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MODELING WATER PERMEABILITY IN NEEDLE-PUNCHED NONWOVENS USING FINITE ELEMENT ANALYSIS

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Abstract:

This paper presents the results from a study on the water permeability behaviour of nonwovens produced from the hemp fibres. Three different types of needle-punched nonwovens are produced by varying the feed rate of fibres during the needle-punching process. The pore size in the nonwovens is measured by liquid extrusion porometry. Water permeability is measured by the water permeability tester. A finite element analysis is employed to predict the flow velocity through the nonwovens. A good correlation is achieved between the average velocity data obtained from water permeability test and theoretical prediction based on finite element analysis.

1. Introduction

The separation of solid from liquid or gases by fibrous media is an essential part of many industrial applications, contributing to the purity of the product, saving in energy, improvement in process efficiency, recovery of precious materials and general improvement in pollution control. Nonwovens are the major media for gas and liquid filtration and drainage applications, contribute to almost 70% of the above areas. Needle-punching is a mechanical bonding method of producing nonwoven web structure with distinct pore structures which make them suitable for application in filtration and drainage. Needle-punched nonwovens are widely used in above applications in comparison to their woven counterpart because of low cost of production and product can be manufactured in a very short time. Natural fibre based nonwovens offer further advantages due to their renewable nature, excellent biodegradability, and the ease of disposal without adversely affecting the environment.

The water flow through the nonwovens (or permeability) plays important role in many application areas like medical and hygiene, geotextiles, composites etc. For example in nonwoven geotextiles, how ease the flow pass through it will determine the performance characteristics. Ideally it should allow smooth flow of water, so that unnecessary pressure build-up can be avoided. Therefore, the pore characteristics namely, pore size and its distribution, mainly influence water permeability behavior. Also the permeability characteristics in nonwovens vary from region to region due to variation in the orientation of the fibres and processing parameters [1, 2]. When the feed rate of fibres is varied during needle-punching process, keeping needle depth of penetration constant, it may result in different structural arrangement of fibres in nonwovens and subsequently affecting the resulting pore size. As there is lack a of research work reported on this important aspect, first time we attempt to link changes in pore size with the measured water permeability values of nonwovens. This present work focus on the liquid flow through the hemp fibre based nonwovens. This flow is often assumed to be laminar [3] and laminar flow through anisotropic nonwovens can be described by the Darcy's law [4, 5] as:

$v = -\frac{k}{\eta}\frac{dp}{dx}$, where v is the volume flow rate of the fluid in a unit area (m/s); η is the liquid viscosity (Pa.s); dp is the difference in hydraulic pressure (Pa); dx is the conduit distance (m) and k is the specific permeability (m^2). In practical applications of Darcy's law, it is preferable to use the permeability coefficient, K, which is also known as Darcy's coefficient. The permeability coefficient, K, is defined in Darcy's law as: $v = K \times i$, where v is the volume flow rate of the fluid in a unit area (m/s); i is the hydraulic gradient (m/m), and K is the permeability coefficient (m/s). The above coefficient (K) normally represents the permeability of the porous medium.

Mathematical modeling and computer aided simulations are important tools in maximizing efficiency of the process, as theoretical understanding of the process is very important so that specific parameters can be fine tuned according to requirement in future processing. The Finite Element Analysis (FEA) is used for simulating a wide range of technical and modeling problems. There is a lack of comprehensive research work in modeling aspects and the subject is still under development, so new studies and approaches need to be carried out in order to understanding the flow through the nonwoven fibrous assemblies. FEA was preformed by commercially available software Comsol Multiphysics [6]. Different types of fibre orientations were considered in the FEA of nonwovens and the flow velocities through it were computed. The pore size is measured experimentally by liquid extrusion poromerty. The water permeability is measured experimentally by Eco Mess liquid permeability tester. The water flow velocity data obtained from the instrument and FEA are compared.

2. Experimental

2.1 Sample Preparation

Hemp fibres used for production of nonwovens were first cottonised on a Temfa Cottonizing line by passing it twice through a coarse opener and then subjecting it to the action of a fine opener to improve fibre fineness and to reduce fibre length, so as to obtain suitable fibres for carding. The length and fineness of fibres utilized for sample preparation are 66 mm and 12.5 dtex, respectively. The average measured diameter of the fibres is found to be 33 μm. Needle-punched nonwovens are produced by subjecting the fibres to carding, then orienting the carded web in the cross direction by using a cross lapper, subsequently subjecting it to the action of barbed needles in needle-punching machine. The following processing parameters during needle-punching were used for producing the nonwovens: feeding speed, 0.4, 0.6, 0.8 m/min; depth of needle penetration, 8 mm; stroke frequency, 250/min; output speed, 4 m/min. The nominal area density of the nonwovens were 180, 230, 260 g/m^2 respectively depending on the different feeding speed used in this work. The nonwovens are conditioned at a standard temperature and relative humidity of 20±2 °C and 65±2 % respectively, prior to testing.

2.2 Measurement of Pore Size

The liquid extrusion porometry is often used to characterize the pore structure of nonwovens [7]. In this technique, a wetting liquid with known surface tension of 15.9 dynes/cm fills the pores spontaneously and it is then removed by pressurized non-reacting gas (air) to give pore size and its distribution. Three kinds of pores may be present in nonwoven fabrics, namely, closed pores, through pores, and blind pores. Closed pores are not accessible and therefore do not allow passage of liquid and air. The blind pores terminate inside the material and do not permit the fluid flow. Through pores are open and allow the flow through the medium and they are important for filtration and drainage applications [8]. The important pore structure characteristics of nonwoven filter media are the most constricted through pore diameter (smallest detected pore diameter), the largest pore diameter (bubble point pore diameter), and mean pore diameter (mean flow pore diameter). Mean flow pore diameter is the diameter of the majority of the pores. It is defined as half of the flow through the pores having diameter greater than mean flow pore diameter and other half of the flow is through the pores having diameter smaller than mean flow pore diameter [8-10].

2.3 Measurement of Fibre Orientation

The fibre orientation is measured by using image analysis programme 'analySIS' version 3.2. The relative frequency of fibres for 10° orientation interval with respect to cross direction is computed.

2.4 Measurement of Water Permeability

The water permeability test is carried out by the Permeameter GE-TE-FLOW-K according to the principle of falling hydraulic head method according to EN ISO 11058 standard [11]. In this method, a column of water is introduced normal to the fabric plane to induce a laminar flow through its structure and both the water flow rate and the pressure change against time are taken to measure the permeability. The test is carried out without adding any weight to the sample with a diameter of 67.8 mm. The temperature of the water is maintained at 20°C.

3. Finite Element Analysis

The basic idea of FEA is to build a complex model with simple elements. The complex structure is divided into a number of manageable elements. The system is then described by the physical properties of each element. These elements are connected to their neighbors by nodes. This forms an approximate system of equations for the entire structure. In the next step the system of equations is solved involving unknown quantities at the nodes. After the solution, the desired quantities at selected elements can be calculated. For the present work, *velocity inlet* and *velocity* *outlet* boundary conditions with *no slip* at wall are taken into account and following assumptions are considered:

a) Fibres are assumed as long circular cylinders
b) Fibre crimp is neglected
c) Thickness of fabric is very small compared to other two dimensions.

A modeling approach based on assuming a single fibre as cylindrical rod is adopted in this study. The representation of fibres by a single element allows a significant reduction in computation time. The behavior of single fibres can be combined and mapped onto the elements representing a bundle of fibres and ultimately representing these bundles of fibres in the nonwoven fabrics. The cylindrical rod element is assumed as a straight bar, loaded at its ends with uniform properties from end to end. This type of element has two degrees of freedom at each node, i.e. displacements in X- and Y- directions. Suitable equations are used at node points to describe the non-linear behavior of the fibres. In the nonwoven web structures, fibres are oriented in different directions, i.e. some fibres are in the machine direction, some fibres are in the cross-machine direction and other fibres do not have any preferential orientations or randomly oriented. In the modeling work, these three different fibre orientations are taken into account. Since there is variation in the diameter of the natural fibres, these variations are also taken into account. The flow of incompressible non-Newtonian fluid through the pores of nonwovens can be solved by Navier-Stokes equation [12, 13] along with Darcy's law. The Navier-Stokes equation for fluid flow is given by:

$$\rho \frac{\partial u}{\partial t} - \nabla .[\eta \ (\nabla u + (\nabla u)^T)] + \rho (u.\Delta) u + \Delta p = F$$

$$\nabla . u = 0$$

where, η is the viscosity, ρ is the density, u is the velocity, p is the pressure, F is the force. The first equation is the momentum balance equation, and the second is the equation of continuity for incompressible fluids.

4. Results and Discussion

4.1 Orientation Distribution of Fibres in Nonwovens

A typical orientation distribution of fibres in the needle-punched nonwovens (sample S1 and S2; Table 1) is shown in Figure 1. The vertical dashed arrow line at 90° angle represents the machine direction, the cross direction being perpendicular to this. Lower frequency values in the machine direction indicate that fewer fibres are oriented in the machine direction and higher frequencies in the other direction indicate the majority of fibres are oriented in the cross direction, which is due to cross-lapping process of laying the web. Similar trend is also found for the other sample (S3) and is not shown here.

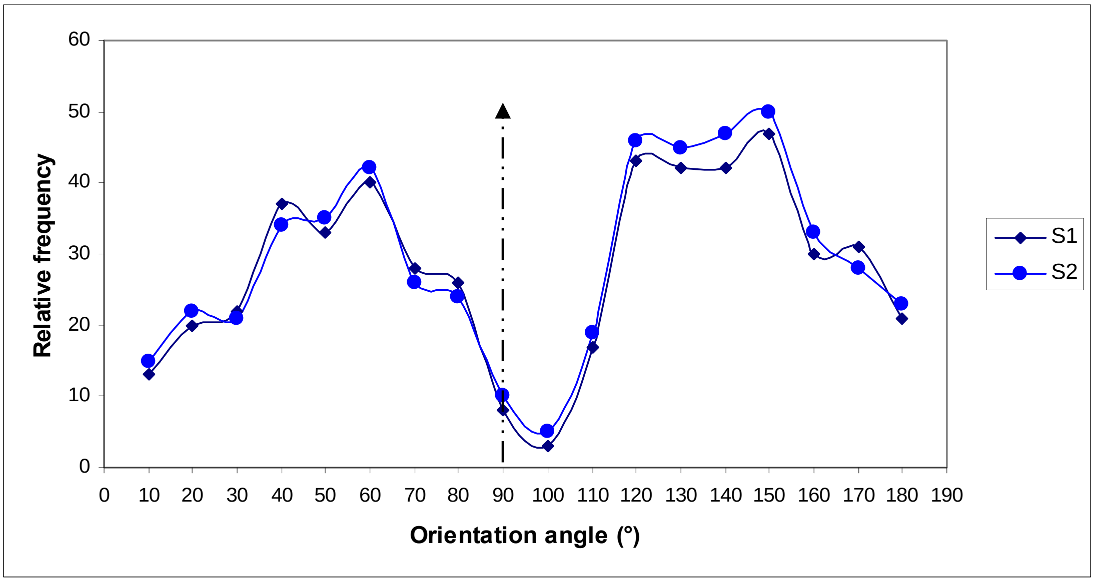


Figure 1. Distribution of fibres in needle-punched nonwovens.

4.2 Pore Size and Permeability Characteristics of Nonwovens

Various type of pore size obtained from liquid extrusion porometry is shown in Figure 2. There is decrease in smallest, maximum, and mean flow pore diameters, as feed rate of fibres increases during the needle-punching process. With the increase in feed rate, more number of fibres was feed to the needle action area. So the effectiveness of needle-punching through the thickness of web decreases as there is an increasing chance that some of the fibres may escape the needle action. As a result of this, there is less consolidation of the web and the web thickness increases. The nonwoven fabric produced with lowest feed rate is consequently an open structure and is of the lowest thickness in comparison with the one which is produced with higher feed rate, which is less open, and thickness of the fabric is the highest. The smallest and maximum detected pore diameter decreases with an increase in feed rate, as pores may be getting covered by the neighboring fibres. There is a 23% decrease in mean flow diameter as we increase feed rate from 0.4 m/min to 0.8 m/min, the diameter of which is normally a measure of the size of the majority of pores. This may be due to the fact that pores which are originally created by the random arrangement of fibres are getting covered by the excess fibres, which might escape the needling action and covering the pores.

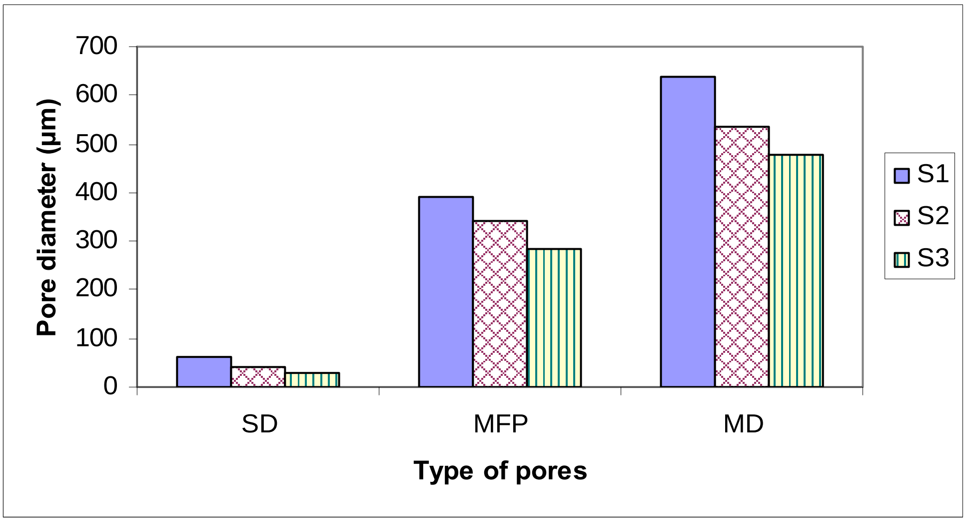


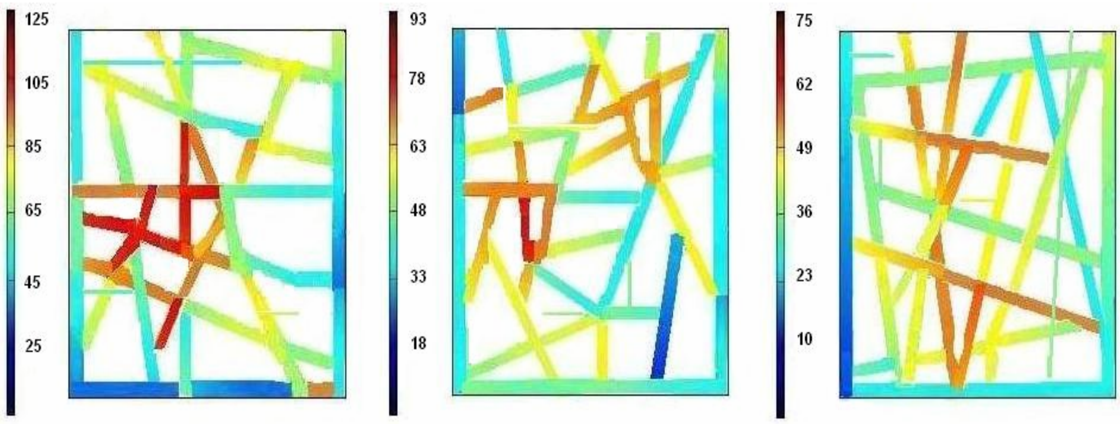
Figure 2. Various types of pores in needle-punched nonwovens.

Table 1 Thickness and permeability characteristics of needle-punched nonwovens.

Sample code	Thickness (mm)	Permeability K_{20} (m/s $\times 10^{-2}$)	**Velocity (mm/s)	+Velocity (mm/s)	R^2
*S1	1.9	1.05	105	87	0.85
S2	2.3	0.89	89	76	0.87
S3	2.7	0.78	78	67	0.84

*Feed rate (m/min): S1- 0.4; S2- 0.6; S3- 0.8; **Average velocity measured from water permeability tester; +Average velocity obtained from FEA.

The water permeability characteristics of needle-punched nonwovens measured on a water permeability tester and corresponding average velocity values obtained from it and FEA are shown in Table 1. The water permeability decreases as the feed rate of fibres increases during the needle punching process. This may be due to variation in the pore characteristics of the three different nonwoven fabrics. The water passes more easily through S1, than S2 and S3 because it is the most open structure among the three. The pore characteristics play an important role in the water permeability behavior. The velocity values of water (mm/s) flowing through the needle-punched nonwovens obtained from a 2D FEA is shown in Figure 3. The water flow through the nonwovens is measured perpendicular to its plane. So the fibres which are assumed as circular cylinders in the nonwovens, when viewed from top, will look like a rectangular bar. Each color in Figure 3 represents a particular velocity value in mm/s, red being the highest and blue is the lowest. Each pore arises due to different arrangement of fibres, is represented by same or different colors of velocity values of liquid flowing through. The average velocity of water flowing through sample S1 is the highest followed by S2 and S3, due to variation in the pore size of the nonwovens which subsequently governs the permeability behavior. Different pore sizes can be observed from the three different samples as the feed rate of fibres increases during the needle punching process (Figure 3). The sample S1 consists of a majority of bigger pores, in comparison with samples S2 and S3, followed by medium and smaller pores. The sample S3 mainly consists of medium and smaller pores and sample S2 is in between of two samples. The average velocity values obtained from FEA is under evaluated. This may be due to the fact that when observing the nonwoven fabric from the top, some of the pores which are below the top layer may not get covered during this measurement, although the fabric thickness is very small. Another reason may be these pores have different configurations which may affect the results. Nevertheless, there is a good correlation between the average velocity values obtained from FEA and water permeability tester as shown in Table 1.



(a) (b) (c)

Figure 3. Velocity values of water (mm/s) through the needle-punched nonwovens: (a) S1; (b) S2; and (c) S3.

5. Conclusions

The water permeability behavior of needle-punched nonwovens produced by varying the processing parameters during needle punching process is investigated. There is a trend of lower water permeability values with increasing feeding rate of fibres during needle punching. A theoretical prediction of water flowing through the nonwovens is carried by the finite element analysis. A good correlation is achieved between the average velocity data obtained from water permeability test and theoretical prediction based on finite element analysis.

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