

Article

# Clays of Different Plasticity as Materials for Landfill Liners in Rural Systems of Sustainable Waste Management

Marcin Konrad Widomski \*, Witol Stępniewski and Anna Musz-Pomorska

Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka 40B, 20-618 Lublin, Poland; w.stepniewski@pollub.pl (W.S.); a.musz-pomorska@pollub.pl (A.M.-P.)

\* Correspondence: m.widomski@pollub.pl; Tel.: +4-881-538-4781

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**Abstract:** This paper presents a study assessing the possible application of seven clay substrates of various particle compositions and plasticity, sampled locally in rural regions, as materials allowing affordable construction of the waste landfill liners, which meet the main principles of sustainability, utilize locally available materials and limit the environmental threats posed by landfill leachate to water, public health and arable land. The researched substrates were tested according to their long-term sealing properties by their saturated hydraulic conductivity after compaction, swelling and shrinkage characteristics and ability to sustain their sealing capability after repeated drying and rewetting. The basic characteristics of soils were determined by the standard methods. Saturated hydraulic conductivity after compaction and after repeated shrinking and swelling were tested in laboratory falling head permeameters. Shrinkage characteristics were based on dimensionless indicators of the geometry and linear extensibility. The obtained results showed that the tested clay substrates were found applicable to construction of compacted clay liner for sustainable waste landfill. The environmental sustainability of a local, rural waste landfill, isolated by compacted earthen liners utilizing local materials is, in our opinion possible, but strongly related to the compaction parameters applied during liner construction for the given clay substrate.

**Keywords:** sustainable waste management; sustainable landfilling; compacted clay liners; hydraulic conductivity; swell and shrink; clay soils

## 1. Introduction

The sustainable development of the rural region and society, directly related to availability of fresh water and clean arable lands, may be significantly affected by contamination of water, soil and atmosphere caused by the improper handling of municipal solid wastes (MSW) during the process of waste management [1–4]. The proper sustainable solid wastes management in rural areas, supported by the financial sustainability, inclusivity, coherent institutions and proactive public policies may minimize the negative ecologic and environmental effects of wastes generation, transport, treatment and final disposal, also supporting the social and economic pillars of sustainability [5,6]. The final steps of the sustainable waste management are landfilling of residual waste (waste after reducing the volume and quantity, unable to be processed by any other measures) as well as aftercare and reclamation of closed landfills [4,7–10].

The final disposal of residual solid waste in the developing countries is generally based on landfilling and open-dumping sites, commonly recognized as the main source of environmental pollution limiting the availability of unpolluted water and arable land [8,11–13]. Waste landfills, despite their known disadvantages, are in contrast to the common practice of the uncontrolled dumping of wastes and

remain a dominant cost-effective method of final deposition of municipal solid waste [7,8,13]. However, landfills may be expensive (significant required amounts of clay, sand and gravel, plus additionally PEHD (high-density polyethylene) membranes, geomembranes or geotextiles), problematic and difficult to maintain.

Sustainable landfilling in rural areas may be crucial for the availability of resources and transaction of goods between generations [7,13]. The technical sustainability of a landfill may be related to the level of the locally available skills and technologies for design, construction, operation and maintenance, application of affordable local materials, level of performance considering expected goods and, finally, adaptability [14]. In the rural areas, the environmental impacts of landfilling, affecting sustainable land management in the region, may be related mainly to the contamination of surface water and groundwater through leachate, and to pollution of soil by direct contact with wastes or leachate percolation, long after closure of the landfill [4,12]. The potential impacts of capital goods consumption by the landfill were assessed as low, or even marginal, in relation to the environmental pressure [15]. Thus, a sustainable landfill, from the ecological and environmental point of view, should pose negligible, or even zero, risk to the environment, both during the operation phase and long after the closure, hence isolation of landfills should be long-term and self-sustainable [16,17].

Bottom and top liners of sanitary landfills are often based on the natural materials, including clays, characterized by appropriate coefficient of hydraulic conductivity ( $K_s$ ), usually below  $1.0 \times 10^{-9}$  m/s [18], and are often additionally supported by plastic or geosynthetic membranes [17, 19–22] but the application of sophisticated sealing materials, such as geosynthetic clay liners, geomembranes, geonets and geotextiles, is often limited in the developing countries of low- and medium-income [9–11,23]. Various types of clays are natural materials of a very low hydraulic conductivity, commonly applied, under their natural conditions or after the additional compaction [20, 24,25], as materials for sealing liners of the landfills [26]. However, their application should be verified with regard to the compliance to the local legal standards and popular technical guidelines [19,26–29].

Unfortunately, no unified and comprehensive international legal regulation of applicability of mineral material for use in the construction of a compacted clay liner (CCL) is available. Generally, legal regulations of several countries refer only to the coefficient of saturated hydraulic conductivity and structure of mineral liner composition [18,30,31], while the more developed guidelines suggest also the analyses of particle size distribution, mineralogy, strength parameters, Atterberg limits (including liquid and plastic limits as well as plasticity index) and forming characteristics, usually usage of specimens with a significant clay content and medium or high plasticity is suggested [19,27–29,32,33]. However, clayey substrates containing significant clay content, high amounts of swelling minerals (e.g., unstable illites and smectites) and presenting resultant high plasticity are expansive mineral materials prone to intense swelling, shrinkage and cracking [34,35]. Swelling and shrinkage are both possible during the construction and operation of the sanitary landfill [36]. They are generally correlated with the plasticity of clays, mineral composition, particle size distribution and type of cations in clay matrix [35]. Shrinkage of non-rigid soils may be recognized as horizontal and vertical. Vertical shrinkage results in soil subsidence, while predominant horizontal shrinkage produces cracks, highly dangerous for the sustainability and durability of sealing capabilities of the compacted clay liner [37].

The desiccation cracks created during the shrinkage affect the physical and hydraulic properties of the cracked expansive soil specimens, including hydraulic conductivity [38]. The final coefficients of saturated hydraulic conductivity of cracked soils may be greater even by several orders of magnitude in relation to the uncracked soils of the same type [6,39–41]. Additionally, the above-mentioned processes of swelling and shrinkage are irreversible, soils once swelled or shrunken are generally unable to return to their initial characteristics [42]. Each cycle of drying and rewetting changes the properties of clays, the state of equilibrium is usually being achieved after 3rd–5th cycle, [34,40,43,44]. The development of cracks and resultant increase in the  $K_s$  of cracked compacted clays are also dependent on the applied forming water content [40,45].

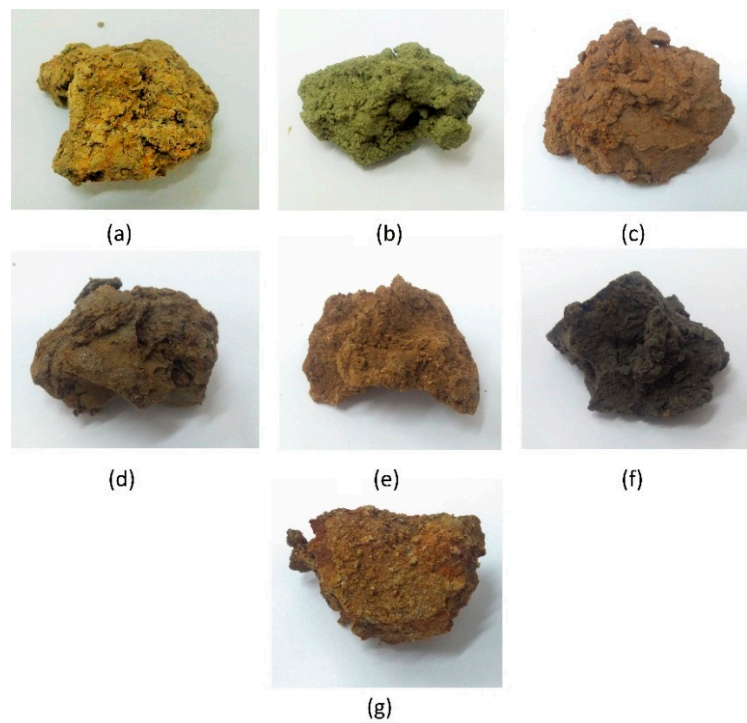
Taking the above-mentioned into consideration, the compacted clay liners, despite their drawbacks, alone or combined with the artificial liners, are still a worthwhile option for sealing of landfill, especially in the rural areas of developing countries. The CCLs utilizing the locally available materials, equipment, workmanship and technologies, may be in many cases successfully adopted under various local conditions. Therefore, the application of landfills based on compacted clay liners in rural regions of developing countries, principally constructed of local clayey materials (where possible), may achieve the social acceptance and become economically affordable for local communities and governments.

In our opinion, the sustainability of landfill, limiting the impacts of waste on the natural environment, allowing the most financially efficient and socially acceptable safe disposal of residual wastes prolonged after closure of the landfill, depends directly on the ability of top and bottom liners to sustain their sealing capabilities over time. Hence, the long-term performance of a landfill liner, limiting possible streams of pollution, is, in our opinion, strongly reliant on three interrelated characteristics of the applied compacted earthen material, related directly to its particle composition, mineralogy, Atterberg limits, plasticity and compaction initial water content: hydraulic conductivity under natural conditions and after compaction, swell-shrinkage characteristics and, finally, the ability of soil/substrate to sustain its hydraulic conductivity after cyclic changes of saturation, resulting in repeated shrinkage and swelling, commonly leading to serious cracking [24,34,35,38,40,41,45–47]. In our opinion, it is also important that the above-mentioned characteristics are easy to determine and measure, without the sophisticated laboratory and field equipment and may be easily understood.

This paper presents the study considering the applicability of seven clayey substrates, sampled locally in countryside regions in Poland, as the materials allowing construction of successful, durable and sustainable liners of waste landfill capable of meeting the main principles of sustainability in rural regions, limiting the environmental threats posed by waste to the natural environment by preventing leachate generation and seepage. The studied earthen materials were tested according to their capability in assuring the long-term sealing properties, due to their saturated hydraulic conductivity after compaction at variable initial water contents, swelling and shrinkage characteristics as well as the ability to sustain their sealing capability after several cycles of drying and rewetting leading to subsequent shrinkage and swelling. We believe that, taking into account the shrinkage and swelling properties of clays as well as their ability to sustain the sealing capabilities, not only the high plasticity materials, but also the ones of low and medium values of plasticity index should be advised as the materials for compacted earthen liner construction. In our opinion, the obtained results may contribute to the actual knowledge considering the application of various clay substrates, of different composition and plasticity, as locally available materials for compacted clay liners of sustainable rural landfills by pointing out the most important issues related to their easy measurable characteristics and allowing for obtaining a sustainable and durable liner. The proposed method of the earthen material applicability is clear and sound and may be adopted under the local conditions to the decision-making process considering construction of sustainable landfill.

## 2. Materials and Methods

The applicability of various clayey soils of different particle and mineral composition as well as of diversified plasticity was tested for seven substrates sampled locally in rural areas in Chotyłow (Ch), Gawłowska (G), Jelen (J), Markowice (Ma), Mejsnerzyn (Me), Pawłow (P) and Zgorznica (Z), all located at Wyzyna Lubelska (Lublin Upland, Poland), the SE part of Poland. The sampled clay substrates are presented in Figure 1. The tested materials were sampled directly from the local open casts of mining pits, from the depth of approx. 0.6–1.0 m (see Figure 2).



**Figure 1.** Sampled locally available clay materials: (a) Chotyłow; (b) Gawlowka; (c) Jelen; (d) Markowicze; (e) Mejznerzyn; (f) Pawłow; (g) Zgorznicza.



**Figure 2.** (a) Open cast of mining pit in Zgorznicza; (b) measurements of saturated hydraulic conductivity under natural conditions.

Our research covered (i) the determination of the basic characteristics and Atterberg limits (plastic and liquid limits, plasticity index) of the studied clay materials; (ii) measurements of their saturated hydraulic conductivity under their natural conditions; (iii) laboratory measurements of coefficients of saturated hydraulic conductivity ( $K_s$ ) of the specimens compacted by the standard Proctor method at various water contents; (iv) determination of swelling and shrinkage potential characteristics of the studied materials after compaction at various water contents; and (v) measurements of  $K_s$  of the considered materials following three cycles of drying and wetting.

The particle size distribution of studied specimens was determined directly according to the Polish national standard PN-B-04481:1988 [48]. Solid particle density was measured in Le Chatelier flask and by means of the air pycnometer, produced by Eijkelkamp, Giesbeek, the Netherlands. Qualitative

mineralogical composition of tested clay materials was determined by X-ray diffraction (XRD) method using X'Pert APDm, by Panalytical, Almeo, the Netherlands with a PW 3020 goniometer, Cu lamp and graphite monochromator. Semi-quantitative composition of the clay fraction was determined with the means of differential thermal analysis (DTA) method with application of TG-DTA/DSC (thermogravimetry and differential scanning calorimeter) Setsys 16/18 thermobalance, produced by Setaram, Caluire, France.

The Atterberg limits, including the plastic limit and liquid limit of the tested clay materials, were determined through the standard procedures [49], while the plasticity index was calculated as the difference between the liquid and plastic limits. The gravimetric water content was obtained with the standard weight method [50].

The saturated hydraulic conductivity of the tested materials under their natural conditions was measured in situ by the GeoN, Geo Nordic, Stockholm, Sweden, field permeameter for fine grained soils (see Figure 2). The applied falling head permeameter is advised to be used for soils of Ks between  $1.0 \times 10^{-7}$  m/s and  $1.0 \times 10^{-12}$  m/s [51]. The outflow falling head method of measurements for unsaturated soils conditions was used. Measurements were repeated at three points for each testing location.

The laboratory measurements of saturated hydraulic conductivity of the tested seven clay materials compacted at various water contents were performed in H-4145 Humboldt Mfg. Co., Elgin, IL, USA falling head method [52] permeameters for compacted soils, meeting the requirements of ASTM D5856-95 [53]. The samples of the tested soils were prepared and compacted directly inside the permeameters by the standard Proctor test with 24.5 N rammer and a compactive effort of 600 kJ/m according to the PN-B-04481:1988 [48] and ASTM D698-12e2 [54] standards. Three molds were formed for the each applied initial water content. The compaction was performed for several, up to 10 values of molding water content, from both sides of the Proctor curve.

After the laboratory measurements of saturated hydraulic conductivity, the swelling and shrinkage characteristics of compacted clays were determined in order to assess the swelling and shrinking potential of the tested compacted clays. The swelling characteristics were measured for the saturated samples following the saturated hydraulic conductivity measurements, directly in the applied molds of H-4145 permeameter for compacted soils. The height of the sample for calculation of the swelling was measured using a vernier caliper at 10 regularly distributed locations for each sample.

Swelling index, *SI* (%), was calculated according to the following formula:

$$SI = \frac{h_s - h_i}{h_i} \times 100\%, \quad (1)$$

where:  $h_s$ —height of the swelled sample, m;  $h_i$ —initial height of the specimen, after molding, before saturation, m.

Shrinkage characteristics of the tested compacted clay materials were determined in 100 cm<sup>3</sup> cylinders, sampled directly from the H-4145 compaction molds, according to the methodology similar to the one presented by Peng et al. [55], Dörner et al. [43] and Gerbhardt et al. [38]. Shrinkage of the studied cylindrical samples was measured by means of a vernier caliper, accuracy of 0.05 mm, in eight selected locations (as repetitions), separately for the determined diameter and height.

Thereafter, the measured dimensions of the shrunken samples were used to calculate two dimensionless shrinkage indicators, the geometry factor  $r_s$  and coefficient of linear extensibility *COLE* [56,57], according to the following formulas:

$$r_s = \frac{\ln \frac{V_d}{V_s}}{\ln \frac{z_d}{z_s}}, \quad (2)$$

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

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

where:  $COLE$ —dimensionless coefficient of linear extensibility;  $V_d$ —dry specimen volume,  $m^3$ ; and  $V_s$ —saturated specimen volume,  $m^3$ .

The threshold values for the dimensionless geometry factor  $r_s$  were assumed as follows: (i) for vertical deformation  $r_s = 1.0$ ; (ii) for the predominant vertical deformation  $r_s$  should be between 1.0 and 3.0; (iii) for isotropic deformation  $r_s = 3.0$ ; and (iv)  $r_s$  greater than 3.0 are typical for predominant horizontal deformation. Similarly, the following thresholds for the coefficient of linear extensibility ( $COLE$ ) determining the different shrinkage potentials were adopted; (i) low shrinkage potential,  $COLE$  lower than 0.03, (ii) moderate shrinkage potential, values between 0.03 and 0.06; (iii) high potential for  $COLE$  between 0.06 and 0.09; and (iv) a very high shrinkage potential for  $COLE$  values greater than 0.09 [38,58]. Shrinkage and swelling potentials for the applied values of forming water contents for each tested specimen were also determined as the differences between the dry bulk density after compaction and the dry bulk density following swelling and shrinkage [16,59].

### 3. Results

The determined basic characteristics, also including the Atterberg limits, for seven tested clayey specimens, studied as possible materials for durable compacted clay liner for sustainable rural solid waste landfill are presented in Table 1.

**Table 1.** Basic characteristics of tested clay substrates.

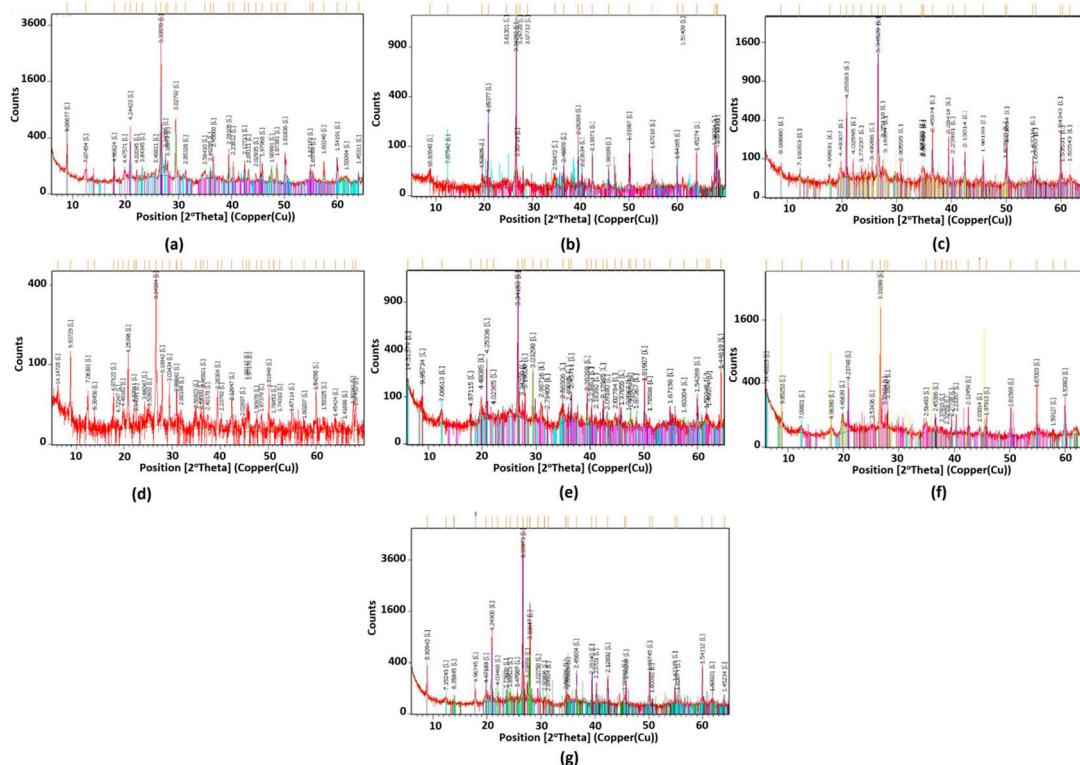
		Ch	G	J	Ma	Me	P	Z
Particle composition	Sand (%)	54	74	43	56	5	29	41
	Silt (%)	36	7	26	40	55	35	35
	Clay (%)	10	19	31	14	40	36	24
Soil texture type		Sandy loam	Sandy loam	Clay loam	Sandy loam	Silty clay	Clay loam	Loam
Solid particle density ( $Mg/m^3$ )		2.84	2.86	2.74	2.76	2.79	2.61	2.76
Non-swelling clay minerals (K + Ch) <sup>1</sup> (%)		19	20	8	10	28	22	20
Swelling clay minerals (I + S) <sup>1</sup> (%)		41	30	22	40	52	48	40
Ratio of non-swelling to swelling clay minerals (K + Ch)/(I + S) <sup>1</sup>		0.46	0.66	0.36	0.25	0.55	0.45	0.50
Quartz and feldspars (%)		30	50	69	40	12	29.5	39
Plastic limit (%)		23	15	15	27	28	23	21
Liquid limit (%)		42	27	37	51	66	53	42
Plasticity index (%)		19	12	22	24	38	29	21
Saturated hydraulic conductivity in situ, $\pm SD$ (m/s)		$1.04 \times 10^{-9}$ $\pm 1.6 \times 10^{-10}$	$4.73 \times 10^{-10}$ $\pm 1.5 \times 10^{-11}$	$1.16 \times 10^{-10}$ $\pm 1.3 \times 10^{-11}$	$1.00 \times 10^{-10}$ $\pm 1.9 \times 10^{-11}$	$2.05 \times 10^{-10}$ $\pm 1.6 \times 10^{-11}$	$2.51 \times 10^{-10}$ $\pm 1.4 \times 10^{-11}$	$5.81 \times 10^{-10}$ $\pm 9.9 \times 10^{-11}$

<sup>1</sup> (K + Ch), (I + S) means (kaolinite and chlorites) and (illites and smectites).

The basic characteristics of the tested clayey substrates presented in Table 1 show that the applied soils belonging to four USDA (United States Department of Agriculture) particle sizes groups (loam, sandy loam, silty clay and clay loam) presented different particle composition, Atterberg limits and coefficients of saturated hydraulic conductivity under the natural conditions. The following clay minerals were recognized during XRD studies in the tested samples: Chotyłow—illite, smectite and chlorite; Gawlowka—illite (glaucinite) and kaolinite; Jelen—illite, kaolinite and smectite; Markowicze—illite, chlorite, kaolinite and smectite; Mejnierzyn—illite, chlorite, kaolinite and smectite; Pawłow—illite, kaolinite and smectite; Zgorznicza—illite, kaolinite and smectite. The XRD patterns of tested samples are presented in Figure 3.

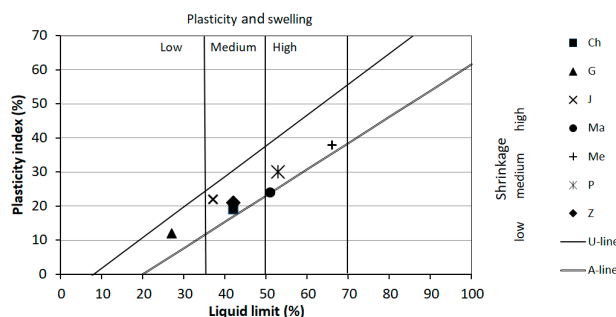
The Ks tested in situ, directly inside the deposit, showed in most cases (for six tested substrates) the values lower than  $1.0 \times 10^{-9}$  m/s, which is the threshold value commonly required for the natural geological barrier of solid waste landfill [18,19,28–30,60]. Only the sandy loam sampled in Chotyłow presented the in situ saturated hydraulic conductivity slightly greater than the threshold

value. The remaining substrates should be able to provide the appropriate sealing capabilities of the geological barrier under their natural conditions. Thus, the solid waste landfill could be positioned directly above the natural layers of such clay materials if their thickness meets the local requirements concerning the natural geological bottom isolating barriers.



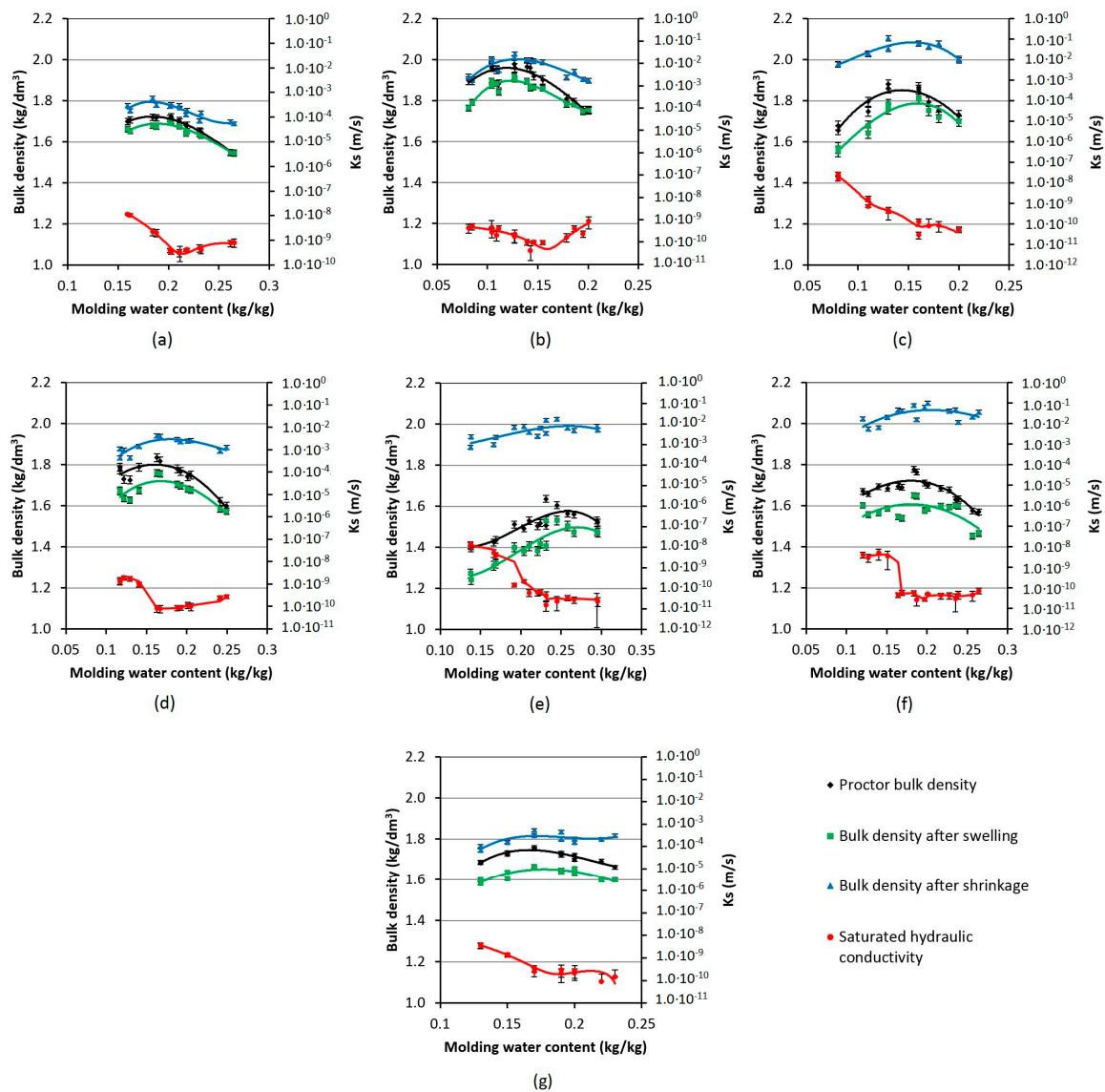
**Figure 3.** The XRD patterns of tested samples: (a) Chotylow; (b) Gawlowka; (c) Jelen; (d) Markowicze; (e) Mejnierzyn; (f) Pawlow; (g) Zgorznica; modified after [61].

The plasticity chart for all tested substrates was presented in Figure 4 to illustrate the relations between the selected Atterberg limits, including plasticity index, as well as their effects on swelling and shrinkage characteristics [62–65].



**Figure 4.** Plasticity chart for seven tested substrates.

Figure 5 presents the determined bulk density values after the standard Proctor compaction at variable initial water content for all of the tested clayey substrates, supported by the measurement results of bulk density after swelling and shrinkage as well as the coefficient of saturated hydraulic conductivity after forming.



**Figure 5.** Effects of standard Proctor compaction at different molding water contents, error bars represent SD of measurements: (a) Chotylow; (b) Gawlowka; (c) Jelen; (d) Markowicze; (e) Mejnierzyn; (f) Pawlow; (g) Zgorznica.

The results of research presented in Figure 5 show that, despite the different particle compositions and saturated hydraulic conductivity values, obtained during the in situ and laboratory tests, all seven tested clayey materials after standard Proctor compaction at optimum water content (optimum value of molding water content allows to achieve the maximum bulk density after compaction) were able to achieve value of  $K_s$  significantly below the usually required maximum value of  $1.0 \times 10^{-9}$  m/s. The observed values of maximum bulk density after compaction (optimal Proctor density) varied between  $1.64 \text{ kg/dm}^3$  for Mejnierzyn samples and  $1.98 \text{ kg/dm}^3$  for Gawlowka sandy loam. The observed values of  $K_s$  at the optimal water content were in the range between approx.  $1.8 \times 10^{-10}$  m/s for Gawlowka specimens and  $1.5 \times 10^{-11}$  for Mejnierzyn substrate, one and two orders of magnitude lower than the required threshold. The lowest values were achieved for the high plasticity clays, the materials containing significant amount of clay fraction, i.e., the substrates sampled in Mejnierzyn, Pawlow and Markowicze. On the other hand, the highest determined values of  $K_s$  were noted for low plasticity clay sampled in Gawlowka. Generally, the higher determined clay and the lower sand fraction content, the higher optimal water content and lower saturated hydraulic



conductivity were obtained after compaction. The changes in saturated hydraulic conductivity related to molding water content are also clearly visible in Figure 5. In some cases, the lowest values of  $K_s$  were observed at molding water contents higher than the optimal, i.e., in the cases of Chotyłow, Jelen, Gawłowka, Pawłow, and Zgorznicza. The obtained hydraulic conductivity in most cases generally decreased due to the increase in the applied molding water content. The observed  $K_s$ , in most cases of applied variable water contents on the right “wet” side of the Proctor curve, reached the values lower than commonly required  $1.0 \times 10^{-9}$  m/s.

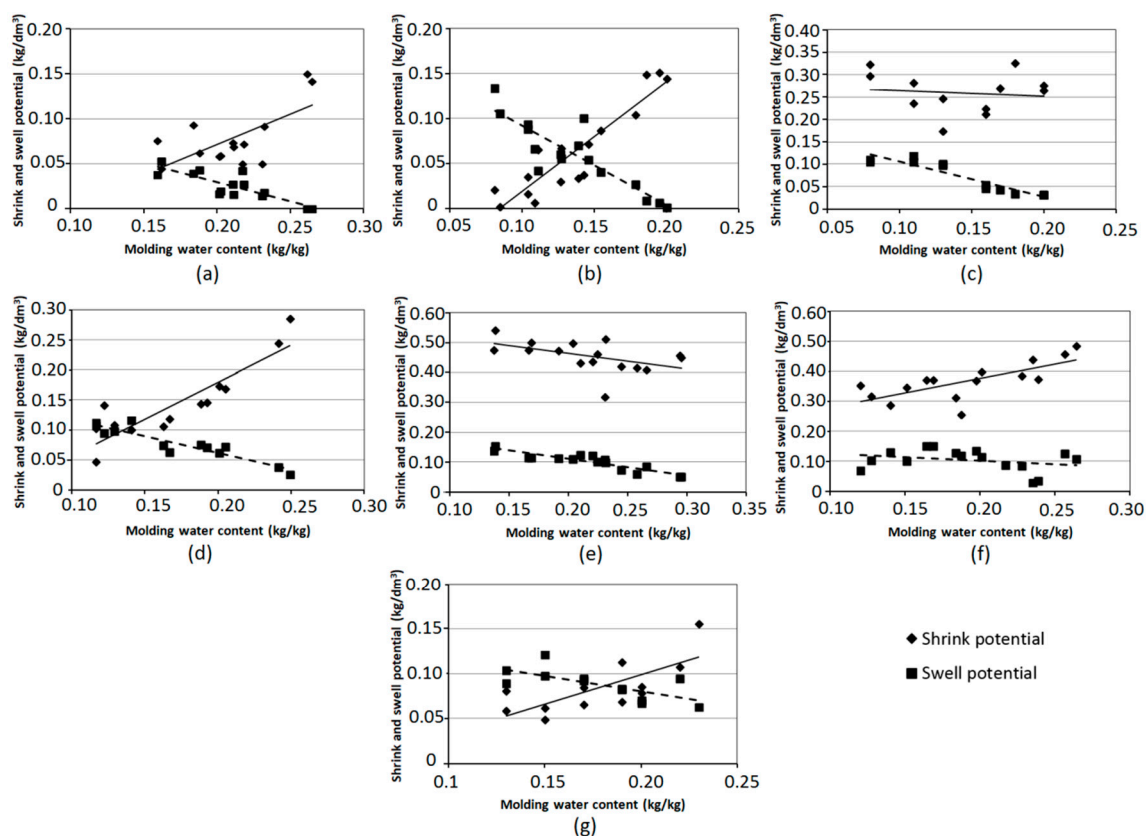
As for the commonly suggested molding water content [29] allowing for obtaining 95% of the Proctor density requested during the construction of compacted clay liner, i.e., molding water content equal to 1.0–1.2 of  $w_{opt}$ , wet of optimum, on the right, “wet” side of the Proctor curve, the values of  $K_s$  obtained for forming water content ( $w_f$ ) at range of  $w_{opt} \leq w_f \leq 1.2w_{opt}$  were lower than the above-mentioned popular statutory threshold. The determined values for  $K_s$  at  $w_{opt} \leq w_f \leq 1.2w_{opt}$  were in the range between  $1.2 \times 10^{-10}$  m/s for sandy loam sampled in Markowicze to  $2.9 \times 10^{-11}$  m/s for silty clay from Mejnierzyn. Thus, in our opinion, all the tested clay materials presented sufficient isolating properties required to construct a successfully operational compacted clay liner as a part of multilayer landfill capping in which the compacted earthen liner is supported by drainage and cultivation layers, allowing for sustaining the required saturation degree of the CCL of the top cover to avoid desiccation.

However, the values of coefficients of saturated hydraulic conductivity at low molding water contents on the left, “dry” side of the Proctor curve for most tested materials, excluding Gawłowka sandy loam, higher than the required threshold value were observed. Thus, in our opinion, the influence of initial molding water content at the final sealing capabilities of compacted clay liner, represented by saturated hydraulic conductivity, is clear. The locally available clay substrates, before their application to landfill construction, should be carefully tested to select the range of molding water content for which the required value of coefficient of saturated hydraulic conductivity is achievable.

Figure 5 also shows the changes in dry bulk density of the non-rigid tested substrates caused by swelling and shrinkage. The observed difference in density for the compacted material and the material after swelling generally decreased along with the molding water content increase. On the other hand, the determined relation between bulk density of compacted material and after shrinkage had the opposite direction. The differences between curves showing the dry bulk density after swelling and after shrinkage were clearly visible in all seven discussed cases. However, the relative differences between the bulk density after compaction and after swelling were relatively smaller (from 0% to approx. 10%) than differences between the dry bulk density after shrinkage, where the observed relative increase in density reached the level from 1% to approx. 39%. The highest determined increase in density after shrinkage was observed for high initial water contents applied during the compaction of high plasticity clays, including the substrates sampled in Mejnierzyn and Pawłow, substrates containing the highest contents of clay particles as well as swelling clay minerals. On the other hand, the lowest determined increases in bulk density were noted for the specimens of low and medium plasticity clays sampled in Gawłowka, Chotyłow, Markowicze and Zgorznicza, containing a significant amount of sand fraction and the lowest share of clay particles and swelling clay minerals.

The above-mentioned phenomena may be better illustrated by Figure 6, showing curves of swelling and shrinkage potentials understood, after Horn and Stępniewski [16], as differences between the dry bulk density after compaction and after swelling and shrinkage, related to the values of applied molding water content. Generally, the observed swelling and shrinkage characteristics of the tested compacted clays may be related to fine particles content (clay and silt), presence of expansive, swelling clay minerals and forming conditions. The swelling capabilities of clays decreased along with the increased molding water content for the same compaction effort applied. On the contrary, the determined shrinkage potential was in all the tested cases related to the increase in the initial water content. The highest values of shrinkage potential were noted for substrates of high fine particles

content and low ratio of non-swelling to swelling clay minerals (see Table 1). On the contrary, the lowest values of shrinkage potential were observed for tested substrates of low or medium plasticity and significant share of sand fraction. In most cases presented in Figure 6, the observed shrinkage potential was higher than the swelling potential in all of the ranges of water content. The only exceptions were noted for the substrates sampled in Gawlowka, Markowicze and Zgorznica, containing significant amounts of sand fraction, establishing the rigid, non-expansive part of soil or substrate structure, for which, for the selected water contents, lower than optimum, the observed shrinkage potential was lower than the swelling potential. The discussed clay materials from Gawlowka and Zgorznica, beside high sand and low clay particles content, showed also a significant ratio of non-swelling to swelling clay minerals (see Table 1), additionally affecting their swell and shrink capabilities, clearly reducing their shrinkage potential.



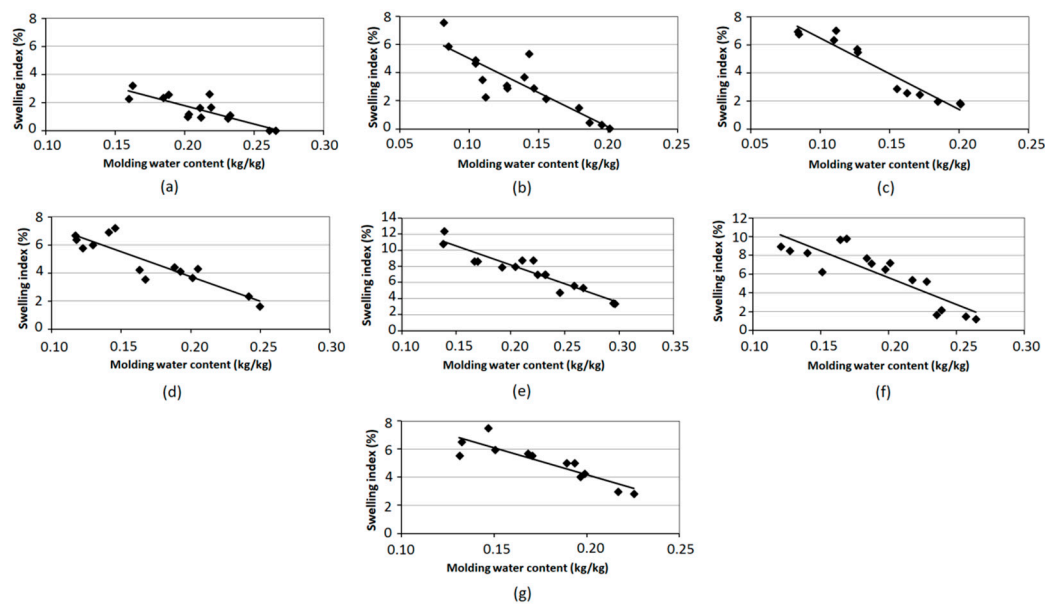
**Figure 6.** Calculated swelling and shrinkage potentials for tested substrates: (a) Chotylow; (b) Gawlowka; (c) Jelen; (d) Markowicze; (e) Mejznerzyn; (f) Pawlow; (g) Zgorznica.

The performed measurements of swelling for all tested substrates after testing of saturated hydraulic conductivity allowed for determining the values of swelling index for all applied forming water contents. The obtained values of  $SI$  are presented in Figure 7.

In all of the tested cases presented in Figure 7, there was a clear decrease in the values of determined swelling index along with the applied molding water content, and the observed  $R^2$  was in the range of 0.696–0.925. Thus, the higher the applied molding water content, the lower the resultant measured swelling. Additionally, it may be also noted that the highest values of the determined swelling index were observed for the clayey materials of high plasticity, such as the substrates sampled in Mejznerzyn and Pawlow, formed at low initial water contents.

The mean values of two determined dimensionless volumetric shrinkage indicators, the  $r_s$  and  $COLE$ , are presented and recognized in Table 2 [38,56–58].

The values of mean  $r_s$  and  $COLE$  presented in Table 2 allowed the assessment of shrinkage characteristics of the tested specimens. In most cases of substrates with low and medium plasticity, the determined mean  $r_s$  resulted in classification of deformation type as predominant vertical, safer for the compacted clay liner. On the other hand, for two the studied clays, sampled in Markowicze and Mejnierzyn, the observed deformation after shrinkage was classified as predominant horizontal, posing a significant risk of compacted liner desiccation cracking [37,38], dramatically reducing its sealing capabilities. In our opinion, the different deformation presented by samples from Markowicze and Mejnierzyn were related not only to their texture and structure composition, but also to their mineral composition. Both contained illite, chlorite, kaolinite and smectite, and presented similar, high, values of plastic limit.



**Figure 7.** Determined values of swelling index for tested clayey substrates: (a) Chotyłow; (b) Gawłowska; (c) Jelen; (d) Markowicze; (e) Mejnierzyn; (f) Pawłowa; (g) Zgorznicza.

**Table 2.** Mean values of dimensionless  $r_s$  and  $COLE$  shrinkage indicators of tested clays.

Substrate	Mean $r_s$ (–) ±SD	Deformation Type	Mean $COLE$ (–) ±SD	Shrinkage Potential
Chotyłow	2.48 ± 0.41	predominant vertical	0.022 ± 0.004	low
Gawłowska	2.22 ± 0.26	predominant vertical	0.024 ± 0.008	low
Jelen	2.81 ± 0.45	predominant vertical	0.057 ± 0.009	moderate
Markowicze	3.79 ± 0.27	predominant horizontal	0.035 ± 0.011	moderate
Mejnierzyn	3.14 ± 0.31	predominant horizontal	0.107 ± 0.015	very high
Pawłowa	2.68 ± 0.30	predominant vertical	0.085 ± 0.012	high
Zgorznicza	2.15 ± 0.23	predominant vertical	0.026 ± 0.004	low

Similarly, the determined values of  $COLE$  allowed classification of shrinkage potential for shrunk low and medium plasticity clays as from low to moderate. For two high plasticity clays, their shrinkage potential, determined by  $COLE$  values, was classified as high–very high.

In order to underline the close relation between plasticity and determined shrinkage indicators, the curves presented in Figure 8 were plotted. Figure 8 shows that increase in plasticity of the tested earthen substrates containing different clay content is related to the increase in the values of  $COLE$  and  $r_s$  indicators. Thus, high plasticity of the studied clays resulted in entering the zone of high and very high shrinkage potentials and predominant horizontal deformation, conducting cracking, and dramatically increasing the permeability of compacted clays.

Finally, in order to allow wider assessment of applicability of locally sampled clays of various plasticity as materials for compacted liners for rural sustainable waste landfills, the measurements of coefficients of saturated hydraulic conductivity after one, two and three cycles of drying and rewetting, leading to repeated shrinkage and swelling, were performed. The obtained results of mean Ks for each substrate during the given cycle of wetting and drying are presented in Figure 9.

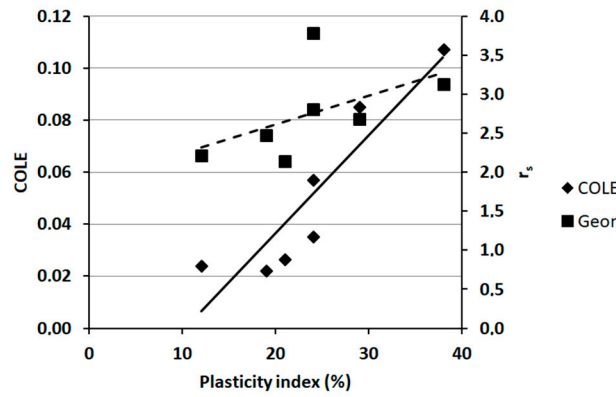


Figure 8. Relation of dimensionless shrinkage indicators,  $r_s$  and  $COLE$  to plasticity.

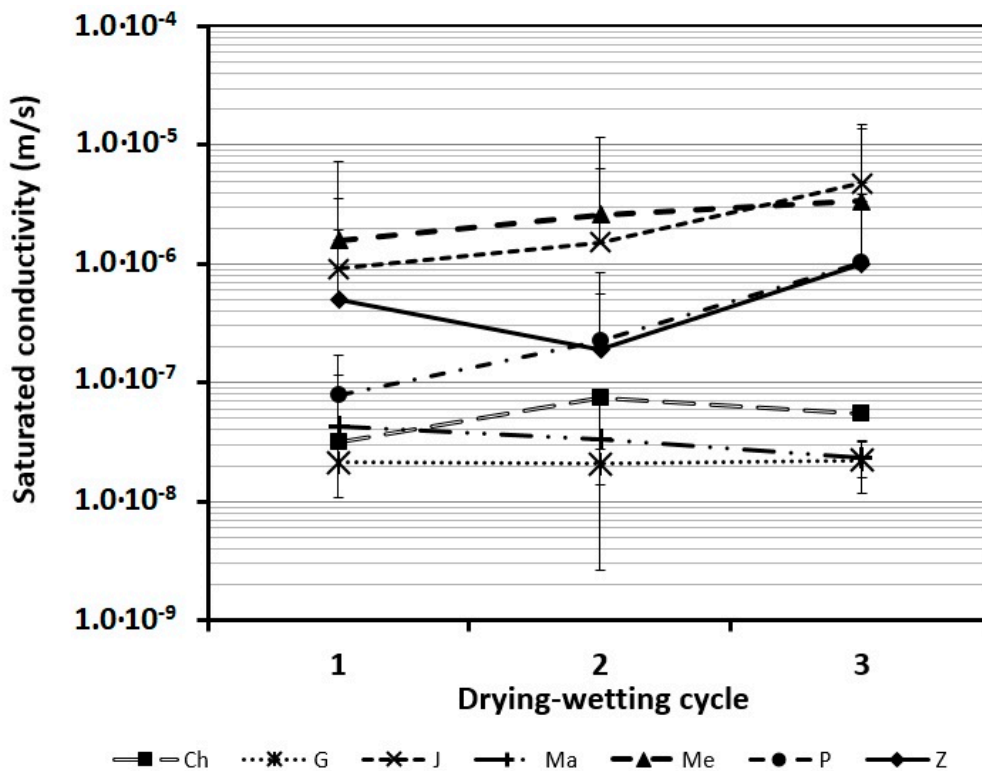


Figure 9. Mean coefficients of saturated hydraulic conductivity for tested substrates after cyclic drying and rewetting, error bars represent SD of measurements.

The results of Ks measurements shown in Figure 9 indicate that, in all the tested cases, the applied drying and rewetting of samples resulted in the loss of their sealing capabilities, reflected by an increase in their saturated hydraulic conductivity. No tested sample, regardless of its particle size composition and the applied molding water content, was able to sustain the required  $K_s = 1.0 \times 10^{-9}$  m/s. The above means that compacted clay liners utilizing the tested substrates in case of exposition to the unfavorable meteorological conditions, caused by several possible issues, including prolonged

construction of landfill capping without any cover, design and construction errors, failures or landslides of the drainage and recultivation layers or activity of plants and animals, may partially lose their sealing capabilities. It is also visible that the final saturated hydraulic conductivity after the third cycle of shrinkage and swelling reached the highest values, from the range  $1.0 \times 10^{-6}$ – $4.7 \times 10^{-6}$  m/s for the substrates of high and medium plasticity, containing a significant amount of clay particles, including the samples from Mejnierzyn, Jelen and Pawlow. On the other hand, the substrates sampled in Chotylow, Markowicze, Gawlowka and Zgorznica, of low or medium plasticity and containing a considerable share of coarse sand fraction, showed the substantial resistance to the increase in Ks value caused by repeated air drying and wetting. The measured Ks for these samples after the final, third drying and rewetting reached the level  $9.9 \times 10^{-7}$  m/s– $2.2 \times 10^{-8}$  m/s. Thus, the rapid and significant deterioration of compacted clay liner sealing capabilities, allowing increased infiltration of surface water into the waste body, was not so obvious. This feature of compacted clay liners utilizing low and medium plasticity earthen materials may considerably sustain the sustainability of top capping systems under variable atmospheric conditions, during possible failures, top recultivation layers landslides leading to the exposition of clay liner to direct atmospheric conditions including sunlight and wind. Additionally, in these four cases, the final values of Ks after the third cycle of shrinkage and swelling was lower than the value of  $1.0 \times 10^{-7}$  m/s for compacted earthen liner required by the US EPA (United States Environment Protection Agency) technical manual [32].

#### 4. Conclusions

The performed studies allowed to draw the following conclusions considering the possible application of the tested substrates, and generally locally available clay materials, into sustainable waste management systems:

- According to the popular requirements regarding the sealing capabilities of the earthen liner, all of the tested clayey substrates were found to be applicable to the construction of a compacted clay liner for sustainable rural waste landfill, both as a bottom liner or as a part of a properly designed and constructed multilayered top cover also supported by artificial membranes.
- However, the applied clay material particle composition and molding conditions should be selected very carefully because they may trigger the future behavior of the compacted clay liner e.g., define not only the saturated hydraulic conductivity but also the swell and shrink potentials, and resistance against cycles of drying and wetting determined by the appearance of cracking. Our studies showed that low applied molding water contents, dry of optimum, prevented in most cases the reduction of saturated hydraulic conductivity to values lower than  $1.0 \times 10^{-9}$  m/s.
- Our studies showed that clay materials of high plasticity index, approx. greater than 30%, allowed very good sealing capabilities but showed high shrinkage potentials, horizontal deformation during shrinkage as well as susceptibility for desiccation, triggering the increase in permeability and were unable to regain their initial hydraulic conductivity after rewetting.
- Application of the low plasticity substrates or medium plasticity materials, of plasticity index values even lower than 20%, with the significant share of sand, even in range between 50–75%, may allow for retaining at least partial sealing capabilities after repeated drying and rewetting and should improve the sustainability of the compacted clay liner in case of top capping failure.
- The durability and environmental sustainability of a local, rural waste landfill, isolated by the affordable compacted earthen liners utilizing local materials is in our opinion possible but strongly related to the proper choice of process parameters during CCL construction for the given clayey substrate. In our opinion, the locally available materials should be carefully studied considering not only their particle size distributions and coefficients of saturated hydraulic conductivity after compaction, but also their shrink and swell capabilities and resistance to desiccation cracking. The performed tests may help to select the most suitable molding water content for the individual material, allowing not only achieving the required sealing capabilities but also limiting swell and

shrink potentials as well as diminishing vulnerability of the liner to increase in the hydraulic conductivity caused by drying and rewetting.

- The presented studies should be continued and should include studies of a greater number of locally available clay substrates as well as tests of applicability of various additives, including products of sustainable recycling of different types of municipal or industrial wastes.

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