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Gradient non-woven fabrics with a modified surface nanolayer for water filtration in construction industry

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ABSTRACT: Introduction. The aim of the work is to determine the influence of the structure of the filter materials formed as a result of modification of the surface layer on their water permeability and the size of trapped solid particles. **Materials and methods.** The non-woven fabrics from a mixture of polyethylene-terephthalate (PET) (70 wt.%) and bicomponent fibers (BCF) of the core-shell structure were used as objects of the study. The non-woven fabrics were obtained by mechanically forming the canvas with its subsequent hardening by needle punching. The resulting materials were modified by heat treatment. The water transfer in the modified materials was determined by the permeability coefficient. The filtration efficiency was determined by the number of trapped particles of a certain size. **Results and discussion.** The needle-punched non-woven fabrics without additional heat treatment are not suitable for water filtration. The proposed method of thermal and deformation-thermal modification provides the production of gradient materials with a controlled thickness of the nanoscale surface layer. Although a decrease in water permeability is observed, the modified material traps solid particles with a smaller (compared to unmodified ~ 20 μm) equivalent diameter of 2–4 μm, which is sufficient to prepare water for use in steam generators and in the production of building materials. **Conclusion.** The optimal parameters of deformation-heat treatment for obtaining the high-effective filtration non-woven materials were established: the temperature – 180°C, the processing speed – 3.5 m/min.

KEYWORDS: needle-punched non-woven fabric, heat treatment, water filtration, filter nanolayer.

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INTRODUCTION

The water and the water vapor are widely used in the construction industry [1–9]. The quality of construction works and materials, as well as the duration of uninterrupted operation of steam generators [10–15], largely depend on the content of solid impurities of various nature in water. Given the need to use relatively large volumes of water in construction, the filtration materials in water preparation systems must not only capture solid particles of a given size but also have high water permeability. The permeability and trapping of solid particles depend on the pore size of the material differently. The filtration efficiency decreases with pore size increasing, but at the same time there is an increase in water permeability.

The authors of the article proposed the methods for thermal and deformation-heat treatment of the non-woven needle-punched fabrics [16–22] to obtain gradient materials in which the pores reduce when deepening into the material [11,15, 19–22]. The non-woven fabrics with a modified surface layer of nanoscale thickness and fixed or adjustable porosity in the volume have been obtained. The thickness and the pore size of the modified layer determine both the water permeability and the filtration efficiency. The permeability of the material depends on changes in the volume porosity. The accumulation of filterable particles (in form of sludge) occurs in the modified surface layer, which makes it possible to remove it from the filter with a reverse flow of water and, thus, allows to reuse the filtration material.

The purpose of the work is to determine the influence of the filtration material surface layer structure on the water permeability and on the size of the trapped solid particles.

MATERIALS AND METHODS

As the objects of study, we used the non-woven needle-punched fabrics from a mixture of PET (TU 6-13-0204077-95-91) and bicomponent fibers (BCF) (70:30 wt.%). The linear density of PET fibers was 0.33 tex (diameter 20–25 μm), BCF – 0.44 tex (diameter 30–33 μm). Bicomponent fibers had a core-shell structure [17, 18], where the shell consisted of low molecular weight PET with a melting point of 110–120°C, and the core was made of high molecular weight PET with a melting point of 250–270°C.

The non-woven fabrics were obtained by mechanically forming a canvas on the attachment of a Spinbau carding unit (Germany) with its subsequent hardening by needle-piercing on a Dilo unit (Germany) while varying the needle-punching density to obtain non-woven fabrics with different values of surface and volume density. Further, the canvas with a surface density of 0.35 kg/m^2, a thickness of 3.0 mm, and a bulk density of 117 kg/m^3 was subjected to thermal modification in two ways.

The first one was the non-woven fabrics heating (180°C) on a metal plate for 0.5; 1.0; 3.0; 4.0; 6.0 and 10.0 min. The second one required the specially designed equipment (Fig. 1) using. The fabric was subjected to thermal deformation in the gap between the heated (180°C) shaft and the conveyor belt. The processing speed made up 3, 5, 12 и 15 m/min.

The technical problems related to the elimination of fiber sticking to the surface of the heated roll, centering and adjusting the belt tension and rapid cooling of the multilayer material when leaving the zone of deformation-heat impact were solved during the development of the proposed equipment. The lining the surface of the heated roll with fluoro-rubber reduced the sticking of fibers to the surface of the roll. The production of a conveyor belt from aramid fibers by piercing a looped canvas ensured long-term operation at a high roll temperature which reached 220°C.

The pressure on the fabric in the gap between the conveyor belt 4 and the heated roll 2 is regulated by the position of the guide rolls 3 which movement limits the lateral shift of the conveyor belt 4 with its centering. The rolls 3 are tensioned by pneumatic cylinders. The high cooling rate of the processed materials is achieved by intensive air blowing. The mechanical impact on the fabric is in the gap between the roll and the conveyor belt. The forced transportation of the material by a conveyor belt in the zone of deformation-heat treatment reduces the stretching and uncontrolled changes in porosity. The fixation of the modified structure of the processed materials is achieved by intensive cold air blowing when the fabric leaves the gap between the roll and the conveyor. The high cooling rate limits the stretching of the multilayer material when it leaves the gap between the conveyor belt and the heated roll and the termination of the forced transportation. The wrapping of a 1-meter-diameter roll with a fabric increased the duration of the deformation-heat effect and made it possible to reduce the processing temperature and to regulate the heating of the material in thickness while varying the bulk density in some sections of the reel.

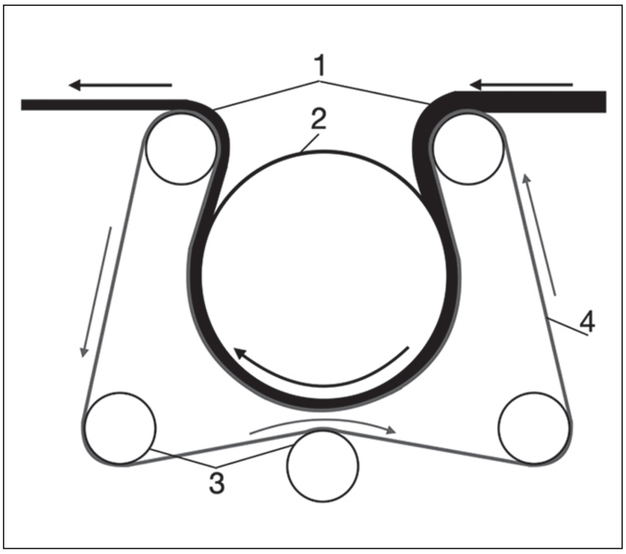

Fig. 1. **The scheme of the equipment for the non-woven fabrics deformation-heat treatment**:
1 – canvas; 2 – heated shaft; 3 – guide shafts;
4 – conveyor belt (narrow arrows – the direction of movement of the conveyor belt; bold arrows – the canvas movement)

The transfer of water in the modified materials (obtained using thermal and deformation-thermal processing techniques) was determined by calculating the permeability coefficient (K, m^2) according to the equation:

$$K = \frac{\mu d w}{\Delta P}, \quad (1)$$

where μ – the water viscosity coefficient, Pa×s; d – the material thickness, m; ΔP – water flow head, Pa; w – water filtration rate, m/s.

The water filtration rate in sheets and processed materials was determined experimentally according to the requirements of GOST 52608-200 at a constant water pressure of 500 Pa (water column height 50 mm).

RESULTS AND DISCUSSION

The study of the modified fabrics porous structure

The micrographs of multilayer materials obtained in the gap between the heated roll and the conveyor belt from the mixture of PET fibers with linear density of 0.33 tex and from the bicomponent fibers in the ratio of 70 and 30%, respectively, are shown in Fig. 2. The materials were obtained at a constant roll temperature of 180°C and processing speeds: 3,5; 12 и 15 m/min.

As it can be seen from the micrographs, each mode of heat treatment is characterized by the appearance of a surface modified nanolayer with high fiber packing density in the structure of the material. The difference in packing density contributes to the formation of a material with a gradient in the distribution of density and porosity over the thickness. At the same time, the thickness of the surface modified layer and the structure of the bulk part of the material depend on the processing speed, that is, on the duration of contact between the canvas and the hot surface of the shaft (Fig. 2).

At a high processing speed (15 m/min) a poorly distinguishable nanosized thickness modified surface layer with a pronounced interface between it and the bulk part of the canvas is formed.

The volume structure of the material corresponds to the structure of the fabric. But the density of bundles increases in comparison with the fabric in the bulk (Fig. 2, a). The different packing density of fibers along the length of the bundles in the transition layer leads to the formation of the pores that have the shape of a cone directed by their apex towards the modified layer (Fig. 2, b). The dense spherical patterns of various sizes located at a small distance from each other appear in the surface layer and in the bulk of the material. The pattern formation is a consequence of the melting of PET fibers in the bundles. A system of communicating tortuous capillaries is formed in the spaces between the patterns. The patterns in the bulk of the material are formed with sizes exceed the sizes of the patterns in the modified layer where the space between the patterns is filled with fibers (Fig. 2, c).

The processing speed affects the thickness and structure of the modified surface layer and volume (Fig. 2). A thin modified layer is formed with a clear interface between it and the volume at a speed of 15 m/min. A decrease in the speed from 15 to 12 m / min leads to an increase in the thickness of the modified layer. The thickness of the bundles in the transition between surface and bulk decreases. The modified surface layer has a significant thickness at a processing speed of 3.5 m/min case.

The effect of the processing speed in the gap between the heated roll and the conveyor belt on the formation of the surface structure of gradient materials is shown in Fig. 3.

Due to the use of needle punching in the non-woven fabrics manufacture process they inevitably have two main, very common types of surface defects that affect the quality of water filtration.

The first one is associated with an uneven distribution of fibers on the surface which is a consequence of continuous stretching of the fabrics during piercing and is expressed in the alternation of strips with high and low fiber packing density. The second type of defects is represented by the holes from the needle action (Fig. 3, a).

It is obvious (Fig. 3 b, c, d) that the above defects are leveled during the deformation-heat treatment: the pronounced holes on the modified surface disappear and there are no bands indicating a more uniform distribution of fibers in the surface layer.

The elimination of surface imperfections is a consequence of the shear and compaction of the fibers in the surface layer in which (compared to the bulk) the fibers have a low packing density and, therefore, increased mobility.

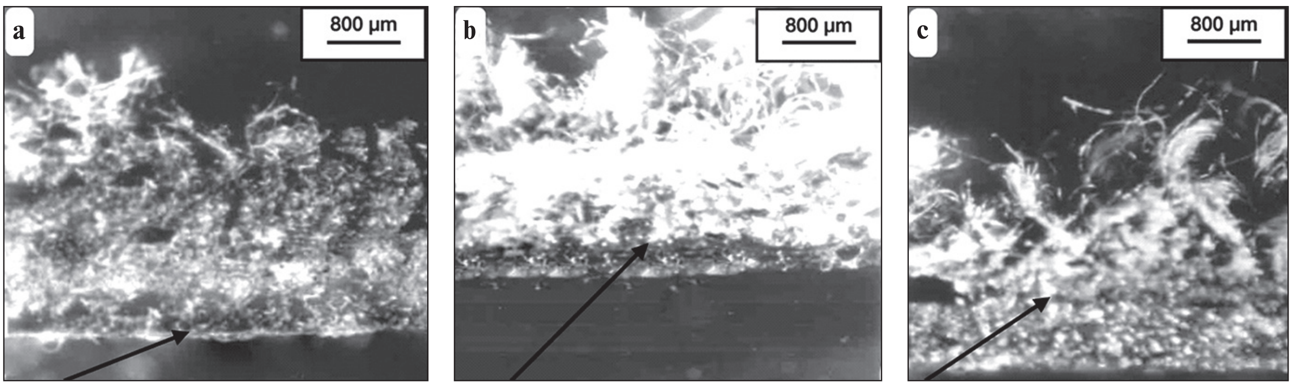

Fig. 2. **The cross section of PET (70%) and BCF (30%) based heat-treated fabrics.**
Processing speed, m / min: a – 15; b – 12; c – 3.5. Shaft temperature – 180°C
(The arrows show the boundary between the modified surface layer and the volume)

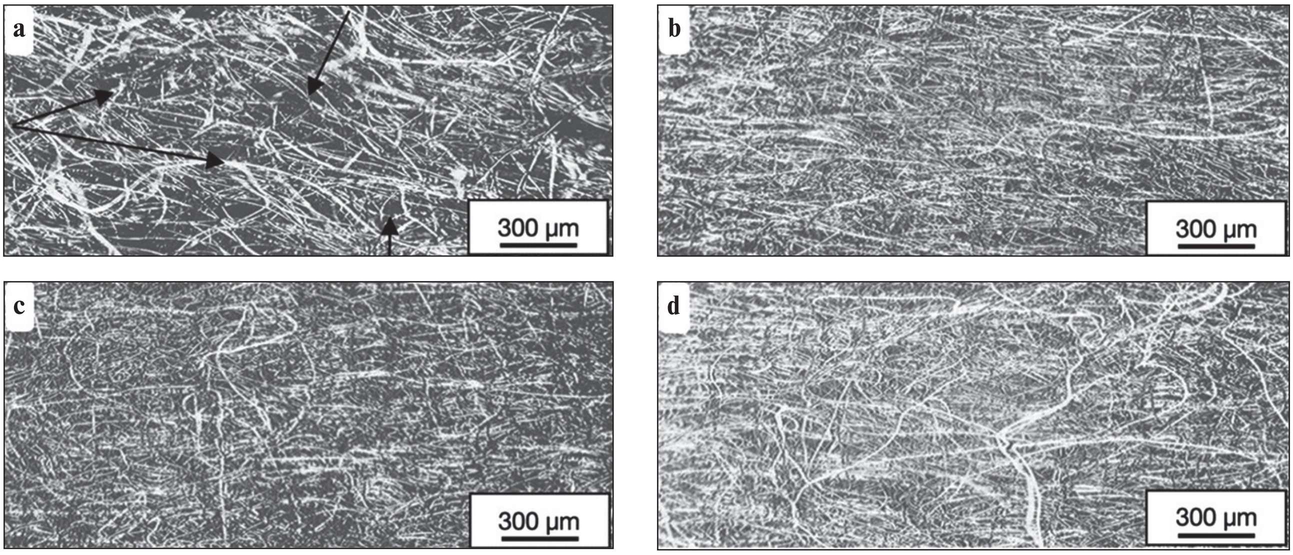

Fig. 3. **The surface of the non-woven fabrics based on PET (70%) and BCV (30%) mixture:**
a – original unmodified non-woven material. Material processed at speed, m/min: b –15; c – 12; d – 3.5.
Shaft temperature – 180°C (Arrows on the surface of the canvas show the holes from the action of the needles, the direction of treatment is shown by the arrows on the side)

The structure of the surface layer and the volume of multilayer materials obtained under the conditions of placing fabrics with different content of bicomponent fibers on a metal plate heated to 180°C with a holding time of 4 minutes (Fig. 4) was investigated.

A modified layer with a uniform packing density of fibers in the bulk is formed (Fig. 4) when held a fabric containing 30% bicomponent fibers on a heated plate.

The proposed by the authors techniques for the based on a mixture of PET and bicomponent fibers fabrics' modifying provide the production of multilayer materials with a controlled bulk and surface structure that can be used as water pretreatment filters.

The investigation the water permeability of treated fabrics

The permeability coefficient of non-woven fabrics (K) containing bicomponent fibers and materials obtained

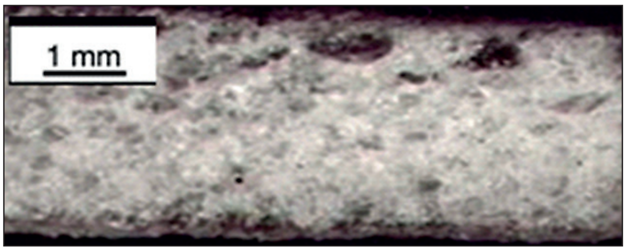

Fig. 4. **The cross section of the heat-treated non-woven fabrics based on a mixture of PET (70%) and BCV (30%).**
Shaft temperature – 180°C
(The contact with the metal plate is at the bottom)

at a constant shaft temperature (180°C) and varying the speed of the conveyor is related to the specific pore volume, which was calculated as the pore volume per unit mass of the sample (V_M, m³/kg).

The dependences of K on V_M for unmodified and modified methods of deformation and heat treatment of non-wovens are presented in Fig. 5.

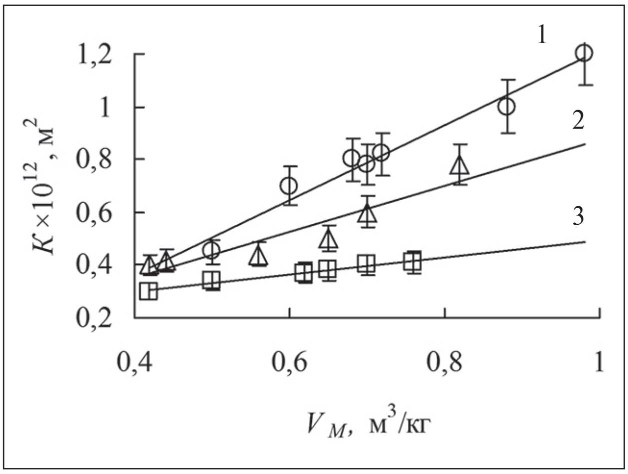

Fig. 5. **The dependences of the water permeability coefficient on the specific pore volume of the canvas with different bulk density**: 1 – the original unmodified canvas; 2 – the materials heat-treated on the plate for 0.5; 1.0; 3.0; 4.0; 6.0 and 10.0 min; 3 – the materials obtained by processing between the shaft and the conveyor belt at the speed of 3,5, 12 and 15 m/min. The heat treatment temperature – 180°C

The V_M parameter was adjusted using unmodified canvases with different volume densities, as well as by varying the duration of exposure of the canvas on metallic plastic and the processing speed when obtaining modified materials.

The ratio between K and V_M for the fabrics made from PET fibers with a linear density of 0.33 tex and for the multilayer materials based on a fabric with a 30% content of bicomponent fibers obtained by holding on a heated metal plate and rolling between the roll and the conveyor belt is described by linear equation:

$$K = k \times V_M, \qquad (2)$$

where k is the reduction factor equal to 1.2 for fabrics, 1.0 – for multilayer materials obtained by holding on a metal plate and 0.6 (kg × m^2) / m^3 – during rolling.

The linear form of the dependences K on V_M for the fabrics and for the multilayer materials indicates the dependence of the permeability of fiber systems on the separation of the water flow in the surface layer. In addition, for multilayer materials, the linear dependence reflects a directly proportional relationship between an increase in the thickness of the surface modified layer (accompanied by the decreasing of the V_M) and the decrease in the permeability coefficient for multilayer materials.

The permeability of multilayer materials obtained by holding on a heated metal plate approaches the permeability of fabrics with a corresponding specific porosity (Fig. 5). Thus, the permeability of multilayer materials obtained by rolling between the heated roll and the conveyor belt depends on the shear of the fibers of the surface layer. It results in an increase of the packing density and in the reorientation of the fibers.

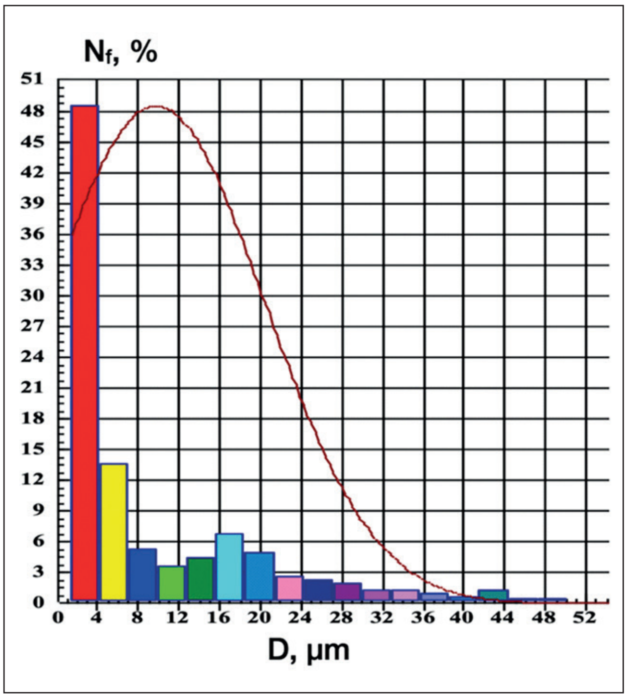

Fig. 6. **The metal particle size distribution before the filtration**

The investigation of the water filtration efficiency

The filtering characteristics of the fabric (which was used for modification by holding it on a heated metal plate and rolling between a heated roll and a conveyor belt) was determined using a pumpless vacuum filtration unit at a pressure drop of 0.5 atm.

The granulometric composition of the particles (determined by the parameter of the equivalent particle diameter (D, μm) before filtration (Fig. 6) was identified by analyzing the images of the VideoTesT system.

Note that 70% of the particles had an equivalent size of less than 10 microns. *The* change in the particle size distribution (N_f,%) after water filtration in the fabric and multilayer materials obtained by holding on a metal plate and rolling is shown in Fig. 7. The parameter N_f was calculated from the equation:

$$N_f = \frac{N_0 - N_1}{N_0} 100, \qquad (3)$$

where N_0 and N_1 are the number of particles of a certain fraction before filtration and the number of particles of this fraction in the filtrate, respectively. The higher the N_f value the more particles of a given fraction are extracted from the water during the filtration process which makes it possible to evaluate the filtration fineness.

The objects of the study were a multilayer material obtained by holding on a heated plate of a fiber with a surface density of 0.35 kg/m^2 and containing 30% bicomponent fibers by weight, as well as a multilayer material obtained at a rolling speed between the heated roll and the conveyor belt of 3,5 and 12 m/min of a fiber with a surface density of 0.35 kg/m^2 and containing bicomponent fibers 30% of the mass.

The original canvas and the modified material, obtained by processing on a metal plate for 4 minutes, practically do not filter water from solid particles (Fig. 7, dependences 1 and 2), which is explained by the high defectiveness of their surface layers.

The size of the particles that trap the gradient nonwoven materials, obtained under the deformation-thermal treatment, depends on the processing speed. At a processing speed of 12 m/min, there was obtained the filtration material that retains 75% of particles with an equivalent diameter of 6 microns and completely retains particles with an equivalent diameter of more than 12 microns (Fig. 7, dependence 3). When the processing speed is

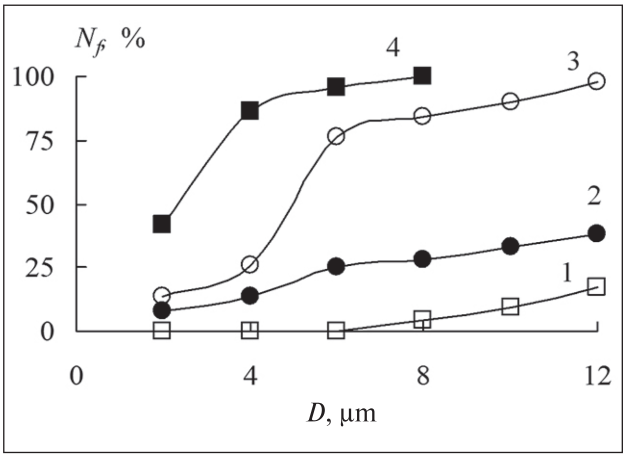

Fig. 7. **Granulometric composition of iron oxide particles after water filtration through**:
1 — unmodified canvas; 2 — material obtained during exposure for 4 minutes; 3, 4 — modified material obtained by deformation-heat treatment at a speed of 12 (3) and 3.5 (4) m / min

reduced to 3.5 m/min, the material captures 75% of particles with an equivalent diameter of 3 microns and completely captures particles with an equivalent diameter of more than 8 microns (Fig. 7, dependence 4).

To remove the sediment of filtered particles from the surface of materials obtained at a processing speed of 3.5 and 12 m/min, the method of flushing the filter with a reverse flow of water was used. After the first filtration cycle, which was performed until the permeability of the material decreased by 50%, the particle mass on the filter decreased by 92% with a gradual decrease in the mass of the removed particles after 8 filtration cycles to 72%.

CONCLUSION

– A deformation-thermal method for the non-woven needle-punched fabrics (from a mixture of polyethylene terephthalate and bicomponent fibers in a ratio of 70:30) modifying is proposed. It allows obtaining the gradient materials with a controlled thickness of the modified surface layer which structure determines the permeability and the efficiency of water filtration.

– As a result of deformation-heat treatment at a speed of 3.5 m/min, the non-woven filter material was obtained with a water permeability coefficient of about 10^{-11} m^2. It captures the 75% of solid particles with an equivalent diameter of 3 μm and completely captures the particles with an equivalent diameter of more than 8 μm. It is sufficient for water filtration in construction and production of building materials.

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AUTHORS' CONTRIBUTION

Viktor G. Nazarov – scientific guidance, concept of research, drawing up a plan for experimental work, conclusions of the article.

Leonid A. Ivanov – participation in the development of the scientific concept of the work, correction of the text of the article.

Alexander V. Dedov – carrying out experimental work, processing the results of the experiment, writing the original text.

Elena S. Bokova – participation in the development of a scientific research program, finalization of the text.

Evgeny S. Statnik – carrying out experimental work.

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