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Application of newly developed fibre orientation measurement techniques for needle-punched nonwoven

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New structural characteristics based on tracer fibre and Lindsley's techniques to measure the fibre orientation in X, Y and Z directions of needle-punched nonwoven have been investigated. The results are verified with variable cylinder speed, punch density and needle depth penetration. It is evident that measured structural characteristics and fabric tensile strength show very good correlation in machine direction but poor correlation in cross-direction.

Keywords: Filtration efficiency, Nonwoven structure, Needle-punched nonwoven, Punching parameters, Structural characteristics

1 Introduction

The orientation of fibres in carded fibrous web governs the quality of nonwoven fabric[1-3]. But Ciach and Gradon[4], Lisowski *et al.*[5], Das, *et al* [6] and Das *et al.*[7] have reported that the orientation of fibres is a useful parameter to estimate the effectiveness of the manufacturing processes and their products Pourdeyhimi *et al.*[8, 9] observed that fibre orientation becomes more random with the increase of needle punch density and the mean fibre length is found to be reduced up to 30%. Xu and Ting[10] developed skeletonization algorithm to study two dimensional nonwoven structure using image analysis. The structural characteristics like fibre length, fibre curl factor and fibre orientation were measured in XY plane. Similarly, Hearle and Stevenson[11,12] used projection method for measuring the fibre orientation and fibre curl in nonwoven structure. But all these methods ignore the fact that the nonwoven fibrous assembly is 3-dimentional in nature and the constituent fibres are distributed randomly in three planes X, Y and Z. Jeddi *et al.*[13] addressed the utility of optical Fourier transformation to determine the fibre orientation in nonwoven fabrics. They concluded that the optical method is simpler, faster as well as more accurate. Further, it is suitable for both offline and online monitoring of fibre distribution. On the other hand, Boulay *et al.*[14] studied the fibre orientation and distribution in paper by measuring the intensity distribution in the diffraction pattern. Pourdeyhimi *et al.*[15] conducted comparative study of Fourier Transformation Analysis and Image Analysis and concluded that Fourier Transformation Analysis is more accurate and robust over the later.

Neckář *et al.*[16] evaluated the fibre orientation of carded fibrous web by employing tracer fibre technique. The frequency distribution of angle of inclination in the machine direction was obtained using the following theoretical relationship:

$$g(\psi) = \frac{1}{\pi}\frac{\xi}{\xi-(\xi^2-1)cos^2\psi} \quad ... (1)$$

where g (ψ) denotes the probability density function of angle ψ of fibre orientation; *C* indicates the measure of anisotropy of the fibre orientation, and α refers to the preferential direction of fibres taken from the machine direction of the web.

But it is a well-known fact that the mechanical and functional properties of nonwoven fabrics are highly influenced by the fibre orientation and the properties of the constituent fibres. Thus, the use of tracer fibre technique to study fibre orientation in different layers of fibrous structure may lead to a new possible direction. Therefore, the study of fibre orientation using tracer fibre technique in layered nonwoven structure and in particular vertical orientation (Z direction) due to needle punching is very much required. Further, the use of Lindley's technique to study the fibre orientation in sliver and roving is very well covered in the literature. But the potential of this technique is not very well exploited to study the fibre

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orientation of nonwoven fabrics. Therefore, an attempt has been made to develop few new structural characteristics to measure the fibre orientation in carded web. This will provide better understanding about the mechanical and functional properties of needle-punched nonwoven air filter.

2 Materials and Methods

The viscose fibres (staple length 38 mm, 1.5 denier) were used for the study, as these fibre are easy to dye and have good optical visibility which is supposed to help in image analysis. Also, the considered fibre length is handy in working with Lindsley's apparatus.

Both direct (tracer fibre technique) and indirect (Lindsley cutting and combing) methods were used to measure the horizontal (X and Y directions) fibre orientation. Image processing technique was used to evaluate the vertical fibre orientation (Z direction).

Tensile tests were carried out on Zwick/Roell Z100 using ASTM D 5035-5(R2003) standard test method for breaking force.

2.1 Methodology Proposed to Study Fibre Orientation

2.1.1 Application of Tracer Fibre Technique for Layered Nonwoven Structure

In general, tracer fibre technique is applied to study the internal structure of yarn. In order to study the fibre orientation in X, Y and Z directions of nonwoven layered structure, a modified novel approach has been proposed to meet the requirements.

Two-dimensional Nonwoven Structure

Initially, the trails were conducted with 0.3%, 0.5% and 1.0% of coloured fibres in the parent mixing. Accordingly, carded webs were prepared with respective colour to optimise the percentage of different colour tracer fibre in different layers. Finally 0.3% of different colour tracer fibres are used for respective layer of four layered carded web. The photographs of the carded webs using α-methyl styrene as optical reagent are given in Fig. 1(a).

The fibres in nonwoven fabric are oriented in X and Y directions which invites challenges to study the configuration of full length of fibre. The sample is placed in a glass dish filled with α-methyl styrene. The microscope with moveable platform in X and Y directions is used.

The fibre path is tracked by placing a marked template having windows of defined area under transparent glass dish. The number of images to be captured for a specific fibre length largely depends on fibre configuration in X and Y directions which varies from 3 to 6 images. Finally, the images were stitched in sequence. The images were captured and stitched using Nikon SMZ2500 microscope with NIS

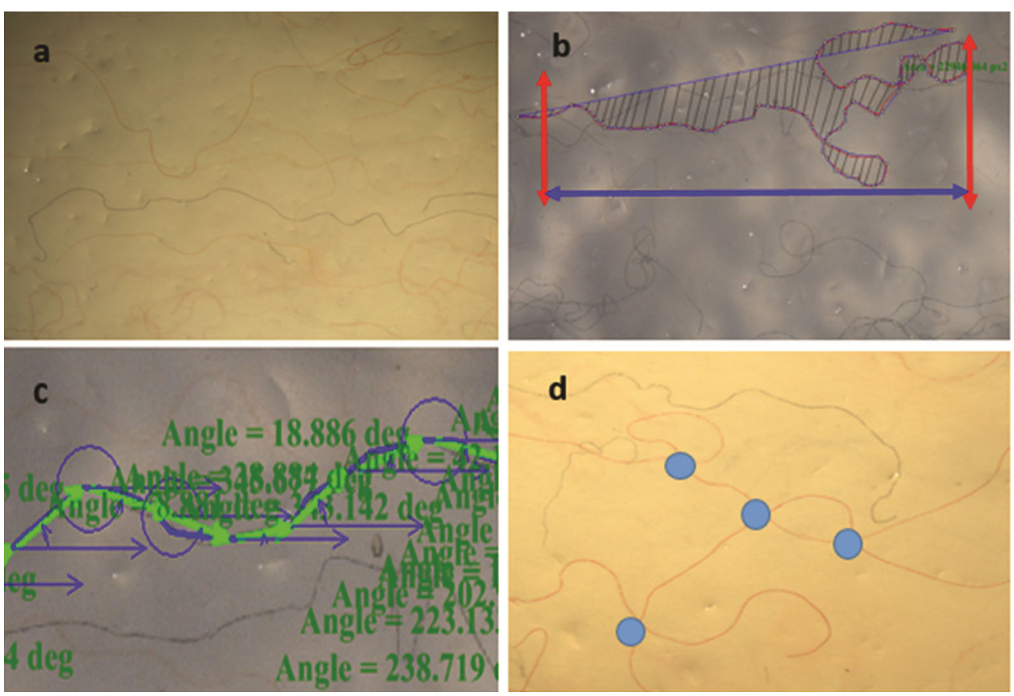

Fig. 1 — (a) Tracer fibre content – 0.3%, (b) fibre extent and area covered by fibre, (c) measurement of fibre inclination angle, and (d) cross-over point

Elements software. The magnification of ×25 was used to capture the images.

Three-dimensional Nonwoven Structure

To analyze the vertical orientation (Z direction) of fibre in needled punched nonwoven fabric, the carded webs of three different colours and grey were produced separately. Finally the webs are placed in a defined order as shown in Fig. 2. The colour summarization technique is used to measure the percentage of different coloured fibres transferred to bottom most grey layer due to needle punching. Optical microscope Nikon SMZ2500 with NIS Elements software was used to measure the vertical orientation of fibre.

2.1.2 Application of Lindsley's Technique for Carded Web

Lindsley's combing and cutting method is widely reported in the literature to study the fibre orientation in sliver and roving. But in the present work, the Lindsley's technique is proposed to study the fibre orientation in carded fibre web.

2.2 Proposed Structural Characteristics to Measure Fibre Orientation

2.2.1 Two-dimensional Nonwoven Structure

The fibres are significantly disoriented in the form of bents, hooks, and loops in the carded fibre web. Accordingly, following structural characteristics are proposed to study the fibre orientation in X and Y directions of a carded web:

Fibre Extent

Fibre extent is defined as the projected length of fibre in X direction (machine direction) of the card web. It is a measure of distance between the starting and the end point of a tracer fibre in X direction as shown in Fig. 1(b).

Coefficient of Fibre Curliness

The coefficient of fibre curliness is defined as the ratio of fibres extent to the actual length of the fibre and is expressed as given below:

Coefficient of curliness $K_{fc} = l_{fe}/l_{fl}$

where l_{fe} is the fibre extent; and l_{fl}, the actual length of the fibre. The value of coefficient of fibre curliness lies between 0 and 1.

Fibre Inclination Angle

Fibre inclination angle is a measure of the angle at an interval of 1 mm segments of a fibre in the machine direction. The mean value of these angles is defined as the fibre inclination angle (F_{ia}) as shown in Fig. 1(c). The considered fibres were then divided into many short segments of 1 mm length. Accordingly, the inclination of these segments of carded web from the

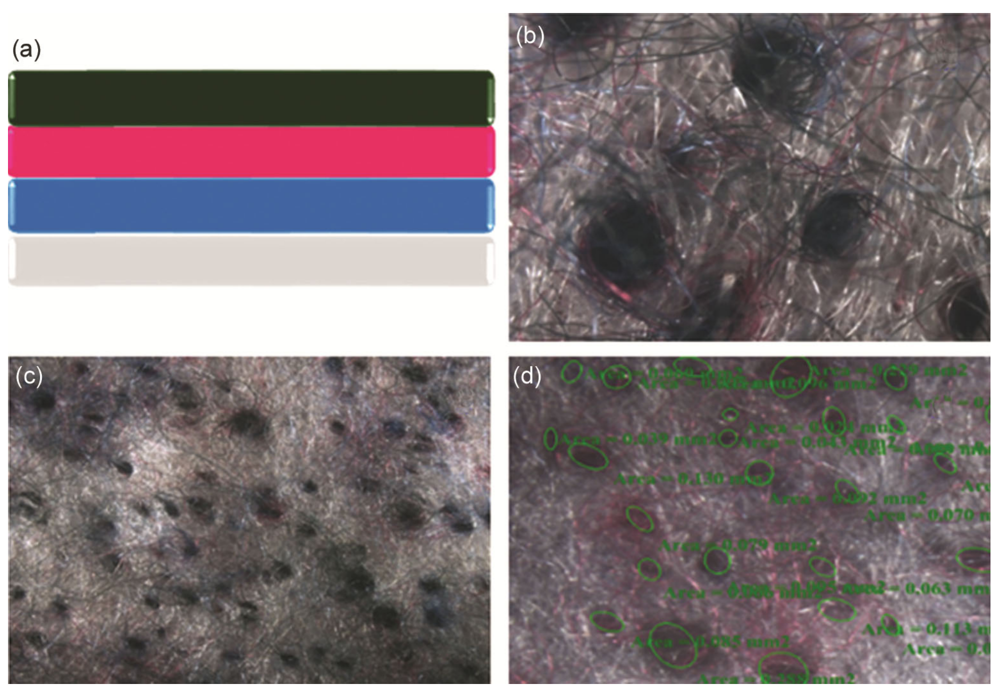

Fig. 2 — (a) Layering sequence of layers, (b) presence of different colours on bottom most layer after punching, (c) number of holes and (d) area covered by the holes

machine direction was determined. Total 100 fibres were taken into consideration for the measurement of fibre inclination angle.

Fibre Coverage Area (F_{ca})

The area covered by the projected length of fibre in X-Y direction of carded web in the machine direction is defined as fibre coverage area. The NIS Elements software is used to measure shaded fibre coverage area as illustrated in Fig. 1(b). The system measures the area in terms of pixel value.

Number of Fibre Cross-Over Points per Unit Area

It is a measure of number of fibre cross-over point per unit area of a carded web. The number of cross over point is likely to depend on the fibre extent, fibre inclination angle and curliness of fibre. Accordingly, the probability of the fibre to come in contact with the other fibres will be governed. In the present work, the number of cross-over points is measured per unit area. Schematic view of cross over points is shown in Fig. 1(d).

2.2.2 Three-dimensional Nonwoven Structure

Following three coefficients are proposed to analyze the vertical orientation (Z direction) of fibre due to needle punching:

Coefficient of Fibre Transfer in Z Direction

Coefficient of fibre transfer in Z direction of nonwoven fabric is the measure of ratio of area occupied by the different colour fibres of respective layer on the bottom most layer to total area of bottom grey layer [Fig. 2], as given below:

$$\text{Coefficient of fibre transfer in Z direction} = \frac{\text{Area occupied by respective colour fibre}}{\text{Total area of bottom grey layer}} \times 100$$

The webs are placed in a defined order as shown in Fig. 2(a). It is evident from Fig. 2(b) that bottom most grey layer shows higher presence of green fibres followed by red and blue.

Punched Hole

Number of punched hole per unit area is defined as actual number of holes created due to needle punching on carded fibre web per unit area as shown in Fig. 2(c).

Area occupied by the punched hole is the summation of the total area of punched holes created due to needle punching as shown in Fig. 2(d). The coefficient of area occupied by punched holes is expressed as given below:

$$\text{Coefficient of area occupied by punched holes } (K_{aoh}) = \frac{\text{Summation of total area of holes}}{\text{Sample area}} \times 100$$

2.3 Fibre Orientation by Lindley's Technique

Lindsley's combing and cutting method [17] is widely reported in the literature to study the fibre orientation in sliver and roving. In the present work, the Lindsley's technique is proposed to study the fibre orientation in carded web. The coefficients (proportion of curved fibre ends and coefficient of relative fibre parallelization) proposed by Leont'eva [18] are also used. The indices used for studying the fibre orientation in carded fibre web are described below.

The cutting ratio, combing ratio, orientation index, proportion of curved fibre ends and coefficient of relative fibre parallelization are defined as per the following equations:

$$\text{Cutting ratio} = \frac{E}{N} \quad \text{... (2)}$$

$$\text{Combing ratio} = \frac{C}{E+N} \quad \text{... (3)}$$

$$\text{Orientation index} = 1 - \frac{E}{N} \quad \text{... (4)}$$

$$\text{Proportion of curved fibre ends (p)} = \frac{E}{E+N} \quad \text{... (5)}$$

This [Eq. (5)] indicates about curved fibre ends as well as their length in fibrous material. Thus, the more the fibre curliness in fibrous material, the more will be the value of p.

The degree of fibre parallelization and straightening in fibrous material is represented by coefficient of relative fibre parallelization. Thus, more the fibre straightening and parallelization in fibrous material, the more is the value of *Kp*. The coefficient of relative fibre parallelization is expressed as given below:

$$\text{Coefficient of relative fibre parallelization (Kp)} = \left(1 - \frac{C}{C+E+N}\right) \times 100 \quad \text{...(6)}$$

where C is the weight of combed out portion under the side plate; *E*, the weight of the projected portion from the edge of the side plate after combing; and *N*, the weight of material after combing and cutting under the side plate.

2.4 Sample Preparation

Sample webs were prepared on trytex miniature card, and punching of webs was carried on Dilo needle punching line. In first set of experiments, the sample were prepared at variable cylinder speeds, i.e. 150 m/min, 180 m/min and 210 m/min but at a constant punch density of 150/cm^2, needle punch penetration of 8 mm and fabric basis weight of 200 g/m^2. In second set of experiments, samples were prepared as per the specification given in Table 1 at constant fabric basis weight of 200 g/m^2 with 4 layers having 50 gm/m^2 weight of each layer.

3 Results and Discussion

3.1 Influence of Cylinder Speed on Fibre Orientation

3.1.1 Tracer Fibre Technique

Fibre Extent

Table 2 shows the increase in fibre extent with the increase of cylinder speed. This is due to increase in centrifugal force on fibre with the increase of cylinder speed which further increases the fibre transfer efficiency with subsequent decrease in cylinder loading. This leads to better fibre opening and more fibre individualization, resulting in fibre straightening and parallelization as well as reduction in number of hooks towards machine direction. The F test was conducted by using ANOVA and results are significant at 95% confidence.

Coefficient of Fibre Curliness

It is evident from Table 2, that coefficient of fibre curliness increases with the increase in cylinder speed. Coefficient of fibre curliness is obviously found to increase with the increase of cylinder speed as explained above in the context of fibre extent.

Table 1 — Samples to find out the influence of punching parameters

Sample code	Punch density punches/cm^2	Needle penetration depth mm
PD100-ND6	100	6
PD100-ND8	100	8
PD100-ND10	100	10
PD150-ND6	150	6
PD150-ND8	150	8
PD150-ND10	150	10
PD200-ND6	200	6
PD200-ND8	200	8
PD200-ND10	200	10

Table 2 — Fibre structural characteristics at different cylinder speeds

Cylinder speed m/min	Fibre extent mm	Coefficient of fibre curliness	Fibre coverage area, mm^2	Anisotropy of fibre webs	Number of cross over points/cm^2
150	9.31	0.23	29.03	2.05	4.6
180	12.11	0.30	28.11	2.79	4.1
210	14.16	0.35	25.57	3.66	3.9

Fibre Coverage Area

The results of fibre coverage area (Table 2) show reducing trend with the increase of the cylinder speed. The possible reason of this trend is due to fibre straightening towards machine direction which is responsible for less curliness of fibre. The F test was conducted by using ANOVA and results are significant at 95% confidence level.

Fibre Inclination Angle

Fibre inclination angle is the angle of fibres along the machine direction of a carded web. The increase of cylinder speed makes fibres aligned towards the axis of machine direction which reduces the isotropy as shown in Table 2. The frequency distribution of inclination angle of fibre as reported by *Neckář et al.*[16] is used to define the isotropy, as shown below:

$$g(\psi) = \frac{1}{\pi}\frac{\xi}{\xi^2-(\xi^2-1)cos^2\psi} \quad ...(7)$$

where $g(\Psi)$ is the probability density function of all inclination angle Ψ measured; and ξ, the measure of anisotropy of fibre orientation in fibre web. Standard nonlinear regression technique is used to evaluate the anisotropy. It can be found that $\xi = \sqrt{g(0)/g(\pi/2)} \geq 1$ where $g(0)$ denotes the maximum probability density and $g(\pi/2)$ represents the minimum probability density of fibre orientation. Obviously, $\xi = 1$ indicates the ideal isotropic orientation and with the increase of ξ, anisotropy increases.

Figures 3(a)-(c) represent the histograms of fibre inclination angles of different fibre webs with different cylinder speeds. The twelve hundred readings of fibre inclination angle were grouped into twelve bins of equal range (15 deg). The values of parameter ξ are found to be 2.05, 2.79 and 3.66 for the cylinder speeds of 150, 180 and 210 m/min in Fig. 3(d). It can be concluded that the fibre webs with higher cylinder speeds are more anisotropic in nature.

Number of Cross-over Points

The results of number of cross-over points with the increase of cylinder speed are given in Table 2. The increase in fibre straightening and parallelisation with the increase of cylinder speed reduces the chances of fibres crossing with other fibres. Accordingly, the

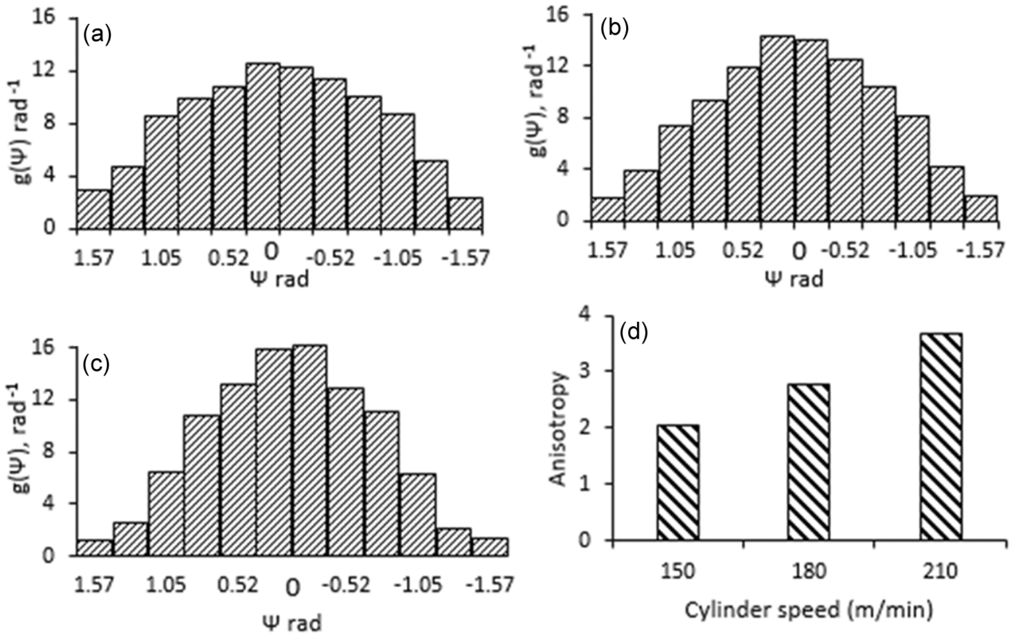

Fig. 3 — Distribution of fibre orientation at different cylinder speed (a)150m/min, (b) 180m/min and (c) 210m/min, and (d) anisotropy of all three fibre webs

Table 3 — Fibre structural characteristics at different cylinder speeds by Lindsley technique

Parameter	Cylinder speed m/min	Cutting ratio	Combing ratio	Orientation index	Proportion of curved fibre ends	Coefficient of relative fibre parallelization
Machine direction	150	0.158	0.665	0.842	0.136	0.601
	180	0.104	0.510	0.896	0.094	0.662
	210	0.034	0.393	0.966	0.033	0.718
Cross direction	150	0.065	2.291	0.935	0.061	0.304
	180	0.075	2.442	0.925	0.070	0.291
	210	0.092	2.626	0.908	0.084	0.276

reduction of number of cross-over points is noticed. The F test was conducted by using ANOVA and results are found significant at 95% confidence level for 150 m/min and 210 m/min of cylinder speeds.

3.1.2 Lindsley's Technique

Cutting Ratio and Combing Ratio

It is evident from Table 3 that the values of cutting ratio and combing ratio decrease in machine direction but increase in cross direction with the increase of cylinder speed. Because the fibres get more parallel in machine direction with the increase in cylinder speed, accordingly in cross-direction, it is found to be reverse. The F test was conducted by using ANOVA and results are significant at 95% level.

Orientation Index

The values of orientation index increases with the increase in cylinder speed in machine direction but decreases in cross-direction as noticed in Table 3. The departure of fibre from the axis of web reduces in machine direction but increases in cross direction. The F test was conducted by using ANOVA and results are found significant at 95% confidence level.

Proportion of Curved Fibre End

The proportion of curved fibre end is a reflection of curved/hooked fibres in the carded web. The higher the value of proportion of curved fibre end, the higher is the presence of curved and hooked fibres in carded web. It is observed from Table 3 that the value of proportion of curved fibre end reduces with the increase of cylinder speed. This confirms the reduction of the number of curved and hooked fibre in machine direction. But the opposite trend is noticed in the cross-direction. The F test was conducted by using ANOVA and results are found significant at 95% confidence level.

Coefficient of Relative Fibre Parallelization

The coefficient of relative fibre parallelization is an interpretation of fibre parallelization in carded web. Higher value indicates more fibre parallelization and lower value represents the disorientation of the fibres. The results of Table 3 depict the increase in coefficient of relative fibre parallelization with increase of the cylinder speed in machine direction but reverse trend is noticed in cross-direction. The F test was conducted by using ANOVA and results are found significant at 95% confidence level.

3.2 Influence of Cylinder Speed on Fabric Tensile Strength

It is observed from Fig. 4, that the tensile strength of nonwoven fabric increases in machine direction but decreases in cross-direction with the increase in cylinder speed. Higher cylinder speed offers more force to fibres to get parallel in the machine direction as explained above.

It is evident from Table 4 that measured structural characteristics based on both tracer fibre technique as well as Lindsley technique and fabric tensile strength show very good correlation in machine direction but poor correlation in cross-direction. Hence, it can be concluded that proposed structural characteristics provide reasonable information to better understand the structure and properties of nonwoven fabric. The F test was conducted by using ANOVA and results are found significant at 95% confidence level.

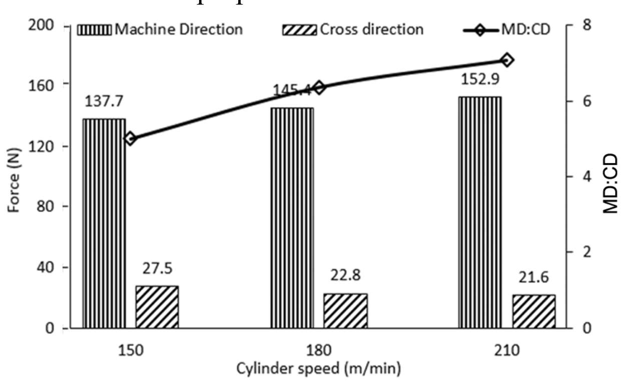

Fig. 4 — Influence of cylinder speed on tensile strength of nonwoven

3.3 Influence of Punching Parameters on Vertical Orientation (Z Direction) of Fibres

Coefficient of Fibre Transfer in Z Direction

Due to needle-punch action, the fibres are carried downward by the barb of the needle from upper layers to the bottom most grey layer. Figure 2(b) confirms maximum presence of green fibres followed by red and blue on bottom most grey layer having green fibre web at the top.

Image colour summarization technique is used to measure the area occupied by respective colour fibres on grey layer. The image processing software works with known pixel density i.e. 200 pixels/mm^2. Accordingly, the area occupied by respective colour fibres in 1.0 cm^2 of carded web is measured in terms of number of pixels.

Table 5 shows an increase in total area occupied by respective colour fibres with the increase of punch density and needle penetration depth. This confirms that more number of fibres are pushed downward by the needle barbs. Table 5 also depicts an increase in coefficient of fibre transfer in Z direction with the increase of punch density and needle depth penetration.

It is interesting to note that area occupied by the fibres of 1st layer (top layer) is found to be maximum followed by 2nd and 3rd layer fibres. It means, the contribution of fibres of 1st layer to interlock the nonwoven layered structure is maximum followed by 2nd and 3rd layer. The barb of the needle pushes the fibres downward during punching action. The number

Table 4 — Correlation between different measured structural characteristics and tensile strength of nonwoven fabric

Technique	Parameter	Machine direction	Cross direction
Tracer fibre	Fibre extent	0.994584	-0.69926
	Coefficient of fibre curliness	0.994584	-0.69926
	Fibre coverage area	-0.96231	0.598765
	Fibre inclination angle	-0.98636	0.70912
	Number of cross-over point	-0.96998	0.716484
Lindsley	Cutting ratio	-0.99523	0.663827
	Combing ratio	-0.99536	0.697599
	Orientation index	0.995233	-0.66383
	Proportion of curved fibre ends	-0.99235	0.654821
	Coefficient of relative fibre parallelization	0.997837	-0.68789

of fibres carried by barb depends on size and shape of the barb. Once barb gets filled with fibres, it will not carry more fibres of remaining layers downward. As the top web is coming against the barbs first, the majority of top web fibres are getting pushed downward in Z direction followed by second and third layered web. Therefore, more number of fibres are transferred from top layer followed by 2nd and 3rd layer on gray layer as observed in Table 6. These Z directional fibres act as binders for needle-punched nonwoven. The above discussions support the increase in web compactness that results in the reduction of fabric thickness with the increase of punching parameters.

It is observed from Fig. 5 that top most layer contributes 52–67 % of total fibres transferred in Z direction. The transfer of fibres in Z direction of top layer reduces with the increase of needle depth penetration. But, it is further noticed that the contribution of 2nd and 3rd layer fibres increases with the increase of punch density and needle penetration depth.

This is due to the higher penetration depth specially, because at higher depth of penetration more number of barbs are carrying the fibres from top to bottom layer. The barbs, situated near the tip of the needle, strike earlier, and carry fibres from top layer. The barbs which strike later (away from needle tip), could not get filled with the fibres of top layer, so they carry small number of fibres from next layers.

Number of Punched Hole per Unit Area

Holes are created by the needle punching action on carded fibre web. It is expected that the number of holes should be equal to the punch density. But in practice actual number of holes are lesser than needle punch density.

It is depicted from Table 6 that number of holes increases with the increase of punch density and needle punch penetration.

Table 5 — Area occupied by different colour fibres on bottom layer

Sample	Area occupied by colour fibre mm^2/cm^2				No. of pixels
	1st layer (red fibre)	2nd layer (green fibre)	3rd layer (blue fibre)	Total area	
PD100-ND6	5.24	1.88	0.70	7.82	1564
PD100-ND8	7.54	3.06	1.18	11.78	2355
PD100-ND10	9.70	5.78	3.17	18.66	3731
PD150-ND6	7.30	2.54	1.22	11.05	2210
PD150-ND8	14.75	6.53	2.90	24.17	4834
PD150-ND10	15.39	8.55	4.56	28.51	5701
PD200-ND6	7.35	2.57	1.75	11.67	2334
PD200-ND8	23.04	9.44	5.29	37.77	7554
PD200-ND10	25.19	11.93	7.07	44.20	8839

Table 6 — Influence of punching parameters on punched holes characteristics

Sample code	No. of holes	Area of holes per unit area of specimen mm^2/cm^2	Coefficient of area occupied by punched holes %
PD-100 ND-6	41	1.51	1.51
PD-100 ND-8	58	2.28	2.28
PD-100 ND-10	63	3.61	3.61
PD-150 ND-6	46	2.14	2.14
PD-150 ND-8	60	4.68	4.68
PD-150 ND-10	69	5.52	5.52
PD-200 ND-6	49	2.26	2.26
PD-200 ND-8	72	7.31	7.31
PD-200 ND-10	66	8.56	8.56

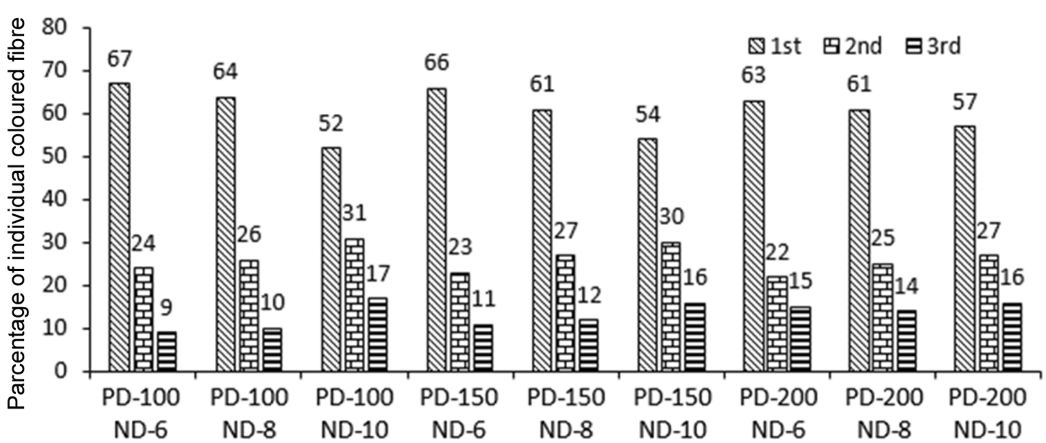

Fig. 5 — Percentage of different colored fibre from different layers on bottom layer

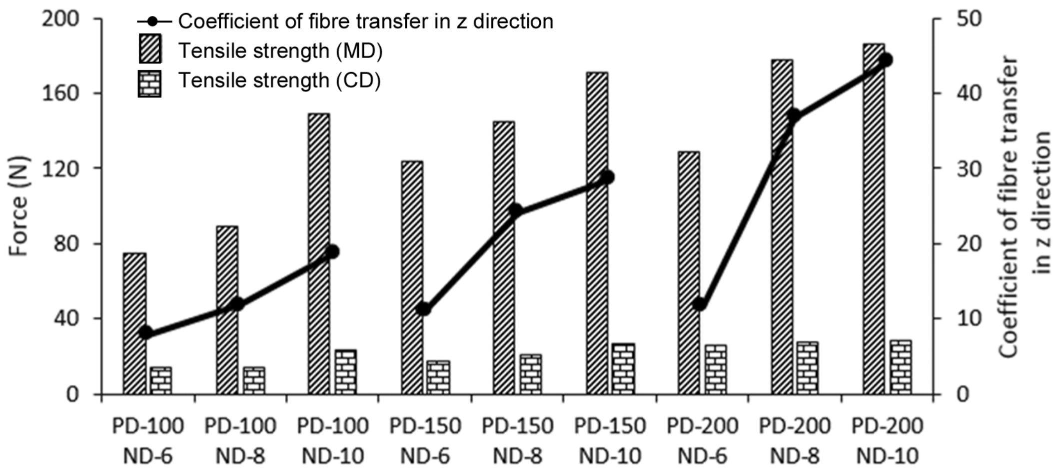

Fig. 6 — Relationship between tensile strength and coefficient of fibre transfer in Z direction

Coefficient of Area Occupied by Punched Holes

Figure 2(b) shows the formation of holes due to needle punching and Fig. 2(a) shows layer sequence used. Area of a specific hole is measured by tracing the boundary of the hole created by needling action as shown in Fig. 2(b).

It is observed from Table 6 that the increase of punch density and needle depth penetration increases the coefficient of area occupied by the punched holes (K_{aoh}). It is further noticed that the area occupied by the punched holes as well as the number of punched holes are increasing with the increase of punch density and needle penetration depth. It is interesting to note that the lowest value of the coefficient of area occupied by punched holes is observed to be 1.51 % at 'PD100-ND6' and the highest value is 8.56 % at 'PD200-ND10'. The F test was conducted by using ANOVA and results are found significant at 95% confidence level.

3.4 Relationship between Tensile Strength and Coefficient of Fibre Transfer in Z Plane

Figure 6 shows the relationship between tensile strength and coefficient of fibre transfer in Z direction. It is found that the tensile strength increases with the increase of the coefficient of transfer fibre in Z direction.

Transfer of more fibre indicates better binding between the layers of web. A strong correlation of 0.89 in machine direction and 0.92 in cross direction between tensile strength and coefficient of fibre transfer in Z direction is observed.

4 Conclusion

4.1 It is evident that measured structural characteristics based on both tracer fibre technique as well as Lindsley technique and fabric tensile strength show very good correlation in machine direction but poor correlation in cross-direction. Hence, it can be concluded that proposed structural characteristics provide reasonable information to better understand the structure and properties of nonwoven fabric.

4.2 Coefficient of fibre curliness increases but fibre coverage area and number of cross over points reduce with the increase of cylinder speed in the machine direction. The nonwoven webs have more anisotropic nature at higher cylinder speed.

4.3 Proportion of curved fibre end and coefficient of relative fibre parallelization give better understanding about the orientation of nonwoven web. Proportion of curved fibre end reduces and coefficient of relative fibre parallelization increases in the machine direction with the increase of cylinder speeds. The opposite trend is noticed in cross direction.

4.4 Coefficient of fibre transfer in Z direction and the coefficient of area occupied by the punched holes increase with the increase of punch density and needle depth penetration,

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