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Pore Characteristics in Aramid and Simulation Nonwoven Fabrics
—through Image Analysis—

Na, Young Joo

Dept. of Clothing & Textiles, Inha University

아라미드와 시뮬레이션 부직포의 기공 크기에 대한 특성
—이미지 분석을 통한 연구—

나 영 주

인하대학교 의류학과

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Abstract

부직포의 기공크기에 대한 특성을 측정하기 위해 이미지 프로세싱을 이용하였다. 아라미드부직포와 그 부직포를 시뮬레이션한 부직포에 대해서 기공의 크기를 대표하는 평균 기공크기와 그 분포를 이미지 분석의 두가지 방법으로, 즉, 형태학적인 방법과 기하학적인 방법을 통해 측정해보았다. 아라미드 부직포, 시뮬레이션 부직포이건 상관 없이 부직포의 밀도가 증가함에 따라 기공의 크기특성, 즉 기공의 면적, 수력반경, 그리고 기공내의 최대 내접원의 반경은 감소하였다. 형태학적인 방법과 기하학적인 방법은 부직포의 종류에 상관없이 기공의 크기를 측정함에 있어서 유의한 차이가 없었다. 이는 부직포내의 섬유의 배열방향이 무작위이기 때문이었다. 실제의 아라미드 부직포와 시뮬레이션 부직포의 기공크기에 대한 특성은 서로 비슷한 양상을 보여주었다.

INTRODUCTION

Most fabrics, both conventional textiles and nonwoven fabrics, have pores. The pore dimensions determine the performance of these materials in many end-use applications. Pore dimensions can be represented in several ways, each relating to a specific end use. These dimensions can be expressed in terms of their volume, on which the capacity of a fiber network to absorb liquid depends. They may also be stated in terms of pore diameter, a factor important to filter products; that is, passage of fluid through the network is controlled by the narrowest constriction in each pore and by the internal surface areas of the pores.

Gong and Newton[1] have defined the pore size in three different ways:

1) equivalent diameter, which is the diameter of the circle having the same area as the pore; 2) hydrodynamic diameter, a term drawn from hydrodynamics, the diameter of tunnel being

defined as 4A/P, area as A, and perimeter as P; and 3) diameter is that of the largest circle that can be inscribed in the pore.

Conventional methods of determining pore size, such as dry-sieving and hydrodynamic filtration, are time-consuming and often unreliable. 1) The beads can easily become trapped in the fabric (particularly in bulky nonwovens) and not pass through at all. 2) Fibers in some fabrics(for instance, slit ilms) move easily with respect to on another, allowing the beads to pass through an enlarged void that is not representative of the fabric in service. 3) The test is not readily reproducible because such factors as temperature, humidity, and variations in bead size, all influence the test results[2]. 4) Some of them, furthermore, give no information other than mean size and maximum size of pores.

The image analysis method is attractive, being simple and rapid and readily applied under conditions affording a relatively high degree of reproducibility. In addition to pore size, image analysis, can furthermore, provide more information about pores, such as pore perimeter, height, width, and ellipticity, as well as pore size distribution.

MEAN PORE SIZE

Mean pore size is the most important parmeter governing fluid flow. Many models define mean pore size in terms of the porous media construction parameters.

Johnston[3] has suggested *mean pore diameter (D_p)* as a function of the fiber diameter*(d_f)* and the porosity function $f(\varepsilon)$.

$$D_p=\left(\frac{d_f}{\varepsilon}\right)\frac{1}{\sqrt{2f(\varepsilon)}}$$

where

$$f(\varepsilon)=(1-\varepsilon)^{1.5}[1+56(1-\varepsilon)^3)]$$

Mlynarek[4] has proposed experimental work on nonwoven fabrics in the porosity range of 0.64 and 0.91, and with fiber diameter of about 30μm. His formula for the mean pore size is as follows:

$$D_p=3.3d_f\varepsilon$$

Boyd[5] has suggested that the cross-sectional area of pore can be given by:

$$A=\frac{C_f}{\rho_n}-\pi\frac{d_f^2}{4}$$

C_f=fiber weight per unit length

ρ_n=density of fibrous network

d_f=diameter of fiber.

Hence, the *radius of pore,* assuming it is circular, is:

$$r=\left(\frac{A}{\pi}\right)^{0.5}$$

PORE SIZE DISTRIBUTION

Pore size distribution is the probability density function the relates the distribution of pore volume to a characteristic pore size. The pore size distribution curve in a fabric gives a measure of the variation of its internal pore structure. It is necessary to acquire information about pore size distribution so that the behavior of the pore system can be better understood, interpreted, and predicted.

Morphological techniques of image analysis have been used to determine pore size distribution[1]. This method is similar to sieving filtration of an image. The morphological method measures pore size by finding the size of largest circle or square fitted into the pore. Therefore, circle or square pores can be measured by the size of whole area, while elongated pores are only measured by the size of their narrowest constriction. However, geometrical method measures whole pore area whether pores are circle, or elongated. Both the morphological technique of image analysis and the geometrical method are applied and compared in this study.

METHODS

MATERIALS

The samples used in this research are two kinds of aramid fiber nonwoven fabric with different weights; 13.6 g/m^2 and 34.0 g/m^2. The fabric structures are stiff for being made by a wet-laid process, and the fiber segments in the fabric are straight to a large extent. The fibers that are used to make fabrics are circular in cross-section. The properties of the samples are listed in Table 1.

Aramid 2 has 2.5 times as many fibers as aramid 1, since its weight and thickness are double those of aramid 1 with the same web density and the same fiber diameter. Figure 1 shows binary images of aramid fabrics used in this study.

SIMULATION OF NONWOVEN FABRICS

Computer codes are used to generate random numbers for making random line networks which represent a layer of the nonwoven fabric. A pair of pseudo-random numbers (x, y) is used as a position of random point in 2-D, and a continuous line is drawn passing this point with an angle (θ), which also is generated randomly in the range of 0~180°. This step is repeated until the desired density of lines is obtained[5].

Densities are 50, 100, 150, and 200 fibers with random fiber orientation. Figure 2 shows this simulated images with differences in fiber densities. Thus, 4 kinds of different webs are generated in binary image. Three replicas are repeated for each kind of simulated nonwoven fabrics.

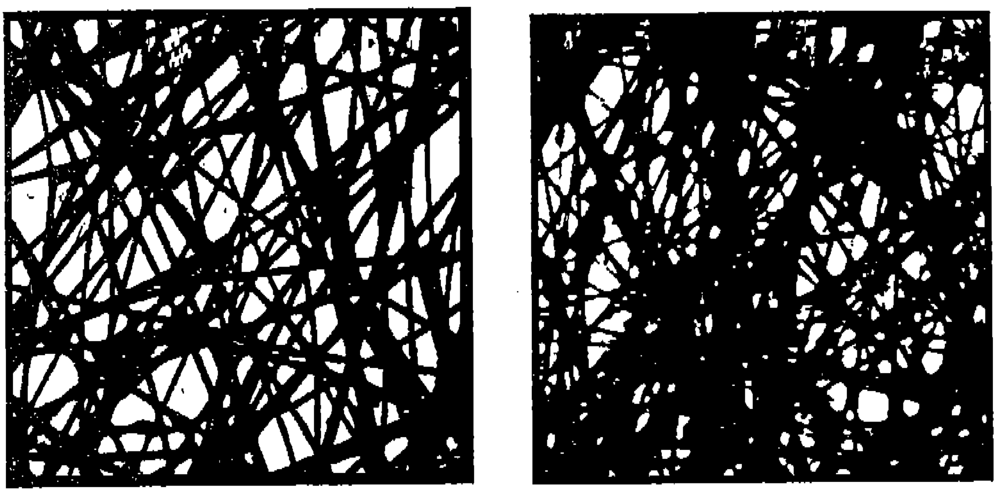
The line width of generated web is controlled to the same thickness for all webs.

Table 1. Characteristics of Aramid Nonwoven Fabric Materials

Fabric	Weight (g/m^2)	Thickness (mm)	Density (g/cc)	Fiber Diameter (μm)	Denier
Aramid 1	13.6	0.20	1.44	11.9	1.5
Aramid 2	34.0	0.47	1.44	11.9	1.5

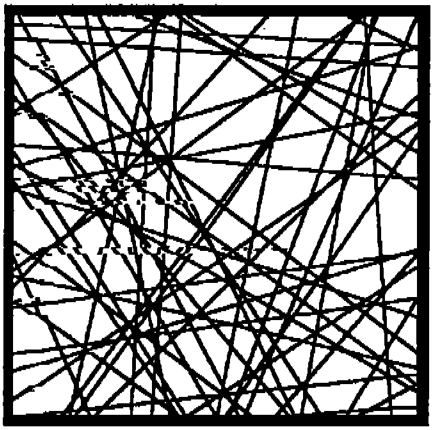
IMAGE CAPTURE AND DIGITIZING

Dry nonwoven fabric specimens are cut and mounted on the microscope without immersion. The nonwoven fabric images are captured by means of a compound light microscope fitted with a Sony CCD camera. The magnification of the objective is 3.5X. Magnification in the horizontal and vertical directions, as results, gives as follows:

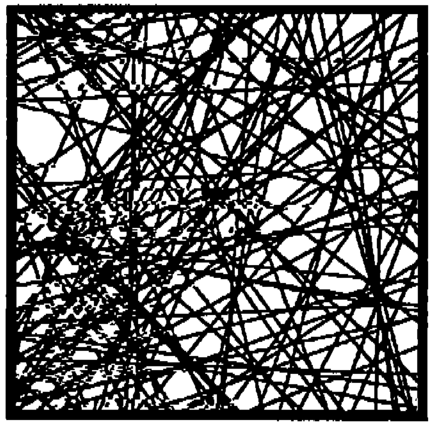


ARAMID 1　　ARAMID 2

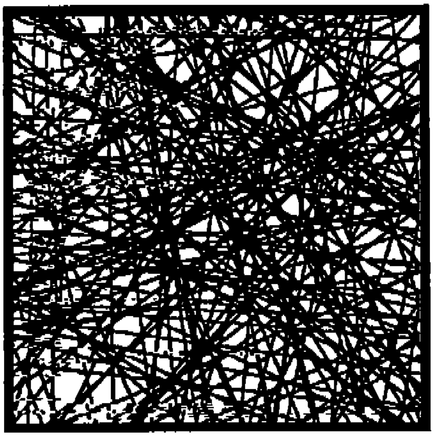
Fig. 1. Binary Images of Aramid Nonwoven Fabrics.



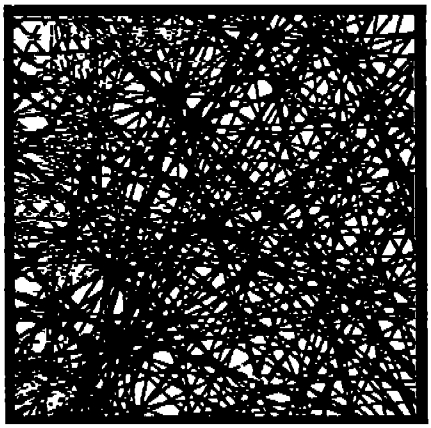
50 FIBERS



100 FIBERS



150 FIBERS



200 FIBERS

Fig. 2. Simulated Images with Differences in Densities

Horizontal direction : 1 *pixel*=1.97 *microns*

Vertical direction : 1 *pixel*=1.94 *microns.*

The captured image is digitized through a True Vision 32-bit color AT-Vista board installed in a 486 IBM, 66MHz microcomputer. The other image-capture conditions are kept constant throughout. Three images for each sample are taken at different locations.

The depth of image is very large because of the large thickness of the sample itself. Because the density of one layer of web is of interest in this study, only partial portion in the thick web is focused and examined. Without compression, using several layers of nonwoven fabrics does not make a filter significantly different in effective opening size or filtration characteristics from a filter that consists of a single layer[6].

The images have a size of 512×486; some of them have bad edges because of the problems associated with image-capture conditions. Therefore, they are resized to 450×450 pixels by taking the center portion of the image. This size of 450×450 is kept constant when the simulation fabrics are generated.

The next step is conversion to a binary image. This includes selecting the mean gray level value as the threshold. A binary image in which every point is either white or black, is distinct from a gray scale image. Binary images take up much less storage space—only one bit per picture point—rather than a byte or even more, and are usually more suitable for measurement than gray scale images.

Next is boundary processing, in which object boundaries turn into the coordinates of line segments. Because the shape of an object is defined by its boundary, the shape of pores becomes dominant in the image. This step may be called a draw chain code. Finally, the actual measurements can be performed with this image. Simulation of nonwoven fabrics is analyzed without the steps of resizing or conversion to binary image.

IMAGE ANALYSIS METHODS

The software of image processing is developed in the Applied Imaging Laboratory. The software has various algorithms for filtering the images and for carrying out various analytical operations, such as texture analysis.

1) Morphological Techniques-Size Distribution

Morphological analysis is the method of successive application of morphological operations and measuring the residues of image. The granulometric size distributions of morphological analysis provide textural information by measuring the manner in which successive opening operations by structural elements of ever-increasing size shrink the activated portion of the image. The number of activated pixels and the number of objects in the residue are measured, yielding an approximate idea of the size distributions. In this case, the structuring elements are 2D (k), where 2D (k) is a matrix of k activated pixels. The images will be successively opened with matrix structuring elements; the number of activated pixels and the number of remaining objects are recorded in each case. Because of the decreasing nature of granulometries, the resulting functions will also be decreasing and will reach 0 for some finite value of k.

The function obtained will be the size distribution for that image. It should de noted that the granulometry OPEN (S, V(k)) can be regarded as a sieving process. For each value of k, only those objects remain whose lengths of both vertical and horizontal sides are at least equal to k. This action is like a sequence of sievers; at each stage, smaller particles than the structuring element slide through the mesh of the sieve and disappear. In linear granulomerty output can be extracted using either H(k), V(k) which is a one dimensional structuring element(horizontal or vertical)[7]. The morphological method can estimate the average of pore size through calculation, assuming pores are circle or square.

2) Geometrical Techniques

Geometrical descriptors are measurements of the geometry of shape analysis. Geometrical descriptors are straightforward measurements of pore geometry. The following descriptors are calculated for each pore object.

Pore Area A and Pore Perimeter P:

$$A=\Sigma_D\Sigma\Delta x_i\Delta y_i$$

$$P=\Sigma_k\sqrt{(x_k-x_{k-1})^2+(y_k-y_{k-1})^2}$$

where $(\Delta x_i, \Delta y_i)$ are points in the pore area, (x_k, y_k), and (x_{k-1}, y_{k-1}) are pixels on the enclosing boundary.

The Radius of an inscribing circle is the minimum distance to the boundary from the gravity center[8].

Hydraulic Radius, HR is calculated by;

$$HR=4\frac{A}{P}$$

where A is the pore area and P is the pore perimeter.

Hydraulic radius is essential to predicting filter properties. The smaller the ratio of cross-sectional area and perimeter of a pore, the larger are the frictional forces that determine the transport of flow.

RESULTS AND DISCUSSION

Relative density ratio means ratio of fiber density relatively to other fiber density. Both a simulation composed of 50 fibers and aramid 1 are represented as 1, 100 fibers as 2, aramid 2 as 2.5, 150 fibers as 3, 200 fibers as 4.

1) The number of pores

The number of pores increases as fiber density of aramid fabrics increases. Pores are fewer in aramid facrics than in simulated fabrics (Figure 3). According to Piekaar[9], one reason can be that the small pores in the real fabric are disappearing. The fibers in real fabric are overlaid, not as randomly as in the simulaiton. Thus, very small pores that are formed by the intersections overlying fibers do not contribute to the pore area analysis. The geometrical and the morphological methods do not yield different results in the number of pores. Geometrical method can detect more pores in denser web than morphological method can.

2) Pore area

The pore area of aramid nonwoven fabrics decreases as the number of fibers increases independently of the measurement methods used (Figure 4). The geometrical method is more sensitive than the morphological one to changes in density of fibers, but their trend resembles each other. The morphological method-square means pores are regarded as squares; the morphological method-circle as circle. The results concerning pore areas of both real fabric and simulated fabric are in agreement. Lombard et al.'s finding that pore area is dependent on the elementary layer numbers or web density is proved because the denser the web is, the smaller the pore area is regardless of simulation or real fabrics[10].

In addition to the considerable differences in the

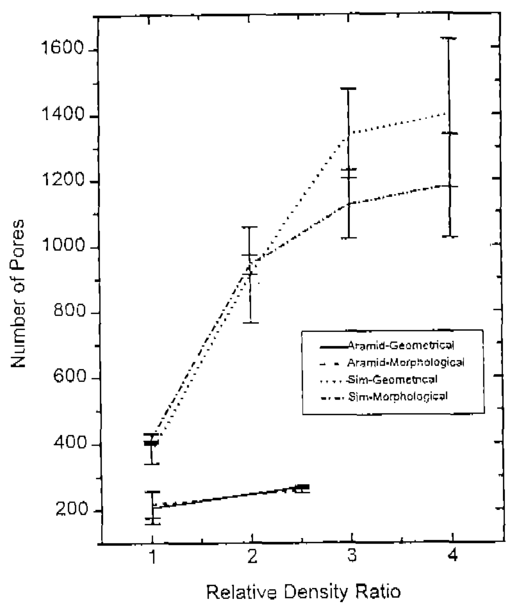


Fig. 3. Number of Pores in Aramid Fabrics

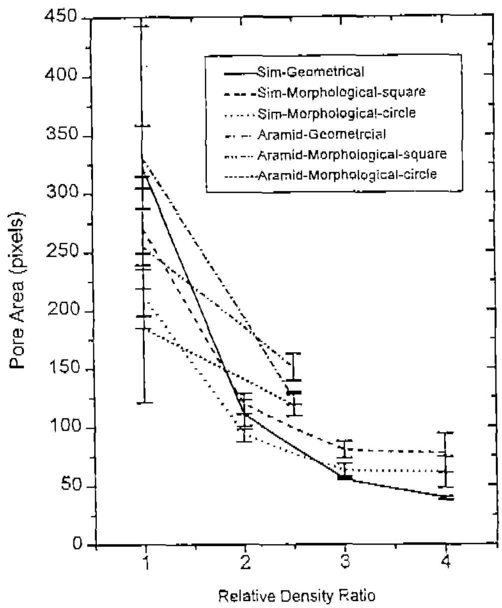


Fig. 4. Pore Area as a Function of Density

mean of pore area, there are also differences in the pore area distributions between the webs of different densities. In pore area distribution (Figure 5), aramid 1 is spread wider than aramid 2 independently of the measurement methods used; aramid 1 has a larger standard deviation independently of the methods used(Figure 6). This corresponds well with that of Fosters[11]. Pore area distribution from lower density web spreads wide. The geometrical and morphological methods give highly resembled results for pore area distribution. Pore area distributions seem to follow lognormal or log-beta distribution independently of web density, and this is a good agreement with Piekaar's[9].

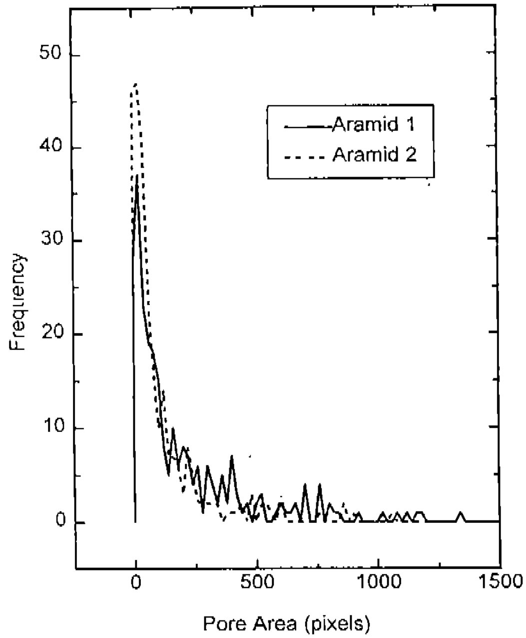


Fig. 5. Pore Area Distrubution (Geometrical method)

3) Hydraulic radius;

Figure 7 shows that as the web becomes denser, its hydraulic radius decreases. This distribution also has a shape of log-normal distribution(Figure 8). The denser web has the smaller standard deviation of hydraulic radius distribution. These results are exactly the same as those in the case of pore area.

4) Radius of the inscribing circle to a pore;

Radius of the inscribing circle to a pore becomes smaller with increases in the number of fibers in the web(Figure 9). This is the same tendency as with

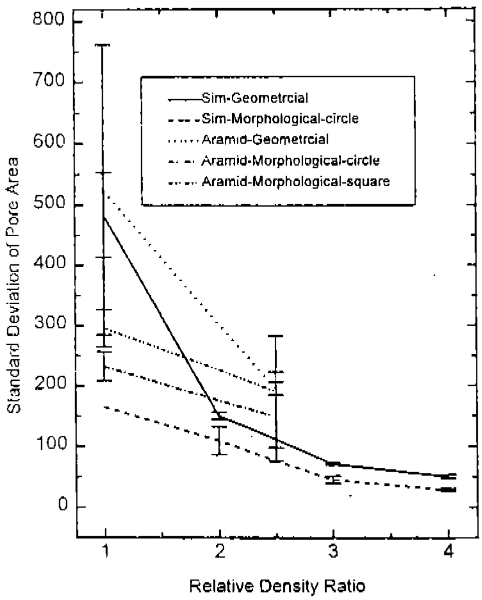


Fig. 6. Standard Deviation of Pore Area of Aramid Fabrics

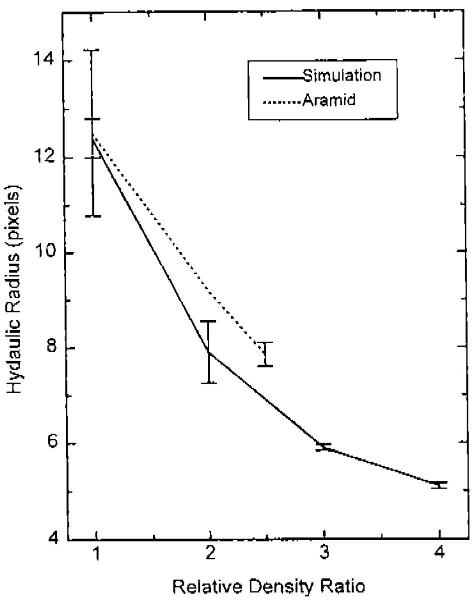


Fig. 7. Hydaulic Radius of Aramid Fabric

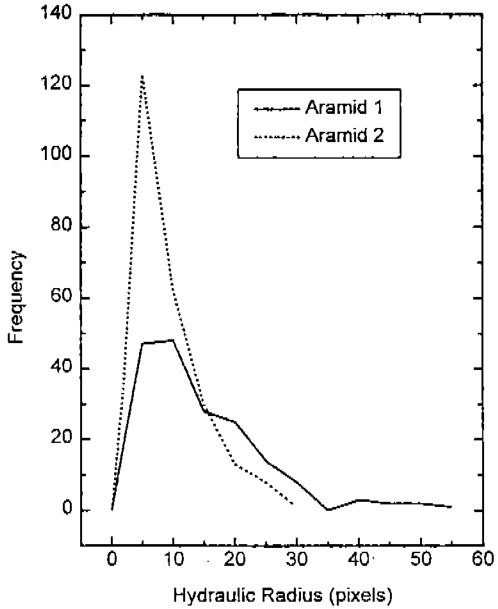


Fig. 8. Hydraulic Radius Distribution of Aramid Fabrics

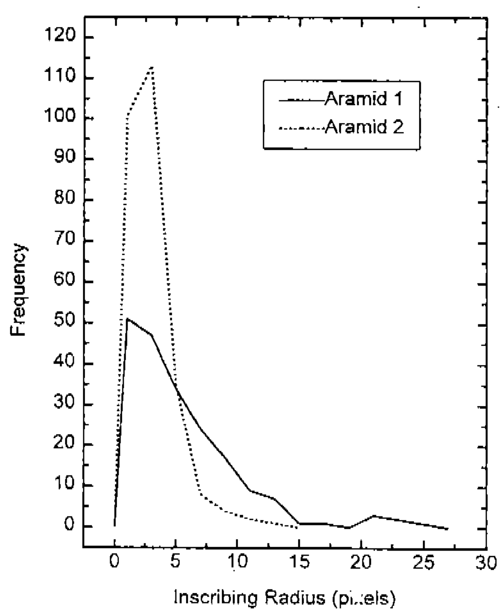


Fig. 10. Inscribing Radius Distribution of Aramid Fabrics

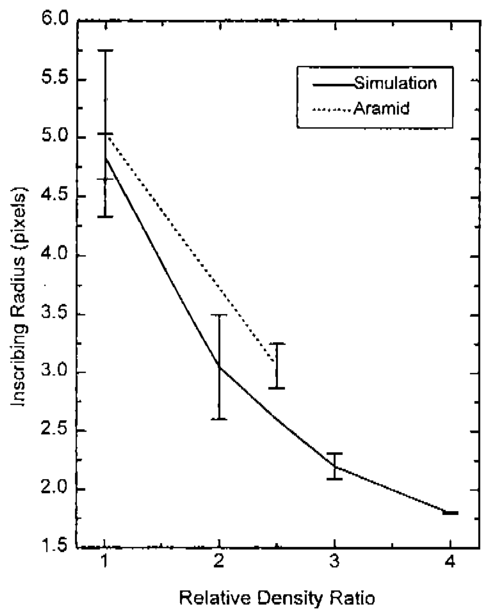


Fig. 9. Radius of Inscribing Circle of Aramid Fabrics

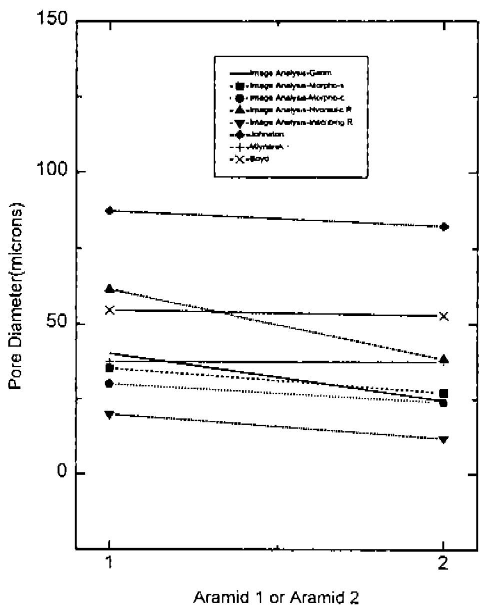


Fig. 11. Comparison of Image Analysis with Other Methods

pore area from both the morphological and the geometrical method and with the hydraulic radius. This distribution(Figure 10) also matches exactly the pore area distribution, and hydraulic radius distribution. Denser fabric, aramid 2 has smaller range of inscribing radius.

Table 2. The Comparison of Pore Size of Aramid Fabrics (microns)

	Johnston	ImageA-Hydraulic Radius	Boyd	Image A-Geometrical	Mlynarek	ImageA-Morpho-Square	ImageA-Morpho-Circle	ImageA-Inscribing Radius
Aramid 1	87.2	61.5	54.6	40.2	37.5	35.2	30	19.9
Aramid 2	82.3	38.4	53.0	24.6	37.4	27.2	24	12.0

5) Comparison of various methods for pore area of aramid fabrics

Pore diameters of aramid fabrics are calculated by the means of many equations. And they are compared with pore areas obtained by various image analysis methods are plotted in Figure 11. Pore areas are converted to diameter. The comparison of pore areas of aramid fabrics obtained by image analysis to those caluculated by other methods follows in Table 2. Pore areas obtained by image analysis agree well to those by other methods in that the denser web has smaller pore area.

SUMMARY AND CONCLUSION

Image analysis, which includes both morphological and gemetrical methods, is applied in the study of pore dimensions in both aramid and simulated monwoven fabrics. Pore size characteristics, such as pore area, hydraulic radius and radius of the inscribing circle to a pore are analyzed as a function of density.

Pore area is inversely proportional in a nonlinear manner to web density no matter what the monwoven fabric is real or simulated. Pore area distribution is also significantly different between different web-densitys from both real and simulated monwoven fabrics; the standard deviation of denser monwoven fabric is larger than that of less dense monwoven fabric. Pore area, hydraulic radius, and radius of the inscribing circle to a pore from both real and simulated monwoven fabrics are relevant; they are proved to be inversely proportional to web density.

As a whole, it is proved that image analysis techniques, such as morphological and geometrical methods can be used for measuring pore size of monwoven fabrics if the fiber orientation of monwoven fabric is random. It is found that simulation of monwoven fabric helps to characterize the real pores. It is therfore possible that the behavior of real pore properties, including size and shape, can be predicted effectively and reliably through simulation.

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