

Araştırma Makalesi / Research Article

INVESTIGATION ON THE INFLUENCE OF KNIT FABRIC STRUCTURE ON THERMAL COMFORT PROPERTIES OF BI-LAYER FABRICS

Natarajan MUTHUKUMAR^{1*}
G. THILAGAVATHI¹

¹ Department of Textile Technology, PSG College of Technology, Coimbatore, India

Gönderilme Tarihi / Received: 25.02.2026

Kabul Tarihi / Accepted: 23.09.2026

ABSTRACT: In this study, the influence of various stitch combinations, namely knit, tuck, and miss stitches, and increasing the number of tuck stitches, on the thermal comfort characteristics of bi-layer fabrics has been investigated. Four bi-layer knit structures were developed with different stitch combinations, namely crackle (8 tuck stitches), canel (5 tuck stitches), cord lite (4 tuck stitches), and cookies (miss and knit stitches only), using micro denier polyester fiber. The developed fabrics were tested for thermal conductivity, air permeability, and moisture management properties. The influence of introducing and increasing the number of tuck stitches in bi-layer fabrics on the thermal comfort characteristics was studied. It was observed that the bi-layer fabric produced with 8 tuck stitches (crackle) had higher air permeability and lower thermal conductivity than other structures. The tuck stitches play an important role in the moisture management characteristics of the developed fabrics. All the developed fabrics had an overall moisture management value in the range of 0.41 – 0.66. It was observed that the crackle structure with 8 tuck stitches had a good overall moisture management value of 0.66. The developed fabrics can be useful for sportswear, active and summer wear.

Keywords: Bi-layer fabric, Moisture management properties, Sportswear, Thermal comfort, Tuck stitch

ÖRME KUMAŞ YAPISAL ÖZELLİKLERİNİN ÇİFT KATLI KUMAŞ TERMAL KONFOR ÖZELLİKLERİ ÜZERİNE ETKİLERİNİN İNCELENMESİ

ÖZ: Bu çalışmada, düz ilmek (knit), askı ilmeği (tuck) ve atlama ilmeği (miss) gibi farklı ilmek kombinasyonlarının ve askı ilmeği sayısındaki artışın çift katlı örme kumaşların termal konfor özellikleri üzerindeki etkisi araştırılmıştır. Mikrodenye polyester lifleri kullanılarak farklı ilmek kombinasyonlarına sahip dört çift katlı örme kumaş yapısı geliştirilmiştir. Bu yapılar; crackle (8 askı ilmeği), canel (5 askı ilmeği), cord lite (4 askı ilmeği) ve cookies (yalnızca atlama ve düz ilmeklerden oluşan) olarak adlandırılmıştır. Geliştirilen kumaşların ısı iletkenlik, hava geçirgenliği ve nem yönetimi özellikleri test edilmiştir. Çift katlı kumaşlarda askı ilmeği kullanımının ve askı ilmeği sayısının artırılmasının termal konfor özellikleri üzerindeki etkisi incelenmiştir. Sonuçlar, 8 askı ilmeği içeren çift katlı crackle yapısının diğer yapılara kıyasla daha yüksek hava geçirgenliğine ve daha düşük ısı iletkenliğe sahip olduğunu göstermiştir. Askı ilmeklerinin, geliştirilen kumaşların nem yönetimi özellikleri üzerinde önemli bir rol oynadığı belirlenmiştir. Geliştirilen tüm kumaşların genel nem yönetimi (Overall Moisture Management – OMM) değerlerinin 0,41–0,66 aralığında olduğu tespit edilmiştir. Sekiz askı ilmeği içeren crackle yapısının 0,66 değeriyle iyi düzeyde genel nem yönetimi performansı sergilediği görülmüştür. Geliştirilen kumaşların spor giyim, aktif giyim ve yazlık giysilerde kullanılabileceği sonucuna varılmıştır.

Anahtar Kelimeler: Çift katlı kumaş, nem yönetim özellikleri, spor giyim, termal konfor, askı ilmeği

*Sorumlu Yazarlar/Corresponding Authors: nmk.textile@psgtech.ac.in

DOI: <https://doi.org/10.7216/teksmuh.1897405>

www.tekstilvemuhendis.org.tr

1. INTRODUCTION

The human body performs its vital functions properly while in equilibrium with its surroundings. The sweat generated during the body functions should be taken away from the human skin to the atmosphere. Moisture management means the transport of liquid and moisture vapor away from the body. It is defined as the controlled movement of water vapor and perspiration from the skin to the atmosphere through fabric. The wearer's comfort perceptions are determined by the moisture management characteristics of fabrics [1]. The fabric properties required for sportswear application are thermal regulation, body heat management, moisture management, and quick-drying. The factors influencing performance of sportswear fabrics are fibres used, blend ratio, structure of yarn and fabric and functional finishes. [2].

Manshahia et al. found that the cross-sectional shape of filaments used for knitting and fabric parameters have an influence on the comfort characteristics of sportswear fabrics [3]. They also found that the wicking rate throughout the fabric can be increased by increasing the specific surface area of fibres [4]. Sarbayeva et al. investigated the effect of number of miss stitches and tuck stitches in the knit structure on the technological parameters and physical and mechanical properties of the knitted fabrics [5]. Bouagga et al. investigated the effect of tuck stitch on the properties of weft knit fabric and found that the fabric became more porous due to the tuck stitches and also there is an increase in areal density, pilling resistance and drape coefficient [6].

Assefa et al. studied the influence of knit stitch and the combination of knit stitch with tuck and miss stitch on the comfort properties of single jersey fabrics. They found that every stitch has a significant influence on comfort properties of the fabric even yarn and knitting parameters are kept constant [7]. Basra et al. developed 15 hybrid single jersey structures by the combination of knit and tuck stitches with different percentages. They found that percentage of stitch type plays a key role in determining the physical and comfort properties of the fabrics [8]. Nandlal et al. studied the impact of tuck stitches on thermo-physiological comfort properties of single-bed cotton fine-knits and quantified the fabric design by introducing the ratio of knit to tuck stitches in a repeat as a design parameter. They found that the knit-tuck ratio was the main determinant of thermal resistivity whereas its effect on evaporative resistance was negligible [9]. Amin et al. developed several single jersey weft knit fabric samples containing four courses and two wales in the repeating unit of the fabric structure by introducing and gradually increasing the number of tuck stitches in the structure and studied the effect of tuck stitch on fabric properties. They found that tuck stitches could positively affect the areal density, width, and tensile properties of the fabric. For some comfort-related properties, tuck stitches were found to improve wicking and drying properties, reduce water vapor transmission rate, and affect fabric smoothness [10]. Senthilkumar et al. studied the effect of tuck stitch in course direction and also in wales direction on comfort properties of sportswear [11, 12].

In the bi-layer fabrics, the diffusive hydrophobic and conductive components of inner layer remove and transport sweat to the outer layer. The absorptive hydrophilic components of outer layer cover the larger areas of sweat and its evaporation [13]. Krithika et al. produced bi-layer fabrics using different yarn combinations for outer and inner layers. They found that the fabric produced using micro denier polyester for both inner and outer layers had better moisture management properties [14]. Manshahia et al. produced plated knitted fabrics using different combinations of profiled polyester filament yarn on the inner and outer sides of the fabric and studied the moisture management properties for sportswear applications. They showed that fabric having filaments of higher shape factor has better moisture management properties when placed next to the skin layer [15].

In literature, the influence of knit structures on the comfort characteristics of single jersey fabrics has been studied by various researchers. Very little research has been done on bi-layer fabrics. Hence, this study aims to study the influence of introducing and increasing the number of tuck stitches in bi-layer fabrics on the thermal comfort characteristics of the bi-layer fabrics. Four bi-layer fabrics were developed using different stitch combinations, namely crackle (8 tuck stitches), canel (5 tuck stitches), cord lite (4 tuck stitches), and cookies (miss and knit stitches only). The micro denier polyester fiber has been selected for fabric development due to its low weight, high-water transfer, and easy-care properties. The air permeability, thermal conductivity, and moisture management characteristics of developed bi-layer fabrics were studied.

2. MATERIAL AND METHODS

Micro denier polyester fibres (150 Denier) have been sourced from Reliance Industries Limited, India. Bi-layer fabrics were produced on a double-knit interlock machine having a machine gauge of 28, a machine diameter of 34 inches, and 84 feeders. The fabric, which forms the inner layer, is fed into the dial needle, and the outer layer into the cylinder needle. Four bi-layer fabrics were developed using different stitch combinations, namely crackle (8 tuck stitches), canel (5 tuck stitches), cord lite (4 tuck stitches), and cookies (miss and knit stitches only). The cam and needle order of the developed bi-layer fabrics is shown in Figure 1.

2.1 Characterization methods

The areal density and thickness of the developed fabrics were determined following the ASTM D3776-20 and ASTM D1777-96 standards, respectively. KES-F8 air permeability tester was used to study the air permeability of the developed fabrics following the BS 5636-1990 standard. The thermal conductivity of the developed fabrics was studied using Lee's disc instrument following ASTM D7340-07 standard. The moisture management properties of the developed fabrics were studied using a Moisture Management Tester (MMT) following AATCC 195-2011 standard.

Moisture Management Tester is designed to measure the liquid moisture transport behaviour of fabric in multiple directions.

When moisture is transported in a fabric, the contact electrical resistance of the fabric changes and the change in resistance value depends on two factors: the components of liquid and the water content in the fabric. The liquid components are fixed, so that the measured electrical resistance is related to the water content in the fabric. Based on the signals measured, a set of indices is calculated according to AATCC test method 195-2011; the indices are graded and converted from value to grade based on a five-grade scale (1-5). The five grades of indices represent the following: 1 - poor; 2 - fair; 3 - good; 4 - very good; 5 - excellent. Table 1 shows the range of values converted into grades.

3. RESULT AND DISCUSSION

The physical properties of the developed bi-layer fabrics are given in Table 2. Tuck stitches contain knit loops and held loops. Tuck

stitches are formed by not clearing the old loop from the needle after a knitting cycle while catching a new yarn. Instead, both loops are kept in the latch of the needle, and then, when a course containing the knit loop arrives in the cycle, the held loop from the previous cycle is released, and due to being held in the needle for more than one knitting cycle, this loop is called the held loop. Because it is held by the needle for more than one knitting cycle, the held loop withstands more tension than other loops, and it expands horizontally as the legs of this loop spread to the left and right. Hence, the courses per inch are higher than wales per inch in crackle, canel, and cordlite fabrics. The developed fabrics had an areal density of 141 to 155 and a thickness of 0.38 to 0.45 mm. The developed fabrics had porosity in the range of 72.50 % to 75.10%.

Sample name	Cam and needle order																																																																																																																							
Crackle	<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><th>F11</th><th>F12</th><th>F13</th><th>F14</th><th>F15</th><th>F16</th></tr><tr><td>CN1</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr><tr><td>CN2</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr><tr><td>CN3</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr><tr><td>CN4</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>o</td></tr><tr><td>DN1</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>DN2</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr></table>		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	CN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	CN2	x	o	x	o	x	o	x	o	x	-	x	-	x	-	x	-	CN3	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	CN4	x	-	x	-	x	-	x	-	x	o	x	o	x	o	x	o	DN1	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	DN2	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16																																																																																																								
CN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
CN2	x	o	x	o	x	o	x	o	x	-	x	-	x	-	x	-																																																																																																								
CN3	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
CN4	x	-	x	-	x	-	x	-	x	o	x	o	x	o	x	o																																																																																																								
DN1	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
DN2	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
Canel	<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></tr><tr><td>CN1</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr><tr><td>CN2</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>o</td></tr><tr><td>CN3</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>o</td><td>x</td><td>-</td></tr><tr><td>CN4</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>o</td></tr><tr><td>DN1</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>DN2</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr></table>		F1	F2	F3	F4	F5	F6	F7	F8	CN1	x	-	x	-	x	-	x	-	CN2	x	-	x	-	x	-	x	o	CN3	x	o	x	o	x	o	x	-	CN4	x	-	x	-	x	-	x	o	DN1	-	x	-	x	-	x	-	x	DN2	-	x	-	x	-	x	-	x																																																								
	F1	F2	F3	F4	F5	F6	F7	F8																																																																																																																
CN1	x	-	x	-	x	-	x	-																																																																																																																
CN2	x	-	x	-	x	-	x	o																																																																																																																
CN3	x	o	x	o	x	o	x	-																																																																																																																
CN4	x	-	x	-	x	-	x	o																																																																																																																
DN1	-	x	-	x	-	x	-	x																																																																																																																
DN2	-	x	-	x	-	x	-	x																																																																																																																
Cord lite	<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><th>F11</th><th>F12</th><th>F13</th><th>F14</th><th>F15</th><th>F16</th></tr><tr><td>CN1</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>CN2</td><td>x</td><td>x</td><td>-</td><td>x</td><td>x</td><td>o</td><td>-</td><td>o</td><td>x</td><td>o</td><td>-</td><td>o</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>CN3</td><td>-</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>CN4</td><td>x</td><td>x</td><td>-</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></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>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</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>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr></table>		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	CN1	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	CN2	x	x	-	x	x	o	-	o	x	o	-	o	-	x	-	x	CN3	-	x	x	x	-	x	x	x	-	x	x	x	-	x	-	x	CN4	x	x	-	x	x	x	-	x	x	x	-	x	-	x	-	x	DN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	DN2	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16																																																																																																								
CN1	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
CN2	x	x	-	x	x	o	-	o	x	o	-	o	-	x	-	x																																																																																																								
CN3	-	x	x	x	-	x	x	x	-	x	x	x	-	x	-	x																																																																																																								
CN4	x	x	-	x	x	x	-	x	x	x	-	x	-	x	-	x																																																																																																								
DN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
DN2	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
Cookies	<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><th>F11</th><th>F12</th><th>F13</th><th>F14</th><th>F15</th><th>F16</th></tr><tr><td>CN1</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>-</td><td>x</td><td>-</td></tr><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>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>CN3</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></tr><tr><td>CN4</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td></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>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</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>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td><td>x</td><td>-</td></tr></table>		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	CN1	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x	-	CN2	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	CN3	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	CN4	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	DN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	DN2	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16																																																																																																								
CN1	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x	-																																																																																																								
CN2	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
CN3	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
CN4	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x																																																																																																								
DN1	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
DN2	x	-	x	-	x	-	x	-	x	-	x	-	x	-	x	-																																																																																																								
CN – Cylinder needle; DN – Dial needle; F1,F2,F3.....F16 – Number of feeders x - Knit stitch; o - Tuck stitch; - - Miss stitch																																																																																																																								

Figure 1: Cam and needle order of the developed bi-layer fabrics

Table 1: Grading table of all indices on moisture management properties

Index	Grade				
	1	2	3	4	5
Wetting time (s)					
Top	≥ 120	20-119	5-19	3-5	< 3
Bottom	≥ 120	20-119	5-19	3-5	< 3
Absorption rate (%)					
Top	0-9	10-29	30-49	50-100	> 100
Bottom	0-9	10-29	30-49	50-100	> 100
Maximum wetted radius (mm)					
Top	0-7	8-12	13-17	18-22	>22
Bottom	0-7	8-12	13-17	18-22	>22
Spreading speed (mm/s)					
Top	0.0 -0.9	1.0-1.9	2.0-2.9	3.0-4.0	>4.0
Bottom	0.0 -0.9	1.0-1.9	2.0-2.9	3.0-4.0	>4.0
One way transport capability (%)	< -50	-50 - 99	100-199	200-400	>400
Overall moisture management capability (OMMC)	0.00-0.19	0.20-0.39	0.40-0.59	0.60-0.80	>0.80

Table 2: Physical properties of the developed bi-layer fabrics

Sample Name	CPI	WPI	Thickness (mm)	Areal density (GSM)	Porosity (%)
Crackle	58	46	0.38	141	75.10
Canel	62	44	0.45	155	74.70
Cord lite	44	42	0.43	150	73.00
Cookies	46	44	0.40	152	72.50

3.1 Air permeability

The transportation of moisture vapors from the skin to the outside atmosphere depends on the air permeability of the fabrics, and this property is heavily affected by the fabric porosity [16]. Fabric porosity depends on yarn density, fabric areal density, fabric structure, and other factors. As the fabric became denser, porosity decreased, reducing the amount of air passing through the fabric. When tuck stitches were included, pores were created, allowing air to pass through the fabric with relative ease. The air permeability of the developed fabrics is given in Figure 2. The developed fabrics had an air permeability value in the range of 69.4 to 88.3 cm³/cm²/sec. The non-overlapping standard error bars indicate that the difference between the means is statistically significant. The crackle fabric has a high air permeability value compared to other structures because its porous structure allows more air to pass through it. It also has a lower thickness compared to other structures, which allows air to flow freely through the fabric and can increase the sweat evaporation rate from the skin.

3.2 Thermal conductivity

The thermal conductivity of the fabric indicates its ability to conduct heat. The fabric's material, thickness, and structure influence thermal conductivity [17]. The fabric's thermal conductivity is strongly influenced by the raw material, but since all samples were made with the same micro denier polyester yarn, this factor was not considered in this study. Figure 3 shows the thermal conductivity of the developed fabrics. The developed fabrics had a thermal conductivity value ranging from 0.026 to 0.044 W/mK. The non-overlapping standard error bars indicate that the difference between the means is statistically significant. The crackle fabric had a lower thermal conductivity than other fabric structures due to its highly porous nature. Although increasing the number of tuck stitches increased porosity, the fabrics became heavier with tuck stitches, which reduced heat-transfer ability. In addition, tuck stitches made the fabrics rougher. The rough surface helped retain air and improve the fabric's insulating properties, which may have contributed to its lower thermal conductivity. Among the developed fabric structures, the cookies fabric has lower air permeability and a higher thermal conductivity value than the other structures.

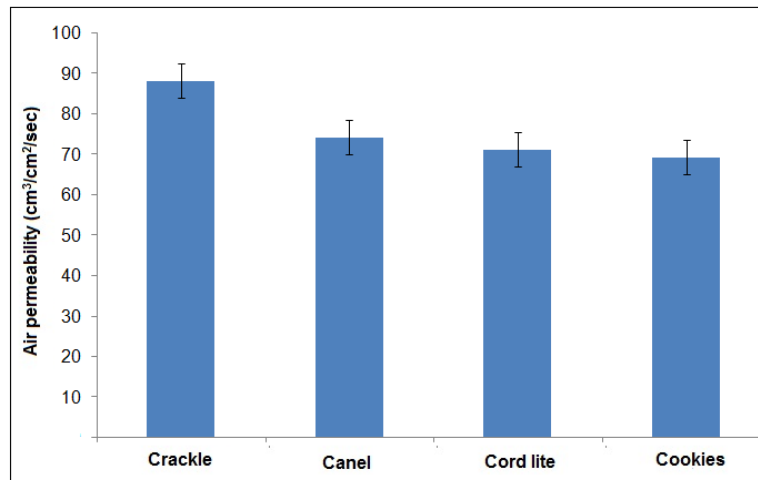


Figure 2: Air permeability of the developed bi-layer fabrics

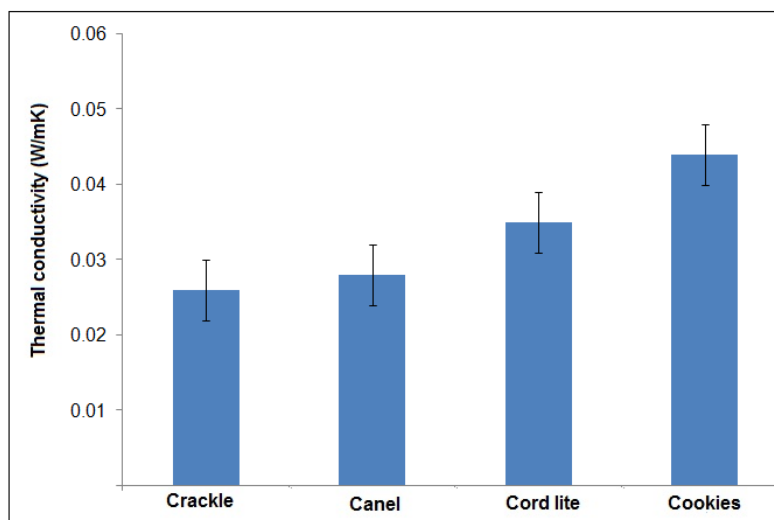


Figure 3: Thermal conductivity of developed bi-layer fabrics

3.3 Moisture management properties

3.3.1 Wetting time (top and bottom)

After the test has started, the wetting time is determined by noticing the time period in seconds for the top and bottom surfaces of the fabric begin to wet. It depends on the wicking characteristics of its fibers and yarns and water absorption and water resistance properties of the fabric structure [18]. The wetting time of the developed fabric samples is shown in figure 4. In general, the test liquid initially wets the top surface and then moves towards the bottom surface of the sample. It was noticed from Figure 4 that there is no significant difference in wetting time of the top and bottom surfaces of the developed bi-layer fabric structures. Among the developed bi-layer fabrics, the crackle fabric has lower top and bottom wetting time compared to other structures. It may be due to its porous nature and also lower fabric thickness compared to other structures. The wetting time is less than 3

seconds in both bottom and top surfaces, indicating very fast wetting. The cord lite and cookies had wetting time in the range of 3-5 seconds, indicating fast wetting. The canel fabric structure had medium wetting (5-19 sec) because of its higher thickness compared to other developed fabric structures.

3.3.2 Absorption rate (top and bottom)

The liquid absorption ability of the top and bottom surfaces of the fabric samples is defined as absorption rate. It has been observed from Figure 5 that all the developed bi-layer fabrics (except cookies structure) had a slow absorption rate (10-30 %/sec) for the top surface and a medium absorption rate (30-50%/sec) for the bottom surface. It may be due to the diffusion of moisture from inside without any absorption by the tuck stitches. The cookies fabric made with miss and tuck stitch only had a slow absorption rate (10-30 %/sec) for both surfaces.

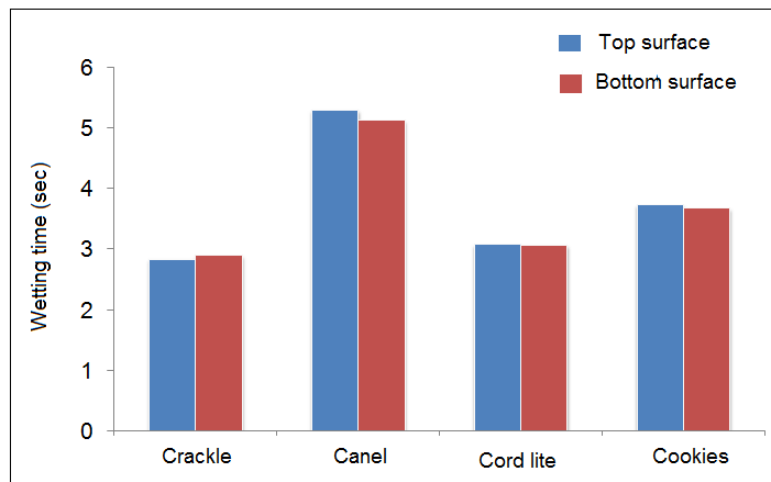


Figure 4: Top and bottom wetting time of the developed bi-layer fabrics.

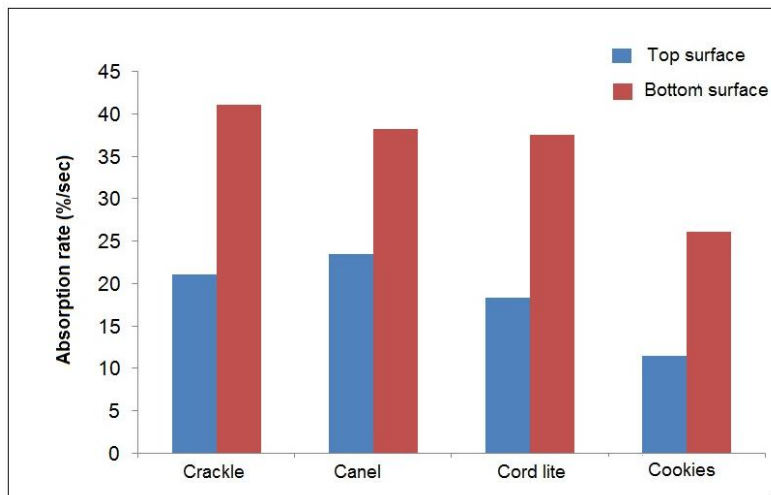


Figure 5: Top and bottom absorption rate of the developed bi-layer fabrics

3.3.3 Maximum wetted radius and spreading speed

The profile of liquid spreading across the fabric surfaces is described by maximum wetted radius (MVR) and spreading speed of the fabric. The figures 6 & 7 show MVR and spreading speed of the developed bi-layer fabrics. MWR of top and bottom surfaces was found to be very large (greater than 22 mm) for the crackle structure compared to other structures. The spreading speed of the crackle structure was found to be very fast (>4 mm/sec). Due to the porous structure, the crackle structure transports vapour outward by capillary action. The other fabrics have medium maximum wetted radius (12-17 mm) and medium spreading speed (2-3 mm/sec). It may be due to the wicking properties of micro denier polyester. The bi-layer fabrics developed with tuck stitches exhibit quick absorption and drying, which makes the wearer feel comfortable.

3.3.4 One-way transport capability

In the human body sweat is generated during body actions because of the heat loss from the body. Because of the heat loss and sweat formation, the wearer feels cool, chill, or clammy. If the fabric structure has good wicking property, then sweat will be easily transferred from the body skin to the atmosphere through the fabric [19]. The transfer of sweat from skin to atmosphere through the fabric is described by accumulative one-way transport capability (OWTC), which is the difference in the accumulative moisture content between the two surfaces of the sample. Figure 8 shows the OWTC values of the developed bi-layer fabrics. It was observed that crackle and canel fabrics have very good OWTC (200-400%) and the cord lite and cookies fabrics have good OWTC (100-200 %). This is due to the structure's ability to transport water to the outer system. During testing the fabric does not absorb the test liquid and the test liquid is transferred to the atmosphere through the fabric because of the wickability of micro denier polyester fibres [20].

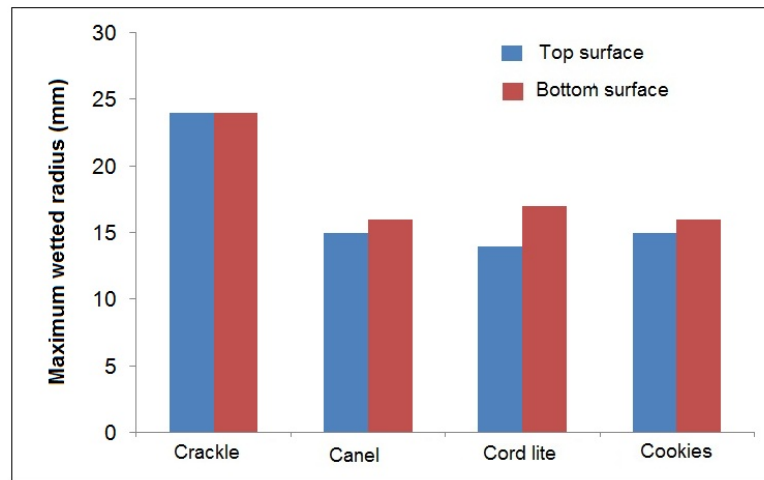


Figure6: Top and bottom maximum wetted radius of developed bi-layer fabrics.

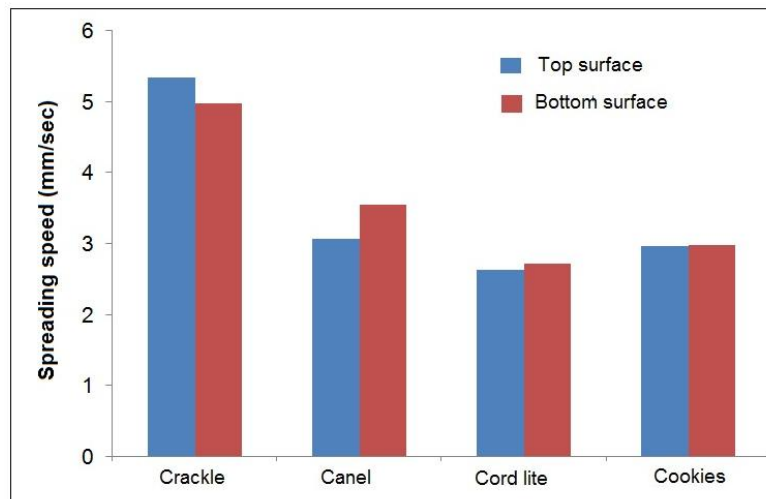


Figure 7: Top and bottom spreading speed of developed bi-layer fabrics.

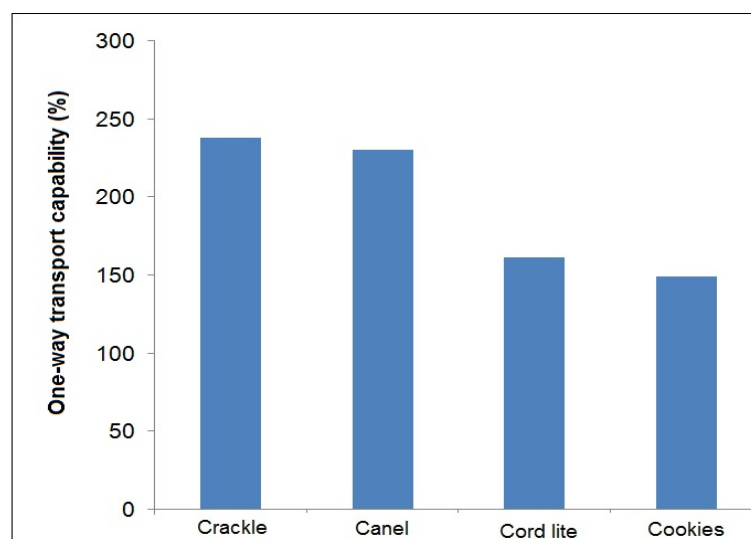


Figure 8: OWTC values of the developed bi-layer fabrics

3.3.5 Overall moisture management capability

The moisture management performance of the fabric is mentioned as overall moisture management capability (OMMC) value. It is an index value, calculated from the three values: one-way liquid transport capability, the spreading drying rate of the bottom side and moisture absorption rate of the bottom side. Figure 9 shows the overall moisture management capability of the developed bi-layer fabrics. It was observed that the bi-layer fabric produced with 8 tuck stitches (crackle) has very good OMMC with grade 4. The crackle structure will dry quickly due to the higher spreading speed and maximum wetted radius on the bottom surface, and low absorption rate on the top surface. The other three fabrics have good OMMC value (lies in the range of 0.4 to 0.6) with grade 3-good. The developed bi-layer fabrics will be useful for summer, sportswear, and active wear applications.

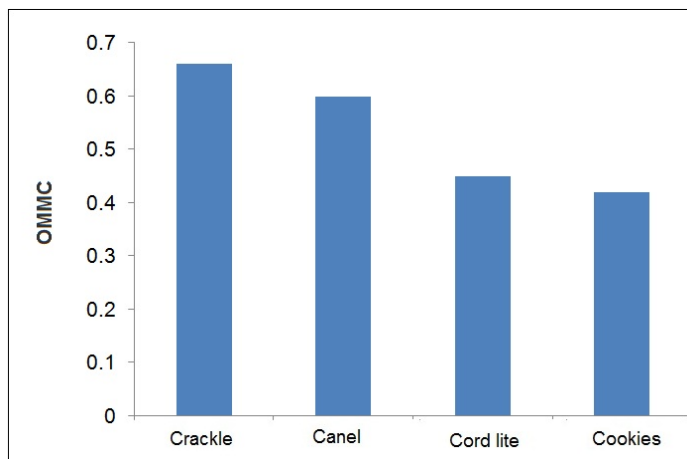


Figure 9: Overall moisture management capability (OMMC) of the developed bi-layer fabrics.

4. CONCLUSIONS

In this work, four bi-layer knit structures, namely crackle (8 tuck stitches), canel (5 tuck stitches), cord lite (4 tuck stitches), and cookies (miss- and- knit stitches only), were developed using micro-denier polyester fiber. The influence of introducing and increasing the number of tuck stitches on thermal conductivity, air permeability, and moisture management properties of bi-layer fabrics was studied. It was observed that increasing the number of tuck stitches increases the courses per inch (CPI) while simultaneously decreasing the wales per inch (WPI) in the developed bi-layer fabrics. Increasing the number of tuck stitches increased porosity, and the fabrics became heavier with tuck stitches, which reduced heat-transfer ability. It was observed that the bi-layer fabric produced with 8 tuck stitches (crackle) had higher air permeability and lower thermal conductivity than other structures. It was found that the presence of tuck stitches in the bi-layer fabric significantly influences the moisture management capability. The developed bi-layer fabrics had an overall moisture

management value ranging from 0.41 to 0.66. Among the developed fabrics, the crackle structure with 8 tuck stitches had a good overall moisture management value of 0.66. The outcome of this study will provide a useful and effective method for developing bi-layer fabrics with better comfort properties.

REFERENCES

1. M.Manshahia and A. Das, "High active sportswear - A critical review", *Indian J. Fibre Text, Res.*, vol. 39, pp. 441-449, 2014.
2. A.K. Choudhary and Ramratan, "The influence of yarn and knit structure on moisture management properties of sportswear fabric", *J. Inst. Eng. India Ser. E.*, vol.101, 77-90, 2020.
3. M.Manshahia and A. Das, "Comfort Characteristics of knitted active sportswear: Heat and mass Transfer", *Res. J. Text. Appar.*, vol.17, pp. 50-60, 2013.
4. M.Manshahia and A. Das, "Comfort characteristics of knitted active sportswear: Liquid water transportation". *Res. J. Text. Appar.*, vol.17, pp.38-49, 2013
5. E. Sarbayeva, M.Kuramysova, M.Mukimov et al. "Influence of tuck stitches on the physical and mechanical properties of knitted fabrics " *Res J Text Appar*, vol. 28(4), pp. 798-818,2024.
6. T. Bouagga, T.Harizi, and F. Sakli, "The Effect of Tuck Stitch on the Properties of Weft Knitted Fabric", *J.N. Fibers*, vol.19 (15), pp. 9874-9885, 2022
7. A. Assefa and N. Govindan, "Physical properties of single jersey derivative knitted cotton fabric with tuck and miss stitches", *J. Eng. Fiber. Fabr.*, vol.15, 2020.
8. S.A Basra, E. Kumpikaite and N. Asfand, "Development and investigation of hybrid knitted structures for sensorial comfort properties. Part I - Tuck stitches", *J. Nat. Fibers.*, vol.20 (2), 2222554, 2023.
9. V.D.Nandlal, R Unmar, S. Rosunee, and L.Hes, "Investigating the Effects of Tuck Stitches on the Thermophysiological Comfort Properties of Cotton Weft Knitted Fabrics", *Proceedings of the 50th Textile Research Symposium*, Springer, 2024.
10. Amin MdR, Mahmud MdA, Anannya FR. Structural Impact on Some Common Physical Properties of Single Jersey Weft Knit Fabric. *AATCC J.Res.*, 2021;8(4):36-46. doi:10.14504/ajr.8.4.6
11. P.Senthilkumar and T.Suganthi, "Influence of tuck stitch in wale direction on thermal comfort characteristics of layered knitted fabrics", *Indian J.Fibre.Text. Res.*, vol.44, pp. 65-74, 2019.
12. P.Senthilkumar and T.Suganthi, "Influence of tuck stitch in course direction on thermal comfort characteristics of layered knitted fabrics", *Indian J. Fibre. Text. Res.*, vol. 44, pp. 163-172, 2019.
13. T. Suganthi, P. Senthilkumar P and V. Dipika, "Thermal comfort properties of a bi-layer knitted fabric structure for volleyball sportswear", *Fibres Text. East. Eur.*, vol. 25, pp.75-80, 2017.
14. S. Krithika, B. Sampath, C. Prakash and Senthil Kumar, "Comfort properties of moisture management finished bi-layer knitted fabrics: Part I -Thermal comfort", *Indian J. Fibre. Text. Res.*, pp. 175-178, 2022.
15. M.Manshahia and A. Das, "Moisture management of high active sportswear", *Fibers Polym.*, vol.15, pp.1221-1229, 2014.
16. S. Uyanik and M. Topalbekiroğlu, "The effect of knit structures with tuck stitches on fabric properties and pilling resistance", *J. Text. Inst.*, vol.108, 1-6, 2017

17. R Mishra, H. Jamshaid, S.H.S Yosfani, et al., "Thermo physiological comfort of single jersey knitted fabric derivatives", .Fash Text (8), 40, 2021
18. MG Chakroun, S Benltoufa, A Ghith, F Fayala, "Design Effect on Wear Comfort Properties of Polyester Knitted Fabrics", J Fashion Technol Textile, 11(3), pp.1-8, 2023
19. Y.Yang, W. Zhang, Z. Liu and P. Zhang, "Thermal comfort properties of bi-layer knitted fabrics made up of polyester yarns and nylon yarns with varied specification", Int. J. Cloth. Sci. Tech., vol. 35(3), pp. 435-453, 2023.
20. M.B.Sampath, C. Prakash, J. Hayavadana , G.K.Indu and V. Kapoor, "Study on comfort characteristics of moisture management finished micro-denier polyester knitted fabrics", AATCC J.Res., 0(0), 2023.