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Investigation of the Relationship Between the Structural Properties and Air, Water Drop and Particle Permeability of Different Masks Available in the Market

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Abstract

This study was performed on the masks which started to have vital importance after the Covid-19 which were first seen in China at the end of 2019 and spread all over the world in a short time and became a global epidemic. By examining the structural and morphological properties (number of layers, fabric properties used in different layers, average fiber diameter, fiber distribution, average porosity diameter, etc.) of different masks procured from local producers, air permeability, water drop and particle permeability were investigated. Structural and morphological properties of different layers of masks were observed through SEM analysis. The air permeability analysis of the masks was performed at 100 pascals pressure, in an area of 5 cm^2 in 4 repetitions using Textest-Fx 3300 Air Permeability Device. The water drop permeability analysis was carried out with 0.3 μM NaCl solution under standard atmospheric conditions in a non-pressurized environment. A crocmeter was used for particle permeability analysis. And it was tested whether the fine particulate dust passed to the back of the mask. It has been determined that the air permeability, water drop and particle permeability behavior of the masks with different structural and morphological properties are very different.

Keywords: Areal density, Air permeability, Fiber diameter, Mask, Meltblown nonwoven, Spunbond nonwoven, Water drop permeability

1. Introduction

Surgical masks have been used since the early 1900s to minimize the risk of infection and to keep the current epidemic under control [1-3]. Health scientist Carl Friedrich Flügge (1847-1923) and his team who were working on tuberculosis and droplet infection in Breslau first suggested in 1897 the use of mouth bandages to prevent droplets scattered around [2]. This mouth bandage recommended had a single layer and is made of cotton gauze [2].

The first use of surgical masks started in the operating rooms in Germany and America in the 1920s. Following World War, research were carried out on face masks. These studies generally focused on the thickness of face masks made of gauze and fabric. In the 1940s, washable and sterilizable masks consisting of different number of layers were accepted and widespread in Germany. In the mid-1960s, disposable paper masks were first produced in America and spread all over the world [2,4]. Again in the 1960s, disposable synthetic nonwoven masks were produced in America and their use became widespread [5, 6].

As is known, Covid-19, which was first seen in China, and spread and turned into a global epidemic in a short time, affected all humanity and caused the death of nearly 7 million people [7-9]. Due to the Covid-19 pandemic surgical masks came into our life and became one of our most effective weapons in order to protect against the virus and keep its spread under control [10]. It is reported in the studies performed that virus protection can reach over 90% if all people in the society wear masks properly. When an infected person does not wear a mask and a normal person wears a mask, the transmission rate reaches 70 percent, and in cases where only the infected person wears a mask, the transmission rate reaches 5 percent [11]. However, since it is not known who is infected and who is not, everyone needs to wear a mask. The mask prevents getting sick by preventing the virus from entering the body. Or, it causes the person to encounter less virus and thus overcome the disease more mildly [12, 13].

The rapid spread of the Covid-19 pandemic all over the world and the fact that the world was caught unprepared caused in the first instance the need for masks to be not met all over the world. Later, after mask manufacturers and even local apparel manufacturers had started to manufacture, the need for masks was able to be met [14, 15]. The need for a large amount of masks in a short time due to the pandemic has caused a large amount of uncertified masks to be produced and put on the market [16, 17].

Masks are produced with different certifications in different countries. These certificates guarantee and standardize the filtration efficiency at certain levels. These masks are divided into different mask classes according to their filtering efficiency. [16-18]. One of the certificates widely used in certified mask production is the European Union standards [18]. Certified face masks are subject to the European Union EN 14683 Standard. And according to filtration efficiency, there are classes such as Type I, Type II (Medical face masks) and Type IIR (Fluid resistant surgical face masks). Type I and Type II are suitable for medical use, but are not suitable and sufficient for clinical environments. For clinical settings, Type IIR is the appropriate class [18, 19].

Masks with higher filtration efficiency are masks that fall into the Personal Protective Equipment class (FFP) and are subject to the European Union EN 149-A1 Standard. These masks have three classes according to their filtration efficiency: FFP1, FFP2 and FFP3 [18, 19]. These masks provide protection against biological aerosols (including bacteria and viruses) suspended in the air. FFP3 mask has fluid resistant feature like Type IIR mask. Masks, which are classified as Personal Protective Equipment (FFP), are produced mostly for healthcare professionals [18, 19].

Spunbond and meltblown nonwoven surfaces are used in the production of disposable multilayer nonwoven masks. Techniques for obtaining spunbond nonwoven surface and meltblown nonwoven surface are different techniques. The most obvious differences between these two processes are:

- Temperature and speed of air used in thinning the filaments
- It is where the filaments are pulled and the thinning force is applied.

Due to these technical differences; meltblown nonwoven production technique is more ideal for microfiber production. However, it does not provide the necessary polymer orientation to create good physical properties. Spunbond nonwoven production technique is not ideal for microfiber production. However, it provides the necessary conditions for improving polymer orientation and physical properties. Although the initial investment cost of the meltblown nonwoven production technique is much lower than the spunbond nonwoven production technique, the meltblown nonwoven production cost increases several times the spunbond nonwoven production cost due to the effect of the energy cost used during production [20, 21].

The middle layer of the three-layer mask must have a filtering feature. The outer and inner layers should be made of spunbond nonwoven surface, and the middle layer should be made of meltblown nonwoven surface, which performs the main filtering function [22-25]. Masks that use a spunbond nonwoven surface in all layers without a meltblown nonwoven layer provide less protection against the virus. Again, fabric masks provide limited protection [26, 27]. The filtration performance of masks is closely related to parameters such as areal densities of the meltblown and spunbond layers used, fiber diameter, fiber distribution, and porosity size [28].

2. Materials and Methods

2.1. Materials

1 unit single-layer fabric mask produced from 100 % cotton (Mask 10) and 9 different surgical face masks were purchased from local vendors.

2.2. Methods

The areal density is to determine the mass per unit area. The areal density of nonwoven was calculated according to the following Equation (1),

$$D_A = m / A \quad \textbf{(1)}$$

where D_A is areal density (g/m^2), m is mass (g) measured by an electronic balance, and A is area (m^2). Five measurements were taken and the average value was calculated [29].

Surface morphologies of spunbond nonwoven, meltblown nonwoven and cotton fabrics in the layers forming surgical masks were observed with SEM (scanning electron microscope). In addition, the average fiber diameter was calculated by taking 4 different measurements. While examining the different layers of the surgical masks, 4 different measurements were taken from the maximum porous areas and the average porosity diameter was calculated.

The air permeability analysis of the masks was performed at 100 pascals pressure, in an area of 5 cm^2 in 4 repetitions using Textest-Fx 3300 Air Permeability Device.

The water drop permeability analysis was carried out with 0.3 µM NaCl solution under standard atmospheric conditions in a non-pressurized environment. The movement of the water droplet on the mask surface was observed for 4 hours in nonwoven surgical masks and until it is absorbed from the surface and disappears completely in the cotton single layer mask.

A fine powder was used as the particle in the particle permeability analysis. The analysis was carried out using an equal amount of powder for each mask using a crocmeter (Figure 1). The purpose of using the crockmeter device is to provide a pressurized environment in particle permeability analysis.

Figure 1. Crocmeter

3. Results and Discussion

3.1. Surface Analysis with SEM (The Relationship Between Average Fiber Diameter, Fiber Diversity, Fabric Feature and Porosity)

9 of the 10 masks examined are made of nonwoven fabric, each of which is 3-layer surgical face masks. And the layers of each mask (outer / middle / inner layers) show different properties (in terms of weight, average fiber thickness and fiber distribution, porosity). In some masks, spunbond polypropylene nonwoven fabric is used in all three layers, while in others, meltblown polypropylene nonwoven fabric is used, which performs the main filtration function, in the middle layer.

One of the masks is a single layer mask made of 100% cotton fabric (166 g/m^2) fabric. In the SEM analysis performed, it was found out that two different fiber groups (with different average fiber diameters) had been used in different layers of some masks (mask no 1,2,3,4,5 and 9) in which spunbond polypropylene nonwoven fabric had been used. In some masks, nonwoven surfaces were obtained by using a single fiber group (masks no 6,7,8,10). When the relationship between the pore size and the properties of the fiber used (such as fiber diameter, using more than one fiber group with different diameters together in fabric production) is examined, it has been observed that the spunbond nonwoven fabrics manufactured using coarser fibers (with higher fiber diameters) have higher porosity size.

Again, much smaller porosity was observed in spunbond nonwoven fabrics where two different fiber groups with different fiber diameters were used. In these fabrics where two different fiber groups are used, the porosity decreases to much more lower degree, as the pores formed at the intersection points of the fibers with higher fiber diameter are covered with other fibers with much smaller fiber diameter. This can clearly be seen in Figure 2 and Figure 3.

The critical factor here is the amount of difference between the fiber diameters of the two different fiber groups. The smaller the diameter of the fiber (nano size or 1-2 µm size) used in the production of spunbond nonwoven fabric, the lower the porosity is.

It is observed in SEM analysis that in the masks where meltblown nonwoven fabric is used in the middle layer, fibers with much smaller fiber diameter (between 0.6 nm and 1-2 µm) are used, so the porosity is much lower. Such that, it is seen that the porosity level of some meltblown layers is so low that cannot be detected or measured (Figure 4). This confirms that masks with a meltblown nonwoven middle layer are more protective.

According to the results of SEM analysis, the average fiber diameter in a single layer mask made of 100% cotton fabric is 14.12 µm. And the average porosity diameter is 119.7 µm (Figure 5).

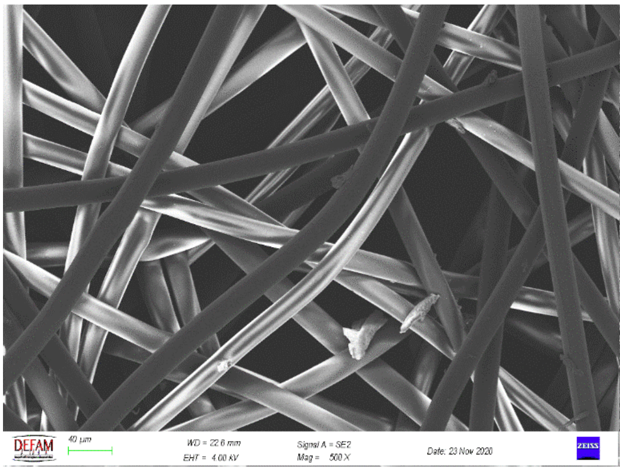

Figure 2. Spunbond surface with single fiber group

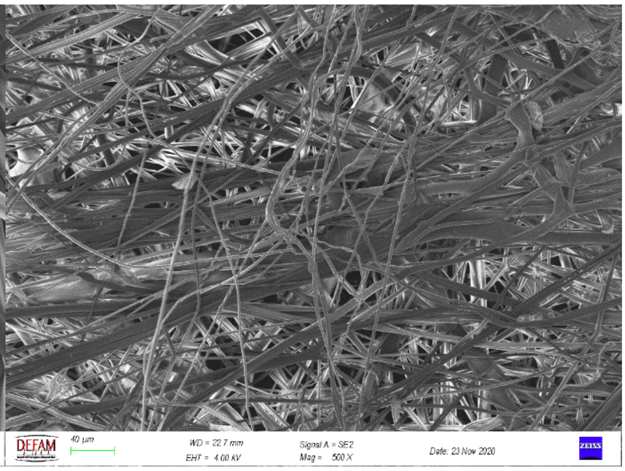

Figure 3. Spunbond surface with two fiber groups

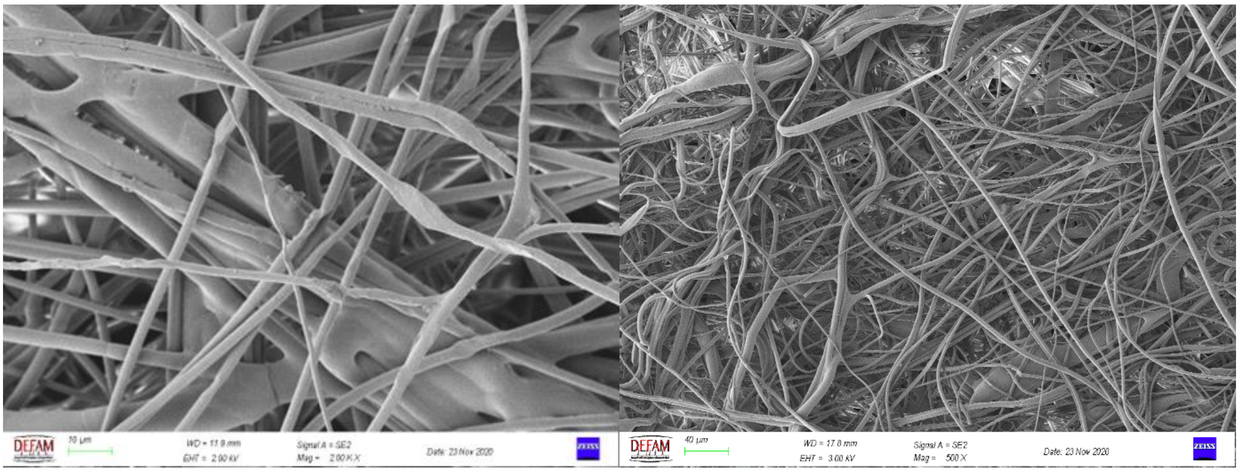

Figure 4. Meltblown surface

Figure 5. Image of 100% cotton fabric mask surface

3.2. Air Permeability Analysis

The air permeability analysis of the masks was performed at 100 pascals pressure, in an area of 5 cm^2 in 4 repetitions using Textest-Fx 3300 Air Permeability Device.

According to results of air permeability analysis, the permeability of the surgical face mask with meltblown nonwoven layer (85.5-189.25 $l/m^2/sec$) are much lower that of the masks without metlblown layer and all three layers of which are made of spunbond nonwoven fabric (360.25-950.25 $l/m^2/sec$). Considering their air permeability, it can be said that surgical masks with meltblown nonwoven layers are more protective than surgical masks without meltblown nonwoven layers and 3 layers of which are made of spunbond nonwoven fabrics.

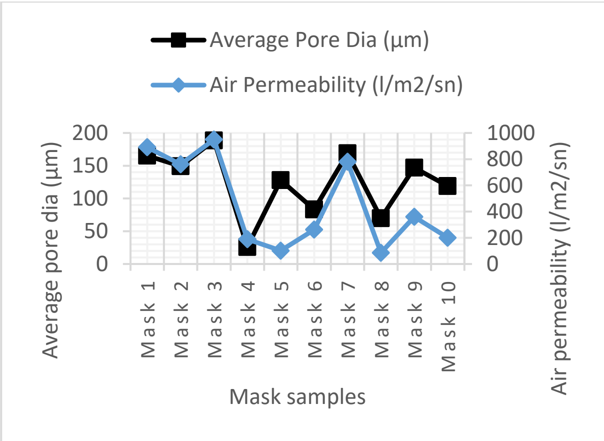

Figure 6. Relationship between mean pore diameter and air permeability

According to the results of the air permeability analysis, air permeability of single layer mask made of 100% cotton is 201 l/m2/sec. Its air permeability is much lower compared to surgical masks 3 layers of which are made of spunbond nonwoven fabric. This fact can be seen in Figure 6.

3.2.1. The Relationship Between Areal Density and Air Permeability

The field densities of spunbond and meltblown nonwoven layers are not related to air permeability alone, but parameters such as field density, fiber diameter, fiber group number, fiber density have a combined effect on air permeability. This fact can be seen in Figure 7.

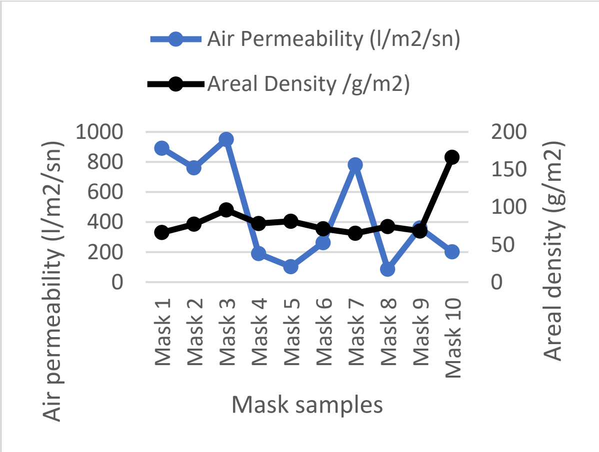

Figure 7. Relationship between field density and air permeability

3.3. Water Drop Permeability

The Water Drop Permeability Test is based on the principle of leaving water drops containing 0.3 µM NaCl on the masks and checking the amount of drops passed to the other side. The test was carried out in an unpressurised environment. And it was calculated with the formulation below.

$$P = C0\text{-}C1 / C0 \times 100 \quad \textbf{(2)}$$

Where, P is the filtration efficiency (%), C0 is the mass concentration of NaCl in the upstream, and C1 is the mass concentration of NaCl in the downstream [29].

According to the results of the water drop permeability test performed in a non-pressurized environment, the duration during which water drop stays on the surface is more than 4 hours in all surgical face masks and no transition to the back surface of the fabric has been detected. The single layer mask made of 100% cotton fabric absorbs the water drop in less than 120 seconds. During this time, 58.032 % of the water drop passes to the second layer. Structural properties and air, water drop permeability of masks were given in Table 1 below.

3.4. Particulate Permeability

A crocmeter was used for particle permeability analysis. An equal amount of fine particulate powder was used for each mask. And as a result of tidal movements of the crocmeter, it was tested whether the fine particulate dust passed to the back of the mask.

Table 1. Number of Layers, Layer Properties, Area Density, Average Fiber Diameter, Average Porosity Diameter, Air Permeability, Water Drop Permeability Values of Different Masks available in the Market

Masks	Number of Layers	Layer Origin Outer/middle/inner	Areal Density(g/m^2) Outer/middle/ inner	Average Fiber Dia. (µm) Outer/middle/inner	AveragePore Dia. (µm)	Water Permeability	Air Permeability (l/m^2/sn)
1	3	SB/SB/SB	29/18/19	20.55-19.03 16.76-15.70 16.76-15.70	106.5 195.3 195.3	> 4 hours	891.25
2	3	SB/SB/SB	32/19/26	22.38-18.86 19.78-18.96 22.38-18.86	116.5 216.2 116.5	> 4 hours	760.5
3	3	SB/SB/SB	32/34/30	33.02-28.25 28.96-23.84 33.02-28.25	195.6 176.5 195.6	> 4 hours	950.25
4	3	MB+SB	26/25/27	15.02-1.44 16.32-1.86 16.32-1.86	NA 39.38 39.38	> 4 hours	189.25
5	3	SB/MB/SB	34/23/24	22.34-20.36 1.915 22.40	145.8 7.603 233.8	> 4 hours	102
6	3	SB/MB/SB	19/27/25	15.86 2.02 18.75	83.92 NA 167.6	> 4 hours	262.25
7	3	SB/SB/SB	30/15/20	15.53 25.95 25.60	108.1 291.9 108.9	> 4 hours	780.5
8	3	SB/MB/SB	30/21/23	30.22 2.39 22.57	80.55 8.845 123	> 4 hours	85.5
9	3	SB/SB/SB	30/18/20	19.67-1.235 23.69 23.69	NA 221.4 221.4	> 4 hours	360.25
10	1	Cotton 100%	166	14.12	119.7	<120 seconds/% 58.032	201

SB: Spunbond polipropilen nonwoven, MB: Meltblown polipropilen nonwoven, NA: Not available

The particle size analysis of the fine particulate powder used in the analysis was performed on the Mastersizer 3000 device. Analysis parameters were here:

Dispersant Name: Water
Dispersant Refractive Index: 1,330
Particle Refractive Index: 1,550

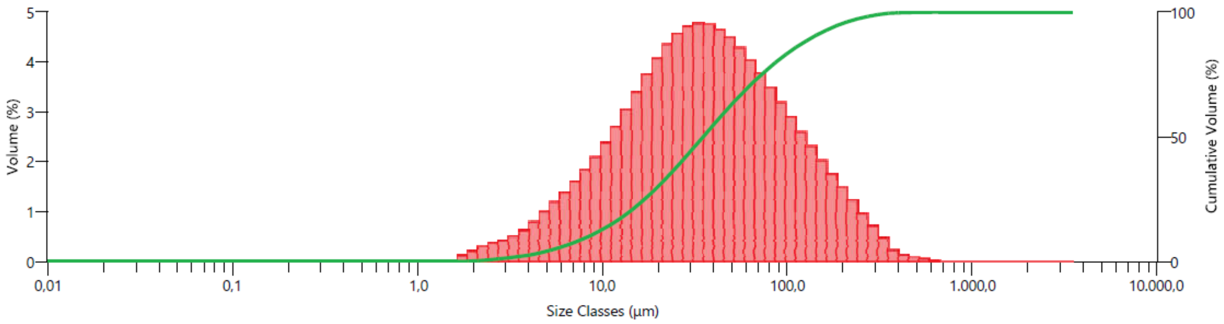

Figure 8. Particulate Size Histogram of the Fine Particulate Powder

Volume In Range (0,1;10) µm 12,78 %
Volume In Range (10;100) µm 70,58 %
Volume Below (2) µm 0,23 %
Volume Below (45) µm 59,18 %

According to the results of the particle size analysis of the powder used in the particle permeability analysis, the volumetric ratio of the particles in the range of 0.1-10 µm is 12.78%. The volume fraction of particles in the 10-100 µm range is 70.58%. The volume fraction of particles below 2 µm is 0.23%. The volume fraction of particles below 45 µm is 59.18% (Figure 8).

Particle permeability analysis was applied to all masks. None of the multi-layered nonwoven disposable masks had any back-to-face particle transfer. However, a small amount of particle migration was observed on the back side of the 100% cotton single-ply fabric mask. However, it could not be analyzed due to the small amount passed.

4. Conclusion

When the relationship between number of layers, fiber diameter, field density and porosity size of masks and their air permeability, water droplet permeability and particle permeability performance is examined; the following results have been reached:

•An increase in air permeability was observed in the masks in which spunbond nonwoven fabric was used in all three layers compared to the mask the middle layer of which was made of meltblown nonwoven fabric. The air permeability of single layer mask made of 100% cotton fabric is higher than that of the masks with middle layer made of meltblown nonwoven, but it is quite better than masks 3 layers spunbond nonwoven.

•In the layers using spunbond nonwoven fabrics, an increase in the porosity size was observed on the surfaces where single fiber group was used compared to the surfaces where two separate fiber groups were used. Since much thinner fibers are used on the surfaces where meltblown nonwoven fabric is used, the porosity is quite less than the surfaces where spunbond nonwoven fabric is used, and even the porosity size cannot be determined in some layers.

•According to the results of the water drop permeability test performed in a non-pressurized environment, the duration during which water drop stays on the surface is more than 4 hours in all surgical masks and no transition to the back surface of the fabric has been detected. The single layer mask made of 100% cotton fabric absorbs the water drop in less than 120 seconds. And during this time, 58,032 % of the water drop passes to the second layer.

•According to particle permeability analysis none of the multi-layered nonwoven disposable masks had any back-to-face particle transfer. However, a small amount of particle migration was observed on the back side of the 100% cotton single-ply fabric mask. However, it could not be analyzed due to the small amount passed.

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Author's Contributions

Candan Akça: Assisted in characterization of the structure, supervised the experiments' progress, result interpretation and helped in manuscript preparation.
Mehmet İsmail Katı: Assisted in analytical analysis on the structure, supervised the experiment's progress, result interpretation and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

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