Proceedings of ECOpole

DOI: 10.2429/proc.2015.9(1)019 2015;9(1)

Marcin K. WIDOMSKI[1], Witold STĘPNIEWSKI[1] and Rainer HORN[2]

HYDRAULIC PROPERTIES OF CLAY LINERS OF WASTE LANDFILLS COMPACTED AT VARIOUS WATER CONTENTS

WPŁYW WILGOTNOŚCI ZAGĘSZCZANIA MATERIAŁÓW ILASTYCH NA WŁAŚCIWOŚCI HYDRAULICZNE PRZESŁON MINERALNYCH SKŁADOWISK ODPADÓW

Abstract: According to the actual standards, municipal landfill cells, as highly dangerous to the natural environment, have to be isolated from the environment by liners in order to prevent the migration of anthropogenic pollutants. The properly prepared mineral liners sealing the top, sides and bottom of landfill limiting water infiltration to waste body and leachate seepage are the popular manner of landfills isolation. The mineral liners are usually constructed of compacted clay soils to obtain, the required value of the sealing layer saturated hydraulic conductivity lower than $1 \cdot 10^{-9}$ m s^{-1}. The value of hydraulic conductivity of saturated soil is directly affected by the molding water content during compaction. Additionally, the sustainability of clay liners is highly related to its shrinkage and swelling properties. This paper presents researches concerning the effects of molding water content of selected clay soil on saturated hydraulic conductivity and shrinkage/swelling properties of compacted soil as well as hydraulic properties of the top sealing liner, constructed according to the actual standards, of compacted clay material. Range of our studies covered the laboratory and field measurements as well as numerical modeling. Saturated hydraulic conductivity under the natural field conditions was measured by BAT probe, GeoNordic, hydraulic conductivity of the compacted clay soils was tested in the laboratory by Humboldt Mfg. Co. permeameters for compacted soils, according to ASTM D5856. Water retention characteristics of compacted soil in range of 0-15 bar were determined by application of sand box and pressure chambers with ceramic plates methods. The assessment of hydraulic properties of liner made of clay materials was performed for the 2012 hydrologic year by the method of numerical modeling of infiltration process for a selected section of landfill top cover constructed in Rastorf, Germany, adjusted to Polish standards. The numerical calculations were performed in FEFLOW, DHI-WASY modeling software.

Keywords: clay materials, mineral liners, hydraulic conductivity, numerical modeling

Introduction

Landfilled municipal wastes pose a considerable threat to the natural environment due to the possible migration of numerous pollutants to soil and water, especially by leachate seepage. Generation of leachate is triggered by infiltration of surface water, originated form precipitation and snow cover melting, entering the waste body. Thus, negative environmental impact of landfills depends on the efficiency of limiting the pollution by the applied techniques of sealing [1].

Prevention of surface water infiltration and leachate migration to soil-water environment is realized by barriers, known as liners, based on natural and geosynthetic materials. One of the most popular and durable solution are compacted mineral clay liners meeting the requirements of the local standards [2, 3]. These barriers are constructed of natural clays of permeability capable to meet the required value of hydraulic conductivity [4, 5], which should be lower than $1 \cdot 10^{-9}$ m s^{-1} in the European Union. The saturated

---

[1] Faculty of Environmental Engineering, Lublin University of Technology, ul. Nadbystrzycka 40B, 20-618 Lublin, Poland, email: M.Widomski@wis.pol.lublin.pl

[2] Institute for Plant Nutrition and Soil Science, CAU Kiel, Hermann Rodewald-Str. 2, 24118 Kiel, Germany

[*] Contribution was presented during ECOpole'14 Conference, Jarnoltowek, 15-17.10.2014

hydraulic conductivity of clayey soils under natural conditions may be higher than the above value [6-8] so the application of compaction process may be required. The compaction increases the resistance of soil to water flow, significantly reducing the saturated hydraulic conductivity of soil [9], however, the degree of reduction depends on the applied molding water content of the soil. So the molding water content becomes one of the most important factors influencing the hydraulic characteristics of compacted clay liner [10-14]. On the other hand, molding water content affects also the swelling and shrinking properties of clays, influencing the sustainability of the liner [15-17]. Higher shrinking potential results in a significant risk of liner cracking, thus, increase of its permeability. This paper presents an attempt of determination of the effects of soil molding water contend on its saturated conductivity, shrinking and swelling potentials and finally the hydraulic properties of the top sealing liner, constructed according to the actual standards.

Materials and methods

The presented studies were focused on mineral clay material sampled in Lazek Ordynacki, approx. 90 km south of Lublin, Poland. The basic characteristics of sampled soil are presented in Table 1.

Table 1

Basic characteristics of the clay material sampled in Lazek Ordynacki, Poland

Particle fraction name	Sand [%]	4.5
	Silt [%]	51
	Clay [%]	44.5
Solid particle density [Mg m^{-3}]		2.614
Bulk density [Mg m^{-3}]		1.693

The particle size distribution of the soil was determined by the standard sedimentation method according to PN-B-04481:1988 [18], solid particle density was measured in le Chatelier flask and gravimetric water content was obtained by the standard weight method according to ASTM C566-13 [19]. The saturated hydraulic conductivity of the tested soil under natural, undisturbed conditions was measured by the field permeameter for fine grained soils GeoN by Geo Nordic, Stockholm, Sweden. Laboratory measurements of saturated conductivity of the soil compacted at various water contents were performed in the permeameters for compacted soils by Humboldt Mfg. Co, USA. The H-4145 compaction permeameters and the falling water head method of measurements, meeting requirements of ASTM D5856-95 [20], were applied to our studies. The soil was compacted, with different molding water contents, according to PN-B-04481:1988 [18]. The following values of molding water contents (by weight) were applied during our laboratory studies: 17, 19, 21 and 23%. Water retention capabilities of the compacted clay material were tested in pressure range 0-15 bar by the standard sand box (IMUZ, Lublin, Poland) and pressure chambers with ceramic plates by Soil Moisture, Santa Barbara, USA. Numerical modeling of hydraulic efficiency of a mineral liner constructed of the compacted clay material was performed by FEFLOW, WASY-DHI, Germany modeling software. The developed two dimensional model represented a 10 m wide section of mineral liner of 2 m thickness, required by the actual Polish and European standards [2, 3], consisting of three layers: clay sealing layer of 0.5 m thickness, sand drainage layer of 0.5 m and soil recultivation layer of thickness equal to 1.0 m. The applied slope shape reflected morphology of the liner in Rastorf, Germany. Top surface of modeled liner was assumed as covered by perennial grass mixture. The prepared model consisted of 5965 nodes and 11549 elements. The developed model was presented in Figure 1.

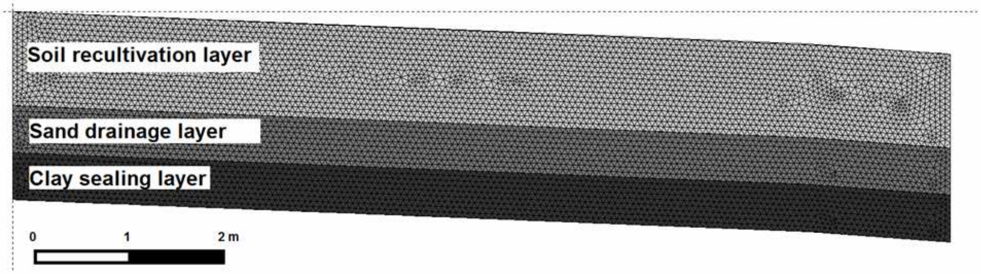

Fig. 1. Developed model of the selected section of municipal landfill top liner

Numerical calculations of the two dimensional water flow in FEFLOW were based on standard forms of Darcy's and Richards' equations [21-23]:

$$\boldsymbol{q}_i = -\boldsymbol{K}_{ij} \frac{\partial h}{\partial x_j}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial \boldsymbol{q}_i}{\partial x_j} \mp Q$$

where: $\boldsymbol{q}_i$ - groundwater flux vector [m s^{-1}], h - hydraulic potential [m], t - time [s], $\boldsymbol{K}_{ij}$ - hydraulic conductivity tensor, $i, j = 1, 2$ [m s^{-1}], Q - sink or source term [s^{-1}].

Mathematical description of water retention curve assumed to our simulations was presented by van Genuchten [24]:

$$\theta = \frac{\theta_s - \theta_r}{[1 + (Ah)^n]^m} + \theta_r$$

where: θ_s - saturated volumetric water content [m^3 m^{-3}], θ_r - residual volumetric water content [m^3 m^{-3}], $\theta_r = 0$ m^3 m^{-3}, h - hydraulic potential [m], A - water retention curve fitting parameter [m^{-1}], n, m - dimensionless water retention curve fitting parameters, $m = 1 - n^{-1}$.

Hydraulic conductivity of unsaturated soils K was calculated in the presented model according to van Genuchten's formula [24]:

$$K = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2$$

where: K_s - saturated hydraulic conductivity [m s^{-1}], l - dimensionless fitting parameter, $l = 0.5$ [23], S_e - dimensionless effective saturation defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

Characteristics of sand and recultivation layer assumed to modeling are presented in Table 2. The isotropic clay and sand soil were assumed to our calculations due to the developed small scale model [25].

Table 2

Soil characteristics for drainage and cultivation layers assumed to modeling

Parameter	Recultivation layer	Sand drainage
Saturated hydraulic conductivity [m s^{-1}]	$0.02 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$
Saturated water content q_s [m^3 m^{-3}]	0.29	0.37
Residual water content q_r [m^3 m^{-3}]	0	0.11
Water retention curve parameter A [m^{-1}]	7.645	2.3
Water retention curve parameter n [-]	1.104	7.7
Anisotropy ratio a [-]	0.17	1
Anisotropy rotation angle f [deg]	90	0

Numerical modeling of water infiltration through the mineral liner required assumption of the necessary initial and boundary conditions. The initial condition was assumed as 90% liner's soil saturation, $S = 0.9$. The bottom boundary condition was assumed as the constant gradient type Neumann condition of value equal to saturated hydraulic conductivity of the soil in sealing layer. Such as boundary condition reflects the undisturbed free water drainage, *ie* gravitational seepage to the lower domain. The Neumann type top boundary condition assigned to upper limit of the model reflected water flux entering and leaving the modeled domain. The daily values of water flux were based on measured and calculated daily precipitation, interception, evapotranspiration and surface runoff for municipal landfill in Rastorf, Germany for 2012 hydrologic year.

Results and discussion

The results of saturated hydraulic conductivity measurements as well as bulk density, and water retention characteristics according to van Genuchten model for the applied molding water contents are presented in Table 3.

Table 3

Saturated hydraulic conductivities, bulk densities and water retention parameters of the soil dependently on molding water content

Parameter	Molding water content [% by weight]			
	17	19	21	23
Saturated hydraulic conductivity [m·s^{-1}]	$1.00 \cdot 10^{-10}$	$7.33 \cdot 10^{-11}$	$3.69 \cdot 10^{-11}$	$3.21 \cdot 10^{-11}$
Soil bulk density after compaction [Mg m^{-3}]	1.66	1.70	1.71	1.70
Bulk density after swelling [Mg m^{-3}]	1.52	1.59	1.63	1.60
Soil bulk density after shrinkage [Mg m^{-3}]	1.86	1.97	1.98	2.02
Saturated water content q_s [m^3 m^{-3}]	0.365	0.350	0.346	0.350
Water retention curve parameter A [m^{-1}]	0.105	0.928	0.675	0.100
Water retention curve parameter n [-]	1.197	1.123	1.116	1.155

The results presented in Table 3 show a clear decrease of saturated hydraulic conductivity of clay resulting from the increase of molding water content. All tested cases of compaction with 17, 19, 21 and 23% water content allowed to achieve the values of saturated hydraulic conductivity of clay sealing layer lower than required by the standards [2, 3]. The obtained values of K_s are one or even two orders of magnitude lower than the required. The observed bulk densities of compacted clay show that the maximum value of bulk density, identifying the highest possible degree of compaction, was achieved for molding water content of 21%. The highest swelling potential (difference between soil bulk density and bulk density after swelling) equal to 0.14 Mg m^{-3} was observed for the lowest molding water content applied. On the other hand, the highest shrinkage potential equal to 0.32 Mg m^{-3} was noted for the highest molding water content applied. Taking into account that high shrinkage potential may trigger cracking which significantly increases hydraulic conductivity of soil, it should be suggested that compaction of clay minerals should be performed on the left, "dry", side of Proctor curve. In our case, molding water content between 17 and 21% seems to be suitable.

The results of numerical calculations of water seepage through a 10.0 m section of liner utilizing clay compacted at various molding water content as sealing layer are presented in Figure 2. The results presented in Figure 2 show that hydraulic properties of the mineral clay liner as a barrier for pollutants propagation made of the compacted clay directly depend on the applied molding water content. The lower the molding water content, the higher saturated hydraulic conductivity and the higher infiltration rate for the same upper boundary condition. The observed calculated decrease of unit yearly seepage volume per 1 m^2 was from $4.65 \cdot 10^{-5}$ m^3 to $1.8 \cdot 10^{-6}$ m^3. Figure 2 shows also that there is no significant difference in sealing capabilities after reaching the maximum bulk density during the compaction process.

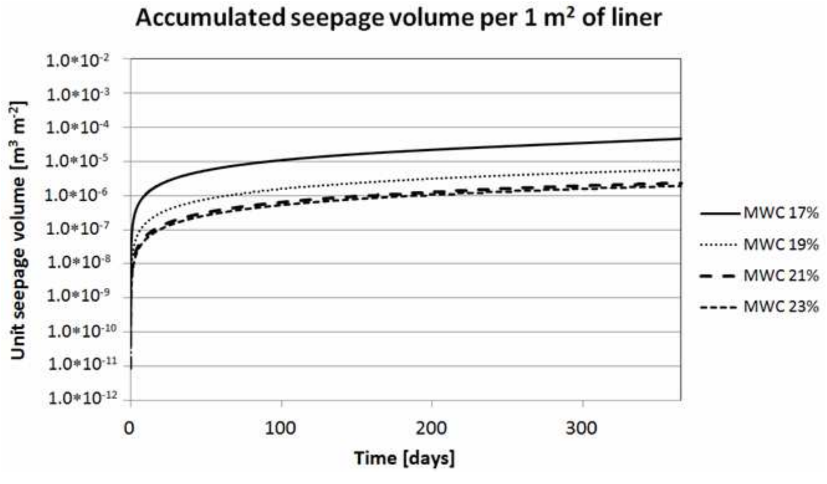

Fig. 2. Calculated yearly cumulative volume of seepage through the bottom boundary of mineral liner made of the clay soil compacted at different water contents (MWC)

Summary and conclusions

Our studies are in agreement with literature proving a direct relation between molding water content applied during compaction of clay and its saturated water conductivity. We observed a decrease of saturated hydraulic conductivity of compacted clay, from $1.00 \cdot 10^{-10}$ to $3.21 \cdot 10^{-11}$ m s^{-1}, due to increase of applied molding water content from 17 to 23%. Additionally, the modeled decrease of seepage percolating through the top liner for the same range of molding water content variability reached one order of magnitude. However, it must be underlined that according to the significant increase of shrinkage potential for values of molding water content higher than value corresponding to the maximum bulk density obtained, the clay utilized in construction of sealing layer should be compacted on the left, dry side of Proctor's curve, below the maximum bulk density. Otherwise, the possibility of soil cracking, reducing the sealing properties of the liner and increasing the possible seepage becomes significant. The above shows that selection of the proper molding water content during construction of the municipal landfill cell liner of the compacted clay material is crucial because it may significantly influence the efficiency of the sealing preventing migration of the pollutants into the natural environment. The lacking validation of our simulation calculations causes that our modeling studies should be treated as preliminary.

Acknowledgements

This paper was supported by Polish Ministry of Science and Higher Education scientific project No 7550/B/T02/2011/40.

References

[1] Bagchi A. Design of Landfills and Integrated Solid Waste Management. Hoboken, New Jersey: John Wiley and Sons Inc; 2004.

[2] Rozporządzenie Ministra Środowiska z dnia 30 kwietnia 2013 r. w sprawie składowisk odpadów.

[3] Council Directive 99/31/EC of 26 April 1999 on the landfill of waste.

[4] Horn R, Stępniewski W. Int Agrophys. 2004;18:317-323.

[5] Horn R, Baumgartl T, Possel H, Koselowske M, Albiker B. Wasser und Abfall. 2001;3:38-41.

[6] Nakano K, Miyazaki T. Soil Till Res. 2005;84:145-153. DOI: 10.1016/j.still.2004.11.010.

[7] Zhang S, Grip H, Lovdahl L. Soil Till Res. 2006;90:117-125. DOI: 10.1016/j.still.2005.08.012.

[8] Islam MR, Alamgir M, Mohiuddin KM, Hasan KMM. Investigation of physical properties of a selected soil to use as a compacted clay liner in sanitary landfill. In: Proceedings of the National Seminar on Solid Waste Management - WasteSafe 2008. Khulna; 2008.

[9] Radford BJ, Bridge BJ, Davis RJ, McGarry D, Pillai UP, Rickman JF, et al. Soil Till Res. 2000;54:155-170. DOI: 10.1016/S0167-1987(00)00091-X.

[10] Osinubi KJ, Nwaiwu ChM. J Geotech Geoenviron Eng. 2005;131(8):1034-1041. DOI: 10.1061/(ASCE)1090-0241(2005)131:8(1034).

[11] Cuisinier O, Auriol JC, Le Borgne T. Eng Geol. 2011;123(3):187-193. DOI: 10.1016/j.enggeo.2011.07.010.

[12] Whalley WR, Matthews GP, Ferraris S. Soil Till Res. 2012;125:23-29. DOI: 10.1016/j.still.2012.05.020.

[13] Bello AA. KSCE J Civil Eng. 2013;17(5):939-948. DOI: 10.1007/s12205-013-0155-x.

[14] Hamdi N, Srasra E. Waste Manage. 2013;33(1):60-6. DOI: 10.1016/j.wasman.2012.08.012.

[15] Basma AA, Al-Homoud AS, Malkawi AIH, Al-Bashabsheh MA. Appl Clay Sci. 1996;11(2-4):211-227. DOI: 10.1016/S0169-1317(96)00009-9.

[16] Cimen O, Keskin SN, Yildirim H. Arab J Sci Eng. 2012; 37:1535-1546. DOI: 10.1007/s13369-012-0268-4.

[17] Stępniewski W, Widomski MK, Horn R. Hydraulic Conductivity and Landfill Construction. In: Dikinya O, editor. Developments in Hydraulic Conductivity Research. Rijeka: InTech; 2011.

[18] PN-B-04481:1988. Grunty budowlane. Badania próbek gruntu.
[19] ASTM C566-13. Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying.
[20] ASTM D5856-95(2007). Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall Compaction-Mold Permeameter.
[21] Richards LA. Physics 1931;1:318-333. DOI: 10.1063/1.1745010.
[22] Raats PAC. Geoderma 2001;100:355-387. DOI: 10.1016/S0016-7061(01)00028-3.
[23] Diersch HJG. DHI-WASY Software FEFLOW Finite Element Subsurface Flow and Transport Simulation System. Reference Manual: DHI-WASY GmbH. Berlin; 2009.
[24] Van Genuchten MTh. Soil Sci Soc Am J. 1980;44:892-898. DOI: 10.2136/sssaj1980.03615995004400050002x.
[25] Widomski MK, Iwanek M, Stepniewski W. Soil Sci Soc Am J. 2013;77:8-18. DOI: 10.2136/sssaj2012.0142.

WPŁYW WILGOTNOŚCI ZAGĘSZCZANIA MATERIAŁÓW ILASTYCH NA WŁAŚCIWOŚCI HYDRAULICZNE PRZESŁON MINERALNYCH SKŁADOWISK ODPADÓW

[1] Wydział Inżynierii Środowiska, Politechnika Lubelska, Polska
[2] Instytut Żywienia Roślin i Gleboznawstwa, Uniwersytet Christiana-Albrechta, Kilonia, Niemcy

Abstrakt: Zgodnie z aktualnymi wymogami prawnymi, składowiska odpadów jako szczególnie niebezpieczne dla środowiska muszą być izolowane przesłonami w celu zapobiegania rozprzestrzeniania się zanieczyszczeń antropogenicznych. Jednym ze sposobów zapewniania izolacji składowisk są odpowiednio przygotowane i zagęszczone przesłony mineralne, zabezpieczające pokrywę oraz dno i boki składowiska. Przesłony mineralne są najczęściej wykonywane z odpowiednio zagęszczonych gruntów ilastych, tak aby przepuszczalność hydrauliczna warstwy ekranującej była niższa niż $1\cdot10^{-9}$ $m\cdot s^{-1}$. Wartość współczynnika przewodnictwa wodnego gruntu w stanie pełnego nasycenia zależy bezpośrednio od wilgotności ośrodka porowatego w czasie zagęszczania. Dodatkowo, żywotność i efektywność przesłon ilastych jest bezpośrednio uzależniona od charakterystyki skurczu i pęcznienia materiału ilastego. Niniejsza praca przedstawia próbę określenia wpływu wilgotności zagęszczania wybranego gruntu ilastego na przepuszczalność w stanie pełnego nasycenia, potencjał skurczu i pęcznienia gruntu oraz właściwości hydrauliczne przesłony składowiska odpadów wykonanej z zagęszczonego gruntu ilastego, zgodnie z obowiązującym stanem prawnym. Zakres pracy obejmował badania laboratoryjne, terenowe oraz modelowe. Przewodnictwo hydrauliczne gruntów w stanie naturalnym określono za pomocą polowej sondy BAT, GeoNordic, przewodnictwo zaś w stanie pełnego nasycenia po zagęszczeniu wyznaczono za pomocą przepuszczalnościomierzy Humboldt Mfg. Co. do gruntów zagęszczonych wg ASTM D5856. Charakterystykę retencyjną zagęszczonych gruntów w zakresie 0-15 bar wyznaczono za pomocą metody bloku pyłowego oraz komór ciśnieniowych z płytami ceramicznymi. Ocenę właściwości hydraulicznych przesłon wykonanych z badanych materiałów ilastych zrealizowano dla roku hydrologicznego 2012 poprzez modelowanie numeryczne procesu infiltracji przez wybrany fragment przykrycia składowiska odpadów w Rastorf, Niemcy, dostosowany do polskich wymagań prawnych. Badania symulacyjne przeprowadzono za pomocą programu obliczeniowego FEFLOW, DHI-WASY.

Słowa kluczowe: materiały ilaste, przesłony mineralne, przewodnictwo hydrauliczne, modelowanie numeryczne