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The Effect of Structural Characteristics on Thermal and Moisture Management Properties of 3D Fabrics Designed for Pressure Relief Applications

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Abstract

This paper presents a comparative study of different 3D fabrics designed and produced to be used as mattress and seat overlays for bedridden or people with reduced mobility. Two 3D patterns were developed using a double-weaving process. The effect of pick density and filling weft linear density on the thermal properties, air and water vapour permeability and wicking ability of the resulting 3D fabrics was evaluated and compared. The obtained results demonstrated that the fabrics produced with the pattern with less number of intersections and lengthier floats (striped channel structure), less pick density and finer filling weft yarns, depicted the highest air and moisture transfer properties, which makes them a better solution for a cushioning interface material.

Keywords: 3D fabrics; Double-woven fabrics; Thermal and moisture management properties; Pressure-relief materials

Introduction

A frequent problem associated to bedridden and people with impaired mobility are the formation of pressure ulcers. Various factors contribute to the development of these skin injuries, usually localized over a prominent bone. These include pressure, shear, friction, moisture and temperature. Nowadays, the majority of products used to prevent or minimize this problem are gel or foam-based. These cushioning interface materials, primarily focused on pressure-relief, do not ensure adequate temperature and moisture management conditions of the surrounding microclimate, which is also a major factor for skin lesions development [1].

In recent years, an increasing interest towards the use of multi-layered woven fabrics arose, since their structure can provide the compressive and thermoregulation characteristics required by these healthcare applications. These features, which are of paramount importance to impart comfort, are essentially determined by the fabric's structure [2].

Closely related to thermoregulation, thermo-physiological comfort is determined by the fabric's ability to transfer heat and vapour and remove moisture from its surface [3] i.e., by the fabric's thermal and moisture management properties. These properties significantly depend on the fabric composition, type of weave, fabric density and surface texture [4,5], which in turn affect fabric porosity [6]. Porosity is an essential quality for covering matts, as it influences air permeability and consequently, the thermal properties and the moisture transfer ability of the material [6-9]. In multi-layered woven fabrics, the relationship between porosity and air permeability is complex and difficult to determine, as porosity is also influenced by the reed denting and the type of fabric stitching [10].

Previous studies have shown the potential of fabric pattern geometry and texture to generate pressure relief and improve thermo-physiological comfort [4,5]. Furthermore, several research works pointed to the use of cotton fibers in the development of products for pressure ulcers' prevention due to their comfort-related characteristics, namely, good compressibility, thermal regulation and moisture behavior [4,11,12]. Nevertheless, only a few were focused on the design and performance assessment of 3D fabrics for pressure-relief, in particular, based on multi-layered woven fabrics [4,5,13].

The purpose of this study is to evaluate and compare the thermal and moisture management properties of 100% cotton 3D double-woven fabrics specifically developed and produced for cushioning interface coverings pressure-relief applications. Two patterns based on striped and checkered pocket structures were designed to develop the 3D fabrics. The effect of the base-fabrics' pick density and filling yarn linear density on the most relevant thermal and moisture management properties of the resulting 3D fabrics was also assessed.

Materials and Methods

Six 3D double-woven fabrics (100% cotton) were produced based on two 3D patterns (a striped and a checkered pocket structures, 1/1 plain weave) specially designed to create uneven and voluminous fabric surfaces. All the fabric samples were produced with a 60/2 Ne weft yarn and 38/2 Ne warp yarns in the upper and lower fabric sheets. Two pick densities were selected (48 and 58 picks/inch). In the fabric samples produced with 48 picks/inch, a 12/2 Ne weft yarn was used in the 3D patterns' filling floats (filling weft). The fabric samples with 58 picks/inch were produced with 12/2 Ne and 8/4 Ne filling weft yarns. All the designed fabrics were produced at Somelos Tecidos SA, company on a Vamatex rapier loom. After weaving, the fabrics were washed using a standard program. The cross-section of the 3D patterns designed and the constructional characteristics of the 3D double-woven fabrics developed are shown in Figure 1 and Table 1, respectively. The fabric density and porosity were calculated based on equation [14].

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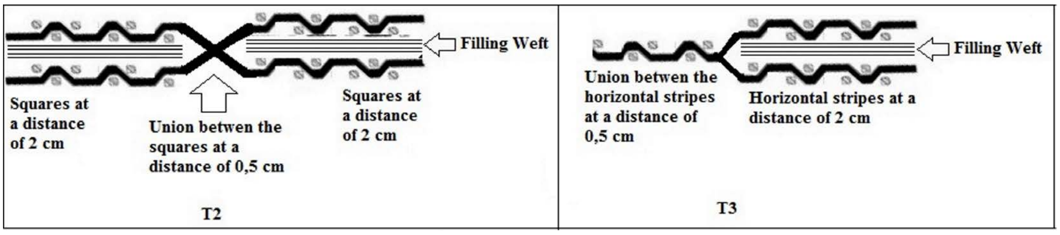

Figure 1: Cross-sectional view (along the warp) of the 3D weave patterns designed.

Sample Code	Weave pattern	Filling weft linear density (Ne)	Upper and lower fabrics		Mass/ unit area (g/m²)	Thickness (mm) at 100Pa	Fabric density** (g/cm³)	Fabric Porosity* (%)
				Fabrics'density (ends x picks /")				
T2-48-N(12/2)		12/2	38/2 Ne x 60/2 Ne	109 x 48	457,88	3,22	0,142	90,8
T2-58-N(12/2)		12/2	38/2 Ne x 60/2 Ne	109 x 58	517,02	3,92	0,132	91,4
T2-58- N(8/4)		8/4	38/2 Ne x 60/2 Ne	109 x 58	751,09	5,20	0,144	90,6
T3-48-N(12/2)		12/2	38/2 Ne x 60/2 Ne	109 x 48 462	462,59	3,97	0,122	92,1
T3-58-N(12/2)		12/2	38/2 Ne x 60/2 Ne	109 x 58	522,11	4,42	0,118	92,3
T3-58-N(8/4)		8/4	38/2 Ne x 60/2 Ne	109 x 58	842,08	6,85	0,123	92,0

*Porosity (%)=1- [Fabric density (g/cm³)/Fibre density (g/cm³)] x100 **Fabric density (g/cm³)=Fabric areal mass (g/cm²)/Fabric thickness (cm)

Table 1: Constructional characteristics of the double-woven fabrics developed.

The developed fabrics were conditioned in standard atmospheric conditions (20°C ± 2 temperature; 65% ± 2 relative humidity, according to ISO 139:1973) before testing and were then characterized regarding air permeability, thermal resistance, water vapour permeability and wicking behaviour.

The air permeability of the double-woven fabric samples was evaluated according to NP EN ISO 9237 on a permeability tester from Textest Instruments (Model FX3300), under a differential pressure of 200 Pa.

The thermal resistance was evaluated using a steady state heat flow meter apparatus (Alambeta) (Hes, 1987) [15] working under a constant temperature of 32°C and 100 Pa of contact pressure. The tests were performed according to ISO 8301 (1991).

The moisture management properties were investigated concerning the wicking ability (vertical and transverse) and water vapour permeability.

The wicking ability of a fabric is defined by the spontaneous dispersion of liquids along and through its structure, due to capillary forces [16,17]. Vertical and transverse (horizontal or in-plane) wicking tests were performed according to standards AATCC TM 197-2011 and AATCC TM 198-2011, respectively. In the vertical wicking experiments (Byreck method), the wicking height was registered at 60 s intervals until 5 minutes and then at 5 min intervals until 30 minutes. In the transverse wicking tests, the wicking area and time needed to disperse 1.0 ± 0.1 mL of distilled water were registered. To confirm the accuracy of the measurement procedure, the water was coloured.

The water vapour permeability of the 3D double-woven fabric samples was evaluated using the Shirley Water Vapour Permeability Tester, from SDL International, (model M261), according to BS 7209: 1990. This method (cup method) allows the calculation of the Water vapour permeability index (%) and rate (g/m².day) and is commonly used to assess the moisture transfer ability of fabrics.

Results and Discussion

The air permeability, thermal resistance, water vapour transfer and wicking characteristics of the 3D bi-layered woven fabrics developed have been evaluated and are reported on the following table (Table 2).

The results obtained will be explained based on the 3D pattern, pick density and filling yarn linear density of the fabrics developed. The quantitative analysis of the data was carried out using the SPSS software tool.

Air permeability

The air transfer ability of the six double-woven fabrics is shown in Figure 2. The calculated fabric density and porosity are also depicted in the graph.

From Figure 2 it can be observed that the 3D pattern clearly affects fabrics' air permeability. Fabrics T3, with fewer intersections between the upper and lower sheets and lengthier filling weft floats, exhibited significantly higher air permeability than fabrics T2. This can be explained by the easier movement of the lengthier floats when the air stream is applied to the fabric [10]. The major air permeability increase (around 75%) was observed between the samples produced with the 8/4 Ne filling yarn (T2-58-N(8/4) and T3-58-N(8/4).

For both patterns the highest air permeability was obtained with the lower fabric pick density (48 picks/"). This behaviour was expected

Sample Code	Air permeability (l/m^2/s)	Water vapour permeability		Wicking height (cm) (after 10 min immersion)		In-plane wicking		Thermal resistance(x10^{-3}) (m^{2o}K/W)
		WVP Index (%)	WVP (g/m^2.day)	Warp wise	Weft wise	Time (s)	Area(cm^2)	
T2-48-N(12/2)	659.70	89.0	676.98	8.8	10.9	7.0	18.76	59.28
T2-58-N(12/2)	449.30	88.1	585.32	9.0	10.3	6.0	18.73	70.58
T2-58-N(8/4)	372.20	82.8	663.17	8.0	9.1	5.6	14.85	77.30
T3-48-N(12/2)	876.90	97.3	697.26	12.0	12.6	5.4	23.47	67.06
T3-58-N(12/2)	569.50	93.0	675.00	11.7	12.0	5.0	22.20	76.50
T3-58-N(8/4)	660.60	94.8	660.27	11.0	12.1	5	21.92	99.86

Table 2: Air transfer, thermal and moisture management properties of the double-woven fabrics developed.

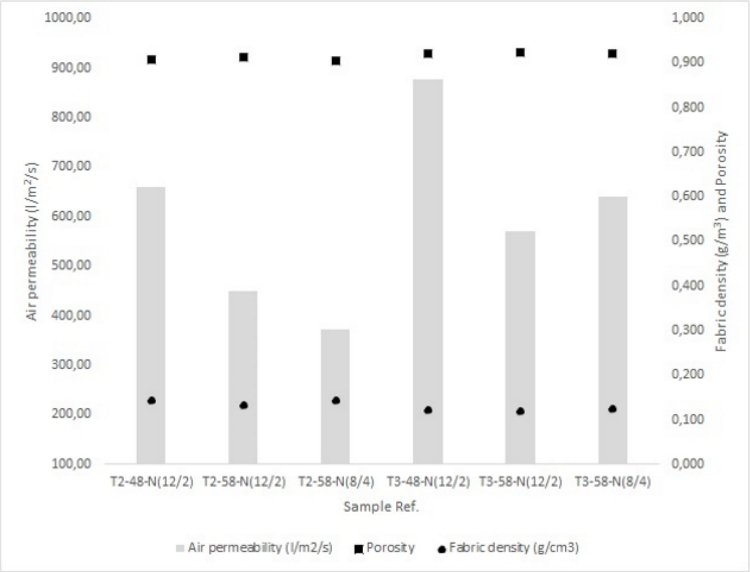

Figure 2: Mean air permeability (l/m^2/s), fabric density (g/cm^3) and porosity of the 3D double-woven fabrics developed.

[3,18] and is mainly due to the increase in the weft yarns spacing, which reduced the fabrics resistance to air flow. The effect of filling yarn linear density on air permeability was not the same for both fabrics. In the fabric T2, the coarser filling yarn (8/4 Ne) led to a decrease in fabric's air permeability, whereas in fabric T3, an increase was observed. As the fabrics T2 and T3 have the same weft density (58 picks/"), it was expected that a reduction in air permeability would occur when the coarser filling yarns were used [19]. The results obtained with fabric T3 are not in accordance with this trend, i.e., the fabrics produced with the 8/4 Ne filling wefts showed higher air permeability than the ones produced with the yarns 12/2 Ne. The combined effect of the 3D pattern and the yarn structure seems to be the main cause for this behaviour. Due to the lengthier filling yarn floats of the 3D pattern (striped tunnel structure), the primary factor affecting air permeability is the yarn uniformity, instead of thickness. Therefore, the higher structural evenness of the 4-ply yarns may have facilitated the air flow within the fabric structure, which resulted in higher air permeability. In fabric T2, the contribution of the filling yarn thickness was preponderant, seemingly due to the shorter filling yarn floats of the 3D pattern (checkered pocket structure).

Overall, the fabric density (g/cm^3) of the fabrics T2 is higher than that of fabrics T3, which means that the fiber compactness in fabrics T2 is higher. This can explain the lower air permeability demonstrated by these fabrics. Furthermore, both fabrics showed a decrease in fabric density and in air permeability with an increase in the pick density. Even though the decrease of the inter-yarn spacing of the upper and lower fabric sheets (due to the higher weft density), led to a decrease on fabric's air permeability, the fiber compactness was reduced, because of fabric thickness and mass per unit area increase. The increase in the filling yarn thickness led, as expected, to an increase in fabric density and air permeability.

All fabrics showed to be highly porous (>90%), but there are no significant porosity differences between them. The analysis of variance demonstrated that there is a significant influence of the fabric structural characteristics on the air permeability. Fabric pattern accounted for F (5.54)=631,211 with a significance of 0.000 and $p < 0.01$ of the variance in air permeability.

Thermal resistance

The thermal characteristics of fabrics are mainly dependant on the type of fibre and on the entrapped air within the fabric. Fabric thickness is a major factor affecting heat transfer [20]. In multi-layered fabrics, the greater the distance between layers, the higher the thermal resistance of the fabric [4].

Figure 3 shows the mean thermal resistance for the six 3D double-woven fabrics developed and the respective thicknesses.

As it can be observed, the thermal resistance of fabrics T3 is higher than that of fabrics T2. The lower fabric density of these fabrics together with the higher thicknesses seems to be major influencing factors.

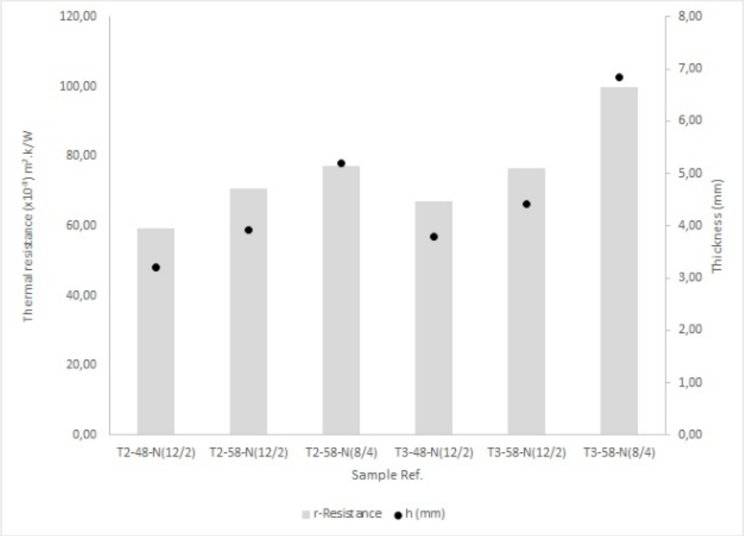

Figure 3: Fabrics' thermal resistance, R (x10^{-3}), m^{2}K/W versus thickness (mm).

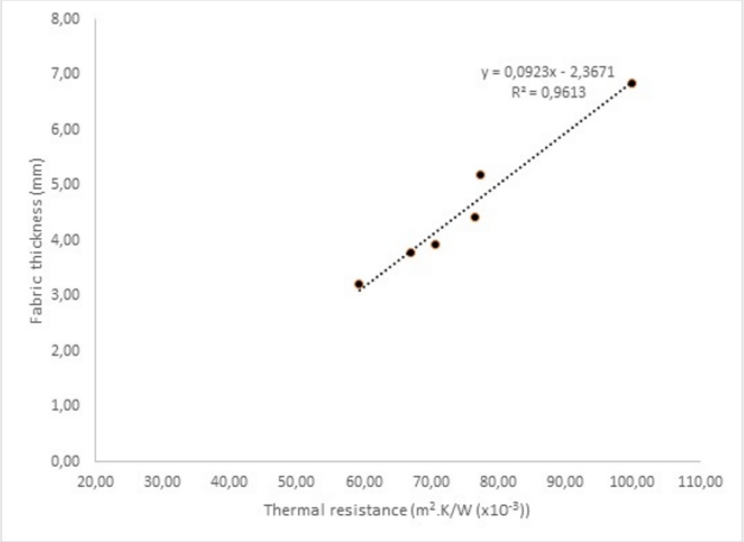

Figure 4: Relation between fabric thermal resistance, R (x10^{-3}), m^{2}K/W and thickness (mm).

Furthermore, the fabrics with higher pick density (58 picks/") and thicker filling wefts (8/4 Ne) showed higher thermal resistance. This trend is in accordance with other research findings [4]. In Figure 4 it is apparent the relation between fabric thickness and thermal resistance. Regardless the fabric pattern, the thermal resistance increases with fabric thickness.

Vertical and transverse wicking

The capillary transport of liquid water through the fabrics was assessed both in the longitudinal and transverse directions. Figures 5 and 6 show, respectively, the wicking height (cm) and the relative wicking rates (cm/min) of the 3D double-woven fabrics obtained in warp and weft directions, for the 30 minutes test period.

As it can be observed on Figure 5, the wicking heights obtained for the 30 minutes period in the warp direction are significantly higher for fabric pattern T3 (striped channel structure). Furthermore, from Figure 6, it is apparent that the wicking rates of fabrics T3 are higher than the ones of fabrics T2. This can be attributed to the 3D pattern of fabric T3 (with fewer intersections and lengthier floats), which promoted a faster movement of the water through the fabrics. These results are in accordance with previous studies on the wicking behaviour of different fabrics [21]. In the weft direction, except for fabric T2-58-N (8/4), there are no significant differences between the fabrics. For both patterns, the effect of pick density and filling yarn linear density on the wicking height and rate is not significant.

After 10 minutes immersion, the wicking height of all T3 samples (in the warp and weft directions) is higher than 10 cm (see Table X above), which qualifies these fabrics with excellent wickability (FTTS-FA-004, 2005).

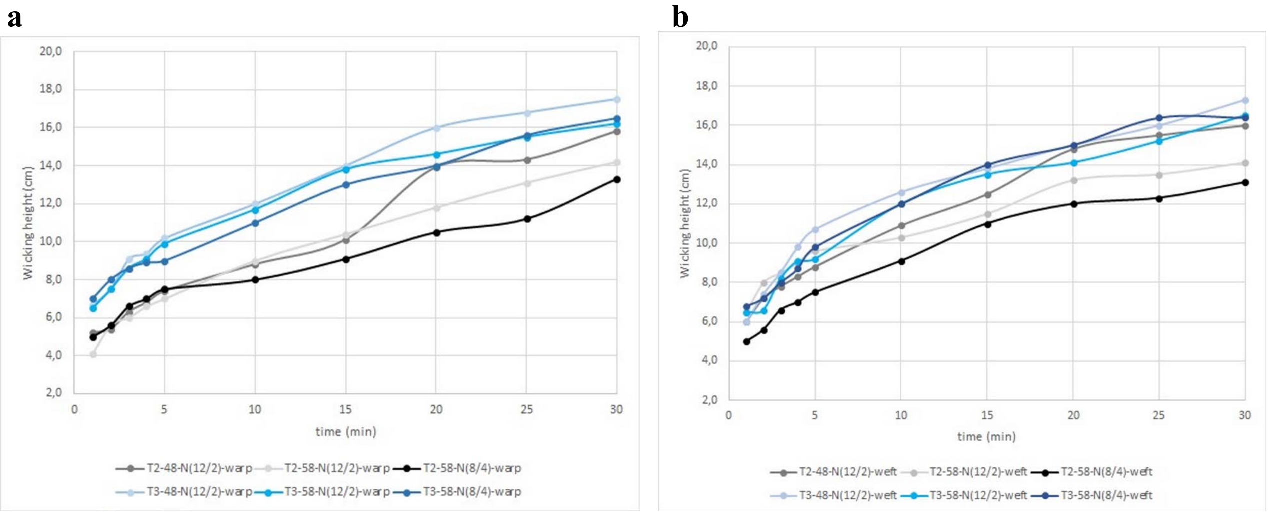

Figure 5: Vertical wicking height: (a) in warp direction; (b) in weft direction.

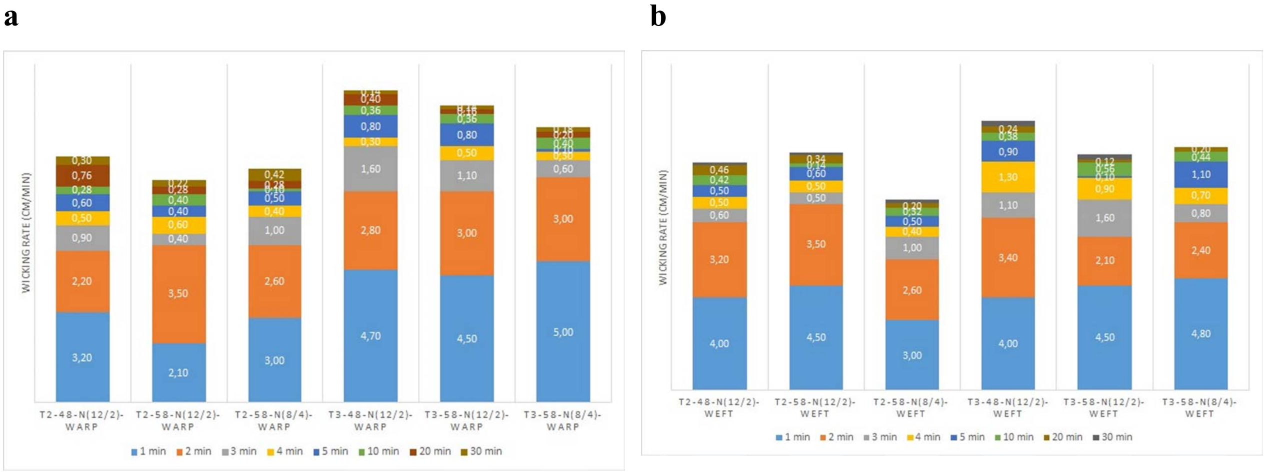

Figure 6: Relative wicking rates for the different time intervals: (a) in warp direction; (b) in weft direction.

The transmission of water through the thickness of the fabrics is illustrated on Figure 7, where the mean values of spreading time (s) versus wetted area (cm^2) are depicted.

As it can be observed, a higher dispersion time and a smaller wetted area was obtained on fabric samples T2 (checkered pocket structure). Fabric surface texture, shorter capillary paths and higher fabric density seem to have slowed the spreading of water through the fabric thickness.

Water vapour permeability

As it can be seen in Figure 8, the fabrics show slight differences in the water vapour permeability behaviour.

Nevertheless, it apparent for both patterns (T2 and T3) a clear drop in the WVP (g/m^2.day) with an increase in the upper and lower sheets pick density (from 48 to 58 picks/"). The higher fabric cover promoted by the weft yarns may be the reason for the reduction in the water vapour permeability rate. According to the ANOVA analysis, the water vapour permeability rates obtained for the developed fabrics are significantly different.

Conclusions

The main purpose of this paper was to evaluate and compare the thermal and moisture management properties of 3D double-woven fabrics, designed for mattress and seat coverings to be used in bedridden and people with impaired mobility. Two 3D patterns, two pick densities in the upper and lower sheets (48 and 58 picks/inch) and two filling yarn linear densities (12/2 Ne and 8/4 Ne) were considered in the fabrics ‘design, to better understand the effect of these structural parameters in the final product properties. It was found that the 3D pattern of the fabric significantly affected the air permeability of the bi-layered woven fabrics. The pattern with less intersections and lengthier floats imparted to the fabrics better air transfer ability, which led to better moisture management properties. The thermal resistance was confirmed to be directly proportional to the fabrics’ thickness. Based on the obtained results, fabrics with the 3D pattern T3 (striped channel structure) were considered preferred candidates to be used as interface coverings for mattresses and seats, as they demonstrated better thermal and moisture management properties. Moreover, the samples produced with lower pick density and finer filling weft yarn depicted the best

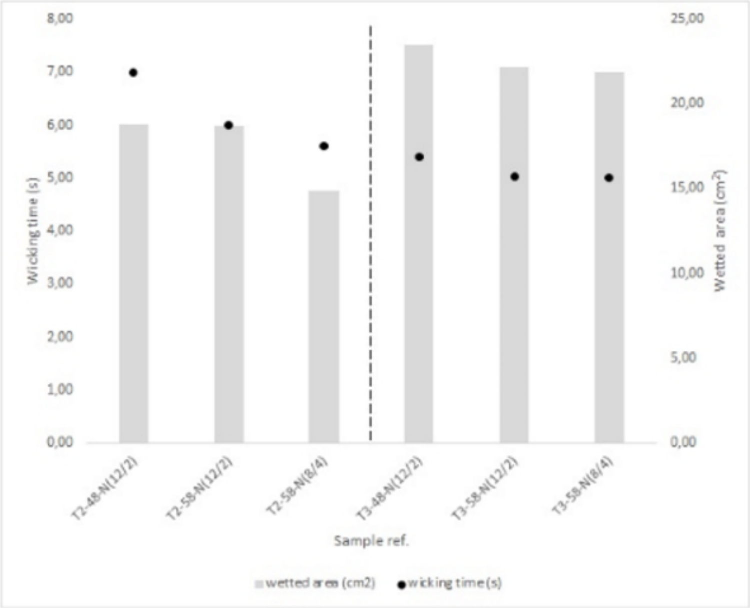

Figure 7: Wicking time and wetted area of the 3D double-woven fabrics.

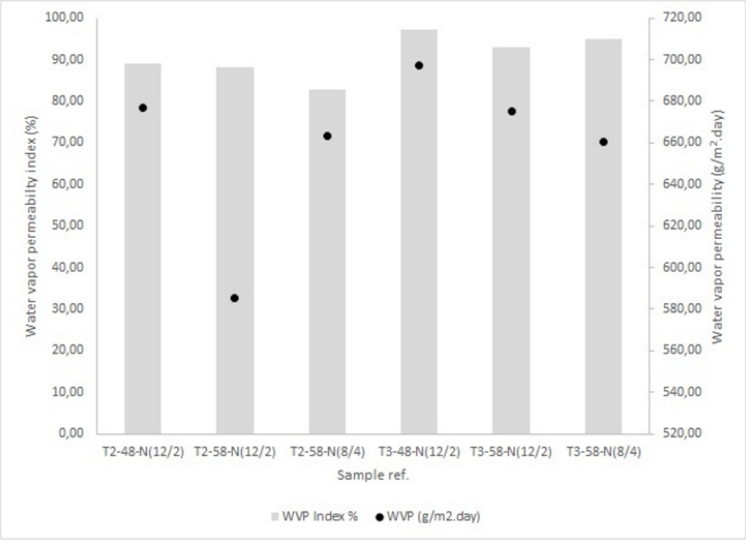

Figure 8: Water vapour permeability of the six 3D fabrics.

results. To validate these 3D fabrics as cushioning interface materials, compression performance studies are being carried out to assess their ability to promote pressure-relief.

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