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A Review Study on the Effect of Needle Punching Machine Parameters on the Filtration Efficiency of Non-woven Fabric used for Development of Face Mask

Tay Poh Jing[1], **Siti Hana Nasir**[1]*

Department of Mechanical Engineering Technology, Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: There are various types of masks in the market, such as surgical masks and industrial masks. A surgical mask is a medical device used for covering the mouth, nose, and chin to make a barrier that limits the transmission of bacteria between the patient and healthy people. For people who do not wear masks, the bacteria or virus may enter through the body through the airway such as mouth, nose and cause infections like pneumonia, influenza and most importantly the current epidemic disease which is coronavirus. The purpose of this research is to identify the most suitable set of non-woven fabric as mask material would be suggested at the end of this review study. For the scope, few parameters such as the depth of needle penetration, needling density and fibre cross-sectional shape of non-woven mat were selected to analyse its relation to non-woven fabric performance. All the lab testing that related to physical properties and filtration efficiency of non-woven fabrics listed, such as porosity, thickness, density, tear strength, air permeability and the water resistance were analysed and discussed. For methodology, this review study was conducted by searching based on data from others research and compiling the data through a series of papers. The literature search used four databases (Google scholar, SAGE, ScienceDirect, Elsevier) and 30 articles were identified. The data from the previous researcher were compared and analysis were made based on these studies. For the result, high needle penetration, high needling density and hollow cross-sectional shape of fibre were suggested for parameters for non-woven fabrics used for face masks production because it provided higher fabrics density, smaller pore size, lower porosity, higher air permeability and excellent water resistance. High air permeability provide greater breathability for face masks and excellent water resistance provide a barrier to avoid droplets passing through the face mask fabrics. However, the filtration efficiency of non-woven fabrics will drop slightly when fabric thickness decreased. Lastly, it is recommended that the parameters such as web weight should be examined and be taken into consideration. This is because in the

Corresponding author: sitihana@uthm.edu.my

data collection process, many sources were noticed that the web weight plays an important role in affecting non-woven fabric physical and filtration performance.

Keywords: Face Masks, Filtration Efficiency, Needle Punching Parameters, Non-Woven Fabrics, Physical Properties

1. Introduction

There are various types of masks in the market, such as surgical masks and industrial masks. A surgical mask is a medical device used for covering the mouth, nose, and chin to make a barrier that limits the transmission of bacteria between the healthy and sick people [1], [2]. The material of the mask can be made from various processes such as non-woven and weaving [3]. Most surgical masks are made using non-woven methods. In Non-woven method, long fibres are bonded together using various methods such as dry lain or wet laid. Non-woven mat is easy and cheap to manufacture, making it suitable to be made into disposable products. In this review study, polyester fibres were selected as the material of non-woven fabric. The non-woven mat was produced by using a needle punching method.

During the global spread of coronavirus, the demand for surgical masks was drastically increased due to the epidemic of coronavirus and caused a shortage of supply worldwide. For people who do not wear masks, the bacteria or virus may enter through the body through the airway such as mouth, nose and cause infections like pneumonia, influenza and most importantly the current epidemic disease which is coronavirus. Compared to knitted fabric and woven fabric, the characteristic of some non-woven mat was excellent in filtration efficiency and suitable to become the material to produce face masks [4]. Hence, this study provides a general review on the impact of the depth of needle penetration, needling density and fibre cross-sectional shape on the physical properties and filtration efficiency of non-woven mat. Also, suggest the parameter of non-woven mat with optimum filtration efficiency suitable to be used as a face mask based on the finding from review. All the lab testing that related to physical properties filtration efficiency of non-woven fabrics listed, such as porosity, thickness, density, tear strength, air permeability and the water resistance were analysed and discussed. The non-woven mat with excellent water resistance and high air permeability was suggested to be used as a face masks production. The results of this research can provide significant information about the parameters that influence the performance of non-woven mat and therefore produce a better face mask to protect the wear.

2. Methodology

This section shows the overall investigation process of this review study based on other research's data and analysis. First and foremost, the project was started by selecting the topic of research and studying some previous journal articles based on the topic. After that, the topic was decided and started to select the parameters of the needle punching machine that will impact the filtration performance of non-woven mat. Next, the data collection of this review study was conducted using database system and search engine such as Google Scholar, Elsevier, ScienceDirect and SAGE. All the article was found based on the keywords and combinations of word such as non-woven fabrics, needle punching machine parameters, filtration efficiency, physical properties of non-woven fabrics, needling density, fibres cross-sectional shape and depth of needle penetration. Most recent articles were selected for this study.

2.1 Sources analyzation

A total of 32 articles were found during the data collection stage. Two "Limiting" filter rules were then applied. First, all the article was found for review based on the keyword such as "polyester non-woven fabrics", "needle punching machine parameters", "filtration efficiency", "physical properties of non-woven fabrics", "needling density", "fibres cross-sectional shape" and "depth of needle penetration". Second, typically the time range of the articles selected was from year 2000 until 2020.

All the sources were found and used for this review were based on the research titles related to non-woven fabrics. The data and analysis of non-woven fabric's filtration performance were reviewed. After that, the data and analysis of each source were used for comparison to produce a conclusion for the review study. The non-woven mat physical properties and filtration efficiency such as porosity, tear strength, thickness, density, air permeability and water resistance were analysed based on the parameters of the needle punching machine.

2.2 Assessment approach

This review study was carried out by searching articles and research all around the world. Those articles and research were acquired by some online medium. Upon encountering some of the article that cannot be downloaded directly, it can be downloaded and get full access to the article by using e-resources from UTHM that is Tunku Tun Aminah Library. Besides, all the articles found from online medium were inserted in the application of Mendeley and it was used to generate the citation and reference for this thesis. Table 1 shows the online sources that include some search engines.

Table 1: Online source

No	Online source
1	SAGE
2	Tunku Tun Aminah Library
3	Elsevier
4	Sci-hub
5	Google
6	Google Scholar

3. Results and Discussion

The impact of the depth of needle penetration, needling density and fibre cross-sectional shape on the physical properties and filtration efficiency of non-woven mat were elaborated and discussed in in this section. All the data were compared and the parameters with optimum performance that would be suitable to be used for face masks production were discussed and suggested. Table 2 shows the outcome measures from selected articles that were used for this review study.

Table 2: The outcome measures from selected articles that were used for this review study

Author (s)	Title	Machine / Fibres Parameter	Outcome Measures
(Maity et al., 2012)	A review on jute nonwovens: manufacturing, properties and applications	Needling density and depth of needle penetration	Air permeability and water resistance
(Madhusoothanan, 2010)	Thermal insulation, compression and air permeability of polyester needle-punched nonwoven	Fibre cross-sectional shape	Air permeability, thickness and density
(Patanaik & Anandjiwala, 2009)	Some Studies on Water Permeability of Nonwoven Fabrics	Depth of needle penetration	Pore size, thickness and water resistance

(Sengupta et al., 2008)	Effect of punch density, depth of needle penetration and mass per unit area on compressional behaviour of jute needle-punched nonwoven fabrics using central composite rotatable experimental design	Needling density	Thickness
(Tascan & Vaughn, 2008)	Effects of total surface area and fabric density on the acoustical behavior of needle punched nonwoven fabrics	Fibre cross-sectional shape	Air permeability and thickness
(Kothari et al., 2007)	Effect of processing parameters on properties of layered composite needle-punched nonwoven air filters	Needling density	Air permeability, thickness and pore size
(Midha & A Mukhopadyay, 2005)	Bulk and physical properties of needle-punched nonwoven fabrics	Depth of needle penetration	Air permeability, density and thickness
(Chatterjee et al., 1997)	Performance characteristics of filter fabrics in cement dust control: part III-influence of fibre fineness and scrim on the performance of nonwoven filter fabrics	Fibre cross-sectional shape	Air permeability and density
(Rakshit et al., 1990)	Engineering needle-punched nonwovens to achieve desired physical properties	Needling density and depth of needle penetration	Air permeability, water resistance, density, thickness and tear strength

3.1 Fabrics thickness

In the research by Patanaik & Anandjiwala, the thickness of 6 mm depth of needle penetration sample was found to be highest which is 1.8 mm whereas the thickness of 10 mm depth of needle penetration sample was found to be lowest which is 1.1 mm followed by 6 mm and 8 mm depth of needle penetration samples. It shows that when the depth of needle penetration increases, the non-woven fabrics thickness for the same basis weight decreases [5]. This is because when the needling depth increased, the barbs number passed through the web increased. With the rise of barbs numbers passed through the web, the high pressure exerted on top fibres pulled further into the web through a long distance (if 10 mm compared to 6 mm depth) thus causing the non-woven mat becoming more compact and the thickness of non-woven mat decreased at higher penetration depth. Table 3 shows that the greatest depth of needle penetration produced the lowest thickness of non-woven mat.

Table 3: Thickness of non-woven mat [5]

Depth of needle penetration (mm)	Thickness of non-woven mat (mm)
6	1.8
8	1.4
10	1.1

Besides, Rakshit et al found the higher needling density produced lower thickness of non-woven mat [6]. This is mainly due to the rise in non-woven mat compactness when the needling density increased. In the process of needling, the fibres were pushed by barbs needles through the web and interlocking of fibres occurred. But the result of non-woven mat thickness from Kothari et al did not follow the similar trend with the result from Rakshit et al. Initially, the thickness of non-woven mat decreased with the increase of needling density. Upon reaching a certain limit of needling density, the thickness non-woven mat increased back due to the fibre breakage happening when needling density over a certain limit. Table 4 shows the changes in non-woven mat thickness as a function of needling density.

Table 4: The changed in non-woven mat thickness as a function of needling density [8]

Author (s)	Fibre fineness (denier)	Needling density ($punches/cm^2$)	Non-woven mat thickness (mm)
Rakshit et al, 1990	6	50	2.68
		150	2.28
		250	2.01
		350	1.81
Kothari et al, 2007	6	120	3.00
		160	3.00
		200	5.00
	6 & 15	120	5.50
		160	4.50
		200	5.00
	15	120	7.00
		160	6.50
		200	7.00

The thickness of non-woven mat was also affected by fibre cross-sectional shape. In this study, polyester fabrics with 3 different cross-sectional shape which are trilobal, hollow and round shape were chosen as the fibre parameters. Madhusoothanan and Tascan et al stated that the minimum thickness of non-woven mat was obtained with hollow fibre followed by trilobal fibre and round fibre [4], [7]. The hollow polyester fibre always provided the thinnest non-woven mat within the same fabrics weight and same needling density due to hollow fibre having greater consolidated structure than trilobal fibre and round fibre.

In addition, the effect of non-woven fabrics thickness was prominent for filtration efficiency. The filtration efficiency increased by the increase the thickness of the non-woven mat [8]. With thicker non-woven mat, a longer distance needed to travel by dust particle through the fabrics and caused the dust particle collided with the fibres more easily. Thus, dust particle pass through the fabrics decreased and better filtration efficiency proved.

3.2 Fabrics density

Rakshit et al shows the highest value of fabrics density were shows in the sample with 16 mm depth of needle penetration and 350 punches/cm^2 needling density followed by 8 mm and 12 mm needle penetration under the same fibres used. It is interesting to note that the higher the depth of needle penetration and needling density, the higher the non-woven fabrics density [6], [9]. This is due to better fibre interlocking within the non-woven mat at higher penetration. At the same time, better fibre interlocking leads the non-woven mat to higher compactness and causes rise of fabric density.

In Chatterjee's study, polyester fibres with 3 different cross-sectional shape which are trilobal shape, hollow shape and round used to conduct the experiment. By keeping the depth of needle penetration and needling density constant at 12 mm and 400 punches/cm^2, the lowest fabrics density was obtained with polyester hollow fibre by round and trilobal fibre samples of non-woven mat [10]. This is because the hollow fibre's structure creating better consolidated and finer denier can lead the non-woven fabrics to more compact structure. Hence, the non-woven mat made with hollow fibre was the lowest fabrics density followed by round and trilobal fibres.

Furthermore, Xiao et al shows that the filtration efficiency of non-woven mat increased as the fabrics density increased [11]. This is due to the changed of fibres arrangement cause the porosity and pore size dropped when the fabrics density was rise. However, filtration efficiency dropped for the further increased of needling density. This is due to the fibre breakage happened and caused more paths created for dust particle to pass through at the further increased of needling density [8].

3.3 Pore size

The result of non-woven mat pore size shows a decrease in the pore size with the increase of depth of needle penetration and needle density [5], [12]. By referring to table 5, it can be found that the percentage of small range pore (0 µm -100 µm) and medium range pore (>100 µm -300 µm) increased when greater depth of needle penetration applied. However, the percentage of large range pore size (>300 µm) dropped from 40.00 % to 28.00 % when the depth of needle penetration increased from 6mm to 10mm. When depth of needle penetration increased, the number of barbs pulled the fibre pass through the non-woven web increased. In the 10 mm depth of needle penetration, the fibres from the top of the non-woven web were pulled by barbs for long distance if compared to the 6 mm depth of needle penetration. Hence, the fibres were entangled together by the barbed needles and converted the large pores to medium pores and medium pores to smaller pores.

Table 5: Pore size distribution of non-woven mat by following the depth of needle penetration [5]

Depth of needle penetration (mm)	Pore size distribution (µm)	Percentage contribution of pores
6	0-100	20%
	>100-300	40%
	>300	40%
8	0-100	23%
	>100-300	50%
	>300	27%
10	0-100	25%
	>100-300	50%
	>300	28%

In addition, the non-woven mat pore size also was affected by needling density. Figure 1 shows the filtration efficiency of needle-punched non-woven with varied sizes of dust particles. The filtration efficiency raised initially with the increment of needling density from 120 punches/ cm^2 to 160 punches/cm^2. This result proved that the pore size of non-woven mat reduced with the increment in needling density due to the rise of compactness and interlocking at initial increment of needling density. But, when the needling density increased to 200 punches/cm^2, the filtration efficiency of non-woven mat dropped especially for smaller particle sizes of dust (0.3 µ and 0.5 µ). This is because the fibres inside the non-woven mat are damaged with further rise in needling density and the increase in pores [12].

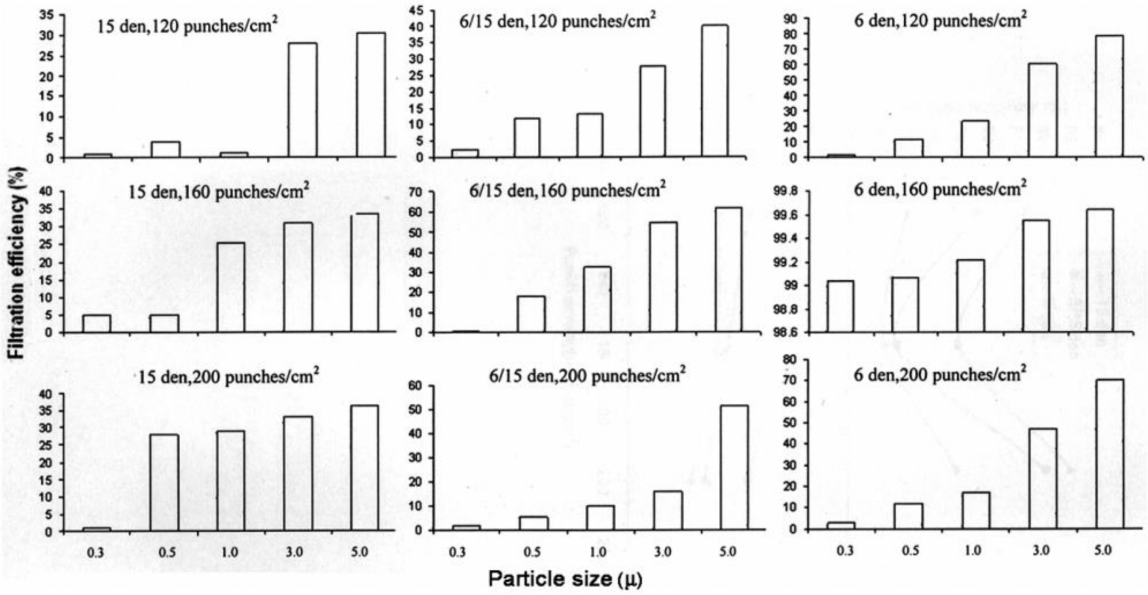

Figure 1: The filtration efficiency of needle-punched non-woven with varied sizes of dust particles [12]

3.4 Tear strength

The tear strength of non-woven mat raised initially with the increased needling density. However, the tear strength of non-woven mat dropped with the further needling density [6]. On the other hand, the relationship between needling density and non-woven mat tear strength also had similar trend with the relationship between depth of needle penetration and non-woven mat tear strength. This is because the tear strength of non-woven mat raised initially due to interlocking of fibres with needling and dropped due to the breakage of fibre occurred at further high needling density and deeper needle penetration. Thus, the depth of needle penetration and needling density determine the behavior of the non-woven fabric tear strength.

3.5 Air permeability

The air permeability of non-woven mat was found to be increased with the increased of needle penetration depth [6], [8], [9], [13]. Table 6 shows the value of non-woven mat sectional air permeability reduced when the depth of needle penetration is raised. The sectional air permeability for polyester and polypropylene non-woven mat reached minimum which are 0.27 m^3/m/min and 0.15 m^3/m/min at 16 mm needle penetration following by 8 mm and 12 mm. This may be due to the non-woven becoming more compact when depth of needle penetration increased and caused more resistance to air flow.

Table 6: The changed in value of non-woven mat air permeability as a function of needle penetration depth [6]

Fibre used	Depth of needle penetration (mm)	Sectional air permeability ($\frac{m^3}{m}/min$)
polyester	8	0.37
	12	0.27
	16	0.27
polypropylene	8	0.30
	12	0.21
	16	0.15

Besides, for finer fibre non-woven mat (6 den & 6 den/15 den), the highest needling density (200 $punches/cm^2$) reached the largest value of air flow rate which represents air permeability compared to 120 $punches/cm^2$ and 160 $punches/cm^2$ within the same pressure drop [12]. This is due to the finer fibre are more easily to break then coarser fibre upon needling process and caused the air permeability increase. However, for the coarser fibre (15 den) non-woven mat, the air flow rate reached the lowest value of air flow rate with the highest value of needling density (200 $punches/cm^2$). Because the decreased air permeability of non-woven mat with the increased needling density due to consolidation and more interlocking of the coarser fibres [6], [8], [12]. Figure 2 shows the experiment result from the Kothari et al study.

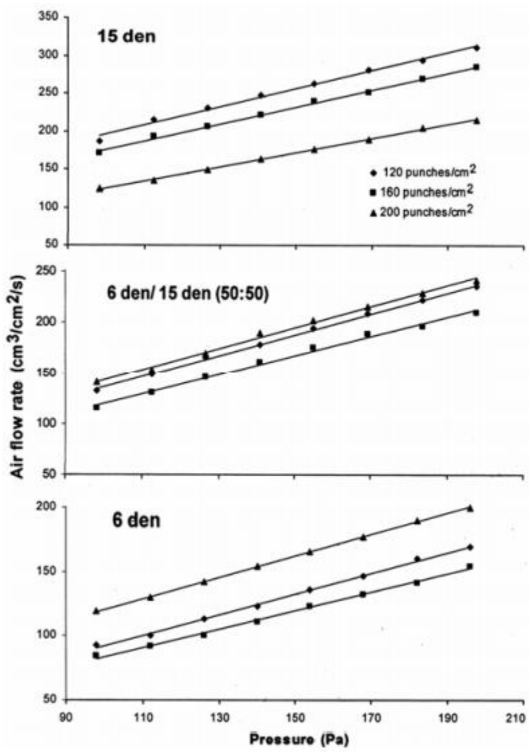

Figure 2: Effect of needling density on air permeability of non-woven mat [12]

For fibre cross-sectional shape, the result gained from Chatterjee's research shows the non-woven fabrics with hollow shape fibre had greater air permeability than trilobal shape fibre and round shape fibres at any level of fabric weight [10]. The non-woven fabrics made by using hollow fibre reached largest value of air permeability which was 143.12 $cm^3/cm^2/s$ if compared to trilobal fibre and round fibre.

3.6 Water resistance

A decreased water flow rate of non-woven mat was shown with the increase of depth of needle penetration. When the depth of needle penetration was set at 10 mm, the water flow rate reached the minimum value of water flow rate which is 81 mm/s if compared to 8 mm and 6 mm depth of needle penetration [5]. This is because the pore size of non-woven mat with high needle penetration was smaller than non-woven mat with low needle penetration and caused the water difficult to pass through. Hence, the non-woven mat with high needle penetration (10 mm) had strongest water resistance. Table 7 shows the water flow rate between 3 non-woven mats with varied depth of needle penetration.

Table 7: The changed in value of non-woven mat water flow rate as a function of needle penetration depth [5]

Depth of needle penetration (mm)	Water flow rate (mm/s)
6	118
8	95
10	81

Furthermore, Rakshit et al shows the non-woven mat produced with highest needling density (350 $punches/cm^2$) shows lowest the sectional water permeability (0.29 $l/m^2/s$) under the same fabrics weight condition [6]. This is because the compactness of non-woven mat raised when the needling density increased and caused the ability of non-woven mat to resist the water increase.

4. Conclusion

In conclusion, it can be said that the parameters of the needle punching machine and fibre cross-sectional shape affected the physical properties and filtration performance of fabric. To ensure the non-woven fabrics have better physical properties and filtration efficiency, high needle penetration, high needling density and hollow cross-sectional shape of fibre were suggested for parameters for non-woven fabrics used for face masks production. This machine parameter and fibre cross-sectional shape provided higher fabrics density, smaller pore size, lower porosity, higher air permeability and excellent water resistance. High air permeability provide greater breathability for face masks and excellent water resistance provide a barrier to avoid droplets passing through the face mask fabrics. However, the filtration efficiency of non-woven fabrics will drop slightly when fabric thickness decreased.

Besides, strong tear strength of fabrics only shown in certain levels of needle penetration and needling density due to fibres breakage at further needling density and needle penetration. The fibres breakage also occurred with the further increase of needle penetration and caused the reduction of air permeability. Thus, coarser fibres were suggested to be used for non-woven fabrics due to coarser fibres not easy to break compared to fine fibres. This method may maintain the physical and filtration performance of non-woven fabrics certainly.

For future studies, it is recommended that the parameters such as web weight should be examined and be taken into consideration. This is because in the data collection process, many sources were noticed that the web weight plays an important role in affecting non-woven fabric physical and filtration performance. All in all, hopefully the information and conclusion from this review study will be useful for face masks development in the future.

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