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Compression behaviour of jute-polypropylene blended needle-punched nonwoven fabrics

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The effect of fabric weight, needling density and blend proportion of jute and polypropylene fibres on compression properties has been studied. Box and Behnken experimental design has been used to study the individual and interactive effects on compression properties, namely initial thickness, percentage compression, percentage thickness loss and percentage compression resilience of jute-polypropylene blended needle-punched nonwoven fabrics. It is observed that the initial thickness increases prominently with the increase in fabric weight at the level of 40% polypropylene content in fabric. The fabric thickness reduces with the increase in needling density and the effect of fabric weight on initial thickness of the fabric is negligible at the higher level of polypropylene content in fabric. The increase in needling density or fabric weight reduces the percentage compression of jute-polypropylene fabric. The percentage thickness loss decreases with the increase in fabric weight. At higher fabric weight, the increase in needling density decreases the percentage thickness loss, irrespective of blends. The percentage compression resilience of the fabric increases with the increase in polypropylene content in the blend.

Keywords: Compression resilience, Jute-polypropylene blends, Needle-punched fabric, Nonwoven, Thickness loss, Woollenised jute

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1 Introduction

The usage of abundantly available (in India and Bangladesh) jute fibre in unconventional applications, like carpets and geotextiles, might open new avenues to the jute farmers to utilise their products. Such utilisation of this golden fibre obviously would result in higher profit and standard of living for the jute farmers. There are number of short comings in this natural fibre which can be reduced to a large extent by treating jute with caustic soda and blending it with man-made fibres, with jute as a lesser component of the blend. The fibre vastly used in carpet, blankets and geotextile is polypropylene. Preference is given to polypropylene for its bulk, inert nature and low density, though it is not cheap. By blending polypropylene with woollenised jute, the cost can be lowered as well as a better fabric property can be maintained.

The present study highlights the effects of machine parameters and processing parameters on compression properties, like initial thickness, percentage compression, percentage thickness loss and percentage compression resilience, of needle-punched nonwoven fabrics. Box and Behnken factorial design for three variables[6] is used to study the individual and interaction effect of the chosen variables (fabric weight, needling density and blend proportion) on the compression properties. The fabric consolidation can be achieved either by increase in depth of needle penetration or needling density of needle-punched fabrics.[1-4] Dynamic loading characteristics of jute and polypropylene show that the thickness loss increases with diminishing rate up to certain limit and thereafter it does not change.[5]

2 Materials and Methods

2.1 Materials

The polypropylene fibre of the fineness 4 denier and length 80 mm, and jute fibres of Tossa-4 grade

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were used to prepare the fabric samples. Sodium hydroxide and acetic acid were used for woollenisation of the jute.

2.2 Experimental Design

To study the individual and interactive effects of fabric weight, needling density and blend composition of woollenised jute and polypropylene fabric, Box and Behnken factorial design was used for three variables. The limitation of this factorial design is that the estimation of the responses from the model equation is suitable, only when the independent variables are within the range for which the model has been developed. Table 1 shows the coded and actual values of three parameters considered and fifteen sets of experimental combinations under which the fabrics are produced.

2.3 Woollenisation of Jute

The raw jute fibres do not produce good quality fabric because there is no crimp in these fibres. To develop crimp, before the fabric production the jute fibres were treated with 18% (w/v) sodium hydroxide solution at 30°C maintaining the liquor-to-material ratio at 10:1, as suggested by Saha *et al*[7]. and Sao and Jain[8]. After 45 min of soaking, the jute fibres were washed thoroughly in running water and treated with 1% acetic acid. The fibres were washed again and then dried in air for 24 h. This process apart from introducing about 2 crimps/cm also results in weight loss of ~ 9.5%.

2.4 Fabric Preparation

The jute reeds were opened in a roller and clearer card, which produces almost mesh-free stapled fibre. The woollenised jute and polypropylene fibres were opened by hand separately, and blended using three different blend proportions (Table 1). The blended materials were thoroughly opened by passing through one carding passage.

The blended fibres were fed to the lattice of the roller and clearer card at a uniform and predetermined rate so that a web of 50 g/m^2 can be achieved. The fibrous web coming out from the card was fed to feed lattice of cross-lapper and cross-laid webs were produced with cross-lapping angle of 20°. The web was then fed to the needling zone. The required needling density was obtained by adjusting the throughput speed.

Combination of the different webs, as per fabric weight (g/m^2) requirements, were passed through the needling zone of the machine for a number of times, depending upon the punch density required. A punch density of 50 punches/cm^2 was applied on each passage of the webs reversing the face of the web alternatively. The fabric samples were produced as per the coded and actual levels of three variables (Table 1).

Table 1—Actual and coded values for three independent variables and the experimental design

Fabric code	Levels of variables					
	X_1 level		X_2 level		X_3 level	
	Coded	Actual	Coded	Actual	Coded	Actual
1	-1	250	-1	150	0	60 : 40
2	-1	250	1	350	0	60 : 40
3	1	450	-1	150	0	60 : 40
4	1	450	1	350	0	60 : 40
5	-1	250	0	250	-1	40 : 60
6	-1	250	0	250	1	80 : 20
7	1	450	0	250	-1	40 : 60
8	1	450	0	250	1	80 : 20
9	0	350	-1	150	-1	40 : 60
10	0	350	-1	150	1	80 : 20
11	0	350	1	350	-1	40 : 60
12	0	350	1	350	1	80 : 20
13	0	350	0	250	0	60 : 40
14	0	350	0	250	0	60 : 40
15	0	350	0	250	0	60 : 40

X_1 – Fabric weight (g/m^2); X_2 – Needling density (punches/cm^2); and X_3 – Blend ratio (polypropylene : woollenised jute).

The depth of needle penetration was kept constant at 11 mm. For all webs, 15 × 18 × 36 × R/SP, 3½ × ¼ × 9 needles were used.

2.5 Measurement of Compression Properties

The initial thickness, compression, thickness loss and compression resilience were calculated from the compression and decompression curves. For measuring these properties, a thickness tester was used.[9] The pressure foot area was 5.067 cm^2 (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 compression properties were studied under a pressure range between 1.55 kPa and 51.89 kPa.

The initial thickness of the needle-punched fabrics 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 next load applied. Similarly, 30s delay was also allowed during decompression cycle at every individual load of 1.962 N. This compression and recovery thickness values for corresponding pressure values are used to plot the compression-recovery curves.

The percentage compression[10,11], percentage thickness loss[12] and percentage compression resilience[11,13] were estimated using the following relationships:

$$\text{Compression (\%)} = [(T_0 - T_1) / T_0] \times 100 \quad \ldots (1)$$

$$\text{Thickness loss (\%)} = [(T_0 - T_2) / T_0] \times 100 \quad \ldots (2)$$

$$\text{Compression resilience (\%)} = (W_c' / W_c) \times 100 \quad \ldots (3)$$

where T_0 is the initial thickness; T_1, the thickness at maximum pressure; T_2, the recovered thickness; W_c, the work done during compression; and W_c', the work done during recovery process.

The average of ten readings from different places for each sample was considered. The coefficient of variation was less than 6% in all the cases.

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.

3 Results and Discussion

3.1 Effect of Fabric Weight, Needling Density and Blend Composition on Initial Thickness

Table 2 shows the effect of fabric weight, needling density and blend ratios on initial thickness. Table 3 shows the coefficients and constants of the response surface equation ($F_{9,5}$ = 5.80 that lead to 95% confidence limit). The response surface (model) for dependent variable (initial thickness under 1.55 kPa pressure), as a function of the independent variables X_1, X_2 *and* X_3 (fabric weight, needle punch density and blend ratio) and their interactions are quite good in that it captures 91% of variation estimated by the R^2 value.

Table 2 – Effect of fabric weight, needling density and blend proportion on initial thickness, compression, thickness loss and compression resilience of nonwoven fabrics

Fabric code	Initial thickness mm	Compression %	Thickness loss %	Compression resilience %
1	3.54	53.64	25.46	32.67
2	3.02	46.73	25.98	32.29
3	4.41	44.80	20.68	32.92
4	3.80	36.47	17.68	33.87
5	3.02	52.48	30.69	29.48
6	4.27	54.88	27.82	32.27
7	4.39	37.24	20.69	30.99
8	3.88	37.80	18.63	31.28
9	3.45	50.24	25.16	32.77
10	4.48	50.06	24.49	31.52
11	3.12	44.91	25.51	31.73
12	3.38	43.75	23.25	30.99
13	3.29	45.16	22.06	33.25
14	3.94	42.45	21.84	33.15
15	3.66	44.09	21.68	33.03

Table 3 – Response surface equations and coefficients of multiple correlation

Response	Response surface equation	Coefficient of multiple correlation (R^2)	F – value at 9 and 5 degree of freedom
Initial thickness	$-1.529375 + 4.975\text{E-}03 X_1 + 8.8625\text{E-}03 X_2 + 8.75\text{E-}02 X_3 + 1.725\text{E-}05 X_1^2 - 1.1\text{E-}05 X_2^2 + 2.1875\text{E-}04 X_3^2 - 2.25\text{E-}06 X_1 X_2 - 2.2\text{E-}04 X_1 X_3 - 9.625\text{E-}05 X_2 X_3$	0.9125	5.80
Percentage compression	$8.93475\text{E+}01 - 3.705\text{E-}02 X_1 - 9.2575\text{E-}02 X_2 - 4.0825\text{E-}01 X_3 - 6.5\text{E-}06 X_1^2 + 1.575\text{E-}04 X_2^2 + 4.4125\text{E-}03 X_3^2 - 3.55\text{E-}05 X_1 X_2 - 2.3\text{E-}04 X_1 X_3 - 1.225\text{E-}04 X_2 X_3$	0.9375	8.33
Percentage thickness loss	$5.782125\text{E+}01 - 3.99875\text{E}{-}02 X_1 + 2.01375\text{E}{-}02 X_2 - 7.74375\text{E}{-}01 X_3 + 2.225\text{E}{-}05 X_1^2 + 3.657\text{E}{-}05 X_2^2 + 5.9375\text{E}{-}03 X_3^2 - 8.8\text{E}{-}05 X_1 X_2 + 1.0125\text{E}{-}04 X_1 X_3 - 1.9875\text{E}{-}04 X_2 X_3$	0.9673	16.42
Percentage compression resilience	$9.073125 + 4.989167\text{E-}02 X_1 - 2.8000417\text{E-}02 X_2 + 6.1225\text{E-}01 X_3 - 5.216667\text{E-}05 X_1^2 + 2.25833\text{E-}05 X_2^2 - 4.266667\text{E-}03 X_3^2 + 3.325\text{E-}05 X_1 X_2 - 3.125\text{E-}05 X_1 X_3 + 6.375\text{E-}05 X_2 X_3$	0.7880	1.98

Figure 1 shows the effect of fabric weight and needling density on initial thickness at 40% and 80% levels of polypropylene content. It is clearly shown in Fig. 1a that the initial thickness increases prominently with the increase in fabric weight and needling density has very little effect. However, the fabric thickness reduces with the increase in needling density and the effect of fabric weight on initial thickness of the fabric is negligible (Fig. 1b).

When the percentage jute content is more in the jute-polypropylene blended needled fabrics, then they can be consolidated easily and the consolidation occurs at lower needling density itself (Fig. 1a). However, any further increase in needling density does not affect the thickness. But the increase in fabric weight, as expected, increases the initial thickness.

On the other hand, when the polypropylene content increases in the blend, the trend is different. This is due to the fact that in polypropylene fibre, which has got a lower density, the number of fibre per unit volume is very high. Due to this, the amount of needling required to completely consolidate the fabrics has to be increased. Because of this reason, the needling density shows a significant effect on initial thickness (Fig. 1b). It can also be observed from Fig. 1b that for a given needling density the initial thickness first decreases and then increases. This trend is due to the presence of polypropylene fibre. At a given needling density, when the fabric weight increases the barbs of the needles can pickup more fibres and consolidate the fabric well beyond a optimum point, when the number of fibre is more the consolidation is rather poor. This justifies the above stated observation. Debnath and Roy[12] also reported similar findings.

3.2 Effect of Fabric Weight, Needling Density and Blend Composition on Percentage Compression

The effect of fabric weight, needling density and blend ratios on percentage compression is shown in Table 2. Table 3 shows the coefficients and constants of the response surface equation ($F_{9,5}$ = 8.33 that lead to 97.5% confidence limit). The response surface (model) for dependent variable (percentage compression under a pressure range 1.55 - 51.89 kPa), as a function of the independent variables X_1, X_2 *and* X_3 (fabric weight, needle punch density and blend ratio) and their interactions are quite good in that it captures 93% of variation estimated by the R^2 value.

Figure 2a shows the effect of fabric weight and needling density on percentage compression at 40%

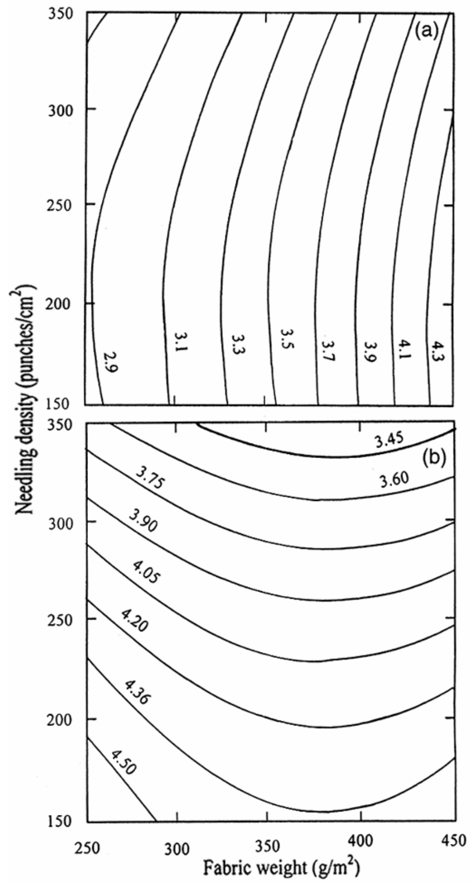

Fig. 1—Effect of fabric weight and needling density on initial thickness at (a) 40% and (b) 80% levels of polypropylene content

polypropylene content. It can be clearly observed from the figure that the percentage compression is much influenced by the fabric weight and needling density. With the increase in fabric weight the percentage compression decreases. This may be due to the fact that there is better consolidation at higher fabric weight due to the presence of more number of fibres, resulting in better entanglement. Midha *et al*.[14] also observed a similar trend in case of hollow polyester needle-punched fabrics.

It has also been observed from the Fig. 2a that the increase in needling density reduces the percentage compression.[15,16] At higher fabric weight the effect of needling density on compression is much prominent than that at lower fabric weight. In case of lower fabric weight, the number of fibres is less and hence higher needling density is required to achieve optimum entanglement resulting in the consolidation of fabric. The case is just the reverse for samples with higher fabric weight. This similar trend is also found in other levels of polypropylene contents. Rakshit

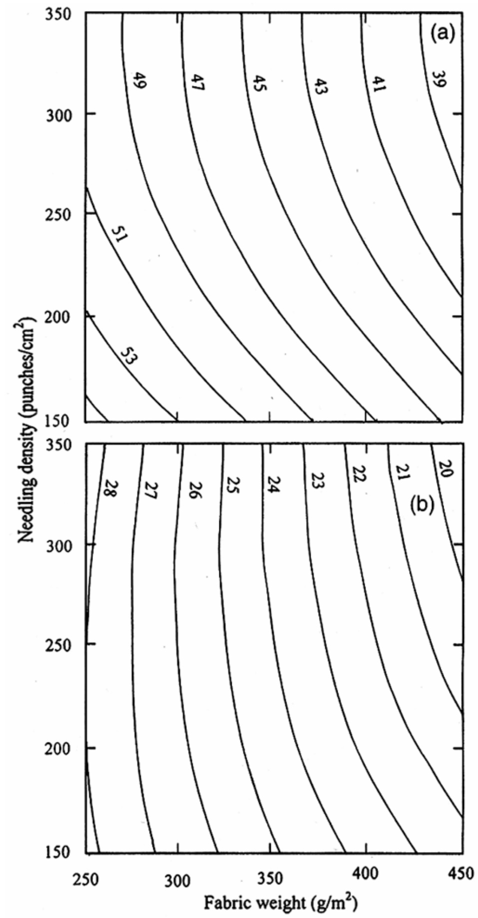

Fig. 2—Effect of fabric weight and needling density on (a) percentage compression at 40% and (b) percentage thickness loss at 80% polypropylene content

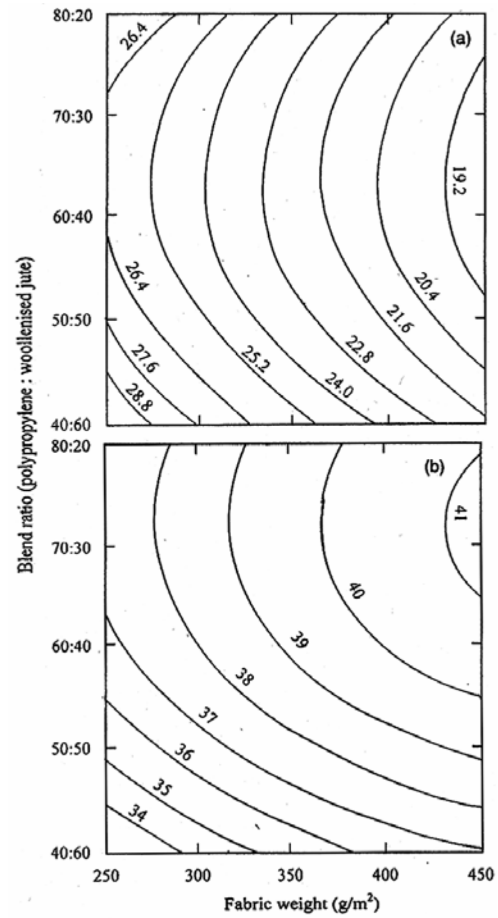

Fig. 3—Effect of fabric weight and blend proportion of jute and polypropylene on (a) percentage thickness loss and (b) percentage compression resilience at 250 punches/cm^2

et al.[15] and Subramaniam *et al*.[17] also found the similar trend of results with other fibres.

3.3 Effect of Fabric Weight, Needling Density and Blend Composition on Percentage Thickness Loss

Table 2 presents the effect of fabric weight, needling density and blend ratios on percentage thickness loss of woollenised jute and polypropylene blended needle-punched nonwoven. Table 3 shows the coefficients and constants of the response surface equation ($F_{9,5}$ = 16.42 that lead to 99% confidence limit). The response surface (model) for dependent variable (percentage thickness loss under a pressure range 1.55 - 51.89 kPa) as a function of the independent variables X_1, X_2 *and* X_3 (fabric weight, needle punch density and blend ratio) and their interactions are quite good in that it captures 96% of variation estimated by the R^2 value.

Figure 2b shows the effect of fabric weight and needling density on percentage thickness loss at 80% level of polypropylene content. The percentage thickness loss decreases with the increase in fabric weight. The needling density has not much significant effect at lower fabric weight, but at higher fabric weight, the increase in needling density decreases the percentage thickness loss. Rakshit *et al*.[15] found that with an increase in needling density, percentage recovery increases. At lower fabric weight, as there is less number of fibres during the compression, the amount of fibre slippage is high due to less entanglement. At higher fabric weight, the number of fibre increases considerably which improves the fibre entanglement and therefore fibre slippage is reduced. Consequently, the recovery value shows improvement during the decompression cycle. This holds good for other levels of jute-polypropylene blends also.

Figure 3a depicts the effect of fabric weight and blend proportion of jute and polypropylene on percentage thickness loss at 250 punches/cm^2 needling density. The optimum blend proportion of jute and polypropylene is found to be 65% of polypropylene content, where the lowest value of percentage thickness loss is observed. This optimum blend demands higher polypropylene content in the blend with the increase in level of needling density. In the higher fabric weight, the lowest value of percentage thickness loss is observed. This may be due to the presence of higher number of finer fibres with a heavier fabric, where proportion of polypropylene is higher. As a result, more consolidated structure occur with the increase in finer fibre proportion (polypropylene) in the blend at specified needling density. However, Roy and Debnath[18] concluded that the percentage energy loss of needle-punched nonwoven fabric is maximum for 100% jute fabric than for 75:25 jute/ polypropylene blended fabric.

Beyond the optimum polypropylene content (about 65%) in the blend, with the further increase in polypropylene content, the amount of fibres per unit area of the fabric remains so high that the amount of interlocking of fibres decreases. This results in large amount of fibre slippage during compression. Once the fibre-to-fibre slippage occurs, those fibres will not be able to retain back to their original position, thereby causing an increase in thickness loss.[19] Similar trend is also observed at other needling densities also.

3.4 Effect of Fabric Weight, Needling Density and Blend Composition on Percentage Compression Resilience

Table 2 shows the effect of fabric weight, needling density and blend ratios on percentage compression resilience of woollenised jute and polypropylene blended needle-punched nonwoven. Table 3 shows the coefficients and constants of the response surface equation ($F_{9,5}$ = 1.98 that lead to 90% confidence limit). The response surface (model) for dependent variable (percentage compression resilience under a pressure range 1.55 - 51.89 kPa), as a function of the independent variables X_1, X_2 *and* X_3 (fabric weight, needle punch density and blend ratio) and their interactions are not good enough as it captures only 78% of variation estimated by the R^2 value.

Figure 3b shows the effect of fabric weight and blend ratio on percentage compression resilience at 250 punches/cm^2. It has been observed that the increase in polypropylene content in the blend improves the percentage compression resilience of the fabric. This effect is more prominent at higher fabric weight than that at lower fabric weight while increasing the polypropylene content. This is probably due to the presence of more number of fibres at higher fabric weight. With the increase in polypropylene content in blend, the number of polypropylene fibres per unit area is increased much largely in comparison to that with jute content because of the much lower density and fineness of polypropylene as compared to jute fibre. At higher fabric weight, with the increase in polypropylene content in the blend, more number of fibres per unit area is available for needling. This causes better consolidation and entanglement of fibres. This reduces the fibre-to-fibre slippage during compression and improves the percentage compression resilience. Similar trend is also observed for other levels of needling densities. Subramaniam *et al*.[16] has also reported this trend.

4 Conclusions

4.1 The initial thickness increases prominently with the increase in fabric weight and the effect of needling density has minor effect on fabric thickness at the level of 40% polypropylene content in fabric. The fabric thickness reduces with the increase in needling density and the effect of fabric weight on initial thickness of the fabric is negligible at the level of 80% polypropylene content in fabric.

4.2 The increase in needling density or fabric weight reduces the percentage compression of jute-polypropylene fabric.

4.3 The percentage thickness loss decreases with the increase in fabric weight. The effect of needling density on percentage thickness loss is not much significant. However, at higher fabric weight, the increase in needling density decreases the percentage thickness loss, irrespective of blends.

4.4 The percentage compression resilience of the fabric increases with the increase in polypropylene content in the blend. This effect is more prominent at higher fabric weight, irrespective of needling densities.

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