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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 landfills 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 the top of the landfills are one of the most popular manners of their isolation. The mineral liners are usually constructed of compacted clay soils to obtain, the required by the Polish Decree of the Minister of Environment of 3rd April 2013 and the Council Directive 1999/31/EC of 26th April 1999 on the landfill of wastes, value of liner's saturated hydraulic conductivity lower than $1 \cdot 10^{-9}$ m $\cdot$ s^{-1}. The value of hydraulic conductivity of saturated soils is directly affected by the conditions of soil compaction, especially a molding water content. This paper presents an attempt of the determination of the effects of the 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, in accordance with ASTM D5856. The assessment of hydraulic properties of a bottom 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 an application of the FEFLOW, DHI-WASY modeling software. The lack of validation in 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

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Introduction

Migration of numerous pollutants by air, surface runoff, and leachates resulting from landfilling of municipal wastes poses a considerable threat to the natural environment. The environmental impact of landfills is directly connected to the efficiency of restraining the pollution of air, water and soil by applied various techniques of sealing [1]. Leachate seepage and migration from landfill cells is prevented by barriers, known as liners, which utilize different technical solutions based on natural and geosynthetic materials.

Mineral clay liners that meet the requirements of local standards [2, 3] are one of several possible popular and durable solutions. These barriers are constructed of natural clays, the permeability of which is capable to secure the required value of hydraulic conductivity [4, 5]. In the European Union its value should be lower than $1 \cdot 10^{-9}$ $\mathrm{m \cdot s^{-1}}$. The saturated hydraulic conductivity of clay soils may be higher under natural conditions than the required value [6–8] so the application of compaction may be necessary. The compaction changes bulk density and increases resistance of soil to water (or leachate) flow, as a result, saturated hydraulic conductivity is reduced [9]; however, the degree of reduction depends on the molding water content of the soil. Thus, the molding water content becomes one of the most important factors influencing hydraulic characteristics of liners consisting of compacted clay [10–14].

In addition to changes in bulk density and hydraulic conductivity, molding water content also affects the subsequent swelling and shrinking properties of clays influencing the sustainability of the liner [15–18]. Even highly compacted clays, are prone to shrinking when drying. The shrinking of clay materials is usually connected with their cracking [19]. Each drying and wetting cycle, combined with soil cracking, results in an increase of bulk density of soil, a decrease of its void ratio and an increase of hydraulic conductivity after resaturation. The aforementioned can be explained by the fact that each change of soil volume caused by wetting and drainage (or subsequent re-wetting) is related to changes in pore volume and distribution of pore sizes [19, 20]. It is therefore important to determine the influence of molding water content on hydraulic properties of clay material used in natural barriers construction in relation to its shrinking and swelling potential.

Additionally, molding water content of compacted clay materials – affecting their swelling-shrinkage properties – also influences the long-term stability of mineral liners [4]. However, in case of the bottom liner the eventual swelling may be treated as an advantageous feature, improving the sealing properties by increasing the water holding capacity of clays. The shrinkage of bottom liner covered by waste body and saturated by groundwater is less possible than the shrinkage of the top sealing clay liner, even with the additional cover by the recultivation layer.

This paper presents an attempt to assess the molding water content influence on saturated hydraulic conductivity as well as on bulk density of compacted clay soil and hydraulic properties of the bottom sealing liner, constructed according to the actual standards. Our studies were based on *in situ* and laboratory measurements, as well as on numerical modeling method.

Materials and methods

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

Table 1

Characteristics of the clay soil sampled in Lazek Garncarski, Poland, under *in situ* conditions

Particle fraction name	Sand [%]	4.5
	Silt [%]	51.0
	Clay [%]	44.5
Solid particle density [$Mg \cdot m^{-3}$]		2.614
Bulk density [$Mg \cdot m^{-3}$]		1.693
Gravimetric water content [%]		21.18
Total porosity [$m^3 \cdot m^{-3}$]		0.352
Saturated hydraulic conductivity [$m \cdot s^{-1}$]		$1.37 \cdot 10^{-10}$

Particle size distribution of the soil, presented in Table 1, was determined by the standard areometric method according to PN-B-04481: 1988 [21], solid particle density was measured in le Chatelier flask and gravimetric water content was obtained by the standard oven drying method according to ASTM C566-13 [22]. 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, directly in the location of soil sampling in Lazek Garncarski.

The changes of the particle size distribution was additionally measured by the laser diffraction method. This method, based on measurement of light intensity scattered on investigated suspension, is wildly used in soil and sediment laboratories [23]. It is particularly useful when it comes to measuring the size distribution of very small volume and/or determination of the small differences in the content of each fraction [24].

The Mastersizer 2000 (Malvern, UK) with hydro MU was used as the laser diffractometer [25]. The following parameters and settings were used: speed of the pump and stirrer (in this dispersion unit both are integrated) – 2500 rpm., 4 min of ultrasounds with 35 W of the power, Mie theory with the refractive index equal to 1.52 and absorption index equal to 0.1. The use two different methods (sedimentation and laser diffraction method) for measurement of particle size distributions was dictated by the fact of significant differences in the results obtained by both [26]. Therefore the sedimentation method was used to determine the particle size distribution of investigated material (it allowed to classify it to the clays) and laser diffraction method allowed to show the subtle differences in the particle distribution (which is impossible in sedimentation methods).

Microscopic analyses of the tested soils structure were performed by scanning electron microscope Quanta SEM 200 FEG by FEI, USA.

Laboratory measurements of saturated conductivity of the tested clay material compacted at various water contents were performed in the permeameters for compacted soils by Humboldt Mfg. Co, USA. The H-4145 cylindrical compaction permeameters of mold's diameter equal to 101.6 mm and height of 116.4 mm and the falling water head method of measurements meeting requirements of ASTM D5856-95 [27] were applied to our studies. The soil was compacted, at different molding water contents, according to Polish standard PN-B-04481: 1988 [21]. The following values of molding water contents (by weight) were applied during our laboratory studies: 14 %, 17 %, 19 %, 21 %, 22 % and 23 %.

Two dimensional numerical modeling of hydraulic efficiency of a bottom mineral liner constructed of the compacted clay soil was performed by FEFLOW 6.0, WASY-DHI, a German 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 [28–32]. The developed two dimensional model represented a 1m wide mineral liner of 1m 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 [33–36]:

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

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

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

Mathematical description of water retention curve was presented by van Genuchten [36]:

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

where: θ_s – saturated volumetric water content [$\mathrm{m^3 \cdot m^{-3}}$],
θ_r – residual volumetric water content [$\mathrm{m^3 \cdot m^{-3}}$], $\theta_r = 0$ [$\mathrm{m^3 \cdot m^{-3}}$],
h – pressure head [m],
α – fitting parameter [$\mathrm{m^{-1}}$],
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 [35, 36]:

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

where: K_s – saturated conductivity [$m \cdot s^{-1}$],
l – fitting parameter, $l = 0.5$ [36],
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 [36] applied to numerical calculations are presented in Table 2. The isotropic soil was taken into consideration in our calculations due to the small scale model developed [32].

Table 2

Retentional characteristics of the clay soil applied to numerical calculations

Saturated water content by volume θ_s [$m^3 \cdot m^{-3}$]	Fitting parameter α [m^{-1}]	Fitting parameter n [-]
0.352	0.0269	1.354

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 a 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 for our calculations. The applied values of assigned pressure head were assumed as 0.01 m, 0.5 m, 1 m and 5 m. The assumed time of simulation covered one hydrologic year, *ie* 365 days.

Results and discussion

The microscopy analyses performed for representative samples of the compacted clay material for all of the tested molding water contents showed visual differences in the spatial structure.

Figures 1 and 2 present the exemplary scanning pictures (magnification 100 and 1000 times) of soil samples surface after cracking of the prepared samples cut out from the mold showing differences in soil particles spatial arrangement. These figures reveal that the increase of water content during soil compaction results in a higher compaction

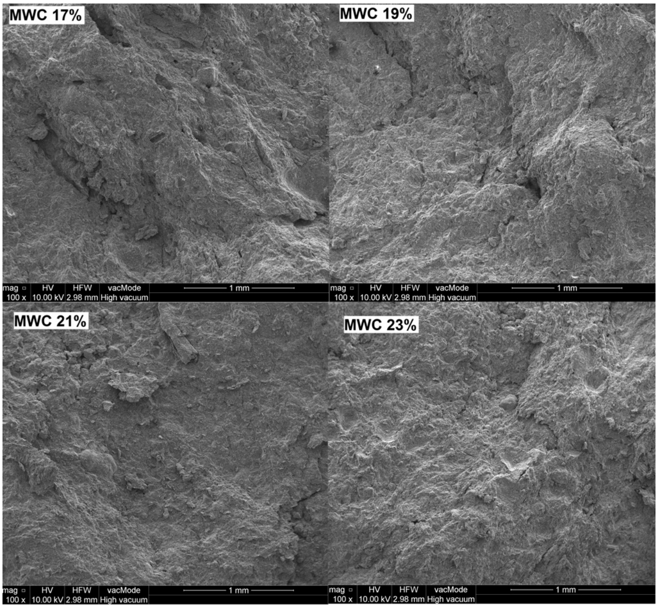

Fig 1. Scanning microscopy pictures of soil samples surface for selected molding water contents (MWC) applied in magnification of 100 times

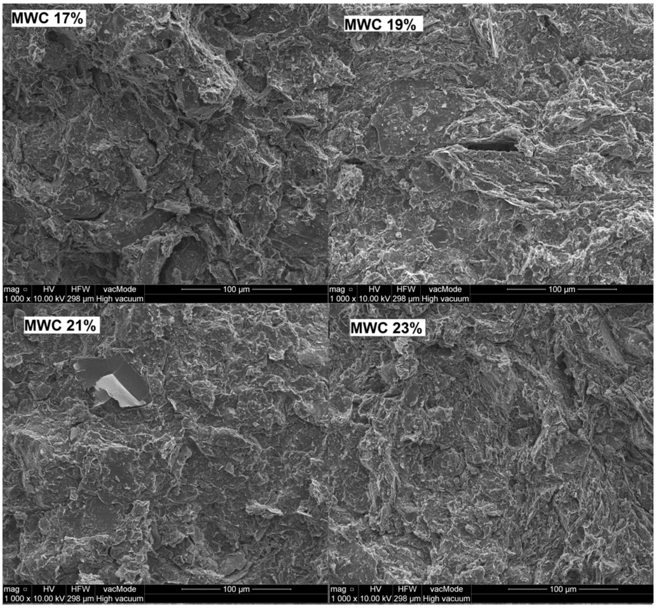

Fig 2. Scanning microscopy pictures of soil samples surface for selected molding water contents (MWC) applied in magnification of 1000 times

of soils particles. In the case of higher molding water content, the macropores (> 75 μm) and mesopores (75–30 μm) appear rarely, if ever observed. Fig. 2 presents the surface of soil samples without macrpores and with limited mesopores, allowing for the assessment of the micropores influence on the total porosity of the presented samples.

The additional measurements of soil particle size distribution performed by laser light diffraction method enabled the assessment of the influence of temporal (approx. 30 days) saturation and the applied permeability tests on washing out of clay particles. After measuring the saturated hydraulic conductivity, a small decrease in the content of clay particles was observed for all tested samples. The range of the previously noted decrease was 1–9 % of clay content. The highest clay removal was observed for soil compacted with molding water content equal to 17 %. All values of clay fraction content decrease are presented in Fig. 3, showing clay content in compacted material related to its initial content in an undisturbed sample (100 %).

The applied method of laser diffraction used as an additional method of soil particle distribution measurement allowed us to assess the changes of particle distribution

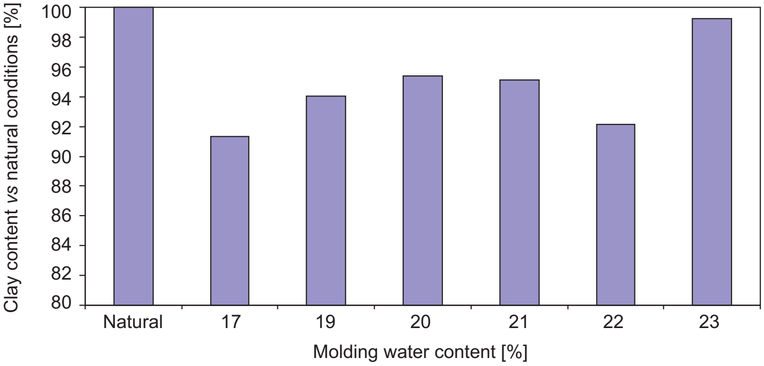

Fig 3. Changes of clay fraction content in compacted soil related to its content in natural undisturbed sample (100 %)

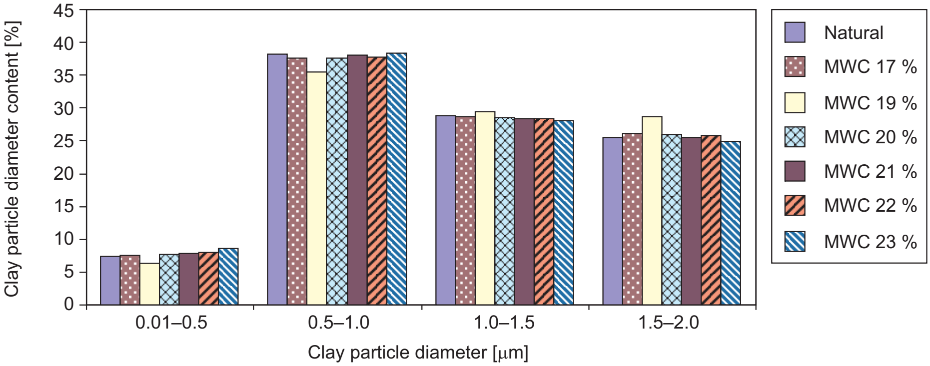

Fig 4. Clay particles distribution in tested soil samples after permeability tests, 100 % = total clay content (MWC = molding water content)

belonging to selected intervals of clay material's diameters inside the 0.01–2.0 micrometers range – see Fig. 4. The following intervals were tested: 0.01–0.5, 0.5–1.0, 1.0–1.5 and finally 1.5–2.0 micrometers. Fig. 4. shows that despite the fact that the total clay content after permeability tests changed to a small extent (Fig. 3), the contents of particles in tested sub-fraction are comparable.

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 and in Fig. 5.

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

Table 3

Saturated hydraulic conductivity, total porosity and bulk density of the soil dependent on molding water content

Tested parameter	Molding water content [% by weight]					
	14	17	19	21	22	23
Saturated hydraulic conductivity [$m \cdot s^{-1}$]	$3.936 \cdot 10^{-9}$	$1.000 \cdot 10^{-10}$	$7.325 \cdot 10^{-11}$	$3.694 \cdot 10^{-11}$	$3.280 \cdot 10^{-11}$	$3.210 \cdot 10^{-11}$
Soil bulk density after compaction [$Mg \cdot m^{-3}$]	1.604	1.659	1.702	1.707	1.707	1.669
Total porosity after compaction [$m^3 \cdot m^{-3}$]	0.386	0.365	0.349	0.347	0.347	0.361
Bulk density after swelling [$Mg \cdot m^{-3}$]	1.447	1.518	1.585	1.629	1.621	1.603
Total porosity after swelling [$m^3 \cdot m^{-3}$]	0.446	0.419	0.393	0.377	0.380	0.387

The decrease of hydraulic conductivity with the increase of molding water content, was very sharp ranging between 14 and 19 %, which is clearly visible in Fig. 5. Then, the value of saturated hydraulic conductivity decreased slightly, reaching an almost constant value for the highest molding water contents, between 21 and 23 %. The results of the laboratory measurement presented in Fig. 5 clearly show that increasing the molding water content for the tested clay soil from 14 to 23 % of gravimetric water content results in a decrease of saturated hydraulic conductivity by two orders of magnitude, *ie* over 100 times.

The changes of bulk density and total porosity are also related to molding water content. The observed changes of soil bulk density and of its total porosity resulting

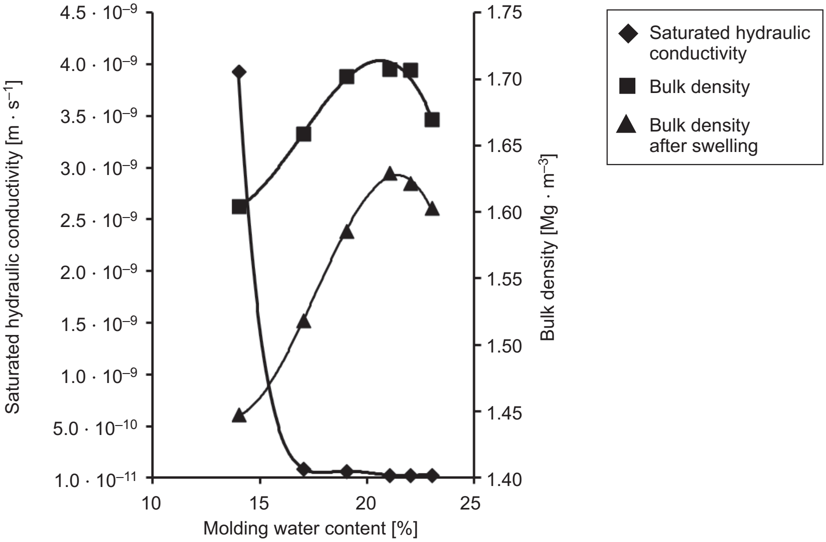

Fig. 5. Influence of molding water content by weight on saturated hydraulic conductivity, bulk density after Proctor test and bulk density after swelling for the tested clay material

from the increase of molding water content showed that for the tested clay soil sampled in Lazek Garncarski, the maximum value of soil bulk density and minimal value of total porosity were achieved for moisture content equal to 22 % by weight. The discussed changes in soil's bulk density induced changes of total porosity. The minimal observed porosity reached a value of 0.347 for the molding water content equal to 21 and 22 %. The highest degree of compaction results in the lowest porosity, limiting retention properties of soil.

Similar situations may be observed for changes of compacted soils bulk density after swelling. The maximum noted value of bulk density for swelled soil was observed at a molding water content of 21 %. Our studies showed the decrease in bulk density after swelling vs. bulk density of compacted soil in the range of 9.8 for 14 % of molding water content to 4.0 % for water contents of 21 and 23 %. The values of 13.5 to 6.6 % of compacted clay total porosity increase after swelling for molding water content of range 14–23 % were observed. These results support literature reports related to the increased water capacity of swelled clay materials.

The results of numerical calculations of water seepage (representing leachate infiltration) through a 1 m thick layer of the clayey material compacted with various molding water contents representing a bottom sealing liner of municipal waste landfill are presented in Fig. 6.

The results presented in Fig. 6 show that the hydraulic properties of the bottom mineral clay liner, which act 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

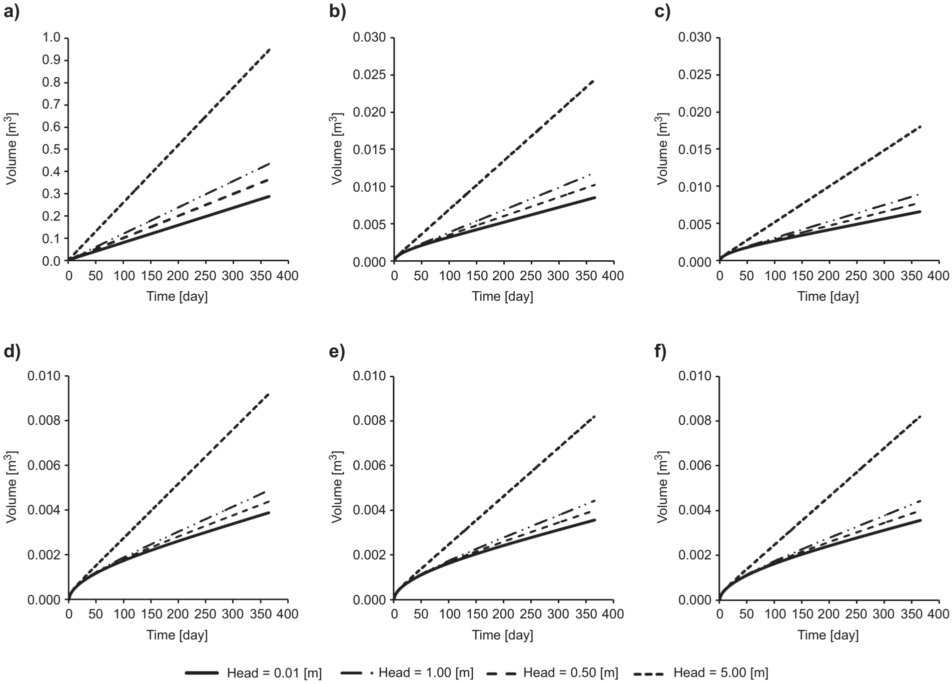

Fig. 6. Calculated cumulative volume of seepage through mineral bottom liner made of the clay soil compacted at different water contents: a) 14 %, b) 17 %, c) 19 %, d) 21 %, e) 22 %, f) 23 %

the bottom 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 for all the tested molding water contents and the applied water pressure head values

Molding water content [% by weight]	Mean daily seepage $[m^3 \cdot day^{-1}]$			
	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	$0.018 \cdot 10^{-3}$	$0.021 \cdot 10^{-3}$	$0.024 \cdot 10^{-3}$	$0.049 \cdot 10^{-3}$
21	$0.011 \cdot 10^{-3}$	$0.012 \cdot 10^{-3}$	$0.013 \cdot 10^{-3}$	$0.025 \cdot 10^{-3}$
22	$0.010 \cdot 10^{-3}$	$0.011 \cdot 10^{-3}$	$0.012 \cdot 10^{-3}$	$0.023 \cdot 10^{-3}$
23	$0.010 \cdot 10^{-3}$	$0.011 \cdot 10^{-3}$	$0.012 \cdot 10^{-3}$	$0.022 \cdot 10^{-3}$

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 bottom liner constructed of compacted clay material is obtained when the clay material is compacted at higher values of water content. This statement does not include the phenomenon of shrinkage potential which is much higher on the wetter branch of the Proctor curve and causes more intense cracking leading to preferential flow higher by several orders of magnitude [5].

Increasing molding soil water content from 14 to 23 % allowed for the reduction of the volume of seepage by two orders of magnitude for all the applied values of pressure head. However, the results of the calculations for the last three tested values of molding water content, *ie* 21 %, 22 % and 25 % show a minimal, insignificant decrease of daily seepage volume.

Conclusions

Our studies support literature reports proving that there is a direct relation between water content in a clay soil during compaction and its saturated water conductivity (inducing the modification of its general hydraulic characteristics). This relation creates more effective sealing properties, *ie* lower permeability of the compacted mineral liner when soil is compacted at higher values of water content. In our case, the increase of molding water content from 14 to 23 % resulted in a decrease of saturated hydraulic conductivity of the compacted soil from $3.936 \cdot 10^{-9}$ to $3.21 \cdot 10^{-11}$ $m \cdot s^{-1}$. Additionally, the performed numerical modeling of infiltration through the compacted clay liner showed that two orders of magnitude decrease daily infiltration rate through the 1.0 m thick clay liner, possible through the increase of molding water content by 9 % (from 14 to 23 %) 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 the construction of the municipal landfill cell liner of compacted clay material is crucial because it may significantly influence the effectiveness of the sealing, thus preventing migration of the pollutants into the natural environment. The possibility of soil cracking induced by dewatering reduces the sealing properties of the liner. This is significant in case of higher molding water contents, as it increases the shrinking potential of the soil. Our studies should be extended to include different types of clay soils and their shrinkage properties. The presented numerical assessment of water/leachate seepage through the modeled bottom liner in future should include various retention characteristics for each molding water content applied. The lack of validation in 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 PRZESŁON MINERALNYCH SKŁADOWISK ODPADÓW

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Abstrakt: Składowiska odpadów jako szczególnie uciążliwe dla środowiska budowle inżynierskie muszą być izolowane przesłonami w celu zapobiegania rozprzestrzeniania się wraz z m.in. odciekami 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 minerale 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 r. w sprawie składowania odpadów, przepuszczalność hydrauliczna przesłony była niższa niż $1 \cdot 10^{-9}$ m $\cdot$ 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, dolnej przesłony składowiska odpadów. Zakres pracy obejmował badania terenowe, laboratoryjne oraz modelowe. Przewodnictwo hydrauliczne gruntów w stanie naturalnym określono za pomocą polowej sony BAT, GeoNordic, przewodnictwo zaś w stanie pełnego nasycenia po zagęszczeniu pomierzono za pomocą przepuszczalnościomierzy Humboldt Mfg. Co. do gruntów zagęszczonych wg ASTM D5856. Ocenę właściwości hydraulicznych przesłon 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