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Sustainability of Compacted Clays as Materials for Municipal Waste Landfill Liner

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1. Introduction

Sustainability of waste management systems is crucial to allow ecological, economic and social sustainable development of not only the urbanized, municipal areas but also the rural ones (e.g. Udo & Pawłowski 2010, Guerrero et al. 2013, Pawłowski 2013, Bielińska et al. 2015, Leźnicki & Lewandowska 2016, Savić et al. 2016). Landfilling of wastes is the final stage of sustainable municipal waste management systems, no matter how developed it is (Allen 2000, Wagner 2011). Even in the developed countries of high economic incomes some small part of wastes, which cannot be processed by any other measures, is being landfilled (e.g. Pires et al. 2011, Shekdar 2013). Sustainable landfilling, according to Allen (2000) should allow safe disposal of waste inside a landfill, subsequent degradation of wastes, by the most financially efficient method available and with the minimal damage to the environment. The environmental impacts of landfills may cover contamination of surface water and groundwater by leachate, pollution of soil by direct contact with wastes or leachate percolation, air pollution by products of waste burning, spreading of diseases and bad odors in landfill area, as well as uncontrolled release of methane by anaerobic decomposition of deposited wastes (e.g. Ngoc & Schintzer 2009). Water inflows and outflows should be permanently prevented by the top and bottom landfill sealing liners, commonly constructed of natural materials of appropriate permeability and often additionally supported by plastic or geosynthetic membranes

(Bagchi 1990, Simon & Müller 2004, Laner et al. 2012). Although geosyntetic clay liners, geomembranes, geonets, and geotextiles, often used for the construction of liners in developed countries, they may not guarantee a long-term impermeability, and may be more expensive. (e.g. Zhang et al. 2010, Pires et al. 2011, Guerrero et al. 2013). Thus, compacted clay liners are still a worthy option. However, sustainability of clay liners may be significantly affected by their long-term sealing capabilities, resulting from the hydraulic conductivity after compaction, swell-shrinkage characteristics, resistance to cyclic drying and rewetting and desiccation cracking (e.g. Allen 2000). There are still unanswered questions regarding the influence of most important hydraulic and geotechnical properties of clayey soils and sustainability of compacted clay liners.

The performed studies concerning properties of clays influencing the sustainability of compacted clay liner covered measurements of saturated hydraulic conductivity and swell-shrink characteristics, and geotechnical properties of two selected clay materials.

2. Materials and methods

The tested substrates were sampled in Łążek Ordynacki and Gawłówka, both Lublin Voivodeship, Poland. The studied clay materials were compacted at various water contents, both wet and dry of optimum, from the range of 0.14-0.25 kg kg^{-1} and 0.08-0.20 kg kg^{-1} for Łążek Ordynacki and Gawłówka substrates, respectively.

The determination of basic and geotechnical characteristics of the tested clay materials was performed during the NN 523 755040 project. The particle size distribution of the tested substrates was determined with the standard sedimentation method (PN-B-04481:1988). Solid particle density was determined in le Chatelier flask and air pycnometer according to Langer, Eijkelkamp, the Netherlands. The gravimetric water content was obtained with the standard weight method (ASTM C566-13). Qualitative mineralogical composition of tested materials was determined by x-ray diffraction (XRD) method using Panalytical X'Pert APDm, the Netherlands. Semi-quantitative compositions of the raw samples and the clay fraction were determined with differential thermal analysis (DTA) method using TG-DTA/DSC Setsys 16/18 thermobalance, produced by Setaram, France. The Atterberg limits, of the studied clay substrates were determined during No. NN 523 755040 project with the standardized procedures (PKN-CEN ISO/TS 17892-12).

Shrinkage limit was calculated according to formula presented by Wysokiński (2007):

$$SL = 0.34 \cdot PL \cdot (1 + clay) \tag{1}$$

where:
SL – shrinkage limit, %, PL – plastic limit, %; clay – clay content, %.

The potential swell S, in %, based on Atterberg limits was calculated as follows (Seed et al. 1962):

$$S = 216 \cdot 10^{-5} \cdot PI^{2.44} \tag{2}$$

where: PI – plasticity index, %.

The in situ saturated hydraulic conductivity (K_S) of the tested clay substrates was measured by the falling head field permeameter for fine grained soils GeoN by Geo Nordic, Sweden (BAT 2006). Measurements were repeated in three points for each testing location. Saturated hydraulic conductivity before compaction of the two tested clay substrates was determined under laboratory conditions in the falling head permeameter for 100 cm^3 samples in standard steel cylinders (Iwanek et al. 2010). The laboratory measurements of saturated hydraulic conductivity of the studied clay materials compacted by standard Proctor method (PN-B-04481:1988 and ASTM D698-12) at various water contents were performed in H-4145 falling head permeameters for compacted soils by Humboldt Mfg. Co, USA, according to ASTM D5856-95. Swelling characteristics were measured for saturated samples after the K_S tests, directly in the applied molds of permeameter for compacted specimens. The height of the samples was measured using vernier caliper at 10 regularly distributed locations for each sample. Calculations of swelling index, SI (%) were based on the following equation:

$$SI = \frac{h_s - h_i}{h_i} \cdot 100\% \tag{3}$$

where:
h_s – height of swollen sample, m; h_i – initial height of substrate specimen, after molding, before full saturation, m.

Shrinkage of compacted clay specimens was measured in the standard 100 cm^3 steel cylinders sampled directly from the compaction molds, according to the methodology similar to that one presented by Peng et al. (2007), Dörner et al. (2009) and Gerbhardt et al. (2012). Volume change of the cylindrical samples was measured by a vernier caliper with an accuracy of 0.05 mm in 10 selected locations, both for the diameter and the height. Afterwards, two dimensionless shrinkage indicators, r_s and COLE (Grossman et al. 1968, Bronswijk 1990) were calculated, according to:

$$r_s = \frac{\ln\frac{V_d}{V_s}}{\ln\frac{z_d}{z_s}} \tag{4}$$

where:
r_s – dimensionless geometry factor; V_d, z_d – volume, m^3 and height, m, of dry specimen; V_s, z_s – saturated volume, m^3 and height, m;

$$COLE = \left(\frac{V_s}{V_d}\right)^{\frac{1}{3}} - 1 \tag{5}$$

where:
COLE – dimensionless coefficient of linear extensibility; V_d – dry volume, m^3; V_s – saturated volume, m^3.

Dimensionless geometry factor r_s is used to determine the type of deformation during shrinkage: for $r_s = 1.0$ deformation is vertical, for 1.0-3.0 predominant vertical, $r_s = 3.0$ deformation is isotropic, for $r_s > 3.0$ deformation is predominantly horizontal. Values of COLE are used to determine shrinkage potential, i.e. COLE < 0.03 means low shrinkage potential, 0.03-0.06 moderate, 0.06-0.09 high and COLE > 0.09 indicates a very high shrinkage potential (Gebhardt et al. 2012).

Shrinkage and swelling potentials for all the applied values of molding water contents were calculated as the differences between dry bulk density after compaction and dry bulk density after swelling and shrinkage (e.g. Bauer et al. 2001, Horn & Stępniewski 2004).

Finally, in order to assess the sustainability of the tested clay materials, the compacted and saturated materials were sampled in standard 100 cm^3 steel cylinders, one cylinder from one mold. All the samples were air dried at room temperature – approx. 20°C – and rewetted through capillary saturation (Suchorab et al. 2010). Then, saturated hydraulic conductivity measurements were performed with constant and falling head method (depending on the value of the measured parameter, above $1 \cdot 10^{-5}$ m s^{-1} the constant head method was used) in a laboratory permeameter, produced by the former IMUZ, Poland (Iwanek at al. 2010). Three cycles of drying and rewetting were performed to obtain the maximum possible increase of hydraulic conductivity (e.g. Basma et al. 1996, Dörner et al. 2009, Fernandes et al. 2015, Widomski et al. 2015).

3. Results and discussion

The general characteristics of tested substrates are presented in Table 1. Both clay materials differed in particle size composition. Substrate sampled in Łążek Ordynacki consisted of more clay and silt particles, while the sand content dominated the Gawłówka substrate. Thus, Łążek Ordynacki substrate, according to USDA texture classification, was recognized as silty clay, while Gawłówka material as sandy clay loam. Gawłówka substrate presented also greater content of quartz and feldspars and higher dry bulk density. Table 1 also presents mineralogical characteristics of both studied substrates. The substrate sampled in Łążek Ordynacki presented greater content of swelling minerals (illites and smectites) and smaller content of non-swelling clay minerals (kaolinites and chlorites).

Taking the above and lower ratio of non-swelling vs. swelling clay minerals into consideration, significant swelling and shrinkage properties of material sampled in Łążek Ordynacki may be expected.

The Atterberg limits: liquid limit, plastic limit and plasticity index were, more or less, higher for Łążek Ordynacki substrate. Additionally, the calculated shrinkage limit and potential swell were also significantly higher for Łążek Ordynacki clay material (Table 2). Łążek Ordynacki substrate was recognized as highly plasticity clay (CH) of high swelling and moderate shrinkage potential and Gawłówka material as low plasticity clay (CL) of low swelling and low shrinkage potential (ASTM D2487-11, Chen 1988).

Results of in situ measurements of hydraulic conductivity, under natural conditions, by BAT GeoN permeameter and in laboratory by permeameter for 100 cm^3 undisturbed samples, are presented in Table 3. Both tested substrates presented in situ saturated hydraulic conductivity lower than commonly required (e.g. Dz.U. 2013 item 523, EPA 1993, EU

1999) $K_s=1.0\cdot10^{-9}$ m s^{-1}. The clay material from Gawłówka presented value of K_s measured in laboratory conditions greater than $1.0\cdot10^{-9}$ m s^{-1}. However, there are known literature reports presenting the typical phenomenon, when results of K_s measurements in laboratory conditions are different, even by one order of magnitude than results obtained by field methods in situ (e.g. Shackelford & Javed 1991, Allen 2000).

Table 1. General characteristics of tested substrates (I – illites, S – smectite, K – kaolinite, Ch – chlorite), modified after Stępniewski et al. (2015)
Tabela 1. Podstawowe właściwości badanych gruntów (I – illity, S – smektyty, K – kaolinity, Ch – chloryty), zmodyfikowano za Stępniewskim i in. (2015)

Characteristic	Unit	Specimen	
		Łążek Ordynacki	Gawłówka
Clay content	%	44.5	31
Silt content	%	51	3
Sand content	%	4.5	66
Fines content	%	95.5	34
Particle density	Mg m^{-3}	2.68	2.86
Bulk density	Mg m^{-3}	1.70	1.95
Total porosity	m^3 m^{-3}	0.37	0.32
Water content	kg kg^{-1}	0.21	0.18
Clay minerals content	%	60	50
Swelling minerals content (I+S)	%	54	30
Non-swelling minerals content (K+Ch)	%	6	20
(K+Ch)/(I+S) ratio	-	0.11	0.66
Quartz and feldspars content	%	25	50

Table 2. Atterberg limits of tested substrates, partially modified after Stępniewski et al. (2015)
Tabela 2. Granice konsystencji oraz stanów badanych gruntów, częściowo zmodyfikowano za Stępniewskim i in. (2015)

Substrate	Liquid limit %	Plastic limit %	Plasticity index %	Shrinkage limit %	Potential swell %
Łążek Ordynacki	59	25	34	12	20
Gawłówka	27	15	12	7	2

Table. 3. In situ saturated hydraulic conductivity of tested substrates, partially modified after Stępniewski et al. (2015)
Tabela 3. In situ nasycone przewodnictwo wodne badanych gruntów, częściowo modyfikowane za Stępniewskim i in. (2015)

Substrate	In situ measurements		Laboratory measurements	
	K_s m s^{-1}	SD	K_s m s^{-1}	SD
Łążek Ordynacki	$1.37 \cdot 10^{-10}$	$3.54 \cdot 10^{-12}$	$4.30 \cdot 10^{-10}$	$4.24 \cdot 10^{-10}$
Gawłówka	$4.73 \cdot 10^{-10}$	$1.50 \cdot 10^{-10}$	$2.25 \cdot 10^{-9}$	$4.89 \cdot 10^{-10}$

Figure 1 shows compaction effects for both tested substrates, including Proctor curves, dry bulk density after swelling and shrinkage as well as K_s to applied molding water contents. The tested materials showed different characteristics of Proctor curve. Maximum density for Łążek Ordynacki, was lower and was obtained for greater water content than in the case of Gawłówka substrate. Different swell and shrinkage characteristics for both tested substrates are also visible. The initial saturation affects the resultant value of K_s, increase of molding water content generally decreases the value of saturated hydraulic conductivity. Both substrates managed to reach a very low hydraulic conductivity, lower than required (e.g. EU 1993, Wysokiński 2007, Dz.U. 2013 item 523) $1.00 \cdot 10^{-9}$ m s^{-1}, for the optimal water content w_{opt}. Substrate sampled in Łążek Ordynacki reached the level of $2.09 \cdot 10^{-11}$ m s^{-1} for w_{opt} while material from Gawłówka – $4.42 \cdot 10^{-10}$ m s^{-1}.

Figure 1 also shows that in case of Łążek Ordynacki silty clay the low applied values of molding water content, i.e. $w_f = 0.14$ kg kg^{-1}, resulted in K_s greater ($3.9 \cdot 10^{-9}$ m s^{-1}) than the required threshold. Conversely, compaction of Gawłówka sandy clay loam in the full range of applied water contents allowed to achieve K_s lower than required $1.00 \cdot 10^{-9}$ m s^{-1}.

Despite the different measured values, the studied clays compacted wet and dry of optimum for ranges of forming moisture $w_{opt} \leq w_f \leq 1.2w_{opt}$ and $w_f < w_{opt}$ and resultant 95% of maximum Proctor density allowed saturated hydraulic conductivity lower than the threshold value and ranged between 10^{-10} - 10^{-11} m s^{-1}. It is also visible that compaction at wet of optimum allowed lower value of K_s. However, during the forming of high plasticity clay wet of optimum, sticky and cohesive clogs were observed at high water contents.

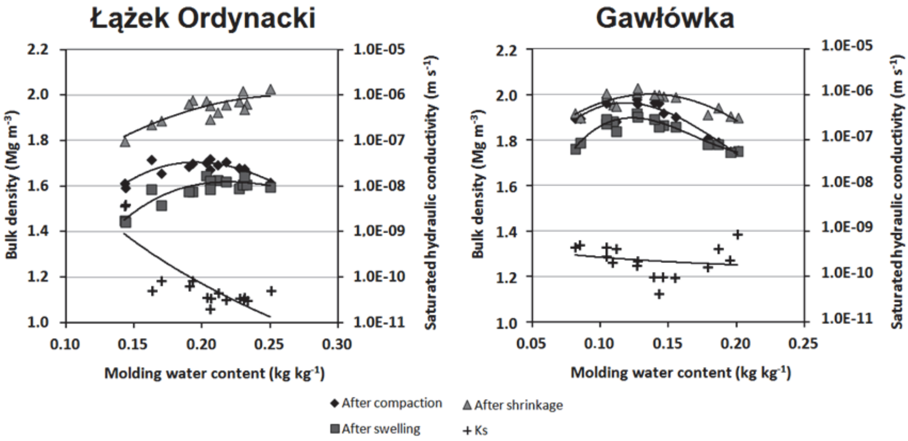

Fig. 1. Compaction effects for both tested substrates
Rys. 1. Wyniki zagęszczenia badanych gruntów

Figure 2 presents swelling and shrinkage potentials, determined after Horn & Stępniewski (2004) for both tested substrates in relation to the applied value of molding water content. There are several interesting issues visible. First, the clear relation between swell and shrink characteristics and applied molding water content was noted. The calculated swell potential decreased due to increase of molding water content, while shrinkage potential increased along with the increasing water content. Secondly, both substrates differed significantly in reached values of swell and shrink potential but the more clayey substrate from Łążek Ordynacki showed definitely higher swell-shrink values. The maximal reached swelling potential for Łążek Ordynacki was greater by approx. 60% then observed for Gawłówka. The observed difference for shrinkage potentials between high plasticity clay sampled in Łążek Ordynacki and low plasticity clay from Gawłówka was even greater, reaching approx. 173%.

Table 4 presents the results of observations of volumetric shrinkage for both substrates compacted wet and dry of optimum (Parker et al. 1977, Bronswijk 1990). Generally, Łążek Ordynacki substrate presented values of COLE setting its shrinkage potential as high for both sides of

Proctor curve and r_s value identifying predominant horizontal deformation related directly to risk of desiccation cracking. Conversely, COLE shrinkage indicator obtained for Gawłówka allowed to assess its shrinkage potential as low for compaction wet and dry of optimum. The calculated r_s values for Gawłówka allowed to determine deformation type as predominant vertical, safer for compacted clay liner.

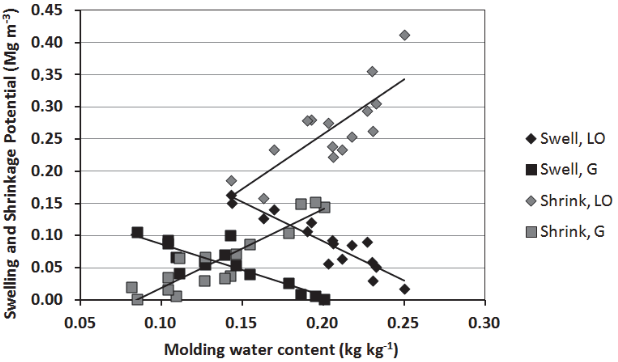

Fig. 2. Swelling and shrinkage potentials of tested substrates related to molding water content, LO – Łążek Ordynacki, G – Gawłówka
Rys. 2. Potencjały pęcznienia i skurczu badanych gruntów w funkcji wilgotności zagęszczania, LO – Łążek Ordynacki, G – Gawłówka

Table 4. Volumetric shrinkage tests for studied substrates
Tabela 4. Wyniki badań skurczu objętościowego badanych gruntów

Substrate	$w_{opt} \leq w_f \leq 1.2w_{opt}$			$w_f < w_{opt}$		
	w_f kg kg^{-1}	COLE	r_s	w_f kg kg^{-1}	COLE	r_s
Łążek Ordynacki	0.25	0.080	3.3	0.19	0.062	3.5
Gawłówka	0.15	0.025	2.2	0.08	0.018	2.4

Results of the final tests allowing to assess the sustainability of tested clay material, covering measurements of saturated hydraulic conductivity for all applied molding water contents after three cycles of shrinkage and swelling caused by cyclic air drying and rewetting, are presented in Figure 3.

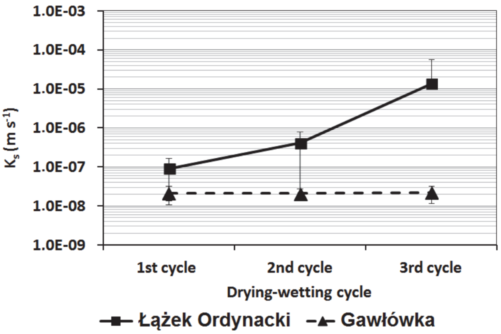

Fig. 3. Mean saturated hydraulic conductivity of tested substrates after cyclic drying and rewetting
Rys. 3. Średni współczynnik filtracji dla badanych gruntów po cyklicznym osuszaniu i nawadnianiu

None of the tested clay materials was able to sustain its saturated hydraulic conductivity obtained after compaction. However, the difference in behavior of high and low plasticity clays during cyclic drying and rewetting showed a significant increase of mean value of K_S after each applied cycle of shrinkage and swelling for the Łążek Ordynacki and finally reached similar values like sandy soils. The behavior of low plasticity sandy clay loam sampled in Gawłówka remained nearly constant even after the third, final applied cycle. Thus, despite the discussed increase of K_S after the first shrinkage and rewetting, sealing properties of Gawłówka specimen remained constant, representing hydraulic conductivity even lower than, e.g. required by EPA's standards for earthen liner of landfill top cover (EPA 1993).

4. Conclusions

The performed studies covered analysis of selected geotechnical and hydraulic parameters of two clay materials affecting sustainability of compacted clay liners commonly used in landfilling. Sustainability of clay materials was considered in relation to their hydraulic conductivity after compaction, swell and shrinkage properties and hydraulic conductivity after three cycles of air drying and rewetting. Our tests were focused on two different materials, recognized as high and low plasticity clays. Both tested materials compacted wet and dry of optimum at 95%

of maximum Proctor density, allowed very low values of saturated hydraulic conductivity, below the commonly required $1.0 \cdot 10^{-9}$ m s^{-1}. However, silty clay from Łążek Ordynacki presented higher plasticity index and significantly greater swelling and shrinkage potentials. Volumetric shrinkage of both tested substrates indicated that high plasticity clay, presented high shrinkage potential and predominantly horizontal deformation during shrinkage, which may result in significant cracking decreasing sealing capabilities of compacted clay liner. Test of cyclic drying and rewetting showed that high plasticity clay was unable to sustain its sealing capabilities because its hydraulic conductivity was increased to the level typical for sandy soils. Conversely, the tested low plasticity sandy clay loam displayed different behavior after swelling and shrinkage, K_s – after an initial increase – remained constant during following processes of shrinkage and swelling. Hence, the tested low plasticity clay allowed at least partial sealing properties, at the level required by EPA's standards.

Our research showed that if the sustainability of compacted clay liner is considered, high plasticity clays, of significant content of clay and fine (clay + silt) particles, clay minerals and swelling clay minerals (illites and smectites), as well as the low content of coarse fraction should be avoided. Taking into account the fact that both tested materials allowed comparable saturated hydraulic conductivity after compaction, in our opinion, low plasticity clays, containing significant amount of sand fraction and non-swelling clay minerals, resulting in low swelling and shrinkage potentials, significant resistance to cycling drying and rewetting and limited or even zero cracking, should be favored as materials for sustainable compacted clay liner construction.

The planned further continuation of the studies presented in this paper assume introduction of landfill leachate as permeating liquid in measurements of hydraulic conductivity of the compacted clay substrates. Thus, the comparative analyses of effects of permeating liquid on sustainability of compacted clay liners, especially used as bottom sealing, should be possible.

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Zrównoważoność zagęszczonych iłów jako materiałów na przesłony mineralne składowisk odpadów komunalnych

Streszczenie

Poniższa praca przedstawia badania właściwości hydraulicznych gruntów wpływających na zrównoważoność i trwałość warstw izolacyjnych składowisk odpadów wykonanych z zagęszczonych gruntów ilastych. Badaniom poddano dwa rodzaje gruntów ilastych, o niskiej i wysokiej plastyczności, zagęszczane przy różnych wilgotnościach wg PN-B-04481:1988. Materiały ilaste do badań zostały pobrane w Łążku Ordynackim i Gawłówce, województwo lubelskie. Podstawowe właściwości gruntów tj. skład granulometryczny, mineraologię oraz granice stanów i konsystencji określono za pomocą standardowych metod. Badania polowe współczynnika filtracji wykonano za pomocą przepuszczalnościomierza do gruntów drobnoziarnistych GeoN, Geo Nordic, Szwecja. Badania przewodnictwa badanych gruntów po zagęszczeniu zrealizowano za pomocą przepuszczalnościomierzy H-4145, Humboldt Mfg. Co, USA spełniających wymagania ASTM D5856-95.

Potencjał i charakterystyka skurczu, oraz możliwe spękanie, zostały opisane za pomocą dwóch bezwymiarowych wskaźników skurczu, r_s i COLE. Następnie, za pomocą przepuszczalnościomierza laboratoryjnego IMUZ, Polska zbadano przewodnictwo wodne badanych gruntów po trzech kolejnych cyklach osuszania i nawilżania. Wg klasyfikacji USDA grunt pobrany w Łążku Ordynackim zakwalifikowano jako ił pylasty a materiał z Gawłówki jako glinę piaszczysto-ilastą. W nawiązaniu do wyznaczonych granic stanów i konsystencji oraz klasyfikacji USCS (Unified Soil Classification System) grunt z Łążka Ordynackiego zidentyfikowano jako ił o wysokiej plastyczności, wysokim potencjale pęcznienia i średnim potencjale skurczu, zaś materiał pobrany w Gawłówce rozpoznano jako ił o niskiej plastyczności oraz niskich potencjałach pęcznienia i skurczu. Obydwa badane grunty charakteryzowały się współczynnikiem filtracji w warunkach naturalnych niższym niż powszechnie wymagana wartość $K_s = 1.0 \cdot 10^{-9}$ m s^{-1}.

Badane materiały charakteryzowały się różnymi właściwościami po zagęszczeniu. W obydwu przypadkach po zagęszczeniu udało się osiągnąć przewodnictwo wodne znacznie niższe niż wymagana wartość ale zaobserwowano różnice w pęcznieniu i skurczu. Zawierający więcej frakcji ilastej materiał z Łążka wykazał zdecydowanie wyższe charakterystyki pęcznienia i skurczu niż grunt z Gawłówki. Badana glina piaszczysto-pylasta wykazała także bezpieczniejsze dla zagęszczonej warstwy izolacyjnej, zmniejszające ryzyko spękania, pionowe odkształcenie w czasie wysychania. Żaden z badanych gruntów nie był w stanie utrzymać niskiego przewodnictwa hydraulicznego po trzech cyklach osuszania i nawilżania ale grunt pobrany w Gawłówce zapewnił chociaż częściowe właściwości izolacyjne, na poziomie 10^{-8}-10^{-7} m s^{-1}. Zatem, badany ił o niskiej plastyczności, w przeciwieństwie do materiału wysokoplastycznego, wykazujący niskie pęcznienie i skurcz oraz znaczną odporność na następujące po sobie, cykliczne, osuszanie i odwadnianie został uznany jako bardziej odpowiedni do konstrukcji zrównoważonej zagęszczonej przesłony mineralnej składowiska odpadów komunalnych.

Słowa kluczowe:
zrównoważony rozwój, zagęszczone przesłony ilaste, składowiska odpadów, przewodnictwo hydrauliczne, właściwości pęcznienia i skurczu

Keywords:
sustainable development, compacted clay liner, landfilling,
hydraulic conductivity, swell and shrink properties