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Cyclic bursting loading on needle-punched nonwovens: Part I – Distention behavior

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The present study aims at examining different needle-punched polypropylene nonwovens under different cyclic bursting pressure. Various fabric parameters including mass density, punch density and fibre fineness have been investigated. For the cyclic test, the distension is measured at different cyclic bursting pressures proportionate to the bursting strength of the fabric. Other parameters including the cyclic pressure magnitude, the number of cycles, and the rest time at peak pressure have also been investigated. It has been found that the bursting strength and distension of fabric increase with an increase in mass density, while they show opposite trend with punch density and fibre denier ($p < 0.01$). The distension value of each sample increases with an increase in the cyclic parameters i.e. number of loading cycle, rest time and pressure peak.

Keywords: Areal density, Bursting strength, Cyclic loading, Needle-punched nonwoven, Polypropylene, Punch density

1 Introduction

Needle-punched nonwoven fabric consists of a random orientation of fibres where the mechanical interlocking is achieved by the movement of a needle bed (having barbed needles) that repeatedly passes into and out of a fibrous web[1]. For an end application, it is comparatively easy to optimize a nonwoven structure to achieve desirable range of properties including porosity, strength, extension, absorbency, filtration and compression, and therefore they are widely recommended for many products in construction, medical, geotextiles, filtration, transmission, etc. A needle-punched nonwoven can be produced from parallel-laid, cross-laid or random-laid carded fibrous web. Compared to a spunboded nonwoven structure, the structure of needle-punched nonwoven fabric is not homogeneous as the production method is entirely different, where the fibres are realigned by the needling action causing reorientation and migration of fibre segments from the surface of the web towards the interior of the fabric. The loops formation takes place during needle punching process either due to buckling of surface fibre or due to force generated at high punch density. The consolidation of needle-punched nonwoven fabric can be enhanced by increase in needling density and depth of needle penetration[2]. However, there is deterioration of the structure or fibre damage with the increase in punch density beyond a certain limit[1]. The fibre organization and entanglement in the web determine the fabric performance.

In many technical applications, such as geotextiles, filter/separator and construction, the nonwoven fabrics are subjected to repeated multidirectional loading and usually they get inflated. This alters their mechanical and other properties in long term performance. It is therefore important to evaluate nonwoven response under repeated loading from multiple directions. For such evaluation, the bursting test holds its significance where a material is subjected to transverse pressure causing multidirectional loading in the structure. Bursting strength of a material is a measure of resistance to its rupture, and the strength of a textile materials largely depends on the fibrous material, the arrangement and orientation of fibres and the entanglement characteristics[3-6]. Koc and Cincik[4] have reported the effect of mass per unit area, punch density and fibre blend ratio for polyester/viscose needle-punched sample. Das and Raghav[5] studied the bursting behavior of heat-sealed spun-bonded fabrics and reported that the bursting strength increases with increase in mass per unit area of spunboded fabrics. They also found that the continuous loading and unloading of the bursting pressure results in creep as well as permanent deformation in the spun-bonded nonwoven structure. In addition, they further extended their study to examine the change in fabric characteristics, i.e. tensile, compressional and

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transmission, after repeated cyclic bursting pressures[7]. Ndaro *et al.*[8] reported the results of bursting performance of hydro-entangled nonwoven fabrics made up of bi-component fibres. Ghosh *et al.*[6] have studied bursting performance of integrated fabrics (woven and nonwoven) made of jute fibres. The slippage of fibre under constant load is also a concern for the deformation in nonwoven fabrics. In this regard, the fibre creep (time-dependent response) could play a critical role in fabric deformation and deterioration process to decide end performance. Kothari and Patel[9] showed the influence of creep of the fabric under constant load which results in significant structural deformation. With the above facts, it can be inferred that the examination of nonwoven under bursting pressure hold more significance in product evaluation and performance.

Among different fibres used in nonwoven production, polypropylene (PP) is popular because of its durability and chemically inert characteristics, and therefore used for aggressive environments especially in geotextiles. In our earlier work[5], we studied the response of spun-bonded PP nonwovens under cyclic bursting pressure. In spun-bond nonwoven, the application of cyclic pressure results in distortion of fabric structure and opening of structural consolidation. The main mode of deformation is primarily because of the breakage of inter-fibre bonds in a spun-bond nonwoven. The deformation in a needle-punched nonwoven fabric might occur either because of fibre slippage, bending or breakages, and hence shows different distension behaviour. This study aims at examining the response of the needle-punched nonwovens under cyclic bursting loading. Different structural parameters including mass density, fibre denier and punch density have been investigated. Also, the effect of different parameters of cyclic tests, i.e. cyclic pressure load, number of cycles and rest time at peak load, are also analysed.

2 Materials and Methods

2.1 Materials

Two linear densities (6 and 15 denier) of the PP fibres were selected for the production of nonwoven samples using a needle-punched nonwoven machine (Model: DILO). The mass density (g/m^2) and punch density (punches/cm^2) of fabrics were varied by changing the machine parameters. The layering factor and output of the card were adjusted to achieve the required mass density, while punching frequency of the needle board was varied to control needle punch density. The depth of needle penetration was kept constant (10 mm) for all samples. By varying the mass and punch density at 3 different levels, a total of 9 different samples were produced for each fibre denier as shown in Table 1.

2.2 Methods

The bursting and repeated cyclic loading tests were carried on the James Heal TruBurst[2] intelligent bursting tester[5]. The tester is fully pneumatic controlled which fulfils the exact requirements of ISO 13938-2 and ASTM D3786- 06. Initially, the bursting strength (peak pressure to rupture) of each sample was measured (Table 2). Different proportions of the bursting strength of the fabric were then selected to conduct the cyclic test. The cyclic pressures chosen for the study were 10, 20 and 30 % of the bursting strength of the fabric. The maximum displacement at each cycle was used to observe the distension effect under repetitive loading. The effect of rest time at peak cyclic pressure was also examined. Analysis of variance (ANOVA) analysis was done to find out the significance of different factors. A p-value less than 0.05 was considered as a statistically significant.

3 Results and Discussion

3.1 Bursting Strength

From Table 2, it can be observed that the bursting strength increases with increasing mass density of the nonwoven ($p < 0.05$). More number of the fibres in a given area results in more interaction, which generates

Table 1 — Details of needle-punched nonwoven polypropylene fabrics [Depth of needle penetration = 10 mm]

Sample code	Fibre linear density den	Mass per unit area, gm^{-2}	Punch density punches, cm^{-2}
S1	15	200	60
S2	15	200	140
S3	15	200	220
S4	15	300	60
S5	15	300	140
S6	15	300	220
S7	15	400	60
S8	15	400	140
S9	15	400	220
S10	6	200	60
S11	6	200	140
S12	6	200	220
S13	6	300	60
S14	6	300	140
S15	6	300	220
S16	6	400	60
S17	6	400	140
S18	6	400	220

Table 2 — Experimental test results

Fabric code	Measured mass per unit area, $g.m^{-2}$		Thickness, mm		Bursting strength, $kg.cm^{-2}$	
	Avg	CV%	Avg	CV %	Avg	CV %
S1	221.10	3.08	3.64	3.76	17.12	2.34
S2	225.30	6.28	3.69	8.4	12.80	6.08
S3	220.97	5.63	3.38	3.56	10.42	4.53
S4	306.25	5.98	5.26	4.17	23.16	2.70
S5	304.30	3.26	5.17	3.42	20.16	3.57
S6	292.12	4.49	4.47	3.38	19.18	4.58
S7	403.27	4.84	6.12	6.44	29.31	4.73
S8	389.05	3.69	5.61	4.30	27.56	3.21
S9	393.40	2.76	5.05	3.02	22.48	6.66
S10	184.41	3.61	3.10	6.76	19.32	4.29
S11	187.90	1.89	2.79	5.35	13.66	3.05
S12	184.13	6.79	2.53	4.44	11.61	4.74
S13	304.25	8.09	4.37	2.47	26.70	6.83
S14	316.10	6.25	4.28	4.99	25.48	6.31
S15	309.10	2.06	3.71	3.25	24.23	6.25
S16	414.63	4.91	4.88	3.73	35.31	6.66
S17	403.06	4.30	4.93	2.76	30.98	7.61
S18	395.64	1.70	4.73	3.35	28.86	2.04

Avg – Average; CV – Coefficient of variation.

more friction among the fibres resulting in higher bursting strength. On looking to the influence of punch density, it can be suggested that the bursting strength decreases with an increase in punch density ($p < 0.05$). Although, more punching causes fibre reorientation in transverse direction, the punching has deteriorative effect of individual fibre strength and more punching causes more fibre breakages which reduces the bursting strength. The strength of the fabrics is more for low denier (6 den) samples compared to high denier (15 den) fabric. This can be explained by the fact that a thin fibre (6 den) has more specific area due to which the frictional resistance within the porous network will be more as compared to a thick fibre (15 den)[10].

3.2 Effect of Cyclic Pressure and Number of Cycles

For cyclic tests, each sample was loaded to different cyclic pressures equals to 10, 20 and 30% of its actual bursting strength. The distension in each sample due to continuous cyclic bursting pressure was measured up to 15 consecutive cycles. Figure 1 show the typical behaviour of a few samples. It can be observed that during initial repeated cyclic loading, lower distension is found for each sample due to low effective pressure and structural consolidation, resulting from fibre alignment on the fabric surface. However as the number of cycles increases, the effective pressure applied on the fabric increases and the structure starts to get deform and loosen, which results in further increase in the distension. The amount of distension for each sample after completion of certain cycles is always more at higher cyclic pressure. As an example, the distention values in sample S2 after completing 15 cycles are around 11.1 mm [Fig. 1(a)] and 8.8 [Fig. 1 (b)] respectively at 10% (1.28 kg/cm^2) and 20% (2.56 kg/cm^2) pressure values. Increasing the pressure magnitude causes more deformation in the fabric structure, resulting in higher distention.

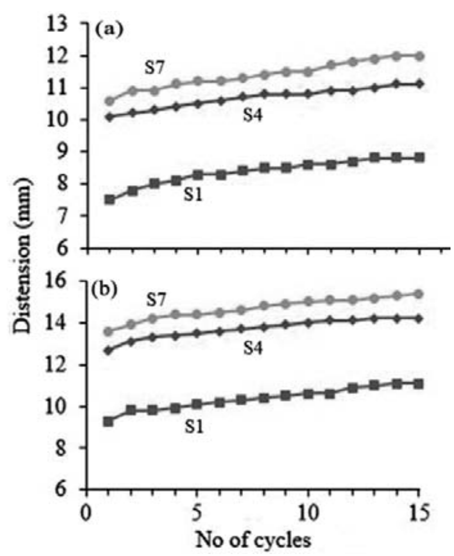

Fig. 1 — Distention behavior of fabrics under cyclic loading at (a) 10% and (b) 20% pressures of bursting strength with different mass densities (60 punches/cm^{-2}, 15 den)

3.3 Effect of Structural Parameters

Figure 1 also shows distension behaviour of fabrics with varying mass densities, keeping the level of other factors same. As an example, sample (S7) having mass density of 400 g/m^2 shows higher distension (12 mm) after 15 cycles at pressure equals to 10% of bursting strength [Fig. 1(a)] compared to the samples S1 (8.8 mm) and S4 (11.1 mm). The magnitude of distention in the sample primarily depends on the pressure magnitude and its structural characteristics. Among these three samples, S7 has the highest bursting strength (29.31 kg/cm^2), while the S1 has the least (17.12 kg/cm^2) as observed in Table 2. At 10% level, the amounts of cyclic pressure magnitude are 2.931 and 1.712 kg/cm^2 respectively for S7 and S1 fabrics. More pressure magnitudes result in higher distension in the S7 as compared to that in S1 and S4. On examining the effect of punch density, it has been found that the amount of distention is more for the sample with lower punch density (Table 2). As discussed above, the increase in punch density leads to reduction in bursting strength of fabric. So, the amount of effective pressure applied on a lower punch density is more compared to higher punch density. For the samples in Fig. 2, S7 has the highest cyclic pressure (2.93 kg/cm^2), while the S9 has the least (2.248 kg/cm^2). Similar trends of mass density and punch density are observed for the 6 den samples (Table 3).

Table 3 — Distension results of all samples
[Pressure level—10% of bursting pressure;
Number of cycles = 15]

Sample code	Distension, mm
S1	8.8
S2	7.9
S3	7.6
S4	11.1
S5	10.4
S6	8.9
S7	12
S8	11.5
S9	11.3
S10	10.8
S11	9.9
S12	9.1
S13	12.1
S14	11.8
S15	11.3
S16	13.3
S17	12.6
S18	12.1

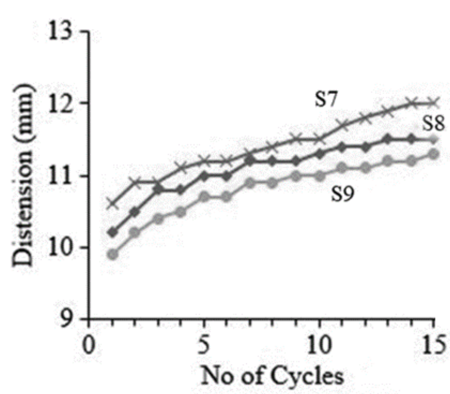

Fig. 2 — Distention behavior of fabrics under cyclic loading at 10% pressure of bursting strength with different punch densities (400 g/m^2, 15 den)

3.4 Effect of Rest Time at Peak Pressure

Figure 3(a) shows the typical behavior of the effect of resting time at peak pressure. It can be seen that the distension behaviour of a specimen is changed if the structure is allowed to relax at peak load. Lower distension values are observed under continuous pressure cycle with no resting time at pressure peak. Allowing resting time at pressure peaks results in significant reorientation and structural deformation of the fibres, especially due to creep behaviour (time-dependent property). Providing more relaxation time in loading shows more creep deformation and fibre slippages in the structure. Additionally, resting at

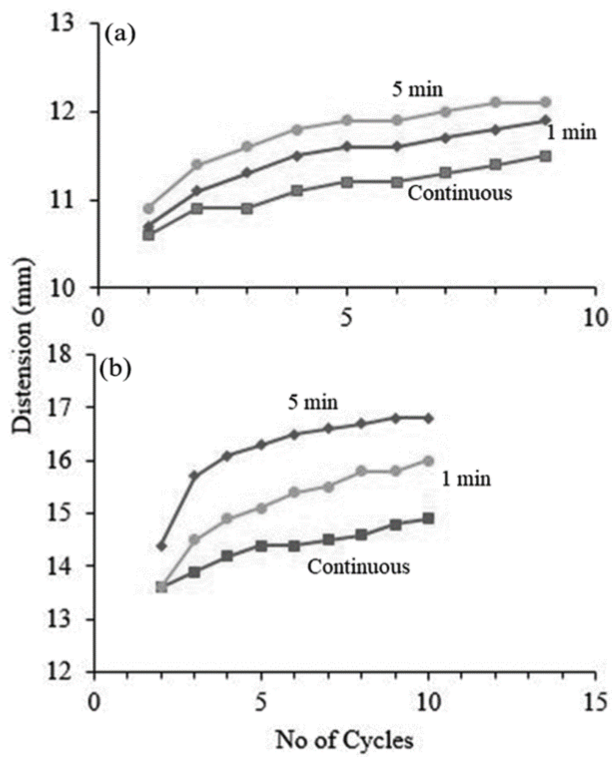

Fig. 3 — Effect of rest time at peak pressure at (a) 10 % and (b) 30% of bursting pressure (S7 sample, 15 den, 400 g/m^2, 60 punches/cm^{-2})

higher pressure magnitude results in even more intensive action and higher distention in the same sample as observed in Fig. 3 (b). All other samples were also showing similar observations.

4 Conclusion

Needle-punched polypropylene nonwoven fabric samples have been investigated under cyclic bursting loading. Different structural parameters including fibre fineness, mass density and punch density have been chosen for the study. For the cyclic testing on a given sample, different magnitudes of bursting pressure proportionate to its bursting strength are chosen. It has been revealed that there is a prominent effect of structural parameters on the bursting strength and cyclic distention value. Both the strength and distention increase with the increase in mass density but has opposite effect with the punch density and fibre denier. Additionally, the magnitude of cyclic pressure, rest time and number of cycles has significant effect on distention behavior under cyclic loading. The distension value in a specimen increases with increase in number of cycles, pressure peaks and resting time.

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