The Study Of The Mechanical Strength Of Polypropylene Filter Material For The Production Of Disposable Respirators

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Abstract. Atmospheric air, which is a natural resource, significantly affects the health and disease level of the population [1, 2], as well as the quality of the environment [3, 4]. However, as a result of anthropogenic activity, the environmental condition of the air has a tendency of constant deterioration [5, 6]. The main anthropogenic source of atmospheric pollution is large industrial conglomerates, which include motor vehicles [7, 8]. Chemical pollution of the air on a global scale leads to the greenhouse effect, the appearance of acid rain [9, 10] and pollution of aquifers [11, 12], and as a result, an increase in diseases [13], pandemics [14].

The goal of the study is to investigate the relationship between the mechanical characteristics of polypropylene filter material and their deformation under external forces for stretching and determine the safe period of use of disposable respirators.

Four types of samples have been used for experimental research. Operational properties were determined by three indicators: elongation from applied force, penetration coefficient by a test aerosol of paraffin oil, and air flow resistance in accordance with the requirements of the DSTU EN 149:2017 standard.

The dependence of relative elongation on tensile force has been established for samples of Eleflen and Meltblown materials with an additional layer of coarse fiber material and without an additional layer. It has been shown that the presence of an additional layer increases the tensile force of the filter material sample by 1.5 times.

It has been found that the longitudinal fibers of the filter material samples withstand 15 % more external force applied for stretching, allowing manufacturers to ensure the proper fit of respirator structural elements, which ensures a longer service life. Research results show that an additional layer of material increases the strength indicators of the main filter layer by 3 times.

Scientific novelty lies in determining the relationship between the mechanical characteristics of polypropylene filter material for the production of disposable protective respirators and their protective properties and deformation under external forces by stretching.

The practical value involves in determining the penetration coefficient, which ensures the appropriate protective efficiency of the respirator within the range of 0 to 10% elongation. The presence of an additional layer of coarse fiber material allows increasing this value based on the properties of the filter material (fiber thickness, packing density).

Introduction

The World Health Organization (WHO) 2023 year report, indicates that non-communicable diseases (NCDs) account for 61% of all deaths worldwide (31 million) [15]. Among them, 4.1 million deaths are attributed to respiratory diseases. This alarming figure compels all health professionals dealing with occupational health issues to seek adequate ways to address this problem [16].

Various types of disposable respirators are used to protect users from harmful airborne particles in the workplace, hazardous aerosols, viruses, and bacteria [17]. Most of these protective masks consist of several filtration layers of different fiber packing densities to ensure adequate mechanical strength and specified protective efficiency [18]. Based on the manufacturing process of polypropylene filter materials by extrusion, this is achieved by forming fibers of different diameters [19]. The smaller the diameter, the better the capture of aerosol particles [20]. However, this significantly compromises mechanical strength, leading to gaps and deterioration of material properties (breathing resistance, dustiness, etc.). To enhance mechanical strength, various additional layers of thick fibers onto which ultra-thin ones are applied are used [21]. At the same time, there are polymer filtering materials that have sufficient breakup resistance and elasticity, allowing their use without additional materials [22]. However, they are characterized by insufficient protective effectiveness. Hence, there is a relevant task of finding a rational structure of filtering materials to ensure the necessary indicators in the manufacture of such high-efficiency materials of disposable respirators.

Analysis of publications

The article [23] shows that despite numerous studies on the effectiveness of filtration respirators and materials for their production, systematic data on the rational combination of filters and respirator design ensuring high protective properties and safety in use are lacking.

The article [24] presents the results of research on a natural nonwoven layer made from bleached flax and cotton fibers, which could replace polypropylene materials. The authors tested this material for mechanical, physical, and biophysical properties, confirming its high capture efficiency and thus recommending it for respirator manufacturing. However, research on determining the penetration coefficient with sodium chloride aerosol, which is a standard protocol, have not been conducted.

The article [25] describes the process of producing polypropylene material for filtering half masks with the addition of 30 % talc. According to the authors, this will improve the mechanical properties of the polypropylene material and simplify the process of manufacturing filtration respirators.

In the article [26], the authors analyzed the filtration efficiency of various disposable respirators and demonstrated significant variability in testing protocols and methods for evaluating different materials. According to their opinion, the inability to replicate all influencing factors on the protective efficiency of respirators in laboratory conditions leads to errors in their selection and requires finding appropriate solutions to increase the reliability of gathered indicators.

The articles [27, 28] discuss the high filtration efficiency of FFP2 and FFP3 masks for all tested particle sizes, while the protective efficiency of fabric respirators is doubtful.

The article [29] presents a study on the relationship between fiber diameter, their packing density, and parameters of the technological process (pressure, heating temperature of polypropylene, feed rate, distance from the spinneret to the drum for forming the filter fabric), allowing the authors to recommend rational settings for the equipment to get the best properties of the final product.

In articles [30, 31], the authors investigated factors influencing the characteristics of materials, enabling them to find pressure ranges in spinners and distances from the spinneret to the drum that would allow to get the fiber size of nonwoven material with the specified packing density.

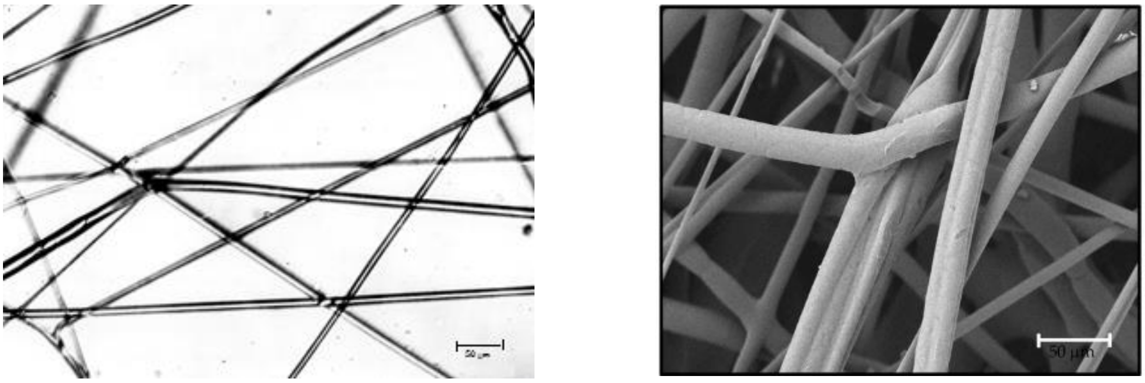
As a result of the analysis, significant interest among respirator developers and researchers in the reliability of test results during the testing process, as well as in the impact of the structure of filter materials (fiber packing density, diameter) on the protective efficiency of respirators, has been established. It is noted that the structure of filter materials significantly affects the respirator manufacturing process. There is a need to find appropriate compositions that would simultaneously ensure high strength, elasticity, and efficiency. On the other hand, it would be preferable to combine all critical qualities in a one filter layer. This requires the development of a clear research procedure and established the correlations between the mechanical characteristics of polypropylene filter material for manufacturing disposable protective respirators and their protective properties. This will allow developers to design appropriate protocols for manufacturing filter materials for the different operating conditions.

Aim of Paper

The goal of the work is to investigate the relationship between the mechanical characteristics of polypropylene filter material and their deformation under external tensile forces to determine the safe service life of disposable respirators.

Materials and Methods

To study the mechanical strength, samples of filter materials such as «Meltblown» and «Eleflen», which are used as the main filter layer for FFP2 class filtering masks, have been selected. Two packs of Eleflen 50 g/m^2 material produced by LLC NVP «STANDARD» and two packs of «Meltblown» 50 g/m^2 material have been purchased freely on the Ukrainian market. Additionally, one pack of «Spunbond» materials with surface densities of 30 g/m^2 and 60 g/m^2 were acquired (see Figure 1).



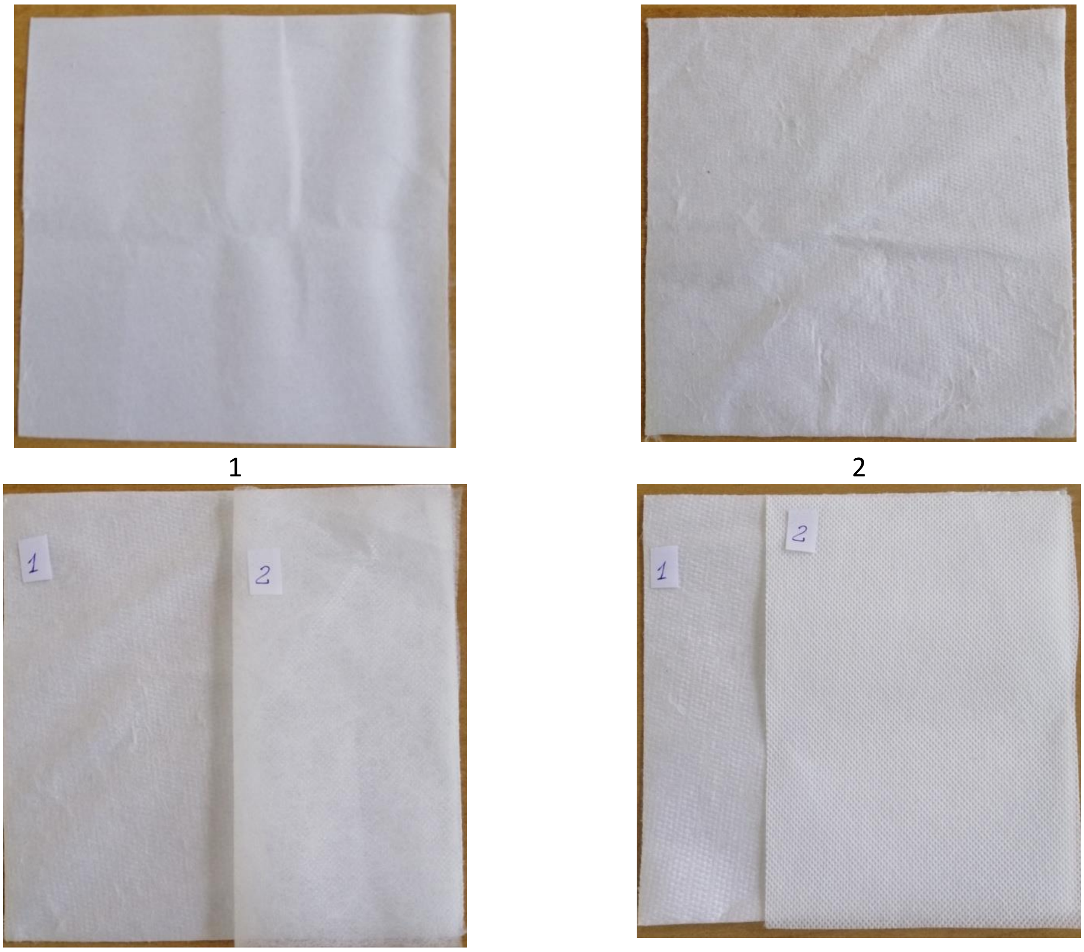
a) *b)*

Fig. 1. Microphotographs of fiber samples: a - polypropylene filtering material; b – meltblown

The surface density of filter materials was determined by weighing a sample of the filter material, which was cut according to a template with dimensions of 100×100 mm, using electronic scales «SVA-300-0.005» with an accuracy of 0.005 g. The obtained data were then correlated to the area of 1 m^2. The results were compared with the data provided in the quality certificate for the respective material. The discrepancy between the laboratory-obtained and manufacturer-provided data was within acceptable limits, which is 5 g/m^2. From the packages of filter materials, four samples (Figure 2) sized 15×50 mm were prepared, which were cut in the longitudinal and transverse directions of the filter material winding. All types of tested materials have certain differences for samples placed longitudinally and transversely in the material, which are due to the technological features of manufacturing.

The technological process for manufacturing «Eleflen» type filter material involves a series of spinners that deposit fibers onto a receiving surface, mainly rotating drums. The polymer fibers exiting the spinneret are drawn by hot air, becoming ultra-thin, and then compacted on the receiving surface of the rotating drum by the same hot air. The fibers in this process remain intact, which is an advantage, but the disadvantage is the relatively larger pore size between the fibers.

Unlike «Eleflen», «Meltblown» materials, in the technological process, involve breaking the polymer jets exiting the spinneret into ultra-thin individual fibers using hot air. These fibers are directed onto a mesh receiving surface and gradually cooling down. As they land on the mesh surface, the warm individual fibers are compacted on the surface by vacuum suction through high-pressure fans. In this process, the pore size of such material is relatively small, but the downside is the low strength of bonding between the fibers.



1 2

3 4

Fig. 2. Appearance of samples of filter material packets for testing: 1 - Eleflen 50 g/m^2; 2 - Meltblown 50 g/m^2; 3 - Meltblown 50 g/m^2 and Spunbond 30 g/m^2; 4 - Meltblown 50 g/m^2 and Spunbond 60 g/m^2

So, to determine the mechanical characteristics of the material, a tensile testing machine «PM-3-1» is used, which ensures strong fixation of the samples during testing. The stretching speed is set at 100 mm/min, and data on elongation and stretching force are recorded from the scale of the tensile testing machine. Testing is stopped when the material is completely torn or begins to tear, which is an indicating of a disruption in its structure.

To determine the penetration coefficient of the test aerosol, paraffin oil, an installation (see figure 4) was used, consisting of an aerosol generator with an average particle diameter of 0.4 µm, a flowmeter «PM-6.3» to control the flow rate of the test aerosol through the tested sample, and a photometer type «FAN», which registers data on the number of particles retained by the filtering material. Testing of the filtering material was carried out at a flow rate of 60 dm^3/min and a clamping diameter of 102 mm for placing the filtering material samples.

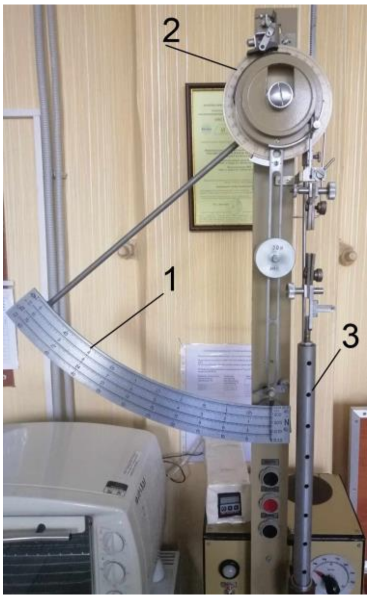


Fig. 3. A general view of the tensile testing machine RM-3-1

Eight samples measuring 150x150 mm made from the same material as the samples used in other tests were gathered to testing.

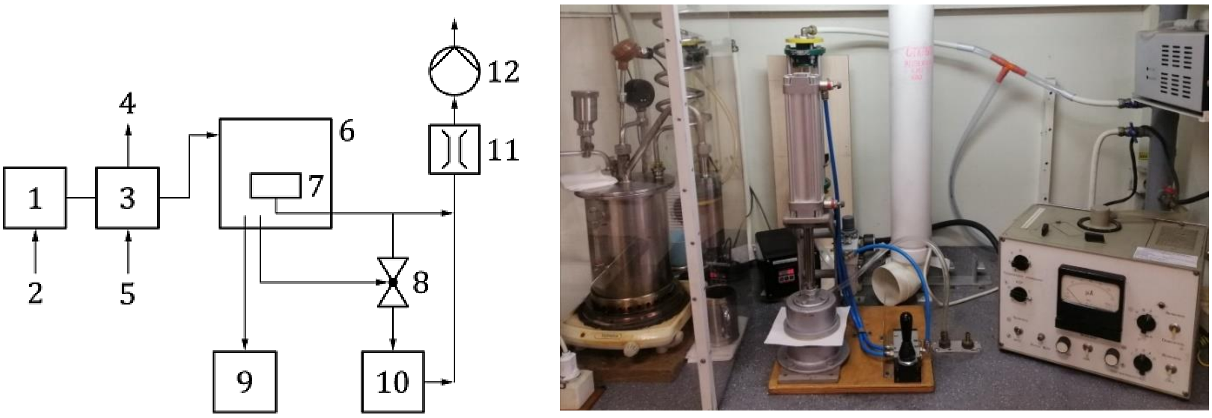


Fig. 4. The schematic diagram of the stand for determining the penetration coefficient of filter materials using the paraffin oil aerosol test: 1 - aerosol generator; 2 - compressed air supply; 3 - mixing chamber; 4 - excess aerosol discharge direction; 5 - compressed air supply, if necessary; 6 - test chamber; 7 - clamp for the test sample; 8 - three-way valve; 9 - additional photometer FAN, if necessary; 10 - photometer FAN; 11 - flow meter RM-6.3 GUZ; 12 - aspirator

The air resistance of the filter material has been determined using a setup (see Figure 5) with an airflow rate of 3 dm^3/min and a clamp diameter of 80 mm. The airflow rate was measured using a flowmeter «RM-0.63», while the pressure drop was measured using a manovacuumeter «Testo 512» with an accuracy of 0.1 Pa. Eight samples measuring 150x150 mm made from the same material as the samples used in other tests were prepared to testing.

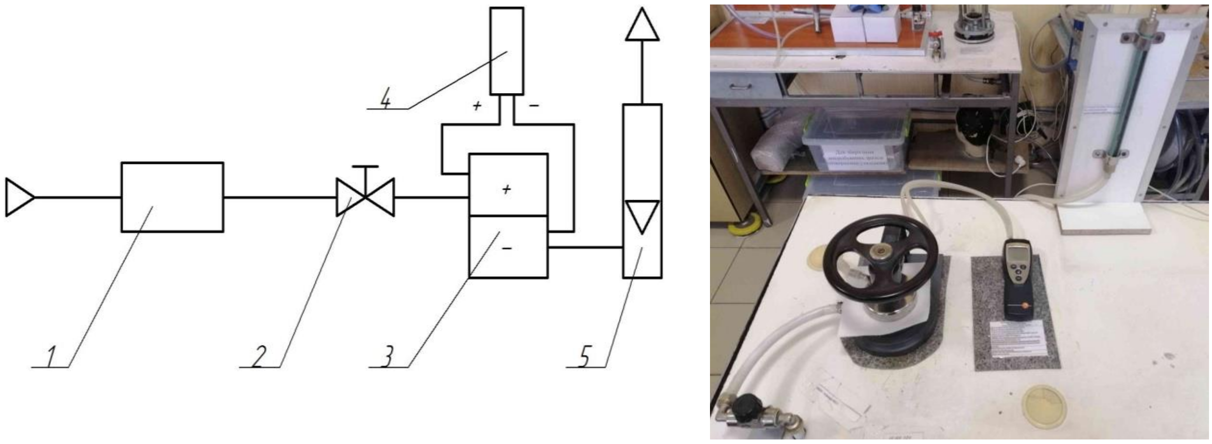


Fig. 5. The diagram and a general view of the stand for determining the pressure drop across the filter material: 1 - pressure stabilizer; 2 - control valve; 3 - flow meter RM-0.63 GUZ; 4 - manometer; 5 - clamp for mounting the filter material sample; 6 - manovacuumeter Testo 512

For processing the experimental data and constructing approximation curves relating to the mechanical characteristics of polypropylene filter material for the production of disposable respiratory masks and their protective properties, Microsoft 365 Excel program has been used.

Research Results

According to the generally known description of the semi-automatic technological process of manufacturing filter respirators, the materials used undergo several stages of mechanical tension.

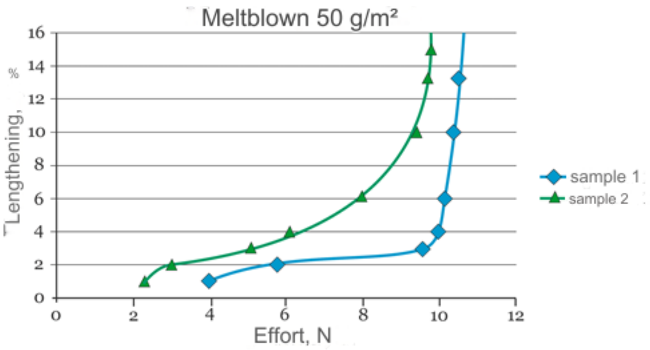
The first stage involves unwinding the material from the roll, during which the material is subjected to unidirectional tensile forces. The stress force in the material equals the frictional force between the layers of the material during unwinding the roll and the force of rolling of the bearings controlling its rotation around the axis of the central plate on which the material roll is mounted.

The second stage involves the direct cutting by a roller of the future filter mask matrix. During this stage, the material is subjected to compressive forces as the roller passes through the material and tensile forces during the cutting of the blank.

The third stage involves folding the blank in half for flat-type masks or according to other proposed forms considering the presence of folds. During this stage, the material is subjected to tensile and bending forces.

The fourth stage involves giving the final shape to the mask from the blank by welding. During this stage, the material is subjected to compressive forces as the roller passes through the material and tensile forces during shaping of the blank.

At the first stage, the mechanical strength of various samples of filter materials used for manufacturing disposable masks has been investigated, as shown in Figures 6-9.



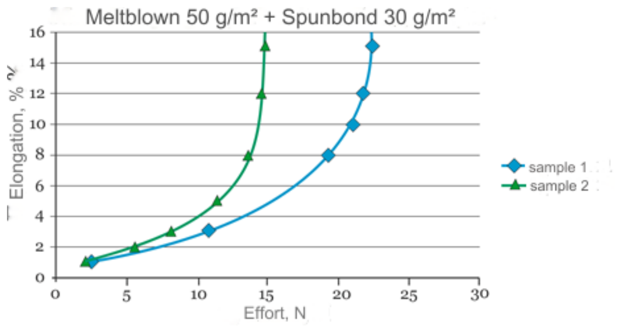


Fig. 6. The dependence of relative elongation (%) on the breaking force for Meltdown 50 g/m^2 material: Sample 1 - longitudinal; Sample 2 - transverse

Fig. 7. The dependence of relative elongation (%) on the breaking force for the package of materials Meltdown 50 g/m^2 and Spunbond 30 g/m^2: Sample 1 - longitudinal; Sample 2 - transverse

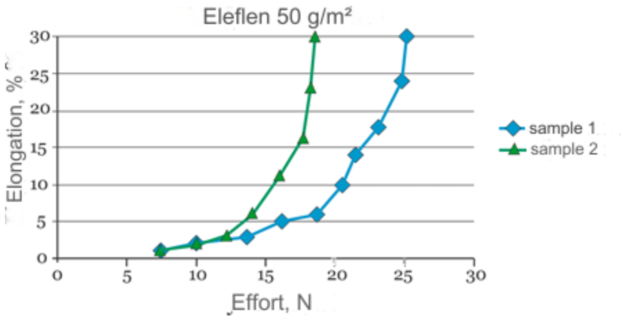


Fig. 8. The dependence of relative elongation (%) on the breaking force for the material Eleflen 50 g/m^2: Sample 1 - longitudinal; Sample 2 - transverse

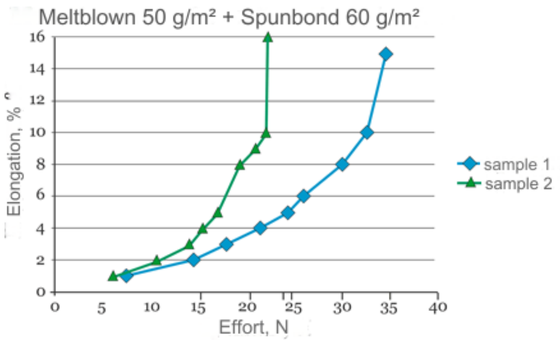


Fig. 9. The dependence of relative elongation (%) on the breaking force for the combination of materials Meltdown 50 g/m^2 and Spunbond 60 g/m^2: Sample 1 - longitudinal; Sample 2 - transverse

The analysis of the gathered results of the relative elongation of filter material samples concerning the tensile strength shows that there is a critical elongation point after which the samples rupture. The presence of an additional layer of material with coarse fibers (spunbond with an average fiber diameter of 12 mm) allows increasing the resistance of the samples to rupture. For example, the rupture of meltblown material samples occurs at 14 N, while the same sample with an additional spunbond layer ruptures at a force of 22 N, which is one and a half times higher. This can be explained by the increase in overall fiber packing density, which increases strength due to adhesive forces between fibers of different layers [32].

The nature of the force response of polypropylene materials to uniaxial stretching depends on both the mechanical properties of their constituent fibers (diameter) and the degree of adhesion between them (adhesive forces). When all fibers, stretched under the action of external force, reach a critical thickness along their axes, rupture and integrity violation of the sample occurs. The thicker fibers require more force for rupture. Therefore, adding an extra layer increases the force required for rupture, as spunbond has significantly thicker fibers than meltblown.

This suggests that respirators manufactured from filter material samples with additional coarse fiber materials will have a longer service life cycle. The next step is to investigate the airflow resistance and penetration coefficient during the relative elongation of filter materials. The results are presented in Tables 1 and 2 and Figures 10-13.

Table 1. Airflow resistance of filter material samples at relative elongation

Filter material sample type	Airflow resistance, Pa	Airflow resistance (%) at relative elongation (%)				
		5	10	15	20	25
Eleflen 50 g/м^2	5.2	4.9	4.2	3.4	2.6	1.9
Meltblown 50гг/м^2	8.4	7.9	6.7	5.6	3.6	2.5
Meltblown 50 g/м^2 + Spundbond 30 g/м^2	8.7	8.2	7.1	6.1	4.8	3.4
Meltblown 50 g/м^2 + Spundbond 60 g/м^2	9.3	8.6	7.9	6.8	5.6	4.5

Table 2. Penetration coefficient of filter material samples at relative elongation

Filter material sample type	Initial penetration coefficient, %	Airflow resistance (%) at relative elongation (%)				
		5	10	15	20	25
Eleflen 50 g/м^2	1.87	3.2	9.6	19.4	48.0	91.2
Meltblown 50gr/м^2	1.28	22.4	76.1	-	-	-
Meltblown 50 g/м^2 + Spundbond 30 g/м^2	1.22	4.4	19.3	61.5	89.7	-
Meltblown 50 g/м^2 + Spundbond 60 g/м^2	1.13	1.82	4.98	14.3	44.9	71.6

Based on the conducted research, it is evident that the penetration coefficient worsens with increasing deformation of the structure of the filter material samples. Furthermore, samples with an additional layer of coarse fiber material will undergo this process at a slower rate. As seen from previous studies, they require significantly greater external force, leading to a substantial change in porosity. The porosity of the samples changes due to the increased distance between fibers as they become thinner, as demonstrated in Table 3. The presented results have been obtained based on the determination of fiber thickness change using an electron microscope after applying a specified force.

Table 3. Changes in fiber thickness of filter material samples under deformation

Filter material sample type	Average fiber diameter of filter material samples (µm) corresponding to the applied force magnitude (N)				
	5	10	15	20	25
Eleflen 50 g/м^2	3.5	3.4	2.6	2.1	1.6
Meltblown 50gr/м^2	2.2	1.6	1.1	-	-
Meltblown 50 g/м^2 + Spundbond 30 g/м^2	3.5	3.3	3.1	3.0	2.6
Meltblown 50 g/м^2 + Spundbond 60 g/м^2	3.5	3.4	3.2	3.0	2.7

Besides, there is a disruption occurring between the fibers, which also alters the structure of the material, leading to changes in the flow field and triggering various mechanisms of aerosol particle capture [33].

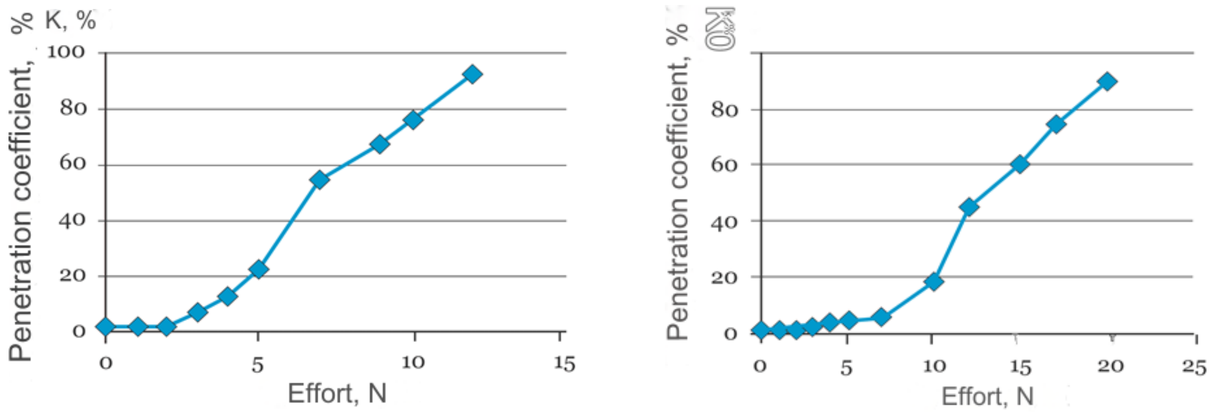


Fig. 11. The relationship between the penetration coefficient (%) and the breaking

Fig. 10. The relationship between the penetration coefficient (%) and the breaking force, N, for Meltdown 50 g/m^2 material

force, N, for the combination of Meltdown 50 g/m^2 and Spunbond 30 g/m^2 materials

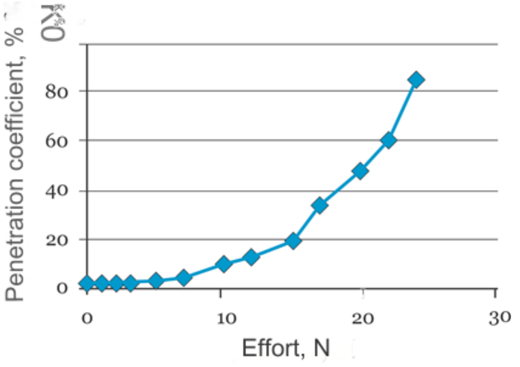


Fig. 12. The relationship between the penetration coefficient (%) and the breaking force, N, for Eleflen 50 g/m^2 material

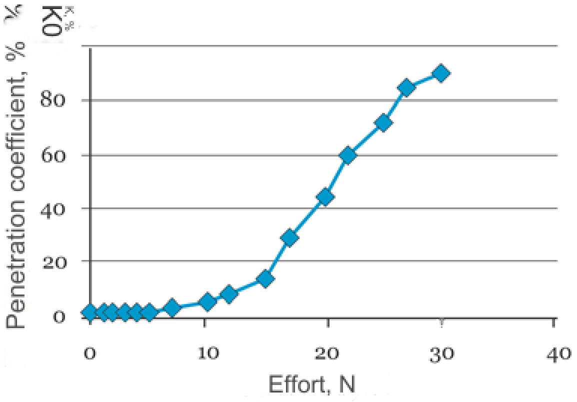


Fig. 13. The relationship between the penetration coefficient (%) and the breaking force, N, for the combination of Meltdown 50 g/m^2 and Spunbond 60 g/m^2 materials

Furthermore, a different outcome is achieved when determining the magnitude of air resistance - it decreases, again for the same reasons outlined earlier. Additionally, during the stretching of the samples, their packing density of fibers changes, leading to a reduction in the pressure drop across the filtering materials [34, 35].

Hence, the research results on the protective efficiency of filtering material samples allow determining the lifespan of disposable respirators during their wearing and removal, based on the packing density setting, which will vary with respirator deformation, by determining breathing resistance, a procedure feasible under industrial conditions [36].

The conducted research establishes a relationship between the mechanical characteristics of polypropylene filtering material for manufacturing disposable protective half-masks and their protective properties, and the extent of their deformation due to external tensile forces. This relationship is based on the characteristics of the fiber diameter of the filtering material and the packing density, which form adhesive forces between the fibers [37]. The study findings reveal that the magnitude of relative elongation to tensile strength for samples of «Meltblown» and «Eleflen» materials with an additional layer of coarse fiber material and without it increases the tensile strength of the filtering material sample by 1.5 times. This is explained by the fact that the magnitude of relative elongation depends on the type of material, fiber thickness, and surface density. It is assumed that the structural elements of the filtering samples have fibers of different thickness, which, when subjected to increased tensile force, stretch, thereby increasing porosity (i.e., gaps between the fibers), affecting the sample's ability to capture aerosol particles. Additionally, it has been found that longitudinal fibers of filtering material samples withstand 15% more external force applied for stretching, allowing manufacturers to appropriately provide a longer service life for respirator structural elements, ensuring increased durability. The results indicate that there is a level of mechanical strength for filtering material samples, exceeding which results in loss of the respirator protective efficiency. The research results demonstrate that an additional layer of material increases the strength indicators of the main filtering layer by 3 times. Moreover, the permeation coefficient value, which ensures the corresponding protective efficiency of the respirator, falls within the range of 0-10% elongation. The presence of an additional layer of coarse fiber material allows increasing this value, based on the properties of the filtering material (fiber thickness, packing density).

The experimental results indicate a progressive decrease in the forces generated during constant stretching, suggesting the tear of some cross-links in the elastomeric material layer. Therefore, it is essential for disposable FFP masks to be equipped with additional layers of a stiffer filtering materials, which help reduce the impact on fiber density as they initially begin to deform.

The limitations of this study included conducting it without additional laboratory tests as prescribed by the EN 149 standard. Additionally, only two types of filtering materials were tested, thus limiting the generalizability of the findings to other filtering material samples with different structures.

Conclusions

The relationship between the mechanical characteristics of polypropylene filtering material for manufacturing disposable protective half-masks and their protective properties, along with their deformation due to external forces, has been established.

Has been found that the relative elongation to tensile strength for samples of «Meltblown» and «Eleflen» materials with and without an additional layer of coarse fiber material increases the tensile strength of the filtering material sample by 1.5 times.

Moreover, it has been determined that the longitudinal fibers of filtering material samples withstand 15% more external force applied for stretching, enabling manufacturers to ensure a longer service life for respirator structural elements, thereby increasing durability. The research results also demonstrate that an additional layer of material increases the strength indicators of the main filtering layer by 3 times.

Furthermore, it has been found that the permeation coefficient value, ensuring the corresponding protective efficiency of the respirator, falls within the range of 0-10% elongation. The presence of an additional layer of coarse fiber material allows increasing this value based on the properties of the filtering material (fiber thickness, packing density).

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