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MECHANICAL BEHAVIOR OF DOUBLE-WOVEN FABRICS DEVELOPED FOR PRESSURE-RELIEF APPLICATIONS

COMPORTAMENTO MECÂNICO DE TECIDOS TECIDOS-DUPLOS DESENVOLVIDOS PARA APLICAÇÕES DE ALÍVIO DE PRESSÃO

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Abstract: Mattress and seat overlays are pressure-relieving support surfaces designed to minimize the formation of pressure ulcers in bedridden or people with reduced mobility. In this article, new support surfaces based on two-layer 3D fabrics were developed, and their mechanical ability to promote pressure relief was investigated. Four 3D fabrics were produced on a bilateral pincer loom, varying the base fabric weave density and the filler weave's linear density. The following properties were evaluated: compression capacity, surface friction, shear, and bending. The increase in the density of the fabric's weft (from 48 to 58 threads/") and in the linear density of the filling wefts (from 12/4 Ne to 8/4 Ne) improved the compression behavior (compressibility 48 -50%), thickness recovery (100-99% recovery after removing the 3 kPa pressure) and increased the kinetic friction coefficient, which provides good adhesion and is more suitable for pressure relief cover fabrics.

Keywords: Double-woven, pressure ulcers, compression ability, mechanical properties.

Resumo: *As coberturas de colhões e assentos são superfícies de suporte para alívio de pressão projetadas para minimizar a formação de úlceras de pressão em pessoas acamadas ou com mobilidade reduzida. Neste artigo, novas superfícies de suporte baseadas em tecidos 3D de duas camadas foram desenvolvidas e sua capacidade mecânica de promover alívio de pressão foi investigada. Quatro tecidos 3D foram produzidos em um tear de pinças bilaterais, variando a densidade da trama dos tecidos de base e a densidade linear da trama de enchimento. As seguintes propriedades foram avaliadas: capacidade de compressão, atrito superficial, corte e propriedades de flexão. Os resultados obtidos mostraram que o aumento da densidade da trama dos tecidos (de 48 para 58 fios/") e na densidade linear das tramas de enchimento (de 12/4 Ne para 8/4 Ne) melhorou o comportamento de compressão (compressibilidade 48-50%), recuperação de espessura (100-99% de recuperação após a remoção da pressão de 3 kPa) e aumentou o coeficiente de atrito cinético, o que proporciona boa adesão e é mais adequado para tecidos de cobertura de alívio de pressão.*

Palavras-chaves: *Tecido duplo, úlceras de pressão, capacidade de compressão, propriedades mecânicas.*

1 Introduction

Pressure ulcers are localized body injuries that often occur over bony prominences and can be caused by any combination of pressure, shear forces, or friction between the bone and the skin's external surface. Despite the advances in products, resources, and strategies for

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preventing pressure ulcers, these lesions persist and represent a health care problem (Lima et al., 2009).

More attention has been focused on designing and developing fabrics to promote comfort and pressure relief to bedridden or people with reduced mobility in the past few years. Double-woven fabric structures emerged as potential candidates for these applications, as they can be designed to promote energy absorption, improved thermo-physiological comfort, moisture management, and breathability (Basal and Ilgaz, 2009; Gokarneshan, 2004). Nevertheless, a few studies were carried out addressing these fabrics' development and mechanical performance for this specific purpose.

Pressure, shear, and friction are the most important extrinsic factors involved in pressure-ulcer formation. The support surfaces should contribute to the reduction of shear and pressure stresses, simultaneously promoting a microclimate that avoids temperature or skin moisture excess to enhance comfort (Reger et al., 2010). Therefore, the mechanical properties of fabrics related to the compression, shear, bending, and friction behavior play a key role in achieving pressure-relief. These properties are closely related to the mobility of warp and weft yarns within the structure, clearly affecting tactile and pressure sensations responsible for sensorial comfort (Sugla and Kwan, 2016). Also, the surface characteristics of fabrics, which are mainly dependent on the weave pattern and the fiber and yarn type, significantly influence the fabrics' roughness and coefficient of friction (Reger et al., 2010).

Previous studies on the development of functional fabrics for pressure relief demonstrated the ability of weave patterns comprising concave and convex structure geometries (such as honeycombs) to relieve pressure and the potential to promote thermo-physiological comfort (Basal and Ilgaz, 2009; Snycerski and Frontczak-Wasiak, 2004). Other studies demonstrated cotton fibers' use in products designed to prevent pressure ulcers due to their comfort-related and non-allergic intrinsic properties (Asanovic et al., 2016; Lima et al., 2005; Sugla and Kwan, 2016). Therefore, it is apparent that the structural characteristics of fabrics, such as composition, weave pattern, and yarns' properties, are decisive for the fabric's conformity with its application (Asanovic et al., 2016; Ghazimoradi et al., 2018).

In this study, 100% cotton double-woven fabrics were developed and produced for pressure-relief applications, to be used as covers for mattresses or chairs, which can be a useful alternative for preventing pressure ulcers in bedridden or people with reduced mobility. Two weave patterns were designed, creating channeled fabric structures with uneven surfaces. These 3D patterns were produced in two variants, in terms of the base-fabrics' pick density and filling linear yarn density. The structural parameters' influence on the most relevant properties in promoting sensorial comfort associated with the tactile and pressure sensations and pressure-relief was investigated.

2 Materials and Methods

2.1 Development of double-woven

The double woven fabrics designed in this investigation to minimize the formation of pressure ulcers were developed according to a detailed study of textile structures, surface patterns, textile fibers, and structural characteristics. This study demonstrated the potential that double woven to generate pressure relief due to optimal energy absorption and the possibility to design its structure according to the intended compression behavior (Basal and Ilgaz, 2009; Eadie and Ghosh, 2011; Eriksson et al., 2011; Mohamed, 2008; Parkova and Vilumsone, 2013; Pryczynska et al., 2003; Snycerski and Frontczak-Wasiak, 2004; Xu and Ge, 2012). Regarding the pattern of surfaces, it was found that fabric surfaces with concave and convex geometric shapes can promote a high area of contact with the body, facilitating the pressure distribution of the body and having the potential to be used in pressure relief applications (Basal and Ilgaz, 2009; Snycerski and Frontczak-Wasiak, 2004; Xu and Ge, 2012).

Studies in healthcare applications for textile fibers indicated the cotton fiber as the preferred material due to its softness (Behera, 2007), excellent mechanical behavior (Asanovic et al., 2016), adequate absorption moisture, good breathability (Pryczynska et al., 2003), and it does not cause allergies.

However, the research for the development of fabrics also showed that the mechanical properties of fabrics for application in the prevention of pressure ulcers depend on the constructive characteristics (Lima et al., 2016; Nayak et al., 2009; Onofrei et al., 2011; Pryczynska et al., 2003). This paper has investigated the effect of different parameters constructive on mechanical properties of fabric due to the relationship between the bending properties, shear, surface friction, and fabric comfort (Behera, 2007; Hu, 2004; Lima et al., 2005; Onofrei et al., 2011; Pryczynska et al., 2003).

Four bilayered-woven 100% cotton fabrics were developed combining different constructional parameters, namely, pattern weave (two channeled patterns, 1/1 plain), base-fabrics' pick density (48 and 58 picks/ inch), and filing linear weft density (8/4 Ne and 12/2 Ne). The number of filling wefts was adjusted to the maximum packing density (maximum weavability). A coarse weft yarn (12/2Ne) was used in the white picks, and a finer one (60/2 Ne) in the red picks to enhance the channeled pattern undulated effect. The parameters related to the warp were kept constant and were the same in the upper and lower fabric sheets. The 3D weave structure of the fabrics is shown in Figure 1, and the developed double-woven fabrics' main constructional characteristics can be seen in Table 1.

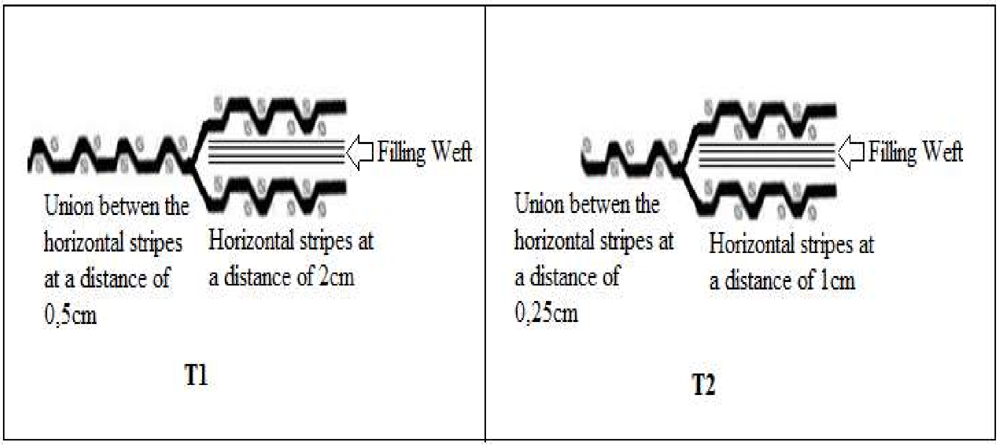

Figure 1. Schematics of the 3D weave structures designed- Sample T1 and T2

Table 1 - Characteristics of the double-woven fabrics developed

Sample Code	Weave pattern	Weft stripes width (cm)	Weft yarn linear density (Ne)		Weft density (picks/")	Filling weft		Mass/ unit area (g/m^2)	Thickness at 100Pa (mm)
			White stripes	Red stripes		Linear density (Ne)	Quantity		
T1-48-N(12/2)		Red -0,5	12/2	60/2	48	12/2	16	462,59	3,79
T1-58-N(8/4)		White- 2			58	8/4	20	842,08	6,85
T2-48-N(12/2)		Red -0,25			48	12/2	7	433,33	3,54
T2-58-N(8/4)		White-1			58	8/4	8	751,26	5,36

The fabrics were produced at Somelos Tecidos S.A. company, on a flexible rapier loom, Vamatex, model Silver HS. The connection by web was the weaving technique used to develop double woven fabrics, changing the position of the threads of the lower and upper web when desired.

The 3D woven fabrics obtained were washed before testing using a standard program. All the tests were performed after conditioning the fabric samples under standard atmospheric conditions (temperature 20 ± 2ºC, 65 ± 2% relative humidity), according to ISO 139: 1973.

A qualitative and quantitative analysis of the data was performed to identify the significant influencing factors and better understand the mechanical behavior of the different 3D developed. The statistical treatment of the data was carried out using the SPSS software tool.

2.2 Compression behavior

The fabric's compression ability is described as a decrease in the intrinsic thickness (also called geometrical thickness) with increased pressure. The intrinsic thickness corresponds to the space occupied by a fabric under almost negligible pressure (Clark et al., 2010; Pazireh et al., 2014).

In this work, the developed fabrics' compression behavior was evaluated by measuring the thickness under different pressures according to the standard ASTM D 1777-1996. The thickness recovery after loading was also evaluated. Sets of five superimposed specimens (aligned in warp and weft directions) from each fabric were used in each test to simulate a covering mat's compression ability better. The tests were carried out at pressures ranging from 70 Pa to 3 kPa. The respective pressure-thickness curves were determined. The fabrics' thickness recovery after 3 minutes at rest was also measured and used to calculate fabrics' compressibility at different pressures, according to the following equation:

$$C = \left(\frac{\mathrm{IT}-}{IT}\right)x100 \qquad (1)$$

C = compressibility (%);
IT = initial thickness (mm);
TAL = thickness after loading (mm).

2.3 Shear properties

The behavior of a fabric subjected to oppositely directed parallel forces (shearing forces) determines how it will deform during its use (Clark et al., 2010). The fabrics were tested on the Kawabata Evaluation System (KES-FB1). A pre-set shear deformation of ± 8º shear angle under a constant tensile force of 10 gf / cm was applied to the samples (Figure 2). The parameters considered in the analysis were the shear rigidity (G) and the hysteresis of shear force at a ±5º angle (2HG5). Three samples of each fabric were tested in the warp and weft directions.

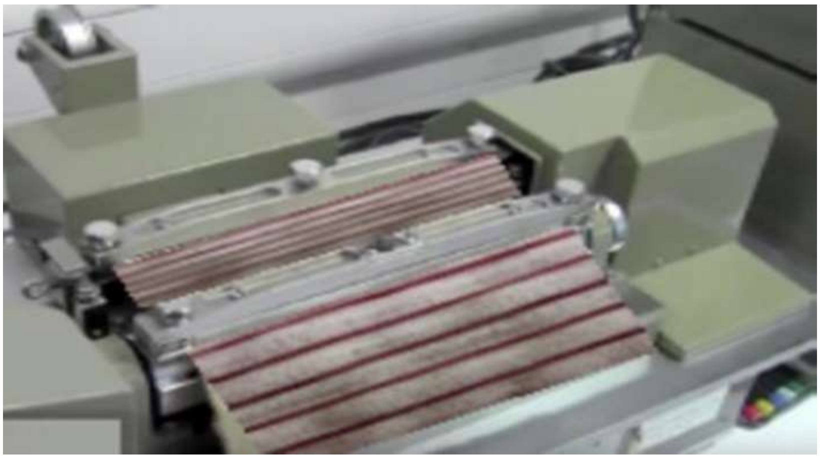

Figure 2. Kawabata Evaluation System-KES-FB1- Tensile and Shear Tester

2.4 Bending properties

Bending is one of the most critical low stress mechanical properties affecting sensorial comfort. The bending or flexural rigidity of a fabric depends mainly on the inter-yarn and intra-yarn friction and affects the conformability, buckling behavior, and handling of textiles. Fabrics with higher bending rigidities are challenging to conform and handle, impairing sensorial comfort (Bonde and Asagekar, 2014; Nayak et al., 2009) .The static bending properties of the fabrics developed were assessed using the Shirley evaluation instrument from SDL, according to standard BS 3356: 1961. This test method uses the cantilever bending principle (based on Pierce's theory). The bending rigidity (G) was calculated considering the bending length and the sample's mass per unit area. The bending modulus (B) took into account the fabrics' thickness, according to equations 2 and 3.

$$\mathrm{G} = (0{,}10.M.C) \qquad (2) \qquad\qquad \mathrm{C} = \left(\frac{12.\mathrm{G}.10}{t3}\right) \qquad (3)$$

G= Bending rigidity (μNm) (Equation 2)
B= Bending modulus (N/ m^2) (Equation 3)
M= Mass per unit area (g/m^2);
C= Bending length (cm).

2.5 Surface friction

Fabric surface friction is defined as its resistance to motion and results from a fabric's movement over another surface in contact, under normal pressure. The coefficient of friction is typically used to assess fabric friction quantitively. Two types of friction can be distinguished: static and kinetic or dynamic friction. This latter is determined when the contacting surfaces have a relative movement. The kinetic or dynamic coefficient of friction of the fabrics developed was evaluated using the Frictorq apparatus (Portuguese Patent application nº102790/2002), equipped with a standard metallic body surface. In this method, the coefficient of friction is computed from the friction reaction torque measured by the torque sensor. Figure 3 illustrates the Frictorq apparatus. Five specimens of each fabric were tested.

Figure 3. Frictorq equipment

3 Results and Analysis

3.1 Compression behavior

According to the method previously mentioned, a set of compression tests was carried out on the layered fabrics to evaluate the suitability of the developed structures to provide comfort and pressure relief for bed or seat coverings. Upon application of pressure, a change in the fabrics' thickness occurs due to the yarns' flattening's structural changes. This change in thickness reflects the compression behavior of fabrics. The pressure-thickness curves of the developed 3D fabrics are shown in Figure 4.

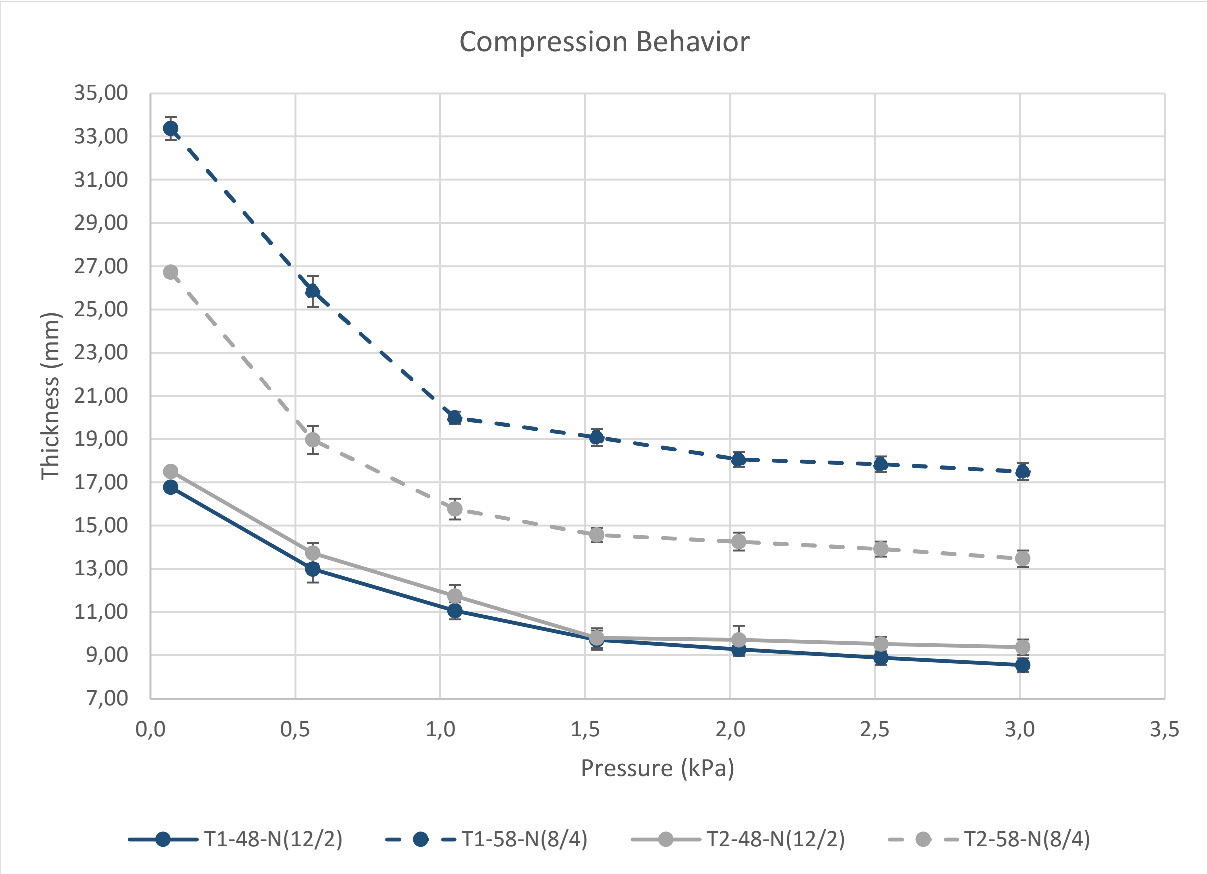

Figure 4. Compression behavior of the four double-woven fabrics developed- change in thickness due to different pressures

As shown in Figure 4, a significant decrease in thickness occurs for all fabrics at the beginning of the compression cycle. Higher slopes are noticed until 1 kPa, indicating that the fabric layers are highly compressible under these pressures. This behavior is mainly due to the reduction of pores and gaps within the double-woven fabrics layered structure. When the fabrics are further compressed, the structures become jammed, tending to their incompressible thickness at around 1.5 kPa. The almost linear segments of the pressure -thickness curves are an indication that the incompressible core of the fabrics is being reached.

From Figure 4, it is also apparent that the fabrics T1-48-N (12/2) and T2-48-N (12/2) have the lowest initial thicknesses, depicting a similar behavior and no significant differences under the different pressures. Fabrics T1-58-N (8/4) and T2-58-N (8/4) produced with the coarser filling weft linear density (Ne 8/4) showed, as expected, the higher initial thicknesses, and simultaneously the more considerable changes in thickness due to different pressures. The effect of the weave pattern is, in this case, clearly visible. The channeled pattern with a higher dimension- 2cm- (T1) promoted an enhanced undulated effect when compared to the fabrics produced with the T2 channeled pattern (1cm).

To better understand the four developed fabrics' compression behavior and their ability for cushioning purposes, the thickness recovery after applying different pressures was evaluated, and the compressibility of the fabrics calculated using equation (1). The results obtained are depicted in Figure 5 and Figure 6, respectively.

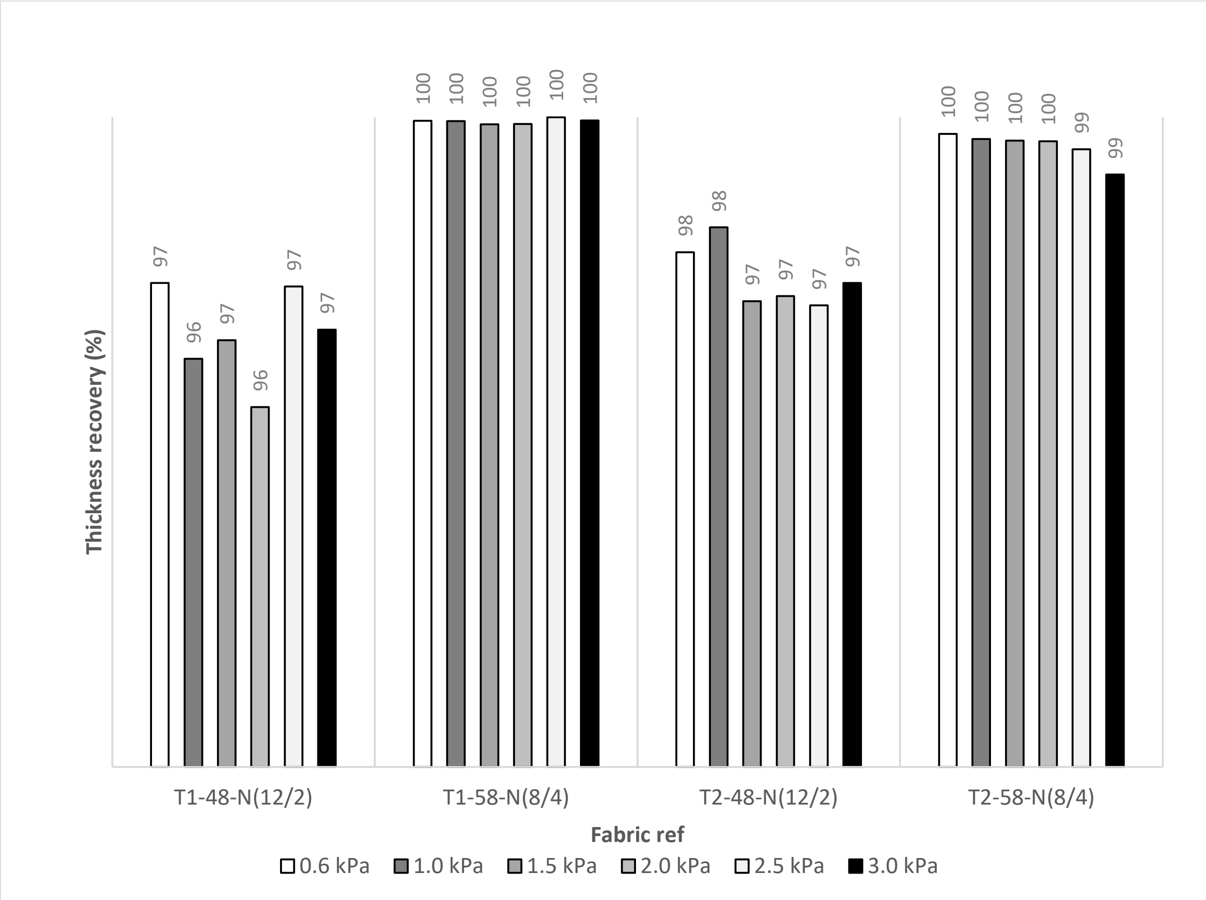

Figure 5. Thickness recovery after different pressure loads

Thickness recovery after compression is a measure of fabrics' resilience and an indicator of cushioning products' functional durability. The results obtained (Figure 5) show that fabrics with lower pick density and adequate filling yarn linear density (T1 and T2-48 N (12/2) did not fully recover the initial thickness after pressure removal, which indicates that a structural deformation may have occurred after compression. The fabrics T1-58-N (8/4) and T2-58-N (8/4) recovered their original thickness after the load withdrawal.

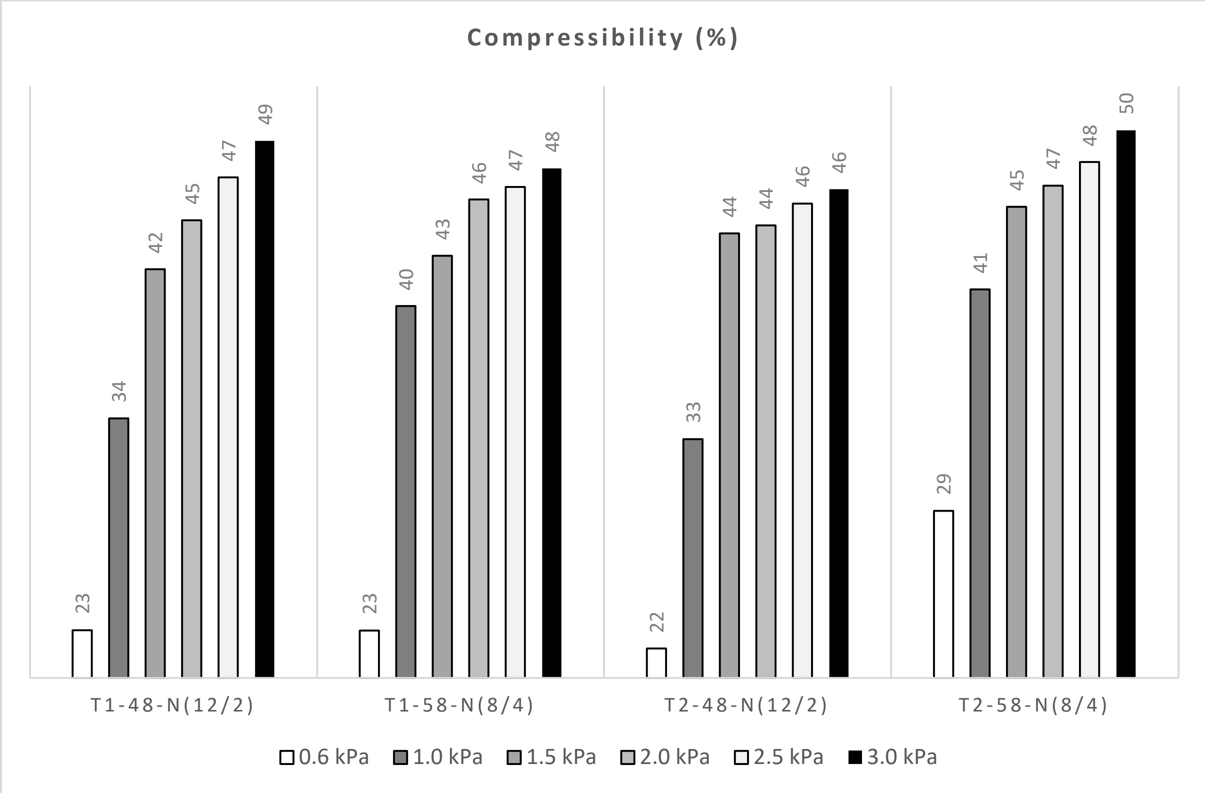

Figure 6. Compressibility of the four double-woven fabrics developed at different pressures

Figure 6 shows that the fabrics' compressibility at pressures equal to or higher than 1.5 kPa is similar for the four fabrics. The values obtained lie between 42% and 50%. Also, it is noticeable that fabric T2-48-N (12/2) reaches its compressibility limit (46%) at 2.5 kPa. The T2-48-N (12/2) fabric has a lower thickness due to the lower weft density and filling weft linear density, which justifies this result, as compressibility is directly related to thickness (Pazireh et al., 2014) and yarns' mobility within the structure. The other fabrics tend to converge to a compressibility limit at pressures higher than 3.0 kPa.

3.2 Shear properties

The shear rigidity (G) and hysteresis of shear force (2HG5) of the developed fabrics, measured in the KES system, is presented in Table 2. An example of the stress-strain curves acquired in the warp and weft directions are shown in Figures 7 and 8.

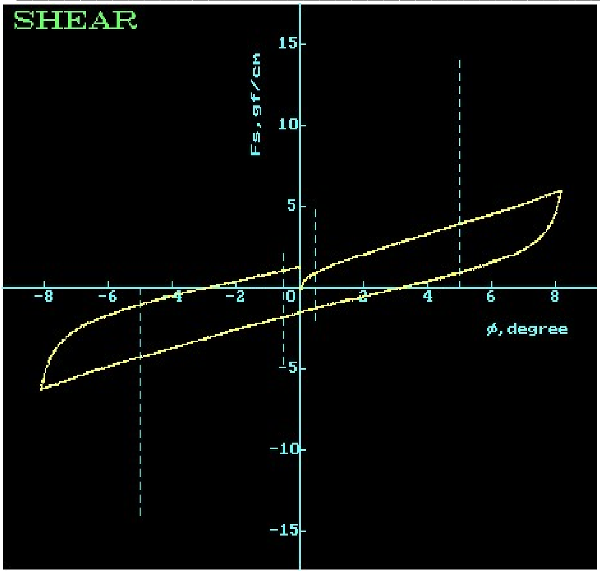

Figure 7. Shear stress-strain in the warp direction of T1-48 -N (12/2) fabric.

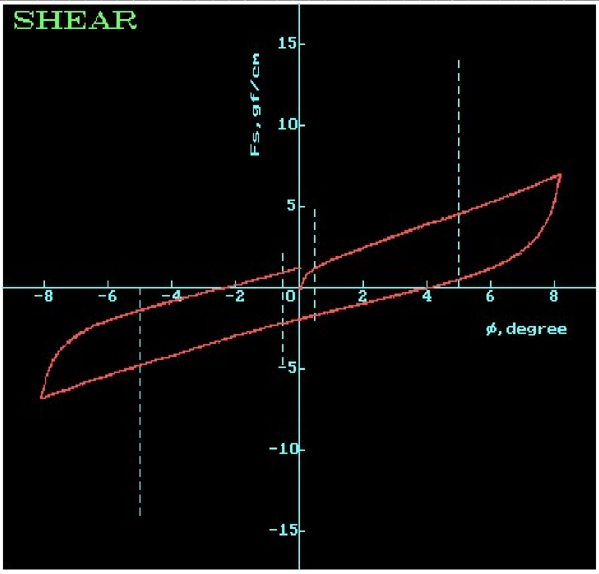

Figure 8. Shear stress-strain in the weft direction of T1-48 -N (12/2) fabric.

Table 2. Shear rigidity (G) and hysteresis of the shear force at 5º (2HG5)

Sample	Shear Rigidity (G) (gf/cmº)		Hysteresis of the shear force (2HG5) (gf/cm)	
	warp direction	**weft direction**	**warp direction**	**weft direction**
T1-48-N(12/2)	0,63±0,03	0,58±0,01	3,59±0,05	3,01±0,05
T1-58-N(8/4)	1,11±0,04	0,58±0,02	6,79±0,06	6,71±0,03
T2-48-N(12/2)	0,84±0,11	0,76±0,02	5,84±1,13	4,34±0,03
T2-58-N(8/4)	0,97±0,02	0,96±0,03	6,39±0,07	5,82±0,04

From the results in Table 2 it is possible to verify that the fabrics have significant differences in shear rigidity (G) and shear force hysteresis (2HG5).

The fabrics with higher pick density, areal density, and thickness showed higher shear rigidity values and hysteresis in both directions -T1-58-N (8/4) and T2-58-N (8/4). This behavior is probably due to a reduction of yarns' mobility within the fabric imparted by the higher pick density (58) and coarser filling weft (Ne 8/4), which led to higher compactness of the fibrous material in the fabric structure. The lower values of shear rigidity and hysteresis were obtained in fabric T1-48-N (12/2).

The statistical analysis demonstrated (Table 3) that there is a significant influence of the fabric structure on the shear rigidity and a clear difference between the fabrics ($p<0,000$).

Table 3. ANOVA and Scheffé's multiple comparison test

Test	ANOVA		Scheffé's multiple comparison test	
	Warp	**Weft**	**Warp**	**Weft**
Shear rigidity	F(3,8)= 56,650	F(3,8)= 405,333	Significant difference in all fabrics.	Significant difference in all fabrics
Hysteresis of the shear force	F(3,8)=19,1116	F(3,8)= 6508,073	Significant difference in fabrics except for T1-58-N (8/4), T2-48-N (12/2) and T2-58-N (8/4).	Significant difference in all fabrics

3.3 Bending properties

The bending or flexural rigidity of fabrics is influenced by the yarns' flexural rigidity and the mobility of the yarns within the fabric. The bending rigidity (G) and bending modulus (B) based on Pierce's theory were calculated using equations 2 and 3). Figure 9 illustrates the mean bending rigidity (G) and bending modulus (B) obtained for the double-woven fabrics developed in the warp and weft directions.

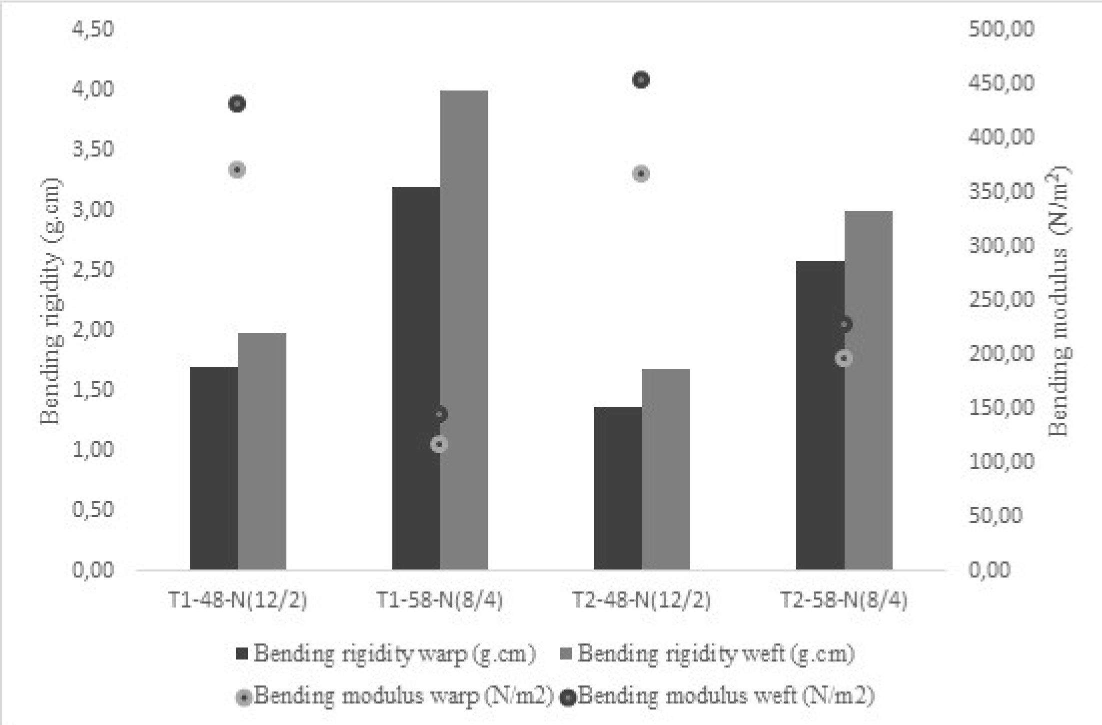

Figure 9. Bending behavior of the four developed fabrics- Bending rigidity and modulus

As it can be seen in Figure 9, the fabrics T1-58 -N (8/4) and T2-58-N (8/4) showed higher bending rigidity (G) and lower bending modulus (B) in the warp and weft directions. This result was expected as the areal density and thickness of these fabrics are higher. Furthermore, the fabrics are more resistant to bending in the weft direction.

This behavior is due to the coarser yarn linear density used in the weft direction, which increased fabric's rigidity in this direction. The same behavior was verified by Bonde and Asagekar (2014) and Nayak (2009).

The statistical analysis performed (Table 4) demonstrated that the fabric structure significantly influences the bending behavior, and significant differences between the fabrics were encountered ($p<0{,}000$).

Table 4. ANOVA and Scheffé's multiple comparison test

	ANOVA		Scheffé's multiple comparison test	
Test	**Warp**	**Weft**	**Warp**	**Weft**
Bending rigidity (G)	F(3,8)= 367,491	F(3,8)= 3702,362	Significant difference in all fabrics	Significant difference in all fabrics
Bending modulus (B)	F(3,8)=1889,28	F(3,8)= 470,517	Significant difference in all fabrics	Significant difference in all fabrics

3.4 Surface friction

Friction occurs when the body moves against a supporting surface and can contribute to pressure ulcer development. The dynamic friction coefficient of the fabrics was assessed using the Fricqtorq equipment (Figure 3). An example of a test result obtained with Fricqtorq equipment can be seen in Figure 10. The kinetic coefficients of friction obtained for all fabrics are shown in Figure 11.

Figure 10. Surface friction of the fabric T1-48-N (12/2)

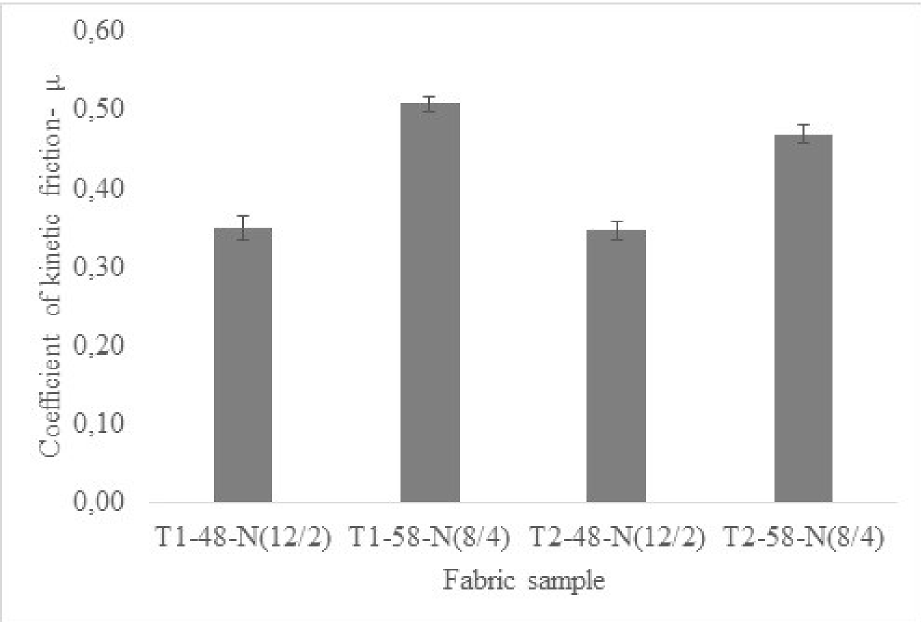

Figure 11. Maximum kinetic coefficient of friction of the double-woven fabrics

As it can be observed in Figure 11, the fabric T1-58-N (8/4) displayed the highest coefficient of kinetic friction, followed by fabric T2-58-N (8/4). These fabrics also revealed a surface with a higher apparent roughness, as a higher friction reaction torque was registered on these fabrics. Fabrics T1-48-N (12/2) and T2-48-N (12/2) demonstrated the lower surface friction. The difference in fabric surface texture promoted by the pick density is the main factor affecting the surface friction, namely the kinetic coefficient of friction.

As it can be observed in Figure 11 and confirmed by statistical analysis (Table 5), there is a significant influence of the fabric structure on the kinetic coefficient of friction (p<0,000).

Table 5. ANOVA and Scheffé's multiple comparison test

Test	ANOVA	Scheffé's multiple comparison test
Coefficient of kinetic friction	F(3,16)= 223,417	Significant difference in fabrics except between T1-48-N (12/2) and T2-48-N (12/2).

4 Conclusions

This work's main objective was the development of a 3D textile-based support surface with the required properties to avoid or minimize the formation of pressure ulcers. Previous studies revealed that 3D fabrics based on double-woven structures were a promising approach to achieve pressure relief and sensorial and thermo-physiological comfort. Furthermore, the weave pattern and the fabric composition, namely cotton-based, were considered prime features to impart these properties.

In this study, four double-woven structures were designed and produced varying in the weave pattern, base-fabrics weft density, and filling weft linear density. These constructional characteristics were considered key design factors due to their influence on fabrics' compression, shear, bending, and surface friction properties.

From the obtained results, it can be concluded that pick density and filling weft linear density determine fabrics' mechanical behavior. An increase in fabrics' weft density (from 48 to 58 picks/") and in filling weft linear density (from 12/4 Ne to 8/4 Ne) led to a significant increase of fabric's thickness and areal density, which enhanced the fabrics compression ability and augmented the shear and bending rigidities. The magnitude of thickness and areal density increase was affected by the dimension of the channelled weave pattern and the filling yarn linear density. Narrower channels with finer filling weft yarns negatively influenced this increase.

The double-woven fabrics T1-58-N (8/4) and T2 -58-N (8/4) showed the best compression performance for pressure-relief covering mats, considering compressibility (48-50% compressibility and limit above 3 kPa) and thickness recovery (100- 99% recovery after removal of 3 kPa pressure). Despite the higher shear and bending rigidities compared to the less dense fabrics, these values are acceptable for a covering mat that is not in direct contact with a nude body. Moreover, the higher kinetic coefficient of friction presented by these fabrics provides a covering mat, good adhesion to the under layer (mattress) and the upper layer (bedsheet), avoiding wrinkles and puckering.

Further tests are being carried out using a Tekscan mapping system to assess the pressure distribution profiles of these 3D fabrics under real use conditions.

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