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Thermal comfort properties of weft knitted interlock layered fabrics

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The main objective of this study is to produce interlock fabrics with two different types of material at the face and back and to evaluate the effectiveness of its air permeability and thermal properties, which, in turn, decide the comfort of the wearer. It is observed that the tightness factor of the fabric has a linear relationship with air permeability, thermal conductivity and Qmax. The polyester modal interlock fabric shows a higher Qmax value which provides a good warm-cool effect, that is important for sportswear applications.

Keywords: Comfort, Cotton, Interlock fabric, Knitted fabrics, Modal, Polyester, Soya, Sportswear, Thermal comfort, Wool

1 Introduction

The concern for health is tremendously increasing nowadays and it is achieved through routine sports activities, yoga, etc. The new scope for various types of sportswear has evolved. The global sportswear market is expected to achieve a record growth of 4.11% of CAGR during 2025. As the sportswear market is growing rapidly, consumer requirements are also phenomenally increasing[1].

During intensive sports activities, the generated body heat is first transferred to the skin from the core. The heat is further transported to the external atmosphere from the skin through the textile fabric, which can permit convection and diffusion of heat. The main requirement of sportswear is to transport generated heat and moisture through a textile material to maintain comfort[2]. Hence, the right choice of material capable of handling the thermo-physiological properties of the fabric is essential. The analysis of thermo-physiological properties of textile material with an Alambeta tester and Togmeter shows that the Alambeta instrument is more suitable and convenient for measurement and evaluation[3-5].

Many researchers have studied various materials for identifying the suitability of the fabric for specific end-use. A study was carried out to compare the performance of two thermo-regulating yarns and found that Outlast yarn was better than Coolmax in thermal comfort and moisture transfer[6]. Textured yarns showed a higher tightness factor, and air permeability was found to be lower. The increase in thermal resistance was caused by the increase in the inter-fibre pore volume of the textured yarn[7]. The thermal properties of circular knitted fabrics were assessed, and it was found that modal pique fabric had significantly higher values of thermal resistance and conductivity than cotton fabric[8]. The thermal comfort properties of different weft-knitted structures were investigated. It was concluded that the interlock and rib structures showed remarkably higher thermal conductivity and thermal resistance values than plain fabric[9]. The thermal insulation characteristics of single and multilayer fabrics were studied and it was realised that heat flow density and other thermal characteristics were influenced by the properties of individual layers[10]. The thermal properties of double-layered knitted fabrics were investigated, and it was realised that the knitted fabrics produced with longer loop length exhibits higher thermal conductivity. The thermal resistance of double-layered fabric was higher than the plated fabric due to increased fabric thickness. Hence, thicker fabrics can give more warmth[11]. When comparing the thermal properties of single jersey, plated and bi-layered structures of weft knitting, air permeability was largely influenced by the thickness of the bi-layered fabric[12].

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Sportswear should have good air, heat, and liquid moisture transmission characteristics to make the wearer comfortable. Out of these, when the required level of air and heat are transmitted to balance the body temperature, the problem of transporting moisture, wetness and cling can be drastically reduced. But in traditional sportswear, the main problems faced by the players are sweating, high levels of moisture, wetness, and cling. In this study, the bi-component interlock fabric having a stable and smooth structure with a technical face and back of different materials has been produced and utilised.

2 Materials and Methods

2.1 Fabric Production

Natural and regenerated yarns, like cotton, modal, wool, and soya of 30^s Ne and 120 micro denier polyester filament were selected and procured from local suppliers. The yarn samples were tested for the count, lea strength and twist following the standard procedures of ASTM D1907, ASTM D2256 and ASTM D1423 respectively. Double jersey circular knitting machine with specifications [X – knit stitch, O – tuck stitch, (—)– miss stitch; CN1 – cylinder needle track 1, CN2 – cylinder needle track 2; DN1 – dial needle track 1, DN2 – dial needle track 2; and F1 to F12 – number of feeders two dials and cylinders, interlock gating, having 24" diameter, 18 gauges, and 48 feeders] was used to develop the fabric samples.

The interlock fabric samples were produced by feeding cotton, modal, wool and soya spun yarns to form the face side and polyester filament yarn to form the back side of the fabric. The cylinder needles were fed with cotton, modal, wool and soya yarns while the dial needles were fed with polyester yarn.

Two different structures (Structure 1 and Structure 2) were produced which is similar to the full plating of interlock. The tuck stitches in Structure 1 are responsible for uniting the face and back layers of fabric. Apart from the tuck stitch, the cylinder needles and dial needles are supplied with separate yarns in two feeders. Hence, the yarn knitted by the cylinder needle will not be collected by the dial needle and vice-versa. The cam set out for Structure 1 is given in graphical notations. Structure 2 is also like Structure 1, but the interlocking of face yarn with dial needles for one full course is responsible for uniting the face and back layers of fabric. Apart from the tuck stitch, the cylinder needles and dial needles are supplied with separate yarns in two feeders. Hence, the yarn knitted by the cylinder needle will not be collected by the dial needle and vice-versa. Fabric samples with three levels of tightness factor, namely low, medium, and high, were produced.

2.2 Evaluation

The produced samples were treated with hot water (70°C) for 30 min. Then, the samples were dried in a tumble dryer. After drying, the samples were conditioned in at standard atmosphere for 24 h at 65±2% relative humidity (RH). Later, the fabric samples were tested for courses/cm, wales/cm, areal density, and thickness, as per the procedures given in ASTM D3887, ASTM D3776, and ASTM D1777 respectively. Tightness is expressed as the ratio between yarn count and loop length of the fabric[13].

For complex structures consisting of tuck and float stitches, the measurement of loop length is complex since the consumption of yarn length for derivative stitches is different. The length of yarn consumed for knitting one structural cell was calculated[14]. The structural cell stitch length (SCSL) is the length of yarn in one structural cell or repeat unit of the structure. The produced samples were tested for air permeability (ASTM D737-04 (2008) and thermal properties using the fabric touch tester to evaluate the comfort related properties[15]. SCSL was calculated using the following equation:

$$\text{SCSL} = \frac{A \times B}{C}$$

where A is the length of yarn in one structural call feed in one revolution; B, the no. of needles forming one structural cell; and C, the no. of needles in m/c.

For conducting the subjective trial, the developed fabric samples were converted into a short raglan-sleeved T-shirt. Twelve badminton players as volunteers in the age group of 18-21 were selected based on a simple random sampling method. The fabricated garment was asked to be worn for the entire 2 h session of badminton. After the completion of the session, the questionnaire sheet was given, and the response was collected. The collected data were analysed and compared statistically to determine the comfort-related properties of fabric samples of different fibre blends and fabric structures.

3 Results and Discussion

The produced fabrics have been tested for their structural parameters, tightness factor and SCSL (Table 1).

Table 1 — Structural properties of knitted fabrics
[Back yarn = polyester]

Fabric structure	Face yarn	Tightness	Thickness, mm	Tightness factor	SCSL, cm
Structure 1	Cotton	Low	0.5	13.1	75.24
		Medium	0.52	14.27	69.08
		High	0.52	15.45	63.8
	Modal	Low	0.61	13.23	74.8
		Medium	0.64	14.51	68.2
		High	0.65	15.72	62.92
	Wool	Low	0.48	13.16	74.8
		Medium	0.5	14.07	69.96
		High	0.53	15.17	64.9
	Soya	Low	0.44	13.04	75.24
		Medium	0.44	14.16	69.3
		High	0.48	15.27	64.24
Structure 2	Cotton	Low	0.53	13.03	198.14
		Medium	0.54	14.01	184.32
		High	0.54	15.19	169.92
	Modal	Low	0.68	13.11	197.57
		Medium	0.7	14.7	176.26
		High	0.74	15.51	167.04
	Wool	Low	0.5	13.28	194.11
		Medium	0.52	13.81	186.62
		High	0.56	15.43	167.04
	Soya	Low	0.46	12.96	198.14
		Medium	0.48	13.85	185.47
		High	0.52	14.86	172.8

Table 2 — Thermal comfort properties of Structure 1 and Structure 2

Parameter	Polyester-Modal			Polyester-Cotton			Polyester-Wool			Polyester-Soya		
Structure 1												
Structural tightness factor (STF)	13.10	14.27	15.45	13.23	14.51	15.72	13.16	14.07	15.17	13.04	14.16	15.27
Yarn count, Ne	29.4	29.4	29.4	29.2	29.2	29.2	29.5	29.5	29.5	29.7	29.7	29.7
SCSL, cm	75.24	69.08	63.8	74.8	68.2	62.92	74.8	69.96	64.9	75.24	69.3	64.24
Fabric thickness, mm	0.5	0.52	0.52	0.61	0.64	0.65	0.48	0.5	0.53	0.44	0.44	0.48
Thermal conductivity (compression), mW/m/K	56.63	60.49	65.12	53.52	57.89	62.73	50.25	52.61	55.72	48.61	51.29	55.46
Thermal conductivity (recovery), mW/m/K	54.72	59.52	63.94	51.69	56.9	60.53	48.38	50.16	53.4	46.53	50.37	54.13
Qmax, watts/m^2°C	693.5	739.3	781.4	638.8	701.6	755.2	627.4	657.54	706.1	620.8	634.44	670.6
Structure 2												
Structural tightness factor (STF)	13.03	14.01	15.19	13.11	14.70	15.51	13.28	13.81	15.43	12.96	13.85	14.86
Yarn count, Ne	29.4	29.4	29.4	29.2	29.2	29.2	29.5	29.5	29.5	29.7	29.7	29.7
SCSL, cm	198.14	184.32	169.92	197.57	176.26	167.04	194.11	186.62	167.04	198.14	185.47	172.80
Fabric thickness, mm	0.53	0.54	0.54	0.68	0.7	0.74	0.5	0.52	0.56	0.46	0.48	0.52
Thermal conductivity (compression), mW/m/K	58.55	59.31	61.72	55.81	56.48	58.45	50.11	51.9	53.47	49.2	50.47	53.12
Thermal conductivity (recovery), mW/m/K	56.4	58.5	60.41	53.02	54.47	55.92	48.45	49.53	51.62	46.73	48.63	51.55
Qmax, watts/m^2°C	685.4	703.6	730.4	672.4	685.2	716.9	616.4	642.6	678.8	604.5	624.8	652.4

3.1 Evaluation of Air Permeability

The results of air permeability of developed weft-knitted interlock fabrics with different structures, blends and structural tightness factors (STF) are given in Table 1. Table 2 shows the relationship between the fibre blend and the structural tightness factors against the air permeability of Structure 1. Structure 1 shows the maximum range of air permeability (231.8-286.4 $cm^3/cm^2/s$) by polyester-modal combination and the lowest range (122.6 - 145.4 cm^3/cm^2s) by polyester-wool sample. Polyester-wool blend records lower values of air permeability due to the lower porosity of wool. Also, it is seen that the STF has a significant and linear relationship with air permeability. When the STF increases, the loop length is reduced, which reduces pore size in the fabric. This is in agreement with the findings of Mavruz and Oğulata[16]. Structure 2 shows a similar trend of linear relationship with STF, which is depicted in Table 2. The highest values are seen with a polyester-modal blend in both structures. But the range of air permeability differs; Structure 1 shows 286.4 $cm^3/cm^2/s$ and Structure 2 shows 205.3 $cm^3/cm^2/s$ air permeability for low STF. It indicates that the modification of fabric pores due to different stitch combinations in Structure 1 and Structure 2 has a significant influence on air permeability.

3.2 Evaluation of Thermal Properties

Out of the various indices shown by the fabric touch tester, the thermal property-related indices are discussed in this section. The three main thermal comfort properties of Structure 1 and Structure 2 dealt with here are thermal conductivity under compression, thermal conductivity under recovery and maximum heat flow (Qmax).

3.2.1 Thermal Conductivity at Compression

Table 2 depicts the influence of fibre blend and structural tightness factors on thermal conductivity at the compression of Structure 1. It is seen that thermal conductivity is linearly correlated with STF. The polyester-modal and polyester-cotton materials are better in thermal conductivity under compression with a range of 56.63-65.12 and 53.52-62.73 W*mm (m^2*C) respectively. It is because, as the STF increases, irrespective of blend combinations, the number of fibres in the unit area increases with shorter loop length and areal density. Structure 2 shows a similar trend as Structure 1, but the individual values are comparatively lower than that of Structure 1. The tight fabrics of Structure 1 show an increase of 6-10% in thermal conductivity than that of Structure 2 for similar STF values. This corroborates with the findings of Suganthi *et al.*[17].

Figure 1 clearly reveals the existence of a highly positive correlation between thermal conductivity, thickness and STF of Structure 1. The correlation co-efficient R^2 ranges from 0.85 to 0.98 for Structure 1 and from 0.92 to 0.98 for Structure 2. This

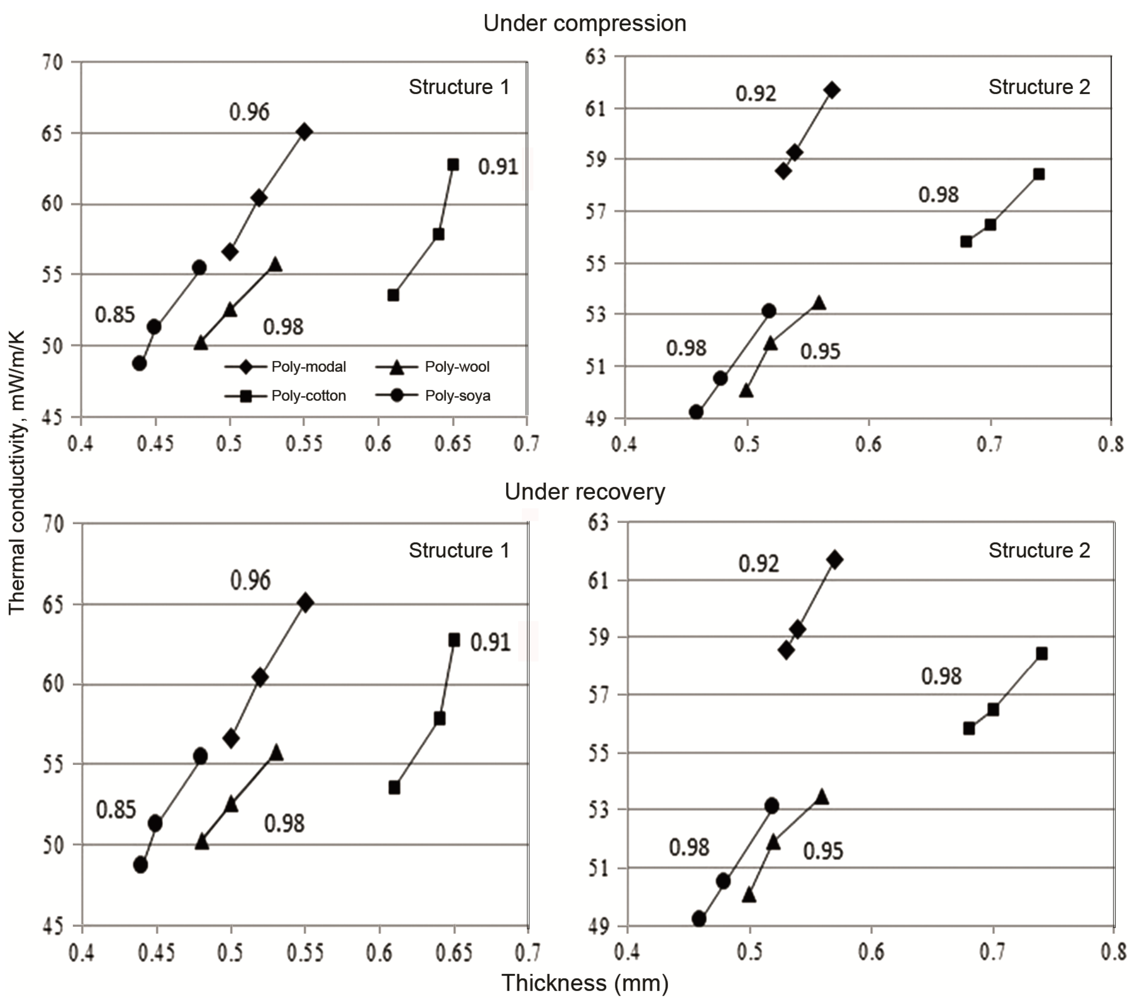

Fig. 1 — Correlation between thermal conductivity and thickness under compression and recovery for Structure 1 and Structure 2

relationship corroborates with the findings of Oglakcioglu and Marmarali[18] on different knitted structures.

3.2.2 Thermal Conductivity under Recovery

Table 2 depicts the relationship between the fibre blend and the structural tightness factor against thermal conductivity under recovery. The thermal conductivity values are slightly less in the recovery state, irrespective of all fibre blends, as compared to that in the compression state. Polyester-soya and polyester-wool blends show higher differences as compared to other blends. Also, the structural tightness factor is linearly influencing the thermal conductivity in the recovery state. A drop of 2-2.5% of thermal conductivity is commonly seen in all blends of Structure 2 when compared with Structure 1.

The correlation between thickness and thermal conductivity under recovery is depicted in Fig. 1 for Structure 1 and Structure 2 respectively. The correlation co-efficient R^2 ranges from 0.85 to 0.98 for Structure 1 and from 0.9 to 0.98 for Structure 2. Polyester-cotton and polyester-wool blends show higher R^2 co-efficient values than the other two blends. The curve inclination indicates that the increase of thermal conductivity with an increase of thickness in polyester-modal, polyester-cotton, and polyester-soya is rapid as compared to polyester-wool. The fibre blend and STF of knitted fabrics have a significant effect on the thermal conductivity under compression [F observed > F critical at $F_{(11,23)}$ = 1071.1 (for structure 1), and 1369.8 (for structure 2) $P < 0.05$], thermal conductivity under recovery [F observed > F critical at $F_{(23, 47)}$ = 905.1 (for structure1), and 1137.3 (for structure2) $P < 0.05$], and Qmax [F observed > F critical at $F_{(23, 47)}$ = 1967.9 (for structure1), and 3272.5 (for structure 2) $P < 0.05$].

Table 2 shows the relationship between the fibre blend and the structural tightness factor on Qmax values. This is a measure of maximum heat flow from the body to the fabric surface. Polyester-modal and polyester-cotton blend materials exhibit higher values indicating maximum heat flow than the other two blends. Polyester-modal records a range from 693.5-781.4 watts/m^2°C. The higher Qmax values indicate a good warm-cool effect which is important for sportswear applications. These findings are in agreement with the findings of Bivainyte *et al.*[19]. There is no significant variation between the Qmax values of Structure 1 and Structure 2 in all the blends. However, Structure 1 is seen with slightly higher values of Qmax in all blends. Polyester-wool and polyester-soya show 8-12% lower Qmax than that of the other two blends in both structures. The fibre blend and STF of knitted fabrics have a significant effect on the thermal conductivity under compression [F observed > F critical at $F_{(11,23)}$ = 1071.1 (for structure 1), and 1369.8 (for structure 2) $P < 0.05$], thermal conductivity under recovery [F observed > F critical at $F_{(23, 47)}$ = 905.1 (for structure1), and 1137.3 (for structure2) $P < 0.05$], and Qmax [F observed > F critical at $F_{(23, 47)}$ = 1967.9 (for structure1), and 3272.5 (for structure2) $P < 0.05$].

3.3 Subjective Trial

The consolidated feedback collected from the players focuses on four important parameters, namely sweat absorbency, breathability, softness and stretch comfort. The ratings are given on a 5-grade scale and the average of the feedback collected is presented as bar graphs.

3.3.1 Sweat Absorbency

With respect to sweat absorbency, it is seen that polyester-modal demonstrates higher sweat absorbency with a score of 50 out of 60 (83.33%) which is shown in Fig. 2 (a). Polyester-cotton blend closely maintains the score of 47. Polyester-soya blend fabric stands third in the rating of sweat absorbency and polyester-wool blend shows lower values with a score of 31 out of 60 (51.67%). Out of all the four fabrics, polyester-modal can be used for rigorous active sports.

3.3.2 Breathability

The feedback on breathability is illustrated in Fig. 2 (b). Polyester-soya and polyester-modal blends got higher scores of 44 and 52 respectively. Polyester-cotton blend also secures 45 out of 60, whereas polyester-wool secures 31 score. From the subjective trial rating, it is confirmed that the polyester-modal blend fabric provides more breathability.

3.3.3 Softness

The feedback on softness is illustrated in Fig. 2 (c). Polyester-soya and polyester-modal blends show higher scores of 52 and 55 respectively. Polyester-cotton blend secures 47 out of 60 and least score is secured by polyester-wool blend fabric (35). Again, the polyester-modal blend felt softer than all the other fabrics.

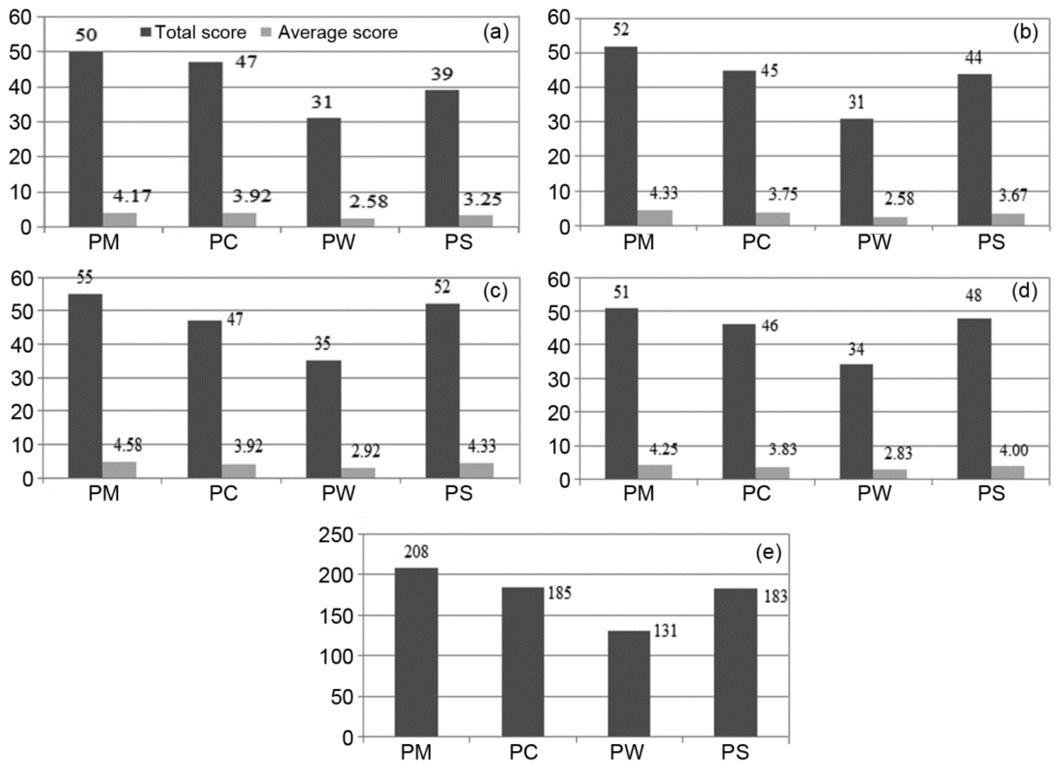

Fig. 2 — Feedback on (a) sweat absorbency, (b) breathability, (c) softness, (d) stretch comfort and (e) overall score

3.3.4 Stretch Comfort

Stretch comfort is an important requirement for sportswear. The total scores and average scores of stretch comfort are shown in Fig. 2 (d). Polyester-modal secure the highest score of 51 out of 60, closely followed by polyester-soya and polyester-cotton with scores of 48 and 46 respectively, whereas polyester-wool secures a 34 score.

3.3.5 Overall Score

The overall rating of all four parameters on the four fibre blends is depicted in Fig. 2 (e). It is observed that the polyester-modal fibre blend secures the highest score (208) out of 240, which is 86.67% of the positive feedback. This result corroborates the test results given in the previous sections. Polyester-cotton and polyester-soya blend closely follow the polyester-modal blend with scores of 185 and 183 respectively. The overall feedback percentage of these blends is 77% and 76.25%. Polyester-wool blend secures a score of 131 (54.6%) which indicates the least preference for sportswear. All the test results are subjected to ANOVA for the determination of statistical significance. The feedback summation of sweat absorbency, breathability, softness and stretch comfort shows that the test results are statistically significant [F observed > F critical, at $F(3, 11) = 19.06$ (for sweat absorbency), 12.52 (for breathability), 19.65 (for softness) and 9.02 (for stretch comfort) $P < 0.05$].

4 Conclusion

The results from the tests and subjective trial rating indicate that the polyester-modal blend combination is significantly better in most of the performance-related properties warranted for sportswear. The test results also confirm that the data are statistically significant and reliable (ANOVA) at a 95% confidence level. It is concluded that the finished garment is accepted as suitable sportswear.

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