Indian Journal of Fibre & Textile Research
Vol. 40, March 2015, pp. 11-18

Comfort properties of plated knitted fabrics with varying fibre type

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Received 28 December 2013; revised received and accepted 18 March 2014

The present study aims to investigate the effect of fibre type and yarn linear density on the thermal properties such as thermal resistance, thermal conductivity and thermal absorptivity along with air permeability and moisture vapor transmission rate of single jersey plated fabrics. Plated fabrics with nylon in the next to skin layer seem suitable choice for warm conditions as these fabrics would feel cooler on initial skin contact owing to high thermal absorptivity and are permeable to passage of air and moisture vapor. Fabrics knitted with yarns of high linear density seem unsuitable in warm conditions owing to higher value of thermal resistance and lower values of air permeability and moisture vapor transmission rate. Two way analysis of variance is conducted to test the significance of categorical variables, i.e. fibre type and yarn linear density on dependent variables. All the dependent variables except thermal resistance are found to be affected by the categorical variables at 95% confidence intervals.

Keywords: Comfort properties, Cotton, Knitted fabrics, Moisture management, Nylon, Single jersey fabric, Thermal properties

1 Introduction

Human body is considered to be a complicated thermodynamic system which maintains thermal equilibrium with the environment by balancing the energy production and dissipation. The energy is produced continuously by metabolic activities and it must be continuously dissipated into the surroundings by dry heat loss (insensible perspiration) or latent heat loss (sensible perspiration), depending on ambient environmental conditions and individual's physical activity[1]. Sensation of warmth-coolness and damp-dryness, which depends on air permeability and capability to absorb and evaporate sweat, is primary determinants of thermal comfort[2]. Clothing considered as the second skin should serve both as an effective transporter and barrier of heat to maintain the thermal balance with the surroundings. Therefore, thermal properties, air permeability and water vapor transmission properties of fabrics are very crucial for the human comfort. The transient heat transfer which gives the sensation of warm-cool feeling upon the first brief contact of fabric with human skin is also an important parameter that affects the clothing comfort[3].

Thermal resistance, air permeability and water vapor transfer are primarily determined by chosen fibres, fibre ratio, yarn spinning method, fabric hairiness, fabric structure especially thickness and porosity[1,4]. The transient transfer of heat energy depends on contact interface between fabric and skin, which, in turn, depends on many morphological and structural parameters like fibre morphology, yarn and fabric structure[5].

The main characteristics of a functional knitted structure to be used in next to skin applications are concerned with the existence of two different fabric layers identified as the separation and the absorption layers. The separation layer is usually composed of synthetic fibres and is the inside layer of the fabric (next to skin) responsible for transferring the sweat to the outer layer by wicking. The absorption layer composed of hydrophilic fibre is the outside layer responsible for absorbing and evaporating the liquid sweat[6,7]. The double layered fabrics can be developed as single jersey plated structures with careful selection of distinct fibre and yarn combinations to appear in the technical face and back side. Figure 1 shows the schematics of distinct face and back layers of plated knitted fabrics.

A variety of natural and synthetic fibres is finding application in double-layered fabrics, active wear, innerwear and sportswear owing to unique characteristics and features of each fibre. While natural fibres are considered suitable for low activity levels,

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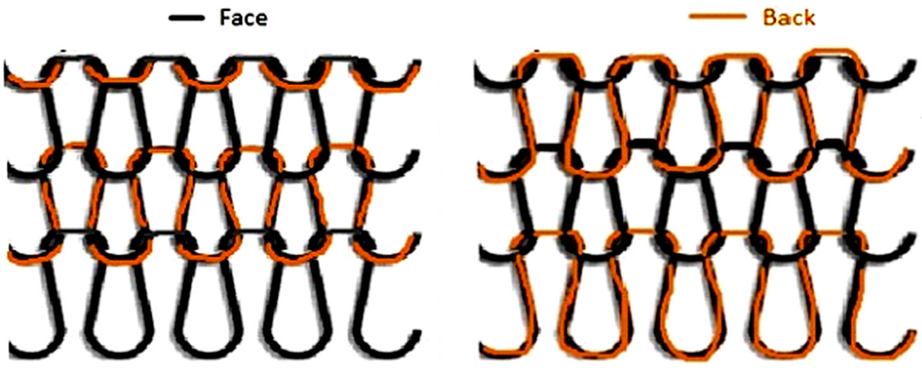

Fig.1—Schematic diagrams of face and back layers of plated knitted fabrics

synthetic fibres are better suited for high activity levels. However, no single fibre or different fibre blends can ensure ideal clothing suitable for varied applications. The right type of fibre needs to be in the right place according to the fabric end use. Cotton remains by far the most important natural fibre of the 20th century. It is characterized by good handle and hygiene properties. Additionally cotton fibre has good water vapor and air permeability, and hence is recommended for summer garments, but it is not a preferred choice as next to skin layer due to skin clinginess and chill feel when wet. Also, cotton fabrics are slow drying particularly in the conditions of high liquid sweat generation[4,7]. Polyester fibre has low moisture absorption and hence its easy care properties are recommended in base fabrics for active wear. Excellent heat resistance, thermal stability, outstanding dimensional stability and durability are some other attributes of polyester fibre. Polypropylene is claimed to be a proven performer in moisture management due to its hydrophobic nature and has the capability to provide insulation even when wet. It is more oleophilic than polyester and thus has a tendency to attract and hold oily body odors. Nylon is often favorable choice in woven outer wears due to its low air permeability and ability to trap heat. Other characteristics include high moisture regain, lightweight, softness, durability and high strength.

Several researches have been directed towards the effect of fibre type, yarn variables such as yarn count, yarn twist and fabric structure on comfort properties of knitted fabrics. It has been reported that fibre type and fabric structure play a crucial role in determining the comfort properties of textile fabrics[1, 2, 8].

Oglakcioglu *et al.*[4] studied the thermal properties of different cotton and angora rabbit fibre blended fabrics and reported that as the angora rabbit fibre ratio increased, the thermal resistance increased but thermal conductivity, thermal absorptivity and relative water vapor permeability decreased.

Stankovic *et al.*[9] investigated the thermal properties of natural and regenerated cellulose fibres and suggested that heat transfer through the fabrics is highly related to both capillary structure and surface characteristics of yarns as well as air volume distribution within the fabrics. Geraldes[6] suggested that percentage of hydrophobic component is crucial to the behavior of functional knits and observed linear relationship among thermal absorptivity, thermal resistance and percentage of hydrophobic component (polypropylene) in the functional knit structures.

Farnworth and Dolhan[10] observed no difference in heat loss between cotton and polypropylene underwear fabrics during period of heavy sweating and suggested that there was no evidence of thermal well-being of wearer enhanced by polypropylene underwear. The study of Cubric *et al.*[11] was focused on the influence of type of textile fibres on water vapor transfer, thus indicating the medium correlation between water vapor resistance and moisture regain.

Majumdar *et al.*[3] studied the thermal properties of knitted fabrics made from natural and regenerated bamboo cellulosic fibres and observed an increase in air and water vapor permeability along with decrease in thermal conductivity as the proportion of bamboo fibre increased. Prakash & Ramakrishnan[12] studied the thermal comfort properties of cotton-bamboo blended yarn knitted fabrics and observed that parameters of air permeability, thermal resistance, relative water vapor permeability and thermal conductivity are significantly affected by fibre blend ratio.

Ozdil *et al.*[13] studied the effect of yarn properties on different thermal comfort properties of rib knitted fabrics and observed that the thermal resistance decreases and water vapor permeability increased with the increase in yarn twist and yarn count. Bivainyte *et al.*[14] established that thermal properties of double-layered knitted fabrics depends on raw material, structural parameters and knitting pattern of the fabric and suggested that thermal resistance depended more on synthetic thread type than on natural fibre yarns. Pac *et al.*[5] studied the influence of fibre morphology, yarn and fabric structure on transient thermal properties and established link between these behaviors and warm-cool touch. It was reported that fabrics made from pima cotton owing to less roughness and hairiness absorbed more energy and would feel cooler when compared to fabrics made from kaba cotton. However, cotton variety seemed to have less influence on warm-cool feeling as the fabric stitch length was increased.

Survey of published literature suggests that the researches have focused on the influence of fibre, yarn and fabric constructional variables on comfort properties of different knitted structures. However, there are limited studies devoted to the comfort properties of single jersey plated structures with distinct face and back layers, and not much has been reported about the correct selection of fibre types to be used in the next to skin layer and yarn linear density in the face layer to achieve wearer comfort. In view of the above, this study has been planned to examine the comfort properties of plated knitted fabrics developed with varying hydrophobic fibres in the back (next to skin) layer and varying yarn linear density in the face layers.

2 Materials and Methods

2.1 Materials

Cotton ring-spun yarns of varying yarn linear density i.e. 29.5, 39.4 and 59.1 tex and polyester, polypropylene and nylon continuous filament yarns of 25.5 tex (229.5D), 24.0 tex (216D) and 23.3 tex (210D) were used for the knitted sample preparation. Nine single jersey plated fabrics were knitted with cotton yarns in the face and polyester, polypropylene and nylon filament yarns in the back layer as per the details given in Table 1. Figure 2 shows different fibre compositions in the face and back layers of plated knitted fabrics.

All nine samples were prepared on hand operated flat knitting machine (Elex, China) with machine gauge of 14, needle bed of 42 inch and 588 needles on each bed. The machine had two needle beds called front and rear bed. The front bed was utilized for the preparation of single jersey plated fabrics.

2.2 Methods

All fabric samples were washed with nonionic detergent (Lisapol N) at 40°C for 30 min followed by tumble drying for 30 min.

2.2.1 Physical Characterization

Fabric aerial density was determined according to ASTM D-1059. The thickness of fabric samples was measured on Alambeta (Sensora, Czech Republic).

Tightness factor of the plated fabrics was determined using the following equation:

$$\text{Tightness factor} = \frac{\sqrt{\text{Tex}}}{\text{Loop length (cm)}} \qquad \dots (1)$$

Table 1—Yarn and fabric characteristics of developed samples

Sample code	Fibre type		Yarn linear density tex		Resultant yarn linear density, tex
	Face	Back	Face	Back	
PC1	C	PET	29.5	25.5	55.0
PC2	C	PET	39.4	25.5	64.9
PC3	C	PET	59.1	25.5	84.6
PPC1	C	PP	29.5	24.0	53.5
PPC2	C	PP	39.4	24.0	63.4
PPC3	C	PP	59.1	24.0	83.1
NC1	C	N	29.5	23.3	52.8
NC2	C	N	39.4	23.3	62.7
NC3	C	N	59.1	23.3	82.4

C- Cotton, PET – Polyester, PP – Polypropylene and N – Nylon.

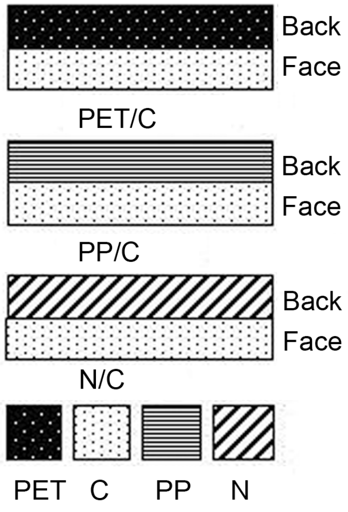

Fig. 2—Fibre composition in face and back layers of plated knitted fabrics

Table 2—Physical, thermal properties and air permeability of plated fabrics

Sample code	Thickness mm	Weight g/m^2	Porosity %	TF tex$^{1/2}$/cm^2	TR 10^{-3}×Km^{2}W^{-1}	TC 10^{-3}×Wm^{-1}K^{-1}	TA Ws$^{1/2}$m^{-2}K^{-1}	AP cm^3/cm^2/s
PC1	1.21	405	76.9	14.0	24.5	50.3	145.6	102.4
PC2	1.30	448	76.2	15.0	25.3	52.4	148.9	60.6
PC3	1.40	470	76.8	17.0	26.0	59.7	190.6	30.3
PPC1	1.20	350	76.1	14.0	24.0	48.5	147.6	75.2
PPC2	1.30	370	76.6	15.0	24.2	50.5	151.0	54.1
PPC3	1.41	400	76.7	17.0	25.0	58.1	201.9	22.6
NC1	1.20	380	76.2	14.0	24.2	51.6	160.7	80.3
NC2	1.31	410	76.5	15.0	24.8	54.7	167.5	56.4
NC3	1.40	440	76.4	17.0	25.2	65.7	245.5	24.7

TF - tightness factor, TR - thermal resistance, TC- thermal conductivity, TA- thermal absorptivity and AP- air permeability.

Fabric porosity was determined using the following equation:

$$\text{Porosity} = \frac{(\rho_o - \rho)}{\rho_o} \times 100\% \qquad \ldots (2)$$

where ρ_0 is the fibre density (kg/m^3); and ρ, the fabric density (kg/m^3).

2.2.2 Comfort Characteristics

Thermal Properties—Fabric samples were evaluated for their thermal properties, such as thermal resistance (TR), thermal conductivity (TC) and thermal absorptivity (TA) on Alambeta. The tests were performed according to ISO EN 31092- 1994.

Air Permeability—Air permeability (AP) of the fabrics was measured on FX 3300 air permeability tester (TEXTEST AG, Switzerland) at a pressure of 100Pa according to ASTM D737.

Moisture Vapor Transmission Rate—Moisture vapor transmission rate *(MVTR)* of the test fabrics was determined by moisture vapor transmission cell (MVTR cell) (Grace, Cryovac division). Amount of water vapor transmitting through 100 inch^2 area of fabric during 24 h can be determined using the instrument by fast and simplified method. The cell was constructed with provision of test sample to be suspended across the center with distilled water below and humidity sensing device above. The increase in the humidity level on a 0-100 arbitrary humidity meter scale at equal intervals of time was recorded and the dry side was dehumidified. Readings at constant time intervals were varied from 5 to 75. Moisture vapor transmission rate of fabrics as a function of humidity change at a particular time interval can be calculated as:

$$\text{MVTR} = (269 \times 10^{-7}) \times (\Delta\text{RH}\% \times \frac{1440}{t}) \times H \qquad \ldots (3)$$

where ΔRH% is the average difference in successive % RH values; t, the time interval in minutes; and H, the gram water per m^3 of air at cell temperature.

2.2.3 Statistical Analysis

The effect of categorical variables, such as fibre type and yarn linear density on dependent variables was statistically analyzed. General linear model was used to perform two-way analysis of variance using SPSS 13 statistical software package.

3 Results and Discussion

All the nine fabrics were tested for thermal properties, air permeability and moisture vapor transmission rate. Results are presented in Table 2.

3.1 Thermal Resistance

Figure 3(a) shows that thermal resistance increases as the face yarn linear density increases from 29.5 tex to 59.1tex for all the fabrics, irrespective of the fibre types. Increase in thermal resistance could be attributed to the increase in thickness, as the face yarn (cotton) becomes coarser. Increase in fabric thickness influences fabric porosity due to corresponding increase in fabric volume, thereby increasing the amount of air in fabric interstices[9]. Since the volume of air enclosed is much higher than the volume of fibres, the insulation is dependent more on thickness of material than on fibre type[13]. The findings are in accordance with the work of Cubric *et al.*[15] , who reported that air entrapped in the knitted fabric structure plays a prevalent role for thermal resistance of knitted fabrics. PET/C fabric is observed to have the highest thermal resistance compared to other two

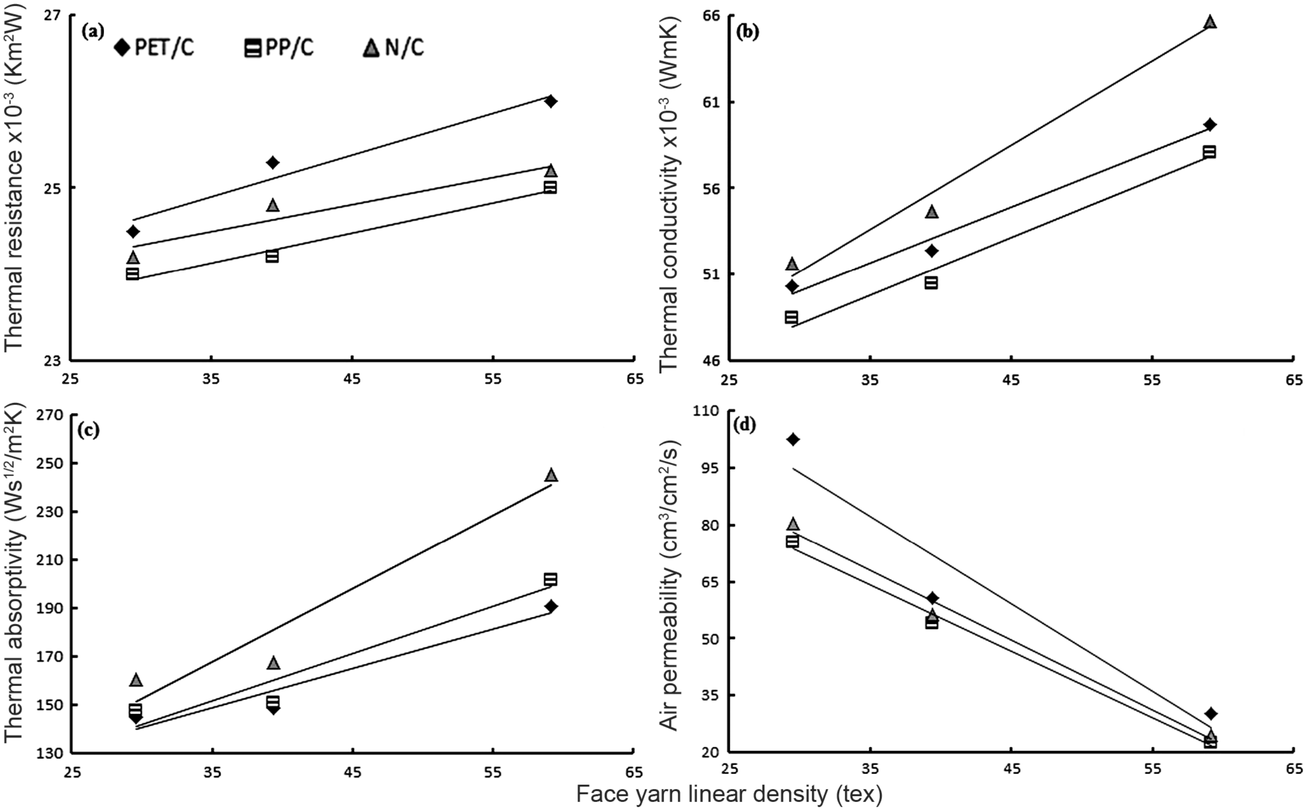

Fig.3—Effect of face yarn linear density and fibre type on (a) thermal resistance, (b) thermal conductivity, (c) thermal absorptivity, and (d) air permeability

types of fabrics (PP/C and N/C). However, fabrics vary marginally in thermal resistance values, further supporting the fact that fabric thickness and enclosed still air are the greatest determinants of insuation of textile fabrics. Since the fabrics are varied only in the fibre type, the thickness is nearly the same for three types of fabrics and hence there is marginal difference in thermal resistance of fabrics with varying fibre types. Table 3 shows the results of two-way analysis of variance. Low values of F and partial eta square show the effect of predictors on thermal resistance to be statistically insignificant.

3.2 Thermal Conductivity

Thermal conductivity (TC) can be expressed by following equation:

$$\lambda = \frac{Qh}{A\Delta Tt} \quad \dots (4)$$

where λ is the thermal conductivity (W/mK); Q, the amount of conducted heat (J); A, the area through which heat is conducted (m^2); t, the time of conduction (s); ΔT, the drop of temperature; and h, the fabric thickness (m).

Thermal conductivity of PET/C, PP/C and N/C plated fabrics decreases as the face yarn linear density decreases, as shown in Fig. 3 (b). The test results indicate that as the thermal resistance decreases, thermal conductivity also decreases for fabrics knitted with finer yarns in the face layer. This contradiction might be explained by fabric thickness. Yarn diameter and therefore, fabric thickness decrease as the yarn becomes finer. If the amount of decrease in thickness is more than the amount of decrease in thermal conductivity, thermal resistance decreases as well and hence reduced thermal conductivity is observed for fabrics knitted with finer cotton yarns. N/C fabric shows the highest value of thermal conductivity compared to the other two types of fabrics, irrespective of the face yarn linear density. The observation may be explained by high value of fibre conductivity of nylon (0.243W/mK) compared to polyester (0.141W/mK) and polypropylene fibres (0.117W/mK). It has been reported that thickness is not independently related to fabric conductivity and

Table 3—Analysis of variances

Dependent variable	Predictor	Type III sum of squares	df	Mean square	F	Sig.	Partial Eta squared
Thermal resistance	Fibre type	5.733	2	2.86	0.32	0.73	0.016
	Yarn linear density	10.233	2	5.12	0.58	0.57	0.028
Thermal conductivity	Fibre type	190.144	2	95.07	5.04	0.01	0.201
	Yarn linear density	1010.144	2	505.07	26.77	0.00	0.572
Thermal absorptivity	Fibre type	7469.644	2	3734.82	32.29	0.00	0.618
	Yarn linear density	35099.678	2	17549.84	151.77	0.00	0.884
Air permeability	Fibre type	1567.678	2	783.84	17.04	0.00	0.460
	Yarn linear density	27102.544	2	1355.27	294.67	0.00	0.936
MVTR	Fibre type	0.520	2	0.26	0.38	0.69	0.019
	Yarn linear density	12.177	2	6.09	8.86	0.00	0.306

that the fibre conductivity also plays a role in determining the fabric conductivity. The conductivity of textile fibres varies from about 5-20 times to that of air and obviously the more the fibres present or higher the fibre conductivity, the higher is the fabric conductivity[8]. Statistical analysis of test results suggests that the effect of fibre type and yarn linear density on thermal conductivity is statistically significant at 95% confidence intervals (Table 3).

3.3 Thermal Absorptivity

Thermal absorptivity (TA) determines the contact temperature of two materials and is the objective measurement of warm-cool feeling of fabrics[4,16,17]. Figure 3 (c) shows the effect of face yarn linear density and back layer fibre type on thermal absorptivity of PET/C, PP/C and N/C plated fabrics. Increase in face yarn linear density results in increase in thermal absorptivity, suggesting that the fabrics knitted with coarser yarns would be perceived cooler on initial skin contact, irrespective of the fibre types. Fabrics knitted with coarser yarns give tighter constructions as suggested by higher values of tightness factor (Table 2) and thus give a cool feeling on initial skin contact. The results are in accordance with the findings of Pac *et al.*[5]. Comparison of thermal absorptivity of fabrics with varying fibre type reveals that N/C fabrics have the highest value of thermal absorptivity, suggesting perception of coolness on initial skin contact which may be attributed to higher thermal conductivity of N/C fabrics. Thermal absorptivity is related to fabric conductivity, density and specific heat capacity, as is clear from Eq. (5). Structural roughness and warm-cool feeling of fabric change according to fibre type, yarn and fabric structure. The specific heat capacity of nylon is high ($1.43 Jkg^{-1}K^{-1}$) compared to polyester ($1.34\ Jkg^{-1}K^{-1}$) and cotton ($1.21\ Jkg^{-1}K^{-1}$). High values of fabric conductivity and specific heat capacity of nylon fibre contribute to higher thermal absorptivity for N/C fabrics.

$$b = \sqrt{\lambda \, \rho \, c} \qquad \ldots (5)$$

where b is the thermal absorptivity ($Ws^{1/2}/m^2K$); λ, the thermal conductivity (W/mK); ρ, the fabric density (kg/m^3); and c, the specific heat capacity ($Jkg^{-1}K^{-1}$). Results are found to be statistically significant as indicated by high values of F & p which is < 0.05 (Table 3).

3.4 Air Permeability

Air permeability (AP) is described as the rate of air flow passing perpendicularly through known area under a prescribed air pressure differential between the two surfaces of material[14, 16]. Air permeability of textile materials depends on yarn, fabric constructional variables and bulk properties particularly thickness, aerial density and porosity. Spacing of yarns is an important parameter influencing openness of fabric structure since air flow takes place through inter yarn pores[9]. Air permeabilty is observed to decrease as the face yarn linear density increases from 29.5 tex to 59.1 tex as shown in Fig. 3 (d). The observations may be attributed to increase in thickness and mass per square meter of fabrics knitted with coarser yarns, irrespective of the fibre type. The higher the thickness and mass per square meter the more is the resistance to passage of air through fabric and hence the reduced values of air permeability for the test fabrics. Moreover, in the case of finer and compact yarn, air in the yarn is reduced but spaces between yarns are larger, and hence the knitted fabrics with finer yarns become more open, and shows permeable structure and higher air permeability. Results are in accordance with the findings of Majumdar[3]. Comparison of plated fabrics with different fibre types in the back layer shows that PET/C fabric exhibits the highest value of air permeability and PP/C fabric is the least permeable to the passage of air. All the fabrics (PC1, PPC1, NC1) are similar in yarn and fabric variables varying only in the fibre types in the back layers, so the fabric porosity is similar. Hence, the difference in air permeability of fabrics could be attributed to the difference in nature of fibres used. Polypropylene fibre yields the greatest volume of fibre for given weight owing to its low specific gravity (0.91g/cm^3), suggesting that it provides good cover and hence lower air permeability for PP/C fabics compared to other two types of fabrics. The effect of two categorical variables on air permeability is found to be statistically significant, as shown in Table 3.

3.5 Moisture Vapor Transmission Rate

Moisture vapor transmission rate (MVTR) is observed to decrease with the increase in face yarn linear density (PC1-PC3, PPC1-PPC3 & NC1-NC3), irrespective of the fibre type. The transmission of water vapor through thick and coarser fabrics would be less compared to finer and thinner fabrics, the reason being that water vapor diffusion through air in fabric is almost instantaneous, whereas diffusion through fabric system is limited due to the low water vapor diffusivity of textile materials[18]. Fine yarns can be packed tightly together, yet spaces between yarns are porous enough, ensuring the higher moisture vapor transmission rate. The difference in moisture vapor transmission rate for three types of fabrics is marginal with N/C plated fabrics, thus showing the highest value and PP/C fabric shows the lowest value of moisture vapor transmission rate, irrespective of the face yarn linear density. The observed trend can best be explained by the mechanism of water vapor transfer through textile structures. Water vapor diffuses through fabrics in two ways viz simple diffusion through air spaces between yarns and along fibre itself. Porosity of material and water vapor diffusivity of fibre affect diffusion rate along textile material at a specific concentration gradient. Diffusivity of material increases with increase in moisture regain[19]. PET/C, PP/C and N/C fabrics are knitted with same constructional variables varying only in the fibre type; hence diffusion through air will be same for three types of fabrics. Moisture regain of material increases with the increase in hydrophilic component, causing higher diffusivity. Therefore, nylon characterized by more water absorbing sites and hence higher moisture regain would transfer more moisture owing to combined effect of diffusion and absorption-desorption. Polypropylene with lower moisture regain and due to hydrophobic nature permits the moisture vapor transfer mainly by diffusion through air spaces and hence shows lower value compared to N/C plated fabrics.

4 Conclusion

Thermal conductivity, thermal absorptivity and air permeability are found to be significantly affected by face yarn linear density and back layer fibre type. The effect of face yarn linear density seems to be more pronounced as against back layer fibre type as indicated by high values of yarn linear density's partial eta square for all the properties under consideration.

Thermal resistance of PET/C, PP/C and N/C fabrics varies marginally, suggesting that the fibre type/raw material do not strongly affect the insulation properties of fabrics with similar thickness and construction. Thermal conductivity, thermal absorptivity and moisture vapor transmission rate are found to be highest for N/C fabrics. Thus, it can be concluded that plated fabrics with nylon in the back layer are suitable choice for warm conditions, as the fabrics would provide cooler feeling on initial skin contact because of high thermal absorptivity and are permeable to passage of air and moisture vapor.

Thermal resistance, thermal conductivity and thermal absorptivity increase while air permeability, moisture vapor transmission rate decrease with increase in face yarn linear density. Thus, it can be concluded that the fabrics knitted with yarns of high yarn linear density (PC3, PPC3, NC3) do not appear to be suitable choice for warm conditions owing to higher value of thermal resistance, and lower values of air permeability and moisture vapor transmission rate.

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