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Studies on nature of anisotropy of tensile properties and fibre orientation in cross-laid needle-punched nonwoven fabrics

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An attempt has been made to study the fibre cross laying as well as fibre orientation angle in cross-laid needle-punched nonwoven fabric and its relationship with tensile properties of fabric. Nine fabric samples have been produced by using three types of fibres, namely 100 % polyester, 100 % jute and 50:50 jute-polyester blend with three different numbers of layers (6, 12 and 18). The tensile properties of different cross-laid structures have been measured not only in machine direction (MD) and cross direction (CD) but also at different angles including the angle of laying with respect to the width of the fabric followed by ANOVA analysis in order to assess the nature of anisotropy in terms of tensile properties. It is observed that the number of layers in the web influences the cross laying angle (LA) as well as tensile properties of the fabric. The maximum tenacity is obtained in case of CD and then the tenacity gradually reduces towards the MD. The ANOVA analysis of the data reveals that the cross-laid needle-punched nonwoven fabric possesses reasonable isotropy in respect of both fibre orientation and tenacity in all the fabrics.

Keywords: Anisotropy, Cross-laid fabric, Fibre orientation, Jute/polyester blend, Laying angle, Needle-punched nonwoven, Tensile properties

1 Introduction

The nature of orientation of fibres in the cross-laid web is very complex and ultimately decides the anisotropic property of the nonwoven fabric. Wilson[1] has stated that the structure and composition of the web assembly, particularly the fibre orientation which is the precursor for the final nonwoven fabric, strongly influences the isotropy of fabric and most nonwovens are anisotropic. Different steps involved as well as the principle of the continuous cross laying using the camel back cross lapper including the calculation of web laying angle and the number of layers of card web in the cross–laid batt in the nonwoven manufacturing technology have been dealt in detail by Das[2] and Stutz[3]. Krcma[4] observed that one of the important factors which influences the final properties of the product is the fibre orientation and defined the expression of the degree of exploitation of the fibre strength to the nonwoven fabric. Cusick *et al*.[5] expressed the anisotropy of the fabric in terms of the ratios of modulus and strength in the length direction to the corresponding values in the cross direction. Hearle and Stevenson[6] suggested that the fibre curl distribution has great importance in determining nonwoven fabric stress-strain properties, particularly if the fabric is not highly oriented. Hearle *et al*.[7] used still and CIN photographic technique to study fibre movement in an operating needle loom. According to their finding, tracer fibre technique can be used to demonstrate fibre transfer through nonwoven fabric thickness as carried out by Miao[8] who used an optical fibre diameter analyser (OFDA) for measuring the level of medullation of a fibre sample. Pourbeyhimi and Ramanathan[9] presented three methods for measuring fibre orientation. The first relies on a direct fibre tracking method, the second method measures orientation using power spectrum from a two dimensional fourier analysis of the image, and third technique is known as flow field fibre analysis. Pourbeyhimi and Kim[10] estimated the orientation distribution function (ODF) by using the Hough transform as an offline method, and recommended the optical fourier transform and image analysis technique using the fourier transform of the image for the purpose.

The most pioneering work in the field of fibre orientation in nonwoven fabrics was carried out by

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Hearle and Ozsanlav[11]. In their study, the orientation and curl of fibre segments in random, parallel and cross-laid fabrics were examined with a scanning electron microscope (SEM). As per their finding, random fabrics differing in weight, thickness and fibre content do not show any significant variation in fibre orientation and curl factor characteristics, but such characteristics are influenced by the cross-laying angle and web producing machinery. The nonwoven fabrics in general have more or less anisotropy in terms of fibre orientation, irrespective of the type of web forming machinery. Das *et al.*[12] measured the fibre orientation parameter in cross-laid fibre webs by using two techniques, viz the tracer fibre technique as well as Lindlsey technique, and compared the characteristics of fibre orientation in the fibre webs. They observed that the fibre webs become more anisotropic with the decrease in number of layers and vice versa. The cross-laid nonwoven has, in general, higher strength in cross direction in comparison to that in machine direction. It is observed from the pioneering works[6, 11] that the ratio of strength in cross direction (CD) and machine direction (MD) is in the range of 1.7 - 1.9. Mao and Russel[13] has mentioned that although it is possible, but tedious and time consuming, to make direct measurement of the fibre orientation in a web, the normal approach is to determine the ratio of the tensile strength measured in machine direction (MD) and cross direction (CD) which reflects the nature of fibre orientation in the web/fabric.

Based on the foregoing information, attempt has been made in this study to observe the fibre laying angle as well as fibre orientation in cross-laid nonwoven fabrics made out of polyester, jute and their blends as well as to measure the tensile properties of the fabrics not only in machine direction (MD) and cross direction (CD) but also at different angles including the angle of web laying with respect to the length or width of the fabric. The difference in tenacity values in a particular direction with respect to other direction of testing has been subjected to the ANOVA analysis in order to gain an insight into the nature of anisotropy in terms of tensile properties and fibre orientation.

2 Materials and Methods

Nine fabric samples have been produced in Laboratory Model Nonwoven Machinery Plant (Make: M/S. Dilo GmbH, Germany), equipped with two needle boards at the top only, using three types of fibres, namely 100 % polyester, 100 % jute and 50:50 jute-polyester blend with three different number of layers (6, 12 and 18). The laboratory model nonwoven machinery plant is comprised of fibre opener, chute feed, worker & stripper type card, camel back lattice, cross lapper, feed lattice and needle punching loom with cloth winding attachment. The important specifications of the barbed needles fitted in the loom are 40 gauge, 75 mm length, 3 apexes, 2 barbs per apex, and regular barb (RB). The needle boards have been set to have 10 mm needle penetration depth. The number of needles per metre in the needle beds is 4500 and the width of the machine is 600 mm.

By varying the delivery speed and strokes per minute the punch density in every sample has been maintained as 234 punches/cm^2. Coloured tracer fibres (0.5%) have been used at the opening/mixing stage during web formation for observing the arrangement of fibre in the web as well as in the final needle punched nonwoven fabric. The orientation as well as the configuration of tracer fibres in the web and nonwoven fabric was recorded by taking photographs with the help of a digital camera and then viewing these photographs in the computer as well as by means of projection microscope. Further the ideal orientation, i.e. the actual fibre laying angle in the web, was assessed by feeding coloured filament yarn over the carded web before cross layering. The actual fibre laying angle has been measured from the position of the coloured continuous filament yarn on the nonwoven fabric. The theoretical fibre laying angle has been obtained from the machine parameters. The magnitude of draft in the web/fabric inside the needle punching machine has also been estimated and considered during the calculation of the theoretical laying angle.

The thickness of the nonwoven fabrics has been measured by means of the digital thickness meter (Make: AIMIL) under the load of 1 kPa on the fabrics for 1 min. The tensile properties of the nonwoven fabrics in cross, machine and other bias directions have been measured using Zwick Roell tensile tester.

For marking and cutting the samples for tensile testing, fabric has been spread over flat table and first marked in the machine direction & cross direction as well as in the bias directions [laying angle (LA), 30°, 45° and 60°] with respect to the cross direction of the fabric with the help of protector (Fig. 1) having 20 cm length & 2.5 cm width[14]. The gauge length and test speed have been maintained at 10 cm and 5 cm/min respectively.

As the fabrics were of various GSM, for comparison purpose, the tenacity of the fabrics has been calculated using the following relationship:

$$\text{Tenacity (cN/tex)} = \frac{\text{Breaking load (cN)}}{\text{Width of test specimen (mm)} \times \text{fabric mass (g/m}^2\text{)}}$$

The tensile properties of polyester and jute fibres have also been tested on the same instrument, but by changing the load cell. The tensile properties of the nonwoven fabrics obtained in different directions have been subjected to ANOVA Analysis.

3 Results and Discussion

The particulars of the raw materials used in the study are shown in Table 1. As observed, out of the two fibres, polyester is finer, stronger and more stretchable than jute. The composition of the nonwoven fabrics made with polyester, jute and their blends having different number of layers along with their codes are shown in Table 2.

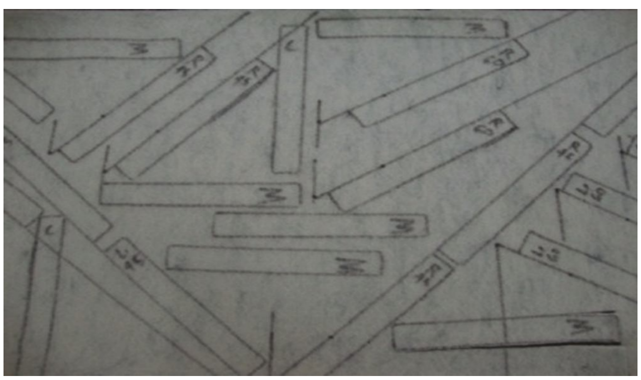

Fig. 1 — Nonwoven fabric marked in different directions before cutting

Table 1 — Particulars of raw materials

Fibre	Fineness den	Cut length mm	Tenacity cN/den	Elongation %
Jute (TD4)	18.0	63	3.6	2.2
Polyester (Crimped)	6.0	64	5.6	38.9

3.1 GSM, Thickness and Packing Fraction of Fabrics

It is observed from Table 2 that both the GSM and the thickness of the fabrics are increased as the number of layers is increased and the GSM is directly proportional to the thickness of the fabric. But the rate of increase in GSM is higher in the case of 12 layers to 18 layers than in case of 6 layers to 12 layers. However, the rate of increase in thickness is lower while number of layers is changed from 12 to 18 as compared to the change from 6 layers to 12 layers. This lower rate of change in thickness is due to achieving higher compactness of the fabric in the higher level of layers. As also shown in the table, the packing fraction of the fabrics varies in the range of 0.039 - 0.090, which is much lower compared to woven fabrics and indicates the high porosity of the nonwoven structures in general. Moreover, for any fibre, it is higher at higher number of layers. It justifies that needling effect is more effective when the web is thicker and heavier, of course within the range of study.

3.2 Fibre Laying and Orientation Angle

As the cross lapping/layering system during continuous web formation cannot lay the fibres, exactly on cross/width direction of the cross-laid web, but at an angle, the angle will obviously depend on the ratio of the cross laying speed and the conveyor lattice speed on which the cross laying takes place. Hence, the angle may be termed as laying angle. The popular tracer fibre technique of observing fibre orientation in textile structure (yarn and fabric) was initially performed with the help of projection microscope by placing & moving the fabric on a liquid having refractive index same to the refractive index of the fibres i.e. optical dissolving of fibres. As

Table 2 — Fabric particulars

Fabric code	Fibre	No. of layers	GSM	Thickness, mm	Packing fraction
NP_1	Polyester	6	222.75	3.66	0.044
NP_2	Polyester	12	393.91	5.67	0.050
NP_3	Polyester	18	769.00	6.20	0.090
NJ_1	Jute	6	152.50	2.56	0.040
NJ_2	Jute	12	209.46	3.21	0.044
NJ_3	Jute	18	337.61	3.83	0.060
NJP_1	Jute/Polyester (50:50)	6	201.43	3.61	0.039
NJP_2	Jute/Polyester (50:50)	12	334.47	5.01	0.047
NJP_3	Jute/Polyester (50:50)	18	507.47	5.16	0.069

the process is tedious and structure of the needle punched nonwoven fabric is complex, it has been decided to initially study the fibre orientation and laying angle by taking photographs with the help of a digital camera.

It is observed from Fig. 2 that neither the tracer fibres nor the majority of the fibres are properly aligned or orientated in any particular direction, instead fibres are scatter oriented. Moreover, only a few fibres in the web are straight; mostly these are looped, bent, entangled and folded. As no specific angle of either laying or orientation of fibres has been observed, it has been tried to investigate the cause of such happening i.e. scatter or random orientation. The probable reasons could be related to (i) the arrangement or orientation of fibres of the carded web which goes to the cross lapping system, and (ii) cross lapping system itself.

In order to investigate the possibility of the first cause (i), a good number of photographs of the web coming out from the card and laid on the camel back lattice conveyor have been taken. It is clearly observed in Fig. 3 that the fibres in the carded web are not fully parallel with the machine direction. Certainly, some amounts of fibres are perfectly oriented towards the machine direction, but majority of the fibres are oriented in different angles. Moreover, the fibres in the carded web are not straight but mostly looped, bent, hooked and entangled. The drawing system adopted in conventional spinning for parallelization of the fibres and removal of hooks has not been incorporated in the nonwoven production. Once the fibres are bent, inclined and hooked in the input material, it is obvious that the alignment or orientation of fibre cannot be on the direction of the cross laying even the cross laying system is perfectly alright. In order to investigate the effectiveness of the cross lapping system, continuous coloured filament yarn (like tracer fibre) has been laid manually parallel over the card web to the machine direction. Thereafter, the orientation of the filament in the cross-laid web as well as on needle-punched nonwoven fabric has been observed taking the digital photographs. It is clearly observed from Fig. 4 as well as in the real fabrics that the filament has been laid in zigzag manner maintaining constant angle of laying as well as orientation throughout the web/fabric. The laying/orientation angle of the coloured filament yarn has also been measured with the help of simple measuring tools.

The theoretical angle of laying (ideal orientation angle) for all the three combinations of layers (6, 12 and 18) have also been calculated. The draft

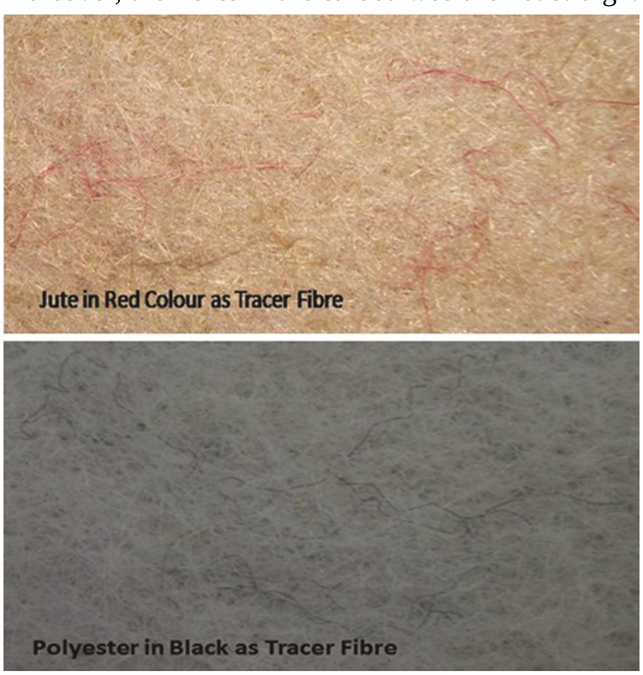

Fig. 2 — Arrangement of tracer fibres in 100% jute and 100% polyester nonwoven fabrics

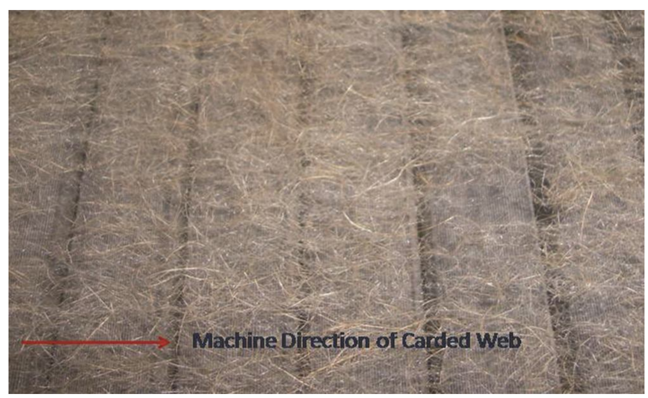

Fig. 3 — Arrangement of fibres in carded web before cross laying

Fig. 4 — Measurement of actual laying angle using straight filament yarn

taking place during punching has also been estimated and considered in calculation of laying angle in the final fabric. The measured angle on the final fabric after needle punching on both sides (two passages) and the theoretically calculated orientation angle have been found almost matching (Table 3). The angle of laying (ideal orientation) changes with number of layers, it decreases as number of layers increases. Once the number of layer is changed with the help of the controller, the speed ratio of the cross lapper and feed conveyor lattice automatically changes, resulting in the change in laying angle.

3.3 Tensile Properties

It is observed from Table 4 that the tenacity is highly influenced by the type of fibre, number of layers and direction of testing with respect to the cross direction. Out of three combinations of fibres (polyester, jute and polyester-jute blend), maximum strength has been obtained for 100% polyester, irrespective of number of layers. The achievement of higher strength in case of 100% polyester nonwoven fabrics is mainly due to higher tenacity of the fibre and better entanglement of fibres or pegging. As the polyester fibres are finer and less rigid compared to jute, better entangling of fibres is achieved during needle punching. Better entangling results in higher cohesion development between the fibres i.e. higher tenacity. Further, the crimp in the polyester fibres produces extra locking between the fibres during punching, whereas in the case of jute, the nonwoven fabric strength is much lower; although the jute fibre is not so weaker compared to polyester fibre. Jute fibres are not only coarser but also more rigid than the polyester fibre. Moreover, individual fibres become much smaller than the cut length in the punching state. As a result, jute fibres are neither well entangled nor interlocked for developing sufficient strength in the fabric. In addition, it may be mentioned that the needles used in the study are of 40 gauge which is suitable for polyester fibre but not appropriate for the coarser jute fibre. The appropriate needle gauge would have been 30 with 3 barbs per apex for the jute, but in order to maintain same needling effect, jute has also been punched with 40 gauge needle. In 40 gauge needles, the lesser depth of barb cannot catch and retain sufficient number of coarser jute fibres for entangling/interlocking of fibres in the web. It may be expected that the 50:50 jute- polyester would result in tenacity equal to the average of jute fabric strength and polyester fabric strength, but in reality this is not the situation. The values are in general less than the expected values, which is mainly due to non-compatibility between jute and polyester fibre in terms of their physical properties.

For the same fibre, the tenacity of the fabric increases as the number of layers increases. However, the rate of increase in tenacity from 6 layers to 12 layers is higher than that from 12 layers to 18 layers. Higher number of layers means more number of fibre in the web. The rate of increase in tenacity is due to the better entangling of fibres as well as higher compactness at the initial increase in number of layers. The strength of needle-punched nonwoven is due to the development of cohesive or frictional forces between the fibres by compressing and entangling the fibres in the web. So, less fibre

Table 3 — Fibre laying angle in nonwoven fabrics made with different numbers of layers

No. of layers	Amount of draft during punching, %	Theoretical laying angle, deg		Actual/measured laying angle deg
		During cross laying	After both side punching	
6	20	10.0	14.4	16.0
12	16	5.0	6.7	6.6
18	12	3.3	4.2	5.0

Table 4 — Tenacity of nonwoven fabrics in MD, CD, LA & other bias directions

Direction	Tenacity, cN/tex								
	100% Polyester			100% Jute			Jute–Polyester (50:50)		
	NP_1	NP_2	NP_3	NJ_1	NJ_2	NJ_3	NJP_1	NJP_2	NJP_3
CD	0.99	1.79	3.27	0.03	0.04	0.07	0.28	0.86	1.35
LA	0.78	1.83	3.35	0.03	0.05	0.05	0.18	0.73	1.32
30^0	0.72	1.78	2.58	0.02	0.04	0.06	0.26	0.66	1.03
45^0	0.69	1.80	2.00	0.02	0.04	0.06	0.17	0.64	0.88
60^0	0.49	1.75	1.60	0.02	0.04	0.06	0.13	0.62	0.66
MD	0.40	1.12	1.38	0.01	0.04	0.06	0.11	0.37	0.57

means less cohesive force and vice versa. The result obtained in the study illustrates the most desirable and interesting findings of the tenacity of cross-laid nonwoven fabrics in various directions. The tenacity values in both cross direction and fibre laying direction are almost same as well as maximum out of all the directions. As the angle of test changes towards the machine direction, the tenacity gradually decreases and minimum strength is obtained in the machine direction.

It is observed from Figs 5 and 6 that the ratio of maximum strength in the cross direction (CD) to machine direction (MD) is 2.09 on the average, and the ratio of tenacity (R) values between CD and all other directions including MD gradually decreases. The ratio of the tensile strength measured in machine direction (MD) and cross direction (CD) as well as other directions reflects the nature of fibre orientation in the web/fabric[13]. It is interesting to observe from Fig. 6 that the trend of the variation of tensile strength obtained in the study matches well with the fibre orientation angle distribution in cross-laid web as

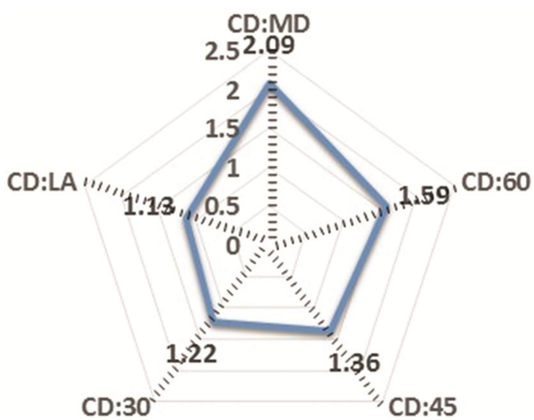

Fig. 5 — Ratio of tenacity at different directions

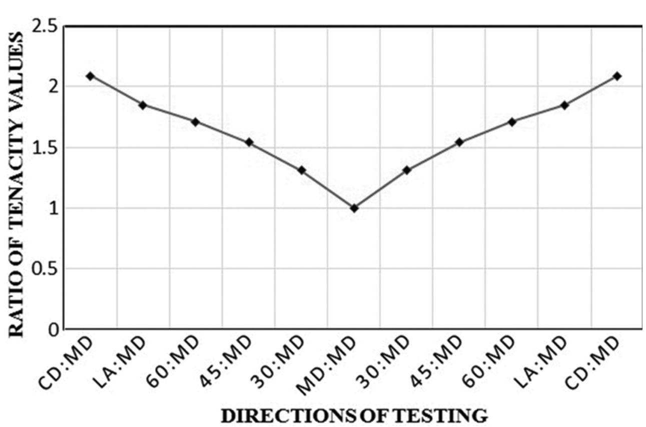

Fig. 6 — Ratio of tenacity between different directions with respect to MD

observed by Hearle & Ozsanlav[11]. Moreover, the photographic view of the real fabric (Fig. 7) obtained in the study also demonstrates the minimum anisotropy of fibre orientation in the cross-laid needle punched fabric. From this finding, it can be concluded that fibres are not well orientated in any particular direction but more or less in many directions. It means, there is reasonable isotropy in respect of both fibre orientation and tenacity in all the fabrics. So, the real-cross laid fabrics possess neither anisotropy like ideal parallel laid and cross laid, nor 100% isotropy like ideal random laid nonwoven fabric.

3.4 Exploitation of Fibre strength

The maximum exploitation of fibre strength to the fabric differs widely from fibre to fibre as well as from different number of layers in the web. The maximum value of exploitation is 6.49% for polyester fabric with 18 layers and minimum is 0.09% for jute fabric with 6 layers. The ranges of variation are 1.96 - 6.49%, 0.09 - 0.22% and 0.68 - 3.26% for polyester, jute and jute-polyester blend respectively. For the same fibre, higher exploitation of strength with increase in number of layers is due to better entanglement resulting higher cohesive force between the entangled fibres. The values are much lower than the exploitation in traditional technique of fabric formation i.e. weaving where the said value is about 50 - 60%. So, it may be stated that needle-punched nonwoven fabrics are much weaker than woven fabrics.

3.5 Breaking Extension

As obtained in the study, breaking extension of needle-punched nonwoven fabrics is much higher than that of woven fabrics. Moreover, the breaking

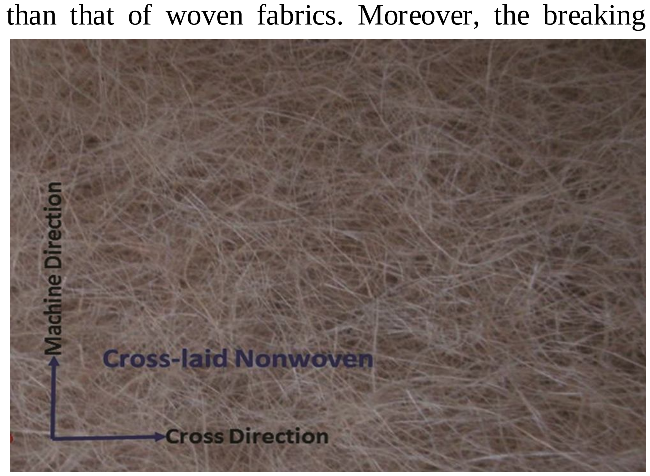

Fig. 7 — Orientation of fibres in jute-polyester cross laid needle punched fabric

Table 5 — Calculated F- values from ANOVA analysis

Parameter	NP_1	NP_2	NP_3	NJ_1	NJ_2	NJ_3	NJP_1	NJP_2	NJP_3
MD:CD	23.97	28.01	366.29	1.14	0.96	0.91	14.28	75.47	84.15
CD:OA	2.69	0.084	0.297	0.92	1.15	5.93	3.68	3.50	0.12
CD:30°	3.28	0.042	38.02	0.87	0.02	1.45	0.012	8.64	14.56
CD:45°	5.26	0.014	123.51	0.49	0.56	2.58	6.69	13.66	19.55
CD:60°	19.58	0.044	313.25	0.64	0.98	4.10	12.24	13.38	53.97
OA:30°	0.12	0.297	34.97	0.49	0.75	1.37	5.22	0.78	29.65
30°:45°	0.06	0.184	35.91	0.29	0.63	0.15	16.55	0.049	6.297
45°:60°	3.45	0.155	29.01	0.05	0.01	0.08	6.32	0.085	2.156
MD:60°	1.16	27.10	20.88	0.02	0.01	1.44	0.60	18.68	0.056

extension varies from fibre to fibre as well as from number of layers to layers. The average breaking extension is minimum (16.3%) for jute fabric and maximum (100.2%) for polyester fabric, whereas the same (79.8%) of jute–polyester blended fabric is in between the minimum and maximum values. The lower breaking extension of jute nonwoven is due to lower extensibility of jute fibre. Moreover, due to lesser compactness and entangling, the jute fabrics with any number of layers show the lower extension due to dominancy of fibre slippage than fibre straightening and breakage. In the case of polyester fabrics, the breaking extension is high due to the higher extensibility of polyester fibre. Further the polyester fibres are crimped fibre. The polyester fabrics are more compact as well as more entangled during punching. During the time of testing the fabric samples continue stretching due to dominancy of fibre straightening and breakage than fibre slippage.

3.6 ANOVA Analysis

The tenacity values of all the fabric samples are subjected to ANOVA analysis for establishing whether the difference in tenacity values in a particular direction with respect to other direction of testing is significant or not. It has been done using Microsoft Office Excel 2007. The calculated values of 'F' for different combinations are shown in Table 5. The nominal F- value for 1 and 18 degree of freedom (df) with 5% level of significance and 95% confidence is 4.41. It is observed from the Table 5 that in majority (51) cases the difference between calculated and nominal values is insignificant and only in 30 cases the difference is significant. From these findings, it can be concluded that the fibres are not only orientated in the cross direction but also in other directions.

4 Conclusion

4.1 Fibre laying angle as well as the effectiveness of needling and ultimately the tenacity of the nonwoven fabric are influenced with the change in number of layers in the web.

4.2 The extent of utilization of fibre strength to the nonwoven fabric is very much low, only in the range from 0.99% (NJ_1) to 6.49% (NP_3) in the present study.

4.3 Out of six directions (CD, LA, 30^0, 45^0, 60^0, and MD) of testing, maximum tenacity has been achieved in CD, and thereafter tenacity gradually decreases in general towards the MD. The tenacity in the direction of LA is very nearer to CD. The average ratio of tenacity between CD and MD is 2.09 and the same between 45^0 direction and MD is 1.54. It means there is reasonable isotropy in respect of tenacity in all the fabrics.

4.4 The ANOVA analysis of the tenacity values measured in the six directions under the study reveals that the fibres are also oriented in various directions in addition to the cross direction, which is also visualized from the close view of the cross-laid nonwoven fabric.

4.5 The trend of variation in tenacity values along the various directions of cross-laid nonwoven fabrics matches with the fibre orientation angle distribution in cross-laid web.

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