Effect of Fiber Orientation on Pore Size Characteristics of Nonwoven Structures

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ABSTRACT: Fiber orientation is a key parameter affecting the geometrical, hydraulic and mechanical properties of nonwoven materials. The effect of fiber orientation on the pore size has been experimentally investigated based on air-laid, parallel-laid, and cross-laid structures following through-air bonding. It was evident that there is a discernible difference between the mean flow and maximum pore sizes of these nonwoven materials. The influence on pore size was further elucidated by evaluating experimental and theoretical models based on sieving-percolation pore network theory including a model that incorporates directional parameter to account for the effect of fiber orientation. It was established that good agreement with experimental data can be obtained using such a model. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 118: 2668–2673, 2010

Key words: nonwoven; pore size; fiber orientation; through-air bonded

INTRODUCTION

Nonwoven materials are porous media consisting of fibers or filaments oriented mainly in the x, y directions according to the method of fabric production. In the majority of nonwoven materials, there is limited orientation of fibers in the z-direction, perpendicular to the plane. The fiber orientation, within such fabrics is normally characterized in terms of in-plane directions and this has a significant influence on the geometrical, hydraulic and mechanical properties of the fabric, particularly in terms of the anisotropy. Industrially, nonwovens are important as flow media in composites, geosynthetics, filter fabrics, and a host of hygiene and medical products. To assist in product engineering, relationships need to be established between structure and the desired macroscopic properties of such fabrics.[1] The pore size distribution of nonwovens is particularly important in respect of transport phenomena within the structure. It is well-known that the pore structure and morphology is highly complex in terms of the sizes, shapes, and the capillary geometries within the fabric. Previously, theories have been put forward for predicting the pore size distribution of random fibrous networks that have been extended for anisotropic structures including nonwovens.[2–7] Furthermore, based on three-dimensional (3D) models of nonwoven structure in which the fibers are stacked in elementary longitudinal planes, the pore size distribution has been calculated based on Poissonian polyhedra theory.[8–10] One limitation of previous models is that the effect of fiber orientation has not been considered in the computation of the pore size distribution in the fabric. Recently, a simple model for predicting the pore size distribution of nonwovens was developed by combining stochastic and geometrical probability approaches.[11] This model has accounted for the effect of fiber orientation on pore size distribution in the nonwoven.

The main objective of this work is to investigate the effect of fiber orientation in the fabric on pore size characteristics of through-air bonded* nonwovens. In such fabrics, bonding relies on the formation of an uncompressed fused fibrous network resulting from molten polymer flow due to surface tension and capillarity. The existing mathematical models of pore size distributions based on Poissonian polyhedra and gamma distribution theories were also analyzed.

THEORETICAL STUDIES OF PORE SIZE DISTRIBUTION

A simple three-dimensional model of nonwoven structure can be represented by assuming the fibers to be stacked in elementary x-y longitudinal planes (i.e., parallel to the plane of the sheet); this is also known as a longitudinal porometry model. Such models are related to sieving by percolation in fibrous networks and have been used in the past for

*Through-air bonded nonwoven structures are produced by applying the heat energy to the thermoplastic component present in fibrous web.

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predicting the pore size distributions of nonwovens and are briefly described below.

Faure model of pore size distribution in nonwovens

Faure et al.[8,9] working in the area of nonwoven geosynthetics formulated a model for predicting the pore size distribution of nonwovens based on Poissonian polyhedra theory in which the distribution of pore conduits within the structure can be determined. Here, the network of fibers is simulated as Poisson line networks in two dimensions that are randomly oriented in the plane. The cumulative probability of obtaining an inscribed circle (i.e., a hole or pore) between the polygons (see Fig. 1) of a diameter that is equal to or less than d, i.e., $G(d)$ can be determined as follows.

$$G(d) = 1 - \left(\frac{2 + \chi(d + D_f)}{2 + \chi D_f}\right)^2 e^{-\chi d} \quad (1)$$

and

$$\chi = \frac{4\mu}{\pi T_g D_f \rho_f} \quad (2)$$

where χ is the specific length representing the total length of lines per unit area, d is the inscribed circle diameter, μ is the mass per unit area of fabric, T_g is the fabric thickness, D_f is the fiber diameter and ρ_f is the fiber density. The pores are assumed as a disc or as an elementary conduit in each layer with axes perpendicular to the plane of the sheet such that the length of each disc can be defined as the fiber diameter. Therefore, the gradation of the conduits provides the cumulative probability of the passage of particles through the nonwoven.

$$Q(d) = 1 - [1 - G(d)]^{T_g/D_f} \quad (3)$$

where $Q(d)$ is the probability of a particle with a diameter d passing through a pore channel within the nonwoven.

Lombard model of pore size distribution of nonwoven structures

Lombard et al.[10] used the same analogy of Poisson's polyhedra theory for obtaining the expressions for probability of diameter distribution of a circle inscribed in a polygon, i.e., $K(d)$,

$$K(d) = \left(\frac{\sigma^2 d^2}{4} + \sigma d + 1\right) \exp(-\sigma d) \quad (4)$$

and

$$\sigma = \frac{8\mu}{\pi T_g D_f \rho_f} \quad (5)$$

where σ is the specific length representing the total length of lines per unit area.

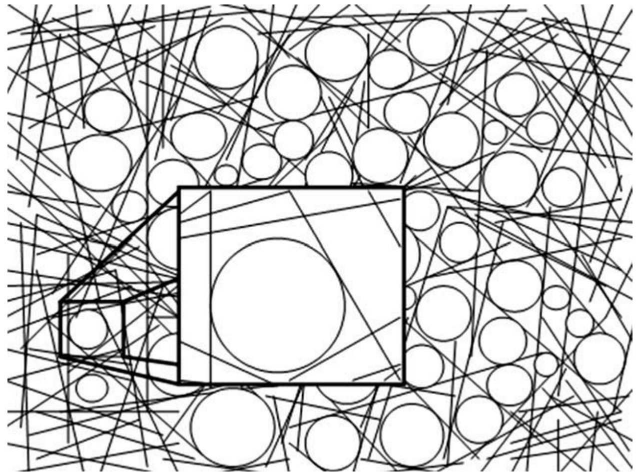

Figure 1 Fibrous Network consisting of polygons and inscribed circles. Insets: Detailed view of a circle inscribed in polygons.

Equation (4) shows the cumulative probability of obtaining maximum conduit/particle diameter (d). However, the particle should travel through the layers of nonwoven. Therefore,

$$F_f(d) = 1 - [K(d)]^{T_g/2D_f} \quad (6)$$

where $F_f(d)$ is the cumulative probability of passage of particles of diameter (d) through the layers of nonwoven.

Rawal model of pore size distribution of nonwoven structures

This model is based upon the combination of gamma distribution of polygon-inscribed circles that includes a directional parameter to account for the effect of fiber orientation.[11] The cumulative probability of a particle with diameter d, passing through the layers of nonwoven ($F_f(d)$) is shown below.

$$F_f(d) = 1 - \left[\left(1 + \omega d + \frac{\omega^2 d^2}{2}\right) e^{-\omega d}\right]^{T_g/2D_f} \quad (7)$$

where

$$\omega = \frac{4\mu K_j}{\pi T_g D_f \rho_f} \quad (8)$$

and

$$K_j = \int_{-\pi/2}^{\pi/2} |\cos\varphi| \Omega(\varphi) d\varphi \quad (9)$$

where $\Omega(\varphi)$ is the fiber orientation distribution function

TABLE I
Properties of Constituent Fibers

Fiber parameter	Value
Fiber length (mm)	51.8
Crimp frequency (n/cm)	4.2
Filament linear density (denier)	4.4
Density (g/cm^3)	1.375
Sheath melting temperature (°C)	112
Core melting temperature (°C)	252.5

The expressions for Faure's specific length as shown in eq. (2) and coverage parameter stated in eq. (8) are similar except that the directional parameter (K_j) is incorporated in the calculation of the coverage parameter (ω). Here, the directional parameter (K_j) is defined as the average distance between the bonds projected on the planar direction (j).

EXPERIMENTAL

Six through-air bonded samples of parallel laid (P), cross-laid (X), and air-laid (A) nonwovens were produced using 100 wt % bicomponent polyester fibers (sheath-core type). This yielded fabrics with markedly different fiber orientation distributions with respect to the peak orientation angle. Each fabric was produced in two mass per unit areas of 150 and 200 g/m^2. The properties of constituent fiber are illustrated in Table I. The mass per unit area and thickness of the samples were determined through standard test methods, ASTM D 6242-98 and ASTM D 5729-97, respectively, and their values are shown in Table II. Here, "A," "P" and "X" represents air-, parallel-, and cross-laid nonwovens, respectively, and "150," "200" denote the mass per unit area of the fabrics. Furthermore, the fiber orientation was measured by digitally capturing and analyzing the images using optical microscopy and LEICA QWIN software. The histograms of the relative frequency of fibers at 10° orientation angle intervals with respect to the cross-machine direction were computed to characterize the orientation distribution as shown in Figures 2–4. Note that 0° represents the cross-machine direction. The pore sizes of the nonwoven fabrics were experimentally determined by liquid extrusion porosimetry. In this method, a specimen of 2.1 cm in diameter is saturated with wetting liquid of low surface tension (16.4 dynes/cm) and unidirectional air pressure is applied to the saturated specimen for forcing the liquid to the other side. An increase in air pressure causes the bubble to escape from the largest pore initially and further increase in air pressure results in removal of the bubbles from smaller pores. This implies that the liquid from the largest pores would be emptied at the lowest pressure which provides the maximum pore diameter. Note that one limitation of this technique is that the sample is subject to a degree of compression during the test, which reduces the effective porosity and modifies the pore structure of the fabric to some extent.

TABLE II
Properties of Nonwovens

Sample ID	Mass per unit area (g/m^2) Actual	Nominal	Thickness (mm)
P150	149.9 ± 16.4	150	1.47 ± 0.17
P200	213.5 ± 9.2	200	3.81 ± 0.19
X150	136.1 ± 1.2	150	1.34 ± 0.11
X200	205.9 ± 12.5	200	2.57 ± 0.10
A150	126.9 ± 28.3	150	1.39 ± 0.56
A200	177.3 ± 7.4	200	2.18 ± 0.39

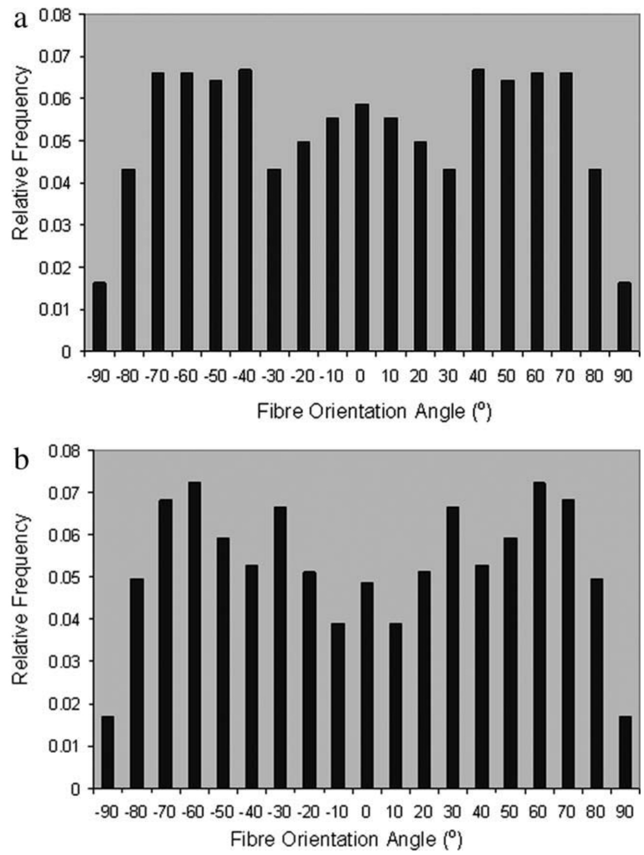

Figure 2 Fiber orientation distributions for airlaid nonwovens (a) A150 and (b) A200. Here 0° represents the cross-machine direction.

RESULTS AND DISCUSSION

The fiber orientation distributions illustrate marked differences between the parallel-, cross- and air-laid nonwovens (see Figs. 2–4). The mean flow pore diameter is a measure of the size of the majority of pores in the structure such that half of the air flow

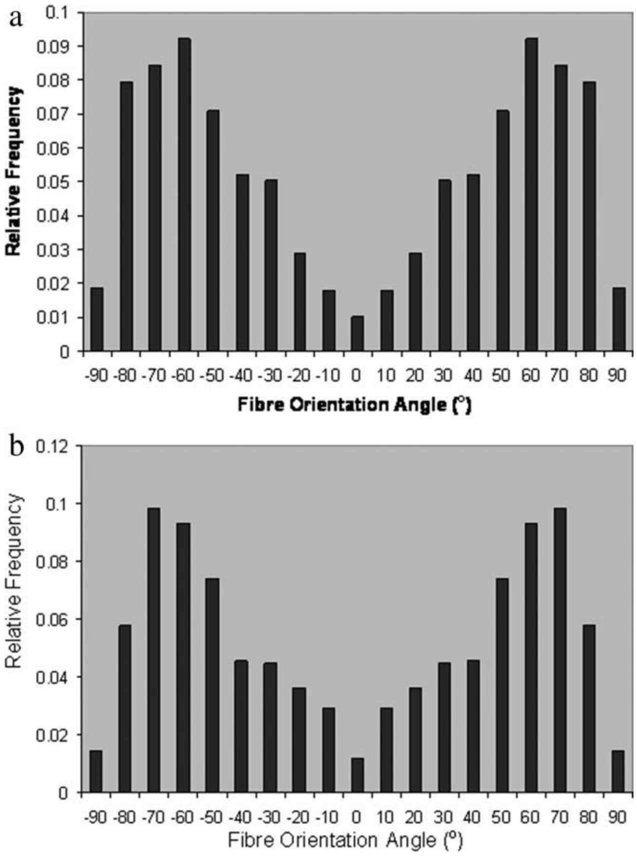

Figure 3 Fiber orientation distributions for parallel laid nonwovens (a) P150 and (b) P200. Here 0° represents the cross-machine direction.

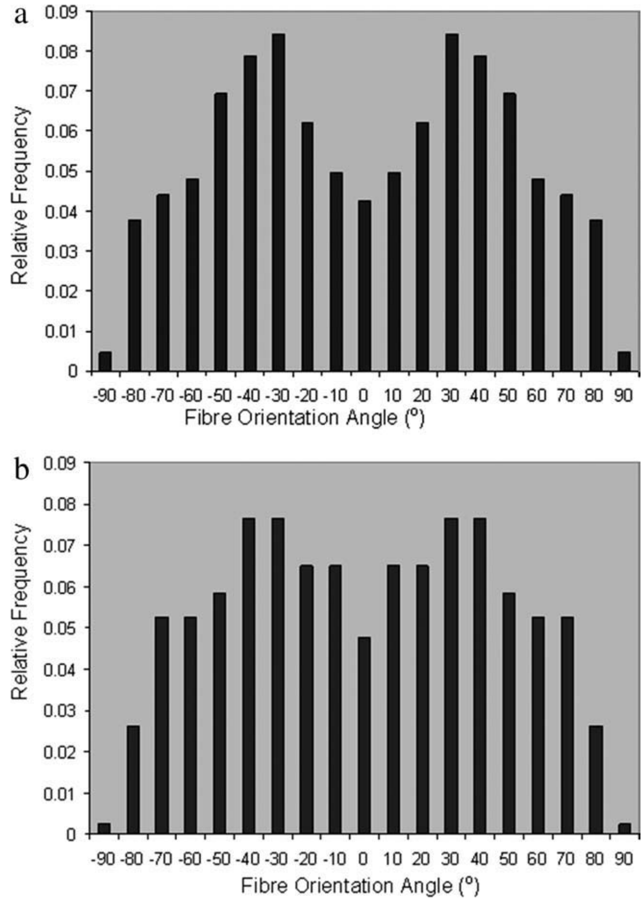

Figure 4 Fiber orientation distributions for cross-laid nonwovens (a) X150 and (b) X200. Here 0° represents the cross-machine direction.

is through the pores larger than the mean flow pore diameter and the other half of the air flow is through the smaller pores.[12] Similarly, the maximum pore diameter is the largest detected pore diameter due to a sudden increase in the flow rate at the beginning of the measurement.[13] The mean flow and maximum pore diameters of the six nonwoven samples were determined, as shown in Figures 5 and 6. Here, the experimental data are compared with the theoretical pore size data that was calculated from the models of Faure et al.,[8] Lombard et al.,[10] and Rawal.[11] It is apparent that the experimental pore size data are in good agreement with the calculated pore size data obtained from the Rawal model[11] in which the effect of fiber orientation is included by incorporating a directional parameter, as shown in eqs. (7)–(9). Note that this applies despite the inherent mass and thickness variation in the samples (Table II) that can be expected to affect the measured pore sizes.

Comparison of the pore sizes obtained from Faure et al.[8] and Lombard et al.[10] models reveal that these models largely underestimated the pore sizes of the nonwoven fabrics. In these early models, the fiber orientation was not considered in the modeling regime as an important parameter that could affect the pore size of the nonwoven structure. Additionally, Lombard and

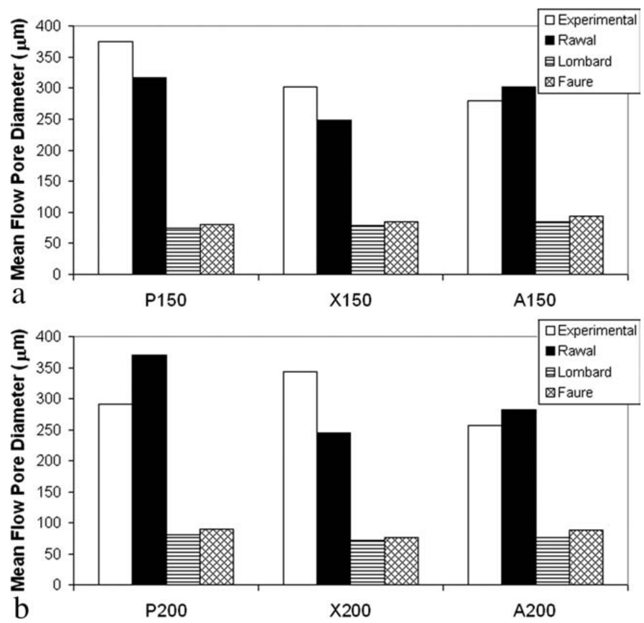

Figure 5 Mean flow pore diameters of parallel-, cross-, and air-laid nonwovens of (a) 150 g/m^2 and (b) 200 g/m^2.

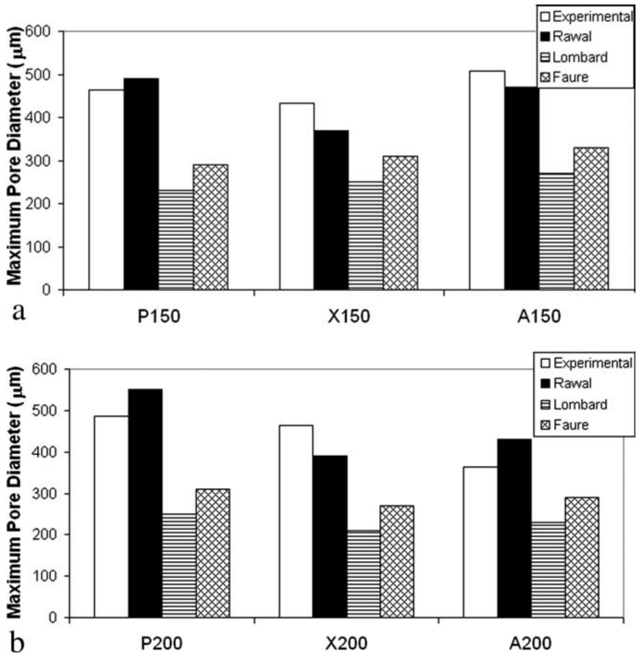

Figure 6 Maximum pore diameters of parallel-, cross- and air-laid nonwovens of (a) 150 g/m^2 and (b) 200 g/m^2.

Faure models of pore size distribution were based on the assumption of a Poisson distribution; Rawal's was based on a gamma distribution function.

To further elucidate the influence of the fiber orientation distribution on the pore size, an additional virtual experiment was carried out based on an analysis of idealized fiber networks rather than the real structures. The fiber orientation distributions, obtained experimentally (Figs. 2–4), were utilized to simulate idealized nonwovens, whilst keeping all other parameters constant. In this way, it was possible to eliminate all other influences apart from changes in fiber orientation. Figure 7 indicates that the random (air-laid) structure exhibits the highest pore sizes in comparison to directional (parallel- or cross-laid) structures.

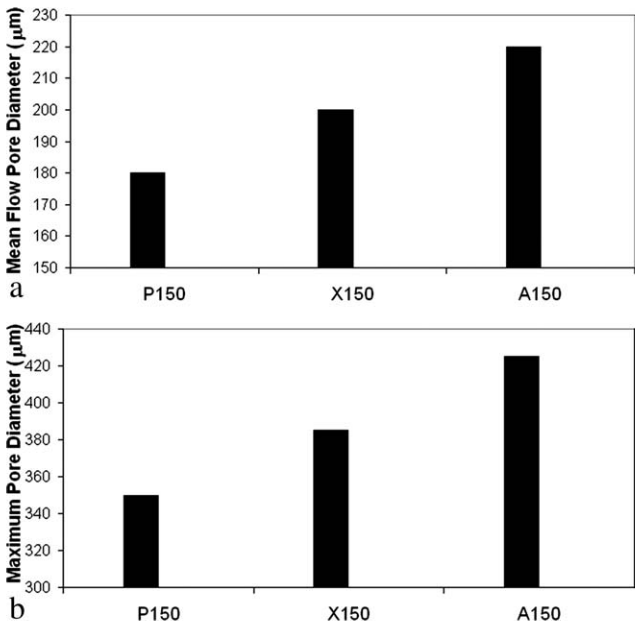

Figure 7 (a) Mean flow (b) Maximum pore diameter of parallel-, cross-, and air-laid fictitious nonwovens of mass per unit area of 150 g/m^2.

TABLE III
Directional Parameter Values of Nonwoven Structures

Sample ID	Directional parameter (K_j)
P150	0.76
P200	0.74
X150	0.69
X200	0.70
A150	0.62
A200	0.63

It is evident that the preferentially orientated structure would have a lower pore size than the random structure. For same fiber volume fraction, it can be envisaged that as the proportion of fibers that are preferentially oriented in one direction increases, there will be a minimum number of fiber–fiber contacts, and a minimum pore size would be approached. In contrast, a randomly oriented fibrous network in which the number of fiber–fiber contacts is maximized would yield the highest pore size. Based on a comparison of the experimental data with calculated data from existing mathematical percolation models of pore size, it is apparent that the fiber orientation distribution of the structure needs to be considered in modeling of pore size. Accordingly, Faure and Lombard models are not suitable for predicting the pore sizes of nonwoven structures because of the routine modifications that are made to the fiber orientation distribution during fabric formation and bonding.

The anisotropic characteristics of nonwoven structures have also been revealed by computing the directional parameter values. Theoretically, the value of directional parameter is 0.6, assuming that the fibers are uniformly and randomly distributed in the structure. Table III shows that the value of the directional parameter is highest in the parallel-laid fabric and lowest in the air-laid structure. It is in good agreement with the previous study carried out by Hearle and Sultan,[14] which indicated that parallel laid nonwovens are highly anisotropic. Air-laid nonwovens tend to be more isotropic than those produced by carding and therefore a relatively low directional parameter value would be expected. In this study the cross-laid nonwoven was found to be less anisotropic than the parallel-laid structure.

CONCLUSIONS

In this work, the effect of fiber orientation on the pore size of through-air bonded nonwoven structures has been studied. It is evident that there is a discernible difference between the pore sizes of parallel-, cross-, and air-laid nonwoven structures. Moreover, the experimental results of pore size are in good agreement with existing sieving-percolation based model that incorporates a directional parameter accounting for the fiber orientation distribution, such as presented by Rawal.[11] Previous percolation models given in the literature have not considered fiber orientation as a key parameter and when compared with experimental data are found to underestimate the pore size of real nonwoven materials.[8,10] It can be inferred that these models are not suitable for predicting the pore size of nonwoven structures where the fiber orientation distribution is routinely altered to modify the macroscopic physical properties of the fabric, usually by changing process parameters in web formation.

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