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INFLUENCE OF STRUCTURAL PARAMETERS OF NONWOVEN GEOTEXTILES ON SEPARATION AND FILTRATION IN ROAD CONSTRUCTION

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Abstract:

Nonwoven geotextiles are often used in road construction as a separation layer. They consist of the web of fibers with different orientations. The orientation of fibers has an important influence on physical and mechanical properties of nonwoven geotextiles. The production of nonwoven geotextiles is cheaper in comparison to woven or knitted fabrics which can also be used as separation geotextiles. The purpose of this research was to study the influence of structural properties of nonwoven geotextiles, namely the diameter of fibers and mass and thickness of nonwoven geotextiles, on their mechanical and hydraulic properties. Six types of nonwoven geotextiles were used in the research. They were produced by the drylaid process (carded) using mechanical bonding technique and also with the combination of mechanical and thermal bonding technique. The research confirmed that the bonding technique and structural properties significantly influence the separation and filtration properties of nonwoven geotextiles, such as opening size and water permeability. It was also found that there are no significant differences in mechanical properties, such as viscoelastic properties and compression creep, between the samples in the dry and wet conditions.

Keywords:

Nonwoven geotextiles, bonding techniques, opening size, water permeability

1. Introduction

The field of technical textiles, which recorded positive economic and employment trends in the EU, is an example of the “traditional sector,” which succeeded in rebuilding itself into a new business model, fully adapted to the needs of the new industrial revolution (smarter, more inclusive, and more sustainable). Textile materials and technologies in the field of technical textiles are key innovations that could help to address the extremely diverse societal challenges.

The nature of fibers (polyester [PES], polypropylene [PP], viscose, cotton, carbon, glass, aramide, etc.) and the choice of the most appropriate production techniques (spinning, weaving, braiding, knitting, nonwovens, etc.), including finishing operations (dyeing, printing, coating, laminating, etc.), enable manufacturers of technical textiles to offer textile solutions that provide mechanical properties, replacement options, or protective properties that meet the specific needs of end users.

In the construction industry, geotextiles perform several functions. Thus, textiles used in earthworks with an aim to improve ground properties are called geotextiles. Based on the standard SIST EN 13249-13256, the functions of geotextiles from the civil engineering point of view are as follows:

- Separation: when we want to prevent the mixing of two different geomaterials.

- Filtering: it is used when we want to prevent the passage of soil fines into drainage geomaterial while the passage of liquid remains unobstructed.

- Drainage: geosynthetics are used to collect and discharge water.

- Protection and antierosion protection: we use to protect the substrate from weather and adverse effects of other materials.

- Reinforcement: geosynthetics are built into the geotechnical construction with the purpose of strengthening the soil and/or increasing the load capacity.

- Sealing: used to create barriers that prevent the penetration of liquids or passage of the substance by diffusion or convection [1-4].

Geotextiles can be composed of three structurally different materials: woven, knitted, and nonwoven structures. Due to their diverse functions (reinforcement, separation, and filtration) and lower production costs, nonwoven textiles (fibers) are primarily used for separation and filtration purpose. The fibers used as geotextiles are mostly produced using drylaid process (carded process) and mechanically bonded (needle bonded) and thermal bonded (calendering or hot air). Fibers, used as geotextiles, can also be manufactured using an extrusion process (extrusion spinning).

The purpose of this research was to study the influence of structural properties of geotextiles on separation and filtration in road construction. Researched geotextiles were produced by the drylaid process (carded) and mechanical bonding as well as with the combination of mechanical and thermal bonding technique. As their primary function is the separation of two different geomaterials in road construction and filtering, geotextiles have to enable the unhindered transition of fluids (water) while simultaneously preventing the passage of soil fines in the direction of the fluid flow.

Particular attention is paid to the structuring of geotextiles, namely defining the orientation of fibers in the geotextile plane (longitudinally, transversely, isotropically) and perpendicular to the geotextile plane. This is conditioned by the openings of the surface and porosity, volumes (masses and specific density) in the direction of the separation and, in particular, the filtration properties.

2. Theoretical part

Previous researches on the structural properties of nonwoven geotextiles for separation and filtration in civil engineering are mainly limited to mechanically bonded nonwoven geotextiles, especially from PES and PP fibers, with great emphasis on mechanical (viscoelastic) properties, which are of primary importance in defining the behavior of nonwoven textiles in use [1-8]. Several studies have been elaborated in the past years on the subject of mechanical properties of geotextiles, whereby deformability (stress/elongation curve), as well as the elastic limit and a very important modulus of elasticity, has been analyzed in detail [5, 6, 9, 10]. Such textiles exhibit high modulus of elasticity in the longitudinal direction from 0.275 kN/m^2 (150 g/m^2) to 7.572 kN/m^2 (500 g/m^2) and in the transversal direction from 0.455 kN/m^2 (150 g/m^2) to 21.248 kN/m^2 (500 g/m^2), which means that they exhibit relatively high stiffness. A large part of the research focuses on chemical fiber geotextiles (PES, PP). Some research was carried out on geotextiles made from recycled PES fibers as well as from natural fibers such as wool and cotton fibers [11].

In addition to stiffness and strength, research on the mechanical properties of geotextiles also focuses on the creep properties. The creeping of geotextiles under load is certainly one of the most important properties affecting the filtration properties, which are closely related to the openings of the geotextile surface and their porosity after a longtime exposure of the geotextile in use [11-13].

Several researches focused on the porosity of geotextiles and its impact upon some structural properties. Some of them linked structural parameters to the mass per unit area of the geotextile which was determined at the time of manufacture, depending on the production program of the individual producer (e.g., 100, 200, 300, 500 g/m^2) [6, 14, 15].

A survey of performance of nonwoven geotextile filters exposed to severe climate conditions in high mountains for 18 years was carried out by Veylon et al. [16].

The analysis of published research results shows that some researchers did not devote particular attention to the structure of nonwoven geotextiles (fiber density, their specific surface, friction between fibers and their orientation, hardening method) and its impact upon the separation and filtration properties of nonwoven geotextiles [17-19].

Other important structural properties of nonwoven geotextiles reported in the literature are the specific structure of fibers, fibers in-plane orientation (longitudinal, transversal, isotropical, and perpendicular), and shape and size of pores as well as volume and area density of fabrics. Likewise, researches so far do not include friction and contact surface between fibers which should affect the mechanical properties of nonwoven geotextiles [6, 13, 14].

2.1. The structure of geotextiles

The method of manufacture (woven, nonwoven, knitted) of geotextiles strongly influences their mechanical properties.

The bonding technique, namely mechanical, thermal, or chemical, is particularly important for nonwoven geotextiles. They are mostly produced by drylaid process and are mechanically bonded by needling or thermally bonded (calendered or hot air bonded). Nonwoven geotextiles are suitable when large-scale deformations are expected and large elongations are required before breakage occurs. The tensile strength of nonwoven geotextiles does not depend on the direction of loading, although for some products certain anisotropic properties are possible, especially in the case of extension. Nonwoven geotextiles have isotropically, mostly longitudinally or transversely oriented fibers. In the case of isotropically oriented fibers, local mechanical deformations cannot be transmitted over the entire surface of the geotextile, as is the case with mechanical deformations of woven geotextiles. In the two-dimensional nonwoven fabric plane, fiber orientation is measured by the fiber orientation angle, α, which is defined as the relative directional position of individual fibers in the structure relative to the machine or longitudinal direction.

Nonwoven geotextiles are particularly suitable as separation and/or filtration layers [1-4]. For the production of geotextiles, monofilament and multifilament yarns are commonly used. Woven geotextiles are woven in canvas, twill, atlas, and in the most cases in ties. Geotextiles made from monofilaments have better permeability properties and are therefore more suitable for drainage and protection against erosion. Woven geotextiles made of multifilament yarn have high tensile strength and are mainly used for reinforcement purposes. Knit geotextiles, however, can be both weft and warp knitted (they are more stable and less stretched) in various constructional designs. In the case of warp knitting, this involves the production of knitted fabrics formed by the formation of loops from a large number of threads that flow in knitting in the longitudinal direction (in the warp direction). In addition, the warp knitting cannot be twisted. The layout and connection of the knitted knitwear depend on the type of interlace. Since the thread bent in the loop is in a forced connection with the adjacent straps, the loops retain a given shape and size, but since the knitted fabric has a more open surface than the woven fabric has, the smaller force causes the stretching of the loops in the direction in which the force acts. This is why knit geosynthetics are rarely used.

Woven and knitted geotextiles are suitable when we require high tensile strength and are thus proper for the soil reinforcement purpose [1-4].

3. Experimental

3.1. Materials

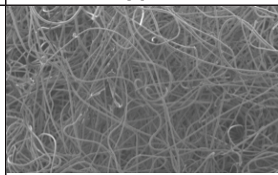
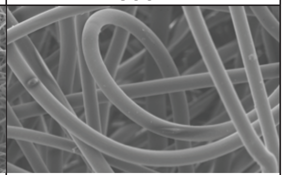
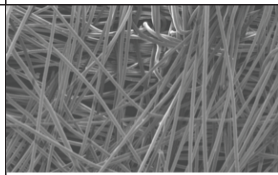
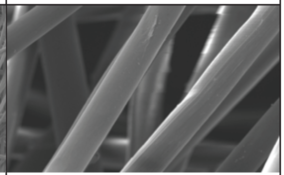
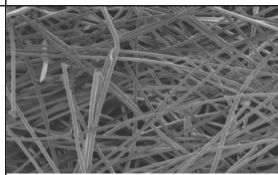
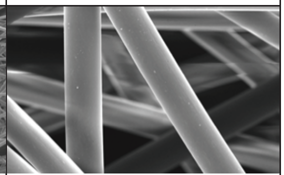
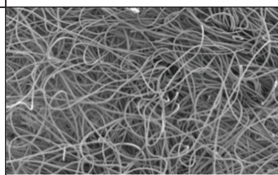
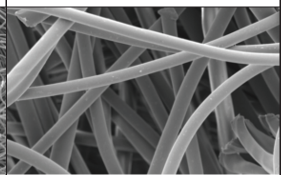
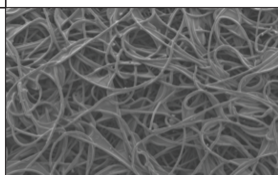
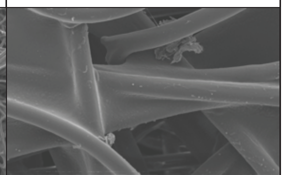
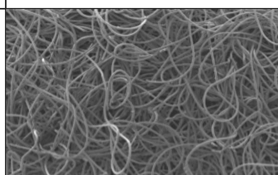
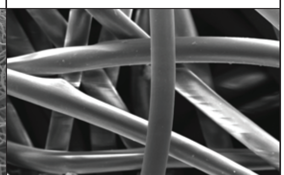
The research is oriented on the nonwoven geotextiles manufactured by the drylaid process (carded) and mechanically bonded (needled or spunlace bonded) and bonded using the combinations of mechanical, thermal, and chemical bonding techniques. Main functions of tested geotextile samples are filtering of groundwater and separation of two different geomaterials in road construction. They must enable the unhindered transition of water while simultaneously preventing the passage of soil fines in the direction of water flow.

The research aimed to study the influence of structural parameters of nonwoven geotextiles on fabric's mechanical and hydraulic properties, i.e., (viscoelastic properties and compression creep), opening size and water permeability properties. Six drylaid (carded) nonwoven fabrics from different manufacturers were analyzed (Table 1). Three samples are needle bonded, one is spunlace bonded, and two of them are bonded using the combination of needle bonding, thermal bonding, and chemical bonding techniques.

Among all analyzed nonwovens, four samples are from PES fibers and two of them from PP fibers. The mass of the samples analyzed is between 129 and 380 g/m^2, and the thickness between 1.027 and 2.081 mm.

Samples analyzed have isotropic orientation of fibers with diameter from 12.73 to 30.6 μm. Table 1 summarizes the microscope images, and Table 2 summarizes the summary of structural properties of analyzed samples.

Table 1. Microscope images of analyzed samples

Sample	Magnification	
	50×	500×
1		
2		
3		
4		
5		
6		

3.2. Testing methods

3.2.1. Tensile properties

Testing of basic tensile properties, e.g., the breaking force and elongation, was conducted in compliance with standard ISO 9073-3 [20] on dynamometer INSTRON 5567. Five tests were performed in the longitudinal and transverse directions for each sample to determine tensile strength and elongation, while the viscoelastic properties, i.e., elastic modulus, the stress and strain at elastic limit, work of rupture, etc., were evaluated from the stress/strain curves. When a geotextile deforms elastically, the stress is directly proportional to strain. The elastic limit (the stress and strain at elastic limit) presents the limit of elastic strains. Work of rupture is defined as the energy required to break the specimen [11].

3.2.2. Compressive creep properties

Determination of compressive creep properties was carried out in compliance with the standard EN 1897:2001 [21]. The geotextile sample with dimensions 100 mm x 100 mm was placed on the fixed base of a compression machine with an upper loading plate. The vertical compressive load was applied with different pressures, 25 , 100 , and 500 kPa, and the change in thickness in millimeter was recorded after 15, 60, 240, and 1440 minutes. The compressive creep was determined on dry and wet samples. If the test was to be carried out with the wet sample, the sample was immersed in water and in a

Table 2. Structural properties of analyzed samples

Sample	Chemical composition	Bonding technique	Diameter of fibers (μm)	Sample thickness (mm)	Mass (g/m²)	Porosity; O_{90} (μm)
1	PES	Needling	15.95	1.027	148.1	80.6
2	PP	Spunlace	30.60	1.186	129.7	65.4
3	PP	Needling	33.15	1.730	181.4	98
4	PES	Needling and thermal bonding	12.73	1.599	286.2	63
5	PES	Needling, thermal and chemical bonding	19.05	1.656	233.2	63
6	PES	Needling	24	2.081	379.7	63

PES, polyester; PP, polypropylene

container to keep the specimen immersed and at a constant temperature. The water level in the container shall cover the specimen, but the height of water above the specimen shall not exceed 25 mm.

3.2.3. Water permeability

The water permeability tests of geotextile samples were measured with the permeameter GE-TE-FLOW according to the standard ASTM D4491-99a-13 [22]. The GE-TE-FLOW PC-program calculates, according to the pressure readings, the difference in height per time and calculates the velocity in millimeter/second according to the corresponding water height. The test is carried on nonloaded sample (diameter = 75 mm) with testing surface diameter of 67.8 mm. The permittivity of sample was measured using constant head test procedure, with a head of 60 mm of water maintained on the sample throughout the test. The quantity of flow is measured versus time. Permittivity is an indicator of the quantity of water that can pass through a sample in an isolated condition.

The permittivity was calculated according to Equation (1):

$$\psi = \frac{1}{t} \cdot \ln\left(\frac{h_0}{h_1}\right) \cdot R_t \qquad (1)$$

where ψ is the permittivity (s^{-1}); t is the time for head to drop from h_0 to h_1 in mm²; h_0 is the initial head (80 mm); h_1 is the final head (20 mm); R_t is the temperature correction factor.

3.2.4. Characteristic opening size O_{90}

Determination of the opening size is made by sieving the particles passing through the geotextile according to the standard ISO 12956:1999 [23]. In principle, this test considers the opening size of the geotextile by looking at the dimension of the particles passing through the geotextile using a set of predetermined experimental conditions. The basic principle is to determine the diameter of particles of soil that can pass through the filtration media that is the geotextile, whatever its structure and complexity.

The method for the determination of the characteristic opening size of analyzed samples was implemented using the wet sieving technique [23]. A quantity of graded granular material (usually soil) was brought on the surface of the geotextile and washed with water. The geotextile acted as a sieve, and the particles that pass through the geotextile were analyzed. The characteristic opening size O_{90} of the geotextile corresponded to a specified size of the granular material passed d_{90} [24]. Results are expressed in micrometerμ, according to Equation (2):

$$O_{90} = d_{90} \qquad (2)$$

where O_{90}= is the characteristic opening size; d_{90} =is the particle size for which 90% (by mass) of the particles is smaller.

3.2.5. Opening area

The percentage of opening area was determined using ImageJ software. ImageJ [25] is an open source image processing program for multidimensional image data. The images on the scanning electron microscope (SEM) JSM-6060 LV with the 50× magnification were analyzed.

3.3. Statistical analysis

The impact of structural parameters (mass, thickness, diameter of fibers, and bonding technique) upon mechanical and hydraulic characteristics of nonwoven geotextiles was analyzed using the statistical analysis of variance (ANOVA). ANOVA was used to determine the significance of the structural parameters that are the consequence of the bonding technique of the sample on the mechanical (tensile and compressive creep properties) and hydraulic (water permeability/permittivity and opening size) properties of the nonwoven geotextiles tested in the dry and wet conditions [26]. ANOVA was performed using the Statgraphics program.

The correlation between the independent (diameter of fibers, thickness of nonwoven geotextile, area density) and dependent factors (tensile strength and elongation, elastic modulus, yield point, work of rupture, compressive creep, water permeability, and opening size) is determined using correlation matrix. Correlation matrix was also obtained by the Statgraphics program. [26]

4. Results and discussion

4.1. Tensile strength

The results of tensile tests conducted on dry and wet samples in the longitudinal and transverse directions are shown in Figure 1.

The highest tensile strength is achieved with dry sample 6 (16.53 N/mm^2), which is mechanically bonded by needling and has the highest thickness and area density. An 8.1% decrease in tensile strength of sample 6 in the wet state (15.19 N/mm^2) is observed compared to the dry state. This might be caused by the highest area density (379.7 g/m^2) and thickness (2.081 mm) and also very high diameter of fibers (24 μm) of sample 6. Generally, differences of tensile strength in dry and wet conditions are less than 8% for other tested geotextiles. Interesting results of the tensile strengths can be observed in case of sample 2, which is spunlaced, where the breaking stress in the wet condition increases by 8.8% compared to dry condition. Sample 2, which is spunlaced, means that the higher friction between the web fibers is achieved during spunlace bonding also because of very high (the second highest) diameter of fibers of sample 2 (30.6 μm). That affects mentioned tensile strength increase in the wet condition.

The lowest tensile strength in the longitudinal direction was measured on sample 1, which is needle bonded and has the lowest thickness (1.027 mm), area density (148.1 g/m^2), and very low (the second lowest) diameter of fibers (15.95 μm). The highest tensile strength in the transversal direction was measured on sample 4, which is needle and thermal bonded (15.32 N/mm^2). In the wet state, the tensile strength of sample 4 in the transversal direction even increased by 5.9%.

On average, the tensile strength for all samples, except for sample 2 (longitudinal direction) and sample 4 (transverse direction), decreases for a maximum of 8.1% in the wet state as compared to the dry state.

4.2. Elongation at tensile strength

The results of elongation at tensile strength of the dry and wet samples analyzed in the longitudinal and transverse directions are shown in Figure 2.

The elongations at tensile strength show the highest value for sample 1 (dry and wet) in the longitudinal direction (106.67% dry and 99.29% wet). Sample 1 is needle bonded and has the lowest thickness (1.068 mm) and the second lowest diameter of fibers (15.95 μm) which influences on the highest elongation level (Figure 2). On the contrary, the elongation at tensile strength of sample 1 is very low in the transverse direction (60.58% dry and 65.87% wet), regardless of the tensile strength being similar in both directions.

The reason probably lies in the orientation of fibers of sample 1 which has isotropic orientation of fibers, but it seems that the lower number of fibers is in the transverse direction. The lowest elongation at maximum tensile strength expresses sample 3 in the longitudinal direction (49.54% dry and 50.65% wet), which has second largest thickness (1.73 mm) and also the highest diameter of fibers (33.15 μm), and means the lowest specific surface area of the fibers and consequently the lowest elongation.

On the contrary, sample 3 expresses very high elongation at tensile strength in the transverse direction (84.14% dry and 86.77% wet). The reason probably lies in the orientation of fibers of sample 3 which has isotropic orientation of fibers, but it seems that the higher number of fibers is in the transverse direction.

4.3. Viscoelastic characteristics

The stresses and strains at elastic limit, elastic modulus, and work of rupture of the dry and wet samples analyzed in the longitudinal and transverse directions are summarized in Table 3.

The highest stress at elastic limit in the longitudinal direction is measured on sample 5 in the dry condition (0.4 N/mm^2) with

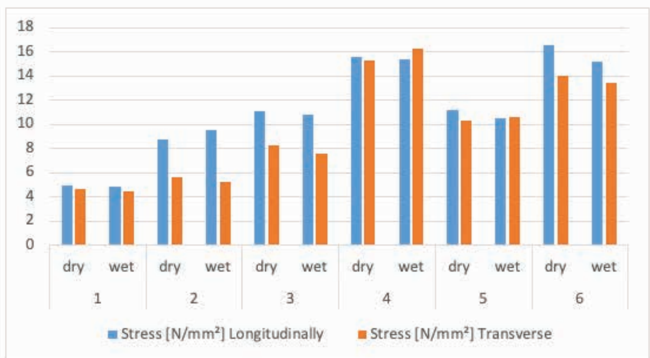


Figure 1. Tensile strength of samples

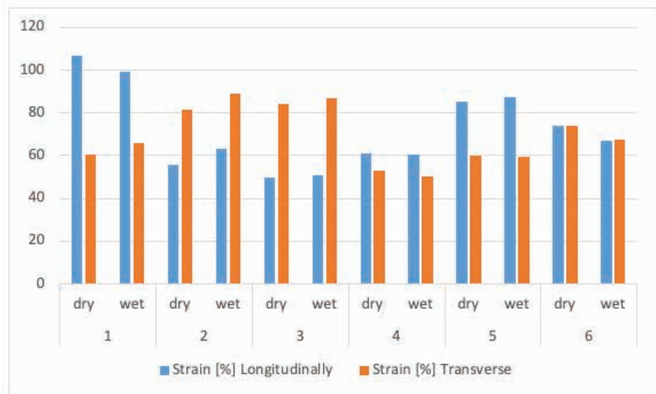


Figure 2. Elongations of samples at tensile strength

Table 3. Viscoelastic characteristics of dry and wet samples analyzed in the longitudinal and transverse directions

Sample	Stress at elastic limit [N/mm²]			Strain at elastic limit (%)		Elastic modulus (N/mm²)		Work to rupture (J)	
		Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
1	Dry	0.20	0.20	2.00	2.50	0.010	0.055	52.8	28.5
	Wet	0.03	0.16	2.51	3.51	0.013	0.044	49.7	29.5
2	Dry	0.30	0.10	2.00	2.00	0.125	0.016	49.3	46.5
	Wet	0.16	0.07	2.50	3.00	0.079	0.021	63.9	32.4
3	Dry	0.30	0.20	2.00	2.00	0.171	0.086	57.1	72.3
	Wet	0.13	0.18	3.20	3.50	0.041	0.044	55.4	66.0
4	Dry	0.20	0.10	2.00	1.00	0.137	0.224	95.8	78.7
	Wet	0.20	0.26	2.00	1.50	0.107	0.204	94.3	83.6
5	Dry	0.40	0.60	2.50	2.00	0.091	0.303	97.9	63.5
	Wet	0.13	0.40	3.50	2.51	0.067	0.136	91.7	65.5
6	Dry	0.20	0.10	2.00	1.00	0.152	0.141	127.4	109.5
	Wet	0.19	0.13	1.50	1.00	0.131	0.127	101.4	96.4

The stress/strain curves of samples (dry and wet) in the longitudinal and transverse directions are shown in Figures 3 and 4.

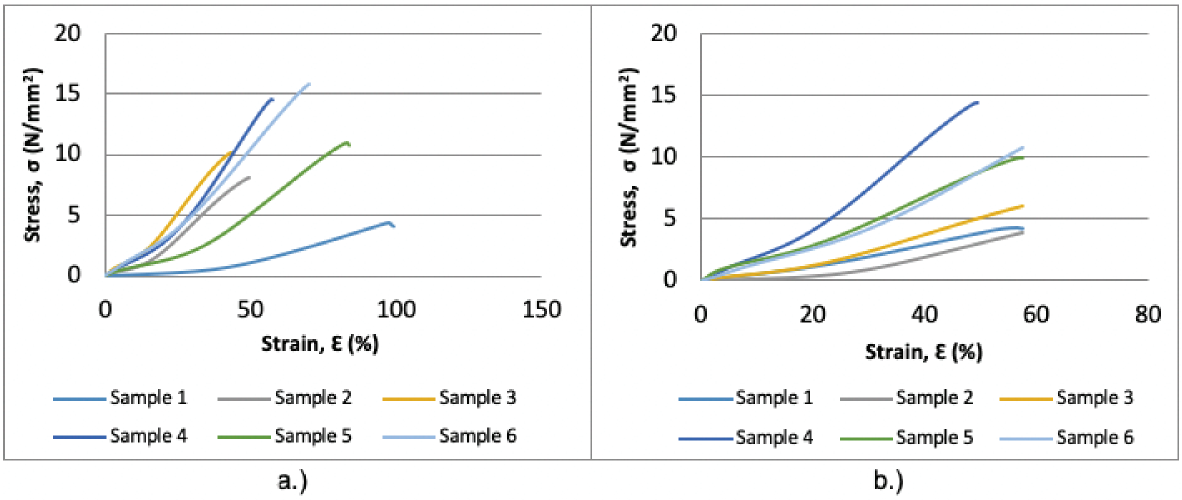


Figure 3. Stress/strain curves of samples in the longitudinal (a) and transverse (b) directions (dry condition)

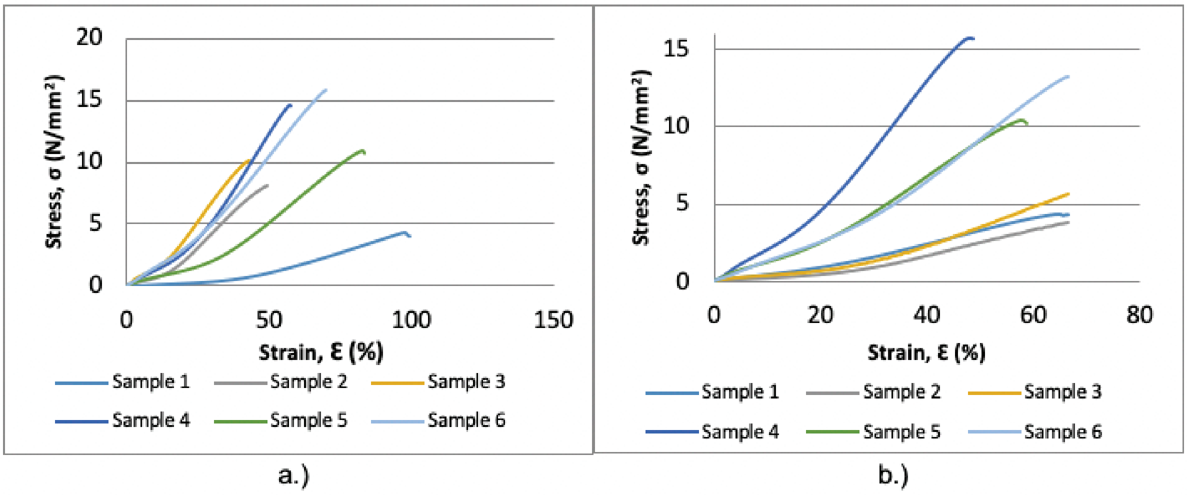


Figure 4. Stress/strain curves of samples in the longitudinal (a) and transverse (b) directions (wet condition)

accompanying strain of 2.5% (Table 3). Sample 5 is bonded with needle and chemical bonding technique has the mass (233.2 g/m^2), thickness (1.656 mm), and the fourth largest diameter of fibers (19.05 μm) and consequently the highest stress and strain at elastic limit, mostly because it is the only one which is bonded with the combination of two bonding techniques.

All other samples analyzed express similar stress at elastic limit from 0.2 to 0.3 N/mm^2 in the dry and from 0.03 to 0.2 N/mm^2 in the wet condition.

In the transverse direction, the highest stress at elastic limit in the dry and wet conditions was also obtained on sample 5 which is bonded with all bonding techniques (0.6 N/mm^2 in the dry condition and 0.4 N/mm^2 in the wet condition).

All samples, except sample 6 with the highest mass (379.7 g/m^2) and thickness (2.081 mm), have lower stress and higher strain at elastic limit in the wet condition in comparison to dry condition. The main reason for that lies in the lower friction between the *web fibres* directions for all samples analyzed decrease in the wet condition, which means that they are more deformable in the wet condition.

The results for the work of rupture were within expectations, with the highest work of rupture obtained on sample 6 in both the directions.

As summarized in Table 3, the work of rupture increases with the increasing mass and thickness of samples. In the wet condition, the work of rupture decreases for all samples. The decrease of work of rupture in the wet condition is the highest for sample 6 (about 20%).

From the results of viscoelastic properties of the samples analyzed, it can be concluded that the mass and thickness and also the diameter of fibers which affect on the specific surface area value, have important influence on the mechanical properties of nonwoven geotextiles.

4.4. Compressive creep

The compressive creep results obtained after 60 and 1440 minutes of loading with pressures of 25 , 100 , and 500 kPa are shown in Figure 5.

The results of compressive creep after 60 minutes of loading show the highest differences under the pressure of 500 kPa, while under pressures of 25 and 100 kPa smaller differences were measured (Figure 5). The highest compressive creep (1.22 mm) under the pressure of 500 kPa was measured on sample 6, which has the highest mass and thickness and also very high diameter of fibers (24 μm). Samples 1–5 with the lower mass and thickness exhibit lower compressive creep, which is between 0.5 and 1.22 mm. Samples 3 and 5 have, similar to sample 6, higher compressive creep than 1 mm (Figure 6). Very small differences were measured under pressures of 25 and 100 kPa. There were very small differences of the compressive creep of the samples in the dry and wet conditions.

The compressive creep measurements after 1440 minutes (24 hours) of loading show the highest compressive creep on sample 6 in the dry and wet conditions (1.28 mm). Samples 3 and 5 also have compressive creep higher than 1 mm. The results also show that the compressive creep of the samples under the pressure of 500 kPa increases to a maximum for about 2.5% during the test (24 hours). The differences of compressive creep measured after 60 and 1440 minutes are barely noticeable.

There were small differences in the compressive creep of samples tested in the dry and wet conditions. The highest decrease in the compressive creep was measured on sample 3 after 60 minutes and 24 hours of loading under the pressure of 500 kPa (16.1%). Sample 3 is needle bonded and has the highest diameter of fibers (33.15 μm) and also the second largest thickness, which has an impact on the highest compressive creep reduction.

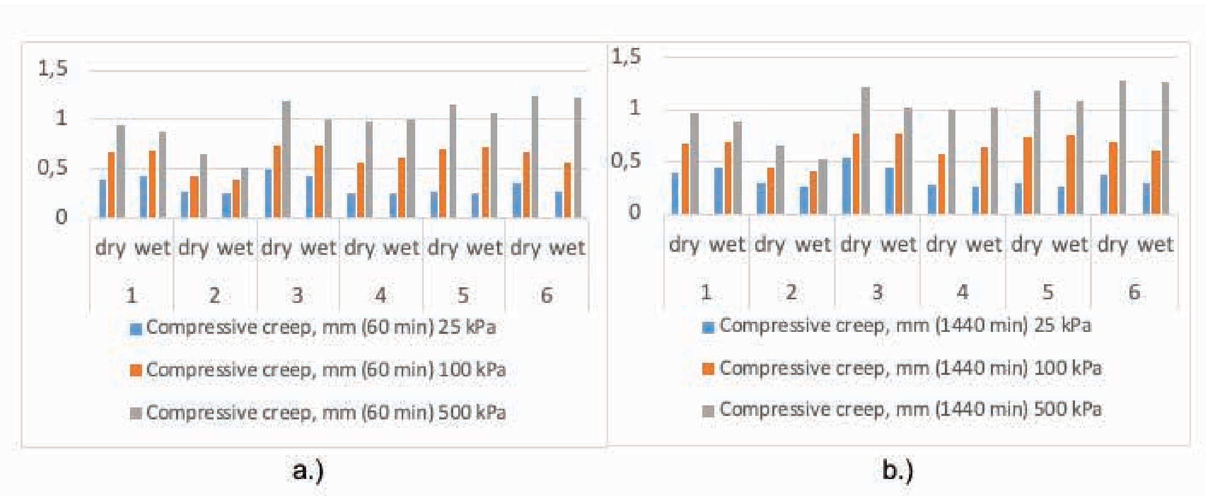


Figure 5. Compressive creep after 60 minutes (a) and 1440 minutes of compressive loading (b)

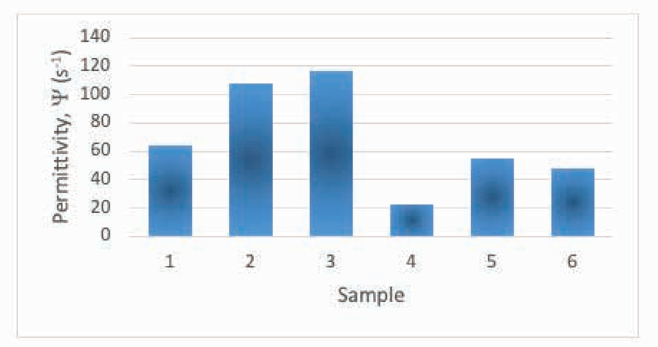


Figure 6. Permittivity of tested samples

4.5. Water permittivity

The results of permittivity of tested geotextiles are shown in Figure 6.

The highest permittivity was measured on sample 3, which is needle bonded and has the highest opening size (98 μm; Table 2). From the permittivity test results, it is also evident that samples with mass lower than 200 g/m² (samples 1–3) have higher permittivity than samples 4–6 with higher mass. The results also show that the samples with higher permittivity have higher opening size (from 65.4 to 98 μm; Table 2), while samples with lower opening size (lower than 63 μm) have lower permittivity.

4.6. Results of opening area percentage

The results of the percentage of opening area measured on intact samples and samples after water permeability and compressive creep tests are listed in Table 4.

The highest opening area was measured on samples 2 and 3 which are both mechanically bonded with masses of 129.7 and 181.4 g/m², respectively, and express the highest diameter of fibers (more than 30 mm). Lower opening area was measured with samples 1, 4, 5, and 6, which have masses in the range from 148.1 to 379.9 g/m². Samples 1, 4, 5, and 6 have also lower diameter of fibers (from 12.73 to 24 mm) than samples 2 and 3 with lower masses (129.7 g/m² [sample 2] and 181.4 g/m² [sample 3]). On the contrary, samples 2 and 3 have the highest diameter of fibers (30.6 mm [sample 2] and 33.1 mm [sample 3]) and the highest permittivity.

Table 4. Results of the percentage of opening area of the samples analyzed

Sample	Percentage of opening area, Op (%)		
	Original	After water permeability analysis	After compressive creep analysis
1	8.60	9.7	3.6
2	11.80	8.2	3.8
3	11.30	5.4	2.6
4	8.00	4.5	3.1
5	7.30	4.1	3.1
6	7.9	4.3	3.1

The analysis of opening area results shows that the percentage of opening area decreases after water permeability and compressive creep tests have been carried out (Table 5). This decrease is expected and statistically significant ($p < 0.05$).

4.7. Statistical analysis

4.7.1. Statistical analysis of breaking stress results

Statistical analysis shows that the breaking stress strongly correlates with the mass and the thickness of the analyzed samples ($R^2 > 0.75$). On the contrary, the correlation between the diameter of fibers and the breaking stress of samples is weak ($R^2 < 0.5$) as summarized in Table 6.

Statistical analysis (ANOVA) and the correlation matrix confirms that the mass increase ($R^2 > 0.82$) and thickness of samples ($R^2 > 0.71$) affect the increase in samples breaking stress, in the dry and wet conditions ($p < 0.05$). Statistical analysis (ANOVA) confirms that the diameter of fibers has significant influence ($p < 0.05$) and also very weak correlation with breaking stress and strain of the samples in the dry and wet conditions.

Statistical analysis (ANOVA) also shows that the external factors (dry and wet condition) do not have significant influence on the breaking stresses ($p > 0.05$).

4.7.2. Statistical analysis of breaking strain results

Statistical analysis (ANOVA) shows that the diameter of fibers, thickness, and mass express the significant influence on the breaking strain in both directions in the dry and wet conditions ($p < 0.05$).

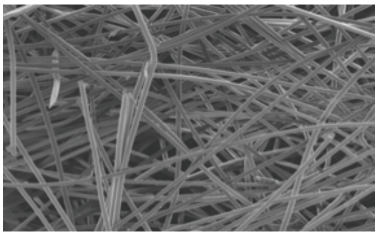
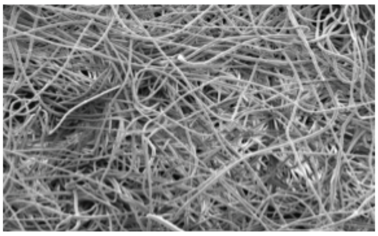
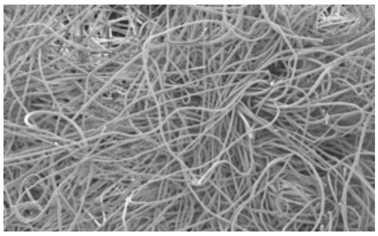
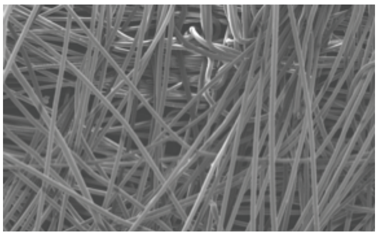
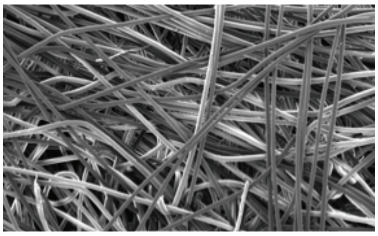
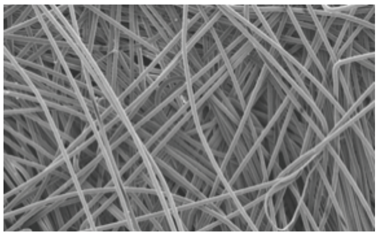
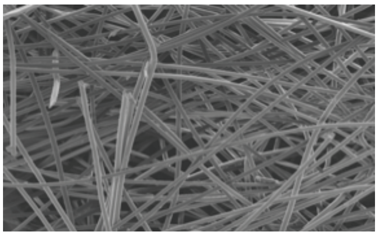
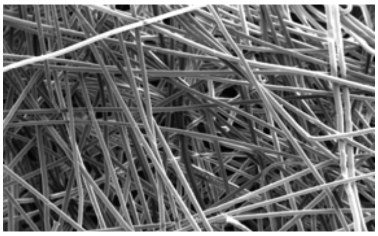
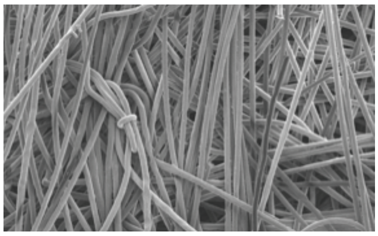
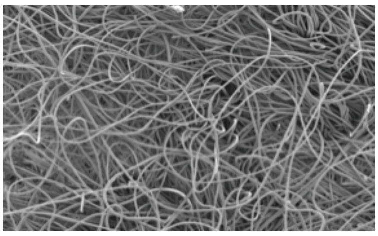
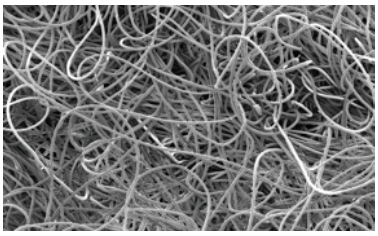
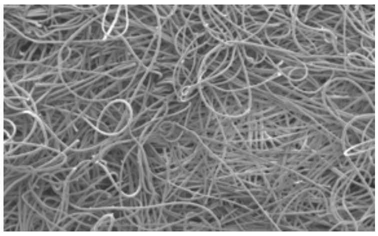
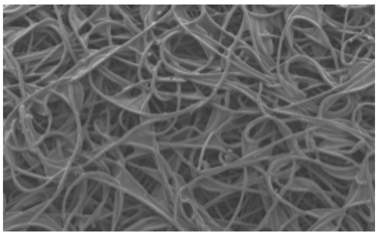
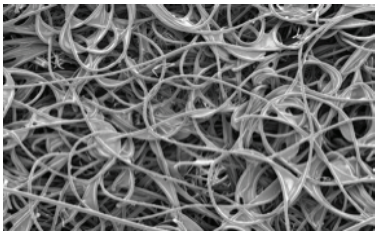
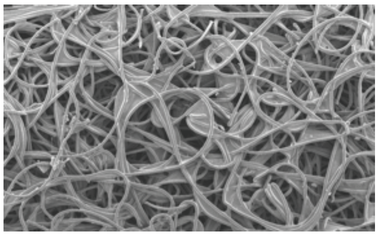
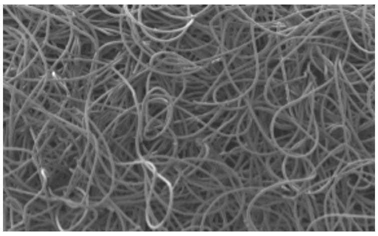
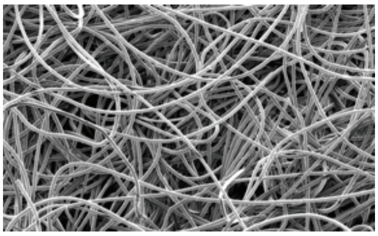
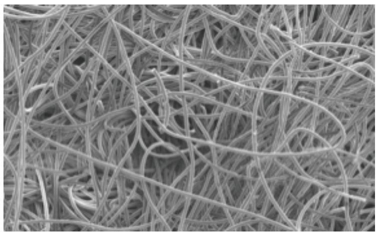
Statistical analysis (ANOVA) also shows that the external factors (dry and wet conditions of the sample) have not significant influence on the breaking strains of the samples analyzed ($p > 0.05$). On the contrary, the correlation matrix confirmed a strong positive correlation only between the diameter of fibers and breaking strain in the transverse direction ($R^2 > 0.9$).

4.7.3. Statistical analysis of the results of viscoelastic properties

Statistical analysis (ANOVA) shows that mass and thickness express significant influence on the stress and strain at elastic limit, elastic modulus, and the work of rupture ($p < 0.05$). Statistical analysis (ANOVA) also shows that the differences in stress and strain at elastic limit, elastic modulus, and work of rupture in both tested directions in the dry and wet conditions are not statistically significant ($p > 0.05$). Statistically, it means that the condition of sample (dry or wet) does not affect viscoelastic parameters.

Results of correlation analysis show a strong correlation ($R^2 > 0.8$) between the mass and thickness of samples and stress and strain at elastic limit, especially in the longitudinal

Table 5. Microscope view of initial samples and after water permeability and compressive creep tests

Sample	Original	After water permeability analysis	After compressive creep analysis
	Magnification 50×		
1			
2			
3			
4			
5			
6			

direction. That is valid for the samples tested in the dry and wet conditions.

The correlation between the diameter of fibers and stress and strain at elastic limit in the longitudinal is undefined. On the contrary, the correlation coefficient between the diameter of fibers and stress and strain at elastic limit is strongly negative ($R^2 > -0.8$). It means that the increase in the diameter of fibers decreases the stress and strain at elastic limit in the transverse direction.

The correlation between mass and thickness of samples and elastic modulus and work of rupture moves between weak ($R^2 > 0.5$) and strong ($R^2 > 0.8$). On the contrary, in the most cases, a weak negative correlation ($R^2 < -0.5$) was found

Table 6. Correlation matrix (diameter of fibers, thickness and mass of the sample, breaking stress)

	FD	T	M	BS_L_dry	BS_L_W	BS_T_dry	BS_T_wet
FD	1.00						
T	0.15	1.00					
M	−0.29	0.85	1.00				
BS_L_dry	−0.08	0.87	0.89	1.00			
BS_L_W	−0.05	0.81	0.83	0.99	1.00		
BS_T_dry	−0.37	0.78	0.90	0.95	0.93	1.00	
BS_T_wet	−0.45	0.71	0.86	0.92	0.91	0.99	1.00

BS_L_dry, breaking stress, dry, longitudinally; BS_T_dry, breaking stress, dry, transverse; BS_L_wet, breaking stress, wet, longitudinally; BS_T_wet, breaking stress, wet, transverse; FD, diameter of fibers; M, mass; T, thickness

between the diameter of fibers and elastic modulus and work of rupture.

4.7.4. Statistical analysis of compressive creep results

Statistical analysis (ANOVA) shows that the diameter of fibers and mass and thickness of samples have significant influence on the compressive creep after 60 minutes and 24 hours of compressive loading with pressures of 25, 100, and 500 in the dry and wet conditions ($p < 0.05$). ANOVA also confirms that the differences of the compressive creep in the dry and wet conditions after 60 minutes and 24 hours are not statistically significant ($p > 0.05$).

The correlation matrix confirms a strong positive correlation between the mass and thickness and compressive creep of samples, especially in the wet condition under the compressive load of 500 kPa.

4.7.5. Statistical analysis of water permittivity results

Statistical analysis (ANOVA) shows that the diameter of fibers and mass of sample have significant influence on the water permittivity ($p < 0.05$), while the thickness of sample shows no significant influence on water permittivity.

The correlation matrix (Table 7) shows that very strong correlation ($R^2 > 0.9$) exists between the diameter of fibers and water permittivity, while only moderate positive correlation ($R^2 > 0.64$) exits between the opening size and water permittivity which is unexpected. The reason for that probably lies in the opening size results of samples 4–6 that express lower opening size, lower than 63 μm, and the exact value in that case is unknown. The correlation coefficient between the mass and water permittivity is moderate and negative ($R^2 > -0.67$).

Table 7. Correlation matrix between the structural parameters (diameter of fibers, mass, thickness, opening size, and water permittivity)

	FD	T	M	OS	P
FD	1.00				
T	0.15	1.00			
M	-0.29	0.85	1.00		
OS	0.46	-0.13	-0.47	1.00	
P	0.90	-0.25	-0.67	0.64	1.00

FD, fiber diameter; M, mass; OS, opening size; P, water permittivity; T, thickness of sample

5. Conclusions

Based on the research of the influence of structural parameters of nonwoven geotextiles on the separation and filtration properties, the following conclusions could be drawn:

- The results of breaking stress of analyzed nonwoven geotextiles are expected. With the increase in mass and thickness, the breaking stress of the samples (samples 4–6) is the highest in the dry and wet conditions. On the contrary, the breaking strain of samples 4–6 is the lowest. The diameter of fibers has a statistically significant influence on the breaking stress and strain level mainly because of the higher specific surface area of the thinner fibers of samples 4–6 (diameter of fibers moves from 12 to 24 μm). Samples, which are mechanically bonded (needled) or produced in combination with thermal bonding technique, express in general higher breaking stress and lower breaking strain level.

- Samples 4–6, with higher mass and thickness, which depend on the bonding technique, express higher elastic modulus and the work of rupture in the dry and wet conditions. Sample 5, which is needle and chemical bonded, has the highest stress and strain at elastic limit in comparison to other samples. The diameter of fibers does not have significant influence on all mentioned parameters mainly because of the lower value of the stress and strain at elastic limit. The differences between the viscoelastic parameters of samples in the dry and wet conditions are not statistically significant.

- The increase in mass, thickness, and diameter of fibers increases the compressive creep. The diameter of fibers shows only moderate (weak) positive correlation with compressive creep. The reason for that lies in the structure of fibers which have accentuated length according to their diameter. The highest compressive creep (1.22 mm) was measured on sample 6, which has the highest mass and thickness and the third largest diameter of fibers. Statistical analysis confirmed that the differences in the compressive creep between the samples tested in the dry and wet conditions are not statistically significant.

- The results also show that after 24 hours the compressive creep of samples under the pressure of 500 kPa is maximized by about 2.5%. Therefore, the differences in compressive creep after 24 hours are not statistically significant.

- Water permeability (water permittivity) of nonwoven geotextiles is very important for filtration. The permittivity test results confirmed that mechanically bonded (needled and spunlace) samples with masses lower than 200 g/m^2 (samples 1–3) express higher permittivity (from 63.8 to 116.9 s^{-1}) than the samples 4–6 which are needled, thermally and chemically bonded, and have higher masses. The statistical analysis shows that the diameter of fibers and sample mass have statistically significant influence on permittivity, while the thickness of the sample shows insignificant influence on permittivity. The fibers with higher diameter have consequently lower specific surface area which affects the higher percentage of opening area. Consequently, the samples with the lowest opening size (63 μm) have the lowest permittivity.

- The diameter of fibers, mass, and thickness show a statistically significant influence on the percentage of opening area of tested nonwoven geotextiles and consequently on filtration properties (permittivity). Samples 2 and 3, which are both mechanically bonded with masses 129.7 g/m^2 (sample 2) and 181.4 g/m^2 (sample 3) and the diameter of fibers more than 30 μm and consequently lower specific surface area, express the highest opening area percentage (around 11%).

Based on the abovementioned conclusions, it could be claimed that higher mass and thickness and combination of bonding techniques (the combination of mechanical, thermal, and chemical bonding) mostly increase the breaking stress and viscoelastic parameters such as stress at elastic limit, elastic modulus, the work of rupture, and compressive creep behavior, while the condition of the sample (dry or wet) and diameter of fibers have a statistically insignificant effect on the mechanical properties of nonwoven geotextiles.

The research also confirmed that mechanically bonded (needled and spunlace) nonwoven geotextiles with mass lower than 200 g/m^2 express higher water permittivity. In such cases, the diameter of fibers and mass have a statistically important influence on permittivity, while the sample thickness shows insignificant influence. The samples with the lowest opening size have consequently the lowest water permittivity.

The research confirmed that the bonding technique and structural properties significantly influence the separation and filtration properties of nonwoven geotextiles. Further important finding is that the differences in the mechanical properties (viscoelastic properties, compression creep after 60 minutes and 24 hours) between the samples in the dry and wet conditions are insignificant.

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