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ASSESSMENT OF SEEPAGE THROUGH MUNICIPAL LANDFILL CLAY LINERS AFTER CYCLIC DRYING AND REWETTING

OCENA PRZESIĄKU PRZEZ CYKLICZNIE OSUSZANE I NAWILŻANE PRZESŁONY ILASTE SKŁADOWISK ODPADÓW KOMUNALNYCH

Abstract: One of the main threats to the sustainability of municipal landfills and quality of water-soil environment is being posed by the leachate percolation through the bottom sealing liner. The compacted mineral liners, utilizing clays of various plasticity to obtain the saturated hydraulic conductivity lower than $1\cdot10^{-9}$ m·s^{-1}, are one of the most popular manners of landfill isolation. However, the clayey substrates of high plasticity present a very high expansivity and are prone to swelling, shrinkage and cracking. Swelling and shrinkage of compacted clay liners, resulting from the cyclic drying and watering of clay substrate, are irreversible and after several cycles may result in a significant increase in the hydraulic conductivity and drastically decreasing sealing capabilities of compacted clay liners. This paper presents the attempt of determination the influence of the selected substrates' plasticity for compacted clay liner of municipal landfill undergoing cyclic drying and rewetting on the isolating capabilities of the municipal landfill's bottom liner. The plasticity of tested clay materials was determined and classified by the standard methods. Saturated hydraulic conductivity of the studied substrates compacted by the standard Proctor method was measured by the laboratory falling head permeameters for compacted soils. Measurements of saturated hydraulic conductivity of the tested substrates after three cycles of drying and rewetting were performed in the standard 100 cm^3 steel cylinders by the falling and constant head laboratory permeameter. Determination of water seepage through the tested bottom compacted clay liners was based on the standard form of Darcy law for the saturated conditions. The obtained results showed influence of plasticity of clays on decrease in their sealing capabilities after several cycles of drying and rewetting and, by extension, undesirable increase in the seepage volume through the compacted bottom liner.

Keywords: clay materials, compacted mineral liners, hydraulic conductivity, sustainable landfilling

Introduction

According to Allen [1] the sustainable landfilling should be understood as "the safe disposal of waste within a landfill, and its subsequent degradation to the inert state in the shortest possible time-span, by the most financially efficient method available, and with minimal damage to the environment". Among the all possible aspects of sustainable landfilling, the environmental impacts, related to limiting the possible threats to water and soil are the crucial issue [2]. The main threats to surface waters, groundwater and soil are posed by leachate percolating through the liners isolating landfill from the environment [3-5]. Thus, seepage of leachate from the deposited wastes should be completely prevented by the bottom liners which are often constructed of natural materials, of appropriate permeability (commonly below $1\cdot10^{-9}$ m·s^{-1} [6-8]) often additionally supported by the plastic or geosynthetic membranes [9-13]. So in the discussed case, the sustainability of the landfill is related to the sustainability and durability of its bottom liner.

Bottom liners of the landfills are commonly based on various types of compacted clays as the natural materials of a very low hydraulic conductivity [14, 15]. But compacted clays,

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or even some sandy soils containing fine particles, present significant expansiveness, related, among the others, to their plasticity and forming conditions [16, 17]. The expansive soils are able to significantly increase their volume (to swell) when saturated and to reduce their volume (to shrink) when dewatered [16]. Both phenomena result in changes of soils' saturated conductivity and sealing capabilities. Moreover, swelling and shrinkage are irreversible processes resulting in cracking and changes in unsaturated and saturated hydraulic conductivity; soils or substrates specimens once swelled or shrinked are generally unable to return to their initial characteristics [18]. The each following cycle of drying and rewetting changes swelling and shrinkage properties as well as hydraulic characteristics of clays. The equilibrium was reported to be usually achieved after several cycles (3 to 5), when changes in expansivity of clays are already limited [16, 19-23]. So, the sustainability and durability of the correctly formed clay liners may be reduced by the decrease in their sealing capabilities caused by changes in their hydraulic properties related to molding conditions and soil properties, including plasticity, as well as to changes caused by cyclic drying and rewetting.

This paper presents the attempt of determination the influence of the plasticity of the selected substrates for compacted clay liner of municipal landfill undergoing cyclic drying and rewetting on the isolating capabilities of the municipal landfill's bottom liner constructed according to the actual standards.

Materials and methods

The presented studies were based on the clay materials sampled in six locations close to Lublin, Poland. Materials sampled in Bychawa and Lazek Ordynacki were recognized as silty clays, while in Pawlow and Mejznerzyn as clays. Finally, substrates from Markowicze and Gawlowka were described as clay loam and sandy clay loam, respectively. The basic characteristics of the sampled substrates are presented in Table 1.

Table 1

Basic characteristics of the tested clay materials, modified after [24, 25]

Substrate		**Bychawa**	**Lazek Ordynacki**	**Pawlow**	**Mejznerzyn**	**Markowicze**	**Gawlowka**
Particle fraction	Sand [%]	12	4.5	11	13	25	66
	Silt [%]	46	51	37	35	37	3
	Clay [%]	42	44.5	52	52	38	31
Solid particle density [$\mathrm{Mg \cdot m^{-3}}$]		2.72	2.68	2.61	2.79	2.76	2.86
Bulk density [$\mathrm{Mg \cdot m^{-3}}$]		1.64	1.70	1.67	1.37	1.97	1.95
Saturated hydraulic conductivity in situ [$\mathrm{m \cdot s^{-1}}$]		$2.75 \cdot 10^{-10}$	$1.37 \cdot 10^{-10}$	$2.51 \cdot 10^{-10}$	$2.05 \cdot 10^{-10}$	$1.00 \cdot 10^{-10}$	$4.73 \cdot 10^{-10}$

The particle size distribution of the tested clay materials was determined according to PN-B-04481:1988 [26], 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 [27].

The plasticity of tested clay materials was determined by the standard methods [28] and classified according to the Unified Soil Classification System [29]. Saturated hydraulic conductivity (K_s) of the studied substrates under their natural conditions was measured in situ by the field falling head permeameter BAT produced by GeoNordic, Sweden.

Laboratory measurements of saturated conductivity of the tested substrates after compaction 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 [30], were applied to our studies. The tested clay substrates were compacted, according to PN-B-04481:1988 [26] at the optimum water content (w_{opt}) and at commonly advised for compacted liner construction 95% of maximum bulk density and $w_{opt} < w_f < 1.2\ w_{opt}$.

To measure the saturated hydraulic conductivity of the tested materials after three cycles of shrinkage and swelling, the compacted and saturated materials were sampled to the standard 100 cm^3 steel cylinders. All the samples were air dried at room temperature, approx. 20ºC, and slowly rewetted by the capillary saturation. After each of the three drying and wetting cycles, saturated hydraulic conductivity measurements were performed with constant or falling head method (depending on the value of the measured parameter, above $K_s = 1\cdot10^{-5}$ m·s^{-1} the constant head method was used) in a laboratory permeameter, produced by the former IMUZ, Lublin, Poland.

Assessment of seepage through the bottom liners utilizing the tested clayey substrates determined for the assumption of its operation at saturated, or very close to saturated, conditions. Thus, the standard form of Darcy equation was used for determination of the seepage flux for 1 m^2 of liner area:

$$q_D = K_s \frac{dh}{dl}$$

where: q_D - Darcy unit flux [m·s^{-1}], $\frac{dh}{dl}$ - pressure head gradient.

Calculations of seepage were performed in MS Excel, for the assumed thickness of bottom compacted clay liner equal to 1 m, meeting the requirements of Poland's national standards [7], and constant pressure head 0.3 m, as typical maximum leachate head over the bottom liner for the normally operating municipal landfill [31]. The assessment was performed for K_s measured in the laboratory conditions for substrates formed at 95% of maximum bulk density and $w_{opt} < w_f < 1.2\ w_{opt}$.

Results and discussion

The results of tested clay substrates plasticity determination, as well as the measured saturated hydraulic conductivity K_s for the optimal water content w_{opt} and the applied molding water w_f content are presented in Figure 1 and Table 2.

The results presented in Figure 1 and Table 2 show that all the tested clay substrates, regarding their different particle composition and Atterberg limits allowed the required value of saturated hydraulic conductivity lower than $1\cdot10^{-9}$ m·s^{-1} for optimum and forming water contents, wet of optimum, for 95% of maximal density and $w_{opt} < w_f < 1.2\ w_{opt}$.

Figure 2 shows results of measurements of K_s after three subsequent cycles of drying and rewetting, resulting in cyclic shrinkage and swelling.

The results of K_s measurements presented in Figure 2 show that none of the tested substrates was able to sustain its sealing capabilities after three cycles of drying and rewetting. In all the tested cases the measured saturated hydraulic conductivity after shrinkage and swelling was greater than commonly allowed $1\cdot10^{-9}$ m·s^{-1}. The greatest increase of K_s was observed for substrates of the highest plasticity indices, *i.e.* Lazek Ordynacki and Mejznerzyn, for which the K_s after the 3rd cycle exceeded even the value of $1\cdot10^{-7}$ m·s^{-1} allowed by the American standards for the top cover of municipal landfill [32].

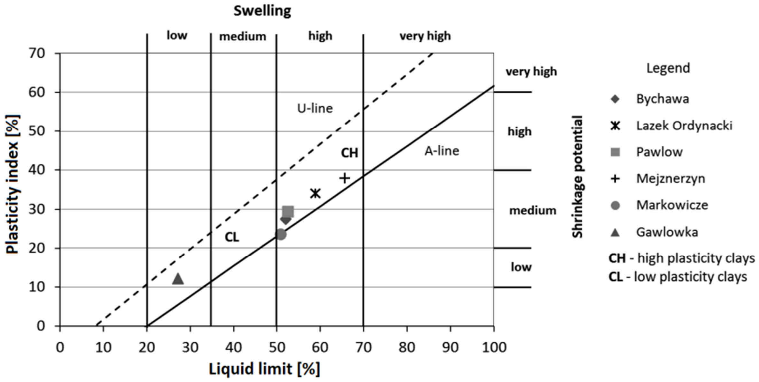

Fig. 1. Plasticity chart of tested clay substrates, modified after [25]

Table 2

Optimum and forming water contents as well as resultant K_s for tested substrates

Substrate	Bychawa	Lazek Ordynacki	Pawlow	Mejznerzyn	Markowicze	Gawlowka
w_{opt}/w_f [kg·kg^{-1}]	0.22/0.25	0.21/0.25	0.19/0.22	0.26/0.30	0.16/0.20	0.13/0.15
K_s at w_{opt} [m·s^{-1}]	$2.75\cdot10^{-11}$	$2.09\cdot10^{-11}$	$5.66\cdot10^{-11}$	$2.86\cdot10^{-11}$	$9.35\cdot10^{-11}$	$4.42\cdot10^{-10}$
K_s at $w_{opt} < w_f < 1.2\ w_{opt}$ [m·s^{-1}]	$6.15\cdot10^{-11}$	$5.20\cdot10^{-11}$	$4.17\cdot10^{-11}$	$2.46\cdot10^{-11}$	$1.17\cdot10^{-10}$	$9.45\cdot10^{-11}$
Recognized type of clay	CH	CH	CH	CH	CH	CL

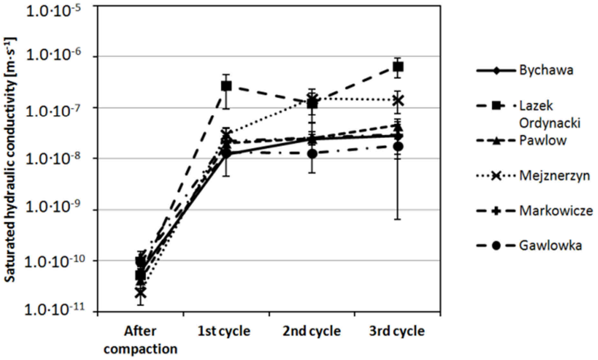

Fig. 2. Measured K_s after subsequent cycles of drying-rewetting for substrates formed wet of optimum

The observed relation between substrates' indices of plasticity and resultant K_s after the final third cycle of drying and rewetting is presented in Figure 3. It is clearly visible in

Figure 3 that the increase in plasticity index of compacted substrate allows to achieve the greater decrease of its saturated hydraulic conductivity after forming, resulting in better sealing capabilities of the compacted clay liner. But, on the other case, the higher plasticity led to increased cracking and decrease in substrates' sealing capability by increase in hydraulic conductivity.

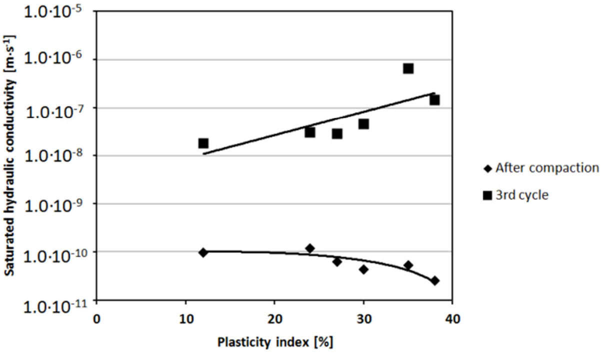

Fig. 3. Relation between plasticity and K_s of clays after compaction and after the final cycle of shrinkage and swelling

To fully underline the above presented phenomenon, daily seepage assessment was performed for 1 m^2 meter of the bottom liner constructed to meet the actual Polish and European landfilling standards [6-8] and utilizing tested substrates as the sealing material. The results of our calculations are presented in Figure 4.

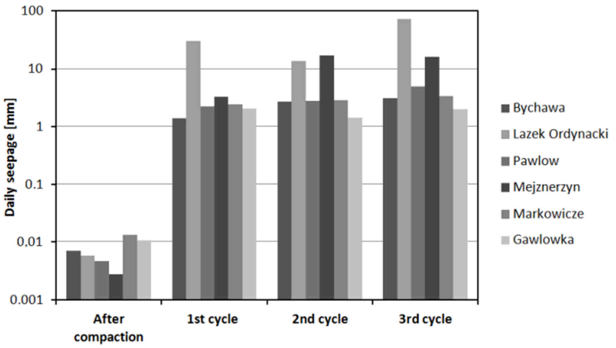

Fig. 4. Calculated daily seepage for each studied substrate and phase of cyclic drying and rewetting

As it is visible in Figure 4, the irreversible changes in compacted clays structure caused by cyclic shrinkage and swelling resulted in clear increase of the calculated daily seepage. The tested clay materials directly after compaction showed satisfactory sealing capabilities allowing the daily seepage max at the level of 0.01 mm. Then, cyclic drying and rewetting drastically reduced the sealing capabilities of the tested clay substrates, the calculated seepage increased by 2-3 orders of magnitude. The greatest increase in calculated seepage values were observed for substrates of the highest noted plasticity indices, *i.e.* materials sampled in Lazek Ordynacki and Mejznerzyn. The observed values of daily seepage reached the level of 16 and 74 mm after the third, final tested cycle of shrinkage and swelling for Lazek Ordynacki and Mejznerzyn substrates, respectively.

Summary and conclusions

Our studies showed that despite the fact that all the tested clayey substrates were able to assure the required significant sealing capabilities due to a very low value of K_s after compaction, the cyclic shrinkage and swelling drastically reduced the sealing capabilities of the tested materials. The irreversible cracking of the studied substrates triggered the significant increase in their saturated hydraulic conductivity, thus, leading to the enhanced volume of daily seepage. However, the observed increase in seepage was not uniform. There was observed the relation between the plasticity index of clays and increase in K_s and resultant seepage after cyclic drying and rewetting. Generally, the higher plasticity index of tested substrate, the greater K_s and resultant seepage after shrinkage and swelling were observed. Thus, in our opinion, the high plasticity clays presenting a significant decrease in their sealing capabilities after several cycles of drying and rewetting should be avoided in construction of compacted clay liners to ensure the long-term sustainability of landfill isolation and prevent increased pollutants migration to the natural soil and water environment.

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Abstrakt: Jednym z głównych zagrożeń dla zrównoważoności składowiska odpadów komunalnych oraz jakości środowiska gruntowo-wodnego jest infiltracja odcieków poprzez dno składowiska. Przesłony mineralne z materiałów ilastych o różnej plastyczności, zagęszczonych tak aby uzyskać współczynnik filtracji niższy niż $1 \cdot 10^{-9}$ $m \cdot s^{-1}$, są jednym z podstawowych sposobów zapewniania izolacji składowisk. Jednakże grunty ilaste o wysokiej plastyczności są materiałami o wysokiej ekspansywności, podatnymi na pęcznienie, skurcz oraz spękanie. Pęcznienie i skurcz, powodowane przez następujące po sobie cykle nawilżania i osuszania ilastej zagęszczonej przesłony mineralnej, są nieodwracalne i po kilku cyklach mogą doprowadzić do znacznego zwiększenia przewodnictwa wodnego, zarazem drastycznie zmniejszając zdolności izolacyjne zagęszczonych iłów. Praca niniejsza przedstawia próbę określenia wpływu plastyczności wybranych gruntów przesłony mineralnej składowiska odpadów poddanego cyklicznemu osuszaniu i nawilżaniu na zdolności izolacyjne dolnej przesłony składowiska odpadów komunalnych. Plastyczność badanych gruntów określono metodami standardowymi i sklasyfikowano według Unified Soil Classification System. Współczynnik filtracji gruntów w stanie pełnego nasycenia po zagęszczeniu wyznaczono za pomocą przepuszczalnościomierzy do gruntów zagęszczonych. Pomiary współczynnika filtracji po trzech cyklach osuszania i nawilżania przeprowadzono dla próbek w cylindrach 100 cm^3 za pomocą przepuszczalnościomierza laboratoryjnego. Obliczenia przesiąku przez dolną zagęszczoną warstwę izolacyjną składowiska oparto na standardowej postaci równania Darcy'ego dla strefy saturacji. Uzyskane wyniki wykazały wpływ plastyczności iłów na zmniejszenie ich właściwości izolacyjnych po kolejnych cyklach osuszania i nawilżania, a co za tym idzie, niepożądany wzrost objętości przesiąku przez dolną warstwę izolacyjną składowiska.

Słowa kluczowe: materiały ilaste, zagęszczone przesłony mineralne, przewodnictwo hydrauliczne, zrównoważone składowiska odpadów