A Study on the Entanglement and High-Strength Mechanism of Spunlaced Nonwoven Fabric of Hydrophilic PET Fibers

Hong Wang, Jingjing Zhu, Xiangyu Jin, Haibo Wu

Donghua University, Songjiang District, Shanghai CHINA

Correspondence to:
Hong Wang email: wanghong@dhu.edu.cn

ABSTRACT
Spunlaced nonwoven fabrics have been widely used recently, but fundamental research on the spunlaced nonwoven process is relatively weak. It is inexplicit until now how fibers are entangled with each other during the hydroentangling process. In this paper, a pull-out experiment designed to study the entanglement properties of spunlaced nonwoven fabrics using common and hydrophilic PET fibers as objects is described. It was found that the broken fiber content can be used to represent the entanglement intensity of the spunlaced nonwoven fabrics. In addition, a formula was set up to calculate the tensile strength of the spunlaced nonwoven fabric based on its pull-out behavior.

Keywords: hydroentanglement, spunlaced, entanglement intensity, pull-out

Nonwoven fabrics are a distinct and important segment of the fabric manufacturing industry. Nonwovens are a sheet or web structure made by bonding or entangling fibers or filaments by mechanical, thermal or chemical methods [1]. Spunlaced nonwoven fabric, also known as hydroentangled nonwoven fabric, is made by using high-pressure water jets to entangle loose assemblies of fibers to impart strength to the final nonwoven fabric [2].

Structure-process-property relationships of the spunlaced nonwoven fabric process have been studied by many researchers, both theoretically and experimentally [3, 4]. Seyam et al [5] studied the influences of the spunlaced process on the properties of the resultant nonwoven fabrics. They found that hydroentangling energy has a significant effect on the mechanical performance of the spunlaced nonwoven fabric. Mao and Russell [6] investigated the structural changes of the fiber web and bonding process during the process, as well as the entanglement intensity. In this work, a formula is established to calculate the entanglement intensity of the spunlaced nonwoven fabric which is defined as the product of the number of fibers hit by the water jet and the deflection depth of each fiber segment in the Z-direction. But it is assumed that the energy applied to the web by the water jets is entirely used to entangle fibers.

Many studies show that the mechanical properties of spunlaced nonwoven fabrics are mainly determined by the mechanical properties of the fibers and the entanglement intensity of the spunlaced nonwoven fabrics [7, 8]. It is widely believed that the entanglement intensity is influenced by the spunlaced process and properties of fibers. But it is not very clear so far how fibers entangle with each other under the high-pressure water jets. Xiang and Kuznetsov [9] investigated the dynamics of the shape of a long flexible fiber subjected to a turbulent flow field caused by high speed water jets in the hydroentangling process by utilizing a rod–chain model. It was found that the straight fiber is curved as a result of the impact of the high speed water jets. But the influences of neighboring fibers and more fine turbulent structures on the shape of the fibers are not considered in the simulation.

In a previous paper, influences of surface properties of PET fibers on the mechanical properties of the resultant spunlaced nonwoven fabrics were studied [10]. It was found that spunlaced nonwoven fabrics with higher mechanical properties were obtained from PET fibers with lower initial modulus, better hydrophilic properties, and higher friction coefficient. It is explained that the mechanical and surface properties of hydrophilic PET fibers make them entangle with each other more efficiently, resulting in high entanglement intensity and bonding points with high strength. But we do not know clearly how the hydrophilicity of fibers influences the entanglement intensity.

In order to study the entanglement properties of spunlaced nonwoven fabrics, common and hydrophilic PET fibers were processed into spunlaced nonwoven fabrics by the same web-making and hydroentangling process. A pull-out experiment was designed to evaluate the entanglement intensity and a formula was set up to calculate the tensile strength of the spunlaced nonwoven fabric based on its pull-out behavior. In addition, influences of cohesive force of the fiber pre-web on the entanglement of spunlaced nonwoven fabrics were investigated.

EXPERIMENTAL

Materials

Common and hydrophilic PET fibers were obtained from Yizheng Chemical Fibers Co. (China) whose properties were shown in *Table I*. Pre-webs of common and hydrophilic PET fibers were formed by carding and cross-lapping processes, respectively. The spunlaced nonwoven fabrics were made by using a Fleissner Aquajet Y500-2 spunlaced machine with 1 manifold under the forming speed of 2m/min. The fiber pre-webs were first compacted and pre-wetted underneath the jet head with the jet pressure of 15bar, and then treated by three passes on each side. *Table II* summarizes the pressure of the water jets used for the hydroentangling process for all the samples.

TABLE I. Properties of common and hydrophilic PET fibers.

Items	Common PET fiber	Hydrophilic PET fiber
Fineness (dtex)	1.56	1.58
Length (mm)	38	38
Tensile strength (cN/dtex)	5.05	5.02
Elongation (%)	17.3	25.8
Initial modulus (cN/dtex)	33.1	27.2

TABLE II. Pressure of the water jets used for the hydroentangling process.

		Pressure (bar)
Pre-wet		15
Pass Number (first side)	1	25
	2	40
	3	60
Pass Number (second side)	1	25
	2	40
	3	60

Tensile Strength Measurement

The tensile strength of the spunlaced nonwoven fabrics was tested by using a YG028-500 Electronic Universal Strength Tester (Wenzhou Fangyuan Instrument Co., China) according to FZ/T60005-1991 (China) standard. The specimens were 50±0.5mm wide and 250mm long. Five specimens of each sample were tested in the machine directions (MD) and cross-machine direction (CD), respectively. The distance between the clamps was 200mm. The testing speed was 100mm/min.

The bonding index (*BI*) is conventionally defined as follows:

$$BI = (MD+CD)/2 \qquad (1)$$

Where MD and CD are the tensile strengths of spunlaced nonwoven fabrics in the MD and CD directions.

In considering the influence of basis weight of the nonwoven fabrics, equation 1 is modified as

$$BI = (MD+CD)/W\ (N/g\cdot m^2) \qquad (2)$$

Where W is the basis weight of spunlaced nonwoven fabrics.

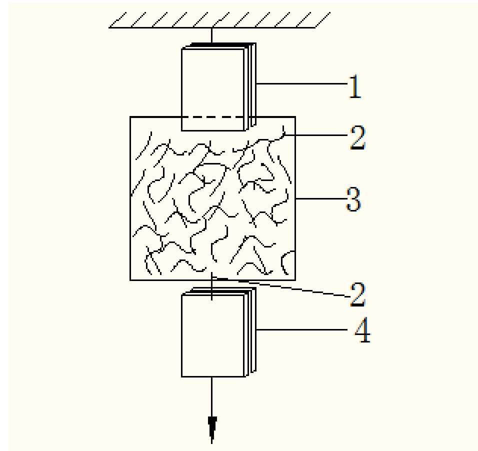
Pull-Out Behavior Measurement

The YG001 fiber tensile strength tester was used to study the pull-out behavior of spunlaced nonwoven fabrics because the pull-out force is not higher than that of the tensile strength of single fibers. Spunlaced nonwoven fabrics of common and hydrophilic PET fibers were cut into 5cm×5cm in MD and CD. One end of the sample in CD was clamped by the top grip of the tester and that the edges of the sample in MD were parallel to the direction of force application. The distance between the clamps was 10mm. A single fiber in the cross-section of the other end of the sample was clamped by the other grip. The fiber was pulled out of the sample by applying a constant speed of 20mm/min after it disentangled from all the entanglement with other fibers. A schematic diagram of the pull-out behavior of fibers is shown in *Figure 1*. 100 fibers were pulled out for each sample. In this paper, only the pull-out force of fibers in the MD cross-section was measured based on the assumption that fibers in the MD and CD have the same entanglement mechanism.

A force-elongation curve can be obtained when the total elongation of the spunlaced nonwoven fabric is drawn as X-coordinate and the force is drawn as Y-coordinate. The peak value of each curve is defined as the pull-out force of each fiber. The pull-out force (F) of fibers from the two kinds of spunlaced nonwoven fabrics were calculated by averaging the pull-out force of 100 fibers respectively. In the test, some fibers were broken and others were slipped without break. Hence the pull-out force can be divided into broken force (F_1) and slipped force (F_2). Broken force is defined as the average pull-out force of those fibers which were broken in the pull-out force measurement. Slipped force is defined as the average pull-out force of those fibers which were slipped from the spunlaced nonwoven fabrics in the pull-out force measurement. Broken fiber content (C) is defined as the ratio of broken fibers to total fibers pulled out.

$$C = N_1/N_0 \times 100\% \quad (3)$$

Where N_1 and N_0 are the number of broken fibers and total number of fibers pulled out, respectively.



1-Top grip 2-fiber 3-sample 4-bottom grip

FIGURE 1. A schematic diagram of the pull-out test.

Cohesive Force Measurement

Cohesive force is defined as the force required to bring about relative movement of fibers. In this paper, the tensile force of the fiber pre-web was tested by using Model a YG020 Yarn Tensile Strength Tester. The maximum breaking force is defined as the cohesive force. Pre-web of common and hydrophilic PET fibers with basis weight of 30 g/m^2 were made by Model ASA181A carding machine and folded by straight-lapping process. The pre-webs were cut into 50mm×300mm (CD×MD). Then the web was put on a clipboard and both ends were fixed by a pair of clamps. Then the clamps were fixed by the grips of the tester. The distance between the grips was 250mm and the speed was 500mm/min. 20 samples were tested for each sample.

Cohesive force of the pre-web is calculated as Eq. (4).

$$B = \frac{F}{M} \quad (4)$$

Where, B is cohesive force of per gram of the fiber pre-web (cN/g), F is the tensile force of the fiber pre-web (cN), M is the weight of the fiber pre-web (g).

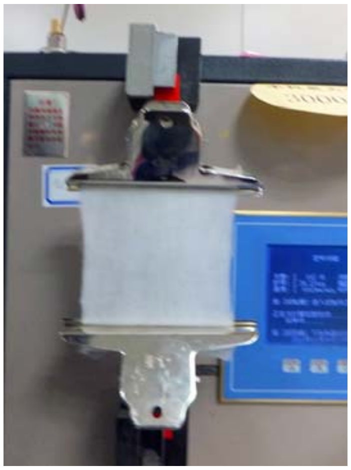


FIGURE 2. Equipment for the cohesive force measurement.

RESULTS AND DISCUSSION

Tensile Strength of PET Spunlaced Nonwoven Fabrics

Tensile strength of spunlaced nonwoven fabrics of common and hydrophilic PET fibers processed by the same web-making and hydroentangling process were tested and shown in *Table III.*

TABLE III. Tensile strength of different spunlaced nonwoven fabrics.

Items	Spunlaced nonwoven fabrics	
	Common PET fiber	Hydrophilic PET fiber
Basis weight (g/m^2)	103.5	100.4
MD Tensile stength(N)	101.4	465.6
CD Tensile stength(N)	31.3	181.5
BI ($N*m^2/g$)	1.28	6.45

It can be seen from *Table III* that the tensile strength (both in MD and CD) of the spunlaced nonwoven fabric of hydrophilic PET fibers is significantly higher than that of common PET fibers. The bonding index of the hydrophilic PET spunlaced nonwoven fabric is 5 times of that of common PET fibers. It is in agreement with our previous work which shows that the tensile strength of the spunlaced nowoven fabric increases with the increase of the bonding index [10]. However, it can be found that BI is simply achieved by considering the tensile strength and basis weight of the spunlaced nonwoven fabric. It is useful to compare similar nonwoven fabrics with different basis weight. But it cannot reflect the relationship between the entanglement intensity of the spunlaced nonwoven fabric and the mechanical properties.

In addition, we have studied the influences of hydrophilic and friction properties of PET fibers on the properties of spunlaced nonwoven fabrics [10]. It is believed that the entangling points of spunlaced nonwoven fabrics of hydrophilic PET fibers are much stronger than those of common PET fiber. But there is no experiment set up to prove the conclusion. It is necessary to set up an experiment to investigate the entanglement properties of the spunlaced nonwoven fabrics.

Pull-Out Behaviors of the Spunlaced Nonwoven Fabrics

Akira Watanabe et al [12] estimated the degree of fiber entanglement with a fiber pull-out experiment in which fibers on the surface of the nonwoven fabric were grasped with a clip and pulled out. It is found that the tensile strength of the nonwoven fabrics corresponds with the pull-out force. But there is no description about how many fibers were pulled out each time and the influence of the fiber weight. In this paper, single fibers were pulled out from the MD cross-section of the spunlaced nonwoven fabrics of common and hydrophilic PET fibers by using fiber tensile strength tester to study the entanglement properties. The pull-out force of common and hydrophilic fibers is shown in *Table IV*.

TABLE IV. Pull-out force of fibers from spunlaced nonwoven fabrics.

Items	Common PET fiber	Hydrophilic PET fiber
pull-out force (cN)	3.17	7.17
CV (%)	32	43
Broken force f_1 (cN)	5.07	8.72
CV (%)	20	16
Slipped force f_2 (cN)	3.0	3.87
CV (%)	30	40
Broken fiber content C (%)	8	68

It can be seen from *Table IV* that the pull-out force of fibers from the spunlaced nonwoven fabric of hydrophilic PET fibers is obviously higher than that of common PET fibers, which means it takes more force to pull out fibers from spunlaced nonwoven fabric of hydrophilic PET fibers. In addition, it can be found from *Table IV* that more fibers were broken for spunlaced nonwoven fabrics of hydrophilic PET fibers than that of common PET fibers.

In addition, three kinds of force-elongation curve are obtained from the pull-out experiments as shown in *Figure 3*.

Curve A has a low pull-out force. It is easy to pull-out fibers from the spunlaced nonwoven fabrics without any damage to the fibers, which means that this kind of fibers do not have enough entanglement with other fibers. More common PET fibers exhibit this kind of behavior than hydrophilic PET fibers.

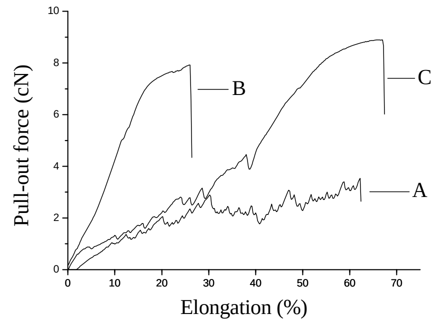


FIGURE 3. Pull-out curves of fibers from the spunlaced nonwoven fabric.

Curve B looks like the tensile strength curve of single man-made fiber. The fibers were broken after they were pulled out from the spunlaced nonwoven fabrics. It means that this kind of fibers entangle intensively with other fibers. Most hydrophilic PET fibers exhibit this kind of pull-out behavior.

Curve C has several upward peaks. The pull-out force is much lower than that of curve B and higher than that of curve A. It is believed that this kind of fibers have several loose entangling points with other fibers. It will disentangle from the entangling points one by one during the pull-out measurement. Hence upward peaks appear on the pull-out curve. Most common PET fibers behave like this.

Relationship Between the Pull-Out Force and the Tensile Strength of Spunlaced Nonwoven Fabrics

In order to find the influences of the fiber properties and entanglement intensity on the mechanical properties of the spunlaced nonwoven fabrics, an equation is established to correlate the pull-out behaviors and tensile strength of the spunlaced nonwoven fabrics.

If the length (L) of fibers of the nonwoven fabric per square meter is summed up, L can be calculated as follows.

$$L= W\times10000/D \quad (5)$$

Where D is the fineness of the staple fiber, dtex. W is the basis weight of the fabric, g/m^2.

The number of fibers (N) in the MD and CD cross-sections of the spunlaced nonwoven fabrics can be calculated based on the assumption that fibers are distributed randomly in MD and CD.

$$N = \frac{1}{2} * L * (1 - J) * (1 - K) * (1 - G) * L_1 \qquad (6)$$

Where J is the crimp rate of fibers, %; K is the non-linear coefficient of fibers based on the fact that fibers are curved after the spunlacing process, %; G is the correction coefficient in consideration that some fibers are distributed vertically to the surface of the nonwoven fabric; L_1 is the length and width in MD and CD of the spunlaced nonwoven fabric.

The number of fibers in the CD section with width of 5cm was calculated and the results are shown in *Table V*.

During the tensile force testing of the spunlaced nonwoven fabric, some fibers are broken and others are slipped from the bonding points. It is believed that the tensile force of the fabric is equal to the total broken force and slipped force of fibers on the cross-section. Hence the tensile force of the spunlaced nonwoven fabrics can be calculated by Eq (7) based on the assumption that fibers were broken or slipped during the tensile force measurement with the same probability as in the pull-out experiments and that the tensile force of the spunlaced nonwoven fabric on MD and CD is equal to each other:

$$F = NCF_1 + N(1 - C)F_2 \qquad (7)$$

Where F is the tensile force of the spunlaced nonwoven fabric, F_1 is the broken force of fibers from the spunlaced nonwoven fabric, F_2 is the slipped force of fibers from the spunlaced nonwoven fabric.

It can be seen from Eq. (7) that the tensile force of the spunlaced nonwoven fabric (F) is mainly determined by the number of fibers on the cross-section (C), which is consistent with the conventional conclusion that the tensile force of the spunlaced nonwoven fabric increases with the increase of the basis weight. In addition, it can be found that F is influenced by the broken fiber content (C), broken force (F_1) and slipped force (F_2) as well.

The calculated tensile strength of the spunlaced nonwoven fabrics of common and hydrophilic PET fibers were shown in *Table VI*. It can be found from *Table VI* that the calculated tensile force of the spunlaced nonwoven fabrics of common and hydrophilic PET fibers correspond to the measured value despite it is a little higher. During the measurement, some fibers were pulled out by scissors when they were clamped by the grip, which were not included in the results. Hence the calculated tensile force is higher than measured.

TABLE V. Number of fiber in the CD section of the spunlaced nonwoven fabrics.

	Common PET fiber	Hydrophilic PET fiber
L(m)	663461	635443
J(%)	13.8	13.5
K(%)	25	25
G(%)	20	25
C(%)	8	68
N/5cm	8580	7729

Normally speaking, the broken fiber force is much higher than that of slipped force. Hence the tensile strength of the spunlaced nonwoven fabric is mainly determined by the broken fiber content. For the spunlaced nonwoven fabric with more fibers broken during the pull-out measurement, more fibers are contributed their strength sufficiently to the strength of the spunlaced nonwoven fabric. Therefore, the spunlaced nonwoven fabric will exhibit high tensile strength. It has been mentioned that fibers entangle intensively with other fibers if they are broken during the pull-out experiment. Hence the broken fiber content can be used to represent the entanglement intensity of the spunlaced nonwoven fabrics.

TABLE VI. Comparison of the calculated and measured tensile force of the fabrics.

	Common PET fiber	Hydrophilic PET fiber
Calculated tensile force (N)	152	506.2
Measured tensile force (N)	101.4	465.6

Influence of Cohesive Force of the Pre-Web on the Entanglement Intensity of Hydroentangled Nonwoven Fabrics

There is no standard method to test cohesive force of fiber web or yarn so far. In this paper, a testing method of cohesive force of the fiber pre-web is set up and cohesive force of hydroentangled nonwoven fabrics of common and hydrophilic PET fibers is shown in *Table VII.*

It can be seen from *Table VII* that the cohesive force of the hydrophilic PET pre-web is obviously higher than that of the common PET pre-web, which means that it is more difficult for the hydrophilic PET fibers to move relative to each other. When the high pressure water jet impacts the fiber pre-web, more fibers around the water jet will be carried together from the surface of the pre-web into the interior of the pre-web. Better entanglement will be achieved as a result. It is believed that cohesive force of the pre-web is related to the curling, friction and surface properties of fibers, which can reflect comprehensively the interaction between fibers and the higher cohesive force, will produce better entanglement of fibers during the spunlaced process.

TABLE VII. Cohesive force of pre-web of different PET fibers.

	Common PET fiber	Hydrophilic PET fiber
Cohesive force (cN/g)	305.5	406.1
CV（%）	5.1	5.5

CONCLUSIONS

In this paper, a pull-out experiment was designed to study the entanglement properties of spunlaced nonwoven fabrics made from common and hydrophilic PET fibers, in order to uncover the reason why the spunlaced nonwoven fabric of hydrophilic PET fibers shows higher tensile strength. It was found that the pull-out force of fibers from the spunlaced nonwoven fabric of hydrophilic PET fibers was higher than those of common PET fibers. More fibers were broken in the pull-out test of the spunlaced nonwoven fabric of hydrophilic PET fibers as well. It was proved by experiment that the entangling points of spunlaced nonwoven fabrics of hydrophilic PET fibers are much stronger than those of common PET fiber. In addition, a formula was set up to calculate the tensile strength of the spunlaced nonwoven fabric based on its pull-out behavior. It was found that the tensile strength of the spunlaced nonwoven fabric studied in this paper is mainly determined by the broken fiber content, which can be used to represent the entanglement intensity of the spunlaced nonwoven fabrics. Furthermore, it was found that the cohesive force of the hydrophilic PET pre-web was higher than that of the common PET pre-web, which causes better entanglement of hydrophilic PET fibers during the spunlaced process, because more fibers around the high pressure water jet will be impacted and carried from the surface of the pre-web into the interior of the pre-web.

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AUTHORS' ADDRESSES

Hong Wang
Jingjing Zhu
Xiangyu Jin
Haibo Wu
Donghua University
2999 North Renmin Rd
Songjiang District
Shanghai 201060
CHINA