

Thermal insulation, compression and air permeability of polyester needle-punched nonwoven

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The normal round, circular hollow and trilobal cross-sectional shaped polyester fibres have been used to prepare needle-punched nonwoven fabrics for technical textile application. Effects of fabric weight and fibre cross-sectional shapes on thermal insulation value (TIV), fabric thickness, density, percentage compression, air permeability and sectional air permeability (SAP) have been studied. Comparison between Marsh and plate methods of TIV measurement has also been studied along with the inter-relation and grouping of parameters using correlation matrix and cluster analysis approach respectively. The TIV, thickness, density, air permeability and SAP fall under different sub-cluster but all these parameters are dependent on fabric weight. Plate method of TIV measurement is preferred over Marsh TIV measurement because of the easy preparation of samples and the reason that the samples retain their original properties and it gives more accurate results. Trilobal fabric sample shows highest TIV, thickness and percentage compression followed by regular and hollow polyester needle-punched fabrics. Thermal insulation value, thickness and density of the fabric increase but percentage compression, air permeability and SAP decrease with the increase in fabric weight. The fabric thickness is significantly correlated with fabric weight and TIV. Fabric weight versus air permeability and fabric density versus SAP are negatively correlated with significant correlation coefficient.

Keywords: Air permeability, Cluster analysis, Compression, Cotton, Fibre cross-sectional shape, Needle-punched nonwoven, Polyester fibre, Thermal insulation value

1 Introduction

Polyester has various textile and industrial applications due to its easy availability at comparatively lower cost, and favorable physical and mechanical properties. With the advancement of fibre technology, this fibre is also available with different fibre cross-sectional shapes. Talukdar *et al.*¹ found that the nonwoven fabrics made with the trilobal fibre require slightly more needling density, higher depth of needle penetration and area density to have the same bending length as those of the fabrics made of round polyester fibre. Thermal insulation property is one of the very important properties of the textile materials for technical textile applications. The methods commonly used to measure the thermal insulation values (TIV) are the disk method, the constant temperature method and the cooling method.

Among these methods, cooling method is the simplest one². Paul and Mukhopadhyay² have measured the thermal insulation of various types of jute fabrics. They found that the TIV is directly proportional to thickness as well as number of layers of the fabric. Recently, in the era of digital electronics, Roy *et al.*³ has developed a digital thermal insulation value tester for jute products as well as for other textile and non-textile materials. Testing with this instrument for sample with area not less than 700 cm² requires no sample preparation. The test is non-destructive and process of sample preparation is free from human error.

Sometimes, various physical properties of needle-punched nonwoven are inter-related among others. Balasubramanian *et al.*⁴ reported that with the increase in web weight, the abrasion resistance of the fabric increases due to better anchoring of fibres with the fabric structure. The bending length also increases due to the increase in consolidation. Studies on the

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Table 1—Properties of polyester fibres

Fibre cross-sectional shape	Fibre staple length mm	Linear density tex	Crimp frequency crimps/cm	Tenacity cN/tex	Breaking extension %	Crimp %
Round	51	0.33	5.04	34.83	51.00	18.00
Circular hollow	51	0.33	4.72	38.43	21.05	17.00
Trilobal	51	0.33	5.12	37.53	50.28	18.00

effect of fabric weight and fibre cross-sectional shapes on other important physical properties like air permeability, compression, thermal insulation value, thickness and density are found to be scanty. Thermal insulation is widely dependent upon the structure of final textile material². In the present study, polyester fibres of three different cross-sectional shapes i.e. normal round (regular), circular hollow and trilobal have been used to prepare the needle-punched nonwoven fabric. Effects of fibre cross-sectional shapes and fabric weight on thermal insulation, thickness, density, compression and air permeability of the polyester needle-punched fabrics have been studied. Correlation matrix and cluster analysis approach have been used to study the relationship and grouping behaviour among the variables.

2 Materials and Methods

2.1 Materials

Polyester fibre of 51 mm length and 0.33 tex fineness was used to prepare needle-punched samples. Cotton fabric was used as reinforcing material. The properties of the polyester fibre and reinforcing cotton fabric are shown in Tables 1 and 2 respectively.

2.2 Methods

2.2.1 Preparation of Polyester Fabrics

The polyester fabric samples were made from parallel-laid webs, which were obtained by feeding opened fibres in the TAIRO laboratory model with stationary flat card. The fine web emerging out from the card was built up into several layers in order to obtain desired level of fabric weight. The needle punching of all parallel-laid polyester fabric samples was carried out in James Hunter Laboratory Fiber Locker [Model 26 (315 mm)] having a stroke frequency of 170 strokes/min. The machine speed and needling density were selected in such a way that in a single passage, 50 punches/cm² of needling density could be obtained on the fabric. The web was passed through the machine for a number of times depending upon the needling density required, for example the web was passed six times through the machine to

Table 2— Properties of cotton reinforcing material

Property	Value
Yarn linear density, tex	
Warp	14.77 (40.00 ^s Ne)
Weft	17.96 (32.88 ^s Ne)
Yarn density	
Ends/cm	23.62
Picks/cm	18.90
Fabric weight, g/m ²	76.25
Breaking extension, %	17.25
Tenacity at break, cN/tex	6.23

Table 3— Constructional details of experimental fabric samples

Fabric code	Fibre cross-sectional shape	Nominal fabric weight, g/m ²	Needling density punches/cm ²
R1	Round	415	300
R2	Round	515	300
R3	Round	680	300
R4	Round	815	300
H1	Circular hollow	415	300
H2	Circular hollow	515	300
H3	Circular hollow	680	300
H4	Circular hollow	815	300
T1	Trilobal	415	300
T2	Trilobal	515	300
T3	Trilobal	680	300
T4	Trilobal	815	300

obtain fabric with 300 punches/cm². The needling was done alternatively on each side of the polyester fabric⁵. Constructional details of experimental fabric samples are shown in Table 3. The dimension of the needle was taken as 15 × 18 × 36 × R/SP 3½ × ¼ × 9, as is used generally for all jute-polypropylene, jute and polyester samples. The depth of needle penetration was kept constant at 11 mm in all the cases. The actual fabric weights of the final needle-punched fabric samples were measured by randomly cutting 1 m² specimen at five different places from each sample.

2.2.2 Measurement of Thermal Insulation Value

The thermal insulation value was measured by two different methods, viz. thermal insulation by Marsh cooling method² and plate method³ (BS 4745-1974).

In Marsh cooling method^{2,6}, a hot body was wrapped with the fabric sample and its rate of cooling

was measured. The outer surface of the fabric was exposed to air. The time taken by a hot body covered with fabric sample (t_c) and without the fabric sample (t_u) to cool through a particular temperature range under identical atmospheric conditions was observed. In this experiment^{2,6}, a brass cylinder (45 cm length, 5 cm external diameter and 2 mm thickness) closed at one end with a cork was filled with distilled water heated to about 50°C. The mouth of the cylinder was closed with a cork through which a thermometer was inserted. A rectangular specimen of fabric was used to cover the whole of the outer surface of the brass tube. The experiment was started when the temperature of the water was exactly 48°C. A stopwatch was used to measure the time taken for the temperature to drop down to 38°C. The thermal insulation value was calculated using following relationship:

$$\text{TIV} = t_c / t_u \quad \dots(1)$$

$$\text{TIV} (\%) = [1 - (\text{Heat loss by covered hot body}) / (\text{Heat loss by uncovered hot body})] \times 100 \dots(2)$$

$$= [1 - (\text{Fall in temp by covered hot body}) / (\text{Fall in temp by uncovered hot body})] \times 100 \dots(3)$$

In the experiment, as the temperature range (48°C-38°C) through which the covered and uncovered hot body cools is kept the same, the TIV will vary with time and its value is chosen for calculation using the following equation:

$$\text{Marsh}^{2,6} \text{ TIV} (\%) = [1 - (t_{u(48^\circ\text{C}-38^\circ\text{C})}) / (t_{c(48^\circ\text{C}-38^\circ\text{C})})] \times 100 \dots(4)$$

where $t_{u(48^\circ\text{C}-38^\circ\text{C})}$ is the time taken by uncovered hot body to cool under the temp. range 48°C-38°C; and $t_{c(48^\circ\text{C}-38^\circ\text{C})}$ is the time taken by covered hot body to cool under the same temp. range (48°C-38°C). The average of five results was considered and coefficient of variation of results was within 5%.

In the plate method (two plate method), the TIV instrument³ includes a microprocessor and provides automatic results of thermal insulation value in 'tog'. The area of the test specimen used was 706.85 cm² (diameter 30 cm). The test is non-destructive and process of preparation of sample is free from human error. Thermal insulation of each fabric sample was measured randomly at three different places. Average of five readings was taken and the coefficient of variation of readings was < 2%.

All these tests were carried out in the standard atmospheric condition of 65 ± 2% RH and 20 ± 2°C. The fabrics were conditioned for 24 h in the above-mentioned atmospheric conditions before testing.

2.2.3 Measurement of Initial Thickness, Percentage Compression and Density

The initial thickness and compression were calculated from the compression curve. For measuring these properties, a thickness tester was used. The pressure foot area was 5.067 cm² (diameter = φ2.54 cm). The dial gauge with a least count of 0.01 mm and maximum displacement of 10.5 mm was attached to the thickness tester. The thickness and percentage compression were studied under a pressure range between 1.55 kPa and 51.89 kPa.

The initial thickness^{5,7} was observed under the pressure of 1.55 kPa. The corresponding thickness values were observed from the dial gauge for each corresponding load of 1.962 N. A delay of 30s was given between the previous and the next load applied. Similarly, 30s delay was also allowed during decompression cycle at every individual load of 1.962 N. These compression thickness values for corresponding pressure values were used to plot the compression curves.

The percentage compression^{5,7} was estimated using the following equation:

$$\text{Compression} (\%) = [(T_0 - T_1) / T_0] \times 100 \quad \dots(5)$$

where T_0 is the initial thickness in mm; and T_1 , the thickness under the maximum pressure of 51.89 kPa.

The fabric density was estimated using the following relationship:

$$\text{Fabric density (g/cm}^3\text{)} = [W / T] \times 10^{-3} \quad \dots(6)$$

where W is the fabric weight (g/m²); and T , the fabric thickness (mm) under a pressure of 1.55 kPa.

2.2.4 Measurement of Air Permeability

Evaluation of air permeability of needle-punched nonwoven fabric samples was conducted using the Shirley air permeability tester (SDL-21). The results have been expressed as the units of volume of air (cm³) passed per second, through one square centimeter of fabric at a pressure difference of 20 mm or 2 cm head of water. Air permeability value was

calculated by dividing the flow rate reading in cc/s at 2 cm pressure head of water by the test area, which is 5.07 cm² (1 inch²) in this instrument. Sectional air permeability⁸ (SAP) value was used to compare the permeability of different fabric samples. SAP values of all the samples were determined using the following equation:

$$SAP = A \times T \quad \dots(3)$$

where *A* is the air permeability value in cm³/cm³/s; and *T*, the mean thickness in cm at 1.55 kPa pressure. For each sample, 10 tests were performed. Coefficient of variation of the results was within 5%.

3 Results and Discussion

Table 4 shows the effect of fabric weight and fibre cross-sectional shapes of polyester fibre on thermal insulation value measured by two methods, fabric thickness, compression percentage, fabric density, air permeability and sectional air permeability. Table 5 shows the correlation matrix of variables. The inter-relationship among the variables has been studied

using cluster analysis technique (Fig. 1). The effect of fabric weight and fibre cross-sectional shapes on various fabric properties are discussed hereunder.

3.1 Relationship and Clustering among Variables

The independent variable is fabric weight and the dependent variables are TIV (measured by two methods), fabric thickness, density, compression

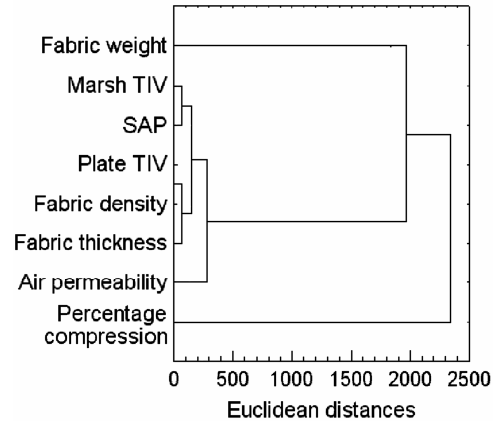


Fig. 1—Tree diagram of different variables using cluster analysis

Table 4—Properties of polyester needle-punched nonwoven fabric samples

Fabric code	Marsh thermal insulation value, %	Thermal insulation value, tog	Fabric thickness mm	Fabric density g/cm ³	Compression %	Air permeability cm ³ /cm ² /s	Sectional air permeability cm ³ /s/cm
R1	18.56	0.660	3.54	0.1172	42.93	91.83	32.51
R2	20.13	0.667	4.14	0.1244	37.00	69.17	28.64
R3	21.50	0.803	5.13	0.1326	28.35	57.83	29.67
R4	24.41	0.937	5.62	0.1450	23.78	45.00	25.29
H1	09.60	0.647	3.17	0.1309	31.66	86.17	27.32
H2	13.42	0.653	3.60	0.1431	24.36	68.00	24.48
H3	22.02	0.697	4.69	0.1450	18.09	52.67	24.70
H4	27.16	0.810	5.53	0.1474	16.13	38.50	21.29
T1	26.75	0.693	3.57	0.1162	42.27	75.33	26.89
T2	29.01	0.743	4.37	0.1178	37.93	73.00	31.90
T3	31.77	0.817	5.58	0.1219	25.43	50.50	28.18
T4	31.86	0.953	6.58	0.1239	23.19	44.67	29.39

Table 5—Correlation matrix of variables

Parameter	A	B	C	D	E	F	G	H
A	1.00	0.55	0.86*	0.94*	0.55	0.40	-0.96*	-0.42
B	0.55	1.00	0.68*	0.74*	-0.26	0.06	-0.60*	0.09
C	0.86*	0.68*	1.00	0.93*	0.18	0.52	-0.78*	-0.08
D	0.94*	0.74*	0.93*	1.00	0.23	0.29	-0.89*	-0.15
E	0.55	-0.26	0.18	0.23	1.00	0.37	-0.56	-0.82*
F	0.40	0.06	0.52	0.29	0.37	1.00	-0.32	-0.21
G	-0.96*	-0.60*	-0.78*	-0.89*	-0.56	-0.32	1.00	-0.55
H	-0.42	-0.09	-0.08	-0.15	-0.82*	-0.21	0.55	1.00

*Significant at *p* < 0.05000

A – Fabric weight, g/m²; B – Marsh TIV, %; C – TIV, tog; D – Fabric thickness, mm; E – Fabric density, g/cm³; F – Compression, %; G – Air permeability, cm³/cm²/s and H – Sectional air permeability, cm³/s/cm.

percentage, air permeability and sectional air permeability. It is observed from Table 5 that the significant ($p < 0.05000$) correlation between fabric weight and TIV by plate method; fabric weight and fabric thickness; and fabric weight and air permeability are 0.86, 0.94 and -0.96 respectively. However, among the dependent variables the significant ($p < 0.05000$) correlations are found between TIV by plate method and TIV by Marsh method ($r = 0.68$); TIV by plate method and fabric thickness ($r = 0.93$); and TIV by plate method and air permeability ($r = -0.78$). The other correlations among the independent variables between Marsh TIV and fabric thickness ($r = 0.74$); Marsh TIV and air permeability ($r = -0.60$); fabric thickness and air permeability ($r = -0.89$); and fabric density and SAP ($r = -0.82$) are also found to be significant ($p < 0.05000$).

It is observed from tree diagram of cluster analysis that fabric weight as well as percentage compression are of different entity as shown in Fig. 1. Among other variables, fabric density, thickness and TIV by plate method form a cluster. Again, Marsh TIV and SAP fall under small separate cluster. The air permeability being a separate entity depends on two sub clusters. From this study, it can be explained that the small clusters are much influenced by an individual variable namely fabric weight, as it shows higher value of Euclidean distance (Fig. 1). In practice, with the change in fabric weight, the TIV, thickness, density, and air permeability of fabric change. Though the percentage compression scores highest values of Euclidean distance, the influence on other variables is poor. This can also be supported by the non-significant low correlation coefficients ($r \leq 0.52$) of the percentage compression versus other variables (Table 5). Though air permeability and SAP are similar representation, in case of SAP the thickness is taken into consideration. Hence, in cluster analysis Euclidean distance of SAP is closer to Euclidean distances of fabric thickness and density rather than to Euclidean distance of air permeability.

3.2 Effect on Thermal Insulation

It is depicted in Table 4 that both the methods of TIV measurement show similar trend in TIV results with different units. The correlations between two different methods of TIV measurement show good agreement ($r = 0.68$) and corroborate the correlation

coefficient significant at $p < 0.05000$ (Table 5). In case of Marsh TIV method the process is more tedious as it requires preparation of specimen and additional heating arrangement for heating of water. However, the plate method is non-destructive and process of sample preparation is free from human error due to the presence of digital recording system. Higher CV% of results is obtained from Marsh TIV method ($< 5\%$) as compared to that from plate method of TIV ($< 2\%$), irrespective of the time consumed for each specimen test. Hence, the plate method of TIV measurement is more preferable.

The thermal insulation values show increasing trend with the increase in fabric weight of the polyester needle-punched nonwoven fabrics (Table 4). This trend is found to be similar for different fibre cross-sectional shapes and for different methods of TIV measurement. With the increase in fabric weight the number of fibres per unit area of the fabric increases. Due to this reason the fabric thickness increases. As thickness of the fabric increases the thermal resistance increases. A significant positive correlation coefficient has been found between fabric thickness and TIV (Table 5) by plate as well as by Marsh methods. This results in an increasing trend of TIV with the increase in fabric weight.

The polyester sample of trilobal cross-section shows highest TIV followed by regular and hollow polyester fabrics (Table 4). This is due to the fact that the thickness of polyester fabric is also highest for trilobal followed by regular and hollow polyester fabrics. As the thickness increases the thermal conductivity reduces, resulting in higher thermal insulation. This can be corroborated with the fact that in case of jute fabrics, TIV is directly proportional to the thickness of fabric². Trilobal polyester sample of heavy fabric weight (815 g/m^2) shows highest TIV among the three different cross-sectional shape polyester samples. Probably, the entanglement of fibre loops during needling is poor at 300 punches/cm^2 needling density due to the presence of lobes on the surface of trilobal polyester. Hence, poor consolidation of trilobal fabric structure results in higher thickness as well as TIV values as compared to other regular and hollow polyester fabrics. In case of hollow polyester fibre, the fibre consolidation is higher during needling due to the use of fine linear density fibre⁹. This results in poor thermal insulation of hollow polyester needle-punched nonwoven.

3.3 Effect on Fabric Thickness, Compression Percentage and Density

The thickness as well as density of the fabric increase with the increase in fabric weight (Table 4). With the increase in fabric weight the number of fibres per unit area increases, resulting in increase in fabric thickness, irrespective of the fibre cross-sectional shape of polyester samples. Again with the increase in number of fibres, consolidated structure can be obtained easily. This is due to the availability of more amount of fibres to be entangled during needling process to form denser fabric at higher fabric weight. The percentage compression decreases with the increase in fabric weight (Table 4) for all the three cross-sectional shapes of polyester samples. Debnath and Madhusoothanan¹⁰ have also been reported a similar trend in case of cross-laid as well as parallel-laid polypropylene needle-punched nonwoven fabrics. With the increase in fabric weight the amount of fibres per unit area of the fabric increases, as a result more number of fibres share the compressive load. Hence, decrease in percentage compression is observed with the increase in fabric weight⁷.

The maximum thickness, close to highest value of percentage compression and lowest density in fabrics, is obtained with trilobal polyester followed by round and hollow polyester fabric samples (Table 4). The trilobal polyester has got higher surface area due to its lobes on the surface which restrict to form consolidated fabric structure for the same needling density. This results in thicker and lower density trilobal polyester fabric¹. The fabrics made with hollow fibre give better consolidated structure than the round polyester fibre fabrics, though the surface area of hollow polyester is much larger than that of round polyester fibre. This is probably due to hollow structure of the fibre, and fine denier of hollow fibre used in the study. The fabric is more consolidated and hence its density is high as well as the percentage compression is less for hollow fibre as compared to other cross-sectional shape polyester samples due to higher stiffness of hollow polyester fibre. Midha *et al.*⁹ has also reported that hollow polyester of finer denier helps in producing a better consolidated fabric structure. It has also been reported in the literature^{11,12} that the fabrics made from coarser fibres show higher compressibility compared to the fabrics made from finer fibres. This was attributed to the fact that finer fibres can bend easily leading to compact structure and higher surface area, resulting in better interlocking of the structure. With hollow fibres also the same effect has been observed, i.e. higher fibre

surface area and bending stiffness of fibres result in easy consolidation in fabric structure. This results in lower percentage compression as well as thickness and higher density of hollow polyester fabric.

3.4 Effect on Air Permeability

Both air permeability and SAP decrease with the increase in fabric weight (Table 4). While increase in fabric weight, the fabric becomes thicker as well as denser, resulting in consolidated fabric structure⁴. Though the amount of pores increases with the increase in number of fibres, the pore size becomes smaller. This, in turn, drops down the air permeability as well as SAP values with the increase in fabric weight. Debnath *et al.*^{6,8} has also reported that the air permeability and SAP decrease with the increase in fabric weight in case of polyester and jute needle-punched nonwoven fabrics respectively. Air permeability also follows similar trend with fabric weight as observed in case of jute-polypropylene blended needle-punched nonwoven¹³.

Hollow polyester fabrics show lowest value of air permeability and SAP followed by regular and trilobal fabrics, irrespective of the fabric weight. Among all the fabric samples, the hollow fabric is found to be denser due to its consolidated structure. However, due to the presence of lobes on the surface of the trilobal polyester, the consolidation is poor which results in lower density of fabric¹. Hence, both the air permeability and SAP are higher for trilobal fabric than those for other cross-sectional shape polyester needle-punched fabrics.

The air permeability and thickness are negatively correlated with significant correlation coefficient as observed from Table 5. The sectional air permeability also follows similar trend.

4 Conclusions

4.1 Marsh and plate methods of TIV measurement show significant positive correlation. Plate method is preferred over Marsh TIV measurement because of the ease of specimen preparation, non-destructiveness of samples with less variation in results and little human dependence.

4.2 The thermal insulation values increase with the increase in weight of polyester needle-punched nonwoven fabrics, irrespective of the fibre cross-sectional shapes and methods of TIV measurement.

4.3 The polyester sample of trilobal cross-sectional shape shows highest TIV followed by regular and hollow polyester fabrics, irrespective of the fabric weight.

4.4 The thickness as well as density of the fabric increase and the percentage compression decreases with the increase in fabric weight, irrespective of the cross-sectional shapes of polyester fabric. Compression percentage stands a separate cluster and non-significant correlation coefficients between the variables.

4.5 The maximum thickness, close to highest value of percentage compression and lowest density in fabrics, is attributed to the trilobal polyester followed by round and hollow polyester fabric samples.

4.6 Both air permeability and SAP decrease with the increase in fabric weight. Fabric weight versus air permeability and fabric density versus SAP are negatively correlated with significant correlation coefficient. In cluster analysis, Euclidean distance of SAP is closer to Euclidean distance of fabric thickness and density rather than to Euclidean distance of air permeability.

4.7 Hollow polyester fabrics show lowest value of air permeability and SAP followed by regular and trilobal fabrics, irrespective of the fabric weight. Both air permeability versus fabric thickness and fabric density versus SAP are negatively correlated with significant correlation coefficient.

4.8 In case of some industrial products where high thermal insulation is essential, trilobal polyester nonwoven fabric is suitable. Hollow nonwoven fabric can be used where least permeability with moderate thermal insulation is required.

4.9 This study may help in designing the needle-punched nonwoven fabric made from polyester fibres of different cross-sectional shapes for specific industrial application. The study will also minimise the cost for development of various technical textiles.

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