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POROSITY AND ITS CHARACTERIZATION IN NONWOVENS

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Introduction

An important characteristic of fibrous assemblies that contributes to the usefulness of textiles in a wide variety of applications is porosity. Two parameters that generally characterize this attribute are pore volume per unit mass and pore size. The former plays a role in determining the amount of air a material will trap or the amount of fluid a structure will hold [1-3]. Pore size is a parameter that determines the rate at which fluids are imbibed by porous materials [4,5]. These characteristics can also be shown to play key roles in determining the effectiveness of textiles in many other applications, such as surgical products, protective garments, and gas and fluid filtration products [6-8].

Of the two parameters, pore volume can be easily determined, i.e. it is simply given by the ratio of the total interstitial space to the dry mass of the specimen. Pore size, on the other hand, is not that easy a parameter to determine experimentally, although several methods are available to assess the quantity [9]. The latter fall into three groups: liquid extrusion from and/or intrusion into a fabric, forced flow of a fluid, and optical scanning of a fabric surface. Each method involves elaborate testing and has limitations regarding material type used and range of pore sizes determined. Additionally, in the first two methods, a fabric interacts with a fluid while it is under pressure over a long period of time (~ several hours) and, therefore, deforms and leads to greatly altered results. The draw back of the third method is that one either characterizes the structure of a thin slice of otherwise a bulky fabric, or of only those pores that extend directly from one side to the other. Accordingly, it is highly valuable to have a means by which one can calculate the value. An added benefit of having a model is that factors affecting the parameter will be known and one could use the information to engineer a product with desired value.

Structural Models

Pore Volume

Pore volume is given by the difference between the volume occupied by a fabric specimen and that occupied by the constituent materials (fiber, binder). A web specimen is shown in Figure 1. It has area A, dry mass W and thickness under the desired pressure, L. It is composed of several components (fiber, resin) differing in density, ρ, and mass fraction, w. If i is the index representing individual components, then,

Mass of a component i in the specimen, $W_i = Ww_i$
Volume of the component in the element = W_i/ρ_i
Total fiber volume in the element, $V_f = W\Sigma w_i/\rho_i$
Total pore (air) volume in element, $V_a = AL\text{-}V_f$

Total pore volume of the element divided by mass of the element gives specific air volume, V_s:

$$V_s = \frac{V_a}{W} = \frac{AL}{W} - \Sigma \frac{w_i}{\rho_i}$$

The second part of the right hand side of the equation represents the reciprocal of the weighted average density of the components. If ρ_{av} represents this quantity, then:

$$V_s = \frac{AL}{W} - \frac{1}{\rho_{av}} \tag{1}$$

where,

$$\rho_{av} = \left[\Sigma \frac{w_i}{\rho_i} \right]^{-1} \tag{2}$$

The quantity calculated by Eq. 1 gives the maximum interstitial space per unit dry mass of fabric under the imposed pressure. This will correspond to the maximum absorption capacity (cc/g) in absorbent products. If a web consists of hydrophilic fibers, such as cotton, the fluid may also be absorbed by the fibers into their internal structure. The total will then be composed of the amount diffused into the fibers and the amount held by capillary forces in the spaces between the fibers. However, it has been discussed in an earlier paper [2] that if the diffusion occurs by local exchange between fiber and water molecules, then the total absorbed can still be correctly given by Equation 1. For this to be true, it is necessary that L in the equation is the final thickness of the specimen, i.e. in the wet state, while W and ρ are the quantities referring to the dry or conditioned state.

The quantity, V_s, may also be expressed in terms of the packing factor, , defined as the ratio of fiber to web volume, or the porosity, ϕ, defined as the ratio of pore volume to total volume (V_d/AL), as follows [1]:

$$V_s = \frac{1}{\rho_{av}}\left[\frac{1-\psi}{\psi}\right] = \frac{1}{\rho_{av}}\left[\frac{\phi}{1-\phi}\right] \tag{3}$$

Pore Size

The treatment is based on the assumption, that a pore is bounded by three fibers, oriented parallel or randomly, and the specific volume of the pore unit cell equals that of the parent web. The model considered is first general and then applied to specific cases later. The fibers may have a coating applied to them as a binder but this feature is dealt with later when specific cases are considered. If out of the three fibers forming a pore, n_i come from fiber type i, and d_i is the corresponding linear density, then

$$n_i \propto w/d_i$$

$$\Sigma n_i = 3.$$

If the fabric consists of only one type of fiber, then:

$$\Sigma n_i = n = 3.$$

The treatment involving the assumption of parallel or the random arrangement of fibers lead to the same estimate of pore size. In either case, it is assumed that the fibers are uniformly distributed through out the structure and packing density is uniform from place to place.

In the parallel arrangement, the three fibers are assumed to lie at the apexes of an equilateral triangle (Fig. 2), which defines a pore. Each fiber contributes $1/6^{th}$ of its area to that of the unit cell. The unoccupied area is the area of the pore. Since the fibers are uniformly distributed throughout the structure, the packing density of the unit cell can be equilibrated with that of the fabric. This allows the determination of the length of the triangle. The radius, r, of the pore is estimated by making the unoccupied area of the triangle equal to that of a circle and applying the equation πr^2 to it.

In the random arrangement, as one can imagine, the pores are not straight or parallel but tortuous and randomly oriented, and they are interconnected, i.e. a given pore starting at one end of fabric and ending on the other may not be bound by the same fibers from point to point. It is assumed that each fiber is surrounded by free space that is proportional to its own volume. An interstitial space is still bounded by three fibers (Fig. 3), and each contributes one-sixth of its free volume at each point along its length to the volume of the pore.

The two treatments give exactly the same solution [1, 12] and lead to the following model for pore size:

$$r = \left[\frac{1}{6\pi B}\left\{\frac{AL\rho_{av}}{W}-1\right\}\left\{\sum \frac{n_i d_i}{\rho_i}\right\}\right]^{1/2} \tag{4}$$

In this, B is the constant whose value is determined by the base length associated with the linear density used. For example, if d is the tex, and all parameters are in the c.g.s. system of units, then B will have the value 10^5.

Specific Cases of Structures

1. One Component Fabric. In this case, two equations characterizing specific pore volume (Equation 1) and pore size (Equation 4) simplify to the following:

$$V_s = \frac{AL}{W} - \frac{1}{\rho} \tag{5}$$

$$r=\left[\frac{1}{6\pi B}\left\{\frac{AL\rho}{W}-1\right\}\frac{3d}{\rho}\right]^{1/2} \quad =\left[\frac{V_s d}{2\pi B}\right]^{1/2} \tag{6}$$

<u>2. One fiber and a binder</u>. This will also cover a fabric containing a regular fiber and a low melt fiber, the latter after melting coating the fiber and serving as an adhesive. The designations used for the binder are w_b for mass fractions and ρ_b for density. It is assumed that ρ_b is the density of the binder in the final or bonded state, and the adhesive or the molten polymer uniformly coats the surface of the regular fiber. The pickup by the fiber will increase the linear density from d to d', and change the density from ρ to ρ'. The new values are plugged in the equations (5 and 6) pertaining to one component fabric and the quantities V_s and r determined. The values of ρ' and d' are as follows:

$$\rho'=\frac{\rho\rho_b}{w\rho_b+w_b\rho}$$

$$d' = d/w$$

<u>3. Two different fibers</u>. Fabrics may contain a blend of two different fibers, which combine characteristics of two different materials not adequately provided by a single component, e.g. wettability and resiliency. The only unknowns for using equations 1 and 4 are the magnitudes of n_1 and n_2, i.e. the number of fibers out of 3 belonging to type 1 and 2. These are determined as follows:

$$\begin{aligned} n_1/n_2 &= w_1 d_2 / w_2 d_1 \\ n_1 &= 3w_1 d_2 / (w_1 d_2 + w_2 d_1) \\ n_2 &= 3 - n_1 \end{aligned} \tag{7}$$

(8)

<u>4. Two different fibers and a binder</u>. As before, it is assumed that the adhesive or the molten polymer will uniformly coat the surfaces of regular fibers. The amount picked up by different fibers will be proportional to their surface areas. The net result will be increases in linear densities, from d_1 and d_2 to d_1' and d_2', and increases in mass fractions, from w_1 and w_2 to w_1' and w_2', and changes in densities, from ρ_1 and ρ_2 to ρ_1' *and* ρ_2', respectively, for components 1 and 2. The values of the new quantities are first plugged in equations 7 and 8 to estimate the values of n_1 and n_2 and then the values of all these quantities are used in equations 1 and 4, to estimate the values of V_s and r. In the equations given below, A_{si} represents the surface area of fiber i in the fabric specimen and A_{st} represents the total surface area of all fibers in the fabric. The quantities related to binder have the subscript "*b*". The values of A_{si}, A_{st}, and of the changed quantities, ρ_i', d_i', w_i' can be shown to be as follows:

A_{si} = circumference x length of fiber i = $2\ \ Ww_iB/(\ d_i\rho_iB)^{1/2}$

$A_{st} = \Sigma A_{si}$

$$\rho_i' = \frac{w_i + w_b \cdot A_{si}/A_{st}}{(w_i/\rho_i) + w_b \cdot A_{si}/(\rho_b \cdot A_{st})} \tag{12}$$

$$d_i' = d_i\left[1 + w_b \cdot A_{si}/(w_i \cdot A_{st})\right] \tag{13}$$

$$w_i' = w_i + w_b \cdot A_{si}/A_{st} \tag{14}$$

<u>5. More complex structures</u>. Calculations can be conducted for a fabric containing three different fibers and also for a fabric containing three fibers and a binder [12]. Such structures are usually not found in cotton nonwovens and, therefore, not considered in this paper.

Factors Affecting Pore Properties

The three parameters that appear in the equations and affect pore characteristics are:

1. The bulk of the fabric, or the thickness per unit mass
2. The linear density of the fiber
3. The density of the constituent material.

Of these, the factors producing the greatest effect are the first two. These are also the parameters one could influence by changing the manufacturing conditions of the web and of the fiber. Out of these two, the first is particularly important since it is itself influenced by the size and shape of the constituent material. The factors affecting the bulk of the fabric, or *T/W*, are as follows:

- The size and the cross-sectional shape of the fiber
- The mechanical properties of the fiber
- The moisture sensitivity of the fiber if the fabric comes in contact with the fluid
- Structure of the fabric, i.e. the orientation of fibers, the type and level of the bonding or entangling
- The conditions under which the fabric is tested or used; in particular the environmental pressure to which the fabric is imposed.

Fibers of high linear density, high modulus and a shape that has circular symmetry but is tri- or multi-lobal or tubular will lead to high bulk fabrics. Moisture or aqueous environment can adversely affect bending rigidity in some fibers, in particular cellulosic, specially rayon, and result in relatively lower pore volume and smaller pore size in structures containing these materials. The type and level of bonding used can influence bulk. Airlaid webs as against carded, and the latter as against wet-laid or spunbonded produce bulkier structures. Likewise needle bonded or through air bonded methods produce higher bulk fabrics than do those bonded by hot calendaring of fabrics containing thermoplastic materials. Another factor found to have a strong influence on a fabric's pore specific volume is the areal density or the weight of the fabric (g/m^2) [3]. In experimental studies, webs of lower areal density have shown higher values of *T/W* and *r*. The most important use related factor is the environmental pressure. An increase in such pressure causes an increase in compression and, therefore, in a decrease of bulk.

From Equation 4, it should be clear that any factors that affect a web's pore specific volume also affect pore size. One may note that a key factor having an effect on pore size is the linear density of the constituent fiber. This is because linear density also affects the bulk and both the linear density and the bulk independently affect the pore size.

Procedure

The equations presented above allow a simple way of estimating the values of the two quantities. The procedure will be as follows. The fabric of interest is cut to the desired size, *A*, and weighed to determine *W*. Its thickness, *L*, is determined under the desired environmental conditions, i.e. of pressure, temperature and humidity or fluid, using an appropriate method. With the linear densities of fibers, and mass fractions and densities (g/cc) of various components known, pore volume per unit mass and pore size are readily determined using the equations.

Sample Results

Three sets of fabrics are chosen below to illustrate the effects of the material and structural factors on the values of the two parameters.

In sample set A (Table 1), higher bulk noted in fabrics containing the 1.8 denier cotton over that containing the 1 denier fiber is obviously due to higher bending rigidity of the fibers in the former. The cottons having higher values of V_s than the rayons, in spite of the latter having higher denier, is due to the relatively much greater wet modulus (~ 4x) found in the former [2]. The trilobal rayon has higher value of V_s than does the round crenulated material; this is significantly due to the trilobal configuration making the former a stiffer fiber. The values of pore size within the two cottons and within the two rayons followed the trends noted for the values of V_s, as expected. The rayons, however, have higher values of *r* than do the cottons and this is due to the former having higher linear densities than the latter. Higher pressure imposed on a specimen during tests led to greater compression and, therefore, to lower values of the two parameters.

In sample set B (Table 2), adding a resilient polyester material to hydrophilic cotton led to an increase in the values of both V_s and *r*, as expected. An interesting result noted, however, is that the lower weight webs led to more resilient structures and, therefore, to relatively bulkier webs, with higher values of V_s and *r*.

In sample set C (Table 3), as noted in the previous set, an increase in the fraction of the resilient synthetic fiber in blend with rayon brought about significant increases in pore specific volume and pore size.

It has been pointed out during the theoretical treatment that V_s represents the void space per unit mass available for imbibing fluid in absorbent structures. A comparison between the calculated values of V_s and the measured values of absorbent capacity on the demand wettability device (GATS) has invariably shown excellent correlation, with the two values falling within ± 10% of each other [1-3]. Pore size, *r*, is a parameter of significant importance in many applications involving transport of fluids and gases, namely barrier, comfort, filtration and absorbency. In theoretical treatments of wicking, pore size appears as a factor directly affecting the rate of absorption [2,4,5]. In several experimental studies involving absorbent structures, the direct effect of the pore size on the rate has been demonstrated [2,3].

Range of Values of Porosity In Fibrous Nonwovens

Examples of fabrics considered above are carded and, in some cases, also needled. These structures tend to be highly bulky. Another mechanical means of bonding is hydroentangling, which has been found to produce a somewhat more compact structure, especially if the fabric is composed of hydrophilic fibers [3]. The values of pore specific volume noted in some of the spunbonded and adhesive bonded fabrics are usually around 5 cc/g [12]. The theoretical lowest value of porosity one can expect is from hexagonal close packed structure, which is not known to be achieved in fibrous materials.

It will be instructive to examine the range of values of porosity related parameters one may expect in cotton nonwovens produced by different manufacturing methods. This is done in Table 4.

In typical mechanically bonded structures, thus, 93 % or more of the space is occupied by air, and only 7 % or less by fibers. In adhesive bonded materials, presumably also in wetlaid fabrics, the space occupied by air is still very large (> 88 %). These results support the high level of inherent insulation potential found in fibrous structures, especially nonwovens. It is interesting to note that although a web is mostly air in volume (88 – 97 %), the pore size is still relatively small, i.e. only about 2 to 4 times the radius of the fiber.

Summary

Methods for determining the porosity related characteristics of nonwovens have been illustrated. The parameters include specific pore volume, pore size, packing factor, and porosity. Many material and manufacturing factors affect the values of these parameters, as do also some of the conditions used during application.

Experimental results show that from 88 to 97 % of the volume of cotton nonwovens is air and only 3 to 12 % fiber. The pore size ranges from about 1.25 to 2.5 cm x 10^{-3}, or from 12.5 to 25 micrometers. This is about 2 to 4 times the size (radius) of the fiber.

References

Burgeni, A.A. and C. Kapur, , “Capillary Sorption Equilibria in Fiber Masses,” *Textile Res. J.*, 37: 356-366, (1967).

Davis, N.C., “Factors Influencing the Air Permeability of Felt and Felt-Like Structures,” *Textile Research J.*, 28: 318-324, (1958).

Dent, R.W., “The Air-Permeability of Non-woven Fabrics,” *J. Text. Inst.*, 67(6): 220-224, (1976).

Gupta, B. S., “The Effect of Structural Factors on the Absorbent Characteristics of Nonwovens,” *TAPPI Journal*, 71(8): 147-152 (1988).

Gupta, B.S., and C.J.Hong, “Absorbent Characteristics of Nonwovens Containing Cellulosic Fibers,” INJ, 7(1): 34-43, 1995.

Gupta, B.S., “Study of the Fluid Uptake Behavior of Nonwovens,” Proceedings, INDA-Tech 1998, Inda, Cary, NC, 21.1-21.29, (1998).

Gupta, B.S., Results to be Published.

Miller, B., “Critical Evaluation of Upward Wicking Tests,” *INDA, INJ.*, 9(1): 35-40, (2000).

Miller, B., and I. Tyomkin, An Extended Range Liquid Method for Determining Pore Size Distribution,” *Textile Res. J.*, 56: 35- 40, (1986).

Sauvage, L.R., K.E. Berger, P.B. Mansfield, S.J. Woods, J.C. Smith, and L.B. Overton, “Future Directions in the Development of Arterial Prostheses of Small and Medium Caliber Arteries,” *Surg. Clin. N. Am.*, 54(1): 213-228, (1974).

Washburn, E.W., “The Dynamics of Capillary Flow,” *Phys. Rev.*, 17(3): 273-283, (1921).

Winslow, D.N., “Advances in Experimental Techniques for Mercury Intrusion Porosimetry, in Surface and Colloid Science, Vol. 13, E. Matijevic and R. J. good (Eds.), Plenum Press, 1984, pp 259-282.

Table 1. Fabric Set A. Carded webs of cellulosic fibers of 100 g/m^2 areal density [3]. Effect of environmental pressure, EP (g/cm^2), and material.

	Vs (cc/g)		r (cm) x 10^{-3}	
	EP = 12	EP = 27	EP = 12	EP = 27
Cotton, 1.8 den	12.8	10.2	2.01	1.79
Cotton, 1.0 den	12.2	9.7	1.47	1.31
Rayon (trilobal), 3 den	11.8	9.1	2.51	2.20
Rayon (round), 3 den	9.9	7.6	2.30	2.02

Table 2. Fabric Set B. Carded and needled webs of a blend of cotton (1.8 den) and 4 Deep Groove polyester (6 den). Needling intensity ~ 60 needles/cm^2. Environmental pressure, 12 g/cm^2. Effect of blend ratio and web areal density (g/m^2).

	Vs (cc/g)		r (cm) x 10^{-3}	
	40 g/m^2	120 g/m^2	40 g/m^2	120 g/m^2
Cotton/polyester, 100/0	14.8	13.9	2.15	2.09
Cotton/polyester, 90/10	15.6	14.2	2.29	2.19

Table 3. Fabric Set C. Carded and needled fabrics of blends of polypropylene (3 den) and trilobal rayon (3 den). Environmental pressure 12 g/cm^2; needling intensity 180 needles/cm^2; web areal density 120 g/m^2. Effect of blend ratio.

Polypropylene/trilobal rayon	Vs (cc/g)	r (cm) x 10^{-3}
100/0	22.4	3.45
50/50	18.2	3.09
0/100	13.2	2.62

Table 4. Porosity Values in Cotton Nonwovens. Calculated values of packing factor ψ, porosity ϕ, pore size r, and ratio of pore size to fiber size (R), i.e. r/R, for different values of specific pore volumes V_s, observed in practice. Fiber density = 1.52 g/cc; denier = 1.8; fiber radius, R = 0.647 x 10^{-3} cm. (The last value in the table is given for a hypothetical structure, assuming circular fibers, and listed to show the theoretical limit.)

V_s (cc/g)	Preparation/Bonding	ψ (x100)	ϕ (x100)	r (cm)x10^{-3}	r/R_f
20	Carded	3.2	96.8	2.52	3.89
	Airlaid				
15	Needle bonded	4.2	95.8	2.19	3.38
	Needle bonded				
10	Hydroentangled	6.2	93.8	1.78	2.75
5	Adhesive bonded	11.6	88.4	1.26	1.95
0.07	Hexagonal Close Packed	90.7	9.3	0.15	0.23

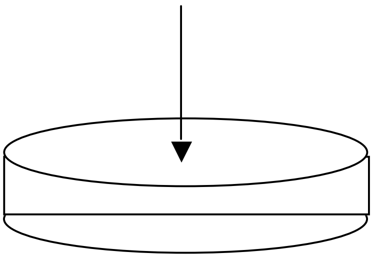

Figure 1. A fabric specimen.

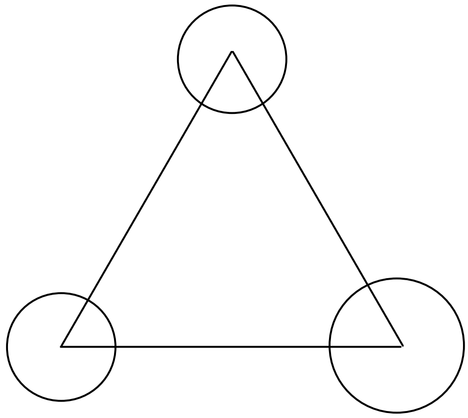

Figure 2. Unit cell of a fabric assumed to contain parallel arrangement of fibers.

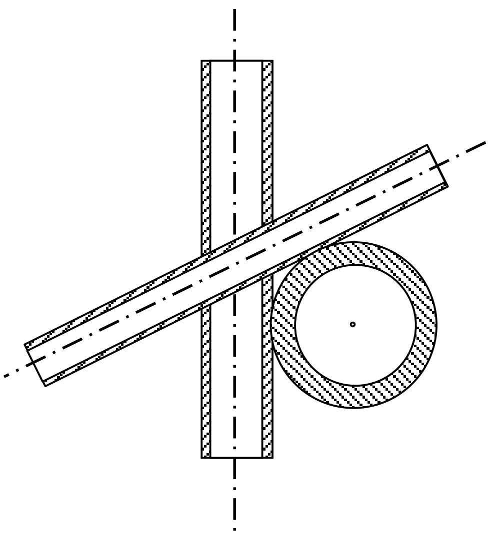

Figure 3. Interstitial space bounded by three fibers in a 3-dimensional randomly arranged structure.