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Thermal Comfort Properties of Bi-Layer Knitted Fabrics

DOI: 10.5604/01.3001.0014.2384

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Abstract
Transmission of sensible and insensible perspiration is an important factor for fabric comfort. Improvement in the thermal comfort properties of knitted fabrics results in the achievement of fabric comfort. In this research, the thermal comfort properties of six bi-layer knitted fabrics were studied. The bi-layer knitted fabrics were made with different combinations of yarn in the inner layer and outer layer. The yarn combinations selected were polyester staple yarn-polyester staple yarn, polyester staple yarn-cotton, cotton-cotton, polypropylene-cotton, micro denier polyester-cotton, and micro denier polyester- micro denier polyester for the inner and outer layers, respectively. To find the thermal comfort properties of the six bi-layer knitted fabrics, an objective fabric test was carried out. The results showed that the bi-layer fabrics made from micro denier polyester, both in the inner and outer layers, exhibit better thermal comfort properties, thereby providing a higher level of comfort; hence, they are preferred for active sportswear. The water vapour permeability, air permeability, thermal resistance and thermal conductivity of the bi-layer knitted fabric made up of micro denier polyester as the outer and inner layer were found to be higher when compared to the other bi-layer structures. The results were discussed together with one – way ANOVA test results at a 0.05 significance level.

Key words: *bi-layer knitted fabrics, polyester, comfort, thermal comfort.*

Introduction

The thermal equilibrium between the human body and the environment is maintained by clothing. It acts as a medium for the transmission of moisture vapour, heat, and liquid moisture [1]. A fabric's ability to maintain this equilibrium is known as thermo – physiological comfort. All major factors such as water vapour transmission, sweat absorption, thermal properties and the drying ability of fabrics are, in general, expressed by thermo-physiological comfort [5-7]. The acceptability of textile fabrics mainly depends on thermo-physiological comfort aspects, which include air permeability, moisture vapour and liquid moisture transfer properties, and thermal properties, for varied applications like active wear, sportswear and inner wear. It is believed that the transient thermal behaviour of textiles, giving an indication of warm and cool feeling on the first brief skin contact with the fabric, plays a major role in the overall comfort properties of textile fabrics [7-9].

In general, single layered knitted fabrics are used for sportswear fabrics. Under normal conditions, single layered knitted fabrics made out of cotton are more comfortable [10]. During strenuous activity, a very high level of moisture is absorbed by cotton fibres, which leads to a feeling of wetness and clinging. Cotton fibres are not suitable for strenuous activity because of their very slow wicking rate. Fibres such as single layered polyester, nylon, polypropylene and acrylic in knitted fabrics have a very higher wicking rate when compared to that of cotton, making them more appropriate for strenuous activity. Active sportswear should possess good air, water and heat transmission as well as water storage properties. Hydrophobic materials such as polypropylene, polyester, acrylic and nylon possess a good moisture transmission property, and hydrophilic materials such as cotton have a very good moisture storage property [11]. Cotton fibres are used in functional fabrics to maintain high moisture. To maximise moisture transfer, cotton fibre is used in functional fabrics. Most of the researches have concentrated on the comparison of different knit structures and thermal comfort properties of woven fabrics. Fewer investigations have concentrated on systematic studies of the effect of the fibre profile and yarn types on thermal as well as moisture vapour and liquid moisture transfer properties of bi-layer knitted fabrics. Bi-layered knitted structures have two main elements: a back (inner) layer, directly in contact with the skin, which also acts as a separation layer. The diffusive hydrophobic components and conductive components of this layer help in removing and transporting sweat to the outer layer. The other element is the face (outer) layer, which serves as an absorption layer and is in contact with the environment. The absorptive hydrophilic components of this layer help in achieving a large area for the absorption of sweat and its evaporation to the outside environment [12-13]. Bi-layer knitted fabrics with cotton or viscose yarns as the outer layer and polypropylene yarn as the inner layer make the wearing more comfortable on doing strenuous activity [14]. The moisture transfer mechanism through clothing during transient conditions plays a major role in deciding the wearer's dynamic comfort. In the case of double-face knitted fabrics, the inner layer can be made up of hydrophobic synthetic filament yarn, whose capillary action is good, and the outer layer can be made out of hydrophilic yarn, which has good moisture absorption as well, allowing it to evaporate [15].

One study of the polyester effect on the physiological properties of polyester fabrics suggests that more resistance to flow of heat is offered by fabrics with non-circular fibres [15]. For the effect of yarn type on the thermal comfort properties of knitted fabrics made from cotton, higher thermal conductivity, thermal resistance and thermal absorption were found in double-plied yarn knitted fabrics compared to single plied yarn fabrics [16]. The thermal comfort properties of the bi-layer knitted structure for volleyball sportswear were investigated and it was found that bi-layer knitted fabric made with polypropylene in the inner layer have good moisture transfer characteristics when compared to a plated and single jersey structure [17].

A combination of different yarns and fibres in the face and back layers of bi-layer knit structures can render completely different comfort properties to these structures. In general, double-face knitted fabric produces comfort at a very high level. In such a fabric, independent parameters can be selected for both the outer and inner layer. In general, a simple double-face construction is used, in which synthetic filament yarn is applied for the inner face, which shows good capillary action and is hydrophobic, while hydrophilic yarn is used for the outer face, which absorbs wicked moisture and allows for evaporation [13].

The aim of this study was to analyse the effect of face layer and back layer yarn on thermal comfort properties i.e. the thermal resistance, thermal conductivity, air permeability, and water vapour permeability of bi-layer knitted fabrics.

Materials and methods

In order to study the effect of the type of yarn on thermal comfort properties of bi-layer knitted fabrics, four different yarns: polyester staple filament (PSF), polypropylene (PP), cotton (C), and micro-denier polyester (MDP) were selected. Polyester is ideal for wicking perspiration away from the skin, cotton shows a good absorption property and polypropylene – good thermal and moisture transfer properties. The yarns selected were knitted with a loop length of 0.30 cm using a 2016 model Mayer and Cie bi-layer 28” circular knitting machine with a 29 gauge and speed of 20 r/min to produce six different double-face fabrics. The yarn combinations were polyester staple filament-polyester staple yarn (PSF/PSF), polyester staple yarn-cotton (PSF/C), cotton-cotton (C/C), polypropylene-cotton (PP/C), micro-denier polyester-cotton (MDP/C), and micro-denier polyester-micro denier polyester (MDP/MDP) for the face and back sides of the fabrics, respectively, to knit a bi-layer fabric. The face and back side of the double-face fabric were named ‘the top surface’ (outer) and ‘the bottom surface’ (inner), respectively. The bottom surface of the fabric is designed to touch the human skin. Geometrical properties of the samples are given in ***Table 1.*** After knitting, the

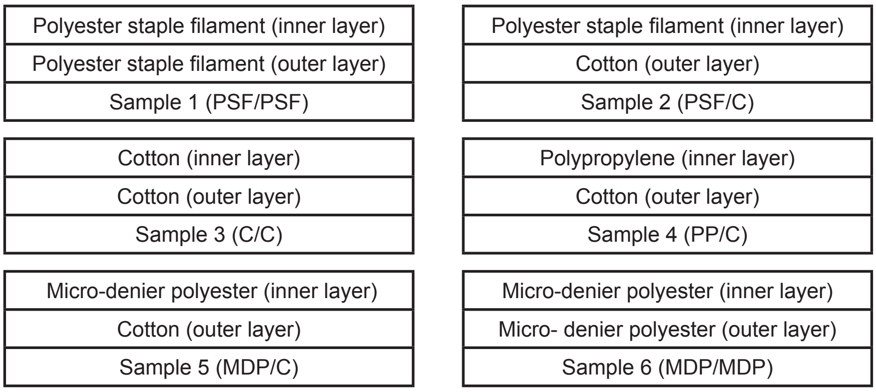

Figure 1. *Bi-layer knitted fabric samples.*

bi-layer sample fabrics were subjected to relaxation as per the relaxation procedure. Standard atmospheric conditions of 65% RH and 27 ± 2 °C were maintained to carry out testing of the double-face knitted fabrics

Dimensional properties

The loop length, thickness and areal density of the bi-layer knitted fabrics were measured. The ASTM D 3887 standard was used to evaluate the wales and courses per unit length [19]. Fabric thickness measurement was carried out using a Shirley thickness gauge according to ASTM D1777-96 [21]. The ASTM D3776 standard, using an electronic balance, was utilised to determine the areal density [20]. The mass per unit area is the mass of the knitted fabric i.e. the GSM (gram per square metre) of the fabric expressed as the areal density. Areal density is the general term for GSM. Areal density varies according to the area of the fabric; here it is calculated for a 1 m * 1 m fabric size.

Filament polyester of 150 micro-denier denier and 108 filaments, polypropylene of 150 micro-denier and 108 multi-filaments, cotton of 36 count, and spun polyester of 2/76 double yarn with a cut staple length of 38 mm and 0.8 denier (micro fibre) were used for the manufacturing of bi-layer knitted fabric.

Comfort properties

The air permeability of the bi-layer knitted fabrics was measured using a KES–F8 AP1 and air permeability tester as per the BS 5636 1990 standard [22]. The thermal conductivity of the bi-layer knitted fabrics was measured using Lee’s disk instrument according to Standard ASTM D7340 [23]. An evaporative dish as per Standard BS 7209:1990 was used for determining the water vapour permeability of the bi-layer knitted fabrics [24].

Statistical analysis

For evaluating the test outcomes, SPSS 13.0 for Windows statistical software was used. One way ANOVA tests were applied to determine the statistical importance of the variations, and p-values were examined to deduce whether the parameters were significant or not. The variables are considered significant if the p-value is less than 0.05.

Results and discussion

Geometrical properties of the fabrics were studied, and the average value of 10 tests conducted for each sample was taken, (***Table 1***). From ***Table 1***, it is observed that if the yarn type is changed, it has an impact on geometrical characteristics of the fabrics related to the course per centimetre and wales per centimetre. A change in the type of yarn results in a variation in the areal density.

Table 1. *Geometrical properties of bi-layer fabrics.*

S. No.	Yarn combination	Loop length, mm	Thickness, mm	Areal density, GSM	CPI	WPI
1	PSF+PSF	3.0	0.752	159.00	55	38
2	PSF+C		0.762	160.24	57	37
3	C+C		0.790	162.36	58	37
4	PP+C		0.674	158.66	58	36
5	MDP+C		0.646	155.91	57	36
6	MDP+MDP		0.562	148.92	56	35

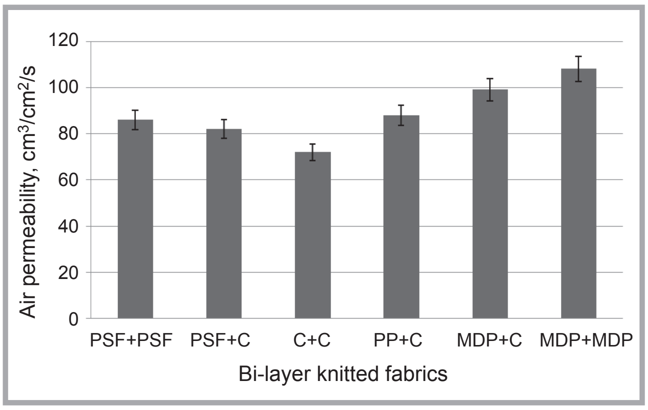

Figure 2. *Air permeability value of bi-layer knitted fabrics.*

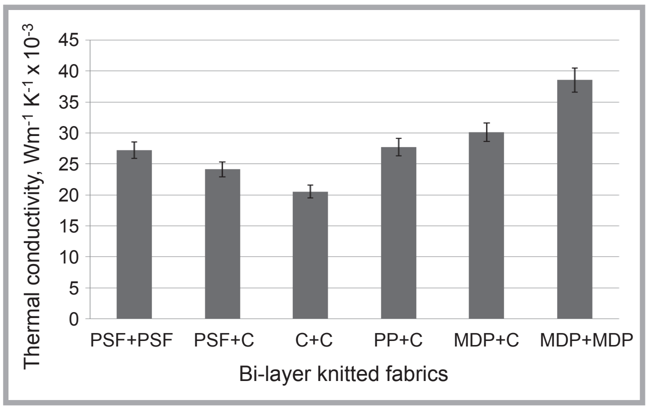

Figure 3. *Thermal conductivity value of bi-layer knitted fabrics.*

The bi-layer knitted fabrics developed were measured for their thermal comfort properties; 10 tests were carried out for each of the samples, and the average value of the 10 tests is given ***Table 2***. The effects of different yarn combinations on thermal comfort performance were analysed statistically with the help of one way ANOVA.

Air permeability

The air permeability of the bi-layer knitted fabrics was measured using a KES–F8 AP1, along with an air permeability tester as per the BS 5636 1990 standard [22] The flow of air through inter yarn spaces plays a major role in providing comfort in hot, humid conditions. Air permeability properties of textiles are majorly affected by yarn and fabric structural parameters, which influence the shape and area of channels through which the flow of air occurs [18]. The air permeability of the knitted fabrics is mainly influenced by the yarn type, fabric construction, thickness, areal density and porosity. The flow of air through inter yarn pores is mainly influenced by the space between yarns in the fabric structure. An increase in inter yarn spaces and fabric porosity due to fibres that are loosely packed might lead to an increase in the air permeability of fabrics made from micro-denier polyester fibre. The air flow through fabrics mainly requires a less tortuous and continuous path. The inter yarn pores may be blocked due to the existence of protruding hair fibres present in cotton yarn fabrics, thereby lowering air permeability. However, unrestricted air passage through inter yarn pores and correspondingly high air permeability is found in manmade yarn due to the absence of hairs. ***Figure 2*** shows that the value of air permeability of MDP bi-layer knitted fabrics is higher when compared to the other fabrics. The reason is that it has higher porosity when compared to all other bi-layer knitted fabrics. Air permeability and fabric porosity are directly proportional, which is found to increase as the fabric porosity increases. An increase in the mass per unit area and thickness results in a decrease in the porosity of layered knitted fabrics. MDP/MDP fabric has a higher air permeability, followed by MDP/, PP/C, PSF/PSF, PSF/C and C/C. This is due to the inter yarn porosity of the micro-denier polyester yarn in MDP/MDP being higher, which results in more gaps, hence permitting air to pass through. The passage of air through the fabric can be increased by decreasing the thickness value. Even though the fabrics have the same loop length (0.30 cm), higher air permeability is found in MDP bi-layer fabric due to micro-denier polyester presence as an inner layer, which provides air flow space. The remaining bi-layer knitted fabrics have lower air permeability due to the presence of fewer pores in the fabric surface area, and hence they resist the flow of air through them. MDP bi-layer knitted fabrics show higher air permeability, providing proper ventilation to the microclimate therein and making the wearer feel comfortable. The air flow principle states that the air flow will be lower in fabrics that are thick, and higher in fabrics that are thin. The lower bulkiness of micro-denier polyester yarn MDP/MDP is another contributing factor towards the improved air permeability. ***Table 3*** shows that the effect of yarn type on the air permeability of bi–layer knitted fabrics is significant at a 95% confidence level (p-value 8.43×10^{-36}).

Table 2. *Thermal comfort properties of bi-layer fabrics.*

S. No.	Combination	Air permeability, $cm^3/cm^2/s$	Thermal conductivity, $Wm^{-1} K^{-1} \times 10^{-3}$	Thermal resistance, $m^2KW^{-1} \times 10^{-3}$	Water vapour permeability, $g/m^2/day$
1	PSF+PSF	86	27.20	27.60	1913
2	PSF+C	82	24.10	31.60	1903
3	C+C	72	20.50	38.53	1901
4	PP+C	88	27.70	24.33	1961
5	MDP+C	99	30.10	21.46	1969
6	MDP+MDP	108	38.50	14.59	1978

Thermal conductivity

Lee's disk instrument was used to measure the thermal conductivity of the bi-layer knitted fabrics according to Standard ASTM D7340 [23]. The ability of the fabric to conduct heat is termed as thermal conductivity. Due to the dissipation of heat, heavy sweat is created in the body, which leads to a lot of moisture accumulation on the skin. Thermal conductivity is a function of fabric thickness, material and structure. From ***Figure 3***, it is found that when compared to other fabrics, the MDP/MDP fabric has higher thermal conductivity. An increase in porosity leads to an increase in thermal conductivity. When compared to the other three fabrics, the porous nature was found to be higher for the MDP/MDP fabric; hence its higher thermal conductivity. Fabric thickness is one of the base properties that gives information regarding the fabric's warmth, stiffness and

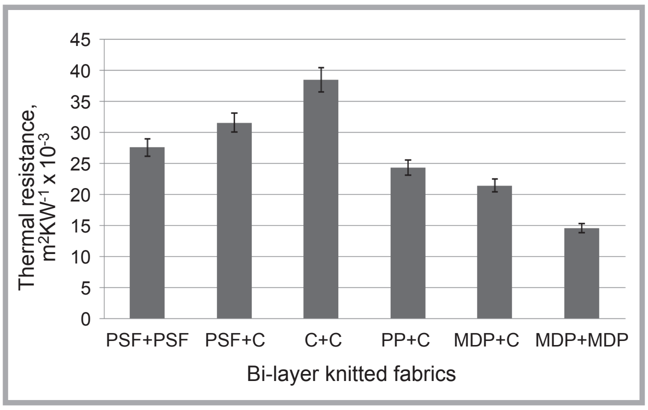

Figure 4. Thermal resistance value of bi-layer knitted fabrics.

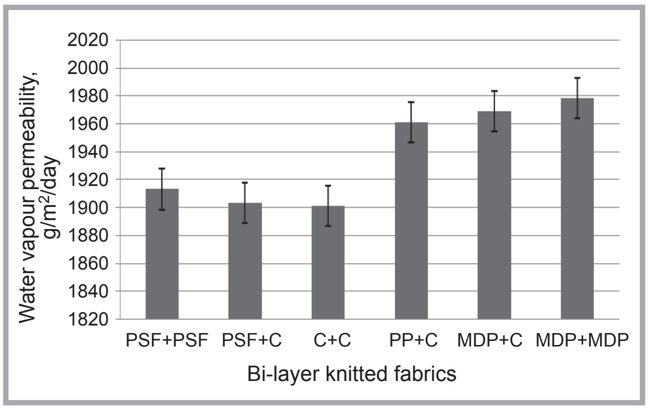

Figure 5. Water vapour permeability value of bi-layer knitted fabrics.

heaviness in use. From ***Table 2***, it can be noted that MDP/MDP (Micro Denier Polyester) possesses the highest thermal conductivity, followed by MDP/C and the other fabrics. It has to be noted that apart from the thickness, thermal conductivity depends on the yarn type as well. Thermal conductivity characteristics of the bi-layer knitted fabric are significantly affected by the same fabric structure and variation of fibre type in the inner layer. A lower thickness and mass per unit area than other fabrics is found in the bi-layer knitted fabric made out of MDP/MDP. Because of the presence of micro-pores in the yarn, MDP/MDP gives a softer and smoother feel than the PSF/PSF bi-layer knitted fabric. The thickness of MDP bi-layer fabric is lower than for the other bi-layer fabrics and more air is entrapped in the structure leading to it possessing higher thermal conductivity. The thermal conductivity value is found to be lower in C/C than in the other bi-layer knitted fabrics, the reason for which is its higher thickness and mass per unit area. Moreover, due to the MDP/MDP fabric having lower thickness, the higher the volume of air within the textile structure, the higher the thermal conductivity will be. Cotton knitted fabric has poorer Thermal conductivity than other fabrics. It has been reported that the thermal conductivity of fabric depends much more on the air entrapped within it than on fibre conductivity. As the areal density of the fabric increases, the thermal conductivity decreases due to the greater thickness. ***Table 3*** shows that the effect of yarn type on the thermal conductivity of bi-layer knitted fabrics is significant at a 95% confidence level (p-value 1.15×10^{-15}). The thermal conductivity of bi-layer knitted fabrics is influenced by the type of yarn in the inner layer and geometrical properties.

Thermal resistance

Thermal resistance is an indication of how well a material insulates. It is based on the ***Equation (1)***:

$$R = h/\lambda \ (m^2K/W) \quad (1)$$

where, R = Thermal resistance,
h = Fabric thickness, m and
λ = Thermal conductivity, W/mK.

Thermal properties are stated as the amount of heat transmitted in a given surface area through the thickness of the fabric. The fabric thickness, density, and structure highly influence the thermal resistance of fabrics. ***Figure 4*** shows the effect of the back layer fibre profile and face layer yarn type on the thermal resistance of bi-layer fabrics. The thermal insulation properties of porous textile structures are influenced by the fabric thickness and air volume fraction. Moreover, the thermal properties are highly affected by the yarn type, yarn spinning system, and yarn count. From ***Figure 4***, the high thermal resistance of cotton bi-layer knitted yarn fabrics is attributed to the hairy structure of cotton yarn, which results in the formation of a thick, insulating air layer. With air being a better thermal insulator than fibrous materials, this prevents heat loss, and hence it has high thermal resistance for cotton yarn fabrics. MDP/MDP bi-layer knitted fabrics have high air permeability due to thickness and structural variation; it is found that these fabrics possess lower thermal resistance. The specific heat of cotton fibre is relatively more than that of other fibres, therefore cotton fibre in any layer results in an increase in the specific heat of the overall fabric, due to which high energy is required for temperature rise and heat transfer to the other side of the fabric. The thermal resistance increases correspondingly as a result of an increase in the fabric's specific heat. Air gaps in the fabric structure increase as the fabric thickness increases. As the entrapped air is a good thermal insulator, by increasing the thickness of the fabric

Table 3. *ANOVA Statistics results.*

Source of variation	SS	Df	MS	F	P-value	F crit
Air permeability of bi-layer knitted fabrics						
Bi-layer fabrics	7642.133	5	1528.427	244.7658	8.43×10^{-36}	2.38607
Error	337.2	54	6.244444			
Total	7979.333	59				
Thermal conductivity of bi-layer knitted fabrics						
Bi-layer fabrics	1703.984	5	340.7967	34.54239	1.15×10^{-15}	2.38607
Error	532.7663	54	9.866043			
Total	2236.75	59				
Thermal resistance of bi-layer knitted fabrics						
Bi-layer fabrics	3491.329	5	698.2657	185.4697	1.03×10^{-32}	2.38607
Error	203.3019	54	3.76485			
Total	3694.63	59				
Water vapor permeability of bi-layer knitted fabrics						
Bi-layer fabrics	62080.4	5	12416.08	648.924	6.64×10^{-47}	2.38607
Error	1033.2	54	19.13333			
Total	63113.6	59				

the thermal resistance increases simultaneously. ***Table 3*** shows that the effect of yarn type on the thermal resistance of the bi-layer knitted fabrics is significant at a 95% confidence level (p-value $1.03x10^{-32}$).

Water vapour permeability

In accordance with Standard BS 7209:1990, an evaporative dish was used to determine the water vapour permeability of the bi-layer knitted fabrics [24]. Water vapour permeability is one of the most important properties of thermal comfort that determine the capability of perspiration transportation through a textile material. Perspiration is formed and the body evaporates the heat when it gets over-heated. Fabric with low moisture vapour permeability is unable to pass perspiration sufficiently, leading to the accumulation of sweat in clothing, and hence discomfort. The rate at which the moisture vapour gets transferred to the fabrics was tested, the results of which are given in ***Table 2***. From ***Figure 5***, it is clear that MDP bi-layer knitted fabric has more water vapour permeability compared to all other bi-layer knitted fabrics. The thickness of MDP bi-layer knitted fabric is lower than for all other bi-layer knitted fabrics, which is a vital feature. The other bi-layer fabrics exhibit lower water vapour permeability because of the increase in the thickness. It is clear that geometrical properties and the material nature have a significant impact on the water vapour permeability of bi-layer knitted fabrics. The MDP bi-layer knitted fabric structure had a higher transport of water vapour than that of the other fabrics due to the thickness and weight being lower than for the others. This is due to the fact that in a steady state, moisture vapour transport through fabrics is controlled by the diffusion process, which is influenced by the structure, thickness and openness of the fabric i.e. the more pores there are in the fabric structure, the higher the porosity and the better the water vapour permeability. The porosity of MDP bi-layer fabric is higher than for all other fabrics. The weight and thickness are lower and less air is entrapped in MDP bi-layer fabric than in the other fabrics. The increase in water vapour permeability in MDP bi-layer fabric is also because of the high tendency of moisture transmission within the filaments of micro-denier polyester. The other bi-layer fabrics exhibit low water vapour permeability because of their decrease in porosity and increase in weight and thickness. The MDP bi-layer knitted fabric gives better water vapor permeability values because of the surface area, which is larger. and fibre structure, which is channeled. Because the gap between filaments in the filament polyester is greater, the water vapour transfer rate through the fabric is lower compared to micro-fibre polyester. Because of the presence of micro-fibre polyester in its inner layer, MDP bi-layer knitted fabric fibre shows a channeled structure, resulting in a transport system that absorbs moisture away from the skin and transmits it to the outer layer. Thickness and mass per unit area play a key role in transferring water in bi-layer knitted fabric. ***Table 3*** shows that the effect of yarn type on the water vapour permeability of bi-layer knitted fabrics is significant at a 95% confidence level (p-value 6.64×10^{-47}).

Conclusions

The present study aimed to research the influence of the type of yarn on the thermal comfort properties of bi-layer knitted fabrics with respect to thermal conductivity, thermal resistance, air permeability and water vapour permeability. The type of yarn affects the thermal comfort properties of the bi-layer knitted fabrics developed. The findings obtained from the research serve as a useful insight for the development of bi-layer knitted fabric with correct yarn selection in the distinct face and back layers, respectively. The combination of MDP/MDP yarn in the face layer and back layer resulted in fabrics that possess high air permeability. The areal density of the fabric was found to be inversely proportion to the thermal conductivity. The air permeability and thermal conductivity of bi-layer knitted fabrics is mainly influenced by the thickness. In general, an increase in the water vapour permeability of bi-layer knitted fabric occurs with a decrease in the thickness and presence of openness of the fabric. The bi-layer fabric structure has the greatest impact on the water permeability of knitted fabrics. The porosity, thickness and areal density of the fabrics affect the air permeability of bi-layer knitted fabrics. Fabric porosity is directly proportional to air permeability. The thickness and structure mainly influence the thermal resistance of the fabrics. Bi-layer fabric made up of micro-denier polyester MDP/MDP as the inner layer and outer layer possess a lower thermal resistance than all the other fabrics, making it more suitable to serve as a sport textile. It is concluded that MDP/MDP bi-layer knitted fabric exhibits all the excellent properties suitable to serve as a sport textile and possesses very good comfort characteristics. The C/C sample does not serve the purpose due to a higher thickness and areal density. It is concluded that yarn selection plays a major role in the determination of thermal comfort characteristics of bi-layer fabrics.

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Received 20.01.2020 Reviewed 06.02.2020