Analysis of Compressibility Behavior in Warp Knitted Spacer Fabrics: Experiments and Van Wyk Theory

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ABSTRACT

Spacer fabrics are mostly formed by two separated surface layers which are connected to each other by connector monofilaments or yarns. The middle layer in such fabrics gives a unique compressibility characteristic to them. These fabrics can be employed as the distributor or damper of pressure in the automobile industry, medical and technical textiles, and sport wear. In these applications, the compressibility behavior plays a significant role in the structural stability of fabrics. The compressibility behavior could be affected by different physical and geometrical parameters of knitted structures such as the density of monofilaments and fabric thickness.

In the present work, the compressibility behavior of single and double layered warp knitted spacer fabrics (WKSF) was investigated. The work of compression and reversibility forces and hysteresis in single and double layered WKSF were experimentally obtained. The compression results for single layer WKSF are compared with the theoretical results obtained by Van Wyk theory. The comparison demonstrates that the results obtained by Van Wyk theory are consistently correlated with the experimental results. The compressibility and reversibility behavior and the hysteresis of double layered WKSFs were evaluated based on their single layer components at different cycles of loading.

Keywords: Compression, Reversibility, Van Wyk theory, Single layer, Double layered, Warp knitting, Spacer fabric

INTRODUCTION

Warp Knitted Spacer Fabrics (WKSF) are three-dimensional structures with two knitted surface layers connected by monofilaments. Due to their specific structures, these fabrics have unique properties that can not be found in traditional fabrics. Cass [1] has defined spacer fabrics as sandwich structures which have two complete layers and the filling layer comes in the middle. Considerable research have been done to analysis the properties of WKSF. Bartles [2] has declared that using WKSF instead of usual foam in the airplane seats brings about more comfort for passengers. Furthermore, Kund [3] has showed that WKSFs have more air circulation than other sandwich structures. Consequently these products are used in automobile seats.

Mecit [4] has analyzed how different texture designs influence the compressibility behavior of WKSFs. He has reported that pile monofilaments properties have a significant role on the compressibility behavior of these products. Moreover, the angle between monofilaments and two surface layers is an additional factor which affects compressibility behavior. In another research, the effect of density has been studied by Murthyguru [5]. He has shown that with increase in density, thermal and humid comfort would be decreased in WKSFs. Compressibility behavior is known as an important mechanical property of textile structures. In Murthyguru theory, compressibility can be defined as the decrease of initial thickness due to the appropriate increase of compressive force at a measuring time [5]. According to this definition, the thickness of a layer without applied force is considered as its initial thickness. The most used and fundamental theory related to the compressibility of textiles is the Van Wyk theory. In this theory, Van Wyk [6] presented a relationship between volume and stress for raw wool fibers regardless of their friction, twist, and strength during compressibility. In 1986, Dejong [7] showed that the compressibility behavior of different types of fabrics, under the pressure of 0.5-50grf/cm^2, follows the Van Wyk theory consistently. The stress relation introduced by Van Wyk is appropriate only for moderate compression forces. At high pressures, incompressible volume (v') has been neglected. Thus, Van Wyk proposed a modification of his theory. He introduced a new equation for incompressible volume of fibers and for fabrics with constant volume under zero pressure as:

$$p = \frac{K E_f m^3}{\rho^3}\left(\frac{1}{(v-v')^3} - \frac{1}{(v_0-v')^3}\right) \quad (1)$$

Where K is Van Wyk coefficient and depends on configuration of fibers, *m* is mass *v* is volume of fibers at *P* pressure and v' is final volume. E_f, ρ and v_0 are young modulus, fiber density and initial thickness respectively.

To follow the previous work [8], in this paper, the compressibility behavior of single and double layered WKSFs with different thicknesses and densities were experimentally analyzed. It should be noted that since all samples have the same wpc (wales per centimeter), the density of monofilaments between two layers is only affected by cpc (courses per centimeter). The results from single layers are compared with those obtained from Van Wyk theory.

FABRIC CHARACTERISTICS

The spacer fabrics required for the experimental work were produced by a warp knitting machine equipped with two needle bars (*Table I*).

TABLE I. Specifications of warp knitting machine.

Specification	Description
Machine model	RD6N
Producer	Karl Mayer
Gauge	E22

The knitted structure of each layer in all produced fabrics was similar to that shown in *Table II*.

TABLE II. Knitting structure of WKSFs.

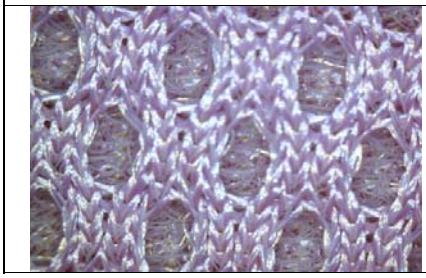
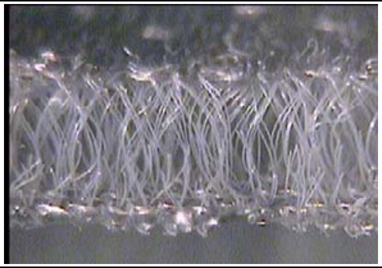
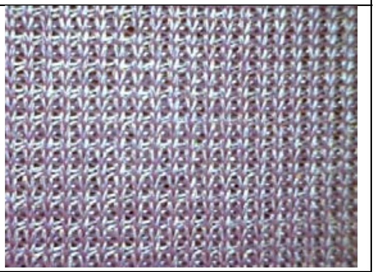
First layer	Connectors	Second layer
Bar1: 1-0-0-0/1-2-2-2/3-4-4-4/3-2-2-2/ Bar2: 3-2-2-2/3-4-4-4/1-2-2-2/1-0-0-0	Bar3: 1-0-1-2/2-3-2-1 Bar4: 2-3-2-1/1-0-1-2	Bar5: 1-0-0-0/1-2-2-2 Bar6: 4-5-5-5/1-0-0-0
		

TABLE III. Characteristics of WKSF samples.

Sample code	Thickness (cm)	Density (cpc)	Weight (gr/100cm^2)	Yarn count and yarn type in each layer (Tex)
3Pt	0.375	14	3.37	First layer yarn: 7.78(34f) Polyester Connectors: 2.23(monofilament) Polyester Second layer yarn: 11.22(48f) Polyester
3Pb	0.343	16	3.91	
2P5	0.457	20	4.33	
P7	0.868	19	5.21	

EXPERIMENTAL TESTS

In this work, four types of WKSF with different thicknesses and densities (course per centimeters) coded: 3Pt, 3Pb, 2P5 and P7, were individually studied as single layer samples (*Table III*).

The compression behavior of four different combinations of two individual WKFSs (3Pb+3Pt, 2P5+3Pb, P7+3Pb and P7+3Pt) was also investigated as double layered samples.

The WKSF specimens with 10cm×10cm dimension were tested by contraction-compression testing device on an Instron 5566 under standard conditions (temp $23 \pm 2\ ^{\circ}C$; RH 65±2%).

The machine jaws had a circular shape of 10cm diameter. The compression was applied at a 1 mm/min rate to reach the maximum pressure of $21\frac{lb}{in^2}$. Five specimens from each sample were tested, and the average of their results was reported as the final results. The unload action was carried out with the similar rate (-1 mm/min) as demonstrated in *Figure 1*. The load and unload processes were repeated for three cycles to study the compression and compression recovery behaviors as well as the hysteresis of single and double layered specimens.

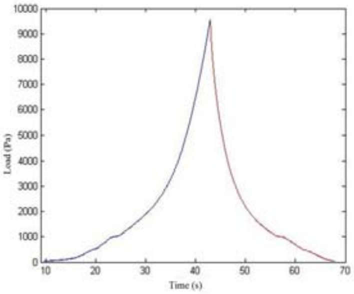


FIGURE 1. Typical load and unload-time test for WKSF (3Pb sample).

RESULTS AND DISCUSSION

Compressibility Behavior

The typical compression result obtained from the 3Pb sample is depicted in *Figure 2* and represents the classical compressibility behavior of WKSF samples. As can be observed in the figure, three different events can be differentiated in the compressibility behavior:

- First: outer layers are compressed,
- Second: monofilaments in the middle layer are buckled,
- Third: outer layers and monofilaments in the middle layer are simultaneously compressed.

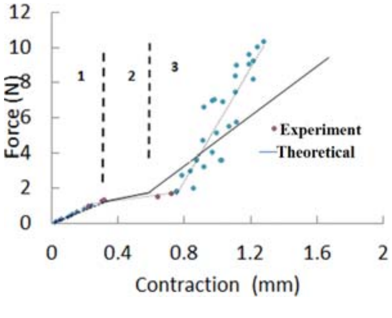


FIGURE 2: Typical load-contraction curve for WKSF (3Pb sample).

Comparison of Experimental Results with Van Wyk Theory

To compare the compressibility behavior of single layer WKSFs with Van Wyk theory, it was assumed that monofilaments of the middle layers act as a homogeneous bundle of fibers. Base on Van Wyk Eq. (1), the force applied on a bundle of fibers has an inverse relation with the cubic of the sample's volume change. In his theory, it is also assumed that the homogeneous bundle of fibers consists of individual fibers which have the ability to bend under the compression force. In *Figure 3,* the pressure versus the inverse of cubic thickness change, ($1/(t-\Delta x)^3$), where t is the initial thickness and Δx is the thickness change, is demonstrated using the experimental results. In order to compare the experimental results with Van Wyk theory, a linear curve fitting was used to extract the K factor in Van Wyk theory. For this purpose, the characteristics of monofilaments were experimentally obtained as given in *Table IV*. The area (A) and the weight (m) of tested samples are presented in *Table III*.

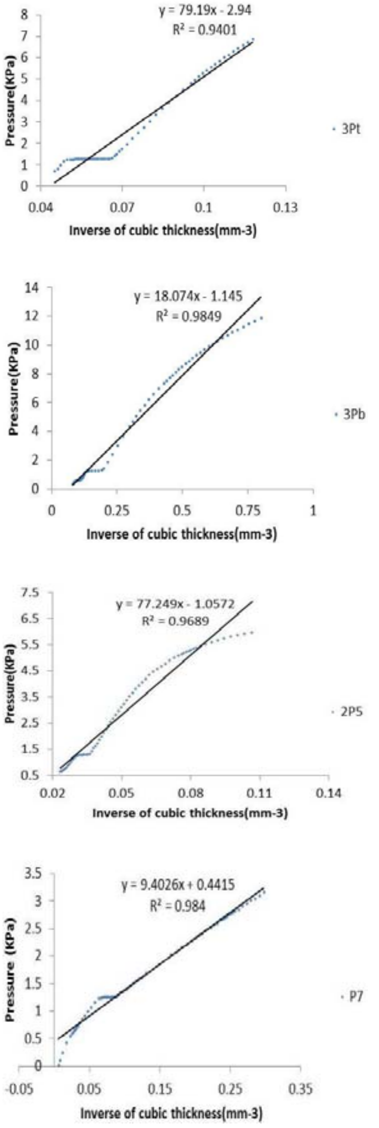


FIGURE 3: Compressibility behavior of fabric samples (▫ experimental data, — curve fitting).

TABLE IV. Characteristics of monofilaments

Young modulus (E_f)	Monofilaments Density $\rho\left(gram/cm^2\right)$	Linear density(tex)
52.39	1.52	2.23

In reality, the slope of each line fitted in the curves represents the coefficient of ($KE_f m^3/\rho^3$) in Eq. (1). Thus, by using E_f, ρ and m given in *Table IV* and *Table III* respectively, K in Van Wyk theory was determined for WKSF samples used in this work (*Table V*).

TABLE V. Parameters related to comparison of experimental results with Van Wyk theory.

Samples	Slope of linear fitting (a)	Correlation coefficients (R2)	Van Wyk factor (K)
3Pt	79.19	0.94	127.349
3Pb	18.07	0.98	20.82
2P5	77.249	0.96	63.55
P7	9.4026	0.98	5.266e

Regarding the correlation coefficients (0.94<R2<0.98) presented in *Table V*, there is a good agreement between the experimental results and Van Wyk theory.

Compression and Reversion Work and Hysteresis

The work required to compress WKSF from initial thickness (T_0) to thickness (T_m) due to the compression load (P) is defined by Eq. (2).

$$W_C = \int_{T_\circ}^{T_m} pdt \tag{2}$$

The work for releasing WKSF from compression is defined by Eq. (3).

$$W'_C = \int_{T_m}^{T_\circ} Pdt \tag{3}$$

Figure 4 shows a typical load-contraction graph of a WKSF during the first cycle of load and unload test. As can be observed, the areas under compression and reversion curves are represented by W_C and W'_C respectively.

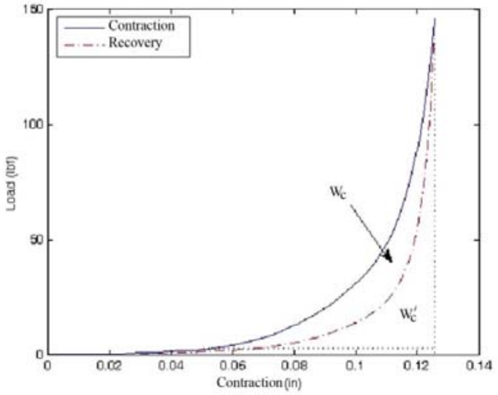


FIGURE 4. Typical load/unload-contraction graph.

Accordingly, the hysteresis (i.e. absorbed energy) can be presented by *Eq. (5)*.

$$H = W_c - W'_c \tag{4}$$

Single Layer

The work of compression force was determined at three test cycles for each single layer WKSF as presented in *Table VI*. As was expected, WKSFs with higher densities (2P5 and P7) require more work to be compressed. It can be also observed that at more cycles of testing, the compression work is decreased. This can be due to this fact that monofilaments are deformed after the first cycle and the curvature's radius of monofilaments is increased. Based on the compressibility behavior of WKSFs, using the curved bar theory, in order to compress monofilaments with higher radius of curvature, lesser work is required under a constant compression force [8].

The reversion work and hysteresis for single layer samples at three cycles are given in *Table VI*. The results show that hysteresis in WKSF increases with increasing the density (2P5 and P7 samples). This is partly because there are more monofilaments which remain deformed after unloading. On the other hand, more density increases the friction among monofilaments during the compression process. This leads to absorbing more irreversible energy.

TABLE VI. Parameters related to compression force for single and double layered at three test cycles.

Sample	W_C	W'_C	H(hysteresis)
3pb	0.46	0.37	0.09
	0.44	0.36	0.08
	0.43	0.35	0.08
3pt	0.94	0.688	0.252
	0.89	0.679	0.211
	0.875	0.673	0.202
2p5	1.613	0.957	0.656
	1.327	0.933	0.394
	1.271	0.919	0.352
P7	1.451	0.848	0.603
	1.271	0.828	0.443
	1.228	0.817	0.411
3pb+3pt	1.718	1.245	0.473
	1.621	1.245	0.376
	1.596	1.238	0.358
2p5+3pb	2.315	1.471	0.844
	2.048	1.421	0.627
	1.977	1.402	0.575
P7+3pb	2.098	1.33	0.768
	1.857	1.325	0.532
	1.801	1.312	0.489
P7+3pt	2.66	1.696	0.964
	2.415	1.668	0.747
	2.361	1.662	0.699

(W_C :work of compression force, W'_C: work of reversion force)

Double Layered

The work of compression and reversion forces and hysteresis were determined at three cycles for each double layered WKSFs as presented in *Table VI*.

The comparison of the results given in *Table VI* shows that the work of compression and reversion forces in double layered samples are much more than the total works of their single components (*Figure 5*). In other words the compressibility and reversibility performance of two single layers in combination is much better than when they act individually. The hysteresis of double layered samples (*Table VI*) confirms this issue because their hysteresis is much lower than the total hysteresis of their single components (*Figure 5*).

Similar to single layer samples, at more test cycles, the compression and reversion work as well as the hysteresis of double layered samples are decreased. The variation of compression and reversion works and the hysteresis with the number of cycles for single and double layered samples are compared in *Figure 5,* based on *Table VI.* The total of compression and reversion works and hysteresis of two single layers are separately displayed in graphs (dashed lines) as comparison with their peers of double layered sample.

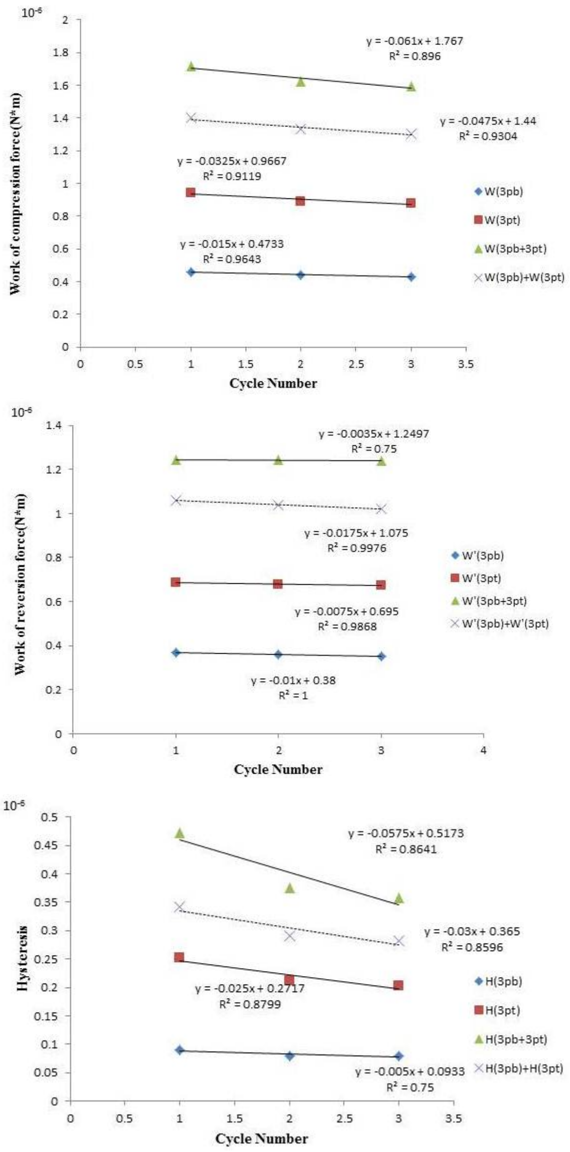


FIGURE 5. Typical comparison of single and double layered compression process parameters (work of compression and reversion forces and hysteresis versus cycle number (3Pb, 3Pt and 3Pb+3Pt samples).

CONCLUSIONS

Compressibility behavior of single and double layered Warp Knitted Spacer Fabrics (WKSF) was studied experimentally. The experimental results for single layer WKSF are compared with theoretical results obtained by Van Wyk theory. The correlation coefficients between the compared samples were found to range from 0.94 to 0.98. The results show that Van Wyk theory can be applied to predict the compressibility behavior of single layer WKSFs adequately.

The hysteresis or absorbed energy in single layer WKSFs increased with increasing connector density.

The compression and reversion works and consequently the hysteresis of single and double layered WKSFs decreased with increased test cycles. The single layer WKSFs demonstrated better compressibility and reversibility performance with two layers combined (double layered).

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