Geotextile Pore Structure Characterization Using Image Analysis

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ABSTRACT: Filtration performance of geotextiles strongly depends on their pore structure parameters, i.e. percent open area (POA), pore opening size distribution (PSD) and constriction size distribution (CSD). Current methods of determination of pore structure parameters contain inherent disadvantages whereas image analysis can be used effectively for this purpose. Two new image-based PSD and CSD determination methods and a new image-based POA determination method were developed specifically for woven and nonwoven geotextiles. The POAs, and a characteristic pore opening or constriction size, \( O_{95} \) or \( C_{95} \), of various geotextiles were determined using the information provided by the image analysis methods. The image-based POAs and the pore opening size of woven geotextiles were comparable to those obtained from the physical measurements and the values reported by the manufacturers. The constriction sizes of nonwoven geotextiles were comparable to the ones using the bubble point test and the values suggested by a theoretical equation. However, the image-based constriction sizes were consistently lower than the manufacturer’s reported apparent opening size, which is typically determined on the basis of the dry sieving test.

1. INTRODUCTION

To assure effective filtration performance, geotextiles must be properly designed. Previous research has shown percent open area (POA) and certain pore opening sizes of woven geotextiles (Austin et al. 1997, Mylnarek and Lombard 1997, Aydilek and Edil 2002) and constriction sizes of nonwoven geotextiles, the minimum pore opening sizes of its flow channels, impact filtration performance and these sizes should be determined before applying filter selection criteria. Current filter design criteria are typically based on ratios of certain
geotextile pore opening size to soil grain size. This is somewhat logical, since large pore openings of a geotextile should be smaller than large size fraction of the soil grains to prevent piping. Similarly, the small pore openings of a geotextile should be larger than the small size fraction of soil grains to prevent excessive blocking. Mostly use of certain pore opening sizes has been suggested in the existing criteria and in recent years the trend has been to remove POA from filter design criteria.

Problems exist with the currently available methods for determining pore opening structure parameters of woven geotextiles, i.e. percent open area (POA) and pore size distribution (PSD). A commonly used method for POA determination is the light projection method, which is highly operator-dependent. Commercial image analyzers and scanning techniques have also been used for this purpose (Mylnarek and Lombard 1997, Dierickx 1999). Various problems have been identified also with the currently available PSD determination methods (Bhatia et al. 1996). These studies showed that PSD is highly dependent on the method used and therefore is not a unique property of geotextile. Due to the two-dimensional structure of woven geotextiles and the presence of relatively large pore openings, a direct method such as image analysis appear to be very appropriate for this purpose.

A number of methods also have been developed to determine the PSD of nonwoven geotextiles (Bhatia et al. 1996). Existing studies (Giroud 1996, Giroud et al. 1998) indicated that constriction sizes of a filter impact filtration performance. Constriction size is different than pore opening size. It may be located at any depth inside the geotextile and not necessarily at the top surface. In its current status, dry sieving test (ASTM D 4751), one of the most commonly used methods, cannot determine constriction size. Dry sieving test measures the nearly largest pore opening size ($O_{95}$) of a geotextile, called the apparent opening size ($AOS$); however, the smaller pore opening sizes determined by this method may not be accurate due to various problems in testing procedure (Van der Sluys and Dierickx 1991; Giroud 1996). Furthermore, this method does not determine the constriction size in flow channels. The bubble point test (ASTM F316), on the other hand, determines constriction sizes indirectly by approximating them from the measured minimum constriction area.

Image analysis method is perceived to provide a more direct and reliable way of determining constriction sizes of a nonwoven geotextile. However, it has not been extensively used due to the lack of a standard and proven procedure. Most existing image analysis methods use two-dimensional planar or cross-sectional view images of a geotextile
(Masounave et al. 1980; Bhatia et al. 1996), and are usually operator-dependent. Moreover, most of the methods do not consider randomness in manufacturing of nonwoven geotextiles, and the measurements are image-specific rather than representing the entire geotextile layer.

Thus, there is a need for a methodology that more accurately and consistently defines the pore structure of geotextiles. In response to this need, a new approach for determining both the percent open area (POA) and pore opening size distribution (PSD) of woven geotextiles based on recent technological advancements in image analysis is warranted and is presented in this paper. Additionally, a new method, CONS (CONstriction Size), was developed for nonwoven geotextiles. This latter method uses image analysis and a probabilistic description of constriction size. The method consists of three steps: specimen preparation, image analysis and probabilistic analysis. It uses planar and cross-sectional views to capture the three-dimensional structure of a nonwoven geotextile and constructs a probabilistic description of pore channels using Markovian process. A characteristic constriction size, \( C_{95} \), was determined for a variety of geotextile specimens and compared with the values based on bubble point tests and theoretical equations. The same constriction size was also compared with manufacturer’s reported AOS value to show the differences between pore opening and constriction sizes (i.e., \( O_{95} \) versus \( C_{95} \)).

2. WOVEN GEOTEXTILES

In the testing program five woven geotextiles were used. The geotextiles were selected from the ones most often used in filter applications with a range of percent open area (POA), apparent opening size (AOS or \( O_{95} \)) and permittivity. They also incorporated a range of polymeric fibers such as slit-film, monofilament, and multifilament. The physical and hydraulic properties of the geotextiles are given in Table 1. Images of geotextiles were captured by a charged couple device (CCD) analog camera and a 18 to 108-mm macro zoom lens. A digital image acquisition board digitized the captured images. Approximately 35 binary images of each geotextile were captured, using a high precision x-y stage table. The images were converted into binary form by employing an optimal thresholding algorithm and pores (white zones) were discriminated from the black zones (filaments). The area of the pores to the entire area provided the POA for each geotextile.

Two different types of imaging algorithms were developed for measuring the pore opening sizes. Firstly, P-IMAQ, was developed using IMAQ, and image analysis software working under LabView. The code reads the images, converts them into a binary form at an input threshold value, and filters them in the optimal form. Secondly, an original code for
Table 1: Physical and hydraulic properties of woven geotextiles

<table>
<thead>
<tr>
<th>Geotextile</th>
<th>Structure, polymer type</th>
<th>Mass/unit area (g/m²)</th>
<th>Thickness (mm)</th>
<th>Apparent opening size, AOS (mm)</th>
<th>Percent open area, POA (%)</th>
<th>Permittivity (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>W, MU, PP</td>
<td>257</td>
<td>0.645</td>
<td>0.425-0.6</td>
<td>8</td>
<td>1.50</td>
</tr>
<tr>
<td>W2</td>
<td>W, MF, PP</td>
<td>207</td>
<td>0.613</td>
<td>0.3-0.425</td>
<td>10</td>
<td>1.36</td>
</tr>
<tr>
<td>W3</td>
<td>W, MF, PP</td>
<td>204</td>
<td>0.664</td>
<td>0.3-0.425</td>
<td>20</td>
<td>2.14</td>
</tr>
<tr>
<td>W4</td>
<td>W, SF, PP</td>
<td>165</td>
<td>0.316</td>
<td>0.212-0.3</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>W5</td>
<td>W, SF, PP</td>
<td>151</td>
<td>0.330</td>
<td>0.212-0.3</td>
<td>2</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Notes: W: woven, SF: slit-film, MF: monofilament, MU: multifilament, PP: polypropylene. Mass/unit area and thickness were measured according to the ASTM D 5261 and ASTM D 5199. AOS, POA and permittivity are manufacturer’s average reported values.

PSD determination of woven geotextiles, named PORE, was written in MATLAB which takes a different approach in defining pore areas in an image. It incorporates several image processing and restoration operations to more accurately define pore areas, and provides actual pore opening size as opposed to a defined pore opening size such as given in dry sieving in terms of the bead size that fits a pore opening. The details of the code development are provided by Aydilek and Edil (2004).

2.1 Percent Open Area

The percent open areas of five woven geotextiles determined by the image analysis are highly comparable to the manufacturer’s reported POAs as shown in Table 2. The accuracy of the algorithm was also checked by comparing the image-based values with those determined manually, i.e. light projection method (LPM). Even though the light projection method gives accurate results when employed carefully, the method is highly time consuming and therefore, image analysis is still preferable. The results suggest that the image analysis method can be effectively used to determine the POA of woven geotextiles.

2.2 Pore Opening Size Distribution

The $O_{95}$ opening sizes of woven monofilament and multifilament geotextiles determined by two different image analysis methods compare well in a general way with the
Table 2: Percent open area and pore size measurements on woven geotextiles

<table>
<thead>
<tr>
<th>Geotextile</th>
<th>POA-MARV (%)</th>
<th>POA - (LPM) (%)</th>
<th>POA- (Image Analysis) (%)</th>
<th>AOS-MARV (mm)</th>
<th>O₉₅ PORE (mm)</th>
<th>O₉₅ P-IMAQ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>0.425-0.6</td>
<td>0.443</td>
<td>0.444</td>
</tr>
<tr>
<td>W2</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>0.3-0.425</td>
<td>0.264</td>
<td>0.233</td>
</tr>
<tr>
<td>W3</td>
<td>20</td>
<td>24</td>
<td>25</td>
<td>0.3-0.425</td>
<td>0.416</td>
<td>0.34</td>
</tr>
<tr>
<td>W4</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.212-0.3</td>
<td>0.166</td>
<td>0.15</td>
</tr>
<tr>
<td>W5</td>
<td>2</td>
<td>1.4</td>
<td>1</td>
<td>0.212-0.3</td>
<td>0.16</td>
<td>0.154</td>
</tr>
</tbody>
</table>

Note: MARV: Manufacturer’s average reported value.

The manufacturer’s reported AOS values (Table 2). However, the image-based values were relatively low for the slit-films possibly due to their heterogeneous structures.

3. NONWOVEN GEOTEXTILES

Five different types of nonwoven geotextiles from four different manufacturers covering a wide range of apparent opening sizes (AOS) and permittivities were analyzed. The physical and hydraulic properties of the geotextiles used in this study are given in Table 3. The

Table 3: Physical and hydraulic properties of nonwoven geotextiles

<table>
<thead>
<tr>
<th>Geotextile</th>
<th>Structure, polymer type</th>
<th>Mass/unit area (g/m²)</th>
<th>Thickness (mm)</th>
<th>Apparent opening size, AOS (mm)</th>
<th>Porosity (%)</th>
<th>Permittivity (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW1</td>
<td>NW, NP, STF, PP</td>
<td>163</td>
<td>1.40</td>
<td>0.15</td>
<td>87.1</td>
<td>1.80</td>
</tr>
<tr>
<td>NW2</td>
<td>NW, NP, STF, PP</td>
<td>492</td>
<td>3.80</td>
<td>0.106</td>
<td>85.6</td>
<td>0.70</td>
</tr>
<tr>
<td>NW3</td>
<td>NW, NP, CF, PP</td>
<td>136</td>
<td>1.13</td>
<td>0.212</td>
<td>86.6</td>
<td>2.30</td>
</tr>
<tr>
<td>NW4</td>
<td>NW, NP, STF, PP/PET</td>
<td>228</td>
<td>2.21</td>
<td>0.075-0.104</td>
<td>88.5</td>
<td>1.35</td>
</tr>
<tr>
<td>NW5</td>
<td>NW, CF, HB, PP</td>
<td>262</td>
<td>0.58</td>
<td>0.075</td>
<td>50</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Notes: NW: nonwoven, NP: needle-punched, HB: heat-bonded, STF: staple fiber, CF: continuous filament, PP: polypropylene, PET: polyester. All properties are the manufacturer’s reported values based on the ASTM standards with the exception of the porosity values, which were determined using the method described by Wayne and Koerner (1993). The lower bound for the AOS values is reported based on a personal communication with the manufacturers.
three-dimensional structure of nonwoven geotextiles presents difficulties in capturing pore structures in contrast to more two-dimensional structure of woven geotextiles which can be captured from two-dimensional images. Planar and cross-sectional thin-sections are necessary to provide detailed three-dimensional information. The thin sectioning process involved planar sections as well as sections normal to the plane of the geotextile, following the procedures generally used for preparing thin sections of soil and rock. This required a series of steps: epoxy-resin impregnation, cutting, grinding, lapping and polishing. Pore structure images of nonwoven geotextiles were captured using an optical light microscope having a digital camera attached to the microscope, which sent 8-bit per pixel digital luminance images to the computer. The images were filtered and restored using the mathematical morphology algorithms. Aydilek et al. (2002) provides details of the specimen preparation, image capturing and analysis techniques.

3.1 **Constriction Size Distribution**

*Methodology:* A method similar to the one developed for 2D wovens was applied to the cross-sectional images of nonwovens, to calculate pore opening sizes. Pore channels in ageotextile are nonuniform across depth (thickness), and distribution of minimum pore size across pore channels is of primary interest for filtration. This minimum size is generally referred to as constriction size, and also corresponds to the pore opening size determined in some physical tests, such as the bubble point method. Based on the principle of stereology, Serra (1982) showed that spatial information about the 3D structure of a material could be estimated from limited number of two-dimensional images of sections cut parallel. Nevertheless, the sections should be uniformly distributed, and the objects of interest in each section should not have any preferred orientation (Kuo and Frost 1996). Masad et al. (2002) used the approach to estimate the volume of images from their area fractions. Therefore, using cross-sectional images is a reasonable way of determining the constriction sizes, since no specific directional structure of fiber orientations was observed in the horizontal slices uniformly extracted from cross-sectional images.

However, a random pore structure exists in the nonwoven geotextiles and to simulate the random distribution of pores and thus to estimate constriction sizes, a Markov chain process was used (Kijima 1997). Markov chain process can be used for modeling pore structure, since the size of a pore opening in a pore channel is generally dependent on the
size of its underlying pore opening. The pore opening sizes in a cross-sectional image were divided into 20 groups, each approximated by a different size. Therefore, each state of the Markov chain referred to one particular pore opening size group. Initial analyses indicated that this choice for the number of states was sufficient for the sensitivity of the model. Specifying a discrete-time Markov chain requires the definition of a set of states and its corresponding transition probability matrix. In order to define the transition probabilities, correlation structures of 20 different pore classes (confrontations) identified in the horizontal slices of cross-sectional images were investigated as a function of slice displacement. The statistical relationship between each pair of pore opening sizes, i.e., the probability of finding a pore opening size $O_x$ under a pore opening size $O_y$, was then identified to form the transition probability matrix.

The paths of the random process defined by the Markov chain model was used to construct pore channel structures. Therefore, in order to construct a random pore channel structure, the evolution of this Markov chain needs to be simulated. The first step of this simulation was the generation of an initial state from which the Markov chain will start its evolution. Since the Markov chain used to model the random pore channels was assumed to be in its steady-state across the entire simulated geotextile thickness, the generation of an initial state was performed in a manner consistent with the stationary distribution of the chain. Considering the use of 20-state Markov chain in the model, the stationary distribution vector $\pi$ and cumulative sum vector $\Pi$ can be written as:

$$\pi = [\pi_1 \pi_2 \ldots \pi_{20}]$$  \hspace{1cm} (1)

$$\Pi = [\Pi_1 \Pi_2 \ldots \Pi_{20}]$$  \hspace{1cm} (2)

where

$$\Pi_i = \sum_{j=1}^{i} \pi_j , \hspace{0.5cm} i = 1, \ldots, 20$$  \hspace{1cm} (3)

The elements of $\Pi$ were interpreted as the right-hand side boundaries of 20 neighboring half-closed (left-closed and right-open) intervals, which partitioned the half-closed interval $[0,1)$ as follows:
[0, \pi_1) \cup [\pi_1, \pi_1 + \pi_2) \cup [\pi_1 + \pi_2, \pi_1 + \pi_2 + \pi_3) \cup \ldots \cup \left[ \sum_{i=1}^{19} \pi_i, \sum_{i=1}^{20} \pi_i \right) = [0, 1) \quad (4)

Note that the length of interval \(i (i = 1, 2, \ldots, 20)\) is \(\pi_i\). Assuming a continuous random variable is uniformly distributed in the interval \([0, 1)\), i.e., \(u \sim \text{uniform}[0, 1)\), the probability of \(u\) assuming a value in any one of the above specified 20 intervals is simply given by the length of that particular interval due to the definition of a continuous uniform distribution.

Therefore, in order to choose one of the 20 possible states of the Markov chain consistent with the probability measure specified by its stationary distribution vector \(\pi\), the generated random variable \(u \sim \text{uniform}[0, 1)\) was placed into one of the 20 intervals. The interval in which \(u\) was located was determined by comparing \(u\) against the elements of the cumulative sum vector, \(\Pi\). The value of \(i\) for which the following inequality was satisfied gave the interval and therefore the state searched for:

\[
\Pi_{(i-1)} \leq u < \Pi_i; \quad i=1,2,\ldots,20, \quad (\Pi_0 = 0) \quad (5)
\]

The procedure stated above for choosing an event is defined for the initial state of the Markov chain. In the second step, the same procedure was also employed for performing the state transitions of the Markov chain using the probability measures specified by the rows of the transition probability matrix \(P\) on a per state basis. More precisely, at any instant during its evolution, the current state of a discrete Markov chain uniquely specified a row of its transition probability matrix. The process of generating a random number \(u \sim \text{uniform}[0, 1)\), and comparing it with the elements of the cumulative sum vector derived from the appropriate row of the transition probability matrix (corresponding to the current state) in order to generate the next state was continued until the desired number of state transitions was reached. In the current study, this number was equal to the number of slices in the cross-sectional image of a geotextile. The probabilistic pore opening sizes were then put in sequence in the order they were generated, in order to construct the random pore channel. Figure 1 shows sample images of the random pore channel structures generated using the Markov chain model described. The constriction sizes of all channels, i.e., the smallest pore opening diameter in the channel, were determined and their distributions were then plotted. This distribution will be referred to as the constriction size distribution (CSD) herein.
**Results:** Constriction size distributions of five geotextiles were determined using a new algorithm based on probabilistic methods and image processing operations (CONS). Many of the previous image-based methods attempted to define pore opening sizes using planar images only. True constriction sizes are different than the size determined by this approach because the minimum size in a pore channel is not necessarily located on the surface of a geotextile. To demonstrate this phenomenon, the PSDs based on planar images were compared with the CSDs. Figure 2 provides this comparison for two geotextiles. The characteristic constriction size $C_{95}$ is compared with the $O_{95}$ determined from planar images, bubble point tests and dry sieving tests in Table 4.

The CONS-based $C_{95}$ sizes are slightly smaller than, but yet comparable to, the bubble point test values of Bhatia et al. (1996). On the other hand, dry sieving tests performed by Bhatia et al. (1996) and the manufacturers overpredicted the $O_{95}$ values. This is consistent with the previous observations that dry sieving test has potential problems in determining constriction sizes in a nonwoven geotextile. Almost in all cases, the CONS-based $C_{95}$ constriction sizes are smaller than the ones determined from the planar images. Giroud (1996) proposed a theoretical equation for calculating the constriction size of nonwoven geotextiles. The equation is based on the porosity, thickness, and fiber diameter of a geotextile. Table 4 compares the CONS-based $C_{95}$ constriction sizes with those calculated by using the Giroud (1996) method. Considering the few available data points, the values are
Table 4: Characteristic pore opening or constriction sizes of various nonwoven geotextiles determined by using different methods

<table>
<thead>
<tr>
<th>Geotextile</th>
<th>$AOS$ (mm)</th>
<th>$C_{95}$ CONS (mm)</th>
<th>$O_{95}$ Dry sieving (mm)</th>
<th>$C_{95}$ Bubble point (mm)</th>
<th>$O_{95}$ Planar images (mm)</th>
<th>$C_{95}$ Giroud (1996) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW1</td>
<td>0.15</td>
<td>0.087</td>
<td>0.15</td>
<td>NA</td>
<td>0.087</td>
<td>0.096</td>
</tr>
<tr>
<td>NW2</td>
<td>0.106</td>
<td>0.078</td>
<td>0.1</td>
<td>0.08</td>
<td>0.1</td>
<td>0.063</td>
</tr>
<tr>
<td>NW3</td>
<td>0.212</td>
<td>0.091</td>
<td>0.212</td>
<td>0.095</td>
<td>0.126</td>
<td>0.103</td>
</tr>
<tr>
<td>NW4</td>
<td>0.075-0.104</td>
<td>0.065</td>
<td>0.065</td>
<td>0.072</td>
<td>0.066</td>
<td>0.049</td>
</tr>
<tr>
<td>NW5</td>
<td>0.075</td>
<td>0.036</td>
<td>0.063</td>
<td>0.046</td>
<td>0.043</td>
<td>0.0356</td>
</tr>
</tbody>
</table>
comparable which gives further substantiation to the accuracy of the image-based probabilistic approach.

4. CONCLUSIONS

A number of image-based methods have been developed to determine the porosity of woven geotextiles and pore opening size distribution of woven and nonwoven geotextiles. Current design procedures generally use $AOS (O_{95})$ using the dry sieving test; however, potential problems exist with this test, particularly in determining constriction sizes. A direct test method such as image analysis coupled with probabilistic methods for nonwovens was carried out in this study. The method used various image algorithms, probabilistic Markov chain processes, and provided a complete pore opening size distribution (PSD) and constriction size distribution (CSD) for geotextiles. A characteristic pore opening size, $O_{95}$ or $C_{95}$, was determined using the information provided by these PSDs or CSDs. The determined sizes were checked against the manufacturer’s reported $AOS$ values as well as values of $O_{95}$ based on laboratory tests.

The results indicate that image analysis method can be effectively used to determine POA and PSD of woven geotextiles. An image-based probabilistic technique can model the pore structure of nonwoven geotextiles, even though future research is needed to develop a less tedious specimen preparation method. Among the previously developed methodologies, Giroud (1996) and bubble-point test methods are the best in terms of accurately measuring the constriction sizes.

5. REFERENCES


