

Marcin K. WIDOMSKI¹ and Witold STĘPNIEWSKI¹

MOLDING WATER CONTENT OF CLAY SOILS AND HYDRAULIC PROPERTIES OF MINERAL LINERS OF WASTE LANDFILLS

WILGOTNOŚĆ ZAGĘSZCZANIA MATERIAŁÓW ILASTYCH A WŁAŚCIWOŚCI HYDRAULICZNE PRZESŁON MINERALNYCH SKŁADOWISK ODPADÓW

Abstract: Municipal landfill cells as engineering constructions highly dangerous to the natural environment have to be isolated by liners in order to prevent the anthropogenic pollutants transport, together with *eg* landfill leachates. Mineral liners, properly prepared and compacted, sealing the bottom, sides and top of the landfills are one of the most popular manners of landfills isolation. The mineral liners are usually constructed of compacted clay soils to obtain, the required by Polish Decree of Minister of Environment of 3rd April 2013 and Council Directive 1999/31/EC of 26th April 1999 on the landfill of wastes, value of liner's saturated hydraulic conductivity lower than $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$. The value of hydraulic conductivity of saturated soils is directly affected by the conditions of soil compaction, especially the molding water content. This paper presents an attempt of determination of the effects of molding water content of a selected clay soil on its saturated hydraulic conductivity and hydraulic properties of the sealing liner, constructed according to the actual standards, of the compacted clay material. Range of our studies covered the in situ and laboratory measurements as well as numerical modeling. Saturated hydraulic conductivity under natural conditions was measured by BAT probe, (GeoNordic) while the hydraulic conductivity of the compacted clay soils was tested by Humboldt Mfg. Co. permeameters for compacted soils, according to ASTM D5856. The assessment of hydraulic properties of a liner made of the clay material under study was performed by the method of numerical modeling of infiltration process with the assumed value of groundwater head with application of the FEFLOW, DHI-WASY modeling software. The lacking validation of our modeling attempt influences the fact that our studies should be treated as preliminary.

Keywords: clay materials, mineral lines, hydraulic conductivity, numerical modeling, waste landfill

Introduction

Landfilling of municipal wastes poses a considerable threat to the natural environment caused by migration of numerous pollutants by air, surface runoff, and leachates. The environmental impact of landfills depends on the efficiency of limiting the pollution of air, water and soil by the applied techniques of sealing [1]. Prevention of leachate seepage and migration is realized by barriers, known as liners, utilizing various technical solution based on natural and geosynthetic materials. One of the most popular and durable solution are mineral clay liners meeting the requirements of the local standards [2, 3]. These barriers are constructed of natural clays of permeability capable to secure the required value of hydraulic conductivity [4, 5]. In the European Union it should be lower than $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$. The saturated 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, thus, in the effect, the saturated hydraulic conductivity is reduced [9], however, the degree of reduction depends on the

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

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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].

This paper presents an attempt of recognition of a selected clay soil molding water content effects on its saturated hydraulic conductivity and hydraulic properties of the sealing liner, constructed according to the actual standards, of the compacted clay material. Our studies were based on *in situ* and laboratory measurements, as well as on numerical modeling method.

Materials and methods

The presented studies were focused on mineral clay soil sampled in the open pit of a former brickyard in Łązek Garncarski, approx. 90 km south of Lublin, Poland. The particle size composition of the sampled soil and its basic characteristics such as bulk density, saturated hydraulic conductivity and water content under natural conditions are presented in Table 1.

Table 1

Characteristics of the clay soil sampled in Łązek Garncarski, 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
Gravimetric water content [%]		21.18
Total porosity [m³ m⁻³]		0.352
Saturated hydraulic conductivity [m s⁻¹]		1.37·10 ⁻¹⁰

The particle size distribution of the soil was determined by the standard areometric 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 a 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 carried out 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: 14, 17 and 19%.

Numerical modeling of hydraulic efficiency of a mineral liner constructed of the compacted clayey soil was performed by FEFLOW, WASY-DHI, Germany modeling software. FEFLOW is a well known and successfully verified numerical tool, based on the finite elements/volumes method allowing calculations of water and mass transport in saturated, unsaturated or variably saturated porous medium [21-25]. The developed two

dimensional model represented a 1 m wide mineral liner of 1 m thickness, required by the actual Polish and European standards [2, 3]. The prepared model consisted of 2831 nodes and 5472 elements.

Numerical calculations of the two dimensional water flow in FEFLOW were based on standard forms of Darcy's and Richards' equations [26-28]:

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

$$S_0 \frac{\partial h}{\partial t} = -\frac{\partial \mathbf{q}_i}{\partial x_i} \mp Q$$

where: \mathbf{q}_i - groundwater flux vector [m s^{-1}], h - hydraulic pressure head [m], t - time [s], \mathbf{K}_{ij} - hydraulic conductivity tensor, $i, j = 1, 2$, [m s^{-1}], Q - sink or source term [s^{-1}], S_0 - specific storage compressibility [m^{-1}], $S_0 = 1 \cdot 10^{-4} \text{ m}^{-1}$.

Mathematical description of water retention curve to our simulations was presented by van Genuchten [29]:

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

where: θ_s - saturated volumetric water content [$\text{m}^3 \text{ m}^{-3}$], θ_r - residual volumetric water content [$\text{m}^3 \text{ m}^{-3}$], $\theta_r = 0 \text{ m}^3 \text{ m}^{-3}$, h - pressure head [m], a - fitting parameter [m^{-1}], n, m - fitting parameters, $m = 1 - n^{-1}$.

Hydraulic conductivity of unsaturated soils K was calculated in the presented model according to van Genuchten's formula [26]:

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

where: K_s - saturated conductivity [m s^{-1}], l - fitting parameter, $l = 0.5$ [28], S_e - dimensionless effective saturation defined as:

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

The retention characteristics of the soil described by van Genuchten model [29] applied to numerical calculations are presented in Table 2. The isotropic soil was assumed to our calculations due to the developed small scale model [25].

Table 2

Retentional characteristics of the soil applied to numerical calculations

	Saturated volumetric water content θ [$\text{m}^3 \text{ m}^{-3}$]	Fitting parameter a [m^{-1}]	Fitting parameter n [-]
Parameter value	0.352188	0.0269	1.354476

The required input data for water retention characteristics were determined by laboratory measurements including a sand box in the range of $h < 0.1$ bar as well as

pressure chambers with 1 bar, 2 bar, 5 bar and 15 bar ceramic plates, produced by Soil Moisture Equipment Corp, USA. Numerical modeling of two dimensional gravitation water flow through the mineral liner required assumption of the necessary initial and boundary conditions. The initial condition was assumed as full liner's soil saturation, *ie* $S = 1.0$. The bottom boundary condition was assumed as the constant Dirichlet type condition in which the water head was equal to -5.0 m. The variable Dirichlet type top boundary condition represented by various values of water pressure head over the modeled liner was selected to our calculations. The applied values of assigned pressure head were assumed as 0.01, 0.5, 1 and 5 m. The assumed time of simulation covered one hydrologic year, *ie* 365 days.

Results and discussion

The results of saturated hydraulic conductivity measurements as well as bulk density and total porosity tests for the applied molding water contents are presented in Table 3.

Table 3
Saturated hydraulic conductivities, total porosities and bulk densities of the soil dependently on molding water content

	Molding water content [% by weight]		
	14	17	19
Saturated hydraulic conductivity [$\text{m} \cdot \text{s}^{-1}$]	$3.936 \cdot 10^{-9}$	$1.000 \cdot 10^{-10}$	$7.325 \cdot 10^{-11}$
Soil bulk density after compaction [Mg m^{-3}]	1.83	1.97	2.02
Total porosity after compaction [$\text{m}^3 \text{m}^{-3}$]	0.300	0.246	0.227
Bulk density after swelling [Mg m^{-3}]	1.66	1.85	1.88
Total porosity after swelling [$\text{m}^3 \text{m}^{-3}$]	0.365	0.292	0.281

The data presented in Table 3 show a clear decrease of the saturated hydraulic conductivity with the increase of bulk density resulting from the increase of the molding water content. The presented results show that in all three cases compaction was performed on the left side of the standard Proctor's curve. Additionally, it is visible that saturation of compacted clay material, leading to swelling of soil, affects its bulk density and total porosity. The degree of bulk density reduction and total porosity increase is related to molding water content.

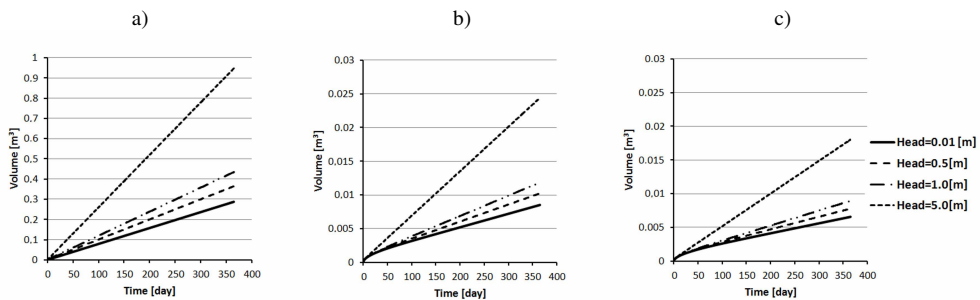


Fig. 1. Calculated cumulative volume of seepage through mineral liner made of the clay soil compacted at different water contents: a) seepage volume for molding water content $u = 14\%$, b) seepage volume for molding water content $u = 17\%$, c) seepage volume for molding water content $u = 19\%$

The results of numerical calculations of water seepage through a 1 m thick layer of the clayey material compacted with various molding water contents are presented in Figure 1.

The results presented in Figure 1 shows that hydraulic properties of the mineral clay liner as a barrier for pollutants propagation made of the compacted clay material directly depend on molding water content. The lower the molding water content, the higher saturated hydraulic conductivity and the higher infiltration rate for the same value of water head applied to the upper boundary of the liner. Table 4 shows the observed mean values of daily seepage volume for all the applied values of water head and the molding water contents under consideration.

Table 4

Mean daily seepage volume [m^3] for all the tested molding water contents and the applied water pressure head values

Molding water content [% by weight]	Water pressure head [m]			
	0.01	0.5	1.0	5.0
14	$0.792 \cdot 10^{-3}$	$0.999 \cdot 10^{-3}$	$1.191 \cdot 10^{-3}$	$2.597 \cdot 10^{-3}$
17	$0.023 \cdot 10^{-3}$	$0.028 \cdot 10^{-3}$	$0.032 \cdot 10^{-3}$	$0.067 \cdot 10^{-3}$
19	$0.018 \cdot 10^{-3}$	$0.021 \cdot 10^{-3}$	$0.024 \cdot 10^{-3}$	$0.049 \cdot 10^{-3}$

The results of the mean daily water seepage related to the water pressure head values triggering infiltration flow show that better sealing of landfill waste body by natural liner constructed of the compacted clay material is obtained when the clay material is compacted at higher value of water content. Increase of molding soil water content from 14 to 19% allowed to reduce the volume of seepage by approx. 98% in cases of all applied values of pressure head.

Summary

Our studies support literature reports proving that there is a direct relation between molding water content in a clay soil during compaction and its saturated water conductivity (inducing modification of its general hydraulic characteristics). This relation allows to obtain better sealing properties, *ie* lower permeability, of the compacted mineral liner when soil was compacted with higher values of water content. In our case, the increase of molding water content from 14% to 19% resulted in a decrease of saturated hydraulic conductivity of the compacted soil from $3.936 \cdot 10^{-9}$ to $7.325 \cdot 10^{-11} \text{ m s}^{-1}$. Additionally, the performed numerical modeling of infiltration through the compacted clay liner showed that the approx. 98% decrease of daily infiltration rate through the 1.0 m thick clay liner was possible due to increase of molding water content by 5% (from 14 to 19%) for all the values of water pressure head under consideration (0.01-5 m). The above shows that selection of the proper molding water content during construction of the municipal landfill cell liner of compacted clay material is crucial because it may significantly influence the effectiveness of the sealing preventing migration of the pollutants into the natural environment. On the other hand the increase of molding water content may result in an increase bulk density and decrease of total porosity after swelling of the clay material after saturation by water. Thus, the possibility of soil cracking, reducing the sealing properties of the liner becomes significant. Our studies should be extended to include different types of clay soils and to

cover the second part of the Proctor's curve, however, compaction of clay material at high molding water content may be impractical. The lacking validation of our simulation calculations influences the fact that our modeling studies should be treated as preliminary.

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WILGOTNOŚĆ ZAGĘSZCZANIA MATERIAŁÓW ILASTYCH A WŁAŚCIWOŚCI HYDRAULICZNE PRZESŁÓN MINERALNYCH SKŁADOWISK ODPADÓW

Wydział Inżynierii Środowiska, Politechnika Lubelska

Abstrakt: Składowiska odpadów jako szczególnie uciążliwe dla środowiska budowe inżynierskie muszą być izolowane przesłonami w celu zapobiegania rozprzestrzeniania się wraz z m.in. ociekami zanieczyszczeń antropogenicznych pochodzących ze składowiska. Jednym ze sposobów zapewniania izolacji składowisk są przesłony mineralne odpowiednio przygotowane i zagęszczone, zabezpieczające dno, boki oraz powierzchnię składowiska. Przesłony mineralne są najczęściej wykonywane z odpowiednio zagęszczonych gruntów ilastych, tak aby, zgodnie z Rozporządzeniem Ministra Środowiska z 30 kwietnia 2013 r. w sprawie składowisk odpadów oraz Council Directive 1999/31/EC z 26 kwietnia 1999 w sprawie składowania odpadów, przepuszczalność hydrauliczna przesłony była niższa niż $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$. Bezpośredni wpływ na wartość współczynnika przewodnictwa wodnego w stanie pełnego nasycenia mają warunki, w których przeprowadzane jest zagęszczenie gruntu, a dokładnie wilgotność ośrodka porowatego w czasie zagęszczania. Praca niniejsza przedstawia próbę określenia wpływu wilgotności zagęszczania wybranych gruntów ilastych na ich przepuszczalność w stanie pełnego nasycenia oraz właściwości hydrauliczne wykonanej z nich, zgodnie z obowiązującym stanem prawnym, przesłony składowiska odpadów. Zakres pracy obejmował badania terenowe, laboratoryjne oraz modelowe. Przewodnictwo hydrauliczne gruntów w stanie naturalnym określono za pomocą polowej sondy BAT, GeoNordic, przewodnictwo zaś w stanie pełnego nasycenia po zagęszczeniu mierzono za pomocą przepuszczalnościomierzy Humboldt Mfg. Co. do gruntów zagęszczonych wg ASTM D5856-95. Ocenę właściwości hydraulicznych przesłón wykonanych z badanych materiałów ilastych zrealizowano poprzez modelowanie numeryczne procesu infiltracji przy zadanej wysokości naporu wód gruntowych zrealizowane za pomocą programu obliczeniowego FEFLOW, DHI-WASY. Ze względu na brak walidacji modelu otrzymane wyniki należy traktować jako wyniki badań wstępnych.

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

