Indian Journal of Fibre & Textile Research
Vol. 43, March 2018, pp. 31-35

A modeling study on lateral compressive behavior of structured needle - punched nonwovens

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Received 3 November 2015; revised received 11 December 2015; accepted 22 April 2016

The aim of this work is to study the compression behavior of cord-structured needled fabrics. In order to achieve the objectives of this research, melt-spun polypropylene fibres of various linear densities have been produced by varying the spinning pump speed. The effect of linear density of melt-spun polypropylene fibres on compressive behavior of the fabrics has been investigated. A Zwick tester set in compressive mode is used to obtain variation of compressive force versus compression thickness. Van Wyk law is adapted to model the lateral compressive behavior of cord-structured needled fabrics. The experimental results are compared with the theoretical curves calculated using Van Wyk law. Results show that the increase in linear density of fibres tends to reduce the compressive force required to compress the samples to a pre-defined thickness. An acceptable conformity between Van Wyk's equation and compressive behavior of cord-structured needled fabrics is also observed.

Keywords: Compressive force, Cord-structured nonwovens, Fibre linear density, Lateral compression, Polypropylene fibres, Van Wyk's equation

1 Introduction

Nonwoven textiles are results of direct conversion of fibres into fabrics without employment of yarns by techniques other than weaving, knitting, twisting, braiding or knotting. The means used to create bonds among constituting fibres of a fibrous assembly determine the type of nonwoven fabric. Needling process results in intensification of degree of fiber entanglement of the initial fibrous assembly. This, in turn, simultaneously leads to increases in both density and strength of the resultant needled fabric [1].

Generally, upon exertion of a compressive force, thickness or volume of any fibrous assemblies reduces. Compression investigation of textiles determines their features, such as compression work, energy absorption, reversible work, compressive linearity, resiliency, and compressive ability. There is wealth of investigations on the compression properties of loose fiber masses[2-4]. Early workers[2, 5-7] have led to the development of several theories and empirical equations related to compression characteristics of fiber masses. Additionally these studies have resulted in design and development of the relevant apparatuses. Carnaby[8] predicted the compression behavior of fibrous assembly at large deformation. Narter *et al*.[9] developed a micromechanical model that could explore the mechanical behaviour of three-dimensional fibre webs. This model is capable of evaluating the effect of structure on the initial elastic moduli of fibre webs. Beil and Roberts[10,11] performed modeling and computer simulation of compression behaviour of fiber assemblies. Huang and Ghosh[12] developed a method for online characterization of compression behaviour of fibrous assemblies. Recent works have reported other aspects of compression behavior applicable to textile structures [13-16]. Pioneering work of Van Wyk is the core stone of investigations carried out on lateral compressive behaviour of conventional textiles. Van Wyk neglects all modes of fiber deformations such as extension, compression, and torsion apart from bending strain of individual fibres. In contrast to conventional textile structures, the reported works on compressive behaviour of nonwoven fabrics are scanty.

Compression behavior of nonwovens has been widely studied. Kothari and Das[17] studied the effect of selected processing parameters on the compression and recovery properties of needled nonwovens. Their work deals with the effect of cyclic loading and ultimate compression pressure of the fabrics. Krucinska *et al*.[18] presented a modified rheological

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model for analysis of compression behavior of nonwoven fabrics. Das *et al.*[19] studied the effect of shrinkable and non-shrinkable acrylic blends on the compression behaviour of needled nonwoven fabrics. In a related study, Das and Pourdeyhimi[20] investigated the effect of fiber composition and manufacturing technologies on the compression and recovery properties of high loft nonwovens. Debnath and Madhusoothanan[21] studied effect of parallel-laid and cross-laid web of polypropylene needle-punched nonwoven fabrics on compression properties under wet condition and concluded that the percentage compression resilience shows increasing trend with the increase in needling density both under dry and wet conditions for parallel-laid web. Ventura *et al.*[22] investigated the effects of needling parameters on some structural and physico-mechanical properties of needle-punched nonwovens.

Nonwoven fabrics meet the requirements of various technical end-uses such as filtration or other technical applications, where fabric compression is of paramount importance. Compression of these fabrics has been the subject of various investigations [23, 24]. Despite of extensive research in the field of nonwoven fabrics compression behavior, hardly any trace of scientific work that encompasses the validity of the Van Wyk model on the lateral compressive behavior of cord-structured nonwovens exists.

Needling of pre-consolidated felt by structuring needle loom equipped with fork needles results in production of so-called structured nonwovens. Fork needles transfer tufts of fibres from pre-consolidated felt to the surface as velour or cord pile. This action of fork needles effectively changes the initial structure into a resilient top and a very dense base layers. The latter has no contribution to the compressive behavior of the fabric. Resiliency of the structured nonwovens in flooring applications affects various properties of the material. This work is therefore aimed at predicting the effect of fibre and production parameters on the resiliency of the structured nonwoven floor covering.

2 Van Wyk's Theory of Compression

Until mid 1940s, compression was the subject of many empirical studies. Van Wyk (1946) initiated research on the mechanics of the compression of fibrous assemblies. The work of Van Wyk deals with the compression of wool fibres assuming that the fibres simply bend as cylindrical rods. This work led to development of following equation, which so far remains the most valid theoretical study in the field of fabric deformation:

$$P = KE(\frac{m}{\rho})^3\left(\frac{1}{V^3} - \frac{1}{V_0^3}\right) \quad ...(1)$$

where P is the applied pressure; V, the fibre assembly volume at the pressure (P); V_0, the initial volume; K, the Van Wyk constant; E, the fibre Young's modulus; M, the mass of fibres; and ρ, the fibre density.

For the purpose of model simplification, Van Wyk [2] assumed that the bending of fibres due to lateral compression of the fibrous structure was the predominate factor while neglecting fibre twisting, slippage and extension. Additionally, this theory neglects fibre crimp and assumes that not only fibres are initially straight rods but also there is no fibre-to-fibre friction. Moreover, the theory assumes that fibre orientation and packing through the fibrous assembly are random and uniform respectively. Separately bent and randomly distributed fibrous loops of structured nonwoven fabrics provide an ideal case for application of Van Wyk's theory.

The use of Van Wyk's theory can lead to development of various pressure-volume or thickness relationships for other fibrous assemblies. Considering the volume-thickness relation for samples (V=At), Eq. (1) leads to following relationship:

$$P = KE(\frac{m}{\rho})^3\left(\frac{1}{(At)^3} - \frac{1}{(At_0)^3}\right) \quad \ldots(2)$$

and

$$P = KE(\frac{m_a}{\rho})^3\left(\frac{1}{t^3} - \frac{1}{t_0^{\ 3}}\right) \quad \ldots(3)$$

where A is the surface area; t_0, the initial thickness; t, the thickness of sample at pressure (P); and m_a, the m/A or areal density.

The following gives the value of thickness (t) at any moment during compressive loading:

$$t=t_0-c \quad \ldots(4)$$

where c is the compressed thickness at pressure (P). Conversion of pressure to compression force (f) gives:

$$f = KAE\left(\frac{m_a}{\rho}\right)^3\left(\frac{1}{(t_0-c)^3}-\frac{1}{t_0^{\,3}}\right) \quad \text{... (5)}$$

This work investigates the lateral compression behaviour of cord-structured nonwoven fabric. The work is based on Eq. (5) derived from Van Wyk theory and assumption that fibres of the surface loops buckle individually and elastically during the compression.

3 Materials and Methods

3.1 Materials

Four samples of nonwoven fabrics using commercially melt spun 90 mm long staple polypropylene fibres at four different linear densities were prepared. Fibre samples of 50 g were prepared. According to ASTM D1577-79, linear densities of 30 selected fibres were determined using Lenzing Vibroscope (model 400). Table 1 shows average linear densities as well as other physical parameters of the samples. The density of polypropylene fibres is assumed to be 0.91 g/cm^3 (ref. 25).

Pre-needled layers weighing 300g/m^2 were prepared using a 220 cm wide double cylinder-carding machine equipped with volumetric hopper feeder together with a horizontal cross-lapper and a pre-needling loom. Superimposition of two pre-needled layers and further needling operation using Fehrere AG NL21 needle loom resulted in production of dense felted material weighing 700g/m^2. Thickness of samples was measured using WIRA thickness gauging apparatus.

The needle looms used were equipped with GROZ-BECKERT felting needles 15×16×32×3.5 M332 G 53017. The samples received a total punch density of 540 punch/m^{2}at needle penetration depth of 8 mm. Automatex s.r.l structuring needle loom equipped with GROZ-BECKERT 15×16×25×63.5 D G 2056 fork needles imparted cord surface effect to the dense felted material. The structured samples attained dimensional stability on a Seller Co, direct gas fired chain-pinned dryer, using commercially available SBR latex. Four different samples of cord-structured nonwoven were prepared. Figure 1 demonstrates magnified surface loops of the structured nonwovens.

3.2 Lateral Compressive Test

Compression behaviour of the samples was determined using Zwick universal testing machine (model 144660) based on CRE method at constant speed of 50mm/min. Changes in the sample thickness in relation to exerted pressure was determined according to ASTM D6571 standard method. Ten circular latex treated samples having a surface area of 50 cm^2 were prepared for each experiment. The top and bottom jaws were equipped with precisely parallel flat and thick steel plates. With tester in compression mode and the specimen placed on the bottom jaw, the latter moves up until the top jaw just touches the specimen. This position defines the point where sample is under no exerted force. Further upward movement of the bottom jaws beyond this point leads to compression of the test sample. While the test is running in compression mode, the tester obtains and records the curve of compressive force (*f*) versus the compressed thickness (c). During loading cycle, maximum compressive force occurred when the thickness of the test sample is reduced to 25 % of the initial thickness.

4 Results and Discussion

Compression testing of samples results in creation of load-compression curves. For each fibre linear density category an average curve is drawn.

According to Van Wyk's equation, the variation in mass of fibres under pressure is in inverse relation to the cube of thickness. Accordingly, fibres in a needled nonwoven structure not only behave elastically but

Table 1 — Specifications of fibres and needled nonwoven samples

Samples	Fibre linear density, dtex	CV % of linear density	Fibre elastic modulus € Gpa	Initial thickness (t_0) mm
1	7.60	2.28	1.59	5.80
2	14.30	2.17	1.45	6.35
3	20.50	2.25	1.52	6.68
4	25.50	2.33	1.33	6.88

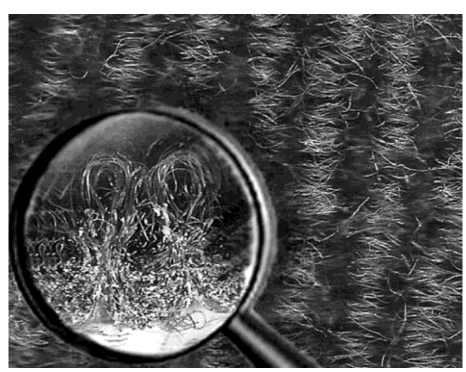

Fig.1— Surface cord loop

also simultaneously resist compression. Zwick tester provides variation of compressive force (*f*) versus compressed thickness(c) for all samples. Figure 2 depicts reconstructed experimentally obtained data, imported to Excel software after consideration of the average curves. The figure shows the plots of variations of compressive load in Newton (N) versus compressed thickness in millimeters.

Equation 5 has been used to find the best correlation curve for experimental data. A program in Matlab 7.1 software is used to perform the calculations using least squares method. Compressed thickness (*c*) is considered as independent variable. Compressive force (*f*) is the response or predicted value. The known parameters i.e. the values of initial thickness (t_0), elastic modulus of the fibres (*E*), density of fibres (ρ), surface area of testing sample (*A*) and mass of unit area (m_a) form the input to program. The only unknown parameter, Van Wyk constant (K), can be calculated from the theoretical correlation equation. The program changes the value of (K) to obtain the maximum value of coefficient of correlation i.e. R-square. Table 2 shows the calculated values of Van Wyk's constant (K) and R-squares. Curves shown by solid lines in Fig. 2 show the predicted theoretical values. As can be observed in Fig. 2, the theoretical and experimental values are reasonably close to each other.

The results show the existence of an initial low modulus i.e. low rigidity at first, which tends to increase at higher compression rate. Additionally Fig. 2 shows the deviation of experimental results from the theoretical results at first i.e. at lower compression rates. In this region, experimental results point to lower rigidity value during compression in comparison to the theoretical results. This can be attributed to the fact that as shown in Fig. 1, corded nonwovens are basically a dual layer structure comprising a top relatively open and a highly dense bottom layer. The less dense layer deforms readily in comparison to the dense top layer thus the lower rigidity of the fabric at the low compression. The difference in elastic behavior of the top and bottom layers may constitute a limitation to the validity of the Van Wyk's equation, which is based on the ideal elastic behavior of the fibre. The variation in elasticity of the two layers is because the initial carded fibrous web is first subjected to the action of barbed needles during first stage of needling. In this stage, depending on the extent of needling operation, the density of the initial fibrous web is vastly increased. The highly dense material is then subjected to the action of fork needles in the second needling operation when the top less dense layer is formed.

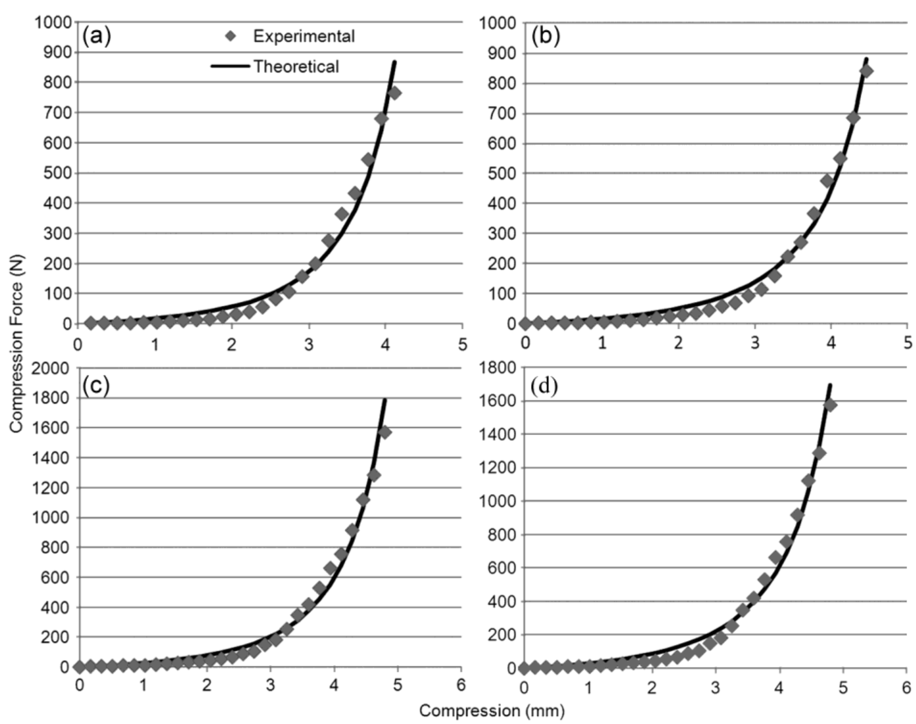

Fig. 2 — Compression behaviour of (a) sample 1, (b) sample 2, (c) sample 3 and (d) sample 4

Table 2 — Calculated results using Van Wyk's equation

Sample	Average fibre linear density dtex	Maximum compressive force, N	R^2	K $\times 10^{-3}$
1	7.60	790	0.976	1.17
2	14.30	850	0.988	1.84
3	20.50	1500	0.982	3.56
4	25.50	1700	0.987	5.11

However, the difference in ease with which the layers are deformed is not statically significant as indicated in Table 2. The fitted curves show high regression coefficient (R-square). Therefore, Van Wyk's equation can accurately explain the behaviour of needled nonwoven subjected to compressive force.

Table 2 also shows that the values of (K), which according to Van Wyk theory[2] is a dimensionless empirical constant, are highly affected by the linear densities of the constituting fibres of the fabric. Various parameters such as fibre arrangement, fibre linear density and elasticity can affect value of (K). The use of experimental samples containing fibres of different linear densities in this work resulted in generation of different values of (K) by Van Wyk's equation.

Table 2 indicates that, the maximum compressive force increases as the linear density of the fibres increases. This is due to the fact that the increase in fibre diameter leads to enhancement of fibre rigidity. The rigidity of the fibre is defined as $B=EI$, where E is the elastic modulus and I is the moment of inertia of the fibre cross-section. In the case of circular cross-section, the moment of inertia (I) of the fibre cross-section is proportional to the fourth power of the fibre diameter. Therefore, coarser fibres have higher rigidity.

5 Conclusion

This study investigated the lateral compressive behaviour of cord-structured nonwoven. The study offers a model based on Van Wyk theory and investigates lateral compressive behaviour of needled nonwovens by comparison of experimentally and theoretically determined sets of data. Acceptable compatibility exists between the theoretical and experimental results. The results imported from model show high compatibility with experimental curves obtained using Van Wyk theory. The results also indicate that the fibre linear density affects compression behaviour of dual structured nonwoven samples.

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