ASPECTS REGARDING THE COMPRESSION RESISTANCE OF GEOSYNTHETICS USED IN BUILDING MUNICIPAL SOLID WASTE LANDFILLS
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ASPECTE PRIVIND REZISTENȚA LA COMPRESIUNE A GEOSINTETICELOR UTILIZATE ÎN CONSTRUCȚIA DEPOZITELOR DE DEȘEURI MUNICIPALE

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ABSTRACT

Choosing the physical characteristics of geosynthetics used in the construction of municipal waste landfills must be carried out according to the functions they must fulfil - sealing, filtration, protection. Since the geomembranes are subjected to significant compressive stress, and tearing by sticking against hard objects, experimental determinations are necessary to be made both in laboratory and in-situ for the determination of its resistance over time. The protection of the geomembranes shall be carried out, usually with geotextile, and its characteristics must also be established by experimental determinations. The results of measurements of the laboratory tests carried out both on a membrane of HDPE and a nonwoven PP geotextile, and the values of their deformation according to the pressing force led to the identification of the best correlate experimental data by regression curve analysis are presented in this paper.

REZUMAT

Alegerea caracteristicilor fizice ale geosinteticelor utilizate în construcția depozitelor ecologice de deșeuri menajere trebuie efectuată în funcție de funcțiile pe care trebuie să le îndeplinească – etanșare, filtrare, protecție. Având în vedere că geomembranele sunt supuse unor solicitări importante de compresiune, dar și de rupere prin înțepare cu obiecte contondente, este necesar a fi efectuate determinări experimentale, atât în laborator, cât și in-situ, pentru stabilirea rezistenței acestora în timp. Protecția geomembranelor se realizează, de obicei, cu geotextil, iar caracteristicile acestuia trebuie, de asemenea, stabilite prin determinări experimentale. În lucrare se prezintă rezultatele unor determinări de laborator efectuate, atât pe o geomembrană din HDPE, cât și pe un geotextil nețesut din PP, iar valorile deformației acestora în funcție de forța de apăsare au condus la identificarea prin analiză de regresie a curbei de variație care corelează cel mai bine datele experimentale.

INTRODUCTION

In the municipal landfill construction, but also for land improvement works, geosynthetics are materials with a wide use and can perform several functions: sealing, filtration, drainage, protection, stability slopes etc. *(Giroud et al, 1992; Koerner R.M., 1998; Mandal J.N., 2014; Richardson and Zhao, 2009; Zornberg and Christopher, 1999)*.

Geosynthetics are materials made from polymers or polymer additives with various components for characteristics diversification and properties improvement. They can replace many conventional materials, with the same performance, showing guaranteed uniform properties over the entire surface. They are easy to apply, with reduced labour and costs, contributing to significant savings in materials and energy, but they also reduce the impact of construction on the environment. They also can work under load immediately after installation, and their price is comparable to the price of conventional materials.

However, geosynthetics are sensitive to contact with traditional materials (hard and tough) because they are, in general, thin and lightweight materials, thus can be easily damaged due to the specialized structure, which makes them usable only for the purpose for which they were designed and tested in laboratory and field. They are often sensitive to UV radiation and presents an aging phenomenon more pronounced than traditional materials *(Narejo et al, 1996*).

The main polymers used for obtaining geosynthetics are:

- polypropylene (PP, 0.895 – 0.910 g/cm^3, melting temperature 155 – 175°C);
- low (LDPE), medium (MDPE) and high density (HDPE) polyethylene;
- polyester (PES, density 1.38 g/cm^3, shrinkage in hot water 5–9%);
- polyamide (PA);
- polyvinyl chloride (PVC, 1.38–1.55 / 1.16–1.35 g/cm^3).

Of all geosynthetics, geomembranes and geotextiles are largely employed in municipal landfills construction and beyond. In general, geomembranes act as a barrier (seal), while geotextiles have the role to protect the membrane or act as a drainage *(Wilson-Fahmy et al, 1996; Narejo et al, 1996; Koerner et al, 1996; Rowe R.K., 2012)*.

Fig. 1 – Examples of geomembrane and protection geotextile utilisation in the construction of waste landfills

The protective properties, thickness and type of material that geosynthetics are made off, significantly require a rational design method.

In the works mentioned above, the authors present the theoretical approach of thinning the membrane in contact with the rounded edges of the stone layer beneath it, using the theory of membrane tension and results of laboratory experiments using a special apparatus and stone or truncated push con, during short and long periods of time. Theoretical study conducted for the geomembrane with or without geotextile protection shows the need for a material protection when membrane is applied. Furthermore, the authors show that the characteristics of the protuberant object and of the protection material are important in designing structures with geomembranes *(Wilson-Fahmy et al, 1996)*.

In the experiments, high density polythene (HDPE) with 1.5 mm thickness (yield load 23 kN/m, 18% yield strain, puncture load 0.44 kN according to ASTM D 4885) and various non-woven textile, with different specific weights (per unit area) were tested. Using the results of the testing program, a design methodology for determination of the geotextile's necessary specific mass to geomembrane's puncture protection for a certain safety coefficient or vice versa has been developed *(Narejo et al, 1996)*. Thus, it was found that the puncture resistance of geomembranes increases with increasing mass per unit area of the geotextile protection for all of the prominent bodies heights. Increasing the protuberances height decreases the geomembrane's perforation resistance, regardless of geotextile protection's specific mass, puncture resistance is inversely proportional to the square of the protrusion's height. Particularly important is the protuberance's shape, the puncture resistance of subrounded stones or rounded was two, respectively four times higher than the puncture resistance using the cornerstones (sharp). Also, the puncture resistance of a geomembrane laid on a bed of stones is two times higher than laid on the isolated rocks of the same height with the previously ones. At the same time, the membrane puncture resistance decreases with time and the time impact is more pronounced with decreasing specific weight of the geotextile protection and increase the protuberance height underneath the membrane.

The maximum permissible pressure on the geomembrane, depending on the height of a single protuberance underneath the geomembrane may be determined by the relation:

$$p_{adm} = 450\ \frac{M_{gtx}}{H^2} \geq 50\ \text{kPa} \tag{1}$$

where M_{gtx} is the specific mass of the geotextile protection (g/m^2) and H is protuberance's height (mm).

Minimum pressure of 50 kN corresponds to a failure pressure of a 1.5 mm thickness HDPE geomembrane, without any protective material *(Narejo et al, 1996)*.

Therefore, the puncture resistance of the geomembrane determines required characteristics of the protection material, both in the case of coatings and to the construction of the landfill's bed foundation. Tests carried out in accordance with ASTM D5514, on a 1 mm PVC geomembrane lead to failure water pressure much higher than for the 1.5 mm HDPE membrane, (*Marcotte et al, 2009*). PVC geomembrane offers better advantages as a hydraulic barrier in designing leachate collection system, including puncture resistance is the most important. For example, under hydrostatic conditions, the disposition of PVC geomembrane on layers of 20 - 100 mm packed angular gravel has presented a decline of the minimum failure pressure when the particle diameter increases. The bottom line is that abrasion is probably the predominant factor for puncture resistance of PVC geomembranes. The authors' recommendation is to test the geomembranes with real granular materials for test results to be as conclusive as possible. Also, testing and analysis of protective geotextiles demonstrated that the use of a non-woven needle-punched geotextile with a specific mass of 270 g/m^2 increase of the burst pressure of the 1 mm PVC membrane up to 800 kPa, which is ten times higher than the value of allowable pressure calculated for a 1.5 mm HDPE membrane protected with a 550 g/m^2 geotextile. Moreover, the HDPE membrane requires a direct contact only with fine granular materials to prevent punctures while PVC geomembrane may be used over layers of coarser granular material.

Other works covering the geomembranes and geotextiles resistance are HAXO and Kamp, 1990; Peggs I., 1990; Koerner, 1998 Blond and Elie, 2006; Jones and Clarke, 2007; Bacas et al, 2011; Lin et al, 2012 ; Qiang et al, 2013; Voicu Gh., 2016.

The results of pre-compression tests performed on a HDPE geomembrane without geotextile protection to relatively small pressure forces (up to 20 N), but also on a geotextile protection using pressure devices with cylindrical or spherical roller bearings in order to identify mathematical relationship between loading force and deformation, both for loading and unloading, and energy hysteresis are presented in this paper. Experimental data are tested with known mathematical relationships and best mathematical equation that correlates the experimental data is established.

MATERIALS AND METHODS

Measurements were carried out in the specialized laboratory of the Department of Biotechnical Systems from the University "Politehnica" of Bucharest, materials used in the experiments being purchased from Chiajna waste landfill, Ilfov County. The thickness of the HDPE geomembrane was 3 mm, and the unit weight of the geotextile was 500 g/m^2 and thickness 4.7 mm, obtained from non-woven polypropylene yarns.

Laboratory bench (shown in Figure 2) has been specially adapted for the compression experimental tests on geosynthetics used, being provided with a rigid support plate (8), on which were placed 100 × 100 mm square tiles of geosynthetics material (9). The hold itself (10) has been either a roll steel cylinder with a diameter of 8.1 or 11.3 mm, or metal spherical ball with a 13.4 mm diameter, reinforced with a top plate (3'), which comes into contact with an external digital comparator (5). Between the metal plates (3 and 3') there is a connecting rod (12) connected to a flexible wire (11) passing over two pulleys (6) and a balancing weight (7) to the left end. On the top plate (3') can be placed different weights (4), whose pressure force is transmitted through the stiffened chain elements (3'-12-3-10) on the geosynthetics material (10). For puncture resistance of the membrane was used a 20° metal tip cone, using the same device.

Experimental determinations were performed by reading the geosynthetics material strain at different weights added to the stand's upper plate (3'), until a predefined force is reached and also on return, by reducing the pressure weight. No determinations were made at discharge for a longer relaxation time of the material. Relaxation time was estimated at about one minute (how long until weights were unloaded from the upper plate (3').

Further on, the values obtained for the material deformation were processed in analysis program Microcall Origin, by plotting data points and regression analysis with different mathematical functions and the regression curves were plotted to identify the best variation law of deformation as a function of pressure force (at loading - unloading).

Mathematical functions used in the regression analysis are:

- linear function:

$$y = ax + b \tag{2}$$

- power function:

$$y = a\, x^b \quad (3)$$

- exponential function:

$$y = a + b \cdot \exp\left(-\frac{x}{c}\right) \quad (4)$$

- logistic function:

$$y = b + \frac{a-b}{1+\left(\frac{x}{c}\right)^d} \quad (5)$$

Estimated calculations were made to determine the energy dissipated in the material.

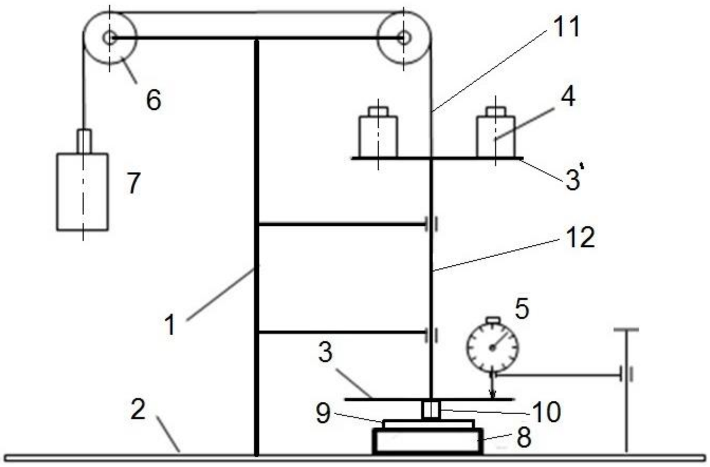

Fig. 2 – Principled layout of the laboratory stand used in experimental tests

1 – support with rod and arms; 2 – support plate; 3 – pressure plate; 4 – weights; 5 – external comparator; 6 – pulleys; 7 – balancing weight; 8 – rigid metal plate; 9 – geomembrane (geotextile); 10 – pressure ball (or roller); 11 – connection thread; 12 - rod

RESULTS

The results obtained for values of deformation according to the strength load are shown in Table 1.

Table 1

Geosynthetics deformation values (in mm) for several different devices and pressure forces

Mass, N	4.7 mm PP Geotextile				Geomembrane HDPE, 3 mm							
	8.1 mm Roll		11.3 mm Roll		8.1 mm Roll		11.3 mm Roll		ϕ 13.4 mm Ball		Edge	
	Pressure	Return	Pressure	Return	Pressure	Return	Pressure	Return	Pressure	Return	Pressure	Return
0	0	1.05	0	1.40	0	0.02	0	0.14	0	0.21	0	0.67
1.36	0.01	1.23	0.16	1.60	0	0.04	0.01	0.21	0.01	0.30	0.09	0.72
2.68	0.04	1.30	0.42	1.70	0.01	0.05	0.04	0.24	0.04	0.38	0.15	0.76
3.99	0.25	1.38	0.65	1.80	0.02	0.05	0.06	0.28	0.08	0.43	0.24	0.78
5.31	0.41	1.43	0.82	1.85	0.03	0.06	0.08	0.31	0.15	0.48	0.32	0.79
6.64	0.60	1.49	0.98	1.90	0.04	0.06	0.10	0.33	0.21	0.52	0.40	0.80
7.96	0.75	1.52	1.15	1.94	0.05	0.07	0.14	0.34	0.29	0.55	0.46	0.81
9.27	0.81	1.54	1.25	1.97	0.05	0.07	0.17	0.35	0.34	0.58	0.51	0.81
10.58	1.01	1.55	1.39	1.99	0.06	0.08	0.22	0.35	0.39	0.62	0.54	0.81
11.91	1.09	1.58	1.50	2.00	0.06	0.08	0.24	0.36	0.45	0.63	0.58	0.81
13.21	1.20	1.60	1.60	2.01	0.07	0.08	0.27	0.37	0.49	0.63	0.61	0.81
14.55	1.32	1.61	1.69	2.02	0.07	0.09	0.29	0.37	0.55	0.65	0.68	0.81
15.88	1.40	1.62	1.78	2.03	0.08	0.09	0.32	0.38	0.58	0.65	0.74	0.81
17.18	1.49	1.62	1.93	2.03	0.09	0.10	0.34	0.38	0.63	0.66	0.78	0.81
18.50	1.62	1.62	2.03	2.03	0.09	0.10	0.36	0.39	0.64	0.67	0.81	0.81
19.51					0.10	0.10	0.38	0.39	0.66	0.67		
20.28					0.10	0.10	0.39	0.39	0.67	0.67		

The curves of geosynthetics deformation, on loading and unloading, depending on the pressure force were plotted based on experimental data from Table 1. The arrangement of data points, together with the variation curves drawn by regression analysis are shown in Figures 3 and 4.

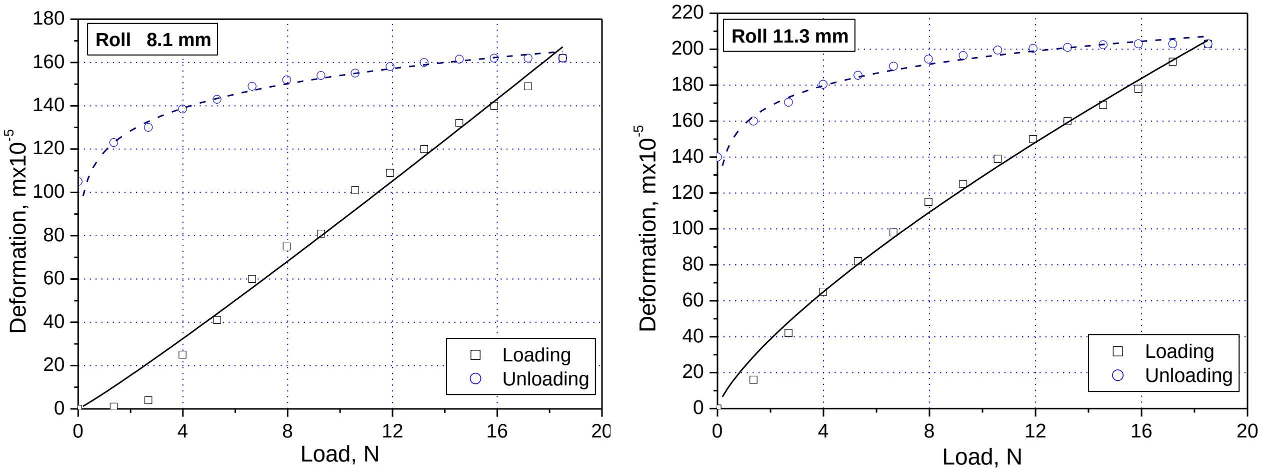

Fig. 3 – The variation of the geotextile deformation curves, as a function of the pressure force, on loading and unloading, for two diameters of the cylindrical roll press

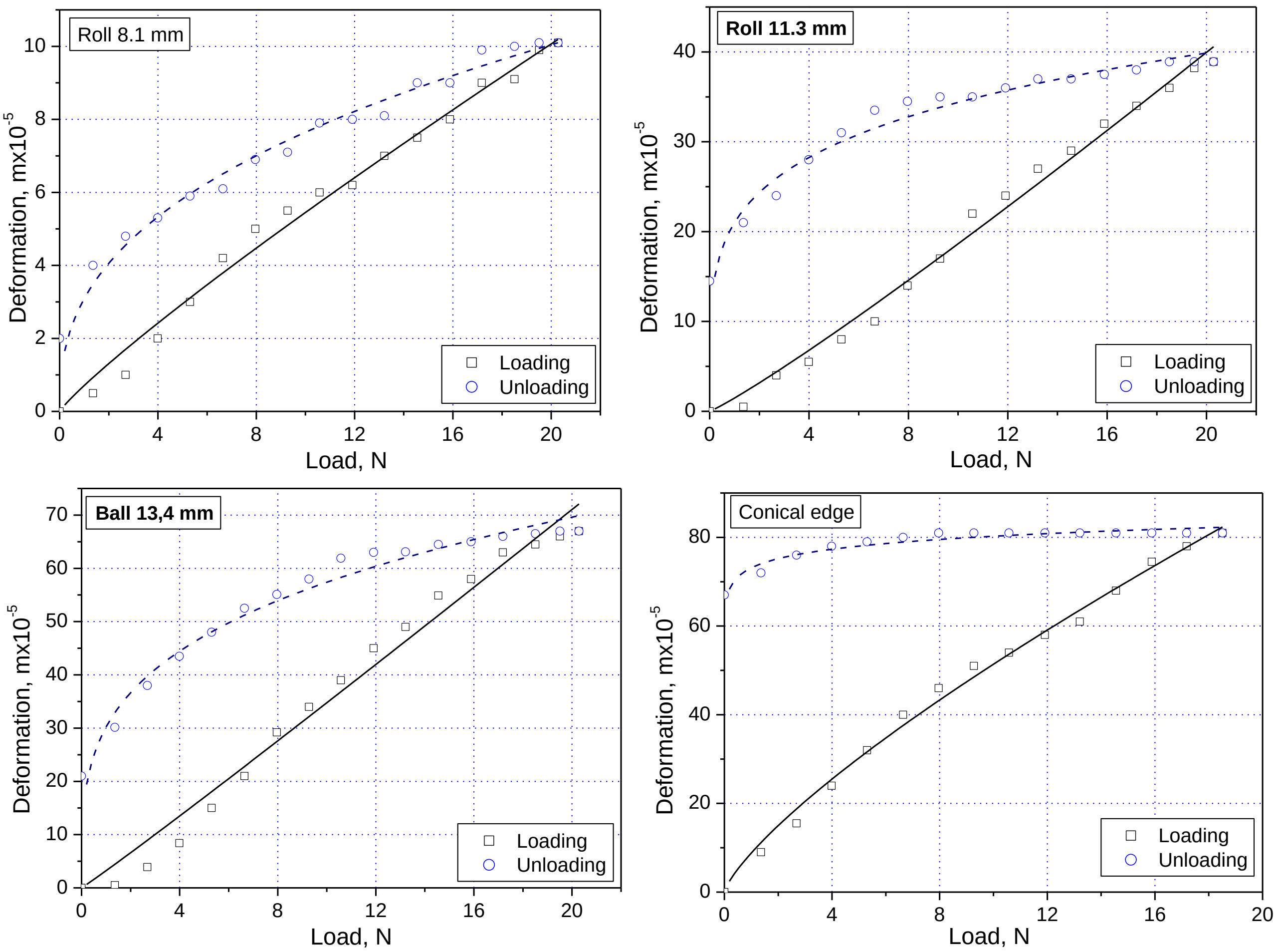

Fig. 4 – The variation curves for geomembrane deformation, depending on the pressure force, on loading and unloading, for different types of work systems (rolls, ball, conical edge)

From the analysis of experimental data and plotted variation curves, it can be seen that the unload takes place on a route different from loading, which indicates that some of the strain remains stored in the material and it can be resorbed after shorter or longer periods of time. Thus, there is the possibility of material thinning and if testing continues, the material can no longer return to the initial form. This thinning inevitably leads to stretching and wrinkling of the material, which induce other types of stresses, together with the existence of an additional weight (waste or drainage material or coating) above the material.

Thus, the deformation is elastic-plastic deformation with a higher degree of recovery from the membrane, especially when cylindrical rollers are used. For geotextile protection, the strain was more pronounced as compared to geomembrane, for the same load, and return much smaller, which means that the coefficient of elasticity is also smaller.

Instead, membrane recovery was much smaller when using the conical tip, possibly due to its retention by material and its friction with the material.

Also, it can be said that a part of the energy consumed for deformation remains in the material, manifested as hysteresis both in case of deformation and consumption of the energy needed for deformation. This phenomenon occurs both for geosynthetics protection and for sealing geomembrane, but less obvious in case of the last one, for loading values used in the paper, but with a greater influence on geomembranes.

Energy stored in material (called lost or dissipated energy) can be determined by measuring the surface area between the two curves (loading - unloading). In the paper, the energy dissipation was calculated with Mathcad software, based on equations derived from regression analysis, as a difference between surface areas under the curves of unloading and loading, form the 0 N load to the load mentioned in Table 1 (18.50 N, respectively 20.28 N) for each one of the experimental samples.

If the energy dissipation for the geotextile lies between (1255–1354)$\cdot 10^{-5}$ N·m, in case of the geomembrane, dissipated energy lies between (37.2–395.9)$\cdot 10^{-5}$ N·m, depending on the type and shape of the pressure device (roller or ball). However, there are slight differences depending on the mathematical relation used (Eq. 2-5). Thus, the calculation error between the values of the dissipated energy calculated by the linear equation (1) and the logistic function (4) lies between 0.15–7.58%, as shown in Table 3:

$$\varepsilon = \frac{E_{linear} - E_{logistic}}{E_{logistic}} \cdot 100 \ (\%) \quad (6)$$

From regression analysis of experimental data with mathematical functions mentioned above resulted the values of the equations coefficients and of the correlation coefficient R2 and they are shown in Table 2.

Table 2

The coefficients values of the regression functions (2-5) and of the correlation coefficient R2 for strain - strength variation curves of the experimental tests on PP geotextile and HDPE geomembrane

Equation	Loading / Unloading	Geotextile, roll ϕ8.1 mm					Geotextile, roll ϕ11.3 mm				
		a	b	c	d	R^2	a	b	c	d	R^2
Eq.2	Loading	0.095	-0.076	-	-	0.988	0.107	0.168	-	-	0.976
	Unloading	0.026	1.237	-	-	0.813	0.027	1.631	-	-	0.759
Eq.3	Loading	0.074	1.070	-	-	0.980	0.230	0.750	-	-	0.992
	Unloading	1.188	0.113	-	-	0.983	1.580	1.766	-	-	0.968
Eq.4	Loading	$6.6\cdot 10^6$	$-6.6\cdot 10^6$	$7\cdot 10^6$	-	0.986	2.9512	-2.9712	16.446	-	0.998
	Unloading	1.6358	-0.5697	4.972	-	0.995	2.0395	-0.631	4.161	-	0.999
Eq.5	Loading	-0.0372	2.4744	13.146	1.718	0.995	-0.0211	4.311	21.247	1.044	0.998
	Unloading	1.0527	1.7753	4.604	1.022	0.996	1.4026	2.123	3.289	1.208	0.997
		Geomembrane, roll ϕ8.1 mm					Geomembrane, roll ϕ11.3 mm				
		a	b	c	d	R^2	a	b	c	d	R^2
Eq.2	Loading	0.005	0.0026	-	-	0.985	0.021	-0.018	-	-	0.993
	Unloading	0.0035	0.036	-	-	0.951	0.0095	0.228	-	-	0.786
Eq.3	Loading	0.007	0.886	-	-	0.987	0.015	1.100	-	-	0.990
	Unloading	0.031	0.394	-	-	0.979	0.210	0.214	-	-	0.955
Eq.4	Loading	0.1258	-0.0989	14.562	-	0.980	$-2.68\cdot 10^4$	$2.68\cdot 10^4$	$-1.3\cdot 10^6$	-	0.992
	Unloading	$-1.456\cdot 10^4$	$1.456\cdot 10^4$	$-2.91\cdot 10^6$	-	0.983	0.3883	0.2417	4.938	-	0.993
Eq.5	Loading	-0.0017	0.2316	25.621	1.172	0.992	0.0029	0.6539	16.393	1.784	0.998
	Unloading	0.021	27.833	$4.92\cdot 10^5$	0.577	0.991	0.1461	0.419	3.950	1.250	0.993
		Geomembrane, ball ϕ13.4 mm					Geomembrane, conical edge				
		a	b	c	d	R^2	a	b	c	d	R^2
Eq.2	Loading	0.037	-0.026	-	-	0.985	0.043	0.064	-	-	0.980
	Unloading	0.0196	0.340	-	-	0.839	0.0053	0.738	-	-	0.581
Eq.3	Loading	0.032	1.032	-	-	0.978	0.088	0.766	-	-	0.995
	Unloading	0.302	0.279	-	-	0.969	0.731	0.040	-	-	0.992
Eq.4	Loading	$-1.07\cdot 10^5$	$1.07\cdot 10^5$	$2.89\cdot 10^6$	-	0.983	1.3052	-1.3044	19.377	-	0.996
	Unloading	0.6912	-0.4832	6.209	-	0.998	0.8119	-0.144	2.698	-	0.996
Eq.5	Loading	-0.0039	0.915	11.983	1.995	0.999	-0.0041	2.2752	34.055	0.976	0.995
	Unloading	0.213	0.7559	5.171	1.287	0.997	0.6704	0.8153	2.017	1.773	0.995

Analysing the data in Table 2, it is clear that the mathematical function that has the best correlation with the experimental data is the logistic function for which the values of the correlation coefficient R^2 are higher (over 0.992 in all analysed cases). However, all four functions used in the regression analysis shows very high values of the correlation coefficient.

Table 3

The dissipated energy (N·m) and the calculation error based on the mathematical relationship used

	Nonwoven geotextile		HDPE geomembrane		
Dissipated energy N·m)	Small roll	Big roll	Small roll	Big roll	Ball
By the linear equation (2)	1255×10^{-5}	1354×10^{-5}	37.16×10^{-5}	269.35×10^{-5}	380.19×10^{-5}
By the logistic equation (5)	1271×10^{-5}	1352×10^{-5}	38.55×10^{-5}	291.45×10^{-5}	395.92×10^{-5}
Calculation error ε (%)	1.26	0.15	3.60	7.58	3.97

CONCLUSIONS

Geotextiles are widely used in the construction of waste landfills. Among them, the HDPE geomembranes are especially used for sealing the bottom and for the final coating of the deposit. These geomembranes are sensitive to mechanical actions of the weights acting on them and of the blunt bodies inside the materials with which they are in contact. Therefore, protective geotextiles are used for their protection, who's mass per unit area is chosen depending on the specific type of land.

Therefore, the compressive strength of the two geosynthetics is particularly important and needs to be determined, both in the field and in the laboratory, whether the manufacturer's technical features are known or not.

Several conclusions result from our measurements, such as:

- geosynthetics deformation under the action of compressive stresses is an elastic-plastic deformation between 1.6 – 2 mm for the pressure forces of 185 – 360 kPa in case of 4.7 mm protective geotextiles and a weight of 500 g/m^2;
- geomembrane deformation is much smaller compared with geotextile, with values of about 0.10 – 0.40 mm, for pressure forces of 205 – 398 kPa;
- the recovery degree of the geotextile (after about 1 minute) is much smaller compared to that of the geomembrane, in our determinations is in the range of 65 – 70% for the geotextile and 20 – 36% for the geomembrane, depending on the loading force and pressure device used;
- the shape of the pressure device on geosynthetics material is very important and, thus, of the objects with which it comes into contact, being transposed into different loading pressure of the various contact surfaces for the same loading degree;
- when using of a spherical ball-type pressure device, the penetration depth into the material has been much higher for the geomembrane compared to cylindrical-type pressure devices (about 1.7 – 6.7 times over);
- the return of geosynthetics material deformation occurs on a curve other than the loading one, due to its elastic-plastic behaviour, which results in the manifestation of the hysteresis phenomenon; lost or dissipated energy in the material is much higher for the geotextile, between 3 – 30 times over, in comparison with the geomembrane, at the same loading degree;
- both loading and recovery of the material has not necessarily a linear trajectory, but being closer to it in case of loading, when the deformation is approximately proportional to the pressure force; the regression analysis with the linear function showed a correlation coefficient R^2 over 0.980 at loading and between 0.759 – 0.951 at unloading, for all samples, except in tests with the conical tip;
- the mathematical function with the best correlation of the experimental data was logistic function, which showed a correlation coefficient $R^2 \geq 0.991$, both for loading and unloading curves;
- utilisation of the linear and logistic functions in regression analysis leads to errors in the verification of the dissipated energy in the material from 0.15% to 7.58%, which shows that it is very important to choose the proper law of variation of the deformation depending on the pressure force, in order to estimate the dissipated energy.

Therefore, knowing the strength characteristics of geosynthetics is particularly important for designers and builders of ecological landfills, thus the success in operation is consistent with the environmental protection laws, and the data presented in our paper can be particularly useful in this sense.

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