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Studies on tensile properties of cross-laid needle-punched non-woven polyester fabric

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Abstract— The tensile properties of cross-laid needle punched nonwoven polyester fabric have been studied in machine laid (MD), cross laid (CD) and bias (45⁰) direction varying the gauge length, test speed and specimen width. Ten samples of desired dimension have been prepared for each varying parameter and also for measuring the fabric areal density, thickness and packing percentage before and after the tensile testing. Fabric strength found to be more in CD than in MD and bias direction in all varying condition. It has been observed that for increasing in gauge length, breaking extension decreases steadily and by increasing the specimen width, value of breaking load increases gradually in all three directions. At 75mm/min test speed, the stress propagation between the fibres within the fabric sample is found to be optimum for strength realization. Under double clamping (less than staple length)condition, breaking extension is almost twice than that for normal (more than staple length) condition due to much less waisting effect. Waisting effect increases the packing percentage at the central portion of sample during the tensile testing. It has been observed that fabric failure during testing mainly takes place mostly in the delta zone.

Index Terms— Bias direction; CD; delta zone; gauge length; MD; test speed; waisting effect.

1 INTRODUCTION

Nonwoven technology is the cheapest and easiest technique of producing fabric directly from fibres, even waste fibres can also be converted into fabric by using this technology. Nonwoven fabric formation consists of two main processes namely – web formation and web bonding. Web formation leads to formation of web from fibres or filament and web bonding strengthen the interaction between them. Both natural as well as man-made fibres can be used in nonwoven technology. Baneerjee[1] stated that specific surface area for bonding depends on linear density and stiffness of fibre. Thus, finer fibres produce softer, opaque fabric with more number of bonding sites. Carding traditionally used in staple fibre spinning plays a vital role in web formation of fibres having length in the range of 20-150 mm. similarly fibre properties such as fibre crimp, cross-section, finish etc. play important role in deciding the physical interaction of fibres within the web. Arrangement of fibres in the web is another criteria which governs the properties of fabric. When the fibres are laid in machine direction it is termed as machine laid or parallel laid fabric, when the fibres are laid perpendicular to machine direction, i.e, in width direction, they are termed as cross laid and while the fibres are laid in various directions of the web, that is called random laid. Ray and Ghosh[2]observed that in cross laid fabric the fibres are laid at an angle but not exactly in width direction. They also stated that the angle of orientation of fibres decides the tensile properties of nonwoven fabric. Burnip and Hearle[3] observed that both the fibre properties and fabric structure determines the fabric properties. Web bonding are of various types, namely mechanical, chemical and thermal. Needle punching technique, one of the mechanical methods, is widely used in industry because of its simplicity where needles are employed to entangle the fibres to strengthen the cohesive force between them. Zamfir et al[4] studied the effect of depth of needle penetration during needle punching on the mechanical properties of fabric. As observed by them, in addition, the gap between the stripper and bed plate, needle density, draw off speed also affect the properties of fabric. Midha and Mukhopadyay[5] stated that fibre consolidation up-to a certain limit is improved if the needle density and penetration increases but after that it damages the fibre which leads to disorientation of fabric characteristics. Hence, fibre properties, fibre bonding, machine parameters, all are influencing the tensile properties of fabric.

Even the testing parameters also affect the properties. Patel and Kothari[6] observed that tensile properties of needle-punched spun bonded fabric are influenced by strain rate and sample width. The breaking stress, breaking strain and initial modulus increases with increase in sample width and with increase in strain rate, the peak strength decreases then increases and then it remains unaffected with further increase in strain rate. Michi[7] studied the adhesive bonded viscose and nylon nonwoven fabric and stated that the strength decreases to some extent with increase in gauge length because of weak link effect. He also explained the double clamping condition. When the jaws are set too close to each other where the gauge length is less than the staple length of fibre, the maximum theoretical strength of the aggregated fibre should be realized. As we increase the gauge length there would be decrease in the number of fibres clamped by both the jaws and as a result the total contribution to strength realization decreases.

Based on the gathered information, a comparative study of tensile properties has been carried out varying the gauge length, specimen width and test speed.

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2 Materials and Methods

2.1 Nonwoven Fabric Production

Polyester fibre of staple length 64 mm and fineness 15 denier have been used for producing the cross laid needle-punched nonwoven fabric in laboratory model needle punching plant (DILO Machine GmbH, Germany). This laboratory model plant consists of fibre opener, card with camel back cross lapper, needle loom with two needle boards punching from one side only, cloth winding unit and electrical control panel for controlling the operations. Fibres were opened manually before feeding into the opener. Opener is followed by card feeder, card, and camel back cross lapper. Finally, the web passes through needle loom as well as cutting and winding device attached to this needle loom consisting of 1 lab winder with 2 edge cutters. Polyester fabric made up of 10 layers of web, was re-feed in the needle loom for punching in the other side of the fabric. Needles of gauge 40, triangular cross-section, 2 barbs per apex with regular barb were used in the study. Depth of needle penetration of needle was set to 10 mm and density of needles/inch^2 in the needle board was 17.

2.2 Determination of Fabric Specifications

Fabric areal density (g/m^2) was calculated from the weight of 10 cm × 10 cm fabric taken on an electronic balance. The fabric thickness was determined at different places before and after the tensile testing by using Aimil made digital thickness gauge. The packing fraction of the fabrics was also calculated from the fabric density and fibre density. In addition to the average or mean value, the standard deviation (SD) and coefficient of variation (CV) of fabric areal density, thickness and packing fraction were also calculated in order to understand the impact of tensile force on the fabric after the testing.

2.3 Testing of Tensile Properties of Fabric

The tensile properties of the fabrics were measured in ZWICK ROELL (Model - Z010) Tensile Tester, which works on constant rate of extension principle. The upper jaw is movable and lower jaw is fixed. Samples are clamped between the jaws. The maximum load capacity is 10 kN having testing speed of 1 mm/min to 2000 mm/min. Tensile properties such as tensile strength, tenacity, extension, initial modulus and work of rupture have been measured in CD, MD and bias (45^0) direction by varying the gauge length, width of test sample and testing speed as well as variable double clamping condition. For studying the effect of varying gauge length (75, 100, 150 and 200 mm), the test speed and sample width were 300 mm/min and 25 mm respectively. For studying the effect of varying test speed (10 mm/min, 50 mm/min, 75 mm/min, 100 mm/min, 300 mm/min, 600 mm/min and 1000 mm/min), the gauge length and sample width were 200 mm and 25 mm respectively. For studying the effect of varying specimen width (10 mm, 25 mm, 50 mm, 75 mm and 100 mm), the gauge length and test speed were maintained to 200 mm and 300 mm/min respectively. Under double clamping condition (less than the staple length of fibre), gauge length was varied to 10mm, 20 mm, 30 mm, 40mm and 50 mm keeping the width 25 mm and speed 10 mm/min constant.

$$\text{Tenacity} = \frac{\text{Breaking load}}{\text{(Fabric GSM × Fabric width)}} \text{ cN/tex}$$

$$\text{Initial modulus} = \frac{\text{(Load at 1\% extension × 100)}}{\text{(Fabric GSM× Fabric width)}} \text{ cN/tex}$$

3 Result and Discussion

3.1 Nonwoven Fabric Properties

The measured fabric parameters like areal density, thickness and packing fraction, which characterize the nonwoven fabrics as well as influence the tensile properties of the fabrics are given in Table 1. The table also contains the values of those parameters obtained after tensile testing.

			Areal density (g/m^2)	Thickness (mm)	Packing (%)
Before tensile testing	Random sample	Mean	295.6	2.8	7.4
		S.D.	25.7	0.3	0.6
		C.V. (%)	8.7	10.9	8.4
After tensile testing	At grip	Mean	156.8	1.3	8.2
		S.D.	29.0	0.2	1.4
		C.V. (%)	18.5	16.3	17.6
	At 5 cm from gripping end	Mean	285.5	2.5	10.5
		S.D.	44.5	0.4	1.6
		C.V. (%)	15.6	15.1	15.4
	At the central portion	Mean	460.4	3.1	11.9
		S.D.	60.7	0.4	1.7
		C.V. (%)	13.2	14.2	14.7

Table 1. Parameters of the nonwoven fabric before tensile testing

As observed in Table 1, areal density of the original sample is 295.6 g/m2 and after tensile testing it varies from 156.8 g/m2 to 460.4 g/m2 from the delta zones to the central portion of the sample respectively. The packing percentage of the original sample is 7.41 % and after testing it changes to 8.2 % and 11.9 % in the gripping ends and in the central portion of the fabric respectively. Variation of these two fabric parameters indicates that fibre displacement takes place and accumulates from the both ends as well as both sides towards the central portion of the fabric during tensile testing making the central portion narrower (Figure 1) and more compact and thicker (Table 1).

Figure 1. Distortion (waisting) of nonwoven fabric during tensile testing

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Due to narrowing (waisting) under tensile load, the area of the sample decreases, as a result the areal density and packing percentage increases, which again vary from zone to zone of the sample. It is also observed that thickness of the original fabric is 2.8 mm but after testing it varies from 1.3 mm to 3.1 mm from the delta zones to the central portion of the fabric respectively. Hence, it is clear from these findings that fibres are moving in the central portion making that portion rigid. In this rigid central portion, the movements of fibres get locked and immobile. This locking of fabric structure reduces the overall extensibility of the fabric. Hence the waisting effect during the tensile testing not only distorts the fabric structure but also influence the overall fabric properties.

3.2 Effect of varying the Gauge Length

The tensile properties obtained under variable gauge length are shown in Table 2. It is observed that fabric strength in CD is more than that in MD and bias (45°) direction. Moreover, the higher strength in bias (45°) direction than MD, but nearer to strength in CD, is an indication that all the fibres are not oriented exactly in CD but preferentially oriented in between bias (45°) and CD.

	Gauge length(mm)	Max. load(N)	Tenacity (cN/tex)	Initial Modulus (cN/tex)	Extension (%)	Work of Rupture (Nmm)
Machine Direction	75	141.9	1.9	12.58	83.8	5084.5
	100	140.6	1.9	13.79	80.2	6241.7
	150	142.2	1.9	13.75	71.6	7937.2
	200	138.2	1.8	13.72	68.8	9894.6
Cross Direction	75	209.8	2.7	13.51	79.0	6871.7
	100	186.5	2.4	12.86	71.1	7195.6
	150	193.2	2.5	13.87	69.3	10149.2
	200	178.1	2.3	13.33	67.2	12115.8
Bias Direction	75	180.5	2.4	6.80	97.7	6793.2
	100	165.2	2.2	7.47	77.3	5888.2
	150	178.4	2.4	6.25	74.8	11113.4
	200	168.6	2.2	7.02	81.3	11396.7

Table 2. Tensile properties at varying the gauge length

Extension gradually decreases in MD and CD. During extension of nonwoven fabric, middle portion of the specimen contracts in width due to higher accumulation of fibres which is not happening near the clamps forming a delta shaped portion near the clamps with less number of fibres. Size of the delta zone is higher in case of higher gauge length. More waisting effect at higher gauge length itself acts as a load and restricts further extension.

Extension value in MD is greater than bias followed by CD. This is because fibres first get oriented longitudinally from their oriented direction and then the waisting occur. In that way fibres oriented in machine direction is subjected to more stress to get themselves oriented in longitudinal direction followed by bias and then in cross direction. Tenacity against the varying gauge length keeping fabric GSM and fabric width constant is same as that of breaking load.

The value of initial modulus in bias direction at 1% extension is almost half than that of the MD and CD. Initial modulus means resistance to deformation i.e. less resistance to deformation in bias direction. It may be due to less no. of entanglement, less slippage resistance in bias direction. Therefore, fewer loads is required to deformation at 1% extension. Max. shock absorption at 200 mm gauge length in MD, CD and bias. Value of work of rupture increases gradually due to increase in elongation.

3.3 Effect of varying the Test Speed

In this case test speeds were varied from 10 mm/min to 1000 mm/min, keeping the gauge length and specimen width constant. It has been observed that there is no specific trend of values against breaking load, tenacity, extension %, initial modulus and work of rupture. However within the limited range of values of test speed at 75mm/min, breaking load and tenacity are maximum in machine, cross and bias direction. This may be because at 75mm/min stress propagation between the fibres within the fabric sample is optimum for strength realization.

Value of initial modulus remain unaffected in MD, CD and bias direction. The value of work of rupture is maximum at 75mm/min due to maximum breaking load.

	Speed (mm/min)	Max. load (N)	Tenacity (cN/tex)	Initial Modulus (cN/tex)	Extension (%)	Work of Rupture (Nmm)
Machine Direction	10	127.9	1.70	13.94	68.4	9489.6
	50	109.6	1.48	14.37	56.3	6947.6
	75	141.0	1.90	14.22	79.4	12088.0
	100	123.7	1.64	13.84	67.1	8682.5
	300	138.2	1.84	13.72	68.9	9884.6
	600	119.1	1.58	13.26	62.4	8347.1
	1000	129.6	1.72	13.30	66.1	9231.6
Cross Direction	10	117.8	1.57	13.91	52.4	7587.9
	50	188.9	2.55	14.85	63.4	13177.9
	75	216.3	2.92	14.93	64.0	14515.1
	100	190.7	2.54	13.82	71.9	13326.5
	300	178.1	2.37	13.30	67.2	12115.8
	600	201.6	2.60	13.07	65.7	13381.1
	1000	185.8	2.40	12.09	64.6	11886.8
Bias Direction	10	149.8	2.03	7.69	71.7	9387.7
	50	164.4	2.22	14.45	70.7	11389.3
	75	187.4	2.53	14.65	74.3	14434.0
	100	160.2	2.17	7.16	77.0	11038.8
	300	168.6	2.28	7.02	81.3	11396.7
	600	168.6	2.28	6.93	76.0	11049.5
	1000	172.6	2.34	8.46	75.9	10944.5

Table 3. Tensile properties at varying the test speed at md, cd and bias direction

3.4 Effect of varying the Speciment Width

Here, we have varied the specimen width from 10 mm to 100 mm and kept the gauge length and test speed constant. It has been found that as the specimen width increases, value of breaking load increases gradually in MD, CD and bias direction. This is because of the waisting effect which takes more time to occur for higher width. When the applied load exceeds the load imposed by the rigid waisting portion, fabric breaks. Higher fabric width leads to lower initial modulus. In lower width sample, fibres get less space for movement and thus requires more load for deformation at 1% extension.

The opposite is the situation for the higher width sample which provides less resistance to deformation. Extension % in MD is greater than bias and followed by CD. This is due to the orientation of fibres and fibres oriented in MD are subjected to more extension for the waisting to occur. The value of extension % increases but not in a specific manner. Elongation occurs till the waisting become prominent whose value increases with increasing width. When the waisting portion becomes dominant it restrict further extension and fabric failure takes place. Work of rupture value increases gradually from 10 mm to 100 mm width with the increase in breaking load and occurs maximum at 100 mm.

	Width (mm)	Max. load (N)	Tenacity (cN/tex)	Initial Modulus (cN/tex)	Extension (%)	Work of Rupture (Nmm)
Machine Direction	10	27.1	0.92	16.75	52.3	1592.8
	25	138.2	1.84	13.72	68.9	9884.6
	50	351.9	2.38	4.07	99.9	28788.1
	75	515.0	2.32	3.10	95.5	44737.9
	100	743.9	2.52	4.23	96.8	61417.3
Cross Direction	10	54.3	1.84	16.56	49.4	2914.4
	25	178.1	2.37	13.30	67.2	12115.8
	50	481.8	3.26	3.95	80.9	31937.1
	75	737.7	3.33	5.84	82.5	50397.0
	100	1000.3	3.38	4.36	83.3	72740.6
Bias Direction	10	21.2	0.72	17.26	30.9	910.1
	25	168.6	2.28	7.02	81.3	11396.7
	50	359.9	2.45	4.47	82.8	31937.1
	75	539.6	2.43	2.90	96.5	41022.6
	100	821.9	2.78	2.10	92.1	59097.6

Table 4. Tensile properties at varying the specimen width

3.4 Effect of varying the Gauge Length Under Double Clamping Condition

When the jaw length is less than the staple length of the fibre, the jaws are set close together so that all the fibres are supposed to be clamped by both the jaws and the condition is called double clamping.

Under double clamping condition, it is expected that at higher gauge length the number of fibres of the specimen fixed by both the clamps would decrease for the given width of the specimen and eventually the strength would fail but no such specific trend has been observed. The value of initial modulus at 50 mm gauge length is lower than 10mm. It may be due to the gripping of fibre ends by both the clamp decreases as gauge length increases, as a result resistance to deformation decreases. In MD, CD and bias direction, extension % is much higher almost twice than at normal gauge length. This may be due to the all total effect of fibre extension and no such waisting effect to restrict the extension as both the clamp grip both the ends of the fibre. But as the gauge length increases, waisting effect becomes more pronounced and as a result extension %decreases as shown in Fig. 6.It has been observed that work of rupture has no specific trend against the varying gauge length under double clamping condition. During testing of samples, it has been observed that tension concentration occurs at jaw and eventually fabric failure takes place mostly in the delta zone. To eliminate this problem, we attempted to cut the sample by narrowing the central part[8] and subsequently more breakages in the middle of the sample was observed instead of delta zone.

	Gauge length (mm)	Max. load (N)	Tenacity (cN/tex)	Initial Modulus (cN/tex)	Extension (%)	Work of Rupture (Nmm)
Machine Direction	10	128.7	1.71	16.67	153.4	1425.6
	20	134.31	1.82	9.7	131.35	2051.6
	30	136.2	1.8	14.89	111.9	3016.8
	40	144.28	1.95	9.1	103.74	3106.8
	50	120.14	1.63	8.1	102.93	3302.1
Cross Direction	10	173.0	2.3	17.04	168.1	2035.6
	20	218.5	2.9	16.4	161.3	4590.9
	30	154.7	2.06	15.0	107.2	3440.6
	40	173.69	2.35	8.6	97.43	3568.3
	50	235.54	3.12	8.4	94.29	5526.8
Bias Direction	10	202.26	2.74	14.00	152.29	2158.2
	20	214.35	2.90	11.34	123.56	3372.5
	30	172.31	2.33	9.11	98.58	2782.8
	40	145.83	1.98	8.6	102.38	3117.2
	50	154.85	2.1	7.9	100.95	3692.2

Table 5. Tensile properties at varying gauge length under double clamping condition

3 Conclusion

i. Fabric strength is maximum in CD, medium in Bias direction (45^0) and minimum in MD, which shows that fibres are preferentially oriented in between CD and bias direction.

ii. Both in MD and CD at higher gauge length, breaking extension% decreases steadily which due to improper force transmission from one fibre to another.

iii. Analyzing the results, it has been concluded that within the limited range of values shock absorption is highest in fabric of 200mm gauge length, 100mm width and at 75mm/min speed.

iv. As the specimen wide increases, value of breaking load increases gradually in MD, CD and bias direction.

v. Higher the fabric width leads to lower initial modulus.

vi. Under double clamping condition, breaking extension is much higher than that for higher gauge length (more than staple length) which shows that waisting effect is the governing cause of lower elongation as we go towards the higher gauge length.

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