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Study of three-dimensional spacer fabrics: Physical and mechanical properties

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ABSTRACT

Spacer is a three-dimensional knitted fabric consisting of two outer textile substrates which are joined together and kept apart by spacer yarns. Spacer fabrics are used for environmental reasons, which can be used in different product groups such as mobile textiles (car seat covers, dashboard cover), industrial textiles (composites), medical textiles (anti-decubitus blankets), sports textiles and foundation garments (bra cups, pads for swimwear). In this study, the characteristics of different spacer fabrics including low-stress mechanical properties, air permeability and thermal conductivity were investigated. Low-stress mechanical properties obtained by the KES-fabric evaluation system revealed that all tensile, bending and compression properties of spacer fabrics are greatly depending on the type of spacer fabric (warp knit or weft knit), the type of spacer yarn used (monofilament or multifilament), the yarn count of the spacer yarn, the stitch density and the spacer yarn configuration. Air permeability and thermal conductivity of spacer fabric are closely related to the fabric density. This experimental work suggests that carefully selecting the spacer fabric according to the envisaged application is of primary importance.

1. Introduction

Spacer fabric is a three-dimensional knitted fabric consisting of two separate knitted substrates which are joined together or kept apart by spacer yarns (New patterning possibilities, 2001; Wilkens, 1993; Lehmann, 1994). There are two types of spacer fabrics: warp-knitted spacer fabric and weft-knitted spacer fabric. The first type is knitted on a rib raschel machine having two needle bars (McCartney et al., 1999; Donaghy and Azuero, 1999), while the second is knitted on a double jersey circular machine having a rotatable needle cylinder and needle dial (Shepherd, 2004; Sytz, 2004; Willmer, 2005).

Spacer fabrics are widely used in different products such as mobile textiles (car seat covers, dashboard cover), industrial textiles (composites), medical textiles (anti-decubitus blankets), sports textiles and foundation garments (bra cups, pads for swimwear) (Heide, 2001; Spacer fabrics in medicine, 1999; Bras cups made from a new spacer fabric, 2001). Spacer fabric as a component material is highly breathable, thus creating a moisture free environment, which in turn reduces the chances of skin maceration. These lead to an increased level of comfort when compared to materials such as foam, neoprene and laminate fabrics. Spacer fabrics are regarded as environmentally friendly textile materials (unlike polyurethane foam), since they can be recycled (Wilkens, 1993; Heide, 2001).

Spacer fabrics have been studied globally for many years (Wilkens, 1993; Lehmann, 1994). However, very little research work has been done on the effect of fabric characteristics on its physical and mechanical properties of spacer fabrics. In part I, the influence of several fabric structures on the physical and mechanical properties of spacer fabric will be discussed.

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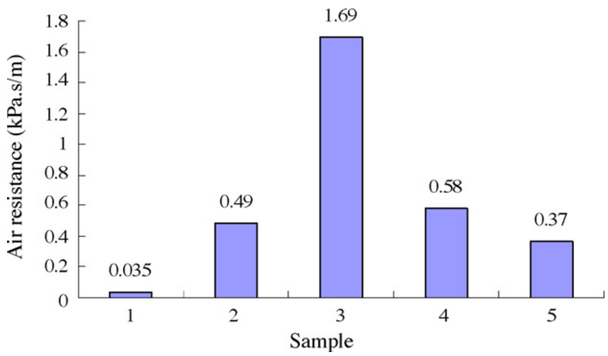


Fig. 1 – Air resistance of different spacer fabrics.

2. Experimental methods

2.1. *Spacer fabric characteristics*

Five different spacer fabrics were used in the present study. Sample 1 was a warp-knitted spacer fabric, while samples 2–5 were weft-knitted spacer fabrics. The fabric characteristics of interest include the fabric density, spacer yarn type, thickness of the spacer fabric, spacer yarn diameter and arrangement. All the experiments were carried out under standard conditions, BS1051, at 20 °C and 65% relative humidity.

2.2. *Air permeability test*

The air permeability of the samples was studied with the KES-F8-AP1 air permeability tester (Yip et al., 2002). The results of the measurements on the air resistance (*R*), reported in Fig. 1, are averages from the values of 10 readings.

2.3. *Thermal conductivity test*

The thermal property was studied by KES-F Thermo Labo II (Kawabata and Niwa, 1996). This test is used to measure the power loss from BT-Box (Watt) to the Water Box through the spacer samples. The sample was put on the Water Box which is in the room temperature (20 °C). The temperatures of the BT-Box and Guard were set to a temperature of 30 °C. The amount of heat passing through the sample (in watts per square meter) was measured from the power consumption of the test plate heater. The thermal conductivity value (*k*) having a unit of W/mK of different spacer fabrics can be calculated by Eq. (1):

$$\text{Thermal conductivity } (k) = \frac{\text{Heat flow rate} \times \text{distance}}{\text{area} \times \text{temperature difference}}$$

$$k = \frac{Q}{t} \times \frac{L}{A \times \Delta T} \quad (1)$$

where, Q = the quantity of heat, *t* = time, *L* = thickness of the sample, *A* = surface area of the sample and ΔT = temperature difference.

2.4. *Bending and compression tests*

The KES-F (Kawabata Evaluation System) was used for measuring spacer samples' low-stress mechanical properties, including the response to bending and compression. The parameters obtained from these hysteresis curves are defined (Kawabata and Niwa, 1996) and shown in Table 1.

2.5. *Stretchability and recovery tests*

The stretch and recovery properties of the spacer samples were tested by INSTRON 4411 according to the British standard 4294. The specimen of standard dimensions was stretched under a specified load. The length of the specimen should be sufficient to allow a distance of 7.5 cm (*L*1) between the inner edges of the clamps to hold the specimen. The load was gradually increased on the specimen to 6 kg within 7.5 s. The load was maintained constant for 10 s and then reduced gradually until the clamps were returned to their original position. The loading conditions were reapplied immediately to the specimen and the length (*L*2) of the specimen was measured after 1 min, following which the specimen was removed from the clamps and placed on a flat and smooth surface. Its dimension (*L*3) was measured before and after 1 min of fabric relaxation time. After 30 min, the distance was measured again (*L*4). The same procedures were applied to both warp and weft directions. The percentage values of elongation (*E*), recovery after 1 min (R_1) and 30 min (R_{30}) of different spacer fabrics were calculated by Eqs. (2)–(4), respectively as shown below:

$$E = \frac{100(L2 - L1)}{L1} \quad (2)$$

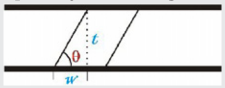
$$R_1 = \frac{100(L3 - L1)}{L1} \quad (3)$$

$$R_{30} = \frac{100(L4 - L1)}{L1} \quad (4)$$

Table 1 – Definitions of bending and compression properties obtained by KES-F system (Kawabata and Niwa, 1996)

Properties	Symbol	Definition	Unit
Bending properties			
Bending rigidity	B	Average slope of the linear regions of the bending hysteresis curve to 1.5 cm^{-1}	uN m
Compression properties			
Compressional resilience	RC	Percentage energy recovery from lateral compression deformation	%
Fabric thickness at 50 gf/cm^2 pressure	T_m	Fabric thickness at 50 gf/cm^2 pressure	mm

Table 2 – Fabric characteristics of different spacer fabrics

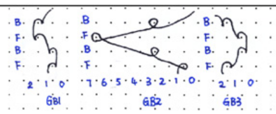
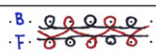
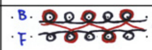
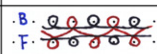
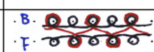
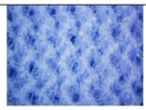
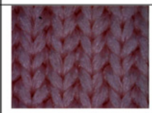
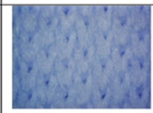
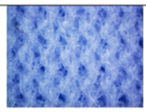
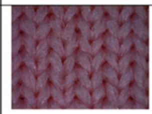
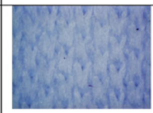
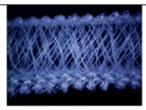
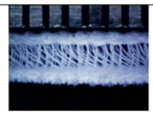
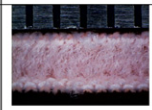
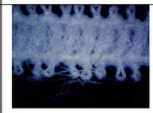
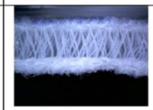
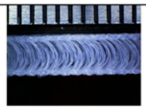
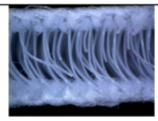
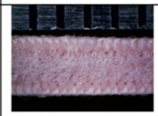
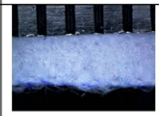
	Sample 1 (WA-MO)	Sample 2 (WE-MO-1)	Sample 3 (WE-MU-1)	Sample 4 (WE-MU-2)	Sample 5 (WE-MO-2)
Fabric type	Warp-knitted	Weft-knitted	Weft-knitted	Weft-knitted	Weft-knitted
Composition	52% Polyester 48% Polybutylene terephthalate (PBT)	56% Polyester 38% Nylon 6% Spandex	92% Polyester 8% Spandex	93% Polyester 7% Spandex	91% Polyester 9% Spandex
Density (kg/m^3)	54.866	117.858	204.269	146.289	125.387
Thickness (mm)	4	3.3	2.87	2.91	3.54
Spacer yarn type	Monofilament	Monofilament	Multifilament	Multifilament	Monofilament
Spacer yarn composition	100% Polybutylene terephthalate (PBT)	100% Polyester	100% Polyester	100% Polyester	100% Polyester
Spacer yarn diameter	0.046 mm	0.057 mm	0.701 mm/32 filaments	0.534 mm/32 filaments	0.058 mm
Spacer yarn arrangement (θ) 	$\theta = \tan^{-1} t/w$ $\theta = 52.33^\circ$	$\theta = \tan^{-1} t/w$ $\theta = 79.49^\circ$	$\theta = \tan^{-1} t/w$ $\theta = 78.07^\circ$	$\theta = \tan^{-1} t/w$ $\theta = 63.43^\circ$	$\theta = \tan^{-1} t/w$ $\theta = 61.08^\circ$

3. Results and discussion

3.1. *Spacer fabric characteristics*

The fabric characteristics of five different spacer samples are shown in Table 2, while the sample fabrics' structures (front, back and side views, for both warp-wise and weft-wise) are shown in Table 3. Generally, the thickness of spacer fabrics can range from 1.5 mm to 60 mm (New patterning possibilities, 2001). The samples thickness used in this study range from 2.8 mm to 4 mm which are the most commonly used values in the sports textile and foundation garment market. The compression resistance of the spacer fabric can be varied

Table 3 – Fabric structure and microscopic view of different spacer fabrics

	Sample 1 (WA-MO)	Sample 2 (WE-MO-1)	Sample 3 (WE-MU-1)	Sample 4 (WE-MU-2)	Sample 5 (WE-MO-2)
Fabric Structure					
Front view					
Back view					
Side view - weftwise					
Side view - warpwise					

depending on the thickness of the structure and the type of joining yarns. Both monofilament and multifilament joining yarns of various diameters were used in this study. The spacer yarns were originally arranged perpendicular to the two outer fabrics, however, there was always a risk that when pressure was applied, the yarns would simply be pushed sideways, thus reducing the compression resistance (Lehmann, 1994). Therefore, the spacer yarns were later arranged in a v-shaped configuration (see the fabric structure shown in Table 3). The spacer yarn arrangement angle (θ) can be calculated with Eq. (5) shown below:

$$\theta = \tan^{-1} \frac{L}{W} \tag{5}$$

where L = thickness of the spacer fabric; W = segment width.

3.2. *Air permeability and thermal conductivity*

In this study, the air resistance (R) of different spacer fabrics was recorded and Fig. 1 shows the results (a higher number of kPa s/m indicates a higher air resistance of the fabric (Yip et al., 2002)). The thermal conductivity of different spacer fabrics was also recorded. Since a higher value of thermal conductivity indicates a faster heat transfer from the skin to the fabric surface, this is usually associated with a cooler feeling (Yip et al., 2002). Fig. 2 shows the thermal conductivity of different spacer fabrics.

An analysis of Figs. 1 and 2 shows that sample 1 (WA-MO) has the lowest air resistance and thermal conductivity, while sample 3 (WE-MU-1) has the highest values for these same properties.

The air permeability of a fabric is closely related to the construction characteristics of the yarns it is made of, in which large volumes are occupied by air. There are several factors affecting the air permeability of the fabric, such as fabric's structure, thickness, surface characteristics, etc. (Zhang et al., 2002). In this study, it is suggested that the fabric density shows the most significant effect on the air permeability and thermal property of the spacer fabric. A higher fabric density will hinder the air flows through the fabric, thus resulting in a poor air permeability of the fabrics. A higher fabric density will however have a better thermal conductivity, as there will be less space to trap air inside. A denser fabric therefore has better thermal ventilation.

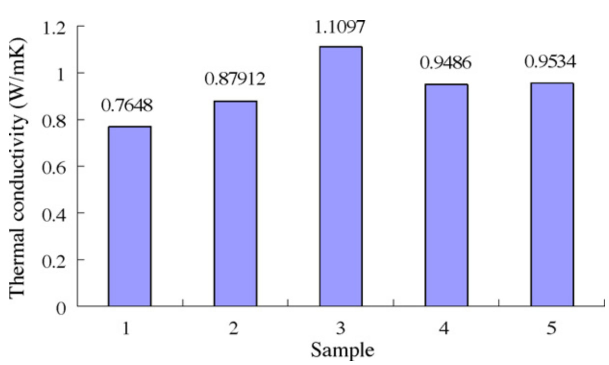


Fig. 2 – Thermal conductivity values of different spacer fabrics.

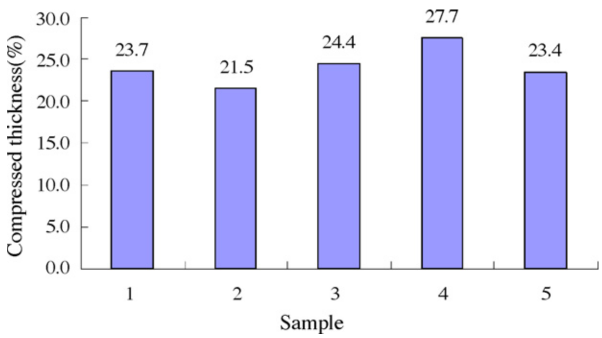


Fig. 3 – Compressed thickness of spacer samples at 50 gf/cm^2 pressure.

3.3. *Compression properties*

The compression resistance of different spacer fabrics under 50 gf/cm^2 pressure in terms of the percentage change in thickness, is shown in Fig. 3. A higher percentage of thickness compressed indicates a lower compression resistance. It is found that samples 3 (WE-MU-1) and 4 (WE-MU-2) have lower compression resistance than samples 1 (WA-MO), 2 (WE-MO-1) and 5 (WE-MO-2). It is apparent that fabrics using monofilament as spacer yarn generally have higher compression resistance than those using multifilament yarn. When the results for spacer fabrics using the same type of spacer yarn were compared, it was found that the compression resistance of a sample is closely related to the spacer yarn arrangement. The resistance force of a spacer yarn is $F \sin\theta$. The sample which has a larger angle θ will therefore have a higher compression resistance, assuming that the material and diameter of the spacer yarn used are the same.

Table 4 shows the compressive resilience RC of different spacer fabrics (RC is the percentage energy recovery from deformation due to lateral compression). A higher percentage indicates a better recovery property. The results indicate that samples 1, 2 and 5 recover better than samples 3 and 4. We observed that the recovery properties after compression greatly depend on the spacer yarn type: spacer samples using monofilament as their spacer yarns have better recovery properties than those using multifilament spacer yarns.

3.4. *Bending properties*

In this study, the bending rigidity of different spacer fabrics was investigated, and Fig. 4 shows results for both warp-wise

Table 4 – Compressional resilience of different kind of spacer fabrics

Sample	RC (%)
1	75.417
2	52.247
3	37.02
4	35.15
5	51.317

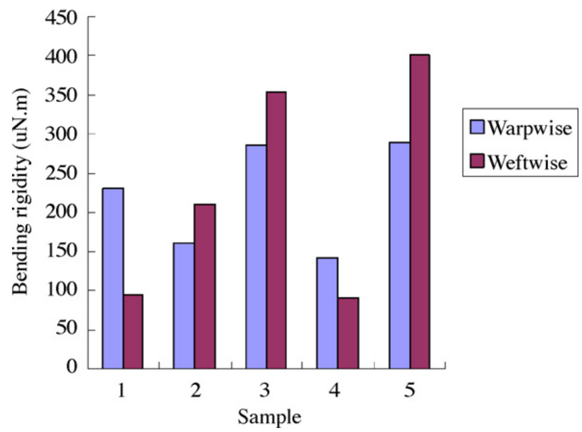


Fig. 4 – Bending rigidity of spacer samples.

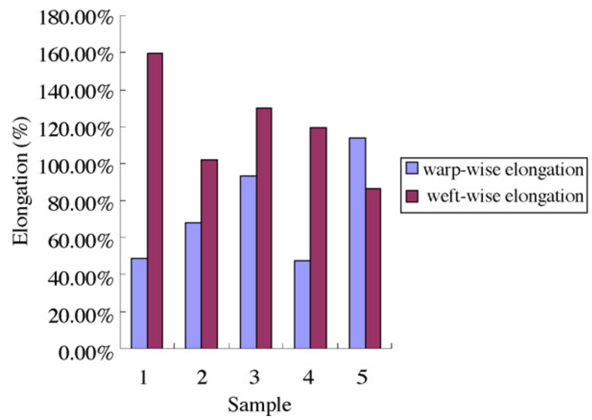


Fig. 5 – Elongation of different spacer samples.

Table 5 – Elongation and recovery of the warp-wise spacer fabrics

Sample	Elongation, E (%)	Recovery after 1 min, R_1 (%)	Recovery after 30 min, R_{30} (%)
1	49.17	86.90	96.83
2	67.96	95.74	98.69
3	93.28	97.38	99.53
4	47.32	94.36	98.59
5	114.03	91.61	96.88

and weft-wise spacer fabrics. It appears that the bending rigidity of a spacer fabric is greatly related to the fabric type. Thus, a weft-knitted spacer fabric has a higher bending rigidity in the weft-wise direction, while a warp-knitted spacer fabric has a higher bending rigidity in the warp-wise direction. This behaviour is mainly due to the directionality of the incorporated yarn (Machova et al., 2006; Reisfeld, 1996). When the samples are of the same fabric type (weft-knitted spacer fabric for example), we can further conclude that the bending rigidity is closely related to the fabric's density, spacer structure and spacer type (Raz, 1993). We also found that weft-knitted spacer fabrics using interlock structure, monofilament spacer yarn and a higher fabric density have a higher bending rigidity.

3.5. *Stretch and recovery*

The stretch and recovery properties of different spacer fabrics were also studied, and results are reported in Tables 5 and 6 (a higher percentage indicates better stretch and recovery properties). These results indicate that sample 1 (WA-MO) has the best stretchability in the weft-wise configuration and the poorest stretchability in warp-wise. Sample 3 (WE-MU-1) has the best recovery property in both the warp-wise and weft-wise fabric configurations while sample 1 (WA-MO) has the poorest recovery property in both directions.

Table 6 – Elongation and recovery of the weft-wise spacer fabrics

Sample	Elongation, E (%)	Recovery after 1 min, R_1 (%)	Recovery after 30 min, R_{30} (%)
1	159.68	78.01	94.30
2	101.77	90.83	96.73
3	129.80	94.86	97.09
4	119.51	85.31	94.79
5	86.73	89.31	96.16

These findings suggest that the stretchability of the spacer fabrics is closely related to their fabric type. The results shown in Fig. 5 reveal that the stretchability of a warp-knitted spacer fabric has a high stretchability only in the weft-wise direction, while the stretchability in the warp-wise direction is very low (below 50%). On the other hand, weft-knitted spacer fabrics have similar and high stretchability in both the weft-wise and warp-wise directions. As the spacer fabric is composed of two separate surface fabrics and linked together by a spacer yarn, it can therefore be concluded that spacer fabrics carry the same fabric stretchability as their fabric types (i.e. warp-knitted or weft-knitted).

When the results of the weft-knitted spacer samples were compared, the stretchabilities of the weft-wise direction of samples 3 and 4 were found to be higher than those of samples 2 and 5. This is due to samples 3 and 4 using multifilament spacer yarns, which have higher stretchability than those corresponding to samples using monofilament spacer yarns (King, 1985).

4. Conclusion

This study performs a quantitative investigation of various fabric characteristics, such as air permeability, thermal conductivity and low-stress mechanical properties (the latter including the stretchability, recovery, bending and compression) of spacer fabrics. It is found that both air permeability and thermal conductivity are closely related to the fabric density. The compression properties depend very much on the spacer yarn type and the spacer yarn arrangement. Bending properties are closely related to the fabric type, structure, spacer yarn type and density while stretch and recovery properties depend very much on fabric type and spacer yarn type. It is believed that the fabric characteristics of spacer fabric show a very significant effect on the air permeability, thermal conductivity and mechanical properties of spacer fabric.

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