Indian Journal of Fibre & Textile Research
Vol. 47, December 2022, pp. 417-423
DOI: 10.56042/ijftr.v47i4.58323

Filtration performance of needle-punched nonwoven air filter media through dyeing process

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Received 17 December 2021; revised received and accepted 3 March 2022

Viscose fibre has been dyed with various dye concentrations and the needle-punched nonwoven fabrics are prepared using the dyed fibre, keeping machine parameters the same. The physical properties, such as tenacity & bursting strength, and functional performance properties, such as mean flow pore size, filtration efficiency & pressure drop, are measured. It is found that the dyeing plays a big role in altering the overall performance of the needle-punched nonwoven. The tenacity of the needle-punched nonwoven fabric is reduced as dye concentration is increased. Filtration efficiency is measured for three different sizes of particles, namely 3μm, 5μm, and 10μm. For all three cases, the filtration efficiency is increased initially till 3% dye concentration and beyond that it is reduced.

Keywords: Bursting strength, Dyeing, Filtration efficiency, Needle-punched nonwoven, Pressure drop, Reactive dye, Tenacity, Viscose fibre

1 Introduction

Over the last few decades, the air quality is deteriorating exponentially due to the increase in air pollution load. Many factors are contributing to air pollution. Vehicle exhaust fumes, fossil fuel-based power plants, exhaust from industrial plants and factories, construction and agriculture activities, natural causes, household activities, etc. are a few to name[1]. US Environmental Protection Agency (EPA) has developed the Air Quality Index (AQI), considering five different air pollutants, viz ground-level ozone, particle pollution (particulate matter of PM2.5 and PM10), carbon monoxide, sulfur dioxide and nitrogen dioxide. The AQI ranges from 0-500, and is divided in to different sub categories like 0-50 is considered as good air quality and very little or no risk here; 51-100 represents acceptable air quality, 101-150 shows health effects with less impact; 151-200 indicate serious health effects; 201-300 indicates heath alert; and 301-500 shows serious health issues with an emergency situation. As we are advancing, the AQI is getting higher and we are forcing to move towards the different health issues due to poor air quality[2,3]. The main reason for increasing pollution load over the past few decades and for air quality getting deteriorated seriously due to deforestation, is rapid urbanization and industrial revolution[4]. Among other air pollutants, fine particles (particulate matter of PM2.5 and PM10) are found to be the most serious source of air pollution, causing a major and adverse health effect ranging from the human respiratory tract to extra-pulmonary organs[5–7]. Moreover, stricter emission, limiting for fine particle emissions, have also contributed to the urgent need for a high-performance filtration medium with low energy costs[8]. Thus, the use of filter media is becoming part of our lifestyle. Textile structures play a big role as filtration media. Nonwoven structure is the best fit for this purpose[9]. Nonwoven filter media in their simplest forms with randomly oriented fibre structures, are usually available in sheet form. Due to the presence of randomly oriented fibres in the nonwoven structures, it forms a tortuous structure of the filter media. Thus, nonwoven filter plays important role in the removal of particulate matter from the air by entrapping the particulate matter in it. Nonwoven air filter media are extensively used for the separation of hazardous contaminants from air streams. The products include but are not limited to

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profilters, heating, ventilation, and air-conditioning filters, automotive cabin filters, vacuum cleaner filters, air purifiers, respiratory filters, and facemasks[10]. In a nonwoven structure, the fibres are loosely oriented in a plane, distributed randomly, layered, and bonded mechanically, chemically, or thermally. They are well known to offer a few specific performance advantages; and also have advantages like high rate of production, low cost of manufacturing, and versatility, over other fibrous filter media for example woven or knitted. Due to their structural advantages, they can capture particles of a wide range of sizes more efficiently from the surface to the interior of the structure and develop much lower pressure drop as compared to the woven and knitted fibrous filter media, thereby resulting in less running cost. Owing to the complex pore geometry of nonwoven filter media, the air stream follows a tortuous path within the structure that results in a higher probability of particle capture inside the media. As known, fibres are the building block of nonwoven materials. Among other nonwoven structures, needle-punched nonwoven structures are very well known for their application in air filtration due to their simple manufacturing process and special construction. Researchers are constantly working to improve filtration efficiency. They found that the physical properties of fibres, process parameters, needle shape and size, structural characteristics of nonwovens and properties of air, are few to name as influencing factors in filtration efficiency of nonwoven filter media[11–27].

From the ongoing discussion, it is observed that for a particular fibre if the process parameters remain unchanged, there is a very limited scope of improving or altering the filtering efficiency. However, there is a possibility of enhancement of performance utilizing fibre surface modification. Fibre surface modification can be achieved easily utilizing simple dyeing or any finish application[28–30]. To the best our knowledge, no literature has been found in this area. Thus, a systematic study has been planned to understand the effect of dyeing and dye concentration on the mechanical and functional performance, especially the filtration efficiency of needle-punched nonwoven made of dyed viscose fibre with different dye concentrations.

2 Materials and Methods

2.1 Preparation of Samples

Viscose fibre of 1.5 denier and 38 mm cut length was used for this research. Viscose fibre was dyed with different concentration of (1, 3, 5, 7, 9, and 11%) using a lab-scale infra-red dyeing machine. Dyeing was carried out following a normal reactive dyeing cycle at 80°C for 60 min and 1:10 material: liquor ratio. A mother solution of dye was prepared and run under an overhead stirrer for 30 min for proper mixing before adding the required dye solution into the dye vessel. After the dyeing is over, the fibres were washed thoroughly and then dried in a hot air oven.

Needle-punched nonwoven manufacturing is a two-step process. A miniature card of TRYTEX was used to open the fibre and Dilo needle punching system was used for punching the fibre webs. Dyed fibres are opened manually before feeding into the feed roller of the miniature card. The targeted basis weight of all the needle-punched nonwoven was 200±5 GSM. Carding and needle-punching process parameters of nonwoven manufacturing are: 240 m/min cylinder sped, 5.5 m/min doffer speed, 0.17 m/min feeder speed, 100 strokes/min stroke frequency, 150 punches/cm^2 punch density and 9 mm depth of penetration.

2.2 Property Measurement

2.2.1 Add-on% Measurement

Add-on% (weight gain) due to dyeing of fibre was measured using the following equation:

$$\text{Add}-\text{on}\% = \frac{\text{Weight of dyed fabric} - \text{Weight of undyed fabric}}{\text{Weight of undyed fabric}} \quad \ldots (1)$$

2.2.2 Basis Weight

ASTM D3776 standard was followed to measure the basis weight of all the needle-punched nonwoven samples. Electronic balance with 0.001g precision was used to measure the weight of the circular specimen cut by circular cutter and cut randomly from different places.

2.2.2 Tenacity

The tenacity of the needle-punched fabrics was measured following ASTM D5035 and ZWICKROELL Z100Tensile tester, which was used for this purpose. Tensile testing was carried out in both machine and cross direction. An average of 10 readings was taken into consideration and reported.

2.2.2 Bursting Strength

ASTM D3786 bursting strength method was used to measure the bursting strength of needle-punched nonwoven specimens by using a hydraulic or pneumatic

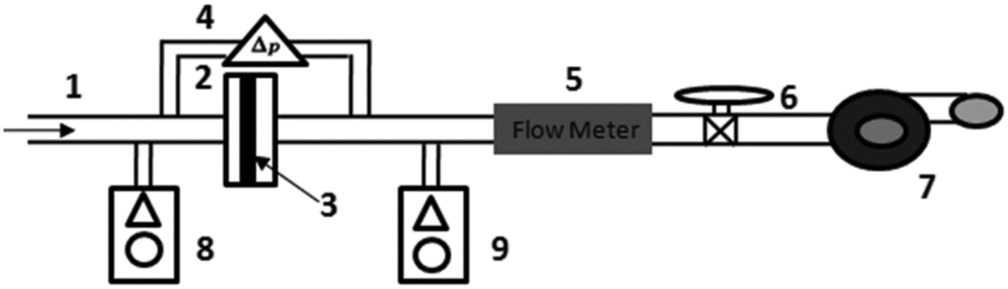

Fig. 1 — Schematics of air filter test rig [1–air inlet, 2-rubber coated sample holder, 3-test filter media, 4-digital pressure gauge, 5-air flow meter, 6- flow control valve, 7-suctionpump, 8- upstream particle counter, and 9- downstream particle counter]

diaphragm bursting tester. Circular samples of 31.5 mm diameters were mounted on an expendable diaphragm, and the diaphragm was allowed to expand by fluid pressure till the point of specimen rupture.

2.2.3 Mean Flow Pore Size Measurement

POROLUX$^{\text{TM}}$1000 Germany, a capillary flow porometer, was used to measure the mean flow pore size distribution, minimum and maximum mean flow pore sizes. POROFIL (low surface tension liquid 16 mN/m) wetted fabric samples were mounted in a sealed chamber that was then pressurized with nitrogen gas.

2.2.4 Filtration Efficiency and Pressure Drop

Filtration efficiency and pressure drop were measured using a purpose-built air filtration set-up (Fig. 1)[31]. Here, sample holder and duct diameter were 100 mm and 50 mm respectively.

To get firm gripping and zero permeability, synthetic rubber-coated rubber seals were used. A ratio of 40:1 between inflow distance and diameter was kept for maintaining uniform pressure difference across the width of the duct. Following equation was used to calculate filtration efficiency:

$$\text{Filtration efficiency } (F_e) = \frac{(\text{Upstream particle count} - \text{Downstream particle count})}{\text{Upstream particle count}} \quad \ldots (2)$$

3 Results and Discussion

3.1 Add-on %

Figure 2 (a) and Table 1 present the add-on% (weight gain) of viscose fibre after dyeing at different concentrations. Viscose fibre was dyed separately with red reactive dye with 1, 3, 5, 7, 9, and 11% dye concentrations. Add-on% increases with an increase in dye concentration.

For 1% dye concentration, 0.38% add-on is obtained. And at 3% dye concentration, it becomes 1.02%, i.e.

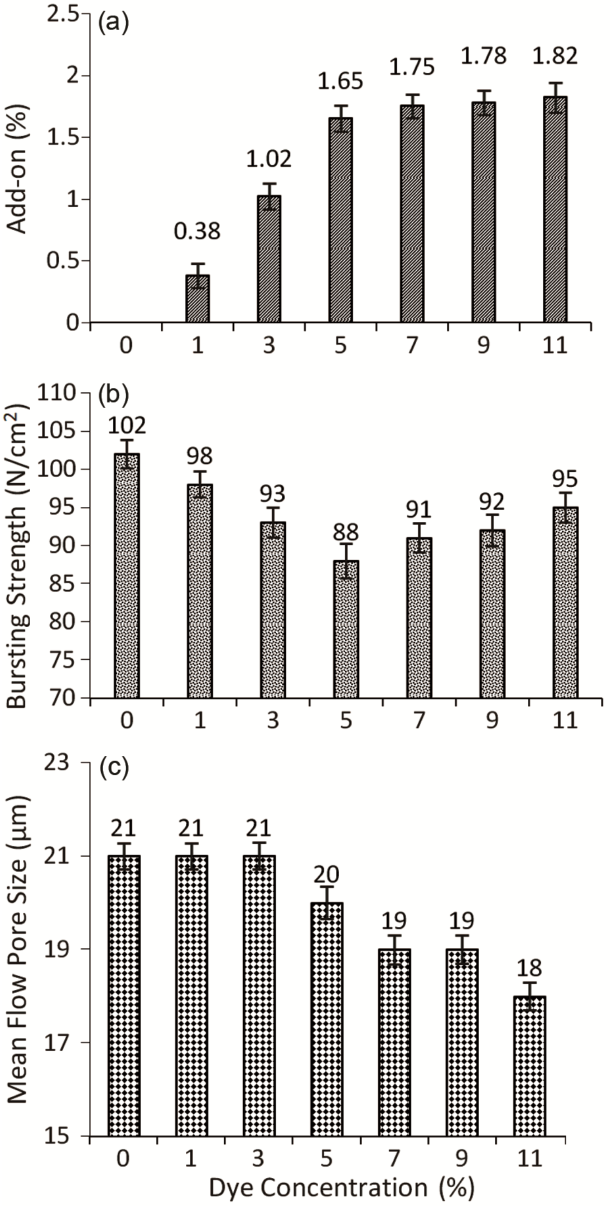

Fig. 2 — (a) Dye add-on%, (b) bursting strength and (c) mean flow pore size at different dye concentrations

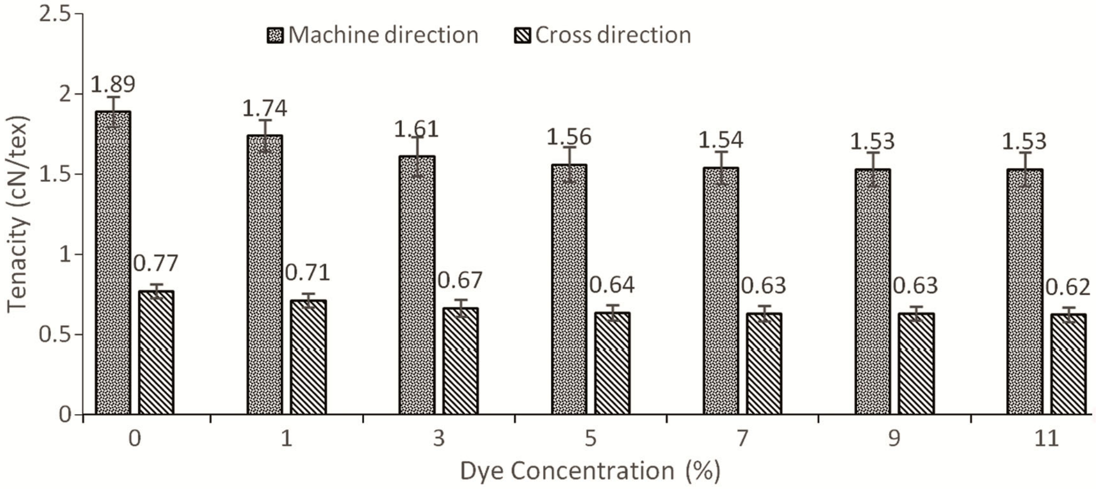

Fig. 3 — Tenacity of needle-punched nonwoven fabrics machine direction and cross direction

Table 1 — Considered dye concentrations and related physical, mechanical and functional properties

Dye concentration, %	Add on %	Tenacity cN/tex	Tenacity cN/tex	Mean flow pore size, µm	Filtration efficiency, %			Pressure drop, Pa	Bursting strength N/cm^2
					3µm	5µm	10µm		
0	0	1.89	0.77	21	45	63	81	78	102
1	0.38	1.74	0.71	21	46	65	85	79	98
3	1.02	1.61	0.67	21	50	70	89	78	93
5	1.65	1.56	0.64	20	48	67	87	79	88
7	1.75	1.54	0.63	19	47	66	84	80	91
9	1.78	1.53	0.63	19	47	66	84	81	92
11	1.82	1.53	0.62	18	45	64	82	80	95

0.64% increase in add-on. This is the highest increase in the add-on. The second highest increase of 0.63% is obtained when the dye concentration is increased from 3% to 5%. Further, the add-on % shows a continuous increasing trend with the increase in dye concentration, but to less extent. Finally, for 11% dye concentration, the add-on% is found 1.82% which is an all-time high.

3.2 Tenacity

Figure 3 and Table 1 present the tenacity of needle-punched nonwoven fabrics made of un-dyed and dyed viscose fibre in both machine direction (a) and cross direction (b). As expected, the tenacity in machine direction is always high as compared to that in cross direction for needle-punched fabrics made of both un-dyed and dyed fibres. The tenacity of needle-punched nonwoven fabric made of un-dyed fibre is found 1.89 cN/tex in the machine direction and 0.77 cN/tex in cross direction. The highest value of tenacity is obtained in both machine direction and cross direction for nonwoven made of un-dyed fibre. Reduction in tenacity is observed after dyeing. The possible reason for the drop in tenacity after dyeing could be due to the breaking and disturbance of internal structural elements of cellulose polymer (viscose) at the molecular level during the exhaust dyeing. A clear and distinct decreasing trend in tenacity is observed for both machine direction and cross-machine direction, with the increase in dye concentration. The lowest tenacity is obtained for the nonwoven made of dyed fibre with a dye concentration of 11%. The value of the same is 1.53 cN/tex and 0.62 cN/tex respectively for machine direction and cross direction respectively.

3.3 Bursting Strength

The bursting strength of needle-punched nonwoven fabrics will depend on the mechanical strength of the fibre and fibre - fibre interaction when other parameters like basis weight and thickness remain unchanged. The mechanical strength of un-dyed viscose fibre is always high as compared to dyed fibre and chances of fibre - fibre interaction are also more due to its inherent ridges and grooves present on the fibre surface. Hence, the bursting strength of un-dyed fibre is highest (102 N/cm^2) [Fig. 2(b) and Table 1]. Bursting strength reduces with the increase in dye concentration, which has good agreement with the hypothesis of reduction in fibre strength due to dyeing.

The lowest bursting strength (88N/cm^2) is obtained for needle-punched fabric made of viscose fibre dyed with 5% dye concentration. After that, the bursting strength shows an increasing trend with the increase in dye concentration. This is probably due to the fact that at 5% dye concentration maximum saturation point is obtained and it is able to cover the natural ridges and grooves present on the fibre surface due to dye molecule deposition, and the fiber surface starts gaining smoothness. This phenomena is also supported by the work of Tissera *et al.*[32]. Hence, there is a chance of fibre rearrangement when bursting force initiates to act on the structure. As a result, there is a slight boost in bursting strength.

3.4 Mean Flow Pore Size

Mean flow pore size represents the size of a web through which at least 50% of total air flow will pass. For a fixed basis weight of needle punched nonwoven with no change in needling parameters, mean flow pore size will depend on the surface roughness of the fibrous material. Untreated viscose fiber has an inherent surface roughness. Hence the mean flow pore size should suppose to be highest in this case. The mean flow pore size for needle punched nonwoven made of untreated fiber was 21 µm, which is the highest [Fig. 2(c) and Table 1].

The dye particle would affix on the fibre surface and makes a layer on it. This would confer the increment in surface smoothness of the fibre. The mean flow pore size remains high at 21µm, till the dye concentration of 3%. This could be due to the surface roughness. Upon further increase in dye concentration to 5%, the reduction in mean pore size is observed. It reduces further with the increase in dye concentration, and the lowest value of 18µm is obtained for a dye concentration of 11%.

3.5 Filtration Efficiency

Needle-punched nonwoven fabric is a kind of mesh like structure of fibrous material. Fibres in the needle-punched nonwoven structure are oriented randomly. Also, in microscopic view, one can find a lot of fine pores in their structure. Now, if a particulate matter impacts the needle-punched nonwoven structure, there is a chance that the particle is arrested by the fibre mesh. The larger the particle size, the more is the chance of particle arrests, i.e. more filtration efficiency.

Figure 4 and Table 1 present the filtration efficiency of three different particle sizes, namely 3 µm, 5 µm, and 10 µm. As expected, filtration efficiency is always high for the largest particle size of 10µm. The filtration efficiency for this particle size is found in the range of 81 - 89%. This is followed by 5µm particle. Here, the filtration efficiency is between 63% and 70%. The lowest filtration efficiency is obtained for the smallest particle (3µm); here the filtration efficiency is in the range of 45-50%.

The filtration efficiency is comparatively on the lower side due to lower basis weight, high air permeability, and high pore size. Filtration efficiency data, as presented in Fig. 4 and Table 1, is another key point to observe that, for all three particle sizes the

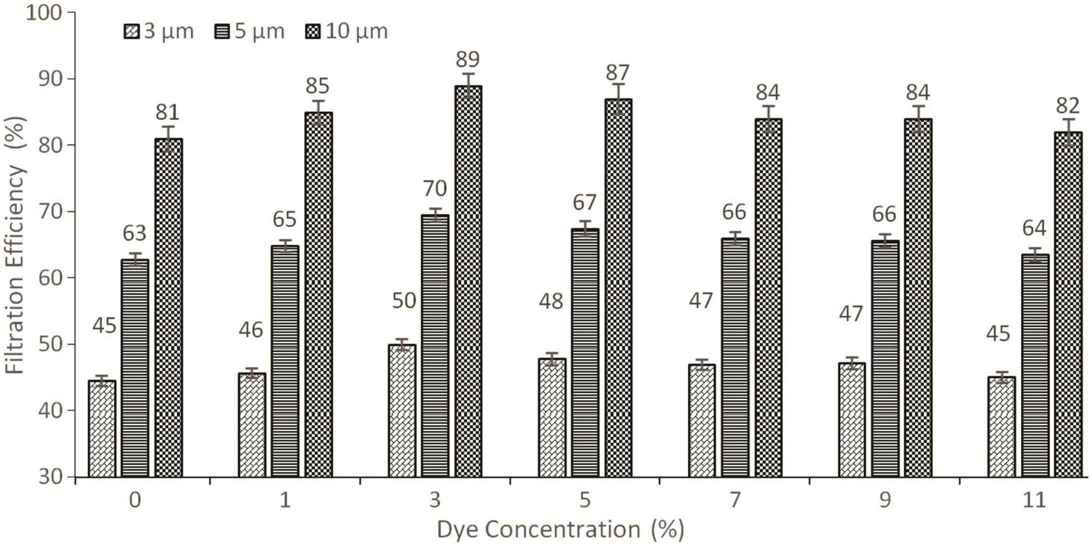

Fig. 4 — Filtration efficiency for particle size of (a) 3µm, (b) 5µm, and (c) 10µm

filtration efficiency is always low for untreated fabric. The filtration efficiency values of needle-punched samples are 45%, 63%, and 81% for 3μm, 5μm, and 10μm size particles respectively. Filtration efficiency increases with the increase in dye concentration, and the trend of filtration efficiency is found to be the same for all three cases. Highest filtration efficiency is obtained for needle-punched nonwoven made of 3% red reactive dyed viscose fibre. The filtration efficiency of the dyed samples are 50%, 70%, and 89% for 3μm, 5μm, and 10μm size particles respectively.

The highest gain in filtration efficiency as compared to untreated one is found 8% for 10μm particle, followed by 7% for 5μm particle and lowest 5% for 3μm particle. Beyond 3% red reactive dye concentration, particle filtration efficiency shows a downward slope. The lowest filtration efficiency is 45%, 64%, and 82% for 3μm, 5μm, and 10μm size particles respectively when dye concentration is 11%. This is due to the increase in dye concentration; the surface of the fibre gets smoother and as the particle size considered for this experiment is much smaller than the mean pore size, lower particle filtration efficiency is obtained.

3.6 Pressure Drop

The pressure drop of any filter media depends on the pore size and pore size distribution. The lower the pore size, the higher will be the pressure drop. As shown in Fig.2 (c), the mean flow pore size of nonwoven made of undyed fibre is high (21 μm). Hence, the pressure drop value should below. When pressure drop is measured, it is found that the lowest pressure drop (78 Pa) is obtained for the needle-punched nonwoven made of undyed fibres (Fig. 5 and Table 1). With the dye concentration of 3%, the pressure drop is increased with the increase of dye concentration. The highest pressure drop (81 Pa) is obtained when the fibre is dyed with 9% dye concentration. Figure 2(c) also depicts that the lowest mean flow pore size of 18 μm is obtained for the nonwoven made of viscose fibre dyed with 11% dye concentration. Hence, the pressure drop should be highest for this nonwoven. Unfortunately, slight decrease in pressure drop (80 Pa) is obtained for this case. One possible reason could be, due to the presence of such a high concentration, the fibre behaves slightly different as it should be in the normal case.

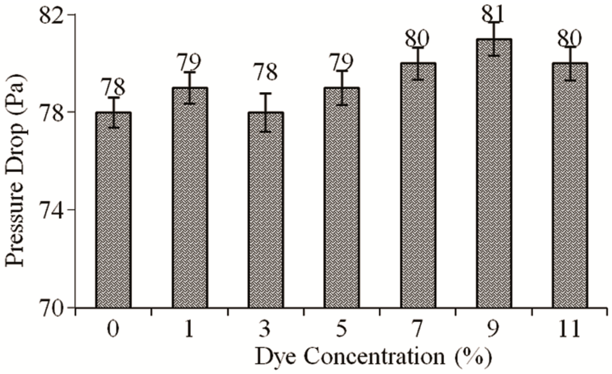

Fig. 5 — Pressure drop of different needle-punched samples

4 Conclusion

A systematic study has been planned and executed to understand the effect of dyeing on the physical properties and filtration efficiency of needle-punched nonwoven fabric. It is found that add-on% increases with the increase in the dye concentration. Highest add-on% is obtained for a dye concentration of 11%. Tenacity in both machine direction and cross direction is decreased with the increase in the dye concentration. In the case of bursting strength, initially it reduces at low dye concentration; lowest bursting strength is obtained for the needle-punched nonwoven dyed with 5% dye concentration and upon a further increase in dye concentration, the bursting strength shows an upward trend. Mean flow pore size distribution is reduced with the increase in dye concentration. Filtration efficiency increases till dyeing with 3% dye concentration and then it reduces with the increase in dye concentration for all three particle sizes, namely 3μm, 5μm, and 10μm. On the other hand, in case of pressure drop, it increases with the increase in dye concentration. Overall, it can be concluded that the dye has a direct impact on the mechanical and functional properties of needle-punched nonwoven fabric.

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