A study on multi-layered surgical masks performance: permeability, filtration efficiency and breathability

DOI: 10.35530/IT.075.01.202356

ŞEVKAN MACİT AYŞE

ABSTRACT – REZUMAT

A study on multi-layered surgical masks performance: permeability, filtration efficiency and breathability

Surgical masks have been widely used in the past for protection purposes against infection as a hygiene product. Masks, which are often used by healthcare professionals, are also widely used by the general public during pandemic periods. Surgical masks were designed in various ways according to colour, nose strip, earloop, grams per square meter and several layers. Some performance features are expected from these masks according to certain standards. In this study, it has been studied on multi-layered surgical masks. Thickness, air permeability, bacterial filtration efficiency and differential pressure properties of these masks consisting of polypropylene spun bond and melt-blown layers were investigated. The effects of an increase in grams per square meter, the number of layers and the melt-blown layer on the mentioned properties were determined. As a result; it has been observed that the optimal mask is one of the 4-ply masks. Also, it has been concluded that increasing the number of layers does not always provide an increase in performance; instead, an increase in grams per square meter can meet the expectation. Therefore, it can be said that it is necessary to determine the appropriate weight in grams and the appropriate number of layers with suitable raw materials to provide the expected features from the surgical masks.

Keywords: *surgical mask, air permeability, bacterial filtration efficiency, breathability, spun bond, melt-blown*

Un studiu asupra performanței măștilor chirurgicale multistratificate: permeabilitate, eficiență de filtrare și respirabilitate

Măștile chirurgicale au fost utilizate pe scară largă încă din trecut în scopul protecției împotriva infecțiilor, ca produs de igienă. Măștile, care sunt adesea folosite de profesioniștii din domeniul sănătății, sunt, de asemenea, utilizate pe scară largă de către populație, în perioadele de pandemie. Măștile chirurgicale au fost proiectate în diferite moduri în funcție de culoare, bandă pentru nas, buclă pentru ureche, grame per metru pătrat și numărul de straturi. Unele caracteristici de performanță sunt necesare pentru ca aceste măști să respecte anumite standarde. În acest studiu, au fost studiate măştile chirurgicale multistratificate. Au fost investigate grosimea, permeabilitatea la aer, eficiența filtrării bacteriene și proprietățile de presiune diferențială ale acestor măști, constând din straturi de polipropilenă consolidată la filare și filată din topitură. S-a determinat influența creșterii în grame per metru pătrat, a numărului de straturi și a stratului filat din topitură asupra proprietăților menționate. Prin urmare, s-a observat că masca optimă este una dintre măștile cu 4 straturi. De asemenea, s-a ajuns la concluzia că mărirea numărului de straturi nu asigură întotdeauna o creștere a performanței; în schimb, o creștere a gramelor per metru pătrat poate satisface cerinţele. Prin urmare, se poate spune că este necesar să se determine greutatea adecvată în grame și numărul corespunzător de straturi cu materii prime adecvate pentru a oferi caracteristicile așteptate de la măștile chirurgicale.

Cuvinte-cheie*: mască chirurgicală, permeabilitate la aer, eficiență de filtrare bacteriană, respirabilitate, consolidare la filare, filat din topitură*

INTRODUCTION

Hygiene products such as masks, gloves, colognes and disinfectants have an important place in human life. Especially masks have been used frequently by people from the past to the present for protection against infection. Products such as masks, which are widely used by healthcare workers, have also been used general public during the pandemic.

Consumption amounts of preventive health and hygiene products have changed during the pandemic (COVID-19) which affects the whole world [1]. The use of masks to prevent transmission of the pandemic-19 has increased considerably with the start of the pandemic. Masks both prevent infected persons from exposing others and also masks protect uninfected wearers [2]. Wearing a mask prevents respiratory virus transmission [3] and also mask use reduces community transmission [4]. Respiratory particles can be classified as droplets or aerosols based on particle size [5] and different types of face masks can filter particles that have various sizes.

Face masks are categorized generally into four groups: elastomeric respirators, N95 masks, surgical masks and cloth masks [6]. First and above all, surgical masks have a general production method: they have layers made of generally nonwoven polypropylene (PP) [7]. Polypropylene is the most widely used polymer for melt-blown surfaces due to its cheapness and versatility [8]. Surgical mask layers are produced with spun bonding and melt blowing methods. Spun bond and melt-blown structures come together and SMS structures are formed. SMS nonwoven structures are produced generally with 3 layers as the inner-middle-outer layer [9]. The inner and outer layers are spun bonds and the middle layer is melt-blown as a filter layer. The spun bond layer is preferred for its hydrophobic property while melt-blown is preferred for its filtration property and high fibre density [10]. Different masks have been designed to improve some properties like filtration performance. In addition to 3-ply masks, 4-ply and 5-ply masks that have different weight in grams are produced.

The requirements for surgical masks according to EN 14683:2019 + AC:2019 [11] in terms of bacterial filtration efficiency, differential pressure, splash resistance and microbial cleanliness are shown in table 1.

Table 1

CLASSIFICATION OF SURGICAL MASKS ACCORDING TO RELEVANT STANDARD [10]

Test	Type I	Type II	Type IIR
Bacterial filtration efficiency	≥95	≥98	≥98
Differential pressure (Pa/cm^2)	<40	<40	<60
Splash resistance (kPa)	-	-	≥16.0
Microbial cleanliness (cfu/g)	≤30	≤30	≤30

Type I masks are intended for patients and the general public [12–14]. Type II and Type IIR masks are improved for healthcare workers [13]. Type IIR masks must have splash resistance in comparison to Type II. Many studies have examined the masks. Seid searched air permeability, particle filtration efficiency and bacterial filtration efficiency of spun bond and melt-blown layers [15]. Lordelo et al. studied about microbiological effectiveness of decontamination methods and they examined the effects of these methods on filtration, air permeability and physco-chemical properties [16]. Li et al. compared N95 respirators and surgical masks in terms of filtration efficiency, air permeability and water vapour permeability [17]. Teo et al. and Bagheri et al. analysed filtration efficiency, breathability, and reusability of face masks [18] and mask materials [19]. There are also other studies examining bacterial filtration efficiency [20–23] and breathability [24–25] in the literature. Celep et al. searched some physical and tensile properties of surgical masks and they examined the effects of weight per unit area and melt-blown layer on the properties of masks [26]. Boz and Küçük investigated the effects of the changes in weight in grams and production methods of the selected textile surfaces consisting of spun bond and melt-blown layers on air permeability, water resistance and bursting strength properties of the seam area after the ultrasonic welding process [27].

Lee et al. investigated reusable face masks as an alternative to disposable masks and they examined the factors that affect their comfort [28]. Ullah et al. compared melt-blown filters and nano-fibre filters to evaluate their reusability [29]. There are several studies examining the reusability of various masks [30–34] and these studies also investigated the effect of the washing process on different properties such as bacterial filtration efficiency, and breathability.

Surgical masks have been widely used in the past and they were designed in various ways according to colour, nose strip, earloop, grams per square meter and several layers. Masks with different numbers of layers designed in different grams per square meter were produced and these masks, which were generally designed as 3 layers, were produced in 4 layers or even 5 layers. Increasing in number of layers of a mask has been commercially presented to users with expressions such as high protection, double protection and double mask protection. A perception has emerged that the protection increases with the increase in the number of layers of the mask.

This study aims to comparatively evaluate 2, 3, 4 and 5-ply masks of different grams per square meter (GSM), consisting of spun bond and melt-blown layers, in terms of thickness, air permeability, bacterial filtration efficiency and differential pressure properties. It was desired to examine especially whether a 5-ply mask always has an extra performance and whether increasing in number of layers provides the expected features. This study focuses on the performance of the 4-ply and 5-ply masks as an original aspect of this study.

MATERIAL AND METHOD

Material

Polypropylene nonwoven spun bonds and melt-blown layers are used to design the surgical masks in this study. The properties of the layers can be seen in table 2.

Table 2

LAYERS USED IN THE STUDY

Layer code	Layer	Raw material	Grams per square meter (g/m^2)
S1	S20 (Spun bond 20)	Polypropylene	20
S2	S40 (Spun bond 40)	Polypropylene	40
M1	M20 (Melt-blown 20)	Polypropylene	20
M2	M40 (Melt-blown 40)	Polypropylene	40

Properties of the surgical masks obtained by combining these layers with different layouts also can be seen in table 3 and these masks with different numbers of layers are given visually in figure 1.

Table 3

IDENTIFICATION OF MASKS USED IN THE STUDY				
Mask code	**Number of layers**	**Layers**	**Grams per square meter (g/m^2)**	**Total grams per square meter (g/m^2)**
SS-1	2	S20-S20	20+20	40
SS-2	2	S40-S40	40+40	80
SSS-1	3	S20-S20-S20	20+20+20	60
SSS-2	3	S20-S40-S20	20+40+20	80
SSS-3	3	S40-S20-S40	40+20+40	100
SMS-1	3	S20-M20-S20	20+20+20	60
SMS-2	3	S20-M40-S20	20+40+20	80
SMS-3	3	S40-M20-S40	40+20+40	100
SMS-4	3	S40-M40-S40	40+40+40	120
SMMS-1	4	S20-M20-M20-S20	20+20+20+20	80
SMMS-2	4	S40-M20-M20-S40	40+20+20+40	120
SMSMS-1	5	S20-M20-S40-M20-S20	20+20+40+20+20	120

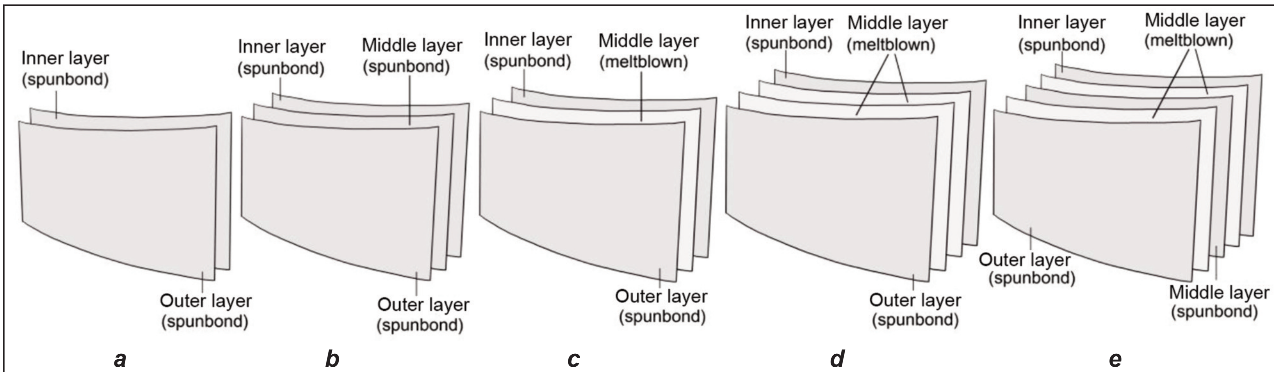

Fig. 1. Masks with different number of layers: *a* – SS; *b* – SSS; *c* – SMS; *d* – SMMS; *e* – SMSMS

Method

Thickness test

The samples were conditioned for 24 hours at a temperature of 20±2°C and relative humidity of 65±4% before the test procedure. Thickness values were measured according to TS 7128 EN ISO 5084:1998 test standard [35] with Schroder/ DM 100 test equipment at a loading pressure of 0.5 kPa. The test process was repeated 20 times.

Air permeability test

Before the test procedure, the samples were conditioned as in the thickness test. Air permeability values were measured according to TS 391 EN ISO 9237: 1999 test standard [36] with Textest FX 3300 test equipment with a 20 cm^2 test area at a loading pressure of 100 Pa. The test process was repeated 10 times.

Bacterial filtration efficiency test

Before the test procedure, the samples were conditioned for a minimum of 4 hours at a temperature of 21±5 °C and relative humidity of 85±5%. The test was performed with a 49 cm^2 test area at a flow rate of 28.3 l/min. The mean particle size was 2.7 µm. The values were measured according to EN 14683: 2019 + AC: 2019 [11]. The test process was repeated 5 times.

Differential pressure test

Before the test procedure, the samples were conditioned as in the bacterial filtration efficiency test and the values were measured according to the same standard of this test [11]. The test was performed at a flow rate of 8 l/min. The test process was repeated 5 times.

Statistical analysis

After the test procedures, the findings were statistically evaluated at a 95% confidence level by using a one-way analysis of variance (One-way ANOVA) via the SPSS 23 package program ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Firstly, air permeability and thickness values of 4 layers and 12 masks were acquired. Secondly, bacterial filtration efficiency tests were applied to 7 masks that can be compared in terms of the number of layers and GSM. Finally, differential pressure tests were implemented on 5 masks that have bacterial filtration efficiency values exceeding 95% of the relevant standard.

Air permeability and thickness results

Air permeability and thickness values of layers and masks can be seen in tables 4 and 5, respectively. As can be seen, by the values, the thickness increases in direct proportion to GSM and several layers. On the contrary, air permeability values are generally inversely proportional to GSM and number of layers. Hence, air permeability and thickness values are also inversely proportional to each other as seen in figures 2 and 3, graphically.

Melt-blown is a layer that affects the air permeability of the mask. That's to say; the mask SMS-2 (with a lower total GSM and more melt-blown weight) in comparison to the mask SMS-3 (with a higher total GSM and less melt-blown weight) has lower air permeability values. This result emphasizes the decreasing effect of the melt-blown layer on air permeability. It is an expected result due to the high fibre density of the melt-blown layer. When statistical analysis for thickness and air permeability values are examined separately, it was observed that there is a statistically significant difference for each of these values. Moreover, GSM and several layers have statistically significant effects on these properties (table 8).

Table 4

THICKNESS AND AIR PERMEABILITY RESULTS OF THE LAYERS

Layer code	Layer	Grams per square meter (g/m^2)	Thickness ±SD	Air permeability ±SD
S1	S20 (Spun bond 20)	20	0.227±0.014	3307.00±377.13
S2	S40 (Spun bond 40)	40	0.393±0.022	1706.00±198.34
M1	M20 (Melt-blown 20)	20	0.213±0.009	453.00±19.11
M2	M40 (Melt-blown 40)	40	0.416±0.012	240.20±6.53

Table 5

THICKNESS AND AIR PERMEABILITY RESULTS OF THE MASKS

Mask code	Number of layers	Layers	Total grams per square meter (g/m^2)	Thickness ±SD	Air permeability ±SD
SS-1	2	S20-S20	40	0.407±0.017	1819.00±116.38
SS-2	2	S40-S40	80	0.732±0.025	1011.30±100.56
SSS-1	3	S20-S20-S20	60	0.597±0.024	1215.00±59.49
SSS-2	3	S20-S40-S20	80	0.749±0.014	992.10±35.46
SSS-3	3	S40-S20-S40	100	0.974±0.031	776.50±27.39
SMS-1	3	S20-M20-S20	60	0.616±0.020	341.00±25.65
SMS-2	3	S20-M40-S20	80	0.803±0.022	211.80±6.39
SMS-3	3	S40-M20-S40	100	0.942±0.024	318.80±11.20
SMS-4	3	S40-M40-S40	120	1.166±0.026	190.40±5.42
SMMS-1	4	S20-M20-M20-S20	80	0.839±0.012	178.50±6.10
SMMS-2	4	S40-M20-M20-S40	120	1.159±0.017	178.50±10.38
SMSMS-1	5	S20-M20-S40-M20-S20	120	1.214±0.030	162.80±3.55

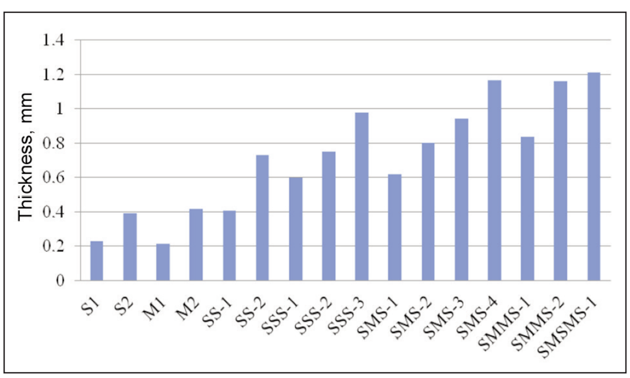

Fig. 2. Thickness results of the layers and masks

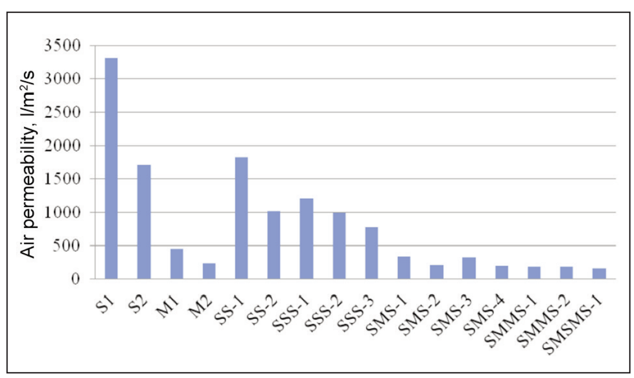

Fig. 3. Air permeability results of the layers and masks

Bacterial filtration efficiency results

The results can be evaluated in terms of containing of melt-blown layer, number of layers and grams per square meter and the bacterial filtration efficiency (BFE) values are given in table 6.

When the masks SSS-1 and SMS-1 with 60 g/m^2 are examined, it can be seen that SMS-1 in comparison to SSS-1 has higher bacterial filtration efficiency. The positive effect of a melt-blown layer on filtration properties has already been pointed out.

As far as three masks with 80 g/m^2 are evaluated, it can be concluded that 2-ply mask SS-2 without melt-blown layer has lower BFE values. In addition to that, the masks containing equivalent weight melt-blown, 4-ply SMMS-1 have higher BFE values than the mask 3-ply SMS-2. It can be understood that the number of layers has an increasing effect on filtration. On the other hand, these two masks meet the requirements for Type I in terms of BFE according to 14683:2019 + AC:2019.

As can be seen in table 6, 4-ply, 120 g/m^2 SMMS-2 has greater BFE values in comparison to 5-ply, 120 g/m^2 SMSMS-1. If their structural differences are evaluated, both masks have 2 “M20” layers and they have equivalent weight spun bonds but the number of spun bond layers they contain is different. On the other hand, inner and outer spun bond layers have lower GSM of 5-ply SMSMS-1. It can be seen that this 5-ply mask designed for high performance has lower BFE values than that of the 4-ply mask. This means that increasing the number of layers doesn’t always work for higher filtration performance. In addition, the 4-ply mask SMMS-2 is the only mask that meets the requirements of Type I, Type II and Type IIR among all masks used in the study.

The only difference between SMMS-1 and SMSMS-1 is that the S40 layer is placed between melt-blown layers. It may have been thought that the 5-ply mask SMSMS-1 would perform higher but it can be seen that the 4-ply mask SMMS-1 has higher BFE values with a slight difference. The “S40” layer, which entered between the melt-blown layers has slightly reduced the filtration efficiency. In essence, both of these masks meet the requirements of Type I according to relevant standards in terms of BFE. In other words, a 4-ply SMMS-1 mask provides the same feature at a lower cost with a lower GSM.

The masks that have different GSM but the same number of layers were investigated to evaluate them in terms of grams per square meter. 3-ply SMS-1 with 60 g/m^2 and 3-ply SMS-2 80 g/m^2 were compared in terms of BFE values. According to the results, increasing the GSM of the mask provides improved filtration performance as expected. A similar result was also observed in comparison to 4-ply SMMS-1 with 80 g/m^2 and 4-ply SMMS-2 with 120 g/m^2. From a commercial point of view; three of the masks mentioned SMS-1, SMS-2 and SMMS-1 meet the requirements for the same type: Type I. That’s to say; if Type I is enough for performance requirements, it would be logical for SMS-1 with lower GSM and, a lower number of layers in terms of cost. No doubt increasing GSM unnecessarily will create an increase in cost. Besides, statistical analysis results show that the difference between the bacterial filtration efficiency values is statistically significant. Additionally, GSM and several layers have statistically significant effects on these values (table 8).

Differential pressure results

Differential pressure value is an indication of breathability [15, 37, 38] and lower DP values mean that the mask is more breathable [15, 37]. On the other hand, air permeability is a fabric property that can be used to evaluate breathability [15]. In addition, lower air permeability signifies higher filtration efficiency due to capturing particles more effectively [39].

The masks with a minimum 95% bacterial filtration efficiency value were subjected to a differential pressure test and the results can be seen in table 7. When the values seen in table 7 are considered in terms of the number of layers; 3-ply SMS-2 with 80 g/m^2 and 4-ply SMMS-1 with 80 g/m^2 are compared. Differential pressure values of the 4-ply mask were higher than those of the 3-ply mask, meeting requirements Type I, Type II and Type IIR. It can be seen that 4-ply SMMS-2 with 120 g/m^2 has higher DP values than that of 5-ply SMSMS-1 with the same GSM.

As far as the differential pressure values are evaluated in terms of grams per square meter; 3-ply SMS-1

Table 6

BACTERIAL FILTRATION EFFICIENCY RESULTS OF THE MASKS (%)			
Mask code	**Layers**	**Total grams per square meter (g/m^2)**	**Bacterial filtration efficiency (BFE) ±SD**
SS-2	S40-S40	80	83.50±0.27
SSS-1	S20-S20-S20	60	79.78±0.13
SMS-1	S20-M20-S20	60	95.92±0.08
SMS-2	S20-M40-S20	80	97.22±0.18
SMMS-1	S20-M20-M20-S20	80	97.64±0.15
SMMS-2	S40-M20-M20-S40	120	98.34±0.21
SMSMS-1	S20-M20-S40-M20-S20	120	97.44±0.18

with 60 g/m^2 has higher DP values than that of 3-ply SMS-2 with 80 g/m^2 as expected. As seen by the values, the increasing effect of grams per square meter on DP values has been observed for also 4-ply SMMS-1 with 80 g/m^2 and 4-ply SMMS-2 with 120 g/m^2.

As seen by the values in terms of breathability property, there is an increase in DP values with increasing GSM of the masks. It can be understood that increasing the GSM of the masks has a negative effect on their breathability. In terms of statistical evaluation, a statistically significant difference was observed between differential pressure values and GSM and several layers have statistically significant effects on differential pressure as can be seen in table 8.

Statistical analysis results are given in table 8.

All masks in table 7 meet the requirements of 3 classes according to EN 14683:2019 + AC:2019 in terms of DP. Therefore, it is necessary to investigate BFE and DP values together to determine the mask performance from table 9. Table 9 shows the classification of the masks used in the study according to the relevant standard.

When bacterial filtration efficiency and differential pressure values are evaluated together in terms of meeting the requirements of classes, SMMS-2 is determined as the optimal mask among all masks. In light of this information, it is clear that the 4-ply SMMS-2 mask showed superior properties compared to the 5-ply SMSMS-1 mask. On the other hand, the mask SMMS-2 meets the requirements of

Table 7

DIFFERENTIAL PRESSURE RESULTS OF THE MASKS

Mask code	Layers	Total grams per square meter (g/m^2)	Differential pressure (DP) ±SD
SMS-1	S20-M20-S20	60	20.28±1.43
SMS-2	S20-M40-S20	80	29.12±1.96
SMMS-1	S20-M20-M20-S20	80	35.75±2.72
SMMS-2	S40-M20-M20-S40	120	39.58±0.84
SMSMS-1	S20-M20-S40-M20-S20	120	37.80±2.68

Table 8

THE ANALYSIS OF VARIANCE TABLE FOR THE RESULTS

Property	Factor	F	p-values
Thickness	Number of layers	60.864	0.000*
	Grams per square meter	2577.958	0.000*
Air permeability	Number of layers	171.709	0.000*
	Grams per square meter	51.501	0.000*
Bacterial filtration efficiency	Number of layers	2118.307	0.000*
	Grams per square meter	6.197	0.005*
Differential pressure	Number of layers	35.319	0.000*
	Grams per square meter	61.260	0.000*

Note: * Statistically significant for $\alpha = 0.05$.

Table 9

CLASSIFICATION OF THE MASKS ACCORDING TO RELEVANT STANDARD

Mask code	Layers	Total grams per square meter (g/m^2)	BFE (%) ±SD	DP (Pa/cm^2) ±SD	Type according to EN 14683:2019 + AC:2019
SMS-1	S20-M20-S20	60	95.92±0.08	20.28±1.43	Type I
SMS-2	S20-M40-S20	80	97.22±0.18	29.12±1.96	Type I
SMMS-1	S20-M20-M20-S20	80	97.64±0.15	35.75±2.72	Type I
SMMS-2	S40-M20-M20-S40	120	98.34±0.21	39.58±0.84	Type I, Type II, Type IIR (DP-at compliance limit for Type I-Type II)
SMSMS-1	S20-M20-S40-M20-S20	120	97.44±0.18	37.80±2.68	Type I

all Type I, Type II and Type IIR in terms of bacterial filtration efficiency and differential pressure.

CONCLUSION

In the study, masks with different grams per square meter and different numbers of layers were designed by using nonwoven spun bond and melt-blown layers and the thickness, air permeability, bacterial filtration efficiency and differential pressure properties of these masks were evaluated comparatively. Based on the findings of these properties, the following general conclusions were reached:

- The increase in GSM and number of layers generally resulted in the thickness, bacterial filtration efficiency and differential pressure values increasing and the air permeability values decreasing. In addition to that, the types of masks change according to EN 14683:2019 + AC:2019 standard, in other words, the user group of masks changes to the general public or healthcare workers. Moreover, it can be said that increasing in grams per square meter gave better results in comparison to increasing the number of layers.
- Surgical masks are usually made of 3 layers as mentioned before. During the pandemic, 4-ply and 5-ply masks were also produced and these masks can also have some advantages in terms of bacterial filtration efficiency depending on weight in grams over 3-ply masks. But presenting 5-ply masks as more protective, double protective than the 3-ply and 4-ply masks should be reviewed. The result may not be like this when the appropriate GSM is not determined. It's necessary here to clarify exactly what is meant by this comparison; in this study, although there is a 5-ply mask, the 4-ply mask SMMS-2 was determined as the optimal mask according to EN 14683:2019 + AC:2019. Only this mask provided the necessary limits for Type I, Type II and Type IIR in terms of bacterial filtration efficiency and differential pressure. It is an obvious fact that the desired performance increase can be observed when the appropriate GSM is determined without any changes in the number of layers.
- Melt-blown layer has resulted great increase in the bacterial filtration efficiency as expected, while having a decreased effect on air permeability and breathability. If changing mask type (Type I, Type II, Type IIR) is important, using a melt-blown layer is important. On the other hand, for the same mask type, masks consisting of only a spun bond layer with a higher GSM compared to the mask containing melt-blown can also provide the expected performance, the same effect can be achieved at a low cost.
- If increasing the number of layers in the mask does not change the mask type depending on the relevant standard, the performance increase does not matter, on the contrary, unnecessary cost occurs. Awareness of this issue is required. Instead of implementation for an extra layer, a slight increase in GSM in existing layers can provide expected mask performance and change mask type.
- Increasing the GSM or the number of layers to increase bacterial filtration efficiency can be considered a solution, but this objective demands greater attention because, on the other hand, the differential pressure may increase too much and exceed the limit value for this feature so it may adversely affect the mask type.
- Given these points, it is apparent that while increasing the number of layers, great attention should be paid to GSM. Equally important, 4-ply masks can have higher performance than 5-ply masks if the appropriate GSM is selected.
- In the study, mask types were expressed according to EN 14683:2019 + AC:2019 standard considering bacterial filtration efficiency and differential pressure. When the splash resistance and microbial cleanliness tests, which are the other requirements in the classification according to relevant standards, are also performed, the type of masks is completely determined.

ACKNOWLEDGEMENT

The author thanks Mogul Tekstil San. Tic. A. Ş. for supplying spun bond and melt-blown nonwovens

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Author:

ŞEVKAN MACİT AYŞE

Uşak University, Faculty of Engineering and Natural Sciences, Textile Engineering Department,
Ankara İzmir Yolu 8.Km Bir Eylül Kampüsü, 64200, Uşak, Türkiye

Corresponding author:

ŞEVKAN MACİT AYŞE
e-mail: ayse.sevkan@usak.edu.tr