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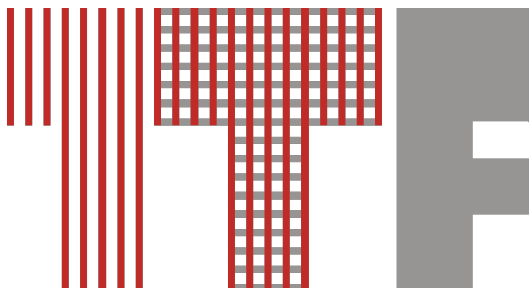
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Influence of Pressure on Water Permeability and Characteristic Opening Size of Nonwoven Geotextiles

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Abstract

Nonwoven geotextiles manufactured by mechanical carding process and bonding by needling process are investigated in this paper. Part of the samples was additionally bonded by thermal calendaring process. Sampling was conducted according to the standard for geotextile with certain modifications. The samples were tested for water permeability perpendicular to the plane of samples using loads of 2, 20 and 200 kPa. Characteristic opening size of geotextiles was tested using sieving method. Research shows that different applied pressures significantly change structure and properties i.e. thickness and water permeability normal to the plain under load of geotextile.

Keywords: Polypropylene; Polyester; Calendaring; Water Permeability with Load; AOS

1 Introduction

Nonwoven textile is a fabric composed of individual fibres mutually bonded by a certain process. For nonwoven productions different types of fibres are used. The choice of fibre depends on the desired properties of the nonwovens and the cost of of the chosen fibres [1, 2]. Artificial fibres are the raw materials for the production of nonwovens, and it dominates the world market, representing about 90% of the total fibre consumption. World consumption of synthetic fibres for nonwoven production is about 63% of polypropylene fibres, 23% of polyester fibres, 8% of viscose fibre, 2% of polyacrylic fibres, 1.5% of polyamide fibres and 3% of other special fibres [2]. From the above, it is evident that in the nonwoven industry, the three most processed types of fibres are polypropylene, polyester and viscose. Regarding to the previously mentioned samples, those made of polypropylene and polyester were chosen for this study.

Geotextile as drainage and filtration materials is used in earthworks for last 30 years. The functions provided by nonwovens in geotechnical applications include drainage, filtration, separations

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and soil protection, particularly in its stability and erosion control [3]. Nonwoven geotextiles are very permeable and are compressible materials. When under stress, as the thickness of the geotextile reduces, so does its coefficient of permeability and pore dimensions [4]. Where the filtration function of geotextile is of paramount importance, water permeability perpendicular to the plane is relevant, and the in-plane water permeability of geotextiles may be of greater significance, in the application of drainage function [5-7]. Therefore water permeability of geotextiles normal to the plane is one of the main parameters that can be used to characterize and compare geotextiles [8]. For separation, filtration and drainage-in-the-plane, the pore sizes, pore geometry and percentage open area of the geotextiles in the direction of flow are critical. Mentioned functions of geotextiles are dominated by their pore space characteristics, as these control the size of particles and the amount of water that may be transmitted through them [8-12].

Their usage is mostly successful, since design is based on an empirical criterion which sometimes differ from the real ones. Such practices can lead to erroneous predictions of the design. The biggest problem in practice is caused by force impact on the geotextile and the influence of external conditions during installation [13]. The issue of actual conditions and their impact on the geotextile has not been studied much [14, 15]. This paper studies the influence of pressures on the thickness (or porosity, which is associated with the structure of geotextiles), water permeability under pressures and characteristic opening size of geotextiles. The goal of this paper is to investigate performance of polypropylene and polyester needle punched and polypropylene calendered geotextile in use.

2 Experimental

The samples investigated in this paper are nonwoven geotextiles manufactured by mechanical carding process, bonded by needling process. Part of the samples was additionally bonded by thermal calendaring process. Two groups of samples were made from polypropylene and polyester fibres and bonded by needling. The third group of samples were polypropylene fibres bonded with needling and also additionally bonded with calendaring. Mass per unit area for all groups of samples is in the range between 200 and 500 g/m². The total numbers of tested samples were 12.

The sampling was conducted according to the standard for geotextile sampling HRN EN ISO 9862: 2005 with certain modifications [16]. The standard where modified, where detailed sampling plan has been made as well as number of measurements per sample was increased. For the sampling, a metal plate sizing of 60.3 cm x 60.8 cm with holes has been used for all specimens of the planned testing. The metal plate was moved according to 5-end satin weave with step of 3, in order to avoid repetition of sampling in longitudinal and transverse direction for the same type of testing. According to the standard for sampling, 10% of the sample width has to be avoided from the edges (40 cm). The sampling is presented in Fig. 1.

The thickness was tested according to the standard for geosynthetic consisting of single layers HRN EN ISO 9863-1: 2005 at specified pressures of 2, 20 and 200 kPa [17]. Density of geotextiles was calculated from mass per unit area and thickness values, using following equation:

$$\rho_{\text{geo.}} = \frac{M}{t} \quad (1)$$

where ρ is the density [g/cm³], M is the mass per unit area [g/cm²] and t is the thickness [cm]. For

calculating density of nonwoven geotextiles, values of thickness measured by specified pressures of 2, 20 and 200 kPa was used. Porosity of geotextiles were calculated from the ratio of geotextile density and fibre density and expressed in percentage.

$$P = 1 - \frac{\rho_{\text{geo.}}}{\rho_{\text{fib.}}} \quad (2)$$

where P is the porosity of geotextiles [%], $\rho_{\text{geo.}}$ is the density of geotextile [g/cm^3] and $\rho_{\text{fib.}}$ is the density of fibre [g/cm^3], whereas polypropylene fibre density is $0.91 \text{ g}/\text{cm}^3$. The investigated nonwoven geotextile samples and their properties are given in Table 1.

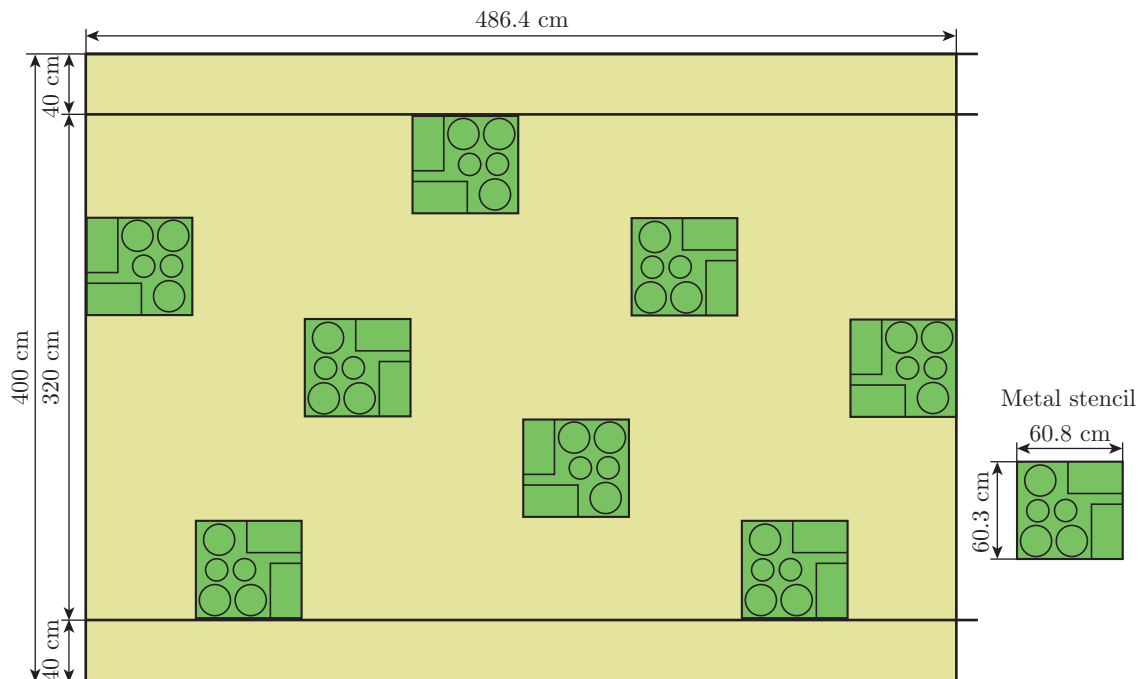


Fig. 1: Sampling of the geotextile samples

2.1 Water Permeability Normal to the Plain under Load

Water permeability through the medium (geotextile) is the amount of water that flows through it per unit time. Nonwoven geotextiles were tested for water permeability perpendicular to the plane of samples using loads of 2, 20 and 200 kPa, according to E DIN 60500-4: 1997 [18]. Measurements were carried out in laminar flow (hydraulic gradient=1) to examine water flow through the sample (Q , cm^3/s) or the volume of water that passed through the sample at a given time. Sample area was 19.635 cm^2 and water flow was measured through the thickness of the “package sample”. “Package sample” is composed of a number of samples whose total thickness should be approximately 4 cm [19–21]. Since the viscosity of the liquid effects the flow, during measurement the temperature of the water should be kept at $20 \pm 2^\circ\text{C}$. For this reason, during measurement water temperature is recorded and based on that registered temperature the correction of calculated hydraulic gradient was made. Permittivity (ψ) is determined by the following equation:

$$\psi = \frac{k_{v, \text{const.}}}{t} \quad (3)$$

Table 1: The investigated properties of the geotextiles

Samples	Mark	Mass per unit area [g/m ²]	Tested and calculated properties
Polypropylene needle punched geotextile	PP_200	199	Thickness was tested according to the standard for geosynthetic consisting of single layers HRN EN ISO 9863-1: 2005 at specified pressures of 2, 20 and 200 kPa
	PP_250	234	
	PP_300	276	
	PP_450	417	
Polypropylene needle punched geotextile additionally bonded with calendaring	PP-C_200	218	Water permeability perpendicular to the plane using loads of 2, 20 and 200 kPa was tested according to E DIN 60500-4: 1997 Characteristic opening size of geotextiles was tested according to HRN EN ISO 12956: 2001 Density of geotextiles was calculated Porosity of geotextile was calculated
	PP-C_250	275	
	PP-C_300	309	
	PP-C_450	465	
Polyester needle punched geotextile	PET_200	210	
	PET_250	251	
	PET_300	299	
	PET_450	490	

where $k_{v,const.}$ is the hydraulic conductivity [m/s], v is the flow velocity [m/s] and i is the hydraulic gradient. Hydraulic gradient and laminar flow are defined by the following expression:

$$i = \frac{h}{t_n} = 1 \quad (4)$$

where and i is the hydraulic gradient, h is the pressure difference of the sample [cm] and t_n is the thickness of the “sample package” [cm] where thickness of the “package specimen” is determined by expression of t_n :

$$t_n = n \cdot t \quad (5)$$

where t_n - thickness of “sample package” in cm [≈ 4 cm], n is the number of samples in “package sample” and t is the thickness of each sample in “package sample” [cm]. Hydraulic conductivity defined by following equation:

$$k_{v,const.} = \frac{Qt_n}{Ah} \cdot \frac{R_T}{129} \quad (6)$$

where $k_{v,const.}$ is the water flow rate in 10^{-3} [m/s], Q is the water flow [cm³/s], t_n is the thickness of sample package [cm], A is the testing sample area that was 19, 635 [cm²], h is the pressure difference in Pa, and R_T is the correction factor for the hydraulic conductivity of water at a temperature of $T=20^\circ\text{C}$. Correction factor of hydraulic conductivity (R_T) is determined by the following equation:

$$R_T = \frac{\eta_T}{\eta_R} \quad (7)$$

where η_R is the water dynamic viscosity at a reference temperature ($T=20^\circ\text{C}$) [mPas] and η_T is the water dynamic viscosity at the measured temperature T [mPa]. η_T is calculated by the following expression:

$$\eta_T = \frac{1,779}{1 + 0,03368T + 0,00022099T^2} \quad (8)$$

where T is the measured water temperature [$^\circ\text{C}$].

2.2 Characteristic Opening Size – AOS

Characteristic opening size of geotextiles was tested according to HRN EN ISO 12956: 2001 [22]. The principle of the method is based on the particles size distribution of different grades of granular material (usually glass pellet or sand) after sieving through a geotextile without applying the load. The characteristic opening pore size corresponds to the specific size of granular material passed through the sample after sowing. This method gives the approximate values of the maximum diameter of the samples pore through which soil particles can pass [23]. Value O_{90} is the size of the opening that allows particle sizes d_{90} to pass through the geotextile or geotextile similar product. The d_{90} is a particle size, where 90% of the particle mass pass through a sieve meshes. The cumulative percentage of sieving material is in function with sieve sizes, and it presents graphically the sieving curve of the determinate O_{90} . Fig. 2 shows the distribution curves of the pore sizes of needle punched polypropylene with 450 g/m^2 tested in this paper. Fig. 2 presents individual curves of the three tested needle punched polypropylene geotextiles of 450 g/m^2 . The individual curves present cumulative percentage of sieving material in function of sieve sizes. From the three individual curves, the mean curve was calculated. From the mean curve O_{90} was determined. Where the horizontal line of 90% of passage of grain through a sieve and the vertical line of sieve size meets on mean curve characteristic opening size of geotextiles is reading [22, 24].

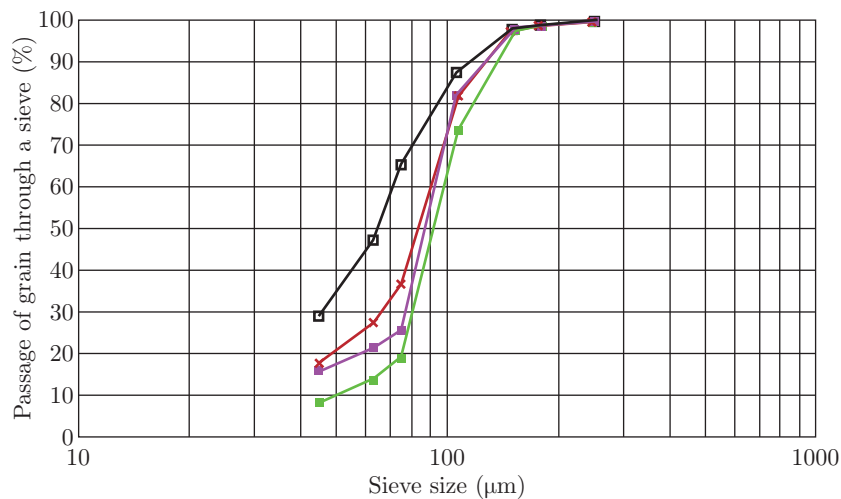


Fig. 2: Distribution curve of the characteristic opening size of needle punched polypropylene sample with 450 g/m^2

3 Results and Discussion

The results of the mass per unit area, thickness of geotextile measured under pressures of 2, 20 and 200 kPa, and the calculated porosity are given in Table 1. Porosity was calculated using Equation 2. The largest thickness has a needle punched polypropylene, followed by needle punched polyester and calendered polypropylene geotextiles at all applied pressures (Table 2, Fig. 3). The standard error bars shows that there are no significant deviations from the empirical regression values of thickness. The calendering process which uses pressure and heat for bonding causes length decrease and diameter increase of fibres within geotextiles. The result for the fibre changes within geotextiles are shown in the increase of mass per unit area.

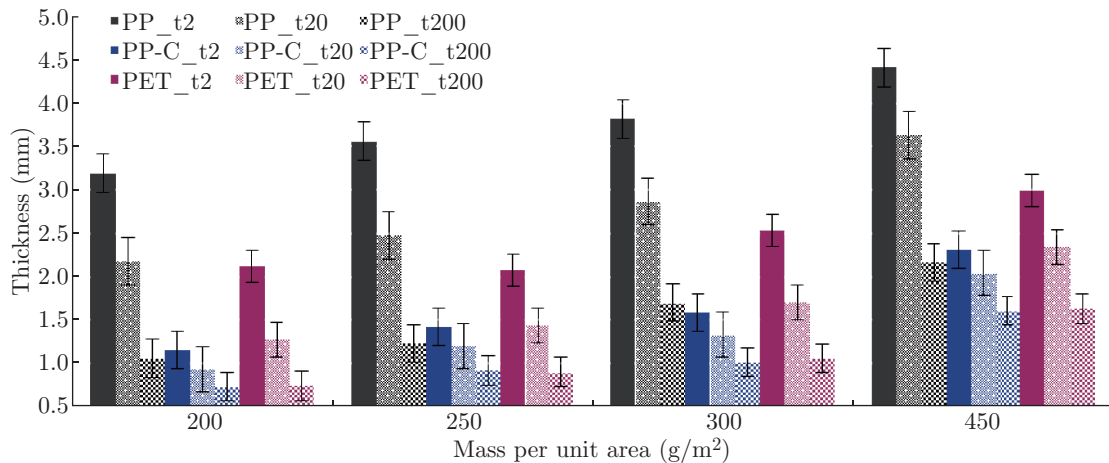


Fig. 3: Change of thickness on nonwoven geotextiles caused by applied pressures in dependence of mass per unit area with associated standard error bars

The increase of mass per unit area caused by calendaring process ranges from 8.7 to 14.9%. After calendaring process, the thickness of the polypropylene geotextiles decreased (Table 2, Fig. 3).

The thickness of needle punched polyester geotextiles are lower than needle punched polypropylene geotextiles; even the mass per unit area is higher for polyester geotextiles.

The decrease of thickness caused by applied pressures (between 2 and 20 kPa) is the highest for needle punched polypropylene, followed by polyester and finally polypropylene geotextiles additionally bonded with calendaring (Table 2, Fig. 3 and 4). The percentage of the geotextile thickness decrease ranges as follows: the needle punched polypropylene amounts from 50.8 to 66.8 %; the needle punched polyester amounts from 45.7 to 65.1 % and the calendared polypropylene amounts from 30.3 to 36.5% (Fig. 3).

All groups of geotextiles at all applied loads show differences in thickness. Based on the obtained results it can be concluded that the change in the average thickness at all pressures are greater for the needle punched polypropylene geotextiles than for calendared polypropylene geotextiles.

The calendaring process uses temperature and pressure for the additional bonding of geotextiles where certain compression of material occurs. The calendaring process results to a more compact structure of calendared geotextiles. That is the reason for the less thickness decrease under applied pressures of the calendared polypropylene geotextiles. It can be concluded that calendared geotextiles have controlled and predictable compressibility, i.e. structure which will not significantly change in the practical application. Decrease of the needle punched polyester geotextile thickness (55.6%) caused by pressures (between 2 and 200 kPa) is smaller than for needle punched polypropylene geotextiles (60.1%). Less change of the needle punched polyester geotextiles thickness can be explained with their smaller porosity, i.e. geometry and properties of polyester fibres (Table 2, Fig. 3 and 4).

Dependence of nonwoven geotextiles thickness and applied pressures are in the form of an exponential regression line with high exponential coefficient of regression (Fig. 3). The standard error bars showing there are no significant deviations from the empirical regression values.

Dependence of characteristic opening size of nonwoven geotextiles and mass per unit area with associated standard error bars is shown on Fig. 8. The standard error bars shows that there are no significant deviations from the empirical regression values of characteristic opening size of

nonwoven geotextiles. The largest characteristic opening size has needle punched polypropylene geotextiles, followed by needle punched polyester and polypropylene calendered geotextiles with smallest characteristic opening size (Table 3).

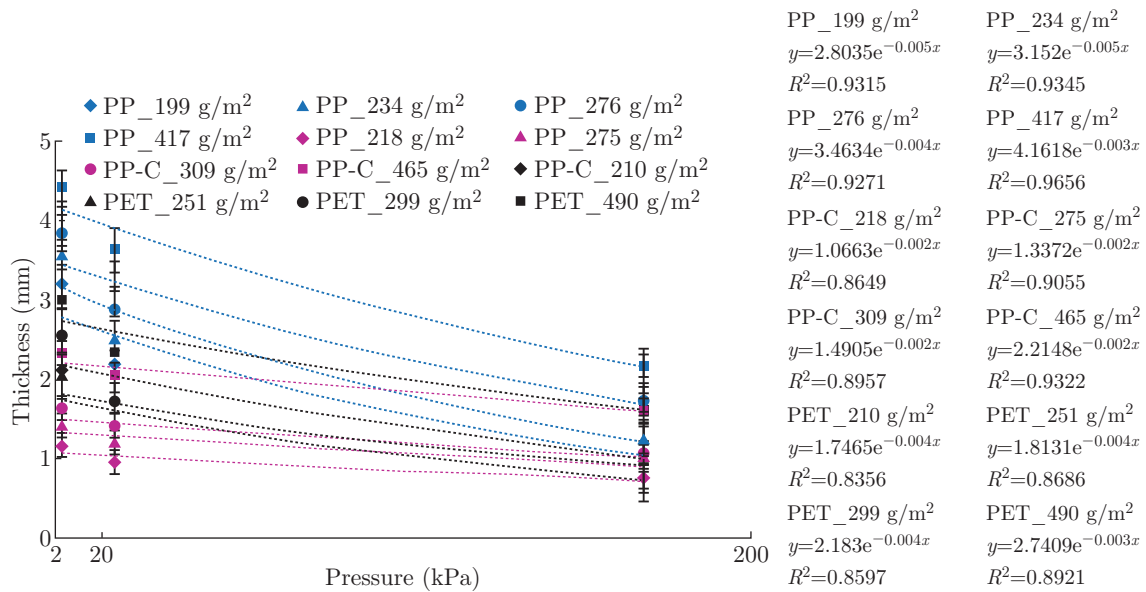


Fig. 4: Change of nonwoven geotextiles thickness under applied pressures

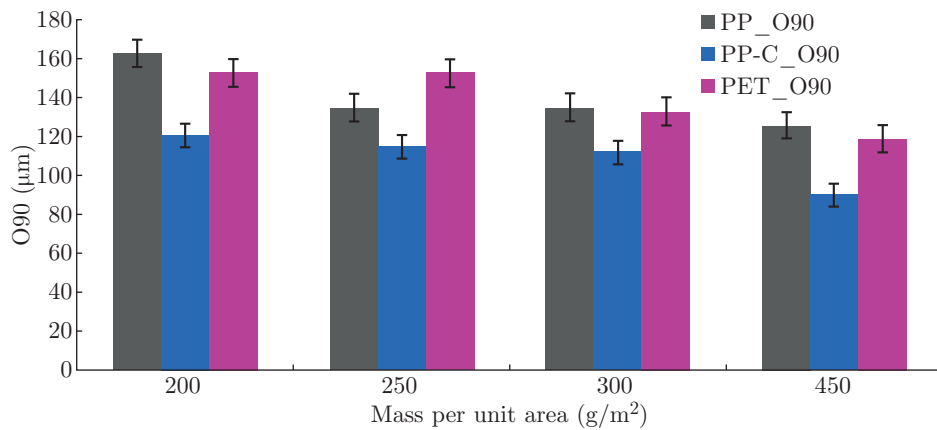


Fig. 5: Dependence of characteristic opening size of nonwoven geotextiles and mass per unit area with associated standard error bars

The influence of the different types of fibres on geotextile characteristic opening pore sizes is apparent. The needle punched polyester geotextiles has smaller pore sizes compared with the needle punched polypropylene geotextiles. After the calendering process, the pore size of calendered polypropylene geotextiles decreased by 23% (Table 3).

The narrow range of porosity for calendered geotextiles compared with the needle punched polypropylene and needle punched polyester geotextiles is shown on Fig. 6. Linear coefficient of correlation is highest for calendered polypropylene geotextiles. The standard error bars shows that there are no significant deviations from the empirical regression values of water permeability of tested geotextiles, where the lowest deviation from the empirical regression values is for calendered geotextiles.

Table 2: Geometric properties of nonwoven geotextile

Samples	Geometric parameters						
	M_A [g/m ²]	t_2 [mm]	t_{20} [mm]	t_{200} [mm]	P_2 [%]	P_{20} [%]	P_{200} [%]
PP	200	3.19	2.18	1.06	0.9315	0.8999	0.7941
	250	3.56	2.48	1.23	0.9277	0.8962	0.7905
	300	3.82	2.87	1.70	0.9205	0.8942	0.8214
	450	4.41	3.63	2.17	0.8962	0.8091	0.7889
	\bar{x}	3.73	2.72	1.49	0.9190	0.8748	0.7987
	CV	11.79	19.85	28.86	0.0138	0.0380	0.0132
	SD	0.44	0.54	0.43	1.4971	4.3432	1.6568
	SEM	0.22	0.27	0.22	0.0069	0.0190	0.0066
PP_C	200	1.15	0.94	0.73	0.7918	0.7453	0.6720
	250	1.42	1.20	0.92	0.7870	0.7480	0.6713
	300	1.59	1.33	1.02	0.7864	0.7446	0.6670
	450	2.31	2.04	1.61	0.7788	0.7495	0.6825
	\bar{x}	1.57	1.33	1.03	0.7860	0.7468	0.6732
	CV	27.39	39.1	32.04	0.0046	0.0020	0.0057
	SD	0.43	0.52	0.33	0.5911	0.2645	0.8470
	SEM	0.21	0.26	0.16	0.0023	0.0010	0.0029
PES	200	2.12	1.28	0.74	0.8912	0.8199	0.6886
	250	2.08	1.44	0.90	0.8676	0.8088	0.6941
	300	2.53	1.71	1.06	0.8702	0.8080	0.6902
	450	3.00	2.34	1.63	0.8207	0.7700	0.6699
	\bar{x}	2.43	1.69	1.08	0.8624	0.8017	0.6857
	CV	15.23	23.67	31.48	2.9903	2.3552	1.3615
	SD	0.37	0.40	0.34	0.0258	0.0189	0.0093
	SEM	0.19	0.20	0.17	0.0129	0.0094	0.0047

Where: M_A – mass per unit area [g/m²], t_2 – thickness under load of 2 kPa [mm], t_{20} – thickness under load of 20 kPa [mm], t_{200} – thickness under load of 200 kPa [mm], P_2 – porosity under load of 2 kPa [%], P_{20} – porosity under load of 20 kPa [%], P_{200} – porosity under load of 200 kPa [%], \bar{x} – mean value of thickness [mm] and porosity [%], CV – coefficient of variation [%]; SD – standard deviation of thickness [mm] and porosity [%], SEM – standard error of thickness [mm] and porosity [%]

Change of water permeability under applied pressures in relation to mass per unit area is shown in Fig. 7. The highest water permeability is visible for needle punched polypropylene, followed by polyester needle punched geotextiles and polypropylene needle punched geotextiles as the lowest (Fig. 7). The standard error bars shows that there are no significant deviations from the empirical regression values of water permeability of tested geotextiles, where the lowest deviation from the empirical regression values is for calendered geotextiles.

Table 3: Hydraulic properties of nonwoven geotextile

Samples	Hydraulic parameters				
	M_A [g/m ²]	k_{v2} 10 ⁻³ [m/s]	k_{v20} 10 ⁻³ [m/s]	k_{v200} 10 ⁻³ [m/s]	O_{90} [μm]
PP	199	6.03	3.53	1.66	163
	234	5.39	3.86	1.39	135
	276	3.99	3.58	1.40	135
	417	3.18	2.40	0.59	126
	\bar{x}	5.08	3.31	0.88	142
	CV	22.11	16.87	43.84	9.80
	SD	1.12	0.56	0.39	13.92
	SEM	0.56	0.28	0.19	6.96
PP_C	218	0.88	0.76	0.20	121
	275	1.07	0.98	0.41	115
	309	0.85	0.83	0.23	112
	465	1.12	0.98	0.24	90
	\bar{x}	0.91	0.80	0.25	110
	CV	12.84	11.97	32.86	10.65
	SD	0.12	0.10	0.08	11.72
	SEM	0.06	0.05	0.04	5.86
PES	210	4.67	3.13	2.01	153
	251	3.04	2.16	2.01	153
	299	2.84	1.96	0.52	133
	490	1.86	1.62	0.52	119
	\bar{x}	3.10	2.22	1.27	139
	CV	32.55	25.27	58.66	10.34
	SD	1.01	0.56	0.75	14.38
	SEM	0.50	0.28	0.37	7.19

Where: M_A – mass per unit area [g/m²], k_{v2} – hydraulic conductivity under load of 2 kPa [10⁻³ m/s], k_{v20} – hydraulic conductivity under load of 20 kPa [10⁻³ m/s], k_{v200} – hydraulic conductivity under load of 200 kPa [10⁻³ m/s], O_{90} – characteristic opening pore size [μm], \bar{x} – mean value for hydraulic conductivity [10⁻³ m/s] and for characteristic opening pore size [μm], CV – coefficient of variation [%], SD – standard deviation for hydraulic conductivity [10⁻³ m/s] and characteristic opening pore size [μm], SEM – standard error for hydraulic conductivity [10⁻³ m/s] and for characteristic opening pore size [μm]

By increasing applied pressures, water permeability decreased for all tested samples. The greatest decrease occurred between 20 and 200 kPa, since this level of pressures leads to a significant change of geotextiles thickness and porosity (Table 2, Fig. 7 and 8).

The greatest reductions in water permeability were caused by the applied pressures from needle punched polypropylene geotextiles followed by calendered polypropylene geotextiles (Table 3, Fig. 8).

Water permeability of calendered polypropylene geotextiles decreased (approx. 10%). The

interval of geotextile water permeability change was due to the applied pressure. The advantage of the calendaring process is that water permeability of calendered polypropylene geotextiles will decrease in the narrow interval compared to only needle punched polypropylene geotextiles, which is important in practical use. Polyester geotextiles has the smallest reduction of water permeability (Table 3, Fig. 8).

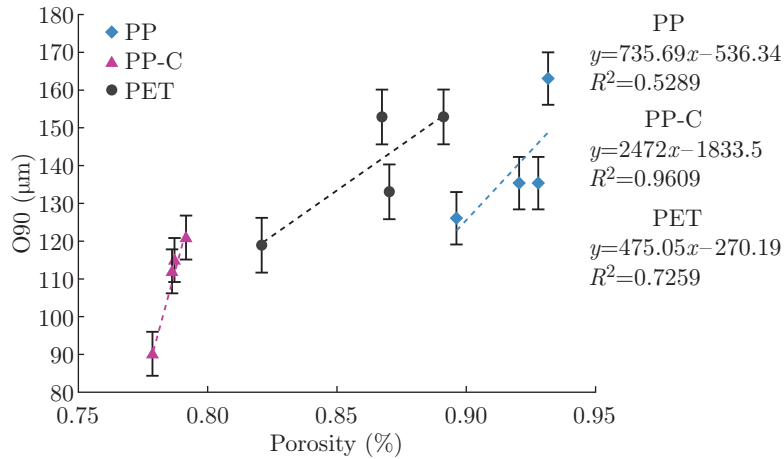


Fig. 6: Relation of geotextile characteristic opening pore size and porosity

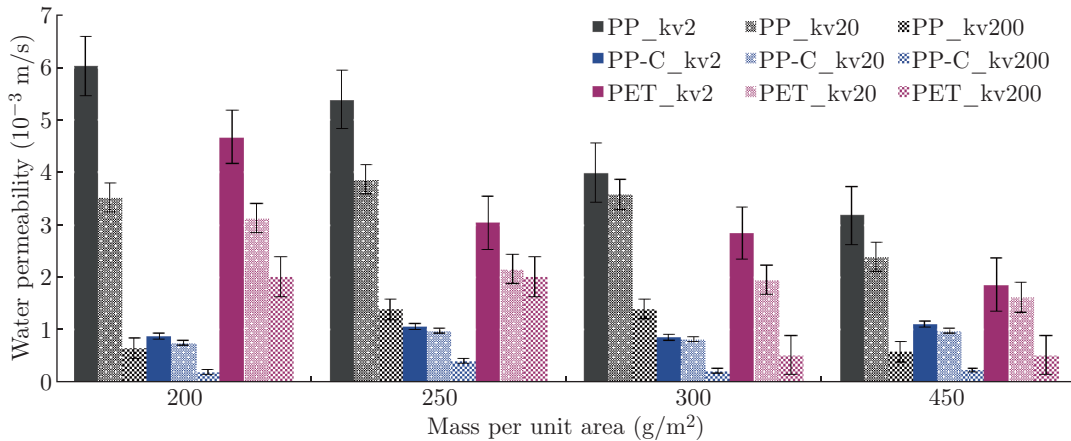


Fig. 7: Change of water permeability on nonwoven geotextiles caused by applied pressures in dependence of mass per unit area with associated standard error bars

The needle punched polyester geotextiles thickness under applied pressures decreased less than the needle punched polypropylene geotextiles (60% for polypropylene and 56% for polyester), whereas the polyester porosity decreased by almost double (13% for polypropylene and 21% for polyester geotextiles) (Table 3, Fig. 8 and 9). This difference of changing thickness and porosity under applied pressures between needle punched polypropylene and needle punched polyester geotextiles is caused by the different type of fibres. It can be concluded that the type and properties of fibres within geotextile have significant influenced the decrease of water permeability under applied pressures.

Dependence of water permeability under applied pressures and porosity of the geotextiles are in the form of the exponential regression line with high exponential coefficient of regression (Fig. 9).

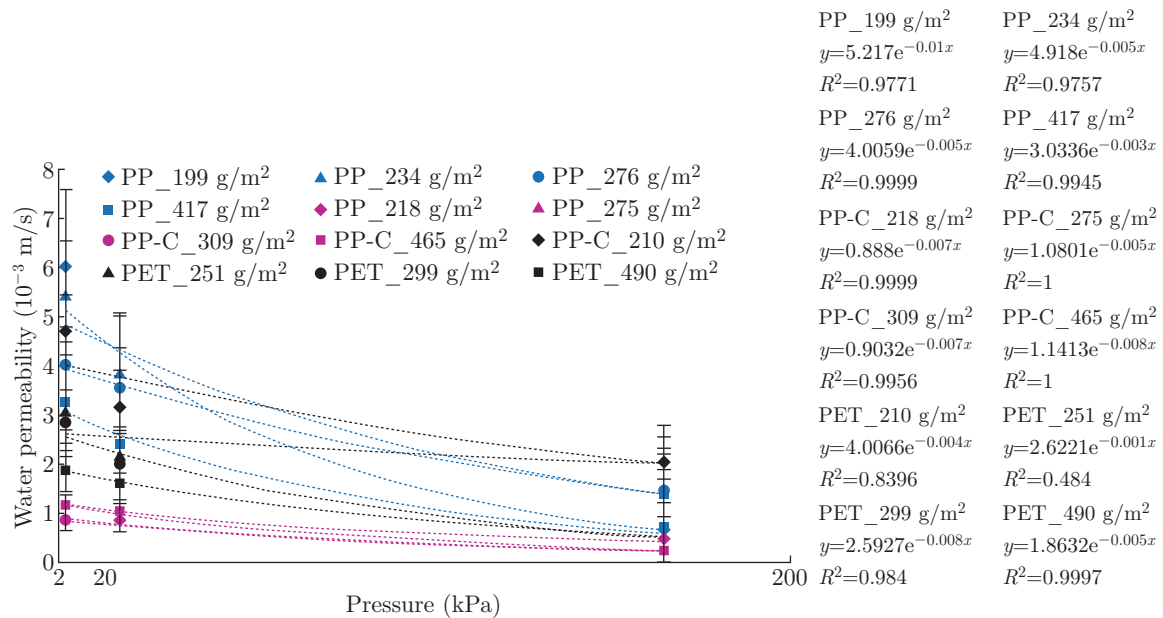


Fig. 8: Change of nonwoven geotextiles water permeability under applied pressures with associate exponential regression line and R-squared value

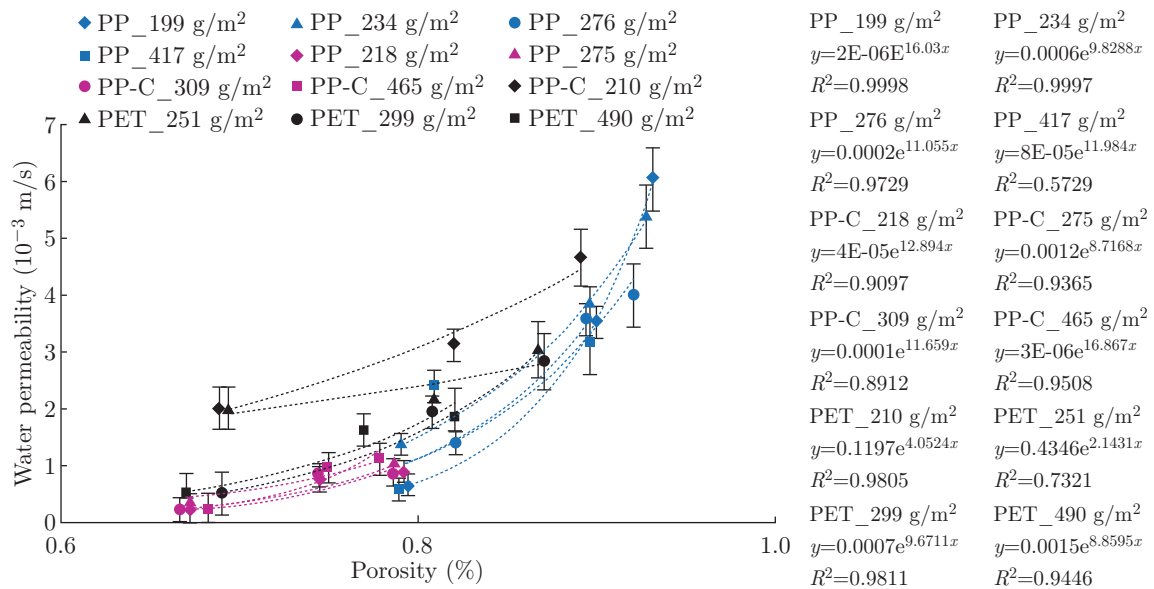


Fig. 9: Dependence of water permeability under applied pressures and porosity of nonwoven geotextiles

4 Conclusion

The calendaring process uses pressure and heat for the bonding which causes length decrease and diameter increase of fibres within geotextiles. The result of fibres changes within geotextiles is shown as increase of mass per unit area. The calendaring process gives a more compact structure of calendered geotextiles which is the reason of less thickness decrease under applied pressures of the calendered polypropylene geotextiles. It can be concluded that the calendered geotextiles have controlled and predictable compressibility, i.e. structure which will not significantly change in the practical application.

The influence of the different types of fibres, namely polypropylene and polyester fibres on thickness change is noticeable. The needle punched polyester geotextiles have less change of thickness under applied pressures which can be explained with their smaller porosity, i.e. geometry and properties of polyester fibres.

The calendaring process decreases the characteristic opening sizes of needle punched polypropylene geotextiles. It is apparent that the different type of fibres has an influence on geotextile characteristic opening pore sizes, where the needle punched polyester geotextiles has smaller pore sizes comparing with the needle punched polypropylene geotextiles.

By increasing applied pressures, water permeability decreased for all tested samples, where the greatest decrease occurred between 20 and 200 kPa. This level of pressures leads to a significant change of geotextiles thickness and porosity. The advantage of the calendaring process is that water permeability of calendered polypropylene geotextiles decreased in the narrow interval compared to only needle punched polypropylene geotextiles, which is important in practical use.

There is a noticeable difference of behaviour polyester and polypropylene needle punched geotextiles under applied pressures. The type of fibres within geotextile has significant influence on decrease of water permeability under applied pressures.

Conducted research shows that the external pressure impact significantly changes structure and properties (thickness and water permeability perpendicular to the plane) of geotextile.

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References

- [1] [Hwang G-S, Hwu B-L, Hsing W-H, Lu C-K. Manufacturing effects on the hydraulic properties of needlepunched nonwoven geotextiles. *Geotextiles and Geomembranes*, 1998; 16: 355-363.](#)
- [2] Nonwoven fabrics. Albrecht W, Fuchs H, Kittelmann W, editors. Weinheim: Wiley-VCH, 2003. p. 9-11.
- [3] Handbook of Nonwovens. Russell SJ, editor. Cambridge: Woodhead Publishing Ltd, 2007. p. 578-581.
- [4] Palmeira EM, Gardoni MG. Drainage and filtration properties of non-woven geotextiles under confinement using different experimental techniques. *Geotextiles and Geomembranes*, 2002; 20: 97-115.
- [5] [Balasubramanian N, Rakshit AK, Patel VK. Opening size and Water permeability of Nonwoven Geotextiles. *The Indian Textile Journal*, 1991; 6: 26-32.](#)
- [6] [Pak A, Zahmatkesh Z. Experimental study of geotextile's drainage and filtration properties under different hydraulic gradients and confining pressures. *International Journal of Civil Engineering*, 2011; 9: 97-102.](#)

- [7] [Palmeira EM, Gardoni MG. Drainage and filtration properties of non-woven geotextiles under confinement using different experimental techniques. *Geotextiles and Geomembranes*, 2002; 20: 97-115.](#)
- [8] Dierick W, Leyman N. Temperature correction for water permeability determination of geotextiles. *Proceedings of the Fifth International Conference on Geotextiles, Geomembrans and Related Products*, Singapore: 1994. p. 845-848.
- [9] [McGown A, Andrawes KZ. An approach to laboratory testing of geotextiles. *QJ eng Geol London* 1982; 15: 177-185.](#)
- [10] *Geosynthetics in civil engineering*. Sarsby RW, editor. Cambridge: Woodhead Publishing in Textiles, 2007. p. 27-29.
- [11] *Geosynthetics in civil engineering*. Van Santvoort GPTM, editor. Rotterdam: AA Balkema Publishers, 1995. p. 153-170.
- [12] Giroud, J.P. Development of criteria for geotextiles and granular filters. Prestigious Lecture, *Proceedings of the 9th International Conference on Geosynthetics*, Guarujá, Brazil, 2010; 1: 45-64.
- [13] [Carvalho R, Figueiro R, Soutinho F. Mechanical properties of needle-punched nonwovens for geotechnical applications. *International Conference on Engineering UBI2011*, Covilhã, Portugal, 2011. p. 1-7.](#)
- [14] [Palmeira EM, Gardoni MG. The influence of partial clogging and pressure on the behaviour of geotextiles in drainage systems. *Geosynthetics International* 2000; 7: 403-431.](#)
- [15] [Aydilek AH, Oguz SH, Edil TB. Constriction size of geotextile filters. *Journal of Geotechnical and Geoenvironmental Engineering* 2005; 131: 28-38.](#)
- [16] HRN EN ISO 9862: 2005 Geosynthetics-Sampling and preparation of test specimens.
- [17] HRN EN ISO 9863-1: 2005 Geosynthetics-Determination of thickness at specified pressures-Part 1: Single layer.
- [18] E DIN 60500-4: 1997 Testing of geotextiles-Part 4: Determination of permeability of geotextiles normal to their planes under load of constant hydraulic head difference.
- [19] HRN EN ISO 12956: 2001 Geotextiles and geotextile-related products-Determination of the characteristic opening size.
- [20] [Iryo T, Kerry Rowe R. On the hydraulic behavior of unsaturated nonwoven geotextiles. *Geotextiles and Geomembranes* 2003; 21: 381-404.](#)
- [21] [Stormont J, Henry K, Evans T. Water retention functions of four nonwoven polypropylene geotextiles. *Geosynthetics International* 1997; 4: 661-672.](#)
- [22] [Bhatia SK, Smith JL. Geotextile Characterization and Pore-Size Distribution: Part II. A Review of Test Methods and Results. *Geosynthetics International* 1996; 3: 155-180.](#)
- [23] Fluet JE Jr. Geotextile testing and the design engineer. *Proceedings of the ASTM Symposium on Geotextile Testing and the Design Engineer*, Los Angeles, 1985. p. 1-7.
- [24] [Dierickx W. Opening size determination of technical textiles used in agricultural applications. *Geotextiles and Geomembranes* 1999; 17: 231-245.](#)