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MODELING STUDIES OF HYDRAULIC EFFICIENCY OF COMPACTED WASTE LANDFILL CLAY LINER

MODELOWANIE FUNKCJONOWANIA PRZESŁONY SKŁADOWISKA ODPADÓW WYKONANEJ Z ZAGĘSZCZONEGO GRUNTU ILASTEGO

Abstract: Compacted clay materials are commonly used worldwide as sealing materials to prevent migration of anthropogenic pollutants from municipal landfill cells to the environment. Such clay barriers known as liners are sealing the top, sides and bottom of the landfill. They limit water infiltration to waste body and leachate seepage, usually with the required saturated hydraulic conductivity lower than $1.0 \cdot 10^{-9}$ m $\cdot$ s^{-1}. The value of resultant hydraulic conductivity of compacted clay liners and their sustainability affected by swelling and shrinking processes are related to molding water content. This paper presents results of studies concerning the influence of molding water content on saturated hydraulic conductivity and shrinkage/swelling properties of selected compacted clay materials as well as hydraulic properties of the top sealing liner, constructed according to the actual standards of compacted clay material. Our studies covered field and laboratory measurements as well as numerical modeling. Permeability and water retention characteristics of the clays were determined during field and laboratory tests. Saturated hydraulic conductivity under the natural in situ conditions was measured by BAT probe, GeoNordic. Hydraulic conductivity of the homogenized compacted clays was tested in the laboratory by Humboldt Mfg. Co. permeameters for compacted soils, according to ASTM D5856. Water retention characteristics of the compacted clays in the range of 0–15 bar pore water tension were determined by application of sand box and pressure chamber methods. The numerical assessment of the hydraulic efficiency of the clay liner was performed for the 2012 hydrologic year 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

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Introduction

Landfilling of municipal wastes and the subsequent possible migration of numerous pollutants to soil and water, especially by leachate seepage, pose a significant threat to the environment. Generation of leachate is usually triggered by infiltration of surface water, from precipitation and snow cover melting, which can enter the wastes body. Thus, the possible negative environmental impact of landfills depends on the efficiency of limiting the pollution by the applied techniques of landfill sealing [1]. The special barriers, known as liners, based on natural and geosynthetic materials prevent surface water infiltration and leachate migration to soil-water environment. One of the most popular and durable solution known and applied worldwide 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], which in the European Union should be lower than $1.0 \cdot 10^{-9}$ $m \cdot s^{-1}$. The saturated hydraulic conductivity of homogenized clays used as a liner construction material under natural conditions may be higher than the above value [5, 6] so the application of compaction is usually required. The compaction, decreasing the porosity of porous material, increases its resistance to water flow, significantly reducing the saturated hydraulic conductivity of the material [7]. The degree of reduction, however, depends on the applied molding water content of the clay. Thus, the molding water content becomes one of the most important factors influencing the hydraulic characteristics of the compacted clay liner [8–12].

On the other hand, molding water content affects also the swelling and shrinking properties of clays, influencing the sustainability of the liner [13–15]. Higher shrinking potential of compacted clays results in a significant risk of liner cracking, and thus, an increase of its permeability. The possible increased permeability of dried clay liners, additionally cracked when dewatered, significantly reduced the sealing capabilities and sustainability of the clay liner. The above issue is crucial in case of top liners where, due to a liner construction and its saturation affected by atmospheric conditions (*eg* precipitation, temperature, moisture). Actual Polish standards [2] require that the clay sealing layer of liner, of saturated hydraulic conductivity lower than $1.0 \cdot 10^{-9}$ $m \cdot s^{-1}$, and top recultivation layer should be separated by the sand drainage layer of saturated hydraulic conductivity greater than $1.0 \cdot 10^{-4}$ $m \cdot s^{-1}$. This feature, combined with possible significant inclination of layers' slope may trigger increased lateral flow and outflow of infiltration water and reduce the possibilities of wetting or rewatering of dried clay sealing layer.

This paper presents an attempt of determination of the effects of soil molding water content on its saturated conductivity, shrinking and swelling potentials and finally the hydraulic properties of the top sealing liner, constructed of tested clay according to the actual standards.

Materials and methods

Our research covered: *i*) determination of the general characteristics of the tested material, including its particle size distribution, particle density, bulk density and field, *in situ* saturated hydraulic conductivity, *ii*) measurement of saturated hydraulic conductivity for soil compacted at various water contents, *iii*) determination of soil's water retention characteristics after compaction, *iv*) measurement of swelling and shrinkage potential of tested soil, *v*) numerical modeling of infiltration process for clay liner allowing to assess its hydraulic efficiency for all applied molding water contents.

The presented studies were focused on mineral clay material sampled in Lazek Ordynacki, approx. 90 km south of Lublin, Poland.

The particle size distribution of the soil was determined by the standard sedimentation method according to PN-B-04481:1988 [16], solid particle density was measured in le Chatelier flask and air pycnometer according to Langer by Eijkelkamp, The Netherlands. Gravimetric water content was obtained by the standard weight method according to ASTM C566-13 [17]. 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 molding 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 [18], were applied to our studies. The soil was compacted, at different molding water contents, according to PN-B-04481:1988 [16].

The following values of molding water contents (by weight) were applied during our laboratory studies: 0.14, 0.17, 0.19, 0.21, 0.22 and 0.23 $kg \cdot kg^{-1}$. Water retention capabilities of the compacted clay material were tested in pore water 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. The retention characteristics were determined for the following values of pressure: 1, 2, 5, 7, 10, 50, 100, 500, 1000 and 1500 kPa.

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 selected part of 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 Fig 1.

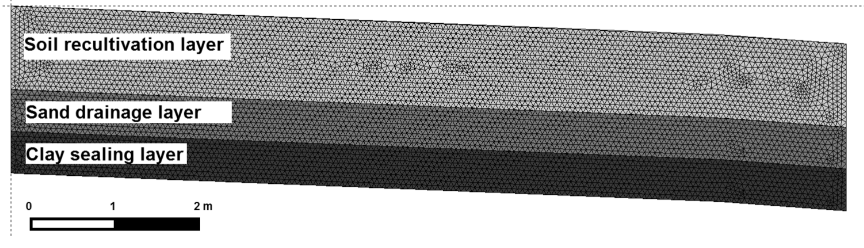

Fig. 1. Developed model of the selected section of municipal landfill top liner

Numerical calculations of the two dimensional water flow in FEFLOW were based on standard forms of Darcy's and Richards' equations [19–21]:

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

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

where: $\boldsymbol{q}_i$ – groundwater flux vector [m · s^{-1}],
h – hydraulic pressure head [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 [22]:

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

where: θ_s – saturated volumetric water content [m^3 · m^{-3}],
θ_r – residual volumetric water content [m^3 · m^{-3}], θ_r = 0 [m^3 · 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 [22]:

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

where: K_s – saturated conductivity [m · s^{-1}],
l – fitting parameter: l = 0.5 [22],
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 1. The isotropic hydraulic characteristics of clay and sand soil were assumed to our calculations due to the developed small scale model [23].

Table 1

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 θ_s [m^3 · m^{-3}]	0.29	0.37
Residual water content θ_r [m^3 · m^{-3}]	0	0.11
Water retention curve parameter A [m^{-1}]	7.65	2.30
Water retention curve parameter n [-]	1.10	7.70
Anisotropy ratio α [-]	0.17	1
Anisotropy rotation angle ϕ [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 a 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 [24]. Daily precipitation and runoff were measured by the local weather station and system of surface runoff measurement [24]. Measured values of daily precipitation were corrected, in order to exclude the series of measurement errors of the weather station (*eg* evaporation and wind loss), in accordance to Richter's correction method [25]. Reference daily evapotranspiration was calculated according to the standard Penman-Monteith formula [26, 27], basing on measured weather data and assumed data. Plant cover data (LAI, leaf area index) and assessment of daily interception were performed according to Mitchell et al [28] and Hoyningen-Huene formula [29].

The developed top boundary condition is presented in Fig. 2. The values of daily water flux through the top boundary of modeled domain were obtained by the following formula [24]:

$$q = -P_{\text{corr}} + EV_a + I + q_{\text{runoff}}$$

where: q – daily water flux [mm · day^{-1}],
P_{corr} – corrected daily precipitation [mm · day^{-1}],
EV_a – actual daily evapotranspiration [mm · day^{-1}],
I – daily interception [mm · day^{-1}],
q_{runoff} – daily surface runoff [mm · day^{-1}].

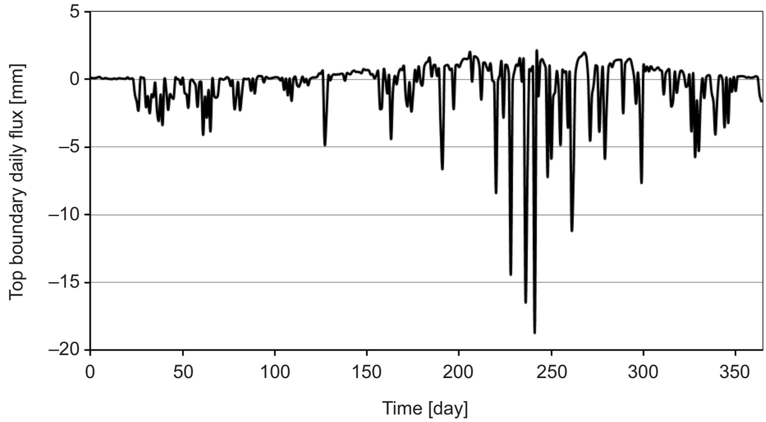

Fig. 2. Assumed top boundary condition, negative values mean infiltration, positive evapotranspiration, based on [25]

Results and discussion

The basic characteristics of sampled clay are presented in Table 2. The tested soil texture class was recognized as silty clay.

The natural, measured in situ hydraulic conductivity of tested soil, lower than $1 \cdot 10^{-9}$ $m \cdot s^{-1}$ meets requirements of the actual Polish and European standards [2, 3] for sealing layers of municipal landfill cells.

Table 2

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 [$Mg \cdot m^{-3}$]		2.61
Bulk density [$Mg \cdot m^{-3}$]		1.69
Saturated hydraulic conductivity [$m \cdot s^{-1}$]		$1.37 \cdot 10^{-10}$

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, Fig. 3 and Fig. 4.

The results presented in Table 3 and in Fig. 3 show a clear decrease of saturated hydraulic conductivity of clay resulting from the increase of molding water content. In most tested cases of compaction at 0.17, 0.19, 0.21, 0.22 and 0.23 $kg \cdot kg^{-1}$ 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. However, in case of molding

Table 3

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

Parameter	Molding water content [kg · kg^{-1}]					
	0.14	0.17	0.19	0.21	0.22	0.23
Saturated hydraulic conductivity [m · s^{-1}]	$3.94 \cdot 10^{-9}$	$1.00 \cdot 10^{-10}$	$7.33 \cdot 10^{-10}$	$3.69 \cdot 10^{-11}$	$3.28 \cdot 10^{-11}$	$3.21 \cdot 10^{-11}$
Bulk density after compaction [Mg · m^{-3}]	1.60	1.66	1.70	1.71	1.71	1.7
Bulk density after swelling [Mg · m^{-3}]	1.45	1.52	1.59	1.63	1.62	1.60
Bulk density after shrinkage [Mg · m^{-3}]	1.80	1.86	1.97	1.93	1.96	2.02
Saturated water content θ_s [m^3 · m^{-3}]	0.388	0.365	0.350	0.346	0.346	0.350
Water retention curve parameter A [m^{-1}]	0.569	0.105	0.928	0.675	0.849	0.100
Water retention curve parameter n [-]	1.118	1.197	1.123	1.116	1.113	1.155

water content equal to 0.14 kg · kg^{-1}, the measured saturated hydraulic conductivity of $3.94 \cdot 10^{-9}$ m · s^{-1} was higher than allowed by the actual Polish and European Union regulations [2, 3].

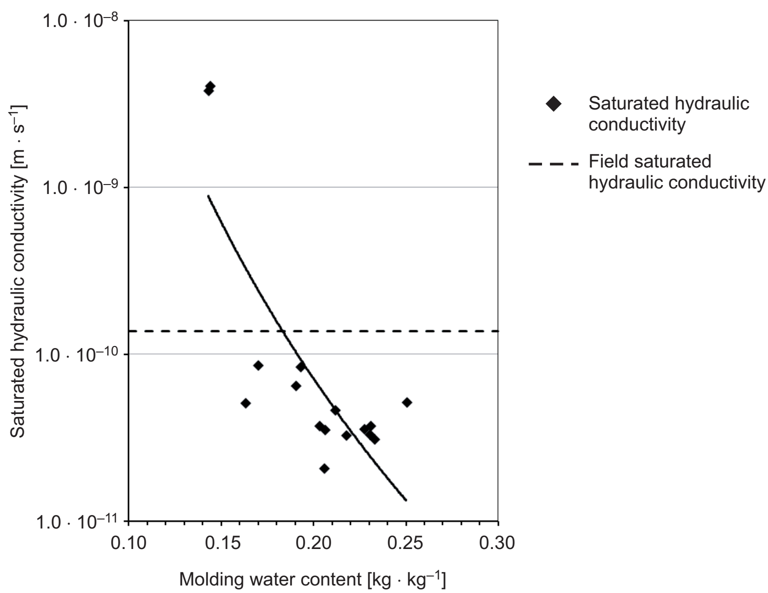

Fig. 3. Saturated hydraulic conductivity of clay material compacted at different water contents

The observed bulk densities of compacted clay, presented in Fig. 4, show that the maximum value of bulk density, identifying the highest possible degree of compaction, was achieved for molding water content of 0.21 kg · kg^{-1}. The highest swelling potential (difference between soil bulk density and bulk density after swelling) equal to 0.16 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 materials should be performed on the left, “dry”, side of Proctor curve. In our case, molding water content between 0.17 and 0.21 kg · kg^{-1} seems to be suitable.

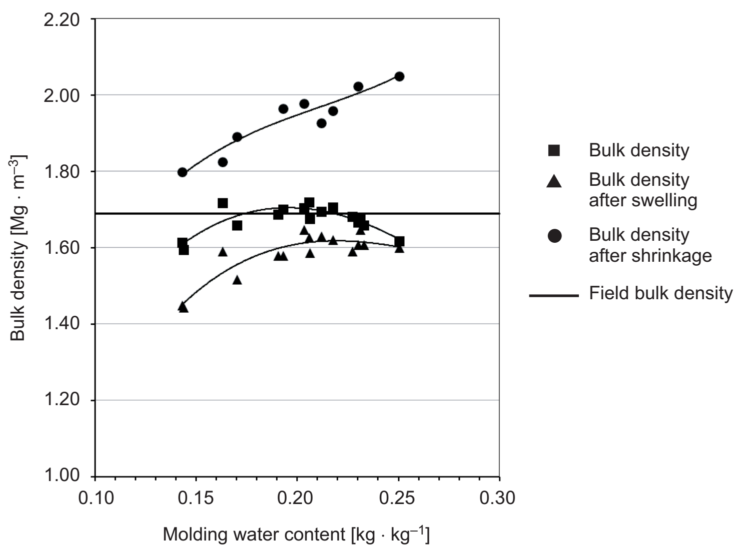

Fig. 4. Bulk density of the clay compacted at various molding water contents

The results of numerical calculations of water seepage through a 10.0 m section of liner utilizing clay compacted at various molding water contents as sealing layer are presented in Fig. 5. The results presented in Fig. 5 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 $5.41 \cdot 10^{-3}$ m^3 to $1.8 \cdot 10^{-5}$ m^3. Fig. 5 shows also that there is no significant difference in sealing capabilities after reaching the maximum bulk density during the compaction process.

Results of our numerical calculations show that seepage rate through the sealing liner is significantly limited due to scarce permeability of compacted clay and construction of the tested liner resulting from actual requirements of Polish standards. The studied layer

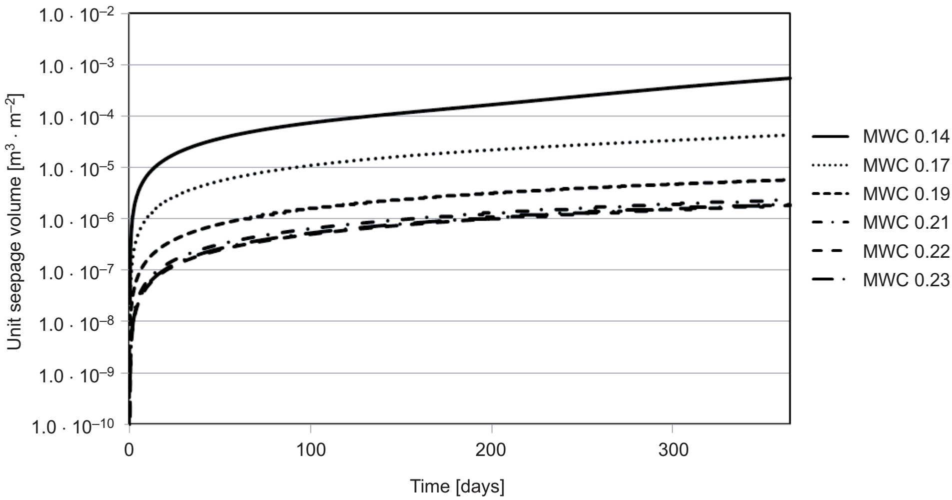

Fig. 5. Calculated yearly cumulative volume of seepage through the bottom boundary of mineral liner made of the clay compacted at different water contents (MWC)

composition, meeting the biding law regulations, assumed the sand drainage layer of thickness 0.5 m located above the compacted clay layer. Thus, two adjacent liner layers were made of materials of a very high difference in permeability, $2 \cdot 10^{-4}$ versus 10^{-9} – 10^{-11} $m \cdot s^{-1}$. In this case, the significant lateral fluxes, above the top boundary of sealing layer are possible, which was also observed in our modeling results. Figure 6 shows contour plots of saturation degree and module of velocity vector, together with velocities vector lines for an exemplary time step for 0.22 $kg \cdot kg^{-1}$ molding water content clay liner.

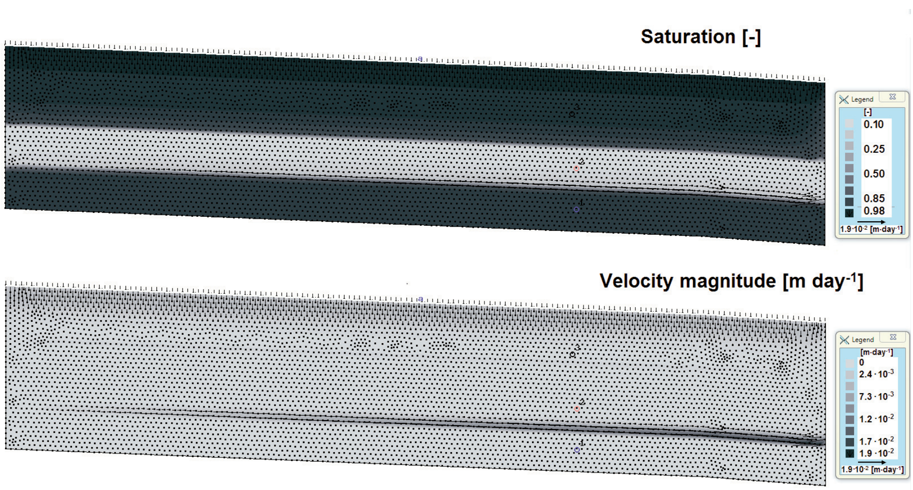

Fig. 6. Contours of saturation degree and velocity magnitude for t = 340 day

It is clearly visible that lateral velocity of flow in drainage layer, directly above the top boundary of compacted clay sealing reaches the highest, dominant values, approx. $2.0 \cdot 10^{-2}$ meters per day, in comparison to water flow in recultivation (range of approx. $2.0 \cdot 10^{-3} – 5.0 \cdot 10^{-3}$m · day^{-1}) and sealing layer (range of $3.0 \cdot 10^{-9}$ m · day^{-1}). As the result, the significant side outflow was observed for the drainage layer. The observed modeled mean daily lateral outflow for the drainage sand layer was approx. $2.0 \cdot 10^{-3}$ m · day^{-1} per m^2, while the modeled mean seepage through the compacted sealing clay liner was in range between $1.5 \cdot 10^{-6}$ and $5.0 \cdot 10^{-9}$ m · day^{-1} per m^2 for molding water content between 0.14 and 0.23 kg · kg^{-1}, respectively. Thus, sealing liners significantly reduces surface water infiltration into waste body. However, the huge lateral outflow through the sand drainage layer limits also increase of sealing layer saturation. The incensement of saturation degree of compacted clay liner in relation to the initial condition was observed only for molding water contents of 0.14 and 0.17 kg · kg^{-1}. So, drying, and shrinkage of clay liner may be possible in case of increased outflow through steep drainage layer.

Conclusions

Our studies are in agreement with literature reports 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 $1.0 \cdot 10^{-10}$ m · s^{-1} to $3.21 \cdot 10^{-11}$ m · s^{-1}, due to increase of applied molding water content from 0.17 kg · kg^{-1} to 0.23 kg · kg^{-1}. Molding water content equal to 0.14 kg · kg^{-1} was insufficient to ensure saturated hydraulic conductivity lower than $1.0 \cdot 10^{-9}$ m · s^{-1}. Additionally, the modeled decrease of seepage percolating through the top liner for the same range of molding water content variability reached two orders 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, at or below the maximum bulk density. There was also no significant decrease of permeability and seepage volume observed for the right side of Proctor's curve. However, 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 environment. Additionally, the construction of top landfill cover should prevent the increased lateral water flow, which may reduce the possibility of clay sealing layer saturation or resaturation after drying. The high difference of permeability and water storage capacities of drainage and sealing layers required by actual Polish standards may result in inhibited infiltration of water to clay liner.

Acknowledgements

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Abstrakt: Zagęszczone materiały ilaste są powszechnie używane jako materiał uszczelniający zapobiegający migracji zanieczyszczeń antropogenicznych ze składowisk odpadów komunalnych do środowiska naturalnego. Bariery ilaste, zwane także przesłonami, uszczelniają powierzchnię, boki oraz dno składowiska, ograniczając infiltrację wód powierzchniowych oraz przesączenie się odcieków, zazwyczaj dzięki wymaganej przepuszczalności wodnej poniżej $1.0 \cdot 10^{-9}$ m $\cdot$ s^{-1}. Wartość wypadkowa przewodnictwa hydraulicznego zagęszczonej przesłony ilastej oraz jej trwałość uzależnione od procesów skurczu i pęcznienia iłów, są bezpośrednio związane z zastosowaną wilgotnością zagęszczania. Niniejsza praca przedstawia wyniki badań dotyczących wpływu wilgotności zagęszczania gruntu na wartość współczynnika przewodnictwa hydraulicznego w stanie nasyconym, charakterystykę skurczu i pęcznienia oraz właściwości górnej przesłony składowiska odpadów zbudowanej zgodnie z aktualnymi normami z gruntu ilastego. Zaprezentowane badania obejmowały badania terenowe, laboratoryjne oraz studia modelowe. Przepuszczalność badanego gruntu oraz jego właściwości retencyjne zostały przebadane in situ oraz w warunkach laboratoryjnych. Współczynnik przewodnictwa hydraulicznego w stanie nasyconym w warunkach polowych zmierzono za pomocą przepuszczalnomierza polowego BAT GeoNordic, przepuszczalność nasyconą zagęszczonych materiałów ilastych zmierzono w warunkach laboratoryjnych za pomocą przepuszczalnościomierzy do gruntów zagęszczonych H-4145 Humboldt Mfg. Co., zgodnych z ASTM D5856. Charakterystykę retencyjną badanego gruntu po zagęszczeniu w zakresie 0–15 barów 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