].

The fibre content of the fabric structure also plays a vital role in the case of water vapour permeability. The bamboo yarns are well known for their good absorbency[27]. The surface area of the activated bamboo charcoal is relatively higher than that of bamboo and hence, there is a limited amount of differences between bamboo based and bamboo charcoal based tri-layer fabrics of same structure (knitted and woven). The science behind the phenomenon can be stated as, with the increase in cellulosic content in the fabric, moisture regain of the material will increase causing higher diffusivity. A hygroscopic fabric absorbs water vapour from the humid air close to the sweating skin and releases it in dry air. This enhances the flow of water vapour from the skin to the environment comparatively higher than a fabric which does not absorb and reduces the moisture built up in the microclimate. However, the fabric with less hygroscopicity offers less resistance to the transfer of moisture vapour to air.

3.4 Water Absorbency of Multilayered Fabrics

The rate of water absrption, measured in face and back of the four tri-layered fabrics are shown in Fig. 2 (a). Bamboo / lyocell combination fabrics are found to have higher water absorbing tendency owing to the combination of three fibres having excellent moisture absorbing and transporting property. There is a strong polar attraction between fibre molecules and water due to the highly hydrophilic nature of lyocell and bamboo. Its higher water retention and liquid holding capacity may be due to the strong hydrophilic attraction between water and lyocell fibres and water retention in the inter fibrillar spaces of the fibres. On the other hand, being hydrophobic in nature bamboo charcoal and micro polyester do not form bonds with water molecules, but due to its positive contact angle (75^o), liquid surface is dragged very smoothly, which offers high transfer of water in case

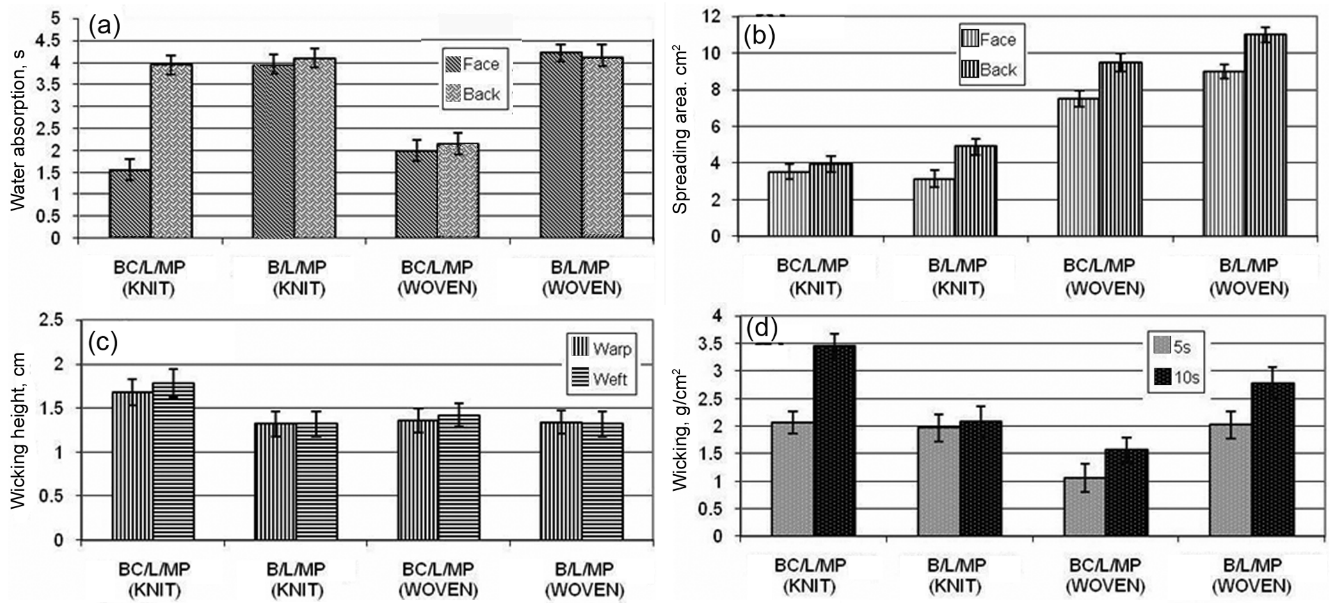

Fig. 2—(a) Water absorption, (b) spreading area, (c) vertical wicking, and (d) in-plane wicking of multilayered fabrics

of micro polyester. So, when a small proportion of micro polyester is added in the system, it acts as a channel to the water and forms capillary which enhances the transfer phenomena. Hence, bamboo / lyocell based tri-layer fabrics exhibit very good water absorbency, resulting in immediate transfer of moisture to the outer layers in both the knitted and woven structures respectively for both face and back side also.

In the case of bamboo charcoal fabric, the water absorption is very less compared to the bamboo/ lyocell tri-layer fabric. This is perhaps due to the carbonisation process. Carbonisation describes the conversion of organic substances into carbon at elevated temperature. The substances undergo dehydration, followed by chemical condensation reaction. In bamboo charcoal, the structure of the bamboo remains unaltered, because the carbonisation temperature is lower than its melting temperature[28].

This makes bamboo charcoal with an enormous surface area to mass ratio and the better ability to attract and hold (adsorption) a wide range of chemicals, minerals, radio waves, and other harmful substances. Thus, these adsorption characteristics of charcoal (converted from bamboo) causes poor physical absorption of the bamboo charcoal fibre than the bamboo fibre. This may explain the lower absorption of the face side of the fabric, and the other side of the fabric, with lyocell, possesses good amount of absorption[29].

3.5 Spreading Area of Multilayered Fabrics

The extent to which a drop of water, spreads in warp and weft directions or in course and wales direction of the fabric is shown in the Fig. 2 (b). It can be understood that the spreading area of the woven fabric is higher than the knitted fabric. This may be due to the more compact or denser structure of woven fabric than the knit structure. This phenonmenon is common for both bamboo and bamboo charcoal try-layer fabrics. The spreading area is found high in the case of lyocell fabric side followed by bamboo and bamboo charcoal side for all the woven and knitted fabrics. The main reason behind this is the superior water management characteristics of lyocell fabrics. This effect can be explained by the strong polar attraction of lyocell fibre with water[30].

Due to hydrophobic nature of micro polyester, it fails to form bonds with water molecules and allows them to easily move along the channels. Attracted by the lyocell fibre content of the yarn, water spreads to the maximum extent. Among the knit and woven structures, tri-layer woven fabric spreads water to a greater extent and it exhibits more distribution of water in both warp and weft directions.

3.6 Vertical Wicking of Multilayered Fabrics

The height to which water is wicked for 10 min in both warp and weft directions is shown in the Fig. 2 (c). The bamboo charcoal tri-layer fabric exhibits higher wicking tendency due to the presence of bamboo charcoal and micro polyester combinations. The bamboo/lyocell combination tri-layer structure shows lower wickability but still 3-4 times higher than that of single layered structure. In the bamboo/lyocell tri-layer fabrics, because of the highly hydrophilic nature of fibres, it has a good absorbency. However, due to its high affinity to water, when water molecule reaches in the capillary, it forms bond with the absorbing group of the fibre molecules, which inhibits the capillary flow along the channel formed by the fibre surfaces. Thus, in case of bamboo/ lyocell fabric, the movement of water is mainly governed by the absorption of water by the fibres and its movement along the fibre, which results in very less movement of water along the fabric. However, being hydrophobic in nature bamboo charcoal polyester does not form bonds with water molecules. Due to its positive contact angle (75^{o}), it drags the liquid surface very smoothly, which offers high wicking in case of bamboo charcoal.

3.7 Transverse Wicking of Multilayered Fabrics

The amount of water absorbed along the plane of the multi layered fabrics in 5s and 10s are shown in Fig. 2 (d). It is observed that layering has an important role in moisture related comfort properties of clothing and the rapidity or rates of absorption here greatly influence the thermo physiological comfort. In general, the knitted structures have more transverse wicking compared to the woven structures. The higher wicking effect in knitted fabrics can be explained by the higher yarn volume per square area compared to the woven material[31]. This increases the contact area and thus the transverse wicking of the knitted fabric.

In the case of woven fabric, the horizontal wicking of the material increases with the increase in bamboo content in the tri-layered fabrics. The bamboo/lyocell combination fabric absorbs more moisture as compared to the bamboo charcoal/ lyocell fibre combination. The cross-section of bamboo fibre is filled with micro-pockets and channels that give the fibre very high wicking properties[32]. The wickability of the fabric increases with the bamboo content[32]. In contrast to that, the poor absorption property of bamboo charcoal leads to the reduced wicking ability in case of woven bamboo charcoal/lyocell try-layer fabric.

3.8 Drying Rate of Multilayered Fabrics

Liquid transporting and drying rate of fabrics are two vital factors affecting the physiological comfort of garments. The moisture transfer and quick dry behaviours of textiles depend mainly on the capillary capability and moisture absorbency of the fibres. These characteristics are especially important in garments worn next to the skin or in hot climates. In these situations, textiles are able to absorb large amounts of perspiration, draw moisture to the outer surface and keep the body dry. The time taken to dry a fabric which is wetted with 30% water on the weight of the fabrics are shown in Fig. 3. Quick drying capability of a fabric could be evaluated by its drying rate. It is observed that bamboo charcoal fabrics have faster drying rate and addition of lyocell delays the drying time of the fabrics. As the moisture content of lyocell and bamboo fibres is higher than the polyester-based bamboo charcoal yarns, bamboo/ lyocell tri-layer fibres have lower drying rate.

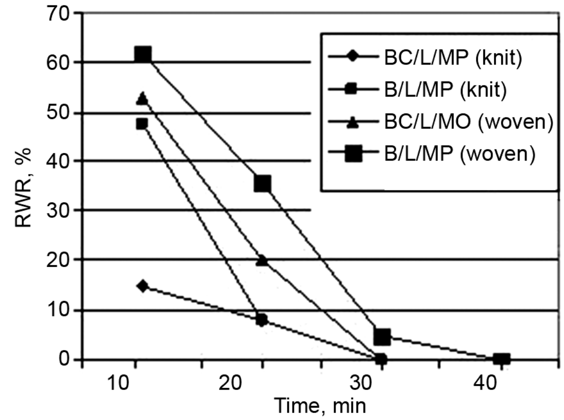

Fig. 3—Drying rate of multilayered fabrics

4 Conclusion

The tri-layer weft knitted fabrics have good thermal conductivity and wickability, which contributes to the garment comfort properties needed for the user. This fabric possesses certain exceptionally good functional characteristics, such as moisture absorbency, where the moisture from the body is absorbed by the base layer, passed through the connecting layer and gets evaporated from the top layer. Based on the analysis of the multilayered knitted and woven fabrics made of bamboo charcoal/lyocell/micro polyester combinations and bamboo/lyocell/micro polyester combinations, the following conclusions have been drawn:

4.1 Air permeability values of the tri-layer fabrics are mainly influenced by the structures and the knitted tri-layer fabric has maximum permeability to air. Among the knit structures, the bamboo charcoal fibre has the maximum permeability to air than the normal bamboo fibre.

4.2 The thermal conductivity values of the fabrics are mainly influenced by the fibre content. Both the bamboo charcoal knitted and woven fabrics have higher thermal conductivity than the bamboo fibre fabrics.

4.3 The water vapour permeability values of the tri-layer fabrics are mainly affected by the structure of the material. Generally, knitted material has higher transmission rate than the woven material. The effect of fibre content seems to be insignificant in both the structures.

4.4 Water absorption of the tri-layerd fabrics are siginificantly affected by the fibre content than the structural variation. The bamboo fabrics having tri-layerd woven and knitted sturcures possess higher absorption than the bamboo charcoal combination.

4.5 The spreading area of the tri-layer fabric is affected by the structure, rather than the fibre. The woven structure has higher spreading rate than the knitted structures. The vertical wicking behaviour of all the structures more or less remains similar; but in the case of transverse wicking, the knitted fabrics perform well, irrespective of the fibre content.

4.6 The drying rate of the tri-layer fabric is higher in the case of knitted structure than in the case of woven structure, which is also influenced by the fibre content. The bamboo charcoal fabric has the fastest drying rate than the knitted bamboo tri-layer fabric.

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