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Anisotropic mechanical behavior of thermally bonded nonwoven fabric

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Anisotropic properties of thermally bonded nonwoven fabric (polypropylene) have been investigated. Firstly, the orientation distribution function of fibre is obtained by applying Hough transform technique to scanning electron microscopy of nonwoven fabric. Secondly, the influence of specimen width on mechanical behavior of nonwoven fabric has been studied, and the relationships between tensile strength of nonwoven fabric and specimen width are acquired by applying nonlinear fitting. Finally, the anisotropic creep behavior of nonwoven is investigated at different stress levels, different directions of nonwoven and different durations by applying nonlinear fitting, and the empirical model for calculating creep elongation is deduced. The results show that the tensile and creep behaviors of nonwoven fabric are influenced significantly by the fibre distribution. The creep elongation of nonwoven fabric is proportional to the level of loading and time. The creep elongation of nonwoven fabrics follows exponential relationships with time and this is true for all the directions of load and for all the levels of loading.

Keywords: Anisotropic property, Orientation distribution function, Polypropylene, Thermally bonded nonwoven fabric

Nonwoven fabrics are most widely used in applications ranging from baby diapers to high performance geotextile. In contrast to woven fabric and knitted fabric, the random and discontinuous microstructure is the most characteristic features of nonwoven. Due to its discontinuous and non-uniform microstructure, the specimen structure plays an important role on tensile behavior [1-5], and different sizes of specimen may demonstrate different types of material behavior. Mechanical properties such as tensile and creep behavior of thermally bonded nonwoven fabrics are of considerable interest for their satisfactory performance. Due to the complex structure of nonwoven fabrics, some researchers have made considerable efforts to understand the mechanical behavior of nonwoven. The mechanical properties such as tensile, shear, bending and compression of thermally bonded nonwoven have been studied [6], and the relationship between the geometrical and the tensile properties of thermally bonded nonwovens is obtained. Debnath and Madhusoothanan [7, 8] investigated the compression creep behavior of needle-punched nonwoven with different constituent fibres based on experiment and analyzed the influences of the fabric weight, fibre cross-sectional shape, needle density and interaction effects of process parameters on compression creep.

Gautier *et al*.[9] investigated the anisotropic mechanical behavior of nonwoven geotextile by using uniaxial tensile test. Rawal *et al*.[10] studied the mechanical behavior of thermally bonded nonwoven fabric by considering the effect of fibre orientation, and obtained the relationship between the geometrical and the tensile properties. Kothari and Patel [11] investigated the stress-strain behavior of nonwoven fabric and the constituent fibres of these fabrics and obtained the relationship between tensile properties of fibres and nonwoven fabrics using the structural parameters of nonwoven fabrics. The stress-strain behavior of fabric could be predicted using the fibre data and structural parameters of nonwoven fabrics. Hou *et al*.[12] investigated the effects of random and discontinuous microstructure of nonwoven on their mechanical properties by incorporating random discontinuous structures, representing micro-structures of a real nonwoven material. Hou *et al*.[13] analyzed the influence of specimen size and shape factor (the ratio of the specimen's length to its width) on mechanical property of low density thermally bonded nonwoven by means of uniaxial tensile tests. Rawal *et al*.[14] investigated the tensile properties of hybrid needle-punched nonwoven geotextiles by means of wide-width tensile test (ASTM D4595) to evaluate its axi-symmetric tensile strength by applying verified model.

Mueller and Kochmann[15] used a FEA approach to simulate the tensile behavior of thermally bonded nonwovens by modeling the single fibre as a spar, and the bond points were modeled using solid elements. Their work successfully involved a nonlinear behavior and described plastic deformation of the material. But one of the disadvantages of their approach is that the model cannot incorporate

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information of the ODF since a real random microstructure of the fibrous network is represented with a periodic structure.

Therefore, it is found necessary to study the influence of specimen width on the tensile behavior of nonwoven. When constant stress is subjected to nonwoven material, there will be an increasing strain on the material as time goes on. This phenomenon is called creep. When the amount of loading is increased the amount of creep will be increased, which has effect on fatigue of thermally bonded nonwoven fabric. In order to improve the creep behavior of thermally bonded nonwoven fabric, the anisotropic creep behavior, i.e. the stress and angle with the machine direction (MD) on creep is investigated. Kothari and Patel[16] developed a mechanical model to predict the creep behavior of nonwoven fabric using the fibre creep data and the structural parameters of the fabric. Debnath *et al*.[17] investigated the anisotropic behavior of needle-punched parallel laid jute nonwoven. Das *et al*. [18] studied the anisotropic creep behavior of needle-punched nonwoven fabric, and considered that the creep of nonwoven depends on the fibre orientation and level of load. The same method has been implemented in this study to investigate the anisotropic creep behavior of thermally bonded nonwoven fabric. In this study, the orientation distribution function (ODF) of fibre is obtained by applying Hough transform to scanning electron microscopy (SEM) of nonwoven fabric. The anisotropic tensile and creep behaviors of thermally bonded nonwoven fabric are experimentally investigated using wide-width strip tensile and creep test. The influence of specimen width of thermally bonded fabric on tensile properties is also studied. The influences of different levels of load and different angle in the machine direction (MD) on creep behavior of thermally bonded nonwoven fabric are analyzed and the empirical equations for calculating creep elongations at different conditions are obtained by applying nonlinear fitting.

Experimental

Thermally bonded nonwovens, manufactured by Dezhou Hualong Chemical Fibre Co., Ltd, using polypropylene fibres with linear density of 1.56dtex were used for the study. The carded polypropylene fibres were laid down randomly on a flat surface, and then thermally bonded by hot air (temperature 160°C, pressure 40 psi) producing nonwoven fabric with 150g/m^2 area density.

Some nonwoven fabrics used in geotextiles have a tendency to neck down (contract) under a force in the gauge length area. In this paper the width of specimen is 100mm, the greater width applied over here minimizes the contraction effect. The SEM images of the nonwoven fabric are shown in Fig. 1.

Tensile Testing

The tensile properties of nonwoven were tested using wide-width strip tensile test using Instron Universal Testing Machine under standard laboratory condition (20^{o}C, 65% RH). Meanwhile, the specimens with six different widths were tested for investigating effect of width on the behavior of nonwoven fabric.

Nonwoven tensile tests were carried out along the machine direction (MD), cross direction (CD) and 45° using 10 nonwoven specimens (200mm×100mm) at a gauge of 100mm clamp distance and a speed of 50 mm/min.

Creep Testing

The conditions of creep test on MD direction were kept the same to that of tensile testing. Firstly, the creep behaviors at varying load and at particular angle were investigated. The loading of nonwoven specimens was done with different levels of constant loads, i.e. 30%, 45% and 60% of tensile strength

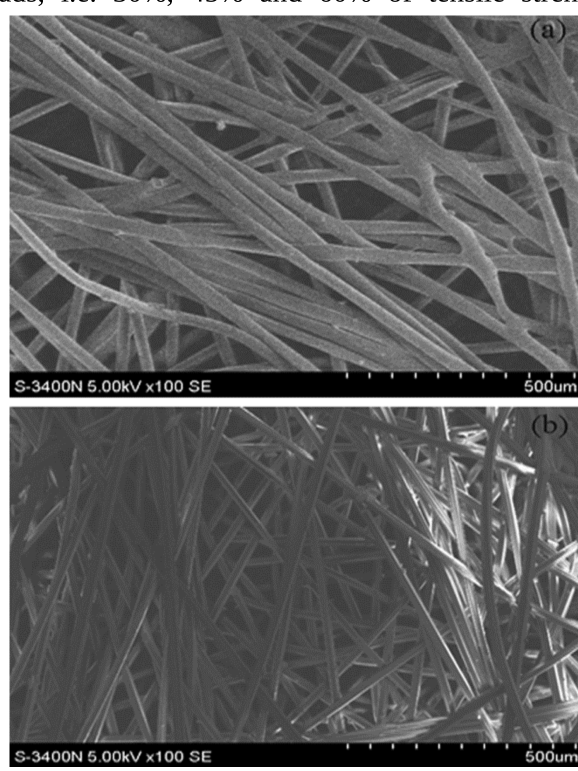

Fig. 1 — SEM images of thermally bonded nonwoven fabric [(a) thermally surface bonded and (b) thermally point bonded]

along the MD direction. For thermally surface bonded fabric, the creep stresses were kept 3.57MPa, 4.17MPa and 4.76MPa respectively. Meanwhile, the creep stresses were kept 5.36MPa, 5.95MPa and 6.55MPa as for thermally point bonded fabrics. Secondly, the creep behaviors at varying direction of loading under constant load were studied at different angles in the machine direction (MD) of fabrics, i.e. 0°, 45° and 90°. The creep stresses were kept 7.11MPa and 5.8MPa for thermally surface bonded and thermally point bonded respectively.

Results and Discussion

Effect of Specimen Width

The tensile results of thermally bonded nonwoven fabric along the different directions are shown in Table 1.

The results show that the tensile strength and tensile elongation have remarkable anisotropic in different directions as far as thermally point bonded fabric is concerned, which is attributed to the random distribution of fibre and regular bonding point[19]. However, the thermally surface bonded nonwoven has approximate isotropy in MD, CD and 45° since the differences in tensile strength and elongation are less than 0.4 MPa and 1.18% in different directions.

The orientation distribution function (ODF) of fibre was obtained by applying Hough transform to scanning electron microscopy of nonwoven fabric (Fig. 2).

Figure 2 shows that the fibres of thermally point bonded fabric have random distribution, the frequency of fibre distribution in MD, 45° and CD are 7.4%, 4.5% and 4.3% respectively. As far as thermally surface bonded nonwoven fabric is concerned, the frequency of fibre distribution in MD is 1.07 and 1.06 times to those in 45° and CD directions respectively. As shown in Table 1, the tensile strength in MD is 1.02 and 1.04 times to those in 45° and CD directions respectively. It can be concluded that the tensile strength of nonwoven fabric is mainly influenced by the fibre distribution.

Table 1 — Tensile behavior of thermally bonded nonwoven fabric

Property	Thermally point bonded			Thermally surface bonded		
	MD	45°	CD	MD	45°	CD
Tensile strength MPa	9.43	4.69	4.26	9.95	9.71	9.55
Tensile elongation, %	10.71	5.72	9.37	24.16	24.23	25.34

Due to the non-uniform microstructure and material properties of the fabric, different size of specimens may indicate different types of material behavior. The tensile results with different widths are shown in Table 2. The relationship between tensile strength and specimen width is shown in Table 3. As shown in Table 3, the tensile strength has exponential and linear relationship with width of specimen for thermally point bonded nonwoven fabric and surface bonded nonwoven fabric respectively.

Creep Behavior at Varying Load at Constant Angle

The creep behaviors of thermally bonded nonwoven fabric at different levels of loading are

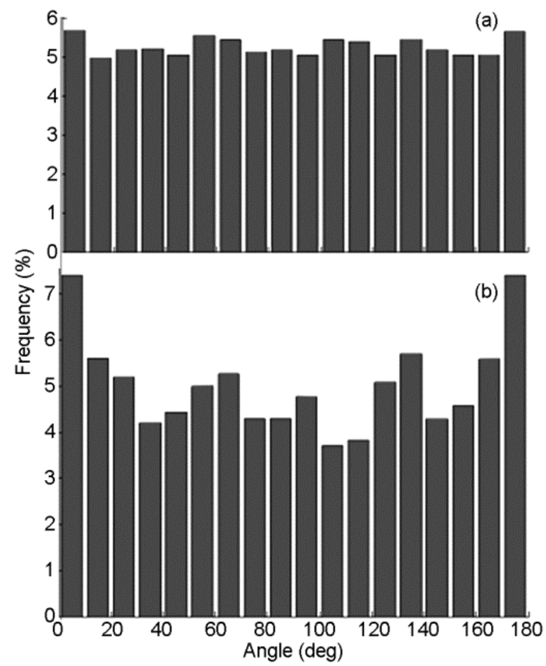

Fig. 2 — ODF of thermally bonded nonwoven fabric [(a) thermally surface bonded and (b) thermally point bonded]

Table 2 — Tensile behavior of thermally bonded nonwoven fabric under different widths

Specimen width, mm	Thermally point bonded		Thermally surface bonded	
	Tensile strength, MPa	Elongation %	Tensile strength, MPa	Elongation %
25	9.26	10.52	9.52	23.37
50	10.06	10.71	9.95	24.16
75	10.64	11.84	10.85	24.94
100	10.68	11.39	11.57	24.21
125	10.96	11.70	11.60	23.82
150	10.98	11.71	12.82	24.49

shown in Fig. 3. The amount of creep increases with increasing the loading level applied to the fabric.

It can be concluded that the creep elongation is proportional to the level of loading and time. The initial extension instantaneously increases and finally stabilizes at a limiting extension value. With the increase in stress the creep increases, since the higher load would definitely increase the fibre-to-fibre slippage and also execute higher force on the individual fibres which results in higher creep elongation.

Creep Behavior at Varying Direction of Loading at Constant Load

The creep behaviors of thermally bonded nonwoven fabric at varying direction of loading but at a constant load are shown in Fig. 4. The curves follow similar trend with a difference in instantaneous extension. The creep extension of nonwoven fabric depends on the fibre distribution and level of loading.

The initial elongation in machine direction is smaller than that in 45° direction and cross direction, since the fibre distribution at machine direction is larger than that in other directions. As shown in Fig. 2, the frequency of fibre distribution in MD is 1.64 and 1.72 times to those in 45° and CD directions

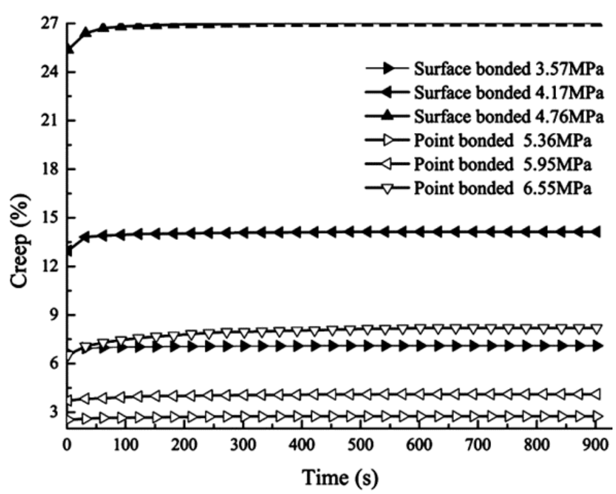

Fig. 3 — Creep behaviors of thermally bonded nonwoven fabric at different levels of loads

Table 3 — Relationship between tensile strength and specimen width

Specimen	Relationship	R^2
Thermally point bonded	$y = 11.06 - 3.38 \times 0.98^x$	0.982
Thermally surface bonded	$y = 8.83 + 0.025x$	0.953

respectively. The maximum extension is observed in a direction with minimum number of fibres and the minimum creep extension is obtained for the sample having maximum number of fibres. Thus, the creep extension is found to be influenced by the fibre distribution.

The relationship between creep elongation and time at different stress and different angles in machine direction of thermally bonded nonwoven fabric is obtained by applying nonlinear fitting and the empirical model for calculating creep elongation is deduced (Table 4). The results show that the creep of thermally bonded nonwoven fabrics follows exponential relationships with time and this is true for all the directions of loading and for all the levels of loading.

The findings of above study show that the tensile and creep behaviors of nonwoven fabric are influenced significantly by the fibre distribution, which can be obtained by applying Hough transform to scanning electron microscopy of nonwoven fabric. And the relationship between tensile strength and specimen width has exponential and linear relationship with width of specimen for thermally point bonded nonwoven fabric and surface bonded nonwoven fabric respectively due to the non-uniform microstructure and material properties of the fabric

The creep elongation of nonwoven fabric is found proportional to the level of loading and time. The creep elongation of nonwoven fabrics follows exponential relationships with time at different stress values and different angles in machine direction of nonwoven fabric.

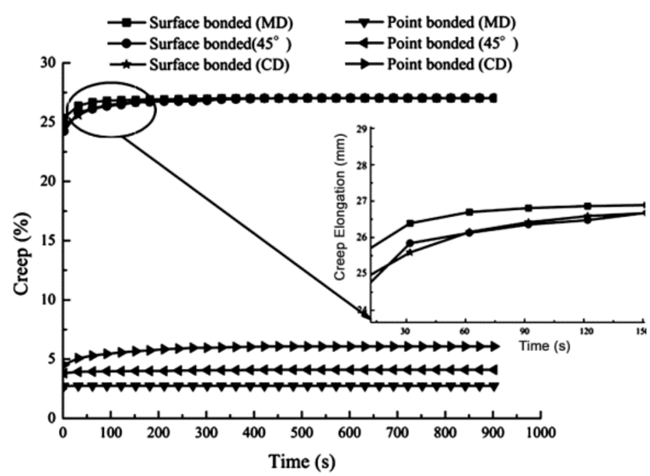

Fig. 4 — Anisotropic creep behavior of thermally bonded nonwoven fabric at different directions

Table 4 — Relationship between creep elongation of nonwoven and time

Fabric	Direction and level of loading		Relationship	R^2
Thermally surface bonded	Levels of loading	3.57 MPa	$y = 7.10 - 0.18e^{-x/134.07} - 0.33e^{-x/9.02}$	0.998
		4.17 MPa	$y = 14.14 - 1.01e^{-x/11.01} - 0.33e^{-x/165.26}$	0.999
		4.76 MPa	$y = 27.05 - 1.40e^{-x/21.97} - 0.40e^{-x/151.48}$	0.999
	Directions of load	MD	$y = 27.05 - 1.40e^{-x/21.97} - 0.40e^{-x/151.48}$	0.999
		45°	$y = 27.04 - 1.36e^{-x/136.41} - 1.73e^{-x/12.54}$	0.997
		CD	$y = 27.04 - 1.40e^{-x/36.59} - 1.07e^{-x/128.97}$	0.999
Thermally point bonded	Levels of loading	5.36MPa	$y = 2.74 - 0.03e^{-x/16.23} - 0.19e^{-x/123.25}$	0.991
		5.95MPa	$y = 4.10 - 0.14e^{-x/1.88} - 0.35e^{-x/154.16}$	0.994
		6.55MPa	$y = 8.21 - 1.23e^{-x/188.54} - 0.51e^{-x/20.48}$	0.998
	Directions of load	MD	$y = 7.06 - 1.27e^{-x/2.47} - 0.68e^{-x/151.35}$	0.995
		45°	$y = 4.10 - 0.22e^{-x/1.87} - 0.21e^{-x/207.76}$	0.979
		CD	$y = 6.08 - 0.68e^{-x/2.16} - 1.30e^{-x/128.83}$	0.998

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References

1 Adanur S & Liao T Y, *Text Res J*, 69(1999) 816.
2 Ridruejo A, Gonzalez C & Llorca J, *Int J Solids Struct*, 48(2011)153.
3 Kim H S, Pourdeyhimi B, Desai P & Abhiraman A S, *Text Res J*, 71(2001)965.
4 Demirci E, Acar M, Pourdeyhimi B & Silberschmidt V V, *Comp Mater Sci*, 52(2012)157.
5 Kim H S, *Fibre Polym*, 5(2004) 177.
6 Rawal A, Lomov S, Ngo T & Vankerrebrouck J, *Text Res J*, 77(2007) 417.
7 Debnath S & Madhusoothanan M, *J Text Inst*, 103(2012) 1328.
8 Debnath S & Madhusoothanan M, *Text Res J*, 82(2012) 2116.
9 Gautier K B, Kocher C W & Drean J Y, *Text Res J*, 77(2007) 20.
10 Rawal A, Priyadarshi A, Kumar N, Lomov S V & Verpoest I, *J Mater Sci*, 45(2010)6643.
11 Kothari V & Patel P, *Indian J Text Fibre Res*, 26(2001) 398.
12 Hou X N, Acar M & Silberschmidt V V, *Comp Mater Sci*, 50(2011) 1292.
13 Hou X N, Acar M & Silberschmidt V V, *J Eng Fibre Fabr*, 4(2009) 26.
14 Rawal A, Sayeed M M A, Saraswat H & Shah T, *Geotext Geomem*, 36(2013) 66.
15 Mueller D H & Kochmann M M, *Int Non J*, 13(2004)56.
16 Kothari V & Patel P, *Indian J Text Fibre Res*, 26(2001) 273.
17 Debnath C R, Roy A N, Ghosh S N & Mukhopadhyay B N, *Indian J Text Fibre Res*, 21(1996) 244.
18 Das A, Kothari V K, Kumar A & Mehta M S, *Fibre Polym*, 6(2005) 313.
19 Demirci E, Acar M, Pourdeyhimi B & Silberschmidt V V, *Comp Mater Sci*, 50(2011) 1286.