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Thermal comfort properties of single jersey fabrics made from recycled polyester and cotton blended yarns

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Thermal comfort properties of single jersey fabrics made from recycled polyester and cotton blended yarns have been studied. Single jerseys knitted fabrics are prepared with different recycled polyester blend ratios, linear density and loop lengths. Box and Behnken, a three level three variable factorial design technique has been used to study the interaction effects of the variables on the characteristics of fabrics. The influence of these variables on thermal comfort properties of fabrics is studied, their response surface equations are derived and design variables are optimized. Fabric becomes thinner, lighter and more porous with the increase in recycled polyester in blend ratio and loop length, whereas thicker, heavier and less porous fabric is resulted with the increase in linear density. Similarly, the increase of linear density results in thicker, heavier and less porous fabric with higher thermal conductivity, lesser air permeability and thermal resistance and high relative water-vapor permeability at medium linear densities. Loose structure results in thinner, lighter and more porous fabric with higher thermal resistance, air permeability and relative water-vapor permeability, and lesser thermal conductivity.

Keywords: Air permeability, Polyester/cotton blend, Recycled polyester, Relative water-vapor permeability, Single jersey, Thermal conductivity, Thermal resistance

1 Introduction

Polyester and cotton account for 40% and 35% of global clothing industry respectively[1]. Polyester is a petroleum-based synthetic fibre and relies on the utilization of non-renewable resources. The stringent environmental requirements coupled with people's increased awareness on environmental friendly practices have facilitated the development and utilization of eco-friendly practices. Recycling of materials is considered to be eco-friendly[2-4] and post-consumer polyethylene terepthalate (PET) bottles are recycled using mechanical and chemical processes[5,6]. Mechanical recycling is basically a melt extrusion process and chemical recycling aims at the reduction of plastic polymers into various levels like oligomers or monomers by reaction with certain chemical agents. Blending of various fibres is a familiar practice in the textile industry. Blending aims at enhancement of the properties of resultant fibre mix and optimizes the cost of raw materials[7]. Polyester/Cotton (P/C) fibre blending displays higher durability and easy care properties than 100% cotton[8]. Of late, recycled fibres are supplemented with the addition of virgin polyester fibres and/or cotton in order to achieve enhanced properties, aesthetics and functional values[9,10]. Researchers[11-16] have successfully studied the blending of recycled PET flakes with virgin PET chips. Recycled polyester blended yarns were successfully produced by ring, rotor and friction spinning[17-22].

Knit fabrics are commonly preferred in sportswear, casualwear and innerwear due to their outstanding comfort properties, extensible loop structure, light weight, warmth, wrinkle resistance and easy care properties[23]. Plain knitting amounts to 90% of all knitted fabric consumption globally[24]. Growing awareness on eco-friendly practices has expanded the production of knitted goods with the inclusion of recycled fibres and their blends[25]. Comfort is typically defined as "the absence of displeasure or discomfort", or "a neutral state compared to the more active state of pleasure"[26]. Clothing comfort can be classified into four categories, namely psychological, thermo-physiological, sensorial (tactile) and garment fit comfort[27]. Psychological comfort relates to the sensory perceptions and fashion trends, thermo-physiological comfort is governed by movement of air, moisture and heat through the fabric, sensorial (tactile) comfort depends upon fabric surface and mechanical properties and garment fit comfort depends on the fit (loose/normal/tight) of the garment on the body. Of these four types of comfort, thermal comfort has drawn the attention of numerous researchers due to significance of maintenance of thermal balance at various atmospheric conditions.

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Literature suggests that thermal comfort depends on a wide variety of parameters such as fibre properties, yarn properties, fabric properties, finishing (mechanical and chemical) treatments and clothing conditions[28-41]. Thermal comfort can be best understood by the measurement of thermal conductivity, thermal resistance, air permeability and relative water-vapor permeability.

Utilization of recycled polyester in the knit apparel is ever increasing but the characterization of knit apparel made from recycled polyester blended yarns is limited to mechanical and moisture management properties. Choi and Kim[42] have characterized the mechanically recycled PET, chemically recycled PET, PET-nylon 6 blend and virgin PET knitted fabrics and found that tensile, compressional and pilling properties of both mechanically and chemically recycled PET knitted fabrics were similar to that of virgin knitted fabrics and wick ability of mechanically recycled PET knitted fabric was better than other recycled PET knitted fabrics and recycled PET–nylon6 blend knitted fabric possess good moisture regain, moisture permeability, smoothest appearance and coolest feeling. The primary objective of the present study is to investigate the thermal comfort properties of single jersey knit fabrics made from recycled polyester and cotton blended yarns. To fulfill this objective, effect of recycled polyester fibre content, linear density and loop length on thermal comfort properties has been studied.

2 Materials and Methods

2.1 Materials

Fifteen single jersey knitted fabrics were prepared using recycled polyester / cotton blended yarns. Box and Behnken, a three level, three variable factorial design technique has been used to study the interaction influence of variables on thermal comfort characteristics of fabrics. Table 1 represents the range of variables and Table 2 shows the Box-n-Behnken sample plan. The three variables of the design, including recycled polyester blend content, linear density (tex) and loop length (mm) at three levels, will be able to study the interaction influence of variables on thermal comfort characteristics of fabrics (thermal conductivity, thermal resistance, air permeability and relative water-vapor permeability).

Single jersey knitted fabrics were manufactured on a weft knitting machine (Mayer & Cie GmbH & Co, Tailfingen, Germany) with the following machine settings: model MV4, gauge 24, cylinder diameter 23″, speed 30 rpm, feeders 74 and number of needles 1728; the ambient knitting room conditions of relative humidity (RH) 65±2% and a temperature (temp.) 30±2°C. All the samples were produced with three different loop lengths (2.7, 2.9 and 3.1mm) which enabled the tight, medium and loose knit structures respectively. Knit fabrics were produced under constant machine settings and ambient room conditions; and the produced samples were conditioned at standard atmosphere conditions (RH 65±2% and temp. 25±2°C) for at least 24 h prior to testing.

2.2 Test Methods

Knit fabric physical properties such as loop length, thickness, areal density (mass per unit area), volume porosity and thermal properties (thermal conductivity, thermal resistance air permeability and water-vapor permeability) were measured and statistically evaluated.

Table 1 — Range of variables

Variables	Levels		
	-1	0	1
Recycled polyester blend content (X_1)	0.33	0.5	0.67
Linear density (X_2), tex	23.6	29.5	39.4
Loop length (X_3), mm	2.7	2.9	3.1

Table 2 — Box and Behnken design sample plan

Standard order	X_1	X_2	X_3
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

2.2.1 Physical Properties

Knit fabric wales per inch (WPI) and courses per inch (CPI) were measured according to the ASTM D-3887 standard. Fabric thickness (mm) was determined according to ASTM D 1777 using Shirley thickness tester. Fabric areal density (g/m^2 or GSM) was calculated according to ASTM D3776/ D 3376 M-09. Knit fabric loop length (mm) was measured according to ASTM D 3887. Volume porosity (%) of the fabric was calculated as explained by Majumdar *et al.*[43]. Averages of ten readings were taken for each physical property measured (Table 3).

2.2.2 Thermal Conductivity and Resistance

The Alambeta instrument (Technical University of Liberec, Liberec, Czech Republic) was used in the measurement of thermal conductivity, fabric thickness and thermal resistance values according to ISO 11092. Heat flux sensors detect the amount of heat flow from the hot plate to the cold plate through the fabric and thickness is measured by another sensor and both of these values are used in the calculation of thermal resistance.

2.2.3 Air Permeability

Air permeability is another important property of textiles which influences the flow of vapor from the human body to the environment and the flow of fresh air into the body. Air permeability of the fabric was observed using Textest FX 3300 (Textest Instruments AG, Schwerzenbach, Switzerland) according to ASTM D737 at a pressure of 100Pa.

2.2.4 Relative Water-vapor Permeability

The water vapour permeability was measured on a Permetest instrument (Sensora Company, Liberec, Czech Republic) according to ISO 11092. The instrument works on the principle of heat flux sensing. The temperature of the measuring head is maintained at room temperature for iso-thermal conditions. When water flows into the measuring head, some amount of heat is lost. This instrument measures the heat loss from the measuring head due to the evaporation of water in bare condition and with being covered by the fabric. Then the relative water vapour permeability was calculated from the ratio of the latter to that of former (ASTM E96).

3 Results and Discussion

3.1 Physical Properties

Table 3 shows the increase in recycled polyester blend ratio tends to decrease the fabric GSM and thickness, but increases volume porosity. The results are substantiated by the findings of researchers[30,34] that the polyester being a finer fibre, has less bending rigidity, enhances packing fraction and results in porous fabric; less bending rigidity of polyester also enhances the compressibility of knit loops and results in thinner and lighter fabric. It is also observed that the increase in linear density is found to increase fabric GSM, thickness and reduces volume porosity. Further to that, increased loop length causes a decrease in fabric GSM and thickness, and increase in volume porosity, which correlate to the common understanding of knit fabric behavior experimentally verified by researchers[29].

3.2 Thermal Comfort Properties of Knitted Fabrics

Thermal comfort properties of knit fabrics are given in Table 4. Statistical package "MINITAB 16" was used to obtain response surface equations (Table 5) and contour plots. Statistical analysis was examined by

Table 3 — Physical properties of single jersey knit fabrics

Sample number	Recycled polyester blend ratio (X_1)	Linear density (X_2), tex	Loop length (X_3), mm	Wales/ inch	Courses/inch	Fabric mass g/m^2	Fabric thickness, mm	Volume porosity, %
1	0.33	23.6	2.9	31	35	113.8	0.664	91.0
2	0.67	23.6	2.9	31	35	115.2	0.626	92.6
3	0.33	39.4	2.9	26	30	124.5	0.675	90.2
4	0.67	39.4	2.9	26	30	127.9	0.634	91.7
5	0.33	29.5	2.7	29	37	118.7	0.671	90.5
6	0.67	29.5	2.7	29	37	117.4	0.631	92.4
7	0.33	29.5	3.1	25	34	120.1	0.673	90.8
8	0.67	29.5	3.1	27	35	123.4	0.632	92.1
9	0.5	23.6	2.7	31	36	109.2	0.625	90.9
10	0.5	39.4	2.7	27	32	134.6	0.632	90.1
11	0.5	23.6	3.1	29	33	108.5	0.657	92.5
12	0.5	39.4	3.1	25	29	130.3	0.662	90.3
13	0.5	29.5	2.9	30	34	125.4	0.631	90.2
14	0.5	29.5	2.9	30	34	124.3	0.631	90.2
15	0.5	29.5	2.9	30	34	123.8	0.631	90.2

two way analysis of variance (ANOVA) with a confidence level of 99% and obtained results are summarized in Table 6. ANOVA test results indicate that the selected parameters are significant and the regression models are adequate.

3.2.1 Thermal Conductivity

Thermal conductivity, an intrinsic property of a material, indicates the materials ability to conduct heat. It is the flux of heat (energy per unit area per unit time) divided by the temperature gradient. Thermal conductivity is calculated by $\lambda = Qh/A\Delta Tt$; where Q is the amount of conducted heat (J), h is the fabric thickness (m), A is the area through which the heat is conducted (m^2), ΔT is the drop in temperature (K), and t is the time of conductivity (s). The thermal property of a fabric depends upon the type of fibre, amount of entrapped air in the fabric structure. It is well known that the thermal conductivity of a textile material is higher than that of the air entrapped in it[27].

Table 4 — Thermal comfort properties of single jersey knit fabrics

Sample number	Thermal conductivity $\times 10^{-3}$, W/mK	Thermal resistance k m^2/W	Air permeability cm^3/cm^2s	Relative water-vapor permeability, %
1	0.0496	21.6	198	35.1
2	0.0537	20.5	206	38.7
3	0.0488	22.7	199	37.0
4	0.0543	19.8	201	37.9
5	0.0542	19.2	194	35.9
6	0.0537	19.8	224	36.7
7	0.0526	21.1	184	37.9
8	0.0531	20.5	206	37.1
9	0.0550	19.5	199	35.2
10	0.0568	18.7	185	33.4
11	0.0484	22.2	209	38.2
12	0.0497	21.4	205	37.8
13	0.0452	22.4	227	37.2
14	0.0465	22.8	225	37.4
15	0.0463	22.6	223	37.0

From response surface equations (Table 5) and contour plots (Fig. 1), the optimized values of thermal conductivity are predicted at recycled polyester blend ratio of 0.49, linear density of 26.55 tex and loop length of 3.1 mm. Increase in thermal conductivity could be justified by the inherently higher thermal conductivity nature of polyester fibre than cotton fibre[29,44], decreased fabric thickness and increased fabric volume porosity[30,34]. With the loose fabric structure, thermal conductivity is found to decrease due to the increase in entrapped air.

3.2.2 Thermal Resistance

Thermal resistance is a measure of the material's ability to prevent heat from flowing through it. It is an indication of how well a material insulates heat. Under certain climatic conditions, low thermal resistance of clothing tends to give cool feeling as the heat energy between the wearer's skin and clothing will gradually decrease. Thermal resistance, for idealized conditions, is calculated by R=h/λ; where R is the thermal resistance, h the thickness and λ the thermal conductivity[43]. Thermal resistance is an important parameter and is greatly influenced by fibre type, yarn properties and fabric structure[27,34].

From response surface equations (Table 5) and contour plots (Fig. 2), the optimal values of the thermal resistance are predicted at recycled polyester blend ratio of 0.41,

Table 5 — Response surface equations

Property	Response surface equation	R^2	Optimized values
Thermal conductivity	$0.047456 - 0.001558 X_1 - 0.00058 X_2 + 0.001233 X_3 + 0.002364 X_1^2 + 0.004329 X_2^2 + 0.000315 X_3^2 - 0.000220 X_1 X_2 - 0.001150 X_2 X_3 - 0.001235 X_3 X_1$	71.33	X_1=0.49, X_2=26.55, X_3=3.1
Thermal resistance	$22.3198 + 0.5839 X_1 + 0.2658 X_2 - 0.7452 X_3 - 1.0135 X_1^2 - 1.5539 X_2^2 + 0.0591 X_3^2 + 0.1067 X_1 X_2 + 0.3846 X_2 X_3 + 0.7750 X_3 X_1$	85.86	X_1=0.41, X_2=32.63, X_3=3.0
Air permeability	$225.163 + 7.403 X_1 - 2.750 X_2 + 0.782 X_3 - 10.750 X_1^2 - 13.413 X_2^2 - 12.250 X_3^2 - 2.741 X_1 X_2 - 2.000 X_2 X_3 + 4.201 X_3 X_1$	77.47	X_1=0.62, X_2=37.56, X_3=3.1
Relative water vapor permeability	$36.4805 + 0.1204 X_1 + 1.1037 X_2 - 0.6647 X_3 + 0.8177 X_1^2 - 0.6718 X_2^2 + 0.5263 X_3^2 + 0.6724 X_1 X_2 + 0.7350 X_2 X_3 - 0.2445 X_3 X_1$	82.7	X_1=0.4, X_2=26.61, X_3=3.1

Table 6 — ANOVA test results

Source of variation	DF*	Thermal conductivity		Thermal resistance		Air permeability		Relative water-vapor permeability	
		F*	P*	F*	P*	F*	P*	F*	P*
Regression	9	1.38	0.377	3.37	0.097	2.85	0.131	2.67	0.146
Residual error	5	–	–	–	–	–	–	–	–

DF– Degree of freedom, F – Variance Ratio and P* – Probability.

linear density of 32.63 tex and loop length of 3.0 mm. It is observed that within the experimental design plan, with the increase in recycled polyester blend ratio, linear density is found to decrease thermal resistance. This can be justified by the decrease in fabric thickness content[30, 34,36], as fabric thickness and thermal resistance are directly related. It is also observed that thermal resistance is higher for lower lengths. It is a well known fact that thermal conductivity and thermal resistance are opposite to each other and the same is established in this study.

3.2.3 Air Permeability

From response surface equations (Table 5) and contour plots (Fig. 3), the optimal values of the air permeability are predicted at recycled polyester blend ratio of 0.62, linear density of 37.56 tex and loop length of 3.1 mm. The results are in conformity with the

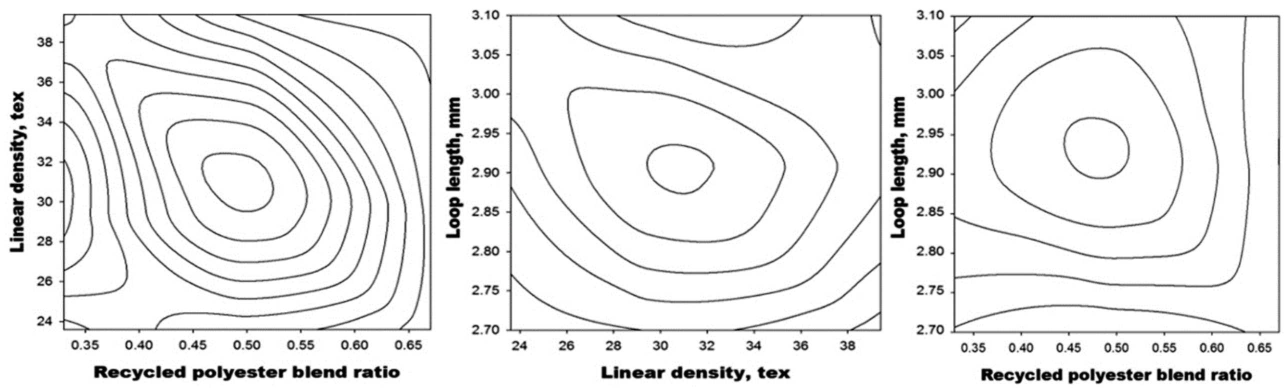

Fig. 1 — Thermal conductivity of single jersey knit fabrics

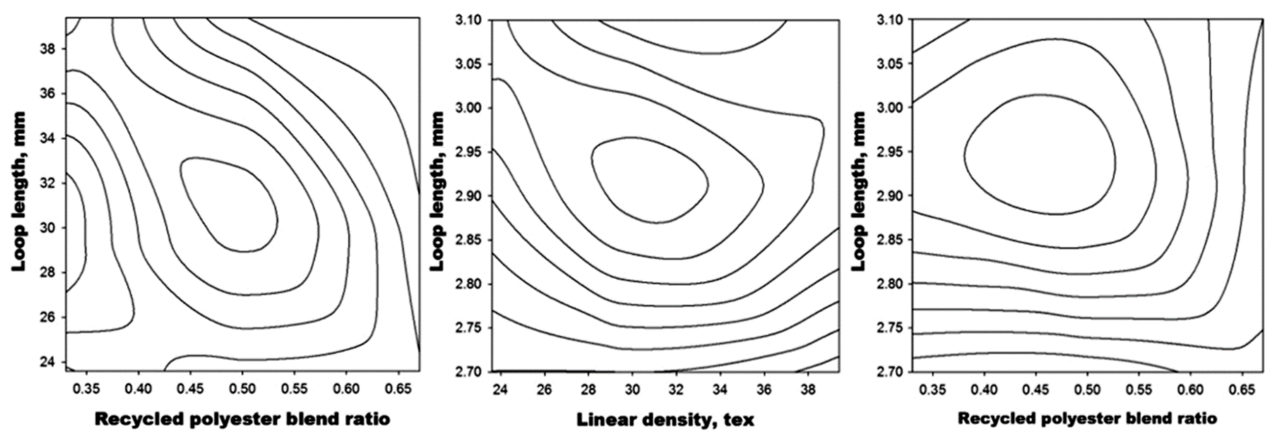

Fig. 2 — Thermal resistance of single jersey knit fabrics

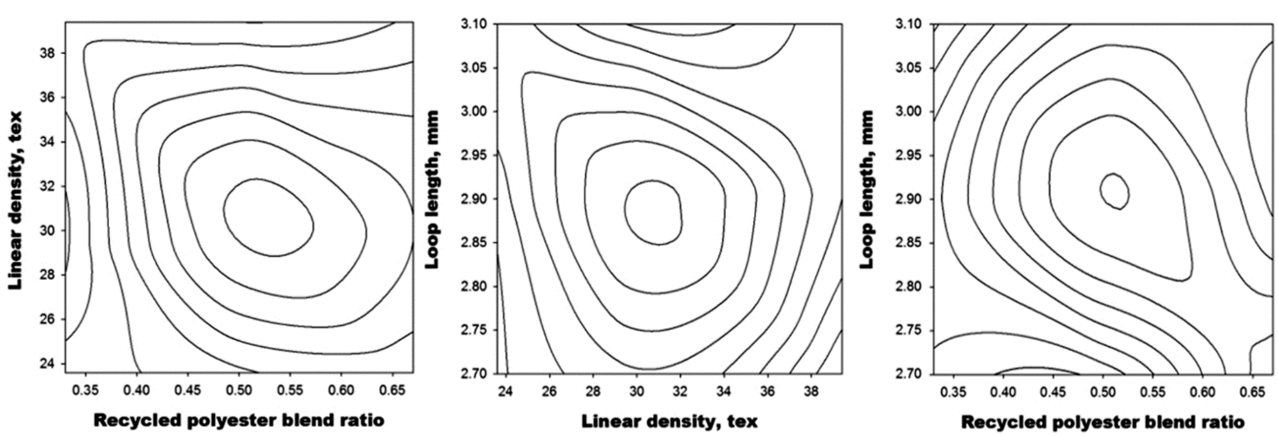

Fig. 3 — Air permeability of single jersey knit fabrics

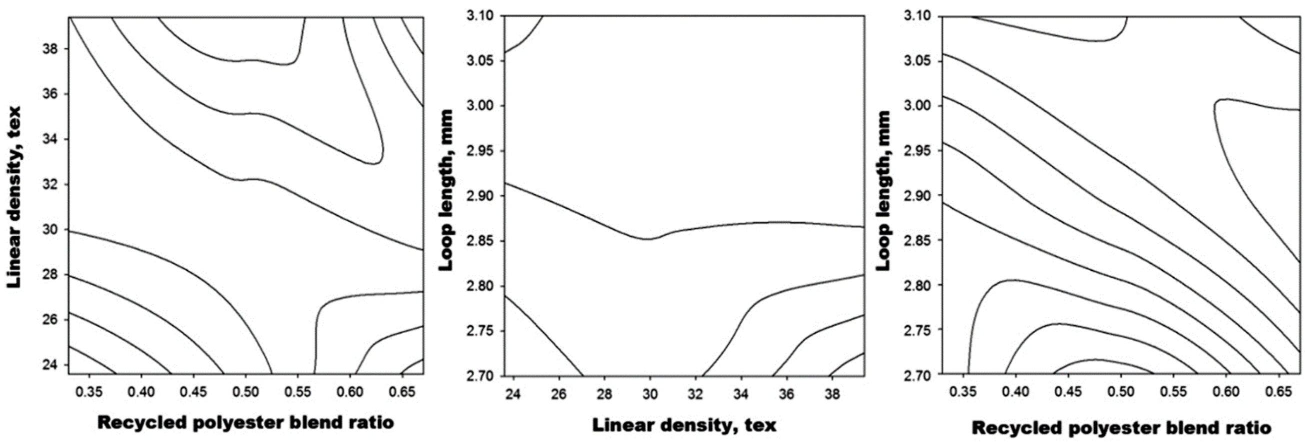

Fig. 4 — Relative water-vapor permeability of single jersey knit fabrics

experimentally verified understanding that the air permeability increases with the decrease in fabric thickness and increase in volume porosity[27, 34, 38, 45].

3.2.4 Relative Water-vapor Permeability

Relative water-vapor permeability of a fabric is the ability to transmit water-vapor from the body. A combination of high thermal resistance and low relative water-vapor permeability can cause uncomfortable situation to the wearer as the heat stored in the body cannot be dissipated. From response surface equations (Table 5) and contour plots (Fig. 4), the optimal values of the relate water-vapor permeability are predicted at recycled polyester blend ratio of 0.4, linear density of 26.61 tex and loop length of 3.1 mm.

Relative water-vapor permeability of a material is highly dependent on the macro-porous structure of the constituent fibres of the yarn [26, 27, 29, 39]. Polyester fibres being finer have less diameter, better packing fraction, increased interstitial spaces or pores and finally contribute to higher relative water-vapor permeability.

4 Conclusion

It is found that the recycled polyester blend ratio, loop length, linear density have significant influence on single jersey fabric’s thermal comfort properties. It is observed that with the increase in recycled polyester ratio, fabric becomes thinner, lighter and more porous with higher thermal conductivity, air permeability, relative water-vapor permeability and lesser thermal resistance. Similarly, increase in linear density results in thicker, heavier and less porous fabric with higher thermal conductivity, lesser air permeability and thermal resistance and high relative water-vapor permeability at medium linear densities. Loose structure results in thinner, lighter and more porous fabric with higher thermal resistance, air permeability and relative water-vapor permeability and lesser thermal conductivity. Optimum blend ratio, linear density and knit structure can be suitably designed to meet the thermal comfort requirements of various ends uses.

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