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Comfort properties of double face knitted fabrics for tennis sportswear

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The comfort properties of different bi-layer knitted structures made from tencel yarn as an outer layer and acrylic/micro-fibre polyester yarn as an inner layer have been studied. Six union fabrics have been produced and then analyzed objectively and subjectively for their comfort properties. The air permeability, water vapour permeability, wicking ability and drying rate are found to be higher and thermal resistance is found to be lower for bi-layer knitted fabric made out of micro-fibre polyester (inner layer) with less tuck points as compared to all other fabrics. The same structure shows good ranking on subjective rating of thermal environment scale. The results are discussed with 95% significant level with ANOVA analysis and Friedman one-way analysis of variance.

Keywords: Acrylic/micro-fibre polyester, Double face fabric, Plated fabric, Sportswear, Subjective assessment, Tencel yarn, Thermal comfort

1 Introduction

In active sports, the performance of sportswear is identical with its comfort characteristics. The important quality decisive factor that affects performance, efficiency and well-being of sportswear is the wear comfort[1]. Any physical activity will produce different levels of the need to release excessive heat and maintain a stable body temperature[2,3]. With the increasing requirement for garment comfort, many studies have focussed on the comfort properties of fabrics[4-6]. The critical properties for thermal comfort of the clothed body are thermal resistance, air permeability, water vapour permeability, and wicking ability[7,8]. Human body perspires in two forms such as insensible (in vapour form) and sensible perspiration (in liquid form). To be in a comfortable state, the clothing should allow both types of perspirations to transmit from the skin to the outer surface[9]. The construction, thickness, and materials affect the heat transfer between the human body and the environment[10]. In addition to that, the enclosed still air, and external air movement are the major factors that affect heat transfer through fabric[11,12].

The thermal comfort property of a clothing system during dynamic conditions should be assessed based on moisture vapour pressure alteration within the clothing, surface temperature of the clothing and heat loss from the body[13]. The garment should have the ability to release the moisture vapour held in the microclimate to the atmosphere to reduce the dampness at the skin[14]. Water vapour permeability plays a very important role when there is only little sweating, or insensible perspiration or else very little sweating[15]. During heavy activity when liquid perspiration production becomes high, to feel comfortable the clothing should possess good liquid transmission property[16]. Wicking is an important property to uphold a feel of comfort during sweating conditions. It applies the capillary theory to rapidly remove sweat and moisture from the skin's surface, transport it to the fabric surface, and then evaporate it[17].

Considering the above, many studies have focused on double-face structures to achieve high level of comfort[18-22]. The performance of layered fabric in thermo-physiological regulation is better than single layer textile structure[23,24]. In the inner side of a multiple layer textile, a synthetic material with good moisture transfer properties, such as polyester, nylon, acrylic or polypropylene, is used whereas on the outside, a material which is a good absorbent of moisture, for example cotton, wool, viscose rayon or their blends, can be placed[25]. Plating is the simultaneous formation of the loop from two yarns and is a common technique to produce sportswear knitted products[26]. The microfibre fabric absorbs and wicks moisture better and seem to breathe which can be utilized to develop new products for apparel and sportswear[27,28]. Two layer fabrics made using 30%

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Tencel and 70% polyester in the outer layer gives better thermal comfort compared to 100% polyester. The plated fabric made from polyester and tencel showed better endurance to the wearer[29]. The thermal resistance was high for wool-acrylic blends investigated for undergarments[30]. Warp knitted raschel fabric was convenient for summer cycling clothing because of its high air permeability, low thermal resistance, low water vapour resistance, and good moisture management properties[31].

The considerable research work has been carried out to study layered knitted fabrics, but very little published work is available on the use of layered knitted fabrics for sportswear. Hence, in this study an attempt has been made to analyze the thermal comfort properties of bi-layer and plated knitted structures made out of acrylic-tencel and microfibre polyester-tencel union fabrics. This study will be of vast help to the researchers who are analyzing the comfort characteristics of layered knitted fabrics for sportswear.

2 Materials and Methods

2.1 Materials

The knitted structures were prepared using tencel (132 denier), acrylic (132 denier) and micro-fibre polyester continuous filament yarn (150 denier). All samples were produced in circular multi-track weft knitting machine (Kumyong-KILM-72AV) with 68 feeders, 18 gauge, 3168 needles and 28 inch diameter using constant setting values. The prerequisites of ideal sportswear are rapid transport of perspiration away from the body and then its rapid evaporation to keep the fabric dry. This is achieved by bi-layer knitted fabric construction in which the inner layer is made of acrylic or microfibre polyester filament yarn that is hydrophobic and has good wicking rate. The outer layer is made up of regenerated fibre such as Tencel which has more absorption character and rapid evaporation. The yarn which has to form as an inner layer is fed into the dial needle and that for the outer layer is fed into the cylinder needle. The graphical representation and yarn arrangements of the double-face fabric are shown in Fig. 1. The four samples were bi-layer knitted fabrics and two samples were plated weft knitted fabric. The entire layered knitted fabrics photograph is shown in Fig. 2.

2.2 Testing Methods

The testing of double-face knitted fabrics was carried out in the standard atmospheric conditions of 65% RH and 27±2^o C. Following properties were tested using the standard methods.

Dimensional Properties

The bi-layer knitted fabrics were measured for their loop length, stitch density, thickness and areal density. Wales and courses per unit length were evaluated using the standard ASTM D 3887: 1996 (RA 2008) and loop length was measured according to the standard ASTM D 3887. The thickness measurement of the fabrics was carried out according to ASTM D1777-96 (ref. 32) using Shirley thickness gauge

Fabric Areal Density

The fabric weight per unit area was determined according to ASTM D3776 standard using an electronic balance[33]. The areal density of layered knitted fabrics was measured by cutting the sample size of 10 × 10cm. The sample was weighed in the electronic weighing balance and the value was multiplied by 100.

Fabric Porosity

Porosity was determined by measuring the total volume of a fabric and calculating the total volume of fibre in the sample. The difference between these two values is considered as air space and when calculated as a percentage of the total volume, it gives the porosity[34]. The porosity was determined by the following equation:

$$P = \frac{100(AT - W/D)}{AT} \quad \text{... (1)}$$

where P is the porosity in percentage; A, the area of the sample in cm^2; W, the weight of the sample in g; T, the thickness of the sample in cm; and D, the density of fibre in g/cm^3.

Tightness Factor

The tightness factor of the knitted fabrics was calculated by the following relationship:

$$TF = \frac{\sqrt{T}}{l} \quad \text{... (2)}$$

where TF is the fabric tightness factor; T, the yarn linear density in tex; and l, the loop length in cm.

Air Permeability

The air permeability of the clothing was determined by the rate of air flow passing perpendicularly through a set area under given pressure over a given time period. The air

<table>
<tr><th>Fabric code</th><th>Fabric structure</th><th>Graphical representation</th></tr>
<tr><td>Type1</td><td>Bi-layer
Inner: Acrylic (40%)
Outer: Tencel (60%)</td><td rowspan="2">
<table>
<tr><th></th><th>F1</th><th>F2</th><th>F3</th><th>F4</th><th>F5</th><th>F6</th><th>F7</th><th>F8</th><th>.....
F36</th></tr>
<tr><td>DN1</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>-</td></tr>
<tr><td>DN2</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>-</td></tr>
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<tr><td>CN2</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>X</td></tr>
<tr><td>CN3</td><td>o</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>X</td><td>X</td></tr>
</table>
</td></tr>
<tr><td>Type 2</td><td>Bi-layer
Inner: Microfibre
Polyester (40%)
Outer: Tencel (60%)</td></tr>
<tr><td>Type 3</td><td>Bi-layer
Inner: Acrylic (40%)
Outer: Tencel (60%)</td><td rowspan="2">
<table>
<tr><th></th><th>F1</th><th>F2</th><th>F3</th><th>F4</th><th>F5</th><th>F6</th><th>F7</th><th>F8</th><th>F9</th><th>F10</th></tr>
<tr><td>DN1</td><td>o</td><td>X</td><td>-</td><td>X</td><td>-</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td></tr>
<tr><td>DN2</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>o</td><td>X</td><td>-</td><td>X</td><td>-</td></tr>
<tr><td>CN1</td><td>o</td><td>-</td><td>X</td><td>-</td><td>X</td><td>-</td><td>-</td><td>X</td><td>o</td><td>X</td></tr>
<tr><td>CN2</td><td>-</td><td>-</td><td>X</td><td>-</td><td>X</td><td>o</td><td>-</td><td>X</td><td>-</td><td>X</td></tr>
</table>
</td></tr>
<tr><td>Type 4</td><td>Bi-layer
Inner: Microfibre
Polyester (40%)
Outer: Tencel (60%)</td></tr>
<tr><td>Type 5</td><td>Plated
Inner: Acrylic (50%)
Outer: Tencel (50%)</td><td rowspan="2">
<table>
<tr><td>X</td><td>X</td></tr>
<tr><td>X</td><td>X</td></tr>
</table>
</td></tr>
<tr><td>Type 6</td><td>Plated
Inner: Microfibre
Polyester (50%)
Outer: Tencel (50%)</td></tr>
<tr><td colspan="3">Dial needles – Two tracks (Tencel)
DN1 – Dial needles Track 1; DN2 – Dial needles Track 2
Cylinder needles – Three tracks (Acrylic or Microfibre polyester)
CN1– Cylinder needles Track 1; CN2 – Cylinder needles Track 2; CN3 – Cylinder needles Track 3
F1, F2, F3,.......F35, F36 – Number of feeders; X–Knit stitch; o –Tuck stitch; – (-) Miss stitch</td></tr>
</table>

Fig. 1 — Graphical representation and yarn arrangement of layered knitted structure

permeability properties of the fabrics were measured using Atlas air permeability instrument according to BS 5636(ref.35) standard with 100 Pa air pressure. It is expressed as the quantity of air in cubic centimetre passing per second through a square centimetre of fabric.

Thermal Conductivity

Thermal conductivity is an intrinsic property of material that indicates its ability to conduct heat. Lee's Disc instrument was used to measure the thermal conductivity according to ASTM D7340 standard[36]. Thermal resistance is inversely proportional to thermal conductivity. For idealized conditions,

$$\lambda = \frac{h}{r}\ \mathrm{km^{-1}\ W^{-1}} \qquad \ldots (3)$$

where r is the thermal resistance; h, the sample thickness; and λ, the thermal conductivity.

Water Vapour Permeability

The water vapour permeability was determined on Shirley water vapour permeability tester according to standard BS 7209:1990(ref.37). As per standards, the test specimen is sealed over the open mouth of a test dish which contains water and the assembly is placed in a controlled atmosphere of 20°C and 65% relative humidity. The water vapour permeability (WVP) in g/m^2/day is calculated by the following equation:

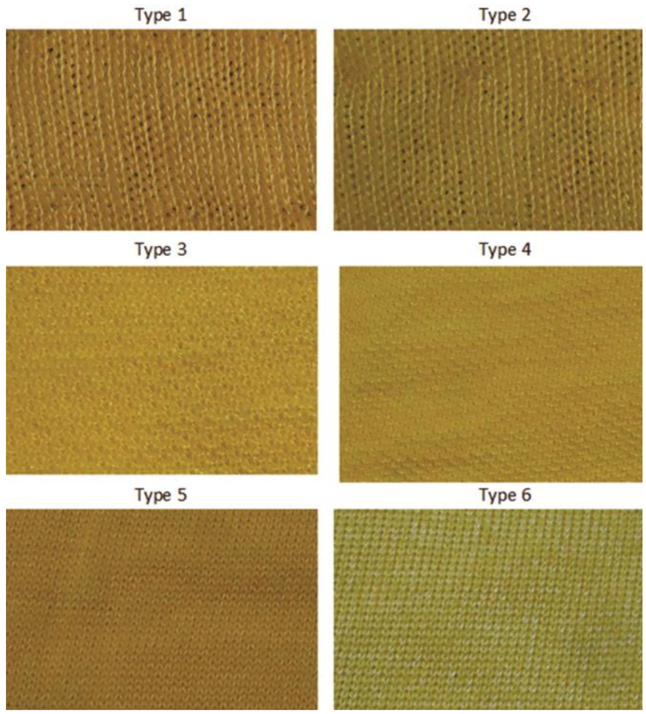

Fig. 2 — Photographs of bi-layer knitted fabrics

$$WVP = 24\, M / At \qquad \text{... (4)}$$

where *M* is the loss in mass of the assembly over the time period t in g; *t*, the time between successive weighing of the assembly in hours; and *A*, the area of the exposed test fabric in m^2.

Vertical Wicking

Vertical wicking was measured in accordance with BS 3424 standard, a strip of 20cm×2.5cm test fabric at 20ºC, 65% RH was suspended vertically with its lower edge (0.5cm) immersed in a reservoir of distilled water. The rate of rise of the leading edge of the water is then measured for every five minutes till it reaches consistency[38].

Transverse Wicking

Transverse wicking was measured according to standard procedure AATCC 198-2011. Static immersion method which follows the standard BS 3449 (ref. 39) was used to evaluate the amount of water absorbed by the fabric. The horizontal wicking rate and the average wicking rate for each sample were calculated by the following formula:

$$W = \pi\, (1/4)\, (d1)\, (d2)/t \qquad \text{... (5)}$$

where *W* is the wicking rate in mm^2/s; *d*, the wicking distance in length direction in mm; *d2*, the wicking distance in width direction in mm; and *t*, the wicking time in seconds.

Drying Behaviour

The fabrics, got wet according to static immersion method, were dried in drying oven at 30°C for 30 min to simulate the natural drying[40]. After they were taken out, the fabrics were weighed and the amount of water loss was calculated from subtracting the wet and dry mass. And also, the drying time of the fabrics was determined by which the wet fabrics reach their dry mass.

2.3 Subjective Evaluation

Short-sleeved T-shirts were produced from six sportswear fabrics. 45 tennis players were selected as the participants with mean age of 23 years (standard deviation of 1.4 year), body mass 59.3 kg (standard deviation of 3.6 kg), and height 1.6 m (standard deviation of 0.02 m). The subjective evaluation was conducted at conditions: air conditioning of indoor temperature of 78-82^{o}F below the outside temperature of 95-98^{o}F and 55-60% humidity. Each participant was informed about the general procedure and purpose of wear trial. They were asked to select the best fitting size for each of the layered fabric by wear and trial method. Participants were instructed to wear the sports garment for 2 h by engaging in tennis activity. After the activity, they completed the questionnaire immediately. The psychological phenomenon of thermal comfort during activity was assessed using ISO 10551 (1995) standard[41]. The questionnaire described the thermal comfort of garment using five subjective assessment scales of thermal state such as thermal perception, thermal comfort, thermal preference, personal acceptability, and personal tolerance.

2.4 Statistical Analysis

Analysis of variance (ANOVA) tests were used to examine significant difference between the thermal properties of samples. In order to infer whether the parameters were significant or not, p values were examined. If the ‘p’ value of a parameter is greater than 0.05 ($p>0.05$), the parameter is not significant and should not be investigated. Subjective evaluation for thermal sensation was done using Friedman one-way analysis of variance by ranks[42]. It is non-parametric analysis, used to find out the significant difference between the rankings of five subjective judgement scales. The spearman’s rank correlation was used to find out the correlation between the responses of players.

3 Results and Discussion

The physical and thermal comfort properties of six layered knitted fabrics were measured and the average values of ten samples are given in Table 1.

3.1 Air Permeability

The air permeability of the knitted fabrics mainly depends upon yarn, fabric construction, thickness, areal density and porosity. The space between the yarns in the fabric structure influences the flow of air through inter yarn pores[43]. Figure 3 (a) shows that the air permeability value of type 1 and type 2 bi-layer knitted fabrics is higher than other fabrics. This is due higher porosity than all other double-face knitted fabrics. Air permeability is directly proportional to fabric porosity and it is found to increase with the increase in fabric porosity. The porosity of layered knitted fabrics decreases with the increase in stitch density, mass per unit area and thickness. Decrease in stitch density and thickness value increases passage of air through the fabric. Even though type 1 and type 2 fabrics have same loop length (0.31cm), type 2 fabric has higher air permeability because of the presence of microfibre polyester as an inner layer which provides space for air flow.

Table 1 shows that there is a strong relationship between stitch density and air permeability of bi-layer fabrics. Type 3 and type 4 fabrics have lower air permeability due to the presence of less pores in the surface area of fabric and hence resists the flow of air through the fabrics. In type 5 and type 6 plated structures, inter loops are very close. These loops are closer than in bi-layer structures and hence show lower air flow through the fabric. Sports person sweats during physical activity and need to release

Table 1 — Physical and thermal comfort properties of layered fabrics

Property	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Physical properties						
Stitch density loops/cm^2	194	189	232	228	113	109
Weight, g/m^2	193	185	232.8	220.4	238.8	229.2
Thickness, mm	0.65	0.55	0.96	0.88	0.78	0.72
Loop length, mm	3.1	3.1	2.7	2.7	2.9	2.9
Porosity, %	55.07	59.42	45.8	51.66	43.03	49.30
Tightness factor	12.39	12.39	14.22	14.22	13.24	13.24
Thermal comfort properties						
Air permeability $cm^3/s/cm^2$	890.65	1245.5	520.65	780.36	160.27	252.32
Thermal resistance, km^2/W	0.013	0.010	0.016	0.014	0.022	0.018
Water vapour permeability $g/m^2/day$	1932.5	2028.5	1205.1	1508.5	985	1016.2
Vertical wicking, cm						
wale-wise	10.1	13.9	9.1	12.8	7.9	8.6
course-wise	10.8	14.1	9.8	13	8.9	9.9
Transverse wicking, mm^2/s	10.2	18.4	8.96	13.9	5.1	9.9
Drying behaviour, s	329.4	280.2	558.6	436.8	492	408

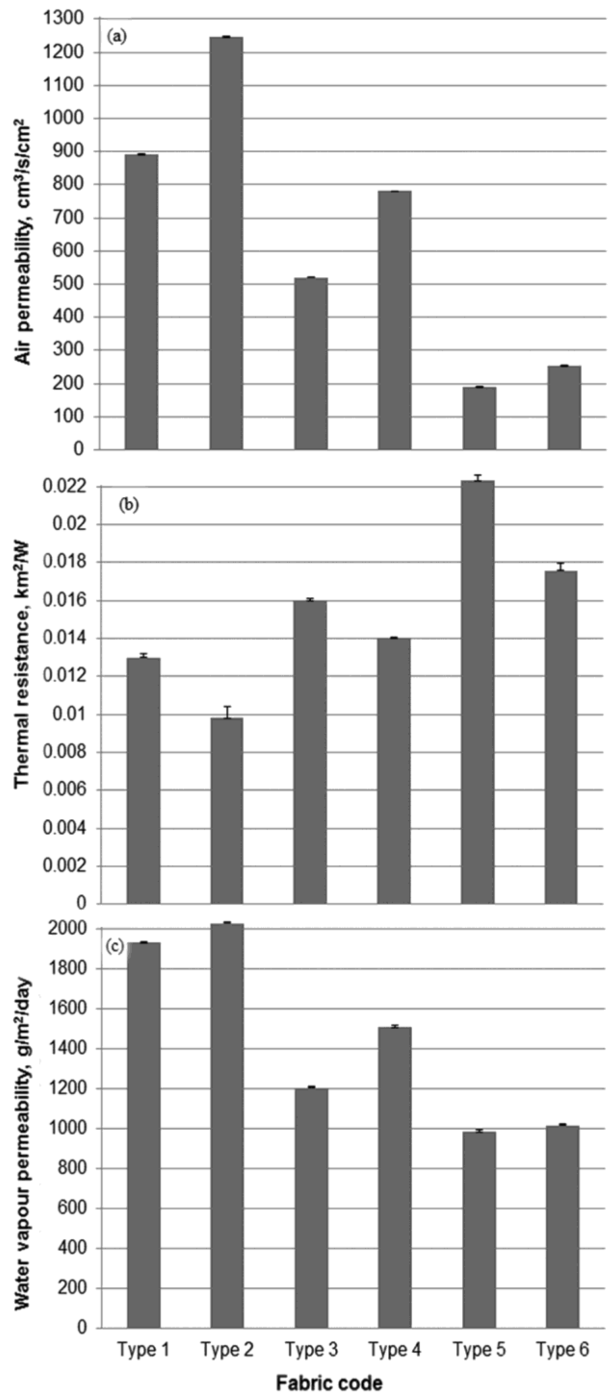

Fig. 3 — (a) Air permeability, (b) thermal resistance, and (c) water vapour permeability value of fabrics

excess heat to feel comfortable. In this regard, type 1 and type 2 bi-layer fabrics can be used for sportswear because of higher air permeability value. Table 2 shows the ANOVA statistical analysis results at 5% significance level. The air permeability of type 1, type 3 and type 5 bi-layer knitted fabrics shows significant difference between bi-layer structure types (F_{actual} = 47343.27 in comparison with $F_{critical}$=3.89) at degree of freedom 12. Similarly, the air permeability of type 2, type 4 and type 6 bi-layer knitted fabrics shows significant difference between the structures (F_{actual} = 72097.24> $F_{critical}$=3.89) at degrees of freedom 12. Tukey's Honest Significant Difference (HSD) test is used to find the possible group-wise (pair-wise) differences of means. The $Q_{critical}$ at (3, 12) value is 3.77 and $Q_{critical}$ is lesser than Q_{actual} for all paired means of differences and there is a significant difference between paired samples of two sets of layered fabric (Type 1, type 3 and type 5; Type 2, type 4 and type 6) as shown in Table 2.

3.2 Thermal Resistance

Thermal properties are expressed as the amount of heat transmitted through the thickness of the fabric in a given surface area. Thermal resistance are greatly influenced by fabric thickness, density, and structure. In three sets of layered knitted fabrics, the layered fabric having acrylic as an inner layer possesses high thermal resistance due to bulkiness of fibre. Thermal resistance of layered knitted fabric is compared in Fig. 3(b). The highest thermal resistance is observed in plated knitted structure while lower thermal resistance is observed in bi-layer structure with one tuck point. It is important to note that bi-layer fabrics type 1 and type 2 have lower thickness and lower stitch density values while type 3 and type 4 fabrics have higher thickness value and higher stitch density. Among type 1 and type 2 fabrics, type 2 shows lower thermal resistance due to the fact that acrylic possesses better heat insulation characteristics. Higher the volume of dead air within a textile structure, lower will be the thermal transmittance which results in higher thermal resistance. Even though type 1 and type 2 possess high air permeability due to thickness and structural variation, it is found that these fabrics possess lower thermal resistance. Among bi-layer and plated structure, type 5 and type 6 fabrics show the highest thermal resistance but lower thickness than type 3 and 4, due to less fabric density and structural variation. This is because the loops on either side of plated structures are tightly packed. The ANOVA results show that with respect to bi-layer structure types, there is a significant difference among the bi-layer knitted fabrics type 1, type 3 and type 5 at degrees of freedom 12 [F_{actual}= 262.64 > $F_{critical}$=3.89 ($p<0.05$)]. On the other hand, among type 2, type 4 and type 6 fabrics, there is a significant difference among the structures [F_{actual}= 180.79 > $F_{critical}$=3.89 ($p<0.05$)]. Tukey's Honest Significant Difference (HSD) test shows significant difference among all groups of bi-layer knitted fabrics as shown in Table 2.

Table 2 — One-way ANOVA of layered knitted fabric structures

Thermal comfort properties	Responses	F_{actual}	P_{value}	Tukey's HSD		
				0.05 Level	0.01 Level	P_{value} (all groups)
Air permeability	Type 1, 3 and 5	47343.27	<.0001	6.32	8.45	<0.01
	Type 2, 4 and 6	72097.24	<.0001	3.6	4.81	<0.01
Thermal resistance	Type 1, 3 and 5	262.64	<.0001	0	0	<0.01
	Type 2, 4 and 6	180.79	<.0001	0	0.01	<0.01
Water vapour permeability	Type 1, 3 and 5	108573.32	<.0001	5.68	7.59	<0.01
	Type 2, 4 and 6	89877.96	<.0001	6.37	8.52	<0.01
Vertical wicking (wale-wise)	Type 1, 3 and 5	205.93	<.0001	0.28	0.38	<0.01
	Type 2, 4 and 6	2160.79	<.0001	0.22	0.3	<0.01
Vertical wicking (course-wise)	Type 1, 3 and 5	411.83	<.0001	0.18	0.24	<0.01
	Type 2, 4 and 6	802.07	<.0001	0.29	0.38	<0.01
Transverse wicking	Type 1, 3 and 5	923.67	<.0001	0.32	0.42	<0.01
	Type 2, 4 and 6	1843.4	<.0001	0.37	0.49	<0.01
Drying behaviour	Type 1, 3 and 5	633.9	<.0001	0.28	0.39	<0.01
	Type 2, 4 and 6	300.3	<.0001	0.31	0.42	<0.01

3.3 Water Vapour Permeability

Water vapour permeability is one of the important properties of thermal comfort that determines the capability of transporting perspiration through a textile material. It is observed from Fig. 3(c) that type 1 and type 2 bi-layer knitted fabric structures with less tuck points have higher water vapour permeability values than the other fabrics though the outer layer is made up of tencel for all the structures. This is due to the fact that more pores in the fabric structure results in high porosity and show good water vapour permeability. The porosity of type 2 bi-layer fabric is higher than other fabrics. The weight and thickness of fabrics are lower and less air is entrapped in type 2 fabric than in other fabrics. The increase of water vapour permeability in type 2 is also due to high tendency of transmitting moisture within the filament of micro-fibre polyester.

The type 3 and type 4 fabrics show low water vapour permeability because of decrease in fabric porosity and increase in weight and thickness. Type 5 and type 6 fabrics show the lowest water vapour permeability value because of its high mass per unit area and fabric structure. In this case, fabric porosity also plays vital role, which is lower for plated fabrics. As a result, it may be difficult to release sweat from the body in the form of water vapour. For this reason, the fabrics used in sports wear must have high water vapour permeability values. The increased water vapour permeability of bi-layer fabric type 1 and type 2 results in high fabric breathability. High physical activity causes increased sweating, and the increased permeability of the water vapour provides better comfort. In Table 2, ANOVA results show that there is a significant difference among type 1, type 3 and type 5 bi-layer knitted fabrics [F_{actual}= 108573.32 > $F_{critical}$=3.89 ($p<0.05$)]. Also it is noticed that there is a significant difference among the layered fabrics made up of microfibre polyester as an inner layer [F_{actual}= 89877.96 > $F_{critical}$=3.89 ($p<0.05$)]. Tukey's HSD shows significant difference among group of bi-layer knitted fabrics (acrylic or microfibre polyester as an inner layer).

3.4 Wicking

The fabric thickness can provide more space to accommodate water, which can lead to more water transfer if the capillary pressure is large enough to activate wicking. Reduction in the capillary size of the fabric (through the introduction of microfibres to the fabric) can also improve the wicking performance of fabrics[44]. Figure 4 presents the curves obtained from vertical wicking in wales and course wise direction. The initial rate of water take-up in vertical wicking is higher for fabrics with microfibre polyester composition than that for the fabrics with acrylic composition. The type 1 and type 2 fabrics with lower stitch density and lowest thickness show higher amount of water take-up compared to other fabrics. The fabric characteristics and structure of type 3 and type 4 fabrics are the determining factors of the amount of water take-up. Type 3 and type 4 fabrics with highest stitch density and thickness show less wickability in both wale and course directions than type 1 and type 2 fabrics. The type 5 and type 6 fabrics with the lowest stitch density and relatively high thickness show the poor vertical wicking in wale and course directions. Table 2 shows the ANOVA statistical analysis. The vertical wicking of bi-layer knitted fabrics has significant difference between the knitted fabrics type 1, type 3 and type 5. F_{actual} is found to be 205.93 in wale-wise and 411.83 in course-

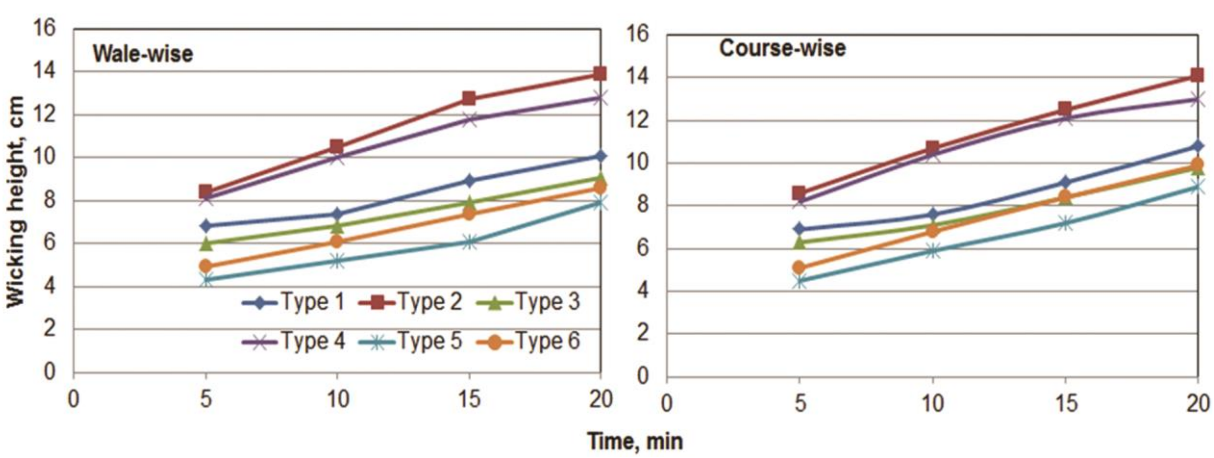

Fig. 4 — Vertical wicking of fabrics (wale-wise and course-wise)

wise in comparison with $F_{critical}$=3.89 with degrees of freedom 12 at 5% significance level. The vertical wicking value of type 2, type 4 and type 6 has significant difference between the structures [F_{actual}= 2160.79 > $F_{critical}$=3.89 in wale-wise; F_{actual}= 802.07 > $F_{critical}$=3.89 in course-wise].

The water spreading on the surface of fabrics at fixed intervals has been measured. Figure 5 represents the curves obtained for transverse or in-plane wicking of layered knitted fabrics. The initial water-take up rate is found high for the fabrics made up of microfibre polyester as an inner layer similar to vertical wicking. Type 2, type 4, and type 6 fabrics have higher wicking rate as compared to type 1, type 3 and type 5 fabrics respectively that are made-up of acrylic as an inner layer. Type 1 and type 2 show higher wicking rate than other fabrics. This behaviour is most probably due to the presence of less tuck points in the structure which has the ability to transport water through it. Type 3 and type 4 with high density and thickness value show relatively better wicking rate. Type 5 and type 6 plated structures are greatly influenced by the structure formation, because plated structures are formed by simultaneous inter-looping of two yarns fed into one feeder. During physical activity of sports, there is a possibility of increasing sweat generation which needs increased water transport. The bi-layer knitted fabric type 2 with good wickability is suitable for sports person which transfer sweat generated through the inner layer and gets evaporated when it reaches outer layer. The statistical tool ANOVA is used to analyze the significance of fabric structures on transverse wicking. The ANOVA results show that there is a significant difference in transverse wicking of bi-layer knitted fabrics type 1, type 3 and type 5 as F_{actual} (923.67) is greater than $F_{critical}$ = 3.89. It is also found that there is a significant difference among the bi-layer knitted fabrics type 2, type 4 and type 6 [F_{actual}= 1843.4 > $F_{critical}$=3.89 ($p<0.05$)]. Tukey's HSD shows significant difference among all bi-layer knitted fabrics such as type 1, type 3 and type 5; type 2, type 4 and type 6.

3.5 Drying Time

Figure 6 shows that the drying ability rate is higher for type 2, type 4, and type 6 layered fabrics compared to type 1, type 3, and type 5 respectively. In bi-layer knitted fabrics, type 1 and type 2 require less time to dry or to reach the initial dry mass of fabric. This is due to low mass per unit area, thickness and high moisture vapour transmission. It is observed that type 3 and type 4 require more time to reach initial dry mass than type 1 and type 2. The reason is more increase of thickness and mass per unit area than in type 1 and type 2. The type 5 and type 6 plated fabrics require more time to get dry and show the lowest drying ability than all other bi-layer fabrics. The reason is high mass per unit area and higher thickness than all other fabrics. The presence of microfibre polyester in type 2, type 4, and type 6 also contributes to quick drying of bi-layer knitted fabrics. The drying ability of bi-layered knitted fabrics is primarily affected by mass per unit area and thickness, and secondarily by the knitted structure parameters. The drying ability of type 1, type 3 and type 5 bi-layer knitted fabrics show significant difference between bi-layer structure types (F_{actual}= 633.9 in comparison with $F_{critical}$=3.89) at degree of freedom 12. Similarly, type 2, type 4 and type 6 bi-layer knitted fabrics shows significant difference in drying ability (F_{actual} = 300.3 > $F_{critical}$=3.89) at degrees of freedom 12. The $Q_{critical}$ at (3,

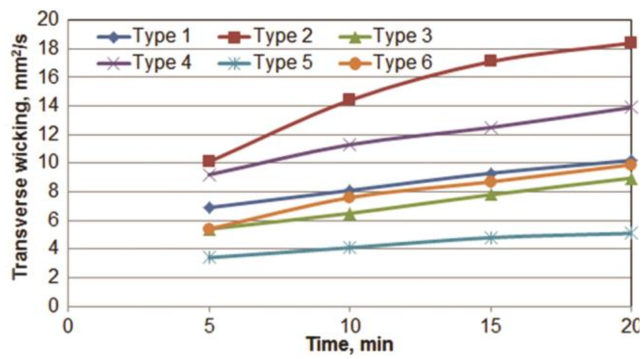

Fig. 5 — Transverse wicking value of fabrics

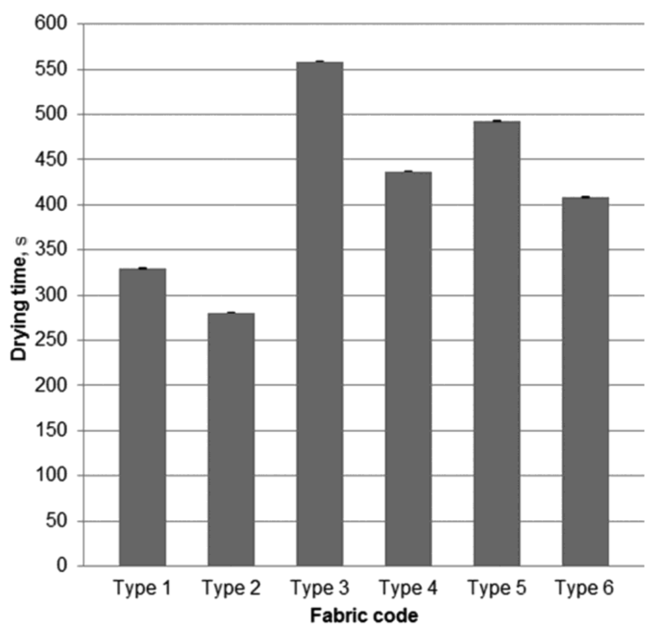

Fig. 6 — Drying time of fabrics

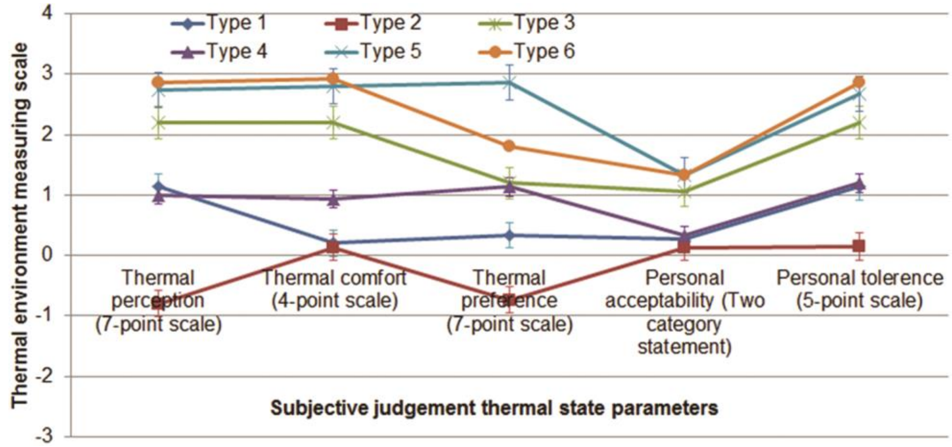

Fig. 7 — Subjective perception rating of fabrics

Table 3 — Thermal state rating-Friedman one-way analysis of variance by ranks

Thermal state parameters	Responses	Mean ranks of respective samples			Chi-square statistic(χ^2_r)	P-value
Thermal perception	Type 1, 3 and 5	1.1	2.2	2.7	21.73	<0.0001
	Type 2, 4, and 6	1	2	3	30	<0.0001
Thermal comfort	Type 1, 3 and 5	1	2.2	2.8	25.2	<0.0001
	Type 2, 4, and 6	1.1	1.9	3	27.3	<0.0001
Thermal preference	Type 1, 3 and 5	1.1	1.9	3	25.43	<0.0001
	Type 2, 4, and 6	1	2.2	2.8	25.83	<0.0001
Personal acceptability	Type 1, 3 and 5	1.2	2.2	2.6	15.23	<0.0001
	Type 2, 4, and 6	1.5	1.7	2.8	14.93	<0.0001
Personal tolerance	Type 1, 3 and 5	1.1	1.2	2.7	20.1	<0.0001
	Type 2, 4, and 6	1.1	1.9	3	28.13	<0.0001

12) value is 3.77 and $Q_{critical}$ is lesser than Q_{actual} for all paired means of differences and there is a significant difference between paired samples of two sets of layered fabric (Type 1, type 3 and type 5; Type 2, type 4 and type 6) as shown in Table 2.

3.6 Subjective Analysis

Figure 7 shows the subjective rating on thermal environment scale which includes five thermal parameters. It is found that type 2 fabric shows good ranking on five subjective judgement scales which describes the thermal state of player. The five subjective judgment scales include thermal perception, thermal comfort, thermal preference, personal acceptability and personal tolerance. Rating points are shown in Fig. 7. The type 2 bi-layer fabric with one tuck point, in which inner layer is made up of microdenier polyester and outer layer is made up of tencel can be preferred for sportswear followed by type1 and type 4. Table 3 shows the values of Friedman one-way analysis of variance by ranks. The number of sample is 15 and hence Chi square is analyzed. The selected significant difference is 0.05, the degree of freedom is 2 and the F value is 5.99. The obtained F value is less than the critical value of chi-square, which proves that there is a significant difference between rankings of layered knit fabrics. The significant difference between the rankings is found for all five subjective judgement scale thermal state parameters.

4 Conclusion

In this study, the thermal comfort characteristics of layered knitted fabric for sportswear are compared in the perspective of air permeability, thermal resistance, water vapour permeability, wicking ability, and drying rate.

4.1 The air permeability of the bi-layer knitted fabrics type 1 and type 2 is affected by porosity, thickness and areal density of fabrics. Fabric porosity is directly proportional to air permeability.

4.2 Thermal resistance of the fabrics is mainly influenced by the thickness and structures. The bi-layer fabric made up of microfibre polyester as an inner layer and tencel as an outer layer with less point have lower thermal resistance than other fabrics.

4.3 It is found that the fabric porosity and thickness are major determinant factors for water vapour permeability. Thinner fabric with porous bi-layer knitted structure type 2 possesses high water vapour permeability and is preferred for active sportswear application because of quick evaporation of sweat from the microclimate part.

4.4 In this study, tencel is used as an outer layer to make the sports person feel comfortable by quick evaporation and drying. Under these circumstances, in addition to low thermal resistance and high air permeability, fabrics must provide higher water vapour transfer, wicking ability and fast drying rate.

4.5 The bi-layer fabric (type 2) with lower stitch density and lowest thickness shows higher amount of water takeup compared to other fabrics. The wicking ability is greatly influenced by thickness and stitch density. The presence of number of tuck points in the fabric structure is also the determining factor of amount of water up-take.

4.6 The drying ability of bi-layer and plated is primarily affected by the mass per unit area and thickness and the secondary factor (structure parameters) also affects the drying ability. Generally, bi-layer knitted fabrics made-up of microfibre polyester (Type 2, type 4, and type 6) as an inner layer shows good air and water permeability and low thermal resistance than the fabrics made-up of acrylic (Type 1, type 3, and type 5) as an inner layer. On other hand, bi-layer knitted fabric with one tuck point feature shows better thermal comfort properties suitable for sportswear.

4.7 It can be concluded that the type 2 bi-layer knitted fabric with one tuck point is a better active sportswear because of its good air permeability, low thermal resistance, good water vapour permeability, wicking ability, and drying rate. This fabric allows excess heat during physical activity and it keeps the wearer dry. These properties make this bi-layer fabric more comfortable and can be recommended for active sportswear.

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References

1 Mounir Hassan, Khadijah Qashqary, Hany A Hassan, Ebraheem Shady & Mofeda Alansary, *Fibres Text Eastern Eur*, 4(93) (2012) 82.
2 Senthilkumar P, *Study of comfort characteristics of cotton hollow yarn knitted Fabrics*, Ph.D. thesis, Anna University, Chennai, India, 2009.
3 Esra Tastan Ozkan & Binnaz Meric, *Text Res J*, 85(1) (2015) 62.
4 Kathryn Hatch L, Nancy Markee L & Howard Maibach I, *Cloth Text Res J*, 10(4) (1992) 54.
5 Das A & Ishtiaque S M, *J Text Apparel Technol Mgmt*, 3(4) (2004) 1.
6 Dias T & Delkumburewatte G B, *Meas Sci Technol*, 18(2007) 1304.
7 Suzanne Sontag M, *Cloth Text Res J*, 4 (1) (1985-1986) 17.
8 Das A, Alagirusamy R & Kumar P, *Autex Res J*, 11(2011) 54.
9 Brojeswari, Das A, Kothari V K, Fangueiro R & Araujo M, *Autex Res J*, 7(2) (2007) 100.
10 Helen Epps H & Min Kyu Song, *Cloth Text Res J*, 11(1) (1992) 10.
11 Shoshani Y & Shaltiel S, *Knitting Times*, 4(1989) 70.
12 Milenkovic L, Skundric P, Sokolovic R & Nikolic T, *The Sci J Facta Universitatis*, 1(4) (1999) 101.
13 Jianhua Huang, *J Therm Biol*, 31(6) (2006) 461.
14 Gamze Supuren, Nida Oglakcioglu, Nilgun Ozdil & Arzu Marmarali, *Text Res J*, 81(13) (2011) 1320.
15 Su Kyoung An, Hae Jin Gam & Huantian Cao, *Cloth Text Res J*, 31(3) (2013) 157.
16 Brojeswari Das, Apurba Das, Vijay Kothari, Raul Fanguiero, & Mario D Araujo, *J Eng Fibre Fabrics*, 4 (2009) 20.
17 Elena Onofrei, Ana Maria Rocha, & André Catarino, *J Eng Fibre Fabric*, 6(4) (2011) 10.
18 Piller B, *Melliand Textilber*, 67 (1986) 412.
19 Hong K, Sun O & Chi D, *J Therm Biol*, 18(1991) 435.
20 Yasuda T, Miyama M & Yasuda H, *Text Res J*, 64 (1994) 457.
21 Kim E, Yoo S J & Shim H, *Text Res J*, 76 (2006) 301.
22 Sathish Babu B, Senthilkumar P & Senthilkumar M, *Industria Textila*, 66(3) (2015) 123.
23 Umbach K H, *Knitting Technique*, 15(3) (1993) 165.
24 Sule A D, Bardhan M K & Sarkar R K, *Man-Made Text India*, (2004) 123.
25 Devanand Uttam, *Int J IT, Eng Applied Sci Res*, 2(1) (2013) 1.
26 Abdessalem S B, Abdelkader Y B, Mokhtar S & Elmarzougui S, *J Eng Fibre Fabrics*, 4 (2009) 30.
27 Ramakrishnan G, Bharathi Dhurai & Mukhopadhyay S, *J Text Apparel Technol Mgmt*, 6(1) (2009).
28 Alagirusamy R & Das A, *Technical Textile Yarns-industry and Medical Applications* (Woodhead Publishing Limited, Cambridge) 2010.
29 Manshahia M & Das A, *Indian J Fibre Text Res*, 39(2014) 441.
30 Ucar N & Yilmaz T, *Fibres Text Eastern Eur*, 12(2004) 34.
31 Sabine Dlugosch, Hong Hu & Allan Chan, *Cloth Text Res J*, 31 (2013) 231.
32 *Standard test method for thickness of textile materials, ASTM D1777* (ASTM International, West Conshohocken, PA) 1996.
33 *Standard test methods for mass per unit area (weight) of fabric, ASTM D3776* (ASTM International, West Conshohocken, PA) 1996.

34 Skinkle J H, *Textile Testing: Physical, Chemical and Microscopical* (Chemical Publishing, New York) 1940.
35 *Method of test for the determination of the permeability of fabrics to air, BS 5636* (British Standards, London, England), 1990
36 *Standard practice for thermal conductivity of leather, ASTM D7340* (ASTM International, West Conshohocken, PA), 2012.
37 *Specification for water vapour permeable apparel fabrics, BS 7209* (British Standards, London, England), 1990.
38 Harnett P R & Mehta P N, *Text Res Inst*, 84 (1984) 471.
39 Saville B P, *Physical Testing of Textiles* (Wood head Publishing Limited, Cambridge) 1999.
40 *Method for resistance of fabrics to water absorption (Static immersion test) BS 3449* (British Standards, London, England) 1990.
41 Erik Johasson, Sofia Thorsson, Rohinton Emmanuel & Eduardo Kruger, *Urban Climate*, 10 (2014) 346.
42 Raechel Laing & Ingham P E, *Cloth Text Res J,* 3(2) (1984-1985).
43 Yamini Jhanji, Deepti Gupta & Kothari V K, *Indian J Fibre Text Res*, 40 (2015) 11-18.
44 Zhuang Q, *Text Res J,* 72(8) (2002) 727.