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SEEPAGE THROUGH MUNICIPAL LANDFILL CLAY LINERS AFTER CYCLIC DRYING AND REWETTING

PRZESIAK PRZEZ CYKLICZNIE OSUSZANE I NAWILŻANE PRZESŁONY MINERALNE SKŁADOWISK ODPADÓW KOMUNALNYCH

Abstract: The sustainability of municipal landfills and quality of water-soil environment is being compromised by the leachate percolation through the bottom sealing liner. The compacted mineral liners, using clays of various plasticity to assure the saturated hydraulic conductivity lower than $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$, are among the most popular isolations of municipal waste landfills. But high plasticity clays present significant expansivity so they are prone to swelling, shrinkage and resultant cracking. Swelling and shrinkage of compacted clay liners, caused by cyclic drying and watering of substrate, are irreversible and after several cycles may result in a huge increase in the hydraulic conductivity and drastically reduced sealing capabilities of compacted clay liners. This paper presents the assessment of selected substrates' plasticity influence on the isolating capabilities of the municipal landfill's bottom liner undergoing cyclic drying and rewetting. The plasticity of tested clay materials was determined and classified by the standard methods. Saturated hydraulic conductivity of the studied clays formed 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. Shrinkage of the tested compacted specimens was determined also in the standard 100 cm^3 steel cylinders and classified basing on dimensionless indicator *COLE*. Determination of water seepage through the tested bottom compacted clay liners was based on the standard form of Darcy law for the saturated conditions of soil medium. 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

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Introduction

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” [1]. The environmental impacts, related to limiting the possible threats to water and soil are the crucial issue among the all possible aspects of sustainable landfilling [2]. The most serious threats to water, including surface water and groundwater, as well as to soil are posed by leachate percolating through the liners isolating landfill from the environment [3–5]. Thus, leachate seepage from the deposited waste body should be completely prevented by the landfill’s bottom liners, which are often constructed using the natural materials of appropriate permeability (commonly below $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$ [6–8]), frequently additionally supported by the plastic or geosynthetic membranes [9–13]. So, in the presented case, the sustainability of the landfill is going to be related to the sustainability and durability of its bottom liner.

Bottom landfills’ liners are commonly based on various types of the compacted clays as the natural mineral materials presenting a very low hydraulic conductivity [14, 15]. But compacted clays, 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 clayey soils significantly increase their volume (swell) when saturated and when dewatered they reduce their volume (shrink) [16]. Swelling and shrinkage are the irreversible processes resulting in cracking and changes in unsaturated and saturated hydraulic conductivity; soils or substrates specimens once swelled or shrunk are generally unable to return to their initial characteristics [17]. The observed increase in hydraulic conductivity is generally related to forming conditions, the grater molding water content applied, the higher possible increment of hydraulic conductivity after shrinkage [15–18].

The each following cycle of drying and rewetting alters 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. But the resultant hydraulic conductivity of clays specimens after reaching equilibrium may increase significantly, even by several orders of magnitude, to the values typical for the coarse sandy soils [17–24]. The discussed decrease in sealing capabilities of compacted clay liners after several cycles of drying and wetting is also related to forming conditions, including initial water content [17, 18].

So in our opinion, the sustainability and durability of the compacted 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 forming water content and 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, bidding standards.

Materials and methods

The presented studies were based on the clay materials sampled in six locations close to Lublin, SE part of Poland: Bychawa, Lazek Ordynacki, Pawlow, Mejnierzyn, Markowicze and Gawlowka [25]. Materials sampled in Bychawa and Lazek Ordynacki were recognized as silty clays, while in Pawlow and Mejnierzyn 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 Stepniewski et al [24] and Widomski [18]

Substrate		Bychawa	Lazek Ordynacki	Pawlow	Mejnierzyn	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 [Mg · m ⁻³]		2.72	2.68	2.61	2.79	2.76	2.86
Bulk density [Mg · m ⁻³]		1.64	1.70	1.67	1.37	1.97	1.95
Saturated hydraulic conductivity in situ [m · 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 clayey materials was determined according to the Polish national standard PN-B-04481:1988 [26], while 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 Atterberg limits, including liquid limit and plasticity index of tested clay materials were determined by the standardized 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 for fine grained soils produced by GeoNordic, Sweden.

Laboratory measurements of saturated conductivity of the tested substrates after forming at different initial water contents were performed in the permeameters for compacted soil specimens by Humboldt Mfg. Co, USA. The falling water head H-4145 compaction permeameters, 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, wet of optimum $w_{opt} < w_f < 1.2 w_{opt}$ and dry of optimum, at $w_f < w_{opt}$.

The applied H-4145 were supplied with water from the top, according to the scheme presented in Fig. 1, after [18].

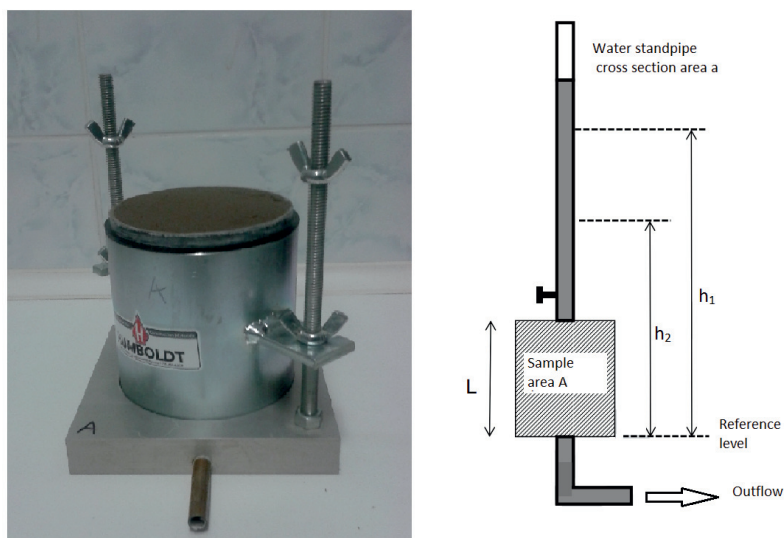


Fig. 1. Laboratory permeameter for compacted specimens H-4145 and scheme of its application, after [18]

Saturated hydraulic conductivity of compacted specimens of tested clayey materials was determined by the falling head method and the standard formula presented below, after *eg* [18]:

$$K_s = \frac{a \cdot L}{A_s \cdot \Delta t} \ln \frac{h_1}{h_2}$$

where: K_s – coefficient of saturated hydraulic conductivity, [$\text{m} \cdot \text{s}^{-1}$];
 a – water standpipe cross section area, [m^2];
 A_s – soil sample cross section area, [m^2];
 L – soil sample height, [m];
 h_1, h_2 – water level heights, [m];
 Δt – time duration required for lowering water level from h_1 to h_2 , [s].

Measurements of saturated hydraulic conductivity in H-4145 rigid wall permeameters were continued until observation of constant values of the resultant K_s .

The saturated hydraulic conductivity of the tested materials after three cycles of shrinkage and swelling, was determined for compacted and saturated specimens sampled to the standard 100 cm^3 steel cylinders directly from the compaction molds. All the samples were first air dried at room temperature, approx. 20°C degree, and afterwards slowly rewetted by the capillary saturation. After each applied drying and wetting cycle, saturated hydraulic conductivity was measured by the constant or falling head method, (depending on the value of the measured parameter, above $K_s = 1 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$ the constant head method was used) in the laboratory permeameter, produced by the former IMUZ, Lublin, Poland.

Shrinkage of clays compacted wet and dry of optimum for approx. 95% of optimum density was measured in 100 cm³ steel cylinders, sampled directly from the compaction molds, according to the methodology similar to that reported by Peng et al [31], Dorner et al [21] and Gerbhardt et al [32]. Shrinkage of the cylindrical samples was measured by a vernier caliper with the accuracy of 0.05 mm in 8 selected locations (as repetitions), both for the diameter and the height. Afterwards, the measured dimensions were used to calculate dimensionless shrinkage indicator, coefficient of linear extensibility *COLE* [33, 34], according to the following formula:

$$COLE = \left(\frac{V_s}{V_d} \right)^{\frac{1}{3}} - 1$$

where: *COLE* – dimensionless coefficient of linear extensibility;

V_d – dry specimen volume, [m³];

V_s – saturated specimen volume, [m³].

The values of the coefficient of linear extensibility (*COLE*) indicate the shrinkage potential according the ranges [32]: i) < 0.03 a low shrinkage potential; ii) 0.03–0.06 a moderate shrinkage potential; iii) 0.06 to 0.09 a high potential; iv) > 0.09 a very high shrinkage potential.

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 m² of liner area:

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

where: q_D – Darcy unit flux, [m · s⁻¹];

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 the Polish 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 [35]. The assessment was performed for K_s measured in the laboratory conditions for substrates formed at 95% of maximum bulk density and two molding water contents $w_{opt} < w_f < 1.2 w_{opt}$ and $w_f < w_{opt}$.

Results and discussion

The results of tested clay substrates plasticity determination, supported by the basic determination of swelling and shrinkage potentials 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 on plasticity chart in Fig. 2 and in Table 2.

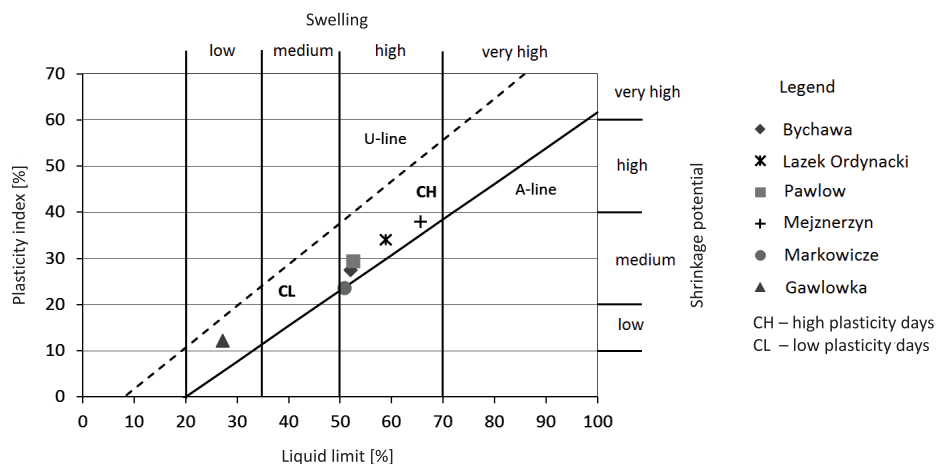


Fig. 2. Plasticity chart of tested clay substrates, modified after [25]

Table 2

Compaction results for tested substrates formed also wet and dry of optimum

Substrate	Bychawa	Lazek Ordynacki	Pawlow	Mejznerzyn	Markowicze	Gawlowka
Maximum density						
w_{opt} [$\text{kg} \cdot \text{kg}^{-1}$]	0.22	0.21	0.19	0.26	0.16	0.13
Bulk density [$\text{kg} \cdot \text{m}^{-3}$]	1.71	1.72	1.78	1.56	1.83	1.99
K_s at w_{opt} [$\text{m} \cdot \text{s}^{-1}$]	$2.75 \cdot 10^{-11}$	$2.09 \cdot 10^{-11}$	$5.66 \cdot 10^{-11}$	$2.86 \cdot 10^{-11}$	$9.35 \cdot 10^{-11}$	$4.42 \cdot 10^{-10}$
Molding wet of optimum						
w_f for $w_{opt} < w_f < 1.2 w_{opt}$ [$\text{kg} \cdot \text{kg}^{-1}$]	0.25	0.25	0.22	0.30	0.20	0.15
Bulk density [$\text{kg} \cdot \text{m}^{-3}$]	1.60	1.62	1.68	1.52	1.74	1.90
K_s at $w_{opt} < w_f < 1.2 w_{opt}$ [$\text{m} \cdot \text{s}^{-1}$]	$6.15 \cdot 10^{-11}$	$5.20 \cdot 10^{-11}$	$4.17 \cdot 10^{-11}$	$2.46 \cdot 10^{-11}$	$1.17 \cdot 10^{-10}$	$9.45 \cdot 10^{-11}$
Molding dry of optimum						
w_f for $w_f < w_{opt}$ [$\text{kg} \cdot \text{kg}^{-1}$]	0.20	0.19	0.16	0.2	0.15	0.08
Bulk density [$\text{kg} \cdot \text{m}^{-3}$]	1.67	1.69	1.69	1.49	1.79	1.89
K_s at $w_f < w_{opt}$ [$\text{m} \cdot \text{s}^{-1}$]	$1.11 \cdot 10^{-10}$	$8.43 \cdot 10^{-11}$	$4.43 \cdot 10^{-11}$	$2.20 \cdot 10^{-10}$	$8.80 \cdot 10^{-10}$	$4.40 \cdot 10^{-10}$
Recognized type of clay	CH	CH	CH	CH	CH	CL

The results presented in Fig. 2 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 $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$ for optimum and forming water contents, wet and dry of optimum, for approx. 95% of maximal density in ranges of $w_{opt} < w_f < 1.2 w_{opt}$ and $w_f < w_{opt}$. However, in case of substrates sampled in

Pawlow and Markowicze, it was not possible to obtain $K_s < 1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$ for precise 95% of optimum density when specimens were compacted at low initial water contents dry of optimum, thus in this case the grater forming water content was applied. It is also visible that most of the tested clay substrates were recognized as high-plasticity clays according to USCS [29]. The only noted exception was Gawlowka sandy clay loam recognized as low plasticity clay.

Figure 3 shows results of measurements of K_s after three subsequent cycles of drying and rewetting, resulting in cyclic shrinkage and swelling.

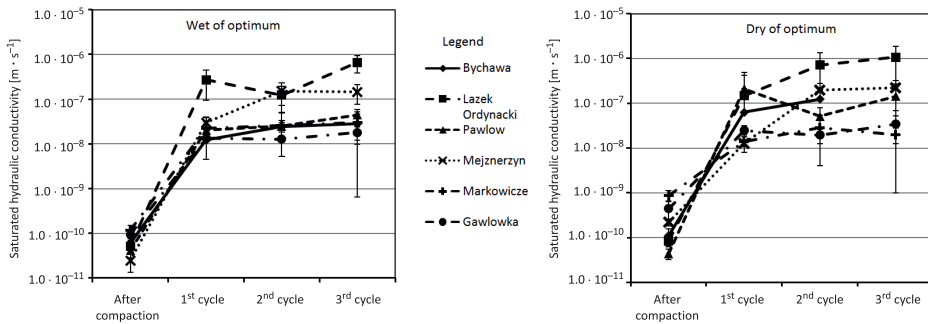


Fig. 3. Measured K_s after subsequent cycles of drying-rewetting for substrates formed wet dry of optimum

The results of K_s measurements presented in Fig. 3 show that none of the tested substrates, compacted both, wet and dry of optimum, 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 the subsequent cycles of shrinkage and swelling was greater than commonly allowed $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$. The greatest changes of saturated hydraulic conductivity were observed for the first cycle of drying and rewetting when measured K_s increased by several orders of magnitude, from the range of 10^{-11} – $10^{-10} \text{ m} \cdot \text{s}^{-1}$ to the values between 10^{-8} and $10^{-7} \text{ m} \cdot \text{s}^{-1}$. The highest increase for compaction wet of optimum after the first drying and rewetting was noted for Lazek Ordynacki clay substrate, the resultant K_s exceeded the level of $10^{-7} \text{ m} \cdot \text{s}^{-1}$. Additionally, for tested specimens formed dry of optimum, the most significant increased values of hydraulic conductivity were noted for samples from Lazek Ordynacki and Pawlow. In all of the mentioned cases the high-plasticity clays were considered.

Similarly, the greatest total increase in K_s values was observed for substrates of the highest plasticity indices, compacted dry and wet of optimum, *ie* Lazek Ordynacki and Mejnierzyn, for which the K_s after the 3rd cycle exceeded even the value of $1 \cdot 10^{-7} \text{ m} \cdot \text{s}^{-1}$ allowed by the American standards for the top cover of municipal landfill [35]. Additionally, we may state that compaction dry of optimum in most cases resulted in higher saturated hydraulic conductivity after forming (as it was presented in Table 2) and after cyclic drying and rewetting. The lowest values of increased K_s were observed for substrates sampled in Markowicze and Gawlowka, containing significant sand

content. The measured K_s for these clayey materials after the third cycle of drying and rewetting reached the level between approx. $1.8 \cdot 10^{-8} \text{ m} \cdot \text{s}^{-1}$ and $3.4 \cdot 10^{-8} \text{ m} \cdot \text{s}^{-1}$, both, for compaction wet and dry of optimum.

The observed relation between determined indices of plasticity and resultant K_s after the final third cycle of drying and rewetting for the tested substrates compacted wet and dry of optimum is presented in Fig. 4.

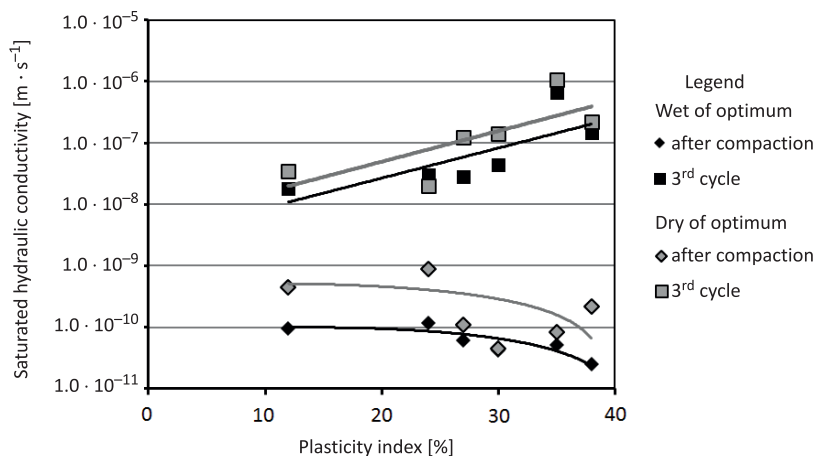


Fig. 4. Relation between plasticity and K_s of clays after compaction and after the final cycle of shrinkage and swelling

It is clearly visible in Fig. 4 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. In both applied cases of the initial forming water content, wet and dry of the optimum, the obtained resultant K_s values were similar but it should be noted that K_s for specimens of the same plasticity were lower when substrates were formed wet of optimum. But, on the other hand, the higher plasticity led to increased cracking and decrease in substrates' sealing capability by increase in hydraulic conductivity. And again, the general tendency of the measured saturated hydraulic conductivity for specimens formed wet of optimum presented slightly lower values than for the specimens of the same plasticity index but compacted dry of optimum.

The performed studies covered also assessment of shrinkage potential in regard to the plasticity of compacted substrate and forming conditions. The results of dimensionless *COLE* determination for substrates formed wet and dry of optimum are presented in Fig. 5.

Figure 5 shows some very important issues concerning influence of plasticity of clayey soils for the different substrates compacted at applied moisture contents wet and dry of optimum. It is clearly visible that plasticity of clayey materials affects its shrinkage properties. The greater plasticity index, the higher value of *COLE* determined, thus the higher shrinkage potential. The greatest values of *COLE*, exceeding 0.10, typical for the very high shrinkage potential were observed for substrate sampled in

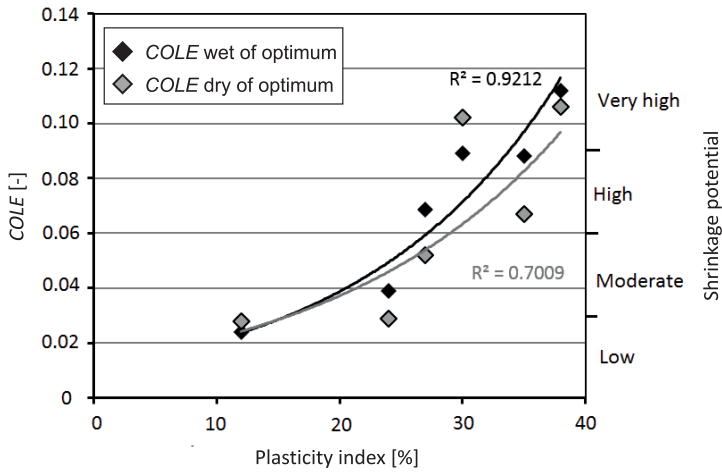


Fig. 5. Assessment of shrinkage potential indicator *COLE* for tested substrates, compacted wet and dry of optimum

Mejznerzyn of the highest plasticity index, equal to 38%. Most of the studied substrates, including Bychawa, Lazek Ordynacki and Pawlow specimens presented high shrinkage potential, while Markowicze clay showed moderate shrinkage potential. The lowest shrinkage was observed for Gawlowka sandy clay loam for which *COLE* indicated low shrinkage potential. Figure 5 shows also that conditions of forming considerably affect the resultant shrinkage, the determined *COLE* indicator for the same values of plasticity was greater for w_f wet of optimum.

To fully underline the above presented phenomena, daily seepage assessment was performed for 1 m² 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, compacted wet and dry of the optimum. The results of our calculations are presented in Fig. 6.

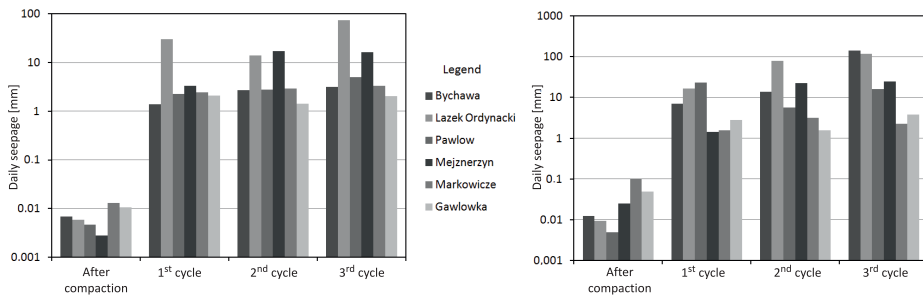


Fig. 6. Calculated daily seepage for each studied substrate and phase of cyclic drying and rewetting

As it is visible in Fig. 6, the irreversible changes in compacted clays structure caused by cyclic shrinkage and swelling resulted in clear increase in the calculated daily seepage for compaction on both sides of Proctor curve. The tested clay materials

directly after compaction wet of optimum showed satisfactory sealing capabilities allowing the daily seepage max. at the level of 0.01 mm. The same specimens compacted dry of optimum showed slightly greater seepage, but lower than 0.1 mm per day.

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, for samples compacted both, wet and dry of optimum. Generally, the higher increase in seepage was observed for samples compacted dry of optimum. The calculated daily seepage for Bychawa and Lazek Ordynacki after the final cycle of drying and rewetting reached the very high level of 143 and 119 mm, respectively.

The greatest increase in calculated seepage values for substrates compacted wet of optimum were observed for substrates of the highest noted plasticity indices, *ie* materials sampled in Lazek Ordynacki and Mejnierzyn. 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 Mejnierzyn substrates, respectively.

Additionally, it is worth to note, that for both tested molding water contents, wet and dry of optimum, the lowest daily seepage from range 2–4 mm per day, were observed for substrates of low plasticity, low clay and significant sand fraction content, *ie* Markowicze and Gawlowka specimens.

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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PRZESIAK PRZEZ CYKLICZNIE OSUSZANE I NAWILŻANE PRZESŁONY MINERALNE SKŁADOWISK ODPADÓW KOMUNALNYCH

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Abstrakt: Zrównoważoność składowisk odpadów komunalnych oraz jakość środowiska gruntowo-wodnego mogą być zagrożone przez infiltrację odcieków poprzez dno składowiska. Zagęszczone przesłony mineralne, wykonane z materiałów ilastych o różnej plastyczności, zapewniające współczynnik filtracji warstwy niższy niż $1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$, są jednym z podstawowych sposobów zapewniania izolacji składowisk. Jednak grunty ilaste o wysokiej plastyczności są materiałami ekspansywnymi, podatnymi na pęcznienie, skurcz oraz spękanie. Pęcznienie i skurcz zagęszczonych gruntów ilastych wywołane przez kolejne, następujące po sobie cykle nawilżania i osuszania zagęszczonej ilastej przesłony mineralnej są nieodwracalne i po kilku cyklach mogą doprowadzić do znacznego zwiększenia przewodnictwa wodnego, jednocześnie drastycznie zmniejszając zdolności izolacyjne zagęszczonych ilów. Praca niniejsza przedstawia próbę oceny wpływu plastyczności wybranych gruntów ilastych na właściwości izolacyjne przesłony składowiska poddanej cyklicznemu osuszaniu i nawilżaniu.

Plastyczność badanych gruntów określono metodami standardowymi i sklasyfikowano według Unified Soil Classification System. Współczynnik filtracji gruntów po zagęszczeniu wyznaczono za pomocą laboratoryjnych przepuszczalnościomierzy do gruntów zagęszczonych. Pomiar współczynnika filtracji dla próbek w cylindrach 100 cm^3 po trzech cyklach osuszania i nawilżania przeprowadzono za pomocą przepuszczalnościomierza laboratoryjnego. Skurcz badanych próbek zagęszczonego gruntu pomierzono także w cylindrach 100 cm^3 i sklasyfikowano z użyciem wskaźnika *COLE*. Obliczenia przesiąku przez dolną zagęszczoną warstwę izolacyjną składowiska oparto o standardową postać równania Darcy dla strefy saturacji. Uzyskane wyniki wykazały wpływ plastyczności ilów 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