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MODELING OF BENZENE PROPAGATION THROUGH CRACKED COMPACTED CLAY LINER OF MUNICIPAL WASTE LANDFILL

MODELOWANIE MIGRACJI BENZENU PRZEZ SPĘKANĄ ZAGĘSZCZONĄ BARIERĘ ILASTĄ SKŁADOWISKA ODPADÓW KOMUNALNYCH

Abstract: This paper presents the results of numerical simulation of benzene migration, pollutant usually observed in landfill leachate, through the bottom compacted clay liner of municipal waste landfill. Our calculations were performed in FEFLOW, DHI software for two tested clay specimens of different plasticity, compacted according to PN-B-04481:1988 and ASTM D698-12e2 and subjected to three cycles of shrinkage and swelling. The plasticity of tested clay materials was determined by the standard methods and classified according to Unified Soil Classification System, ASTM D2487-11. Saturated hydraulic conductivity of compacted tested clay materials was measured by the laboratory falling head permeameters for compacted soils meeting the requirements of ASTM D5856-95. Saturated hydraulic conductivity of the tested substrates after three cycles of drying and rewetting was measured by the falling and constant head laboratory permeameter. Water retention curve parameters were determined in the range of 0-15 bar by sand box and pressure chambers with ceramic plates. The obtained results showed influence of 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

Municipal landfill leachate containing numerous dangerous substances, including benzene [1, 2] percolating through the bottom of the landfill poses a great threat to water and soil [3-5]. Compacted clay liners (CCLs), supported by plastic or geosynthetic membranes [1, 6-8], usually allow satisfactory sealing capabilities due to a very low hydraulic conductivity of clays [1, 9]. However, sustainability and durability of compacted clays as materials for landfills' isolation may be questioned [10, 11] due to significant expansiveness [12, 13]. The expansive clays are prone to swelling and shrinkage under variable water saturation [12] so their hydraulic and isolating characteristics may be alerted. Changes in soils' structure and characteristics caused by cyclic drying and rewetting are irreversible and result in cracking and changes in hydraulic conductivity [14, 15]. Thus, isolating properties of compacted earthen liners, utilizing clays of various plasticity, may be significantly reduced in case of increase in their permeability, below usually required $1\cdot10^{-9}$ $m\cdot s^{-1}$ [16-18], caused by cyclic drying and rewetting due to landfill operation failures, exposure to atmospheric conditions etc. So, in this case percolation of leachate may be significantly increased, triggering expanded pollutant transport from waste body to soil and water environment.

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

Materials and methods

The presented studies covered application of two types of clay specimens of different plasticity sampled in Lazek Ordynacki and Gawlowka, close to Lublin, Poland. Material sampled in Lazek Ordynacki was recognized as silty clay, while specimen from Gawlowka was classified as sandy clay loam. The determination of particle size distribution of the studied materials was based on PN-B-04481:1988 [19], gravimetric water content was obtained by the standard weight method according to ASTM C566-13 [20]. The plasticity of tested clay specimens was determined by the standard methods [21] and classified according to the Unified Soil Classification System [22]. The basic characteristics of the sampled substrates are presented in Table 1.

Table 1

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

Characteristics		**Lazek Ordynacki**	**Gawlowka**
Particle fraction	Sand [%]	4.5	66
	Silt [%]	51	3
	Clay [%]	44.5	31
Solid particle density [$Mg \cdot m^{-3}$]		2.68	2.86
Bulk density [$Mg \cdot m^{-3}$]		1.70	1.95
Plasticity Index [%]		35	12

The tested clay substrates were compacted, according to PN-B-04481:1988 [19] to 95% of maximum bulk density and forming moisture $w_{opt} < w_f < 1.2\ w_{opt}$, commonly advised for compacted liner construction. The applied forming gravimetric water contents for Lazek Ordynacki and Gawlowka clayey substrates were equal to 0.25 and 0.15 $kg \cdot kg^{-1}$, respectively. Saturated hydraulic conductivity (K_s) of the tested substrates after compaction was measured in the falling water head H-4145 compaction permeameters by Humboldt Mfg. Co, USA, meeting requirements of ASTM D5856-95 [23]. The K_s of the tested materials after three cycles of shrinkage and swelling was measured with the falling head method in a laboratory permeameter, produced by the former IMUZ, Poland, after the third cycle of drying (20°C) and rewetting by capillary rise. Water retention of the compacted clays was tested in the sand box (IMUZ, Lublin, Poland) and pressure chambers with ceramic plates by Soil Moisture, USA, in pressure range up to 1500 kPa (15 bar). The results of water retention curve measurements were fitted in Statistica, Statsoft, USA and verified by SWRC model [24] to the standard van Genuchten's formula [25].

Numerical modeling of leachate seepage and benzene transport through cracked bottom liner of the municipal landfill cell for two tested clayey substrates was performed by FEFLOW, DHI, Germany, modeling software based on the standard forms of Richard's and Darcy's equations [26, 27]. The developed model, presented in Figure 1, represented 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 modeled cracks covered 1.0 m section of the studied bottom liner. The prepared model consisted of 1619 nodes and 3078 elements. Time duration of simulation covered full year, 364 days.

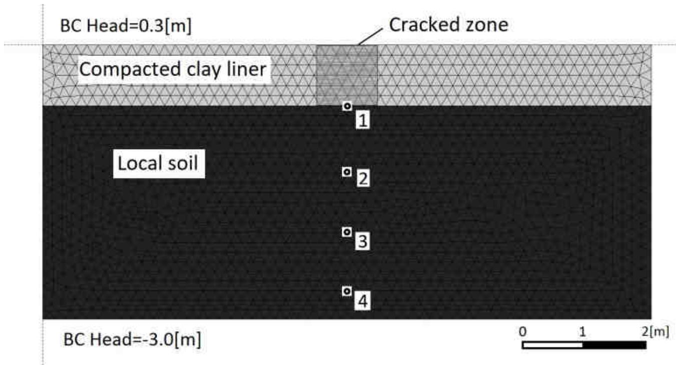

Fig. 1. Developed numerical model of cracked compacted clay liner with applied reference points

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

Table 2

Input data assumed to numerical modeling

	Compacted clay liner		**Local soil**
	Lazek Ordynacki	**Gawlowka**	
K_s after compaction [m·s^{-1}]	$5.20 \cdot 10^{-11}$	$9.45 \cdot 10^{-11}$	$1.1 \cdot 10^{-7}$
K_s after cracking [m·s^{-1}]	$6.58 \cdot 10^{-7}$	$1.8 \cdot 10^{-8}$	-
Saturated water content θ_s [m^3·m^{-3}]	0.396	0.332	0.402
Residual water content θ_r [m^3·m^{-3}]	0	0	0.112
Water retention curve parameter A [m^{-1}]	1.405	0.207	0.82
Water retention curve parameter n [-]	1.082	1.107	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		

Initial conditions for water flow modeling covered degree of soil saturation which was assumed as 0.99 and 0.95, respectively for CCL and local soil. The boundary conditions for water flow, presented also in Figure 1, covered values of the first type Dirichlet condition for top and bottom border of the modeled profile. The value of water head equal to 0.3 m was selected as the top boundary condition as maximum typically observed leachate head over the bottom liner for the normally operating municipal landfill [32]. The concentration of benzene in leachate, treated as the top boundary condition for mass transport, was assumed 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 tested clayey materials were able to limit leachate seepage and resultant benzene migration to the lower layer of soil. However, cracking, caused by cyclic drying and rewetting, may reduce the sealing capabilities allowing the increased seepage and pollutant transport. Figure 2 shows exemplary distribution of benzene concentration in the modeled soil profile after the final time step of calculations, t = 364 days.

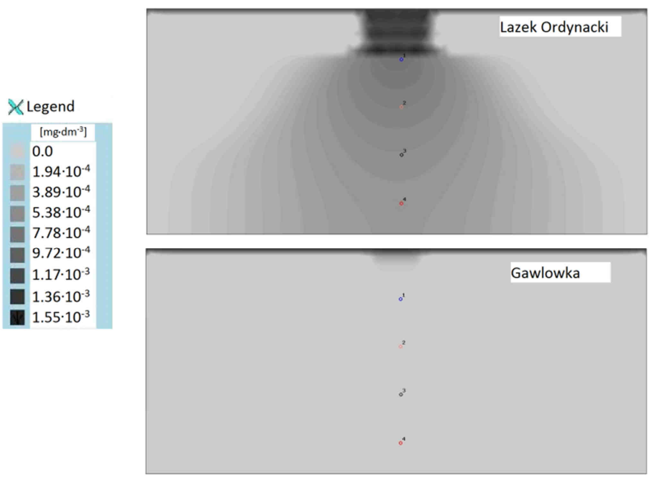

Fig. 2. Benzene concentration [mg·dm^{-3}] distribution in the modeled profile at t = 364 days

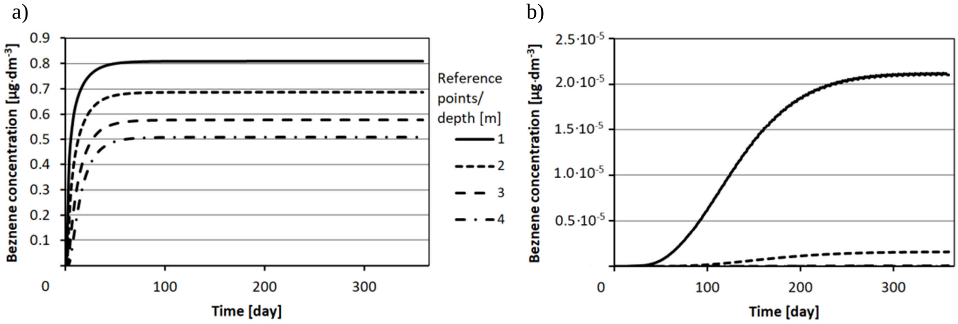

Fig. 3. Modeled concentrations of benzene in applied reference points: a) Lazek Ordynacki, b) Gawlowka

It is also visible in Figure 2 that compacted clay liners utilizing clays of various plasticity, differently responding to cyclic swelling and shrinkage, allowed different isolation capabilities after cracking. The cracked liner constructed of Lazek Ordynacki high-plasticity silty clay allows significantly higher seepage and benzene propagation than cracked liner made of low-plasticity sandy clay loam sampled in Gawlowka. There was no comparable benzene concentration observed below cracked Gawlowka liner. To underline the above observations, time-varying concentrations of benzene in all applied reference points were compared in Figure 3.

Figure 3 shows that modeled concentrations of benzene in soil observed in reference points, from 1 to 4 meters below the liner surface, were in case of Lazek Ordynacki at comparable level, between 0.8 and 0.5 µg dm^{-3}. The calculated concentrations of benzene in the same reference points for cracked liner utilizing Gawlowka clayey substrate were significantly lower, starting from four orders of magnitude.

Finally, Figure 4 presents comparison of accumulated mass of benzene migrated to soil through 1 m^2 of cracked liner using both tested earthen material specimens.

Again, the influence of ability of compacted clay to sustain its sealing capabilities after several cycles of drying and rewetting allowed clear and visible differences in the modeled accumulated mass of benzene transported by water to the natural soil. The compacted sandy clay loam sampled in Gawlowka was able to partially sustain its saturated hydraulic conductivity, at the level of 10^{-8} $m\cdot s^{-1}$, which resulted in significantly lower leachate percolation and benzene migration. The observed difference in accumulated mass of benzene in relation to values for cracked high-plasticity liner using Lazek Ordynacki silty clay reached four orders of magnitude, approx. 0.11 vs. 1305 $\mu g\cdot m^{-2}\cdot year^{-1}$.

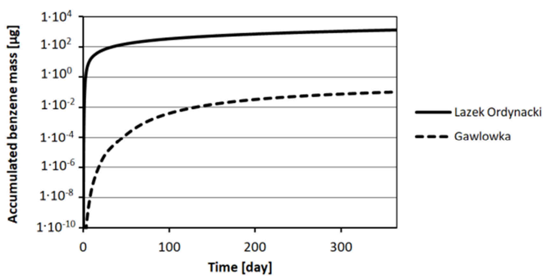

Fig. 4. Comparison of accumulated benzene mass transported through 1 m^2 of cracked liner

Summary and conclusions

Our studies showed that despite the fact that undamaged tested compacted clay liners were successful in limiting leachate seepage and resultant benzene transport, the reduced sealing capabilities caused by the cyclic swelling and shrinkage triggered the increased leachate percolation and benzene migration. The intensity of pollutant transport was clearly related to the ability of soil to sustain even the partial isolating characteristics after cracking caused by cyclic dehydration. The greater accumulated mass of benzene and higher pollutant concentrations in all the applied reference points in the local soil below the cracked compacted clay liner were observed for the high-plasticity silty clay sampled in Lazek Ordynacki. The high value of plasticity index of tested substrate caused the greater saturated hydraulic conductivity and resultant seepage triggering benzene transport was observed. The differences between accumulated mass and concentration of benzene in soil for both 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 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: 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