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Sustainable Landfilling as Final Step of Municipal Waste Management System

Zrównoważone składowiska jako końcowy etap systemu gospodarki odpadami komunalnymi

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Abstract
This paper discusses the role of sustainable landfilling of municipal waste in the current systems of municipal waste management systems as the manner of final disposal of wastes. The actual data considering share of landfilling as final waste disposal in various countries all over the world allowed to asses importance of this method. Special attention was paid to sustainable landfilling in developing or undeveloped courtiers of low economic incomes. Then, the paradigm of sustainable landfilling was presented and the most effective methods of landfill isolation by liners were discussed. The compacted clay liners were presented as the gainful option for the developing countries. The main determinants of the compacted clay liners' long-term liner sustainability were described as hydraulic conductivity, swell-shrinkage properties and, finally, ability of soil/substrate to sustain its hydraulic conductivity after cyclic drying and rewetting. Finally, possible application of low plasticity clays instead materials of high plasticity, prone to shrinking and swelling, to construction of sustainable compacted earthen liner was underlined.

Key words: municipal waste management, sustainable landfilling, compacted clay liners

Streszczenie
Praca przedstawia znaczenie zrównoważonego składowania odpadów komunalnych jako końcowego etapu ich utylizacji w ramach aktualnych systemów zagospodarowania odpadów komunalnych. W artykule zaprezentowano aktualne dane dotyczące procentowego udziału składowisk w końcowym zagospodarowywaniu odpadów komunalnych w różnych krajach na całym świecie. Zwrócono szczególna uwagę na rolę zrównoważonego składowania odpadów w krajach rozwijających się o niskich dochodach. Następnie zaprezentowano paradygmat zrównoważonych składowisk odpadów oraz przedyskutowano najefektywniejsze metody izolacji składowisk. Zagęszczone przesłony mineralne uznano jako atrakcyjną opcję dla krajów rozwijających się. Opisano najistotniejsze wyznaczniki długoterminowej zrównoważoności i trwałości zagęszczonych przesłon ilastych: przewodnictwo hydrauliczne, charakterystyki skurczu i pęcznienia oraz zdolność gruntu do utrzymania właściwości izolacyjnych po cyklicznym osuszaniu i nawilżaniu. Na koniec przedyskutowano możliwość stosowania iłów o niskiej plastyczności jako materiałów na przesłony mineralne zrównoważonych składowisk odpadów, w miejsce podatnych na skurz i pęcznienie wysokoplastycznych gruntów ilastych.

Słowa kluczowe: zarządzanie odpadami komunalnymi, zrównoważone składowisko odpadów, zagęszczone przesłony ilaste

Landfilling in sustainable municipal waste management system

The idea of sustainable development is usually considered at the three independent but linked pillars: environmental (ecological), social and economic, supported by technical, legal, moral and political aspects (e.g. Pawłowski, 2008). Realization of intergenerational justice guaranteeing the needs of the current and future generations depends to the proper management of water, sewerage, wastes and non-renewable energy carries (Pawłowski L. & A., 2016; Cao et al., 2012; Miksch et al., 2015). Thus, the sustainable development is also directly related to the proper handling of municipal solid wastes (MSW) during the whole process of waste management due to the possible contamination of water, soil and atmosphere, negative changes in the ecosystem, reduction of biodiversity, limiting the economic development and posing a major threat to public health (e.g. Al-Khatib et al., 2010; Othman et al., 2013). Rapid urbanization, quick increase of population and growing consumption may have the detrimental effects on the urban population. The generation of waste is related to the urbanization degree so application of principles of sustainable development to local MSW systems may improve the local ecosystems and their residents' quality of life (Jim, 2013). Thus, the system of sustainable management of solid wastes becomes a major priority of social, legal, economic and ecological/environmental concern, especially in the urbanized areas where large amounts of solid wastes are generated (e.g. Erses Yay, 2015).

The sustainable solid waste management systems include all essential activities related to the wastes collection, shipping and transport, treatment, recycling/reuse and final disposal (e.g. Pires et al., 2011). According to Wilson (1985) a municipal solid waste management has implications on all circles of sustainability, including environmental, social and economic. The generation of wastes and the ability of the society to the waste separation may be related to public/community wealth, social development, environmental and ecological awareness and knowledge (Shekdar, 2009; Guerrero et al., 2013). Transport of wastes from the generators to the treatment plants or the final disposal may be performed by various available means but generally the road transport is being dominant (Eres Yay, 2015). Then wastes may undergo various processes of material and energy recovery and/or volume reduction (e.g. Shekdar, 2009; Franus et al., 2011) including reuse, recycling, composting, bio-fuels production, incineration, pyrolysis, gasification etc. etc. (e.g. Santibanez-Aguilar et al., 2013, Werle and Dudziak, 2014; Suchorab et al., 2016). The final step of municipal solid waste management of remaining wastes, which are unable to be processed by any other measures, is their final disposal by landfilling (e.g. Pires et al., 2011; Othman et al., 2013). The share of landfilling in the recent MSW management for selected countries from different continents presented in Fig. 1 shows a very high differentiation of landfilled municipal wastes percentage. Despite the fact that sanitary landfills are frequently being discouraged in the developed countries, due to leachate seepage and gasses emissions or scarcity of available land etc. (Staszewska and Pawłowska, 2011; Othman et al., 2013), they are in contrast to common practice of the uncontrolled dumping of wastes in the developing countries (Oak-

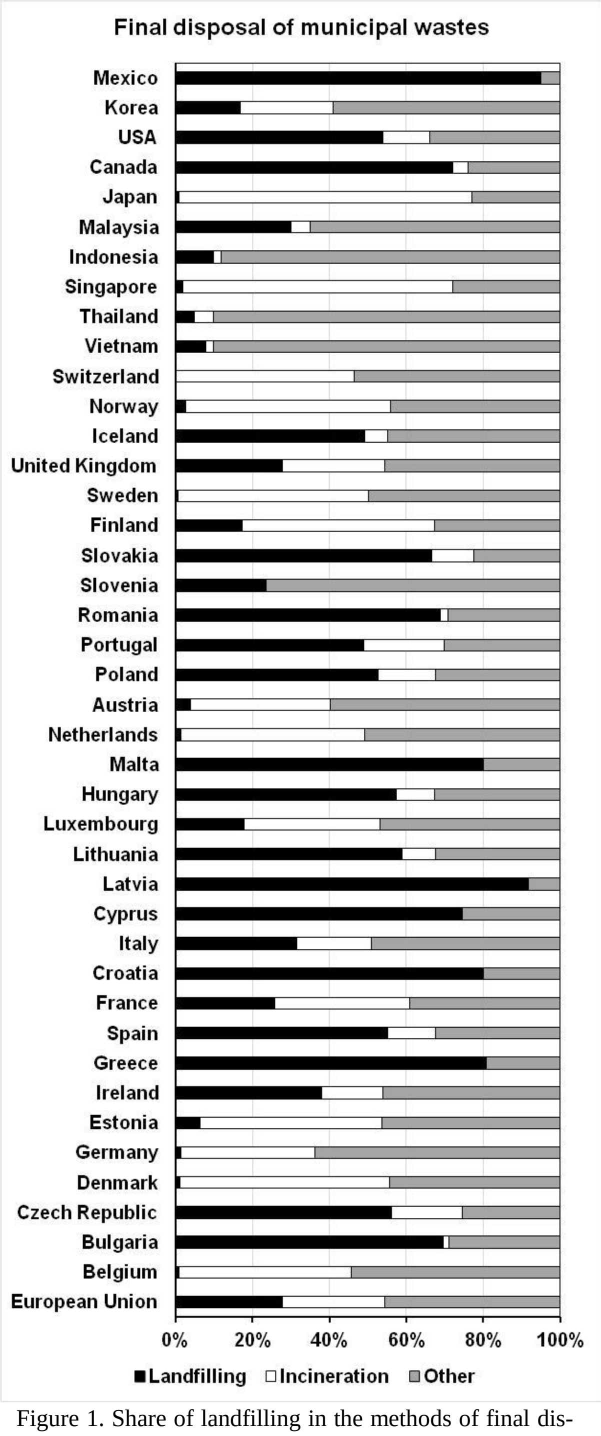

Figure 1. Share of landfilling in the methods of final disposal of wastes in selected countries of the world, combined after Eurostat data (2014), Ngoc and Schnitzer (2009) as well as Eres Yay (2015)

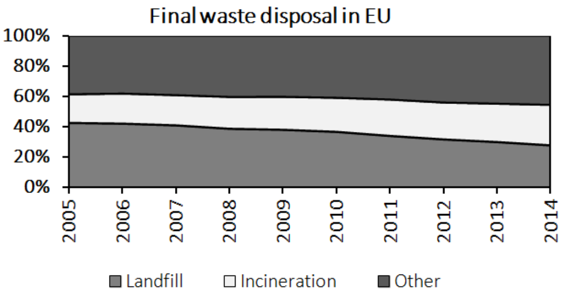

Figure 2. Methods of final waste disposal in the European Union during last decade, developed after Eurostat data

ley and Jimenez, 2012). Landfilling, from the historical point of view was and nowadays remains a dominant cost-effective method of final deposition of the remaining municipal solid waste in many regions (Allen, 2001; Wagner, 2011).

The generally sustainable attitude towards MSW management, based on the several important drivers: public health, environment, resource scarcity and value of wastes, climate change and public concern and awareness are being observed in the developed countries of high economic incomes but the applied practices may vary (e.g. Eres Yay, 2015; Pires et al., 2011; Marshall and Farahbakhsh, 2013). Despite the local differences, the European MSW management systems cover all typical stages: collection, transport, treatment, recycling/reuse and disposal, strictly connected to policies, institutional services, finances, proper technology selection, stakeholders participation and public awareness (Piers et al., 2011). According to Marshall and Farahbakhsh (2013), the current paradigm of sustainable waste management assuming balance between environmental effectives, social acceptability and economic affordability of waste management is commonly accepted in the developed countries.

The historical contribution of various types of final municipal wastes disposal in the European Union during the last decade was presented in Fig. 2. There is a visible decrease in the value of landfilled wastes during the discussed period, from the value of 43% in 2005 to 28% in 2014. Consequently, the share of the other methods of final waste disposal including incineration, increased despite the fact that the presented data included landfilled wastes in the less developed member countries of the EU, which accessed the union in 2004, 2007 and 2013.

Figure 3 shows contribution of landfilling in municipal MSW in the selected Central Europe member countries of the EU, accessed the Union in the XXI century, compared to the European mean value. It is clearly visible, than the decreasing tendency of reduction in the mean landfilling contribution in the EU is accompanied by the similar tendency in most of the new members of the EU, excluding Latvia. Thus, development of new members of the EU during the last decade (see Widomski et al., 2015a) caused the noticeable decrease in the share of landfilling.

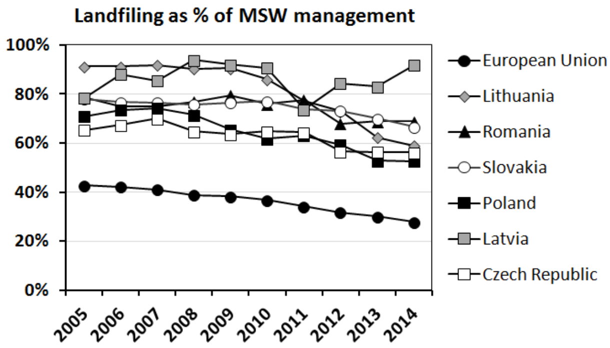

Figure 3. Landfilling as part of MSW management in selected countries of EU, based on Eurostat data

The developing countries of the low economic income in different regions of the globe suffer from a very high municipal waste generation. So, the MSW management becomes a major issue for governments of various levels (national, regional and municipal) and for individuals. Unfortunately, in many cases, the sustainable MSW management systems do not operate properly in many developing countries, regions or cities (e.g. Shekdar, 2009; Zhang et al., 2010; Guerrerro et al., 2013; Marshall and Farahbakhsh, 2013). The main reasons for this situation were recognized by Marshall and Farahbakhsh (2013): i) urbanization, inequality and economic growth; ii) cultural and socio-economic aspects; iii) policy, governance and institutional issues; iv) international influence. Moreover, such waste management systems, without any links to sustainability, were accurately characterized by Permana et al. (2015) as *collect, transport and forget*. Exemplary, dos Muchangos et al. (2015) reported that sustainable waste management system failed in Maputo, Mozambique according to uncoordinated or ad hoc efforts and inadequate investments, combined with economic, administrative and technological weaknesses. Similar situation was reported by Al-Khatib et al. (2010) in Palestine where founding constrains, week law enforcement considering wastes collection, transport, treatment and disposal, lack of expertise and appropriate technologies or facilities were noted. Similarly, Zhang et al. (2010) described formal and informal waste collection, low waste separation and recycling ratio, unsatisfactory quality of sanitary landfills, underdeveloped incineration and discharge/levying fees system for the various regions of China. Finally, the high increase in the wastes generation, low municipal budget available, insufficient infrastructure, low quality and technical capacity of technical personnel as well as high costs of MSW management were reported by Permana et al. (2015) for different regions of Indonesia.

The listed above exemplary problems encountered by societies in the developing countries, show that the simple transfer and application of technical and technological remedies from the developed regions will not help to immediately solve the problems related to the inefficient systems of MSW management. Since the practical remedies for the North America, Japan or Europe, applied directly in the developing countries may be expensive, complex and complicated. The additional energy consumption, qualified services, workmanship and experienced technical stuff, social and governmental mobilization and support, public awareness may be also required.

Therefore, the final disposal of MSW in the developing countries is generally based on landfilling and open dumping sites. The second method is being commonly recognized as the main and most important source of environmental pollution (e.g. Ngoc and Schitzer, 2009; Shekdar, 2009; Zhang et al., 2010; Guerrero et al., 2013). The reported assessed amount of wastes disposed in the open dumping sites in Southeast Asian countries varied between approx. 50% for Malaysia to 80% in Myanmar and Cambodia (Ngoc and Schitzer, 2009). In the same time, the share of wastes disposed in sanitary landfills varied between 5% for Brunei, Cambodia and Thailand, through 8% for Vietnam, 10% for the Philippines, Myanmar and Indonesia to, finally, 30% for Malaysia. In addition, the open dumping sites creating ecological pressure are commonly localized along the roadsides or close to water bodies, at forest edges or in other environmentally sensitive locations, often without any or with limited measures of operation control and isolation by clay liners or geo-membranes (Shekdar, 2009; Ngoc and Schitzer, 2009; Okot-Okumu and Nyenje, 2011; Oakley and Jimenez, 2012; Guerrero et al., 2013).

It was also reported that municipal landfills in the developing countries are commonly not properly constructed (ineffectively isolated by liners), poorly operated (careless operation and maintenance) and the best practices are unknown or misunderstood (Zhang et al., 2010). The several operational and environmental problems of landfills observed in developing country were reported by Okot-Okumu and Nyenje (2011), including: i) location on wetlands, close to rivers or the other surface waters, on the steep slopes, close to residential areas; ii) not fenced, poor access roads, uncontrolled tipping, fire hazard, high accident risk, landslides, indiscriminate dumping; iii) health hazard, accidents risk, odors, water and soil pollution, erosion. Thus we may state, after Ngoc and Schnitzer (2009) that in the developed countries landfilling is not a difficult problem nowadays, while in medium- and low-income countries or regions, environmental pollution from unsustainable and insufficient landfills is openly complained.

Sustainable landfilling

Sustainable landfilling may be understood as *the safe disposal of waste within a landfill, and its subsequent degradation to the inert state in the shortest possible time-span, by the most financially efficient method available, and with minimal damage to the environment* (Allen, 2001). The sustainability of landfilling as method of the final waste disposal is crucial in the processes of transaction of goods, understood as availability of resources between the generations, present and future (Wagner, 2011).

The sustainability of landfilling covers most of the circles of sustainable development, including ecologic/environmental, social and economic issues. Nevertheless, potential impacts of capital goods consumption during landfill operation were reported as from low to marginal in relation to the remaining environmental impacts, mainly direct and indirect emissions (e.g. Brogaard et al., 2013). So, the environmental impacts of sustainable landfilling, the threats posed to water and soil, as well as the possible sustainable manner of landfill sealing become the major issue in this paper.

Landfilling of municipal wastes for a significant period of time, even several hundreds of years, poses a major threat to the environment, resulting from biological, chemical and physical processes occurring in the waste body. Impacts of landfilling on the environment was categorized e.g. by Ngoc and Schintzer (2009) and Othman et al. (2013) as: i) contamination of surface water and groundwater by leachate; ii) pollution of soil by direct contact with wastes or leachate percolation; iii) air pollution by products of waste burning; iv) spreading of diseases by birds, insects and rodents; v) bad odors and vi) uncontrolled release of methane by anaerobic decomposition of wastes. Taking into account that the sustainable landfill should pose zero or minimal risk to the environment, the protection of the natural environment and limiting the threats caused by landfill should cover the minimization of leachate generation and seepage, prevention of uncontrolled migration of landfill gas containing greenhouse gases like well-known carbon dioxide (Lou and Nair, 2009) and less often mentioned methane (also very important in greenhouse effect) (Walkiewicz et al., 2016) as well as the reduction in generation and migration of odors (Butt et al., 2008) for the whole period of waste disposal. The main threats to water, soil and groundwater are posed by leachate, the liquid of various composition, taking its constituents from the solid waste body, through which it percolates (e.g. Mukherjee et al., 2014; Brennan et al., 2015). Municipal solid waste landfills produce leachate also after their closure, so the negative impacts of landfills are possible throughout all of this time duration (Brennan et al., 2015). The leachate generation is triggered by the presence of surface water, from precipitations and snow melting, infiltrating to the waste body through the top cover of the landfill. So, inflow and outflow of water to and from the deposited wastes should, in general, be completely prevented by the top and bottom liners. Both liners are often constructed of natural and/or artificial materials of appropriate permeability (Bagchi, 1990; Simon and Müller, 2004; Laner et al., 2012). Generally, the required by the regulations of numerous standards (e.g. EU, 1999; Journal of Laws from 2013 item 523, DepV, 2009) saturated hydraulic conductivity (K_s) for the mineral sealing liners, is commonly determined as lower than $1 \cdot 10^{-9}$ m s^{-1}. Thus, sustainability of a MSW landfill is in our opinion directly related to the sustainability of its top and bottom liners.

The natural materials like clays, supported by geosyntetics, geomembranes, geonets and geotextiles are commonly used for the construction of liners in the developed countries, but the application of sophisticated sealing materials is often limited in developing countries of low- and medium-income (e.g. Zhang et al., 2010; Pires et al., 2011; Guerrero et al., 2013; Marshall and Farahbakhsh, 2013). Application of clays as construction materials for landfill liners should be verified with regard to their compliance to the local legal standards and the technical engineering guidelines, which are commonly focused on the particle size distribution, saturated hydraulic conductivity, linear shrinkage and the most important geotechnical characteristics such as the Atterberg limits, angle of internal friction, cohesion etc. (e.g. Bagchi, 1990; Daniel and Koerner, 1995; Rowe et al., 1995; Arch, 1998; Wysokiński, 2007). The natural permeability of clay materials, when necessary, especially in construction of top sealing layer, is reduced by an additional compaction (e.g. Benson and Trast, 1995; Simon and Müller, 2004). Compaction of clayey substrates for CCL (compacted clay liner) is usually suggested to be performed for water content wet of optimum (e.g. Wysokiński, 2007). CCLs, on one hand are relatively cheap and utilize the local materials, however they show some serious disadvantages related to compaction effects depending on the applied energy and the molding conditions. They are prone to swelling, shrinkage and cracking, they are also sensitive to cyclic drying and wetting (Benson and Trast, 1995; Allen, 2001; Simon and Müller, 2004; Whalley et al., 2012; Bello, 2013; Widomski, 2016a). Geomembranes (HDPE-GMs), on the other hand, present significant sealing capabilities, creating nearly absolute long lasting barrier for water and gas flow when properly installed and certified. But their certified installation requiring workmanship and state-of art technology is rather costly. They may also become pervious to water and gas, due to faults resulting from material, base preparation, workmanship, earth-works, waste loads and piping installation. Moreover, low heat isolation of HDPE may seriously affect the landfill gas generation in cold weather and cause desiccation of compacted clay liner and cracks formation below HDPE geomembrane. There were also reported liner failure due to interface between various artificial liner layers (Simon and Müller, 2004; Chen et al., 2011; Capaccioni et al. 2011; Hewitt and Philip, 1999; Benson et al., 2012). Finally, geosythetic clay liners (GCLs) are easy transportation and installation, cost-effective and space saving alternatives for CCLs. But their sustainability may be reduced by possible desiccation cracking of highly expansive bentonite, limited long-term shear strength on steep slopes leading to low sliding stability of the cover system, aging affecting strength parameters and limited resistance to roots penetration (Bouazza, 2002; Simon and Müller, 2004; Müller et. al, 2008; Mitchell et al. 1990; Stark et al., 1996; Chang, 2005; Benson et al., 2012). Taking into consideration all the advantages and disadvantages of the discussed different groups of sealing materials, we may state that compacted clay liners, alone or combined with the artificial membranes, despite their drawbacks, are still a worthwhile option, especially in developing countries of medium or low incomes. They can be adopted in various local conditions as easier in installation and maintenance, may utilize local mineral materials, equipment, workmanship and technologies. On the contrary, application of certified artificial liners in the less developed countries requires transfer of know-how, technical support, qualified staff and monitoring system seem to obtained the long-term appropriate performance. However, in many cases the requirements for the successful application of artificial sealings may not fit the principles of sustainable landfilling.

Determinants of sustainable compacted clay liner

If a sustainable landfilling is to be understood as safe disposal of municipal wastes, by the most financially efficient method available, with the minimal threat to the environment, long after closure of the landfill, the sealing capabilities of the bottom and top liners, based on CCLs, should be sustained for the similar time duration. In our opinion, the long-term performance of a sustainable landfill liner reducing the environmental impacts of deposited wastes depends on three interrelated properties of the applied soil/substrate, i.e. hydraulic conductivity, swell-shrinkage properties and resulting cracking as well as, finally, ability of soil/substrate to sustain its hydraulic conductivity after cyclic changes of saturation, frequently understood as several cycles of drying and rewetting (shrinkage and swelling).

The saturated hydraulic conductivity of natural clays, containing significant number of fine particles and clay minerals content, is generally assessed as low or very low (e.g. Benson and Trast, 1995) but in many cases the additional compaction may be necessary. The influence of the compaction process on hydraulic properties (including saturated hydraulic conductivity) of clays is non-uniform, in relation to clay soil composition, Atterberg limits and molding conditions (e.g. Mitchell et al., 1965; Benson and Trast, 1995; Rowe et al., 1995; Whalley et al., 2012; Bello, 2013). The clay substrates of high clay or fine (clay+silt) particles and clay minerals content and more plastic, of higher liquid limit or plasticity index, compacted at higher initial water contents allow lower values of saturated hydraulic conductivity (Benson and Trast, 1995). In short, clayey specimens compacted dry of optimum would have greater hydraulic conductivity than specimens of the same substrate, compacted wet of optimum (e.g. Mitchell et al., 1965; Benson and Trast, 1995, Bello, 2013).

Fine textured soils like clays, or even some sandy soils containing fines, present significant expansiveness, i.e. volume changes due to changes in water content (e.g. Basma et al., 1996; Kalkan, 2011), they increase their volume (swell) when saturated and reduce their volume (shrink) when dewatered (Basma et al., 1996). Hydraulic conductivity of the soils cracked after shrinkage may be greater by several orders of magnitude if compared to uncracked soils of the same type (e.g. Boynton and Daniel, 1985; Albrecht and Benson, 2001). Increased fines content and the applied greater molding water content results in increased cracking, while, on contrary, for the decreased fine particles content, lower cracking appears (Holtz and Kovacs, 1981; Mitchell, 1993; Yesiller et al., 2000). Thus, to avoid significant cracking it was also suggested to perform the compaction of clays at low water contents, dry of the optimum of Proctor curve, where shrinkage potential is definitely lower, despite the expected increased swell (e.g. Daniel and Wu, 1993; Yesiller et al., 2000; Widomski et al., 2015b). The addition of coarse-grained material may reduce the cracking but it may also affect, to some extent, hydraulic and engineering properties of soil (Yesiller et al., 2000), however, reaching the very low values of saturated hydraulic conductivity (10^{-10}–10^{-12} m s^{-1}) of sand-clay mixture was reported by e.g. Ebina et al. (2004). Thus, it is possible to obtain the clayey substrate containing coarse material of limited shrinkage and significant sealing capabilities improving sustainability of the compacted clay liner. Additionally, swelling and shrinkage, changing the unsaturated and saturated hydraulic conductivity, are irreversible processes so soils or substrates specimens once swelled or shrinked are generally unable to return to their initial characteristics (Holtz and Kovacs, 1981). Cracks, once appeared, are always available in the compacted specimen, even after rewetting and swelling of soil (as long as no additional molding is being applied (Yesiller et al., 2000). The significant increase in the K_s was observed for high plasticity fine soils compacted wet of optimum after several wetting and drying cycles, even to the level typical for the coarse sandy soils (Widomski, 2016a,b). On the contrary, lower changes after several shrink-swell cycles were noted for specimens compacted at dry of optimum water contents. Moreover, it was also observed that the hydraulic conductivity before drying-wetting tests for low plastic clays tested was comparable for both dry and wet sides of Proctor curve, while after the first drying and wetting cycle it increased and remained nearly constant (Widomski, 2016a). So, in our opinion, the long-term self-sustainability of a clay sealing layer may be questionable and may be significantly influenced by the proper selection of the material.

The main and general statutory requirement for material selection is commonly related only to the final demanded saturated hydraulic conductivity, usually below $1 \cdot 10^{-9}$ m s^{-1} (EU, 1999; Journal of Laws from 2013 item 523, DepV, 2009). But, as it was described earlier, the sole saturated hydraulic conductivity is insufficient to ensure the durability and sustainability of compacted clay liners.

Numerous guidelines presenting criteria for a clay material selection, applicable for the compacted clay liner construction, generally allow, or even in some cases favor, high plasticity clays of significant content of fine (clay+silt) particles (e.g. Bagchi, 1990; EPA, 1993; Daniel and Koener, 1995; Rowe at al., 1995; Arch, 1998; Wysokiński, 2007). But, as it was mentioned before, such high plasticity clay materials are typically characterized by the significant shrinkage potential, irreversible desiccation cracking after water content drops below the plastic limit and week resistance to cyclic drying and rewetting, causing increase in hydraulic conductivity by several orders of magnitude. So, the long-term durability and sustainability of the compacted clay liners constructed of the high plasticity clays may be at least questionable. In our opinion, the low plasticity clays allowing the appropriate value of saturated hydraulic conductivity after compaction, containing significant share of coarse sand fraction and showing the considerably lower shrinkage potential, lower plasticity and better resistance to cyclic of drying and rewetting should not be discouraged from application in the construction of compacted clay liners (Widomski, 2016a). It was also reported by Widomski (2016a) that compacted low plasticity clays have no negative effect on the hydraulic efficiency of bottom and top liners of municipal waste landfills.

Summary

The main purpose of sustainable waste management system is to minimize the negative environmental, social and economic effects of waste generation, transport, treatment and final disposal. As it was presented and discussed in the paper, landfilling plays still an important role as a manner of final disposal of wastes unsuitable to be further reduced, reused or recycled, especially in the developing countries. In case of undeveloped countries of unregulated municipal waste management and dominant open dumping of wastes, sustainable landfilling, economically and socially accepted and efficient in limiting the environmental threats, is a forward-looking and attractive option. However, meeting the requirements of sustainable landfill paradigm assuming deposition of wastes, their subsequent degradation by the cost effective methods with the minimal damage to the environment may be a difficult task, especially during the lifetime of one generation. Thus, the long-term efficiency of landfill isolation, preventing or significantly reducing the environmental threats posed by municipal landfill to the natural environment is a crucial issue. There are several known, more or less sophisticated manners of landfill isolation, but compacted clay liners utilizing natural materials of a very low conductivity are still a worthy option, especially for local communities of undeveloped or developing regions. But sustainability of landfills isolated by the CCLs may be significantly limited by characteristics of clays which are generally expansive, prone to swelling and shrinkage, undergoing cracking and showing limited resistance to cyclic changes of their moisture conditions. All the above phenomena are related to, or triggered by subtests' particle composition, clay, silt fraction as well as clay minerals content, plasticity and molding conditions. High plasticity clay materials compacted wet of optimum, containing high share of clay fraction and expansive clay minerals, prone to shrinkage, swelling and cracking, despite showing a very low saturated conductivity are often unable to secure the required sealing properties for a prolonged period after landfill closure. So, in our opinion, clay material particle composition and the applied molding water content should be selected very carefully to avoid extensive shrinkage, cracking and increase in hydraulic conductivity of the compacted liner. Moreover, high plasticity clays, prone to desiccation cracking and shrinkage, should be avoided and if possible replaced by substrates containing coarse fraction and presenting lower plasticity, which may allow to retain at least partial sealing capabilities and should improve the sustainability of the compacted clay liner.

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