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Bursting behavior of polyester needle-punched filter fabrics

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The effect of fabric weight, depth of needle penetration and needling density on bursting strength of needle-punched nonwoven filter fabrics prepared from virgin and recycled polyester fibres has been studied. The effect of fabric parameters on bursting behavior trend is found similar in both the virgin and the recycled polyester filter fabric samples. There is considerable fall in bursting strength of recycled polyester fabrics as compared to that in virgin one, under high fabric weight and needling density. Interestingly, it has been found that the recycled polyester filter fabric shows 3.584% lesser strength (average value of all samples) than the virgin polyester filter fabric, which signifies the use of recycled polyester filter wherever applicable, considering the recyclability and sustainability aspects.

Keywords: Bursting strength, Filter fabric, Needle-punched nonwoven, Recycled polyester, Virgin polyester

1 Introduction

Nonwoven fabrics have played a significant role in dust and liquid filtration because of their loftiness, porosity and low cost of manufacturing. Virgin polyester fibre is mainly used for manufacturing filter fabric commercially. In case of filter fabric, multi-directional stress occurs during the use and hence, it is better to study the bursting strength than the conventional uni-directional strength, since the material is anisotropic in nature. As far as the bursting property of polyester-based nonwoven fabric is concerned, Koc and Cincik[1] showed that bursting strength of needle-punched nonwovens is initially decreased and then increased with the increase of polyester fibre in the mixture and with the increase in mass per unit area. When the mass per unit area was kept constant, an increase in needing density caused decrease in bursting strength. In the same line, Chatterjee *et al.*[2]. from their studies observed that the polyester hollow fibre fabrics give higher bursting strength as compared to trilobal and round fibre fabrics. Bursting strength of the fabric increased with the use of reinforcing material and needling density until a critical level[3]. Landage *et al*.[4] from their study observed that the increase in bursting strength values of nonwoven fabric may be due to the increase in punching density which makes fabric denser. Also, the increase in airflow rate and time for filtration attributed lower bursting strength. Bursting strength in the random webs was lower than that in the parallel webs, which may be due to anisotropic arrangement of fibres in the random webs. The bursting strength in the parallel webs was better[5]. Roy and Ray[6] observed that bursting strength of fabric increased with the increase in fabric weight, depth of needle penetration and punch density, but beyond some optimum punch density and depth of needle penetration bursting strength of fabric exhibited declining trend.

Maity and Singha[7] studied structure property relationship of needle-punched nonwoven fabrics. They observed that the bursting strength in the random webs was lower than that in the parallel webs. One possible explanation could be that the fibre arrangement in the random webs was anisotropic, so there were more interlacing spots and voids in these webs. The failure extended from these voids to the perimeter under breaking conditions.

Maity *et al*.[8] studied the effects of various factors on the bursting strength of jute needle-punched nonwoven. It was observed that the bursting strength of fabric increases with the increase in fabric weight, needle punch density and depth of needle penetration, but beyond some optimum punch density and depth of needle penetration bursting strength of fabric exhibited declining trend.

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Ghosh and Chapman[9] investigated properties of needle-punched nonwoven fabrics that were used for automotive applications by blending thermoplastic fibres under various needling parameters. They observed that higher bursting strength was achieved by introducing lower modulus nylon 6,6 fibres into the polyester substrate. Increased bursting strength facilitates the moulding process to produce parts such as trunk liners. Thangadurai *et al*.[10] studied needle-punched nonwoven fabrics for industrial air filter applications. They observed that micro-denier fabric exhibited 24% improvement in bursting strength. Yuksekkaya *et al.*[11] investigated the effect of needling intensity and knitted reinforcement fabric on bursting behavior of needle-punched nonwoven filters. They observed that the usage of reinforcement fabrics in the filters increased the bursting strength of the filters. The bursting strength of filters increases until a critical point after which it exhibited declining trend due to breakage of fibres at higher needling density. As the needling intensity increased, some of the fibres were broken due to the mechanical loads inserted by needles which resulted in low bursting strength of the filters.

Nowadays, several synthetic fibres are available in practice for the manufacturing of needle punched non-woven filter fabrics. However, during survey of different needle punched non-woven filter fabric at manufacturing sites, it has been found that the virgin polyester fibre is in maximum use. The raw material (polyester fibre) contributes around 60% of the total manufacturing cost. The cost per kilogram of virgin polyester and recycled polyester fibres was INR 110 and INR 75 respectively. This difference of the cost shows that the use of recycled polyester fibres will automatically lower the cost of filter fabrics. Further, it may be presumed that if the needle-punched nonwoven filter fabrics manufactured using recycled polyester fibres, automatically lowered down the total cost approximately to INR 17-18 per square meter of filter fabric (considering fabric of 500 GSM).

Today, a lot of waste polyester fibrous materials are generated both from the garment industries in form of garment cutting waste as well as waste polyester bottle after its use from municipal waste. With proper cleaning and washing, the recycled fibres can be recovered from the waste polyester materials. With the present trend of recyclability and reuse these recycled polyester fibres can easily be converted into industrial filter fabrics.

Hence, it was aimed to minimize the cost of production of needle-punched filter by using low cost material without affecting the properties of the end product. The present study was therefore undertaken to examine the suitability of recycled polyester fibres and to analyze the multi directional tensile property and bursting strength by varying independent variables, such as fabric weight, depth of needle penetration and needling density of the fabrics. The findings are compared with those of the virgin polyester fibres fabrics.

2 Materials and Methods

2.1 Materials

In this study, virgin polyester fibre and recycled polyester fibres were used to prepare the fabric samples. Both the fibres had same denier (1.5), equal staple length (42 mm) and similar crimps (10 crimps/cm).

2.2 Development of Nonwoven Fabrics

The samples were prepared keeping in view Box-Behnken design, considering three variables each with three levels. The variables, namely fabric weight, needling density and depth of needle penetration, were used for the study (Table 1).

Central values for each machine parameter were taken from the manufacturer of needle-punched nonwoven filter fabric. In order to improve the integrity, strength and stability of the nonwoven filter, a plain woven polyester scrim fabric was incorporated in the centre of web having GSM 45 g/m^2, ends per inch (EPI) 26 and picks per inch (PPI) 22. The scrim acts as reinforcement to the filter. The manufacturing details of all needle punched nonwoven filter fabrics are discussed hereunder.

Fifteen fabric samples of virgin and fifteen of recycled polyesters were prepared utilizing the different GSM webs individually on the Erko needle loom 1and 2. Loom 1 was used for initial tacking, pre-consolidation and compactness of fibrous web at comparatively lower needling density of 45 punches/cm^2, keeping depth of penetration at 3 mm, while loom 2 was used for final consolidation of different webs obtained from loom 1 during which scrim fabric was centrally sandwiched between the webs of varying GSM and punched

Table 1 — Variables with their levels as per Box-Behnken design

Independent variables	Levels		
	-1	0	+1
Fabric weight (A), GSM	500	550	600
Needling density (B), punches/cm^2	125	250	375
Depth of needle penetration (C), mm	1	1.5	2

at comparatively higher needling density (125-375 punches/cm^2). Finally, the nonwoven fabrics of desired properties was obtained.

2.3 Finishing of Samples

The needle-punched nonwoven fabric were calendared on a 3 roller pair calendaring machine at a pressure of 1.0 bar and temperature of ~230°C and 180°C for upper and lower rollers respectively.

2.4 Physical Properties of Fibres

2.4.1 Denier, Strength and Tenacity

Since the properties of fibres decide the properties of fabrics, both virgin and recycled polyester fibres were tested for denier, strength and tenacity using Lenzing Vibrodyn 500 instrument following ASTM D 1577-07. An average of 50 fibres was considered. The values for linear density and tenacity of virgin (1.53 den & 6.8 g/den) and recycled polyester (1.51 den & 6.0 g/den) were calculated.

2.4.2 Surface Roughness of Fibres

Surface roughness of fibres was determined using a AFM (Atomic force microscopy) and WS×M 5.0 Develop 8.5 software.

2.4.3 Crystallinity Percentage

Singh and Chauhan[12] have studied the crystallinity percentage of virgin and recycled polyester fibre samples, where pellets of both fibres were prepared separately at pressure of 3-4 tons/cm2. The resulting pellets of each fibres were then characterized by x-ray diffraction (XRD). The samples were scanned in 2Θ range of 5o-55o at a speed of 2°/min. The X ray diffractograms of virgin and recycled polyester curves were already obtained for both virgin and recycled fibres[12].

2.4.4 Physical Properties of Fabric

Web Weight (GSM)

The fabric weight of the samples was evaluated using IS: 1964-2001 standard. The specimens of the size 10.0 cm ×10.0 cm were cut randomly from different places of conditioned sample and weighed on electronic balance with an accuracy of 0.005 g. The average of ten readings of each sample was calculated (Table 2).

Bursting Strength

Bursting strength of the developed fabric samples was evaluated using IS: 1966-1975 standard. From the test sample, 10 test specimens were taken, (each of 250 mm×250 mm) to conduct the bursting test. The average of ten values of bursting strength of each sample was taken (Table 2). The percentage difference of bursting strength (δ%) was calculated using the following relationship:

$$\delta\% = \frac{BS_{VPET} - BS_{RPET}}{BS_{VPET}} \times 100$$

where BS_{VPET} is the bursting strength of virgin polyester; and BS_{RPET}, the bursting strength of recycled polyester.

3 Results and Discussion

Effect of fabric weight (GSM), needling density and depth of needle penetration on bursting strength of needle-punched nonwoven polyester filter fabrics

Table 2 — Bursting strength of virgin and recycled polyester nonwoven fabrics.

Expt. No	GSM	ND, punches/cm^2	DP, mm	BS, kg/cm^2		δ%
				VPET	RPET	
1	500	125	1.5	20.54	19.98	2.73
2	500	375	1.5	16.35	14.21	13.09
3	600	125	1.5	33.05	32.15	2.72
4	600	375	1.5	31.05	28.01	9.79
5	500	250	1	21.33	20.73	2.81
6	500	250	2	19.35	18.85	2.58
7	600	250	1	35.27	34.77	1.42
8	600	250	2	32.39	31.59	2.47
9	550	125	1	27.48	26.55	3.38
10	550	125	2	26.31	25.71	2.28
11	550	375	1	25.41	24.91	1.97
12	550	375	2	24.33	23.83	2.05
13	550	250	1.5	30.65	29.95	2.28
14	550	250	1.5	29.08	28.28	2.75
15	550	250	1.5	29.31	28.89	1.43

GSM – g/m^2, ND – needling density, DP – depth of needle penetration, BS – bursting strength, VPET – virgin polyester fabric, RPET – recycled polyester fabric, and δ% – difference in percentage of bursting strength .

made from virgin and recycled polyester fabrics are discussed in this section.

It is depicted from Table 2 that bursting strength of needle-punched nonwoven fabrics prepared from virgin is higher than that of the recycled polyester nonwoven in all the cases, which may be correlated with the higher fiber strength and surface roughness property of virgin polyester fibre[12]. The higher surface roughness of virgin polyester fibre (66.828 nm) as compared to recycled polyester fibre (32.2693 nm) may be related to the fibre manufacturing process. The higher the surface roughness, the better is the fibre-to-fibre cohesion and entanglement during needling. As a result, the virgin polyester nonwoven shows higher bursting strength as compared to recycled polyester fabric. On the contrary, low strength, crystallinity percentage (35.31% for recycled and 40.08 % for virgin)[13] and surface roughness cause low inter-fibre cohesion of recycled polyester fibres; thus contributing low bursting strength in recycled polyester fabric samples.

It is also observed from Table 2 that the percentage difference (δ%) of bursting strength (1.42-13.09) between virgin and recycled polyester nonwoven samples, which depends on the fabric constructional variables (GSM, needling density and depth of needle-penetration). It is also observed that, at higher needling density (375 punched/cm^2), the percentage difference (δ%) of bursting strength is high. This may be due to shortening of fibre length caused due to breakage of fibres during needling density. Higher δ% was found for recycled samples than for virgin polyester samples. The effect of fabric GSM and needling density on bursting strength of virgin and recycled polyester needle-punched nonwoven fabric is presented in Figs 1 (a) and (b) respectively. It is noticed from these figures that with the increase in fabric weight, the bursting strength of the fabric increases. This is due to availability of more number of fibres per unit area of the fabric which resulted higher strength at higher fabric weight. The effect of bursting strength on GSM is more prominent than needling density for the selected ranges in both virgin and recycled polyester nonwoven fabrics as found from Figs 1 (a) and (b). It is further observed that the extent of increase of bursting strength was initially more and later decreased. The initial increase in bursting strength with increasing needling density may be due to better consolidation of fibres in the fabric. The decreased extent of bursting strength during later stage may be

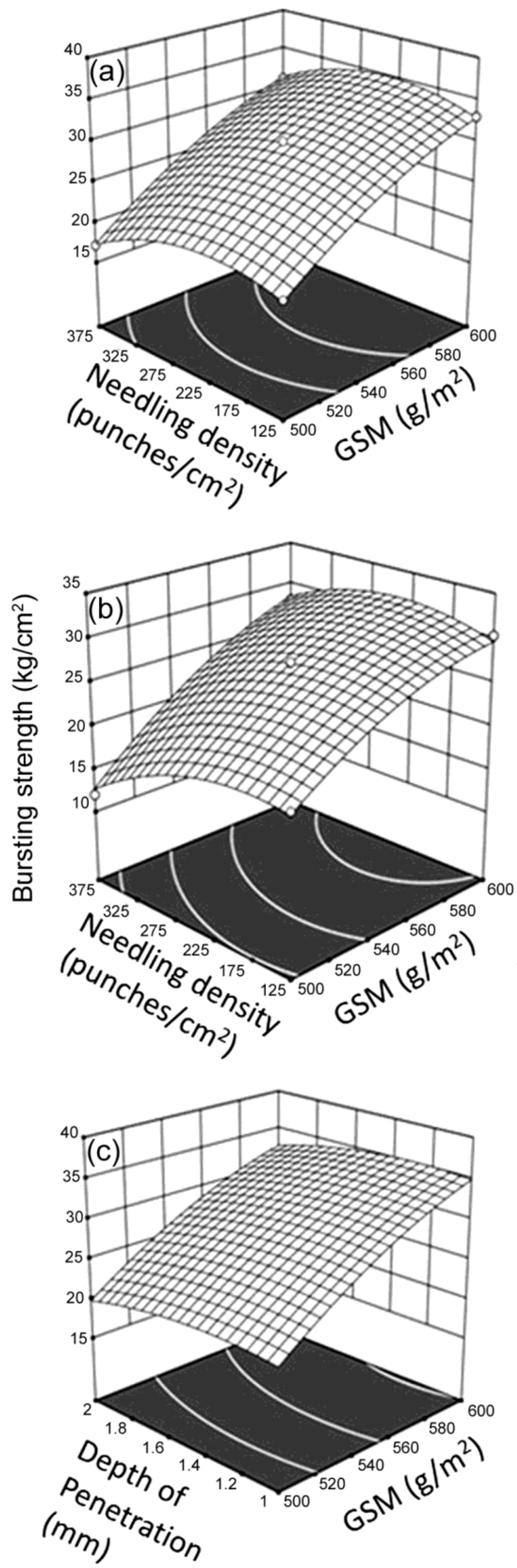

Fig. 1 — Surface-contour plot of bursting strength against needling density & GSM for virgin fibre (a), needling density & GSM for recycled fibre (b), and depth of penetration & GSM for virgin fibre (c)

due to the breakage of fibres caused due to an increased needling density.

Further, it is observed that bursting strength increases initially with the increase in depth of penetration up to a certain limit, but with further increase in depth of penetration, the bursting strength exhibits declining trend [Fig. 1 (c)]. Similar trend is found in case of recycled polyester fabric samples with lower strength values. The initial increase in the extent of bursting strength with increased depth of penetration (1 mm) is due to improved interlocking of the fibres. The decreased extent of bursting strength beyond certain level of increase in depth of penetration may be due to the breakage of fibres.

Figures 2 (a) and (b) show the effect of needling density and depth of penetration on bursting strength of needle-punched nonwoven fabric developed from virgin and recycled polyester fibres respectively. It is observed that bursting strength increases initially with the increase in depth of penetration and needling density up to a certain extent but later when depth of penetration and needling density are increased beyond certain limit, the bursting strength decreases. The initial increase in bursting strength with increase in needling density may be due to improved interlocking of the fibres. The decreased extent of bursting strength during later stage may be due to the fibre breakage caused due to an increased depth of penetration and needling density.

Furthermore, it is worth to say that, under higher needling density (350 punches/cm^2), and fabric weight (600g/m^2), there is more fibre damage which reflect poor bursting strength values ranging between 9.79 kg/cm^2 and 13.09 kg/cm^2 (Table 2).

3.1 Optimizing Key Predictor Variables

The results of the previous section show that the GSM, needling density and depth of needle penetration are the important variables which can directly affect properties of filter fabrics. Using Box-Behnken design of experiments, these variables have been optimized in this section.

3.1.1 Virgin Polyester Filter Fabric

Analysis of variance for bursting strength of fabric made using virgin polyester fibres as shown in Table 3 indicates that the model is significant at 95% level. The individual effects of GSM, needling density and depth of penetration on bursting properties are also found significant at 95% level; the same has been indicated by p-value. The Model *F*-value of 186.90 implies that means between bursting strength of virgin and recycled polyester fabrics are significantly different. Further, the difference of bursting strength observed between virgin and recycled polyester would only be seen about 0.01 % based on the '*p*' value.

The *P*-values of less than 0.0500 indicate that the model terms are significant. In this case A, B, C, A^2, B^2, C^2 are significant model terms (Table 3). Hence, the effect of GSM, needling density and depth of penetration has been found significant at 95% level of significance [Figs 1(a) & (c) and Fig. 2(a)]. In other words, chances to occur only 5% of the values of bursting strength predicted by the model are beyond the limits. The effect of GSM on bursting strength for virgin polyester filter fabric has been found nearly

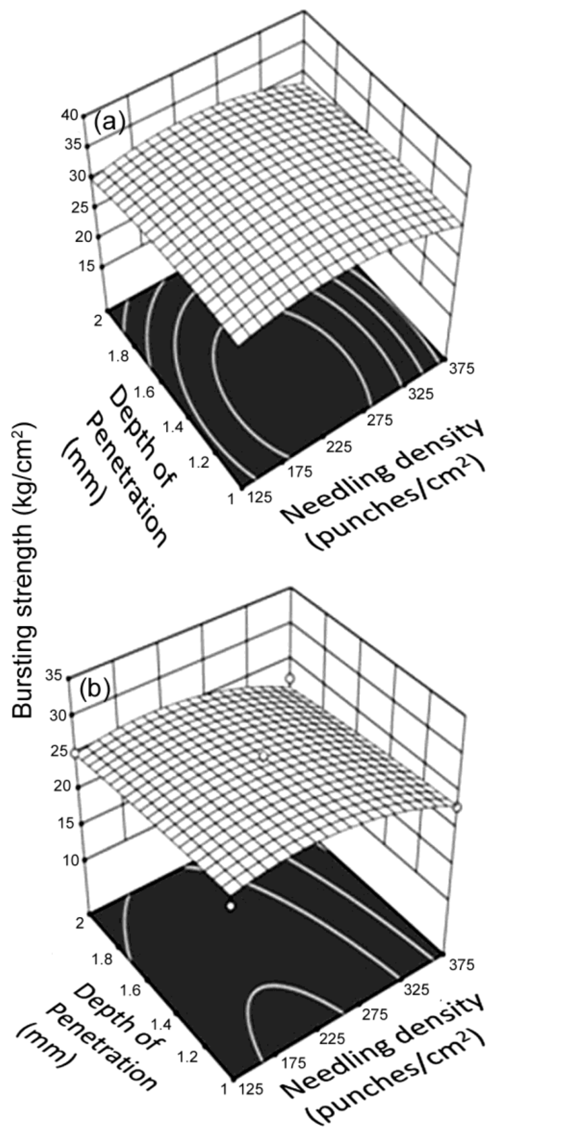

Fig. 2 — Surface-contour plot of bursting strength against needling density & depth of penetration for virgin fibre (a), and for recycled fibre (b)

linear, while the effect of needling density and depth of penetration is found non-linear. The relationships among variables and response are shown in the surface graphs [Figs 3(a) & (b)].

Figure 3(a) shows that the maximum bursting strength for virgin polyester filter fabric optimized at 597 GSM, 215 punches/cm^2 needling density and 1.28 mm depth of needle penetration.

3.1.2 Recycled Polyester Filter Fabric

Analysis of variance for bursting strength of fabric, using recycled polyester fibres (Table 4), indicates

Table 3 — Analysis of variance for bursting strength of virgin polyester filter fabrics.

Source	Sum of squares	df	Mean square	F-value	p-value
Model	408.56	9	45.40	186.90	< 0.0001*
GSM (A)	349.93	1	349.93	1440.72	< 0.0001*
Needling density (B)	11.05	1	11.05	45.47	0.0011*
Depth of penetration (C)	7.39	1	7.39	30.43	0.0027*
AB	0.4970	1	0.4970	2.05	0.2120
AC	0.0961	1	0.0961	0.3957	0.5570
BC	0.0072	1	0.0072	0.0297	0.8698
A^2	8.55	1	8.55	35.20	0.0019*
B^2	30.40	1	30.40	125.14	< 0.0001*
C^2	5.29	1	5.29	21.77	0.0055*
Residual	1.21	5	0.2429		
Lack of fit	1.12	3	0.3740	8.09	0.1120
Pure error	0.0925	2	0.0462		
Cor total	409.78	14			

*Significant values.

Table 4 — Analysis of variance table for bursting strength: recycled polyester filter fabric.

Source	Sum of squares	df	Mean square	F-value	p-value
Model	425.64	9	47.29	35.71	0.0005*
GSM (A)	338.13	1	338.13	255.32	0.0001*
Needling density (B)	30.97	1	30.97	23.38	0.0047*
Depth of penetration (C)	9.44	1	9.44	7.13	0.0444*
AB	7.32	1	7.32	5.53	0.0655
AC	0.6241	1	0.6241	0.4713	0.5229
BC	0.0030	1	0.0030	0.0023	0.9637
A^2	14.37	1	14.37	10.85	0.0216*
B^2	27.62	1	27.62	20.86	0.0060*
C^2	0.3159	1	0.3159	0.2385	0.6459
Residual	6.62	5	1.32		
Lack of fit	6.57	3	2.19	78.45	0.0126
Pure error	0.0558	2	0.0279		
Cor total	432.26	14			

A – Fabric GSM; B – Needling density; C – Depth of needle penetration and * Significant.

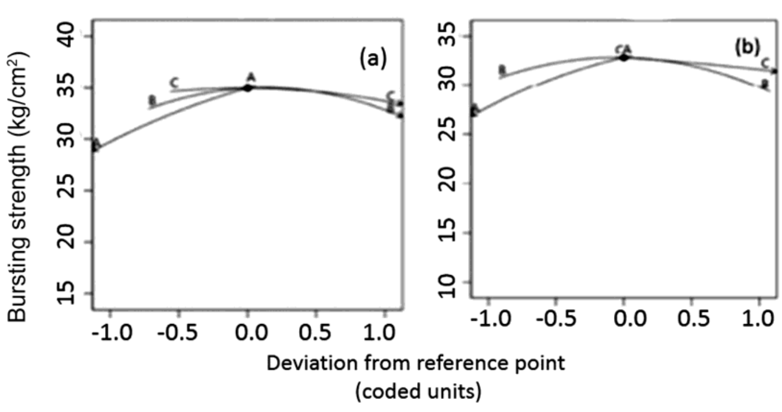

Fig. 3 — Perturbation plots for optimizing predictor variables for bursting strength of virgin polyester filter fabric (a), and recycled polyester fabric (b)

that model is significant at 95 % level. The individual effects of GSM, needling density and depth of penetration on bursting properties are significant at 95% level; the same has been indicated by p-value. Model *F*-value of 35.71 implies that there is only 0.05% change in the existing values which may be considered insignificant.

It is observed from Table 4 that, *P*-values of less than 0.0500 indicate that the model terms are significant. In this case A, B, C, A^2, B^2 parameters are significant.

Effect of GSM, needling density and depth of penetration has been found significant at 95% level of significance [Figs 1(b) and Fig. 2(b)]. The effect of GSM on bursting strength for recycled polyester filter fabric has been found nearly linear, while the effect of needling density and depth of penetration is found non-linear. The relationships among variables and response are shown in the surface graphs. Further, Fig. 3(b) shows that the maximum bursting strength for recycled polyester filter fabric can be achieved at 597 GSM, 240 punches/cm^2 needling density and 1.03 mm depth of needle penetration.

4 Conclusion

Following conclusions can be drawn from the above study:

4.1 Bursting strength increases with the increase in fabric GSM in both the virgin and recycled polyester needle-punched nonwoven. The bursting strength of virgin polyester fabric is found higher than that of recycled polyester fabric samples.

4.2 The bursting strength increases with the increase in needling density as well as depth of needle penetration up to certain limit. Further increase of these two needling parameters decreases the bursting strength.

4.3 The maximum bursting strength for virgin polyester filter fabric can be achieved at 597 GSM, 215 punches/cm^2 needling density and 1.28 mm depth of needle penetration. The maximum bursting strength for recycled polyester filter fabrics can be achieved at 597 GSM, 240 punches/cm^2 needling density and 1.03 mm depth of needle penetration.

4.4 The difference in bursting strength of fabrics prepared from virgin and recycled polyester fibres is between 1.42 % and 13.09 %, which is marginally lesser than the virgin polyester filter fabrics. However, under higher needling density (350 punches/cm^2), and fabric weight (600g/m^2) there are more fibre damage which reflect poor bursting strength values.

From the above findings, it is suggested that the recycled polyester fibres may be substituted in place of virgin polyester for the manufacturing of needle-punched nonwoven filter fabrics for industrial filtration considering the waste utilization and cost aspects.

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