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NUMERICAL SIMULATION OF BENZENE SEEPAGE THROUGH CRACKED COMPACTED MINERAL LINER OF MUNICIPAL WASTE LANDFILL

MODELOWANIE MIGRACJI BENZENU PRZEZ SPĘKANĄ ZAGĘSZCZONĄ BARIERĘ ILASTĄ SKŁADOWISKA ODPADÓW KOMUNALNYCH

Abstract: This paper contains the results of numerical simulation of benzene migration, pollutant typical for landfill leachate, through the bottom compacted clay liner of municipal waste landfill. The FEFLOW, DHI software was used in the numerical calculations for four tested clays of various plasticity, compacted according to PN-B-04481:1988 and ASTM D698-12e2 and subjected to three cycles of drying and rewetting. The plasticity of the tested clay materials was determined by standard methods and classified according to the Unified Soil Classification System, ASTM D2487-11. Saturated hydraulic conductivity of the tested compacted clays was determined by the laboratory falling head permeameters for compacted soils, with agreement to ASTM D5856-95. Saturated hydraulic conductivity of the tested substrates after three cycles of shrinkage and swelling was measured by the falling and constant head laboratory permeameter. The sand box and pressure chambers with ceramic plates were used to determine the water retention curve parameters in the range of 0–15 bar. The obtained results showed the influence of cyclic shrinkage and swelling of clays on leachate seepage, triggering benzene migration, through the cracked compacted bottom liner.

Keywords: pollutant migration, clay materials, compacted mineral liners, municipal landfill leachate

Introduction

Numerous dangerous substances, including benzene [1, 2] available in leachate percolating through the bottom of the landfill pose a serious threat to water and soil [3–5]. The satisfactory sealing capabilities are usually allowed by compacted clay liners

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(CCLs), supported by plastic or geosynthetic membranes [1, 6–8], due to a very low hydraulic conductivity of clays [1, 9]. However, the durability and sustainability of compacted clay liners may be weakened [10, 11] because of the significant expansiveness of clays which are prone to swelling and shrinkage under variable water saturation [12, 13]. As the result, their hydraulic and isolating characteristics may be irreversibly changed due to cracking [14, 15]. Therefore, the increase in permeability of compacted clay liners, over the usually required $1 \cdot 10^{-9}$ m $\cdot$ s^{-1} [16–18], caused by cyclic drying and rewetting may trigger significant reduction of the isolating properties of earthen liners leading to the increased leachate percolation and pollutants transport from the waste body to soil and water environment.

This paper presents an attempt of numerical determination of the influence of type of material of the compacted liner on the possible benzene migration, one of the most typical constituent of landfill leachate, through the partially cracked bottom of CCL of municipal landfill.

Materials and methods

The presented studies covered the application of four types of clay specimens characterized by different plasticity sampled in Lazek Ordynacki, Mejznerzyn, Markowicze and Gawlowka, close to Lublin, Poland. The material sampled in Lazek Ordynacki was recognized as silty clay, Mejznerzyn as clay, Markowicze as clay loam while the specimen from Gawlowka was classified as sandy clay loam. The determination of particle size distribution of the tested clays was based on PN-B-04481:1988 [19], while the gravimetric water content was obtained according to ASTM C566-13 [20]. The plasticity of the tested clay specimens was determined according to [21] PKN-CEN ISO/TS 17892-12. 2009 with the standard methods [21] and classified according to the Unified Soil Classification System [22]. The obtained basic characteristics of the sampled substrates are presented in Table 1.

Table 1

Basic characteristics of four tested clay materials, modified after [11]

Characteristics		Lazek Ordynacki	Mejznerzyn	Gawlowka	Markowicze
Particle fraction	Sand [%]	4.5	13	66	25
	Silt [%]	51	35	3	37
	Clay [%]	44.5	52	31	38
Solid particle density [Mg $\cdot$ m^{-3}]		2.68	2.79	2.86	2.76
Bulk density [Mg $\cdot$ m^{-3}]		1.70	1.37	1.95	1.79
Plasticity index [%]		35	38	12	24

The studied clay materials were compacted, according to PN-B-04481:1988 [19], to 95% of maximum bulk density and at molding water content in range of $w_{opt} < w_f < 1.2\ w_{opt}$, which are commonly advised for compacted clay liner construction. The following values of forming gravimetric water contents were applied: 0.25, 0.29, 0.15 and

0.2 kg · kg^{-1}, respectively for Lazek Ordynacki, Mejznerzyn, Gawlowka and Markowicze specimens. Saturated hydraulic conductivity (K_s) of the compaction tested substrates was determined in the falling water head H-4145 permeameters for compacted soils by Humboldt Mfg. Co, USA, meeting the requirements of ASTM D5856-95 [23]. The K_s of the tested materials altered by three cycles of shrinkage and swelling was measured by a laboratory falling head permeameter, IMUZ, Poland after the third cycle of drying (20 C degree) and rewetting by the capillary rise.

Water retention characteristics of the studied compacted clays, required as input data to numerical modeling, were determined in the range up to 1500 kPa (15 bar) in the sand box (IMUZ, Lublin, Poland) and the pressure chambers with ceramic plates by Soil Moisture, USA. The Statistica, Statsoft, USA and SWRC model [24] were used to fit water retention curve measurements to the standard van Genuchten's formula [25].

The numerical calculations of benzene transport, related to leachate seepage, through cracked bottom liners of the municipal landfill cell for all tested clayey substrates were based on standard forms of Richard's and Darcy's equations [26, 27] and performed by FEFLOW, DHI, Germany. The developed model, presented in Fig. 1, covered 10 m long section of bottom CCL of statutory 1 m thickness and 3.5 m of underlying untransformed local sandy clay loam, described in [28]. The assumed cracks covered 1.0 m long section of the studied bottom liner. The prepared model consisted of 1619 nodes and 3078 elements. The assumed time duration of simulation covered full year, 364 days.

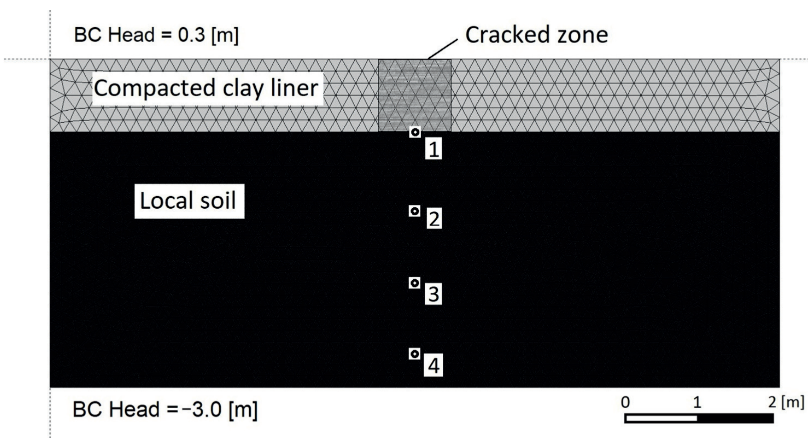

Fig. 1. Developed numerical model of cracked compacted clay liner with applied reference points

Table 2 presents the required input data for water flow and benzene transport through the cracked bottom liner of municipal solid waste landfill. The modeled soils were treated as isotropic. The benzene transport characteristics of the studied clays were assumed from literature [28–31].

The applied initial conditions for modeling of water flow included the degree of soil saturation assumed as 0.99 and 0.95, respectively for CCL and local soil. The boundary conditions for water flow, also shown in Fig. 1, assumed values of the first type

Table 2

Input data assumed to numerical modeling

Characteristics	Compacted clay liner				Local soil
	Lazek Ordynacki	Mejznerzyn	Gawlowka	Markowicze	
K_s after compaction [m · s^{-1}]	$5.20 \cdot 10^{-11}$	$2.46 \cdot 10^{-11}$	$9.45 \cdot 10^{-11}$	$1.17 \cdot 10^{-10}$	$1.1 \cdot 10^{-7}$
K_s after cracking [m · s^{-1}]	$6.58 \cdot 10^{-7}$	$1.44 \cdot 10^{-7}$	$1.8 \cdot 10^{-8}$	$2.99 \cdot 10^{-8}$	—
Saturated water content θ_s [m^3 · m^{-3}]	0.396	0.451	0.332	0.369	0.402
Residual water content θ_r [m^3 · m^{-3}]	0	0	0	0	0.112
Water retention curve parameter A [m^{-1}]	1.405	0.173	0.207	0.151	0.82
Water retention curve parameter n [-]	1.082	1.149	1.107	1.090	1.275
Diffusion coefficient [m^2 · s^{-1}]	$8.6 \cdot 10^{-10}$				$1.16 \cdot 10^{-9}$
Longitudinal dispersivity [m]	0.02				3.0
Traverse dispersivity [m]	0.002				0.3
First order degradation rate [s^{-1}]	$4.40 \cdot 10^{-7}$				
Henry sorption coefficient [-]	0.22				

Dirichlet condition for top and bottom border of modeled profile. The water head equal to 0.3 m was selected as top boundary condition, as maximum typically observed leachate head over the bottom liner for the normally operating municipal wastes landfill [32]. The concentration of benzene in leachate, treated as the top boundary condition for pollutant mass transport, was assigned after [2] as equal to 1.3 μg · dm^{-3}. The initial benzene concentration in CCL and local soil was set as 0.0 μg · dm^{-3}.

Results and discussion

The results of our numerical calculations showed that undamaged CCLs, constructed of all four tested clayey materials, were able to permanently limit the leachate seepage and the resultant benzene migration to a lower layer of soil. However, cracking, as a result of cyclic drying and rewetting, may cause a decrease in the sealing capabilities and allow increased seepage and pollutant transport. Fig. 2 shows an exemplary distribution of benzene concentration in the modeled soil profiles after the final time step of calculations, t = 364 days.

Graphs included in Fig. 2 show that the compacted clay liners based on clays of various plasticity, showing different response to cyclic swelling and shrinkage, allowed different isolation capabilities after cracking. The cracked liner constructed of Mejznerzyn clay and Lazek Ordynacki high-plasticity silty clay allows significantly higher seepage and benzene propagation than the cracked earthen liner made of low-plasticity clay loam and sandy clay loam sampled in Markowicze and Gawlowka. No comparable calculated benzene concentrations were observed below the cracked liners (below the reference point No 1) utilizing clays of higher (above 30%) and lower (12–24%) plasticity. This phenomenon may be explained by different reaction to cyclic shrinkage

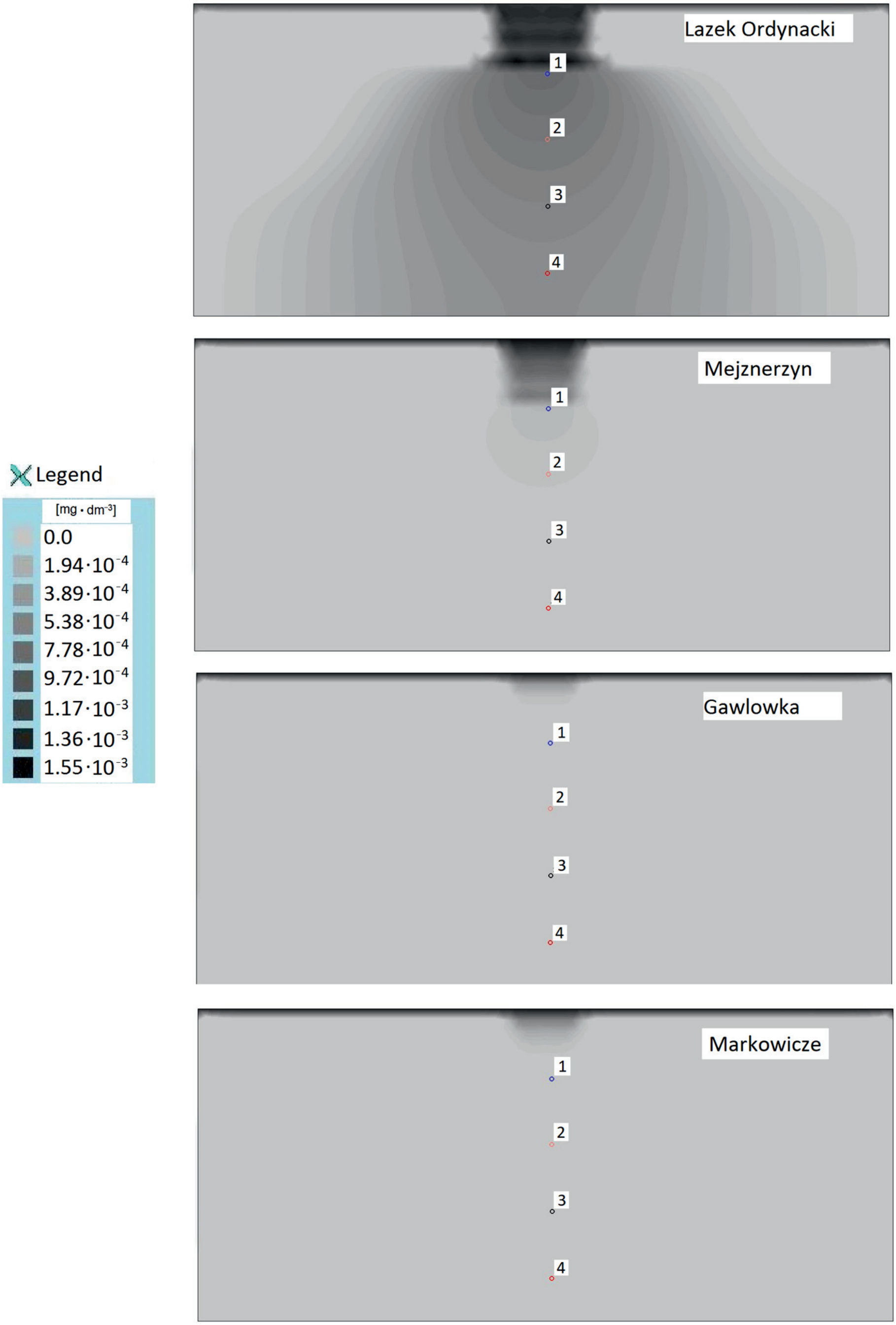

Fig. 2. Modeled distribution of benzene concentration [mg · dm^{-3}] in the four modeled profiles at time t = 364 days

and swelling, triggering increase in saturated hydraulic conductivity after cracking. The differences in the measured K_s for cracked compacted clay specimens of higher and lower plasticity reached one order of magnitude. In order to underline the above-mentioned observations, the time-varying concentrations of benzene in all applied reference points were compared in Fig. 3.

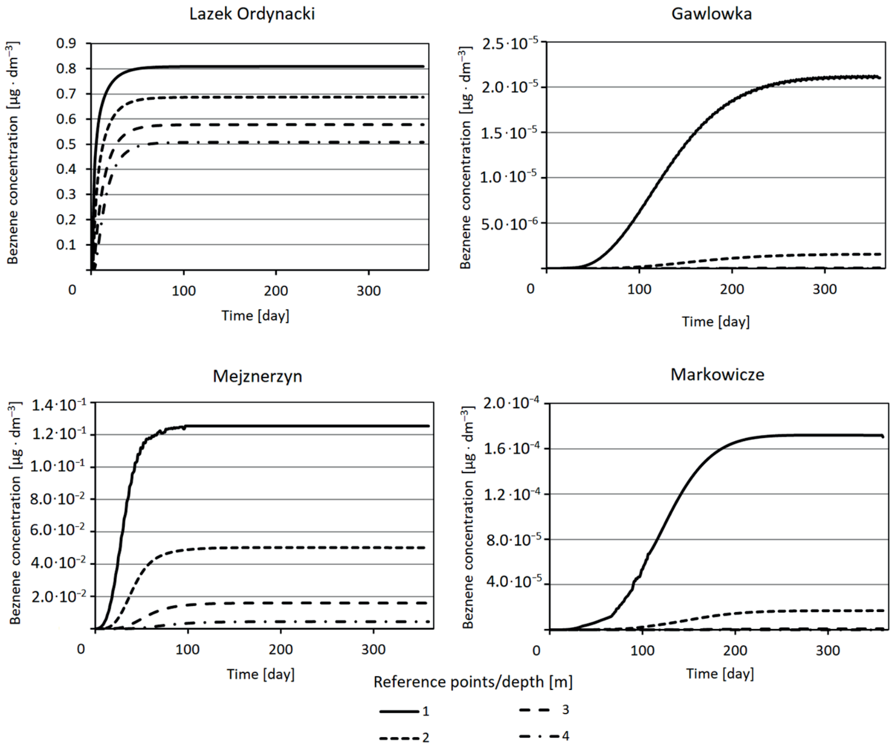

Fig. 3. Modeled concentrations of benzene in applied reference points

Figure 3 shows that the modeled concentrations of benzene in soil observed in the reference points, from 1 to 4 meters below the liner surface, were in the case of Lazek Ordynacki at comparable level, between 0.8 and 0.5 µg · dm^{-3}. The similar situation was observed for the compacted clay liner using high plasticity clay from Mejznerzyn, for which determined concentration of benzene varied in reference points between levels of 1.25 · 10^{-1} µg · dm^{-3} and approx. 4.50 · 10^{-3} µg · dm^{-3}.

On the other hand, the calculated concentrations of benzene in the same reference points for cracked liners utilizing Gawlowka and Markowicze clayey substrates were significantly lower and varied between approx. 2.10 · 10^{-5} µg · dm^{-3} – 9.84 10^{-10} µg · dm^{-3} and 1.70 · 10^{-4} µg · dm^{-3} – 2.73 · 10^{-8} µg · dm^{-3}, respectively. Thus, it is visible that the decrease in plasticity of clays, resulted in lower saturated hydraulic conductivity after cyclic shrinkage and lower, by approximately four orders of magnitude, resultant concentrations of migrated benzene.

Finally, the comparison of accumulated mass of benzene migrated to soil through the cracked liner of area equal to 1 m^2, based on all the tested clayey material specimens is presented in Fig. 4. The observed calculated differences in the modeled accumulated mass of benzene transported by water to the natural soil were clearly related to the ability of compacted clay to sustain its sealing capabilities after several cycles of drying and rewetting.

The compacted sandy clay loam sampled in Gawlowka was able to partially sustain its saturated hydraulic conductivity, at the level of $1.8 \cdot 10^{-8}$ $m \cdot s^{-1}$, which resulted in significantly lower leachate percolation and calculated benzene migration – up to 0.11 μg. Similarly, the studied clay loam sampled in Markowicze, presenting saturated hydraulic conductivity at the comparable level $2.99 \cdot 10^{-8}$ $m \cdot s^{-1}$ allowed the similar accumulated mass of tested pollutant i.e. approx. 0.78 μg.

On the other hand, the applied clay specimens of higher plasticity allowed greater increase in the saturated hydraulic conductivity after cracking caused by cyclic drying and rewetting, reaching values of $6.58 \cdot 10^{-8}$ $m \cdot s^{-1}$ and $1.44 \cdot 10^{-8}$ $m \cdot s^{-1}$ for Lazek Ordynacki and Mejznerzyn, respectively. Thus, the increased mass of migrated modeled pollutant was observed. The calculated accumulated mass of benzene reached the values of 1305 μg and 205 μg for 1 m^2 of cracked compacted liner.

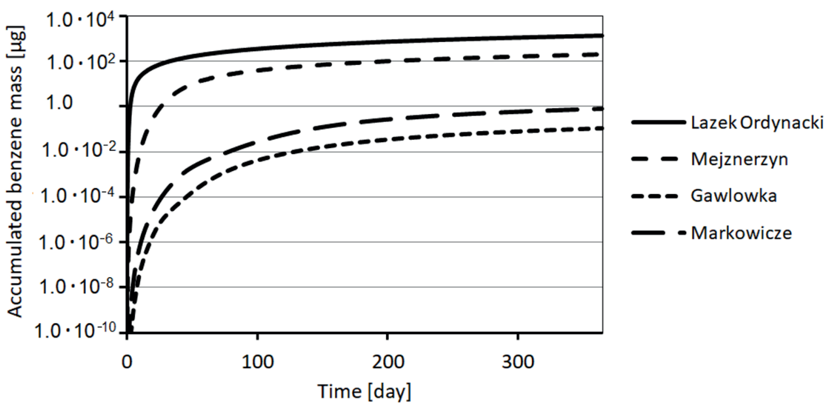

Fig. 4. Comparison of accumulated benzene mass transported through 1 m^2 of cracked liner

Moreover, a correlation between the calculated accumulated mass of benzene migrating through cracked compacted clay liner and saturated hydraulic conductivity after cracking was observed. On the other hand, the measured K_s after cyclic drying and rewetting was clearly related to the plasticity index of the tested specimens. The plasticity of clayey soils depends on, inter alia, their particle composition. Strong positive correlations between plasticity and clay and silt contents and negative versus the sand fraction content were observed. So, in our opinion to reduce the possible migration of pollutants thorough the cracked compacted clay liner the increase in saturated conductivity should be minimized by application of materials characterized by a lower plasticity index, as well as lower silt and clay and higher sand fraction contents.

Summary and conclusions

The undamaged modeled studied compacted clay liners, utilizing clayey materials of different particle composition and plasticity, were successful in limiting the leachate seepage and resultant benzene transport. However, the reduced sealing capabilities caused by cracking triggered by cyclic swelling and shrinkage allowed an increased leachate percolation and benzene migration. It was observed that the intensity of pollutant transport was clearly related to the ability of compacted clay to sustain even the partial isolating characteristics after cracking caused by cyclic dehydration. The greater accumulated values of benzene mass and the higher calculated concentrations of pollutant in all the applied reference points in the local soil below the cracked compacted clay liners were observed for high-plasticity specimens, silty clay sampled in Lazek Ordynacki and clay from Mejznerzyn. The high determined values of plasticity index of the applied substrates resulted in the greater saturated hydraulic conductivity allowing an increase in seepage triggering benzene transport were observed. The calculated differences in the accumulated pollutant mass and concentrations of benzene in the local soil for all tested low- and high-plasticity clayey materials of compacted clay liners reached over four orders of magnitude. Thus, in our opinion, the high-plasticity clays should be avoided in the construction of compacted clay liners to ensure the long-term sustainability of landfill isolation and prevent increased benzene (or other pollutants contained in the landfill leachate) migration to the natural soil and water environment.

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MODELOWANIE MIGRACJI BENZENU PRZEZ SPĘKANĄ ZAGĘSZCZONĄ BARIERĘ ILASTĄ SKŁADOWISKA ODPADÓW KOMUNALNYCH

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Abstrakt: W pracy przedstawiono wyniki obliczeń numerycznych migracji benzenu, zanieczyszczenia często wchodzącego w skład odcieków składowiskowych, przez dolną barierę geologiczną składowiska odpadów komunalnych. Obliczenia przeprowadzono za pomocą programu FEFLOW, DHI dla dwóch wybranych gruntów ilastych o różnej plastyczności, zagęszczonych według PN-B-04481:1988 i ASTM D698-12e2 oraz poddanych kilku cyklom osuszania i nawilżania. Plastyczność badanych gruntów ilastych określono metodami standardowymi i sklasyfikowano wg Unified Soil Classification System, ASTM D2487-11. Współczynniki filtracji wykorzystanych gruntów po zagęszczeniu wyznaczono za pomocą zgodnych z wymaganiami ASTM D5856-95 przepuszczalnościomierzy do gruntów zagęszczonych. Pomiary współczynnika filtracji zastosowanych gruntów ilastych po trzech cyklach osuszania i nawilżania wykonano za pomocą przepuszczalnościomierza laboratoryjnego. Właściwości retencyjne gruntów w zakresie 0–15 bar wyznaczono za pomocą bloku pyłowego oraz komór ciśnieniowych z płytami ceramicznymi. Uzyskane wyniki obliczeń numerycznych wykazały wpływ cyklicznego osuszania i nawilżania gruntów ilastych na przesiąk odcieków oraz migrację benzenu przez spękaną dolną zagęszczoną przesłonę mineralną składowiska.

Słowa kluczowe: transport zanieczyszczeń, zagęszczone przesłony mineralne, odcieki składowiskowe