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Effect of fibre orientation on mechanical and functional properties of needle-punched nonwoven

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An attempt has been made to study the effect of fibre orientation, measured by the structural characteristics, on mechanical and functional properties of needle-punched nonwoven by varying the carding machine and punching parameters. It is observed that all measured physical, mechanical and functional properties of nonwovens have strong correlation with the proposed structural characteristics. Cylinder speed, punch density and needle depth penetration have significant effect on fabric thickness, air permeability, pore diameter, filtration efficiency and pressure drop.

Keywords: Air permeability, Filtration efficiency, Nonwoven structure, Needle-punched nonwoven, Pore diameter, Structural characteristics

1 Introduction

Nonwovens are known as the engineered materials, produced by low cost and high volume processes. The various applications of these nonwovens include filters for industrial separation processes, absorbent for consumers & industrial applications, composites for civil & geotechnical applications, and thermal insulators for buildings & apparel application. It is known that working principle of nonwoven card and flat revolving card (used for manufacturing of yarn) are more or less the same. Both the cards produce the web for their respective end uses. It has been established by researchers[1-3] that carding variables are responsible for influencing the fibre orientation of carded web. Lawrence *et al.*[4] proposed hypothesis for the mechanism of fibre transfer, and also considered its importance on the fibre transfer of the relative angles and tooth lengths of the cylinder and doffer.

It has also been reported[5-7] that among all process parameters of spun yarn technology, the carding parameters are the most contributing factors influencing the yarn qualities. Ishtiaque *et al* [8-9] studied the importance of opening of fibre at carding stage. They found that the increase in fibre openness at carding reduces irregularity and enhances the yarn tenacity but up to a certain limit.

But the literature is quiet silent on very important aspect that how the machine parameters of nonwoven card will influence the fibre orientation in card web which is mainly responsible for the mechanical and functional properties of nonwoven. In practice, the fibre orientation in nonwoven is characterized by the ratio of the tensile strength of the nonwoven in machine direction to that in cross direction. But it is a well-known fact that the mechanical and functional properties of nonwoven fabrics are highly influenced by the fibre orientation of card web and also the properties of constituent fibres.

There are wide range of needle-punched nonwoven filter media of various basis weight (g/m^2) for their use in industrial and home filtration application. Kothari *et al.*[10] have carried out a work on processing parameters. They concluded that finer fibre-based nonwoven fabric provides lower air permeability, and the increase in punching density reduces air permeability. Das *et al.*[11] carried out a comparative study between thermo-bonded and needle-punched nonwoven. They found that needle-punched nonwoven performs better in terms of filtration efficiency and pressure drop. Anandjiwala and Boguslavsky [12] have developed different natural and synthetic fibre-based nonwoven fabrics by systematically changing the machine variables which influence the physical properties of needle-punched nonwoven fabrics. Lee and Kung[13] studied the mechanical properties of nonwovens, and concluded that the tensile strength increases with increase in needle-punch density. Maity and Singha[14] considered

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fibre segments as fibre sections between any two crossover points and this can be treated as minimal units in a web. Owing to fibre bonds or surface contacts at crossover points, even the segments on the same fibre may differ significantly in their mechanical performance.

In the present investigation, an attempt has been made to study the effect of fibre orientation, measured by using structural characteristics[15] on mechanical and functional properties of needle-punched nonwoven by varying the carding machine and punching parameters.

2 Materials and Methods

2.1 Sample Preparation

Viscose fibres of staple length 38 mm 1.5 denier was used. Sample webs were prepared on trytex miniature card, and card web punching was carried on Dilo needle-punching line. In first set of experiments, the samples were prepared at variable cylinder speeds (150 m/min, 180 m/min and 210 m/min) but at a constant punch density (150/cm^2), needle penetration (8 mm), and fabric basis weight (200 g/m^2). For second set of experiments, 9 samples were prepared as per plan given in Table 1, at constant fabric basis weight (200 g/m^2) with 4 layers having 50 g/m^2 weight of each layer.

2.2 Evaluation of Properties

The physical, mechanical and functional properties, like basis weight, thickness, compression/recovery, air permeability, mean pore size and filtration efficiency, were measured by using ASTM and BS standard. ASTM standard D6242 was followed to measure the basis weight of nonwoven fabrics.

2.2.1 Fabric Thickness

The thickness of the fabrics was measured according to ASTM D1777-96 standard with the Essdiel thickness gauge at a pressure of 20 gf/ cm^2.

Table 1 — Experimental plan

Sample code	Punch density/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

2.2.2 Compressional Properties

The study on compression was carried out on Instron tensile tester, using dynamic loading mechanism. The sample was subjected to loading and unloading cycle under the different pressure conditions at an interval of 0.13 N/s. The obtained graph is shown in Fig. 1.

Compressional resilience (R_C) was calculated by the following equation:

$$R_C = \frac{\int_0^{S_M} F_D S\ (ds)}{\int_0^{S_M} F_A S(ds)} \times 100\%$$

where $F_A S$ is the pressure load during the compression stage; $F_D S$, the pressure load during the compression recovery stage; S, the displacement; and S_m, the maximum displacement.

2.2.3 Fibre Volume Fraction

Fibre volume fraction was calculated based on fabric thickness and areal density, using the flowing relationship:

$$\text{Fibre volume fraction} = \frac{\text{density of fabric}}{\text{density of fibre}}$$

2.2.4 Air Permeability

Air permeability of the fabric was measured using Textest FX 3300 air permeability tester at a pressure of 125Pa as per BS 5636. A sample size of ten was considered for air permeability measurement.

2.2.5 Pore Size Distribution

A capillary flow porometer (Porolux™1000, Germany) was used to measure the pore size distribution as well as the mean and maximum pore sizes of the specimen prepared. The membrane was wetted with a low surface tension liquid (Porofil,

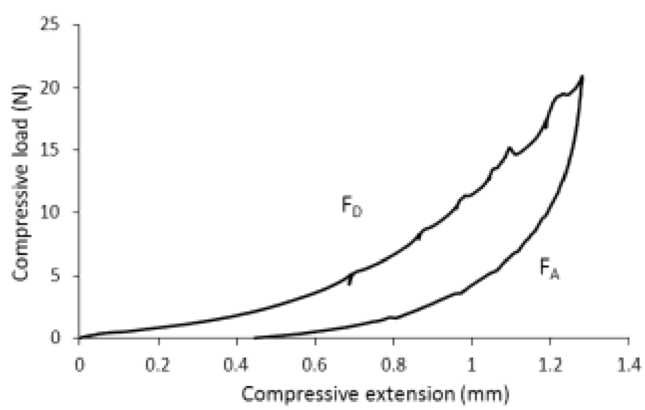

Fig.1 — Typical load elongation curve

16mN/m) and placed in a sealed-chamber that was then pressurized with nitrogen gas.

2.2.6 Filtration Efficiency

The filtration efficiency and pressure drop of the nonwoven fabrics were measured by employing a purpose built air filtration set up, as proposed by Pradhan *et al.*[16].

3 Results and Discussion

3.1 Influence of Cylinder Speed on Properties of Nonwoven

The results of different properties of nonwoven influenced by cylinder speed are given in Table 2.

3.1.1 Fabric Thickness

It is observed from Table 2 that the thickness of nonwoven fabric decreases with the increase in cylinder speed. The decrease in fabric thickness is mainly due to improved fibres orientation as explained by Roy and Ishtiaque[15]. Higher cylinder speed leads to increase the coefficient of relative fibre parallelization but reduces the proportion of curved fibre end with expected outcome of fibre straightening and parallelization as well as reduction in number of hooks towards machine direction which ultimately increases fibre extent.

On the other hand, with the increase in cylinder speed, the fibres get aligned towards the axis of machine direction which also reduces fibre inclination angle, resulting in reduction of isotropy. The decrease in fabric thickness is found to be higher from 150 m/min cylinder speed to 180 m/min cylinder speed in comparison to cylinder speed from 150 m/min to 210 m/min.The F test is conducted by using ANOVA and results are found significant at 95% confidence level at different stages of cylinder speeds.

3.1.2 Compressional Properties

Table 2 shows that at a constant compressive load, the compressive extension is found to be highest at 150 m/min cylinder speed followed by 180 m/min and 210 m/min. The observed trend can be explained on the basis of results of fabric thickness with cylinder speed.

It is noticed from Fig. 2 and Table 2 that the compression percentage and compressional resilience decrease with the increase in cylinder speed. It is further noticed that percentage decrease in compression is more from cylinder speed 150 m/min to 180 m/min in comparison to cylinder speed from 180 m/min to 210 m/min, but percentage decrease in compressional resilience is found to be lower from cylinder speed 150 m/min to 180 m/min in comparison to cylinder speed from 180 m/min to 210 m/min. This may be clue to the structural instability at lower cylinder speed. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.1.3 Fibre Volume Fraction

The fibre volume fraction of nonwoven also increases with the increase in cylinder speed as shown in Table 2. The increase in fibre volume fraction is mainly due to change in fabric thickness with the increase in cylinder speed as explained above. The improved fibres orientation also reduces fibre orientation angle and crossover point per unit area, as observed by Roy and Ishtiaque[15]. All above factors create opportunity to bring fibres closer with each other with the increase in cylinder speed and thus increases the fibre volume fraction.

3.1.4 Air Permeability

It is depicted from Table 2, that air permeability decreases with the increase in cylinder speed. But air

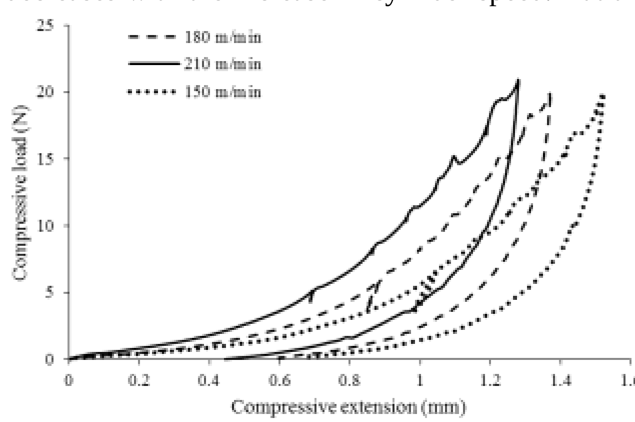

Fig. 2 — Compression and recovery behavior at different cylinder speed

Table 2 — Different properties with varying cylinder speed

Cylinder speed m/min	Thickness mm	Compression %	Compressional resilience, %	Fibre volume fraction, %	Air permeability $m^3/m^2/min$	Pore diameter µm	Pressure drop, Pa
150	2.998	50.7	46.33	0.0448	71.4	24.54	70.32
180	2.852	47.69	44.25	0.0471	67.6	22.52	80.43
210	2.726	46.59	42.03	0.0492	55.6	19.78	88.97

permeability is very much dependent on fibre volume fraction and is inversely proportional to fibre volume fraction. As observed from Table 2, fibre volume fraction shows increasing trend with the increase in cylinder speed. Therefore, the reasoning's given above for fabric thickness and fibre volume fraction support the trend of air permeability with the increase in cylinder speed. The decrease in air permeability is found to be lower from 150m/min cylinder speed to 180 m/min cylinder speed in comparison to cylinder speed from 150 m/min to 210 m/min. The F test is conducted by using ANOVA and results are found significant at 95% confidence level at different stages of cylinder speeds.

3.1.5 Mean Flow Pore Diameter

The results of mean flow pore diameter are reported in Table 2, which clearly shows that the mean flow pore diameter reduces with the increase in cylinder surface speed. It is observed by Roy and Ishtiaque[15] that the increase in cylinder speed results in better fibre extent and lesser fibre orientation angle, which allow the fibres to get closer with each other. Further it is observed that the proportion of curved fibres decreases and coefficient of fibre parallelization increases with the increase in cylinder speed which indicates less number of hooks and improved fibre straightening and parallelization in the carded web.

The observed trends support for higher fabric thickness with smaller pore diameter. The decrease in pore diameter is found to be lower from 150m/min cylinder speed to 180 m/min cylinder speed in comparison to cylinder speed from 150 m/min to 210 m/min. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.1.6 Filtration Efficiency

Filtration efficiency is a dependent variable of air permeability, fabric thickness, fibre volume fraction, pore diameter and pressure drop of nonwoven fabrics. Figure 3 shows that the filtration efficiency increases with the increase in cylinder speed. The observed trends are valid for all different sizes of particles. It is further noticed that the filter efficiency increases as the size of the particles also increases. In earlier discussion, it has been established that the air permeability and fabric thickness decrease but fibre volume fraction increases with the increase in cylinder speed. The results of Table 2 summarise that the air permeability decreases but filtration efficiency increases with the increase in cylinder speed. Further, it is observed that filtration efficiency decreases with the increase in fabric thickness, because the fibre volume fraction reduces with the increase in fabric thickness.

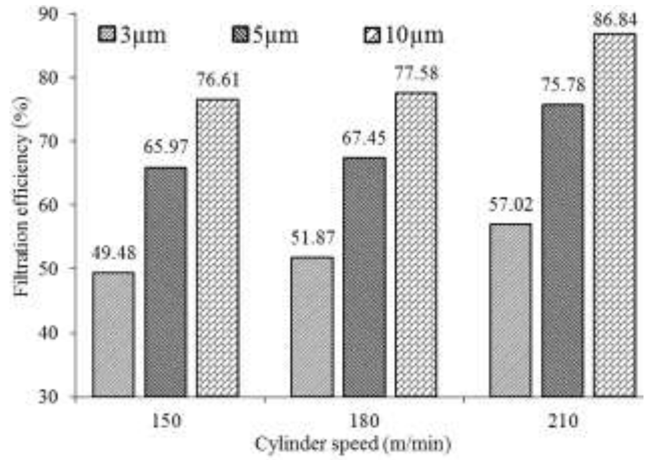

Fig. 3 — Relation between cylinder speed and filtration efficiency

Therefore, it can be concluded that the filtration efficiency increases with the decrease in fabric thickness, air permeability, and pore diameter. These changes are likely to be responsible to affect the filtration performance. The increase in filtration efficiency is found to be lower from 150m/min cylinder speed to 180 m/min cylinder speed in comparison to cylinder speed from 150 m/min to 210 m/min. The trend is valid for all particle size. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.1.7 Pressure Drop during Filtration

A good filter should have high dust arresting capacity with low pressure drop at the same time. Accordingly, pressure drop has been evaluated while measuring the filtration efficiency on the same instrument. Table 2 shows the trend of pressure drop with the increase in cylinder speed. It is noticed that the pressure drop is maximum at 210 m/min cylinder followed by 180 m/min cylinder speed and 150 m/min cylinder speed. It is a known fact that pore size decides the pressure drop during filtration and it is already established above that pore size reduces with increase in cylinder speed. Therefore, the decrease in pore size with the increase in cylinder speed results in more pressure drop.

The increase in pressure drop is found to be higher from 150m/min cylinder speed to 180 m/min cylinder speed in comparison to cylinder speed from 150 m/min to 210 m/min. The F test was conducted by using

ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

It is interesting to note from Table 3 that all the measured physical, mechanical and functional properties of nonwovens have strong correlation with the measured structural characteristics as studied by Roy and Ishtiaque[15]. Therefore, it can be concluded that physical, mechanical and functional properties of nonwovens are largely influenced by the structural characteristics.

3.2 Influence of Punching Parameters on Physical, Mechanical and Functional Properties

The results of punching parameters on physical, mechanical and functional properties of nonwoven are given in Table 4.

3.2.1 Fabric Thickness

The Table 4 shows that fabric thickness decreases with the increase in needle-punch density and needle depth penetration. The obtained results can be explained on the basis of coefficient of fibre transfer in Z direction as reported by Roy and Ishtiaque[15].

The results confirm the increase in coefficient of fibre transfer in Z direction with the increase in both punch density as well as needle depth penetration. The increase in coefficient of fibre transfer in Z direction will provide more interlocking of different layers of nonwoven fabric. It is further noticed that the contribution of fibres of first layer (top layer) to interlock the nonwoven layers is found to be highest followed by second and third layer in four layers fabric with the increase in punching parameters. The above discussions support the increase in web compactness, which results in the reduction of fabric thickness with the increase in punching parameters. The increase in fabric compactness as a result is responsible for influencing the other properties of nonwoven. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.2.2 Compression and Compressional Resilience

The results of compressional behaviour of the fabric are given in Table 4 and Fig. 4. It is an established fact that the compressional properties of the fabric will depend on fabric thickness. The fabric with higher thickness and lower compactness compresses more and accordingly the compressional resilience is also found to be higher.

It is observed that the fabric with higher value of punching parameters shows lower value of

Table 3 — Correlation with structural characteristics and properties of nonwoven

Structural characteristics	Thickness	F/V fraction	Air permeability	Pore diameter	Filtration	Pressure drop
Tracer fibre technique						
Fibre extent	-0.99893	0.969563	-0.92949	-0.9946	0.864472	0.9995
Coefficient of curliness	-0.99893	0.969563	-0.92949	-0.9946	0.864472	0.9995
Area covered	0.953397	-0.93456	0.999687	0.9982	-0.98491	-0.9971
Angle of fibre	0.993308	-0.96226	0.901631	0.9399	-0.82747	-0.9774
Cross over point	0.980039	-0.94715	0.861969	0.8811	-0.7772	-0.9370
Lindsley						
Cutting ratio	0.993532	-0.96856	0.976393	0.9999	-0.93353	-0.9997
Combing ratio	0.999336	-0.97022	0.933059	0.9874	-0.86935	-0.9997
Orientation index	-0.99353	0.968565	-0.97639	-0.9999	0.93353	0.9926
Proportion of curved fibre ends	0.989464	-0.96544	0.98271	-0.9908	-0.94435	-0.9909

Table 4 — Nonwoven properties with varying punch density and needle penetration depth

Sample	Thickness mm	Compression %	Compressional resilience, %	Fibre volume fraction, %	Air permeability $m^3/m^2/min$	Pore diameter µm	Pressure drop Pa
PD-100 ND-6	3.72	56.45	49.12	0.038	62.33	25.36	69.44
PD-100 ND-8	3.26	55.21	38.37	0.042	57.52	22.58	80.82
PD-100 ND-10	2.66	41.35	34.61	0.050	50.02	19.46	105.89
PD-150 ND-6	3.18	51.89	46.58	0.043	57.72	25.33	83.12
PD-150 ND-8	2.75	48.12	35.09	0.049	55.58	22.26	86.90
PD-150 ND-10	2.32	38.79	34.26	0.057	53.77	20.62	94.05
PD-200 ND-6	3.15	39.68	39.16	0.043	52.72	23.81	97.20
PD-200 ND-8	2.63	38.78	31.88	0.052	64.75	24.19	73.40
PD-200 ND-10	2.12	35.38	32.03	0.061	67.05	26.95	64.31

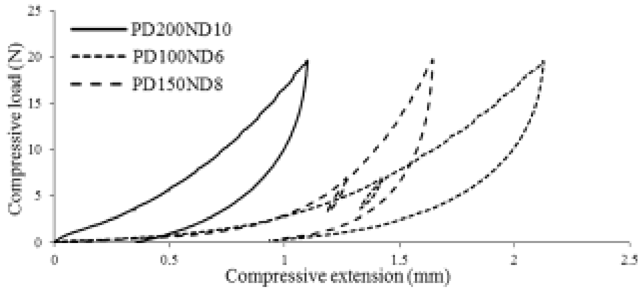

Fig. 4 — Compression and compressional resilience at different cylinder speed

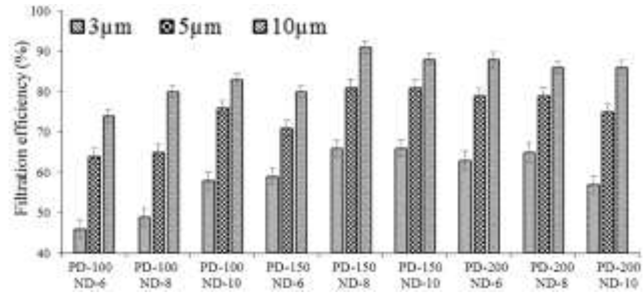

Fig. 5 — Filtration efficiency of 3, 5 and 10 µm particle with different punching parameters

compression percentage and compression resilience in comparison to lower value of punching parameters. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.2.3 Fibre Volume Fraction

Table 4 clearly indicates that fibre volume fraction increases with the increase in punch density and depth of penetration. The obtained trend can be explained on the basis of relationship between punching parameters and fabric thickness, as already discussed above.

3.2.4 Air Permeability

Air permeability is a dependent variable of fabric thickness and fibre volume fraction. A decrease in air permeability is noticed with the increase in punch density and needle penetration. But the air permeability increases with the increase in needle depth penetration at 200/cm^2 punch density. The obtained trend can be explained on the basis of creation of number and size of holes due to needle-punching, as observed by Roy and Ishtiaque[15]. The results confirm the increase in number of holes per unit area and coefficient of area occupied by punched holes with the increase in punch density and needle depth penetration, which allows air to pass through.

It is further noticed that with the increase in needle depth penetration at 200/cm^2 punch density, number of holes as well as coefficient of area occupied by punched holes are found to be highest. On the basis of above explanation, the increase in air permeability with the increase in needle depth penetration at 200/cm^2 punch density can be justified. Pourdeyhimi *et al*. [17] concluded that fibre orientation becomes more random with the increase in needle-punch density and hence reduces mean fibre length up to 30%. Kothari *et al.* [10] observed fibre breakage at high punching density. This leads to increase the short fibre, which in turn, increases air permeability. The F test is conducted by using ANOVA and results are found significant at 95% confidence level at different stages of cylinder speeds.

3.2.5 Mean Flow Pore Diameter

Pore diameter is very important physical property of nonwoven fabric, which decides the air permeability and filtration capability of the fabric. The results of mean flow pore diameter are reported in Table 4.

It is noticed that the pore diameter decreases with the increase in punching parameters up to 150/ cm^2 punch density. However, at 200/cm^2 punch density, pore diameter increases with the increase in needle depth penetration. The initial decrease in pore diameter with the increase in punching parameters can be explained on the basis of decrease in fabric thickness. But the increase in pore diameter with the increase in needle depth penetration at 200/cm^2 punch density can be supported with the results of air permeability. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.2.6 Filtration Efficiency

The results of filtration efficiency for different particle sizes are given in Fig. 5.

Filtration Efficiency of 3µm Particle Size

The results of filtration efficiency of 3µm particle size at different punch density are shown in Fig. 5. The filtration efficiency continuously increases with the increase in needle depth penetration at 100/cm^2 punch density. But at 150 /cm^2 punch density, filtration efficiency increases with the increase needle depth penetration up to 8 mm then remains constant upto 10 mm needle depth penetration.

With further increase in punch density upto 200/cm^2, filtration efficiency increases up to 8 mm needle depth penetration but it reduces with further increase in needle depth penetration. But overall, the filtration efficiency is found to be slightly lower at 200/cm^2 punch density in comparison to that at 150 /cm^2 punch density for all needle depth penetration.

Filtration Efficiency of 5μm Particle Size

Particle size of 5μm gives almost similar trends as already noticed for 3μm particle size with the increase in punching parameters. But the fabrics having higher penetration depth with 150/cm^2 punch density and lower penetration depth with 200/cm^2 punch density are performing better in terms of filtration efficiency.

Filtration Efficiency of 10μm Particle Size

Filtration efficiency of all the fabrics found to be better for 10 μm particle size. Figure 5 shows the increase in filtration efficiency with the increase in needle depth penetration at 100/ cm^2 punch density. But at 150/cm^2 punch density, filtration efficiency increases up to 8 mm needle depth penetration and latter it reduces. On further increase in punch density up to 200/cm^2, the filtration efficiency is found to be maximum at 6mm needle-punch penetration. But latter it reduces and remains constant up to 10 mm needle-punch penetration. However, the fabric with PD150-ND8 punching parameters gives highest filtration efficiency.

Overall Filtration Efficiency

Figure 5 shows a comparative study drawn for all three particle size at different punching parameters. It can be concluded that the fabric with 150/cm^2 punch density and 8 mm needle penetration depth gives maximum filtration for all particle sizes. The F test is conducted by using ANOVA and the results are found significant at 95% confidence level at different stages of cylinder speeds.

3.2.7 Pressure Drop during Filtration

Pressure drop is also measured during the measurement of filtration efficiency and results are shown in Table 4. The result shows an increase in pressure drop with the increase in punch density and punch depth. But the air pressure drop decreases with the increase in needle depth penetration at 200/cm^2 punch density.

The observed trend can be supported with the explanation given above for mean flow pore diameter. Because high needle depth penetration creates more number of holes with higher area at 200/cm^2 punch density, as a result the pressure drop is found to be least for sample PD200-ND10.

3.3 Correlation Between Different Coefficient and Mechanical & Functional Properties

It is now very much required to find out the correlation of all the properties with punching parameters. Table 5 shows the correlation between the coefficient of fibre transfer in Z direction and other parameters.

It is found that the coefficient of fibre transfer in Z direction, coefficient of punched holes and coefficient

Table 5 — Correlation between different coefficient and mechanical/functional properties

Conditions	Coefficients	Thickness	Compression	Recovery	Fibre volume fraction	Air permeability	Pore diameter	Filtration efficiency			Pressure drop
								3μm	5μm	10μm	
Constant punch density with increasing needle penetration depth	Coefficient of transferred fibre in z direction	-0.960	-0.848	0.929	0.931	-0.965	-0.994	0.971	0.971	0.874	0.896
	Coefficient of punched hole	-0.992	-0.921	0.976	0.977	-0.994	-0.999	0.922	0.922	0.786	0.955
	Coefficient of area occupied by holes	-0.944	-0.818	0.908	0.910	-0.950	-0.987	0.983	0.983	0.899	0.871
Constant needle penetration depth with increasing punch density	Coefficient of transferred fibre in z direction	-0.940	-0.990	0.868	0.960	0.751	-0.877	0.836	0.800	-0.795	0.984
	Coefficient of punched hole	-0.742	-0.971	0.991	0.783	0.945	-0.993	0.957	0.937	0.756	0.843
	Coefficient of area occupied by holes	-0.934	-0.992	0.877	0.954	0.763	-0.885	0.826	0.789	0.663	0.980

of area occupied by holes have very strong correlation with the physical, mechanical and functional properties of nonwoven fabrics.

4 Conclusion

After detailed study, following general conclusions are drawn:

4.1 All measured physical, mechanical and functional properties of nonwovens have strong correlation with the measured structural characteristics in X and Y directions of fabric. Coefficient of fibre transfer in Z direction, coefficient of punched holes and coefficient of area occupied by holes have very strong correlation with the physical, mechanical and functional properties of nonwoven fabrics. Therefore, it can be concluded that physical, mechanical and functional properties of nonwovens are largely influenced by the measured structural characteristics.

4.2 Fabric thickness, air permeability and pore diameter decrease but filtration efficiency and pressure drop increase with the increase in cylinder speed.

4.3 Fabric thickness decreases with the increase in needle-punch density and needle depth penetration. But air permeability and pore diameter decreases with the increase in punch density and needle penetration. But at 200/cm^2 punch density, the air permeability and pore diameter increase with the increase in needle depth penetration.

4.4 It can be concluded that the fabric with 150/cm^2 punch density and 8 mm needle penetration depth gives maximum filtration for all particle sizes. Pressure drop increases with the increase in punch density and needle penetration depth but at higher punch density (200/cm^2), the air pressure drop decreases with the increase in needle depth penetration.

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