Design of weft-knitted spacer fabrics: impact of fabric structure parameters on thermal-wet comfort and cushioning performance

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ABSTRACT – REZUMAT

Design of weft-knitted spacer fabrics: impact of fabric structure parameters on thermal-wet comfort and cushioning performance

Weft-knitted spacer fabrics are characterised by their lightweight nature, thermal insulation, air permeability, and elasticity. To explore their application potential in garment fabric development, this study proposes a novel weft-knitting process based on traditional spacer fabric knitting techniques, which incorporates functional yarns into the spacer layer. Based on this process, the influence of varying fabric structures, including the spacer layer structure, the number of spacer layers, and the type of reinforcing yarn, on the thermal-wet comfort and cushioning properties of weft-knitted spacer fabrics is analysed. A three-factor, three-level orthogonal experiment was designed to produce 9 fabric samples, which were tested for compressibility, air permeability, moisture permeability, and thermal insulation. Variance analysis of the test data reveals the relative significance of the three factors. Experimental results indicate that the structure of the spacer layer has the most significant impact on fabric performance, followed by the type of reinforcement yarn, while the number of spacer layers has a relatively minor effect. Furthermore, during the compression tests, the compression stress-strain curves were fitted and differentiated to analyse the cushioning performance of the spacer fabrics based on the trends observed in these curves. The experimental findings reveal that the compressibility of the fabric is inversely proportional to its cushioning properties.

Keywords: *spacer fabrics, spacer structure, knitting process, work of compression, thermal-moisture comfort*

Proiectarea tricoturilor din urzeală distanțiere: impactul parametrilor structurii tricotului asupra confortului higrotermic și asupra performanței de amortizare

Tricoturile din urzeală distanțiere se caracterizează prin greutate redusă, izolare termică, permeabilitate la aer și elasticitate. Pentru a explora potențialul lor de aplicare în dezvoltarea materialelor textile pentru îmbrăcăminte, acest studiu propune un proces inovator de tricotare din urzeală, bazat pe tehnici tradiționale de tricotare a tricoturilor distanțiere, care încorporează fire funcționale în stratul distanțier. Pe baza acestui proces, se analizează influența diferitelor structuri ale tricoturilor – inclusiv structura stratului distanțier, numărul de straturi distanțiere și tipul firului de întărire – asupra confortului higrotermic și proprietățile de amortizare ale tricoturilor din urzeală distanțiere. A fost conceput un experiment ortogonal cu trei factori și trei niveluri pentru a produce 9 eșantioane de tricoturi, care au fost testate pentru compresibilitate, permeabilitate la aer, permeabilitate la umiditate și izolare termică. Analiza varianței datelor de testare relevă semnificația relativă a celor trei factori. Rezultatele experimentale indică faptul că structura stratului distanțier are cel mai semnificativ impact asupra performanței tricotului, urmată de tipul firului de întărire, în timp ce numărul de straturi distanțiere are un efect relativ minor. În plus, în timpul testelor de compresiune, curbele de tensiune-deformație la compresiune au fost ajustate și diferențiate pentru a analiza performanța de amortizare a tricoturilor distanțiere pe baza tendințelor observate în aceste curbe. Rezultatele experimentale relevă faptul că compresibilitatea tricotului este invers proporțională cu proprietățile sale de amortizare.

Cuvinte-cheie*: tricoturi distanțiere, structură distanțier, proces de tricotare, activitate de compresie, confort higrotermic*

INTRODUCTION

Spacer fabric, a three-dimensional textile composed of two independent surface layers and a spacer layer, has attracted significant attention in functional textile research [1]. Scholars have made substantial efforts to explore the structural diversity of weft-knitted spacer fabrics, primarily focusing on two connection types: tuck connections and fabric-layer connections. For tuck-connected structures, Song et al. pioneered the development of such fabrics using glass fibres, demonstrating their ability to effectively utilise high-performance fibres for enhanced mechanical properties [2]. In the realm of fabric-connected designs, Unal and his team expanded beyond traditional loop-connected structures by proposing fabric-based connections, developing single-layer U-shaped and V-shaped weft-knitted spacer fabrics that laid the foundation for subsequent double-layer structures [3]. Abounaim later clarified the knitting principle of 2U-shaped (double-layer U-shaped) spacer fabrics [4], while Li optimised this technology by introducing a double ribbing structure at the spacer layer cross-linking, increasing fabric thickness and imparting cushioning performance to plain knitted fabrics [5]. Huang further advanced this field by developing 2V-shaped (double-layer V-shaped) spacer fabrics and confirming their superior buffering performance for local human body protection compared to 2U-shaped structures and shear thickening fluid-impregnated variants [6]. Atar et al. used finite element modelling to compare spacer fabrics with rectangular, trapezoidal, and triangular cross-sections [7]. They found triangular structures had the highest surface load-bearing capacity (rectangular the lowest) and lower transverse shear stiffness, showing cross-sectional geometry impacts mechanical performance.

The stable three-dimensional structure of these fabrics, attributed to the spacer layer, endows them with unique properties such as impact resistance and thermal insulation [8, 9]. Abbas et al. demonstrated that the number of stitches per repeat (SPR) significantly regulates energy absorption and negative Poisson's ratio (NPR) behaviours in 3D weft-knitted auxetic fabrics, with SPR=81 showing the highest energy absorption capacity [10]. On mechanical performance, Azita analysed the compression behaviour of tuck-connected spacer fabrics and revealed that a larger spacer yarn tilt angle enhances compression resistance [11], while Ryan identified spacer yarn diameter as a key factor influencing impact resistance [12]. Gong et al. and Umair et al. have respectively highlighted the potential of spacer fabrics in thermal-wet comfort for protective clothing and breathable insoles [13, 14], yet these studies often focus on single performance metrics in isolation.

In apparel applications, these structural innovations have enabled breakthroughs in comfort and functionality. For example, Annie et al. developed 3D weft-knitted spacer fabric bra cups, confirming comparable compression strength to traditional foam cups while enhancing breathability via porous structures, thus validating the feasibility of one-step forming technology [15]. Golnaz et al. investigated spacer fabrics for compression stockings, screening structures with pressure values equivalent to commercial products but superior wearing comfort [16]. Umair et al. further emphasised the importance of structural parameters (e.g., stitch density, layer thickness) in balancing cushioning and breathability for sports textiles, noting that gradient designs can optimise pressure distribution without compromising comfort [17]. Zhao et al. developed fully-fashioned weft-knitted spacer fabric helmets using UHMWPE fibres, achieving excellent mechanical properties, structural stability, and industrial production adaptability [18].

Fu et al. integrated intarsia techniques with spacer fabric structures to create sports knee pads, where segmented knitting and curved edge designs enhanced shock absorption while conforming to knee anatomy [19].

Currently, most studies on fabric performance have focused on impact resistance, while research on their thermal-wet comfort remains relatively limited. To address this, this article presents a novel weft-knitted spacer fabric with reinforcing yarns added to the spacer layer. Through a three-factor, three-level orthogonal experiment, the specific impact of the spacer layer (structure, number of layers, reinforcing yarn type) on thermal insulation, comfort, and cushioning properties was investigated. Using Merino wool yarn for the comfort-oriented surface layer and bulked or Kevlar yarn for the functional spacer layer, nine fabric samples were knitted and tested to clarify the structure-performance relationship, providing insights for garment fabric development.

MATERIALS AND METHODS

Material

The experiment involved the use of two strands of ultrafine merino wool, with a yarn count of 2/56NM. The knitting was performed on a STOLL computerised flat knitting machine, model CMS 530 HP, manufactured by the German company STOLL. The machine had a gauge setting of 7.2.

Fabrication of spacer fabrics

The new axial reinforced weft-knitted spacer fabric is based on a weft-knitted stitch structure, in which warp yarn and weft yarn are inserted during the knitting process to form the fabric [20]. The inserted warp and weft yarns mostly use thicker and harder high-performance fibre yarns. Inserting high-performance yarns into the three-dimensional spacer fabric can enhance the three-dimensional structure, and the inserted yarns can greatly improve the performance of the fabric [21]. The specific performance depends on the characteristics of the inserted yarns.

Based on the detailed introduction of the knitting process of traditional weft-knitted spacer fabrics by previous scholars [2–7], this paper designs a weaving process of inserting weft-directional reinforcing yarns into the spacer layer. Taking the 2V-shaped fabric as an example, the specific steps are shown in figure 1. The front needle bed performs plain stitch knitting. This step can be iterated to fine-tune the length of the upper surface layer (L1 in figure 1, *a*). The plain stitch is knitted separately by the front and back needle beds, collaborating with step a to construct the upper surface layer F1 of the fabric (figure 1, *b*). The front and back needle beds alternate between knitting one stitch on and skipping one stitch (figure 1, *c*). Reinforcing yarns are added to the front and back needle beds alternately. Tuck loops and floats are knitted alternately. After inserting three rows of floats, a row of tuck loops is knitted to form the reinforcing structure N1 (figure 1, *d*). The loops are knitted alternately on both the front and back needle beds. Steps (c), (d), and (e) collectively constitute the spacer layer K1 of the fabric (figure 1, *e*). The back needle bed executes plain stitch knitting, and this step can be repeated to adjust the length of the lower surface layer (L2 in figure 1, *f*). Step b is repeated, collaborating with step f to create the lower surface layer F2 of the fabric.

In this experiment, three types of weft-knitted spacer fabrics with different interval structures were designed, such as tuck connection, 2U-shaped fabric

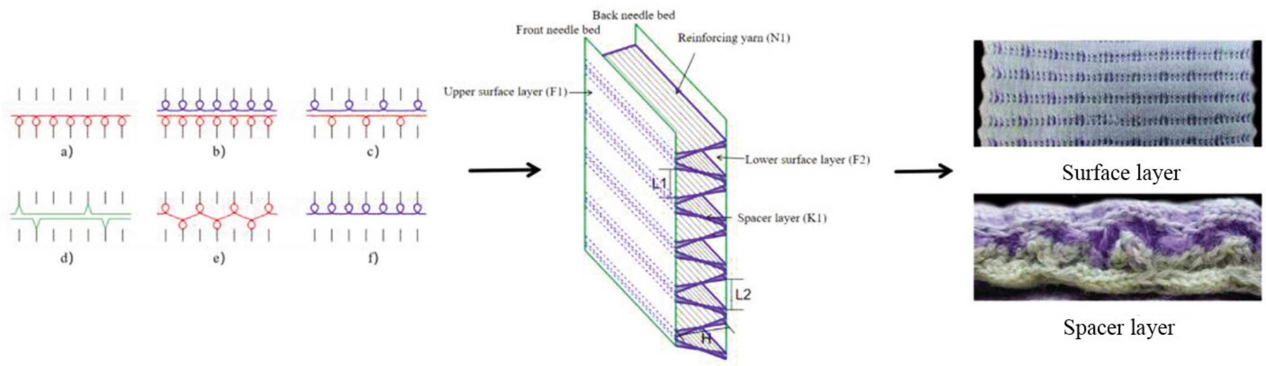


Fig. 1. Knitting flowchart of the new axial reinforced weft-knitted spacer fabric

connection, and 2V-shaped fabric connection. To investigate the effects of reinforcing yarns on the mechanical properties and thermal-wet comfort properties of spacer fabrics, two different types of reinforcing yarns were inserted into the spacer layer of the fabrics. Based on this, an orthogonal experiment with three factors and three levels was designed. 9 types of spacer fabric samples were knitted in total. The specification parameters and fabric structures of the samples are shown in table 1.

Compression tests

The compression testing was conducted in accordance with FZ/T 01054.1-1999 *General Principles for Fabric Style Test Methods* using a YG821L fabric style instrument. Samples were meticulously cut to dimensions of 65 mm × 50 mm and preconditioned before testing. Each sample was placed on a stable platform, and a rectangular compression plate (5 cm × 2 cm) was applied at a constant speed of 3 mm/min to record the compression stress-strain curves.

Thermal and moisture comfort tests

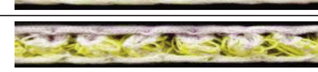
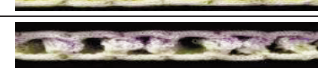
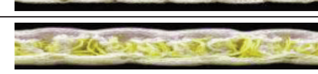
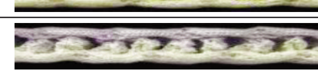
Air permeability tests

Air permeability testing was conducted in accordance with GB/T 5453-1997 *Textiles – Determination of fabric air permeability* using a YG461E-III automated air permeability tester (manufactured by Ningbo Textile Instrument Factory). Each fabric sample was tested over a standardised area of 25 cm^2. Under a test pressure of 100 Pa (as specified in the standard), the instrument measured the volume of air passing through the fabric per unit area and per unit time (mm/s).

Moisture permeability tests

Moisture permeability testing was conducted in accordance with GB/T 12704.2-2009 *Textiles – Test method for water-vapour transmission of fabrics – Part 2: Water method* using the YG601H-III computerised fabric moisture permeability tester. A total of 9 fabric types were evaluated under the evaporation method specified by the standard. Circular samples with a diameter of 70 mm were prepared and tested under controlled environmental conditions of 38±2°C

Table 1

SPACER FABRIC SAMPLES PARTICULARS				
Type	**Factor A**	**Factor B**	**Factor C**	**Cross-sectional view**
L1	Tuck stitch	6	No reinforcing yarn added	
L2	Tuck stitch	8	Bulked yarn added	
L3	Tuck stitch	10	Kevlar yarn added	
U1	2U-shaped	6	Bulked yarn added	
U2	2U-shaped	8	Kevlar yarn added	
U3	2U-shaped	10	No reinforcing yarn added	
V1	2V-shaped	6	Kevlar yarn added	
V2	2V-shaped	8	No reinforcing yarn added	
V3	2V-shaped	10	Bulked yarn added	

Note: Factor A: the interlayer structure of spacer fabrics; Factor B: spacer layer count; Factor C: type of reinforcing yarn.

temperature and 50±2% relative humidity for a duration of 1 hour. The instrument measured the water vapour transmission rate (WVTR) through the fabric, with results reported in grams per square meter per hour ($g/m^2 \cdot h$).

Thermal insulation tests

Thermal insulation testing was conducted in accordance with GB/T 11048-1989 *Test Method for Thermal Insulation Property of Textiles* using a YG606D flat plate fabric insulation instrument. Test samples, each measuring 30 cm × 30 cm, were placed over the instrument's sample plate. The instrument directly recorded key parameters, including insulation rate, heat transfer coefficient, and clo value, which were then documented for analysis.

RESULTS AND DISCUSSION

Compression behaviour of spacer fabrics

By measuring the thickness difference that occurs when two different levels of pressure-light and pressure-heavy are successively applied to the same specimen, followed by the determination of the recovery observed after removing the load, we have calculated 4 key parameters, which are detailed below:

$$\text{Apparent thickness, } T_0 = R_{f1} - R_{o1} \text{ (mm)} \quad (1)$$

$$\text{Stable thickness, } T_S = R_{fh} - R_{oh} \text{ (mm)} \quad (2)$$

$$\text{Compression Rate, } C = \frac{T_0 - T_S}{T_0} \times 100\% \quad (3)$$

$$\text{Recovery thickness, } T_r = R_{fr} - R_{o1} \text{ (mm)} \quad (4)$$

$$\text{Compression Recovery, } RE = \frac{T_r - T_S}{T_0 - T_S} \times 100\% \quad (5)$$

In the equations provided: R_{f1} is the displacement of the pressure plate when the sample is under light pressure; R_{o1} is the initial displacement of the pressure plate under light pressure without a sample; R_{fh} is the displacement of the pressure plate when the sample is under heavy pressure; R_{oh} is the initial displacement of the pressure plate under heavy pressure without a sample; R_{fr} is the displacement obtained when the shape of the sample is restored under high pressure and lightly pressed again.

The pressure settings for automatic stop in the downward direction were 1 cN/cm^2 (light pressure) and 14.7 cN/cm^2 (heavy pressure). For this study, 9 samples were examined, and the mean values are presented in table 2. Using IBM SPSS, we performed an analysis of variance (ANOVA) on the collected data to assess the impact of various factors on fabric compressibility. The results obtained are summarised in table 3. Factor A has a significant impact on the compressibility of the fabric ($p<0.05$). Among the three factors considered, Factor A exhibited the strongest influence, followed by Factor C and then Factor B. However, the three factors have no significant impact on the compression recovery of the fabric.

The degree of fluffiness in a fabric is directly proportional to its compression rate. As evident from figure 2, *a*, the varying levels within factor A exert different degrees of influence on the fabric's compression rate, specifically: 2U-shape > 2V-shape > Tuck stitch. Similarly, within factor B, the order of influence is: 6 > 10 > 8. And within factor C, the impact is ranked as follows: None>Bulk>Kevlar.

Furthermore, the fabric's ability to retain its fullness and softness is enhanced with a higher compression recovery rate. In figure 2, *b*, the hierarchy of influence on fabric compression recovery within factor A shifts to: Tuck > 2V-shape > 2U-shape. Within factor B, the ranking changes to: 8 > 10 > 6. And within factor C, the order of impact becomes: Kevlar > Bulk > None.

In weft-knitted spacer fabrics, those with fabric-layer connections in the spacer layer are typically more fluffy compared to those with tuck-connections in the spacer layer. However, due to their hollow structure in the spacer layer, these fabrics exhibit significantly lower resilience compared to those with tuck connections. The number of spacer layers inversely correlates with both the compressibility and resilience of the fabric. As the number of spacer layers increases, the fabric becomes thicker and less susceptible to compression, yet its resilience improves. Additionally,

Table 2

PERFORMANCE RESULT OF WEFT-KNITTED SPACER FABRICS

No.	T_0 (mm)	T_S (mm)	C (%)	R_E (%)	Air permeability (mm/s)	WVT ($g/m^2 \cdot h$)	Heat retention rate (%)
L1	6.00	5.24	0.13	111.83	58.00	26.49	33.48
L2	6.00	5.64	0.06	162.04	20.02	24.01	37.83
L3	5.61	5.29	0.05	164.79	35.83	24.25	30.57
U1	11.09	8.04	0.27	103.89	545.67	26.52	63.44
U2	13.00	10.55	0.19	122.94	753.07	32.42	63.69
U3	14.39	10.61	0.26	106.28	582.70	32.51	66.74
V1	11.90	10.54	0.11	142.33	655.63	34.07	63.70
V2	15.86	12.60	0.21	101.11	570.03	35.55	69.19
V3	17.71	14.95	0.16	108.83	390.70	32.71	72.75

Note: T_0 – apparent thickness; T_S – stable thickness; C – compression rate; R_E – compression recovery; WVT – the moisture permeability.

Table 3

ANALYSIS OF VARIANCE FOR PERFORMANCE OF SPACER FABRICS										
Dependent variable	**C (%)**		**R_E (%)**		**Air permeability (mm/s)**		**WVT ($g/m^2 \cdot h$)**		**Heat retention rate (%)**	
	F	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Factor A	24.808	0.039	2.769	0.265	318.173	0.003	24.437	0.039	263.187	0.004
Factor B	0.397	0.716	0.190	0.840	10.565	0.086	0.760	0.568	2.600	0.278
Factor C	6.170	0.139	2.690	0.271	20.870	0.046	4.193	0.193	5.576	0.152

Note: C – compression rate; R_E – compression recovery; WVT – the moisture permeability.

adding reinforcing yarn will reduce the fabric's compression rate to a certain extent.

To investigate the relationship between the compressibility and cushioning properties of fabrics, the Elongation (mm) – Force (cN) curves obtained from the tests were processed to generate Compression stress-Compression strain curve diagrams (figure 3). The calculated stress and strain parameters are as follows [22]:

$$\text{Compression strain} = \text{Elongation/Original height} \quad (6)$$

$$\text{Compression stress} = \text{Force}/10 \text{ cm}^2 \quad (7)$$

The compression process of the specimens can be categorised into two distinct stages: the compression phase and the rebound phase, depending on the variations observed in the respective curves. To further investigate the trend of compressive stress with respect to strain during the compression phase, non-linear curve fitting and differential analysis were applied to the stress-strain curves of 9 specimens. The findings obtained from this analysis are presented in figure 4.

Upon examination of the compression rate data tabulated in table 2, it becomes evident that a higher compression rate corresponds to a slower rate of change in compressive stress with respect to strain, resulting in a flatter curve. This observation suggests an inverse relationship between the compressibility

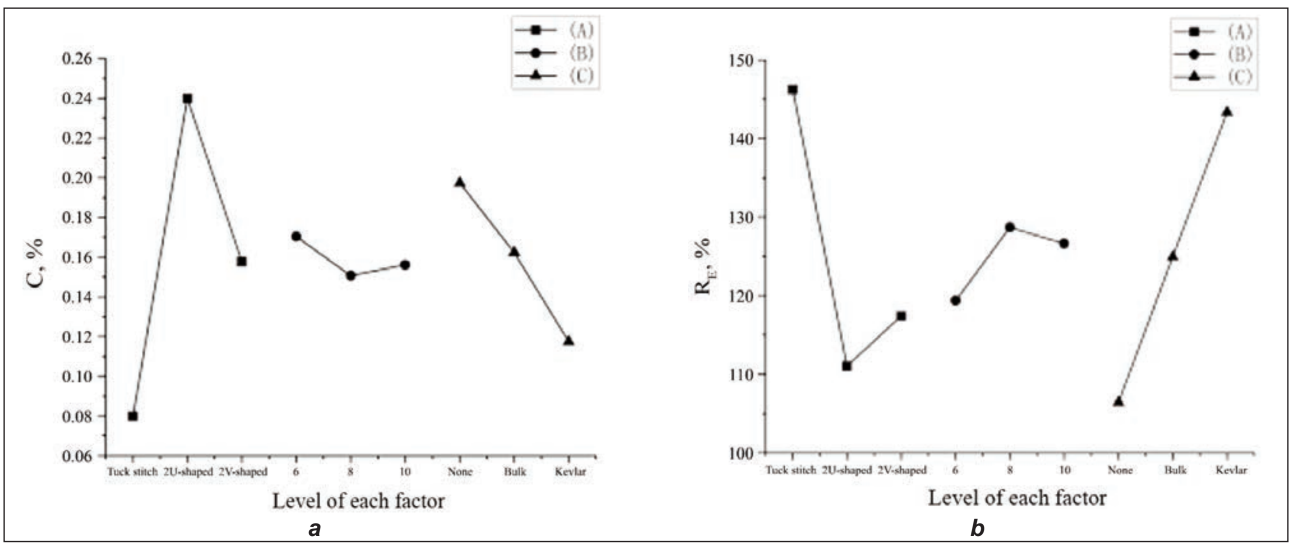


Fig. 2. Chart of compression behaviour for each factor level: *a* – Compression rate; *b* – Compression recovery

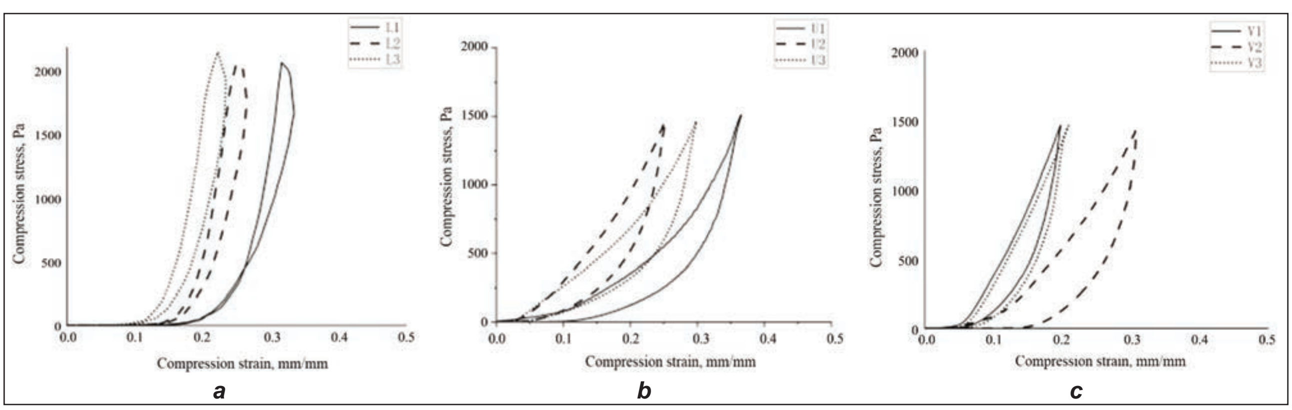


Fig. 3. The compression stress-strain curves of spacer fabric: *a* – Tuck stitch; *b* – 2U-shaped; *c* – 2V-shaped

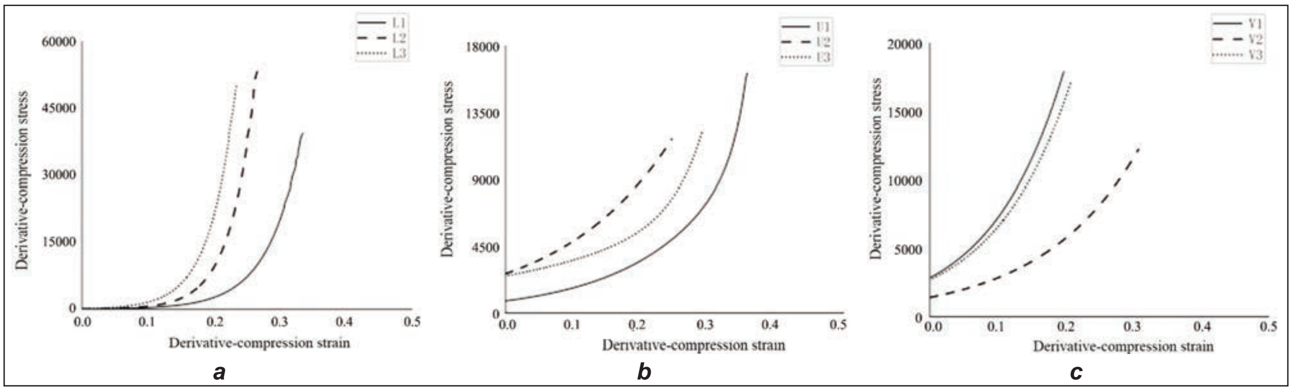


Fig. 4. Derivative of the compression stress-strain curves: *a* – Tuck stitch; *b* – 2U-shaped; *c* – 2V-shaped

and cushioning performance of the fabric. As the compressibility of the fabric increases, its fluffiness also enhances. However, during the compression process, the increment in compressive stress with increasing strain diminishes, indicating a decrease in the fabric's compressive resistance and cushioning capabilities.

Based on the analysis of figures 2 and 3, it can be concluded that the main factor causing the compression stress-strain variation of spacer fabrics is the type of reinforcing yarn, while the number of fabric layers has a relatively minor impact on the compression stress-strain behaviour.

Breathability of spacer fabrics

The results of the air permeability measurements for the 9 specimens are presented in table 2. Through analysis of variance, it was revealed that both Factor A and Factor C exert a significant influence on the air permeability of the fabric ($p<0.05$). Among the three factors, the significance was ranked as Factor A > Factor C > Factor B. To gain a more intuitive understanding of the impact of various factor levels on the air permeability of the spacer fabric, a chart of mean air permeability for each factor level was constructed. As shown in figure 5, *a*, adding bulk yarn to the spacer layer will reduce the air permeability of the fabric. This is because bulk yarn is fluffy, soft, warm, and elastic, and its higher volume allows the fabric to store more stationary air, reducing air flow. The Kevlar yarn, with higher strength and stiffness, enables the spacer layer of the fabric to be more upright, accommodating more flowing air and improving the air permeability of the fabric. Additionally, the structure of the spacer layer also affects the air permeability of the fabric. Compared to spacer fabrics connected by tuck stitches, spacer fabrics connected by fabrics have a certain height, larger air flow space, and better air permeability.

Moisture permeability of spacer fabrics

Based on the moisture permeability test results obtained from table 2. After analysis of variance (shown in table 3), it was found that Factor A has a significant impact on the moisture permeability of the fabric ($p<0.05$), and factors are ranked as follows: Factor A > Factor C > Factor B.

According to the chart of thermal-wet comfort at each factor level (figure 5, *b*), it can be seen that under different spacer layer structures and numbers of layers, the weft-knitted spacer fabric with fabric connections has better moisture permeability than the one with tuck stitch connections. When the number of layers in the spacer is larger, the moisture permeability is better. Therefore, the larger the gap in the spacer layer, the easier it is for water vapour to pass through, and the better the moisture permeability of the fabric. However, the addition of reinforcement yarn in the spacer fabric can cause its fibre diameter to expand after absorbing moisture, which affects the water molecule channels and results in poorer moisture permeability of the fabric.

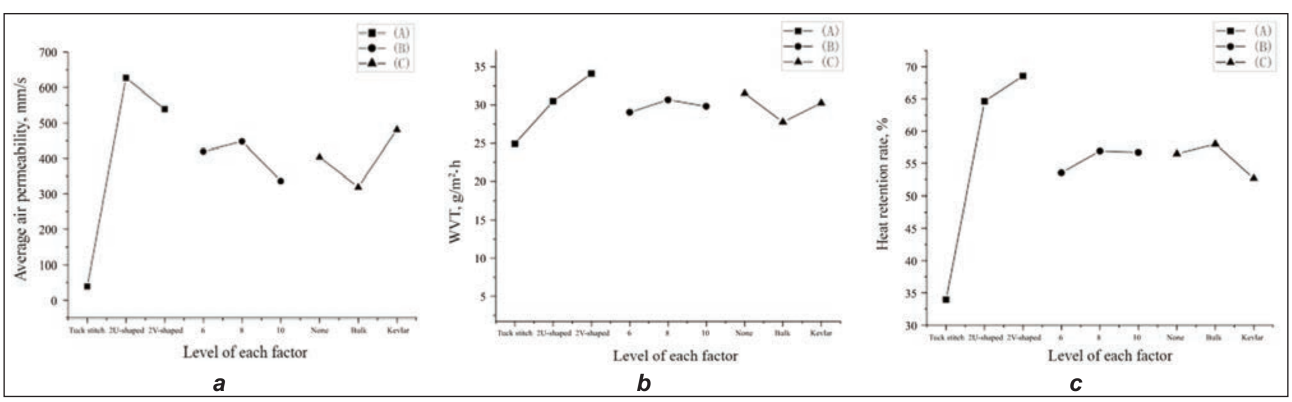


Fig. 5. Chart of thermal-wet comfort at each factor level: *a* – Air permeability; *b* – Moisture permeability; *c* – Heat retention rate

Thermal insulation properties of spacer fabrics

According to tables 2 and 3, it is evident that factor A exhibits a statistically significant impact on the thermal insulation characteristics of these fabrics ($p < 0.05$). Furthermore, the relative significance of the three influencing factors is ranked as follows: Factor A > Factor C > Factor B.

As depicted in figure 5, *c*, the weft-knitted spacer fabrics employing fabric connections possess a higher thickness compared to those utilising tuck stitch connections, thereby conferring a superior thermal insulation performance. Notably, the 2V-shaped configuration demonstrates enhanced stability and a higher heat retention rate than its 2U-shaped counterpart. Additionally, the bulk yarn, attributed to its fluffy texture and larger volume, effectively augments the amount of still air within the fabric, thereby enhancing its warmth retention capabilities.

CONCLUSIONS

This study systematically analysed the effects of spacer layer structure, reinforcing yarn type, and number of layers on the performance of weft-knitted spacer fabrics, with key findings as follows:

- The spacer layer structure exhibited the most significant influence on compressibility, air/moisture permeability, and thermal insulation ($p<0.01$), followed by the type of reinforcing yarn, while the number of spacer layers had a relatively minor impact. The double-layer V-shaped fabric-layer connection structure demonstrated superior cushioning performance compared to the double-layer U-shaped structure. Additionally, the insertion of reinforcing yarns further enhanced compression resistance. Compressibility was significantly negatively correlated with cushioning performance, meaning higher compression rates corresponded to poorer compression resistance and cushioning.
- Spacer fabrics with fabric-layer connections showed significantly better air permeability than those with tuck connections. Fabrics with larger spatial configurations in the spacer layer facilitated smoother water molecule migration, improving water vapour transmission rate and moisture permeability. The addition of bulked yarns significantly enhanced the thermal insulation properties of the fabrics. All tested samples had a thermal insulation rate exceeding 30%, meeting basic thermal insulation application requirements, with fabric-layer connection structures and bulked yarn-reinforced fabrics exhibiting superior heat retention performance.

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