

REVIEW OF TECHNICAL METHODS OF LANDFILL SEALING AND RECLAMATION IN THE WORLD

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ABSTRACT

Landfills, even properly designed, constructed, and operated, are facilities that in the future can be a potential source of pollution of surface and groundwater and atmospheric air. Especially, old municipal landfills were very often established in inappropriate soil and water conditions, which contributed much more to the release of toxic leachate into the ground. This happened due to lack of sufficient regulation and control systems in this area. Reclamation of degraded sites became a kind of rescue for contaminated areas. However, this process was not always carried out in a proper way. This study presents the trends of landfills sealing and their reclamation over the years in different countries.

Key words: waste, landfill reclamation, synthetic barrier, leachates

INTRODUCTION

In the 20th century, waste disposal in landfills and/or open dumps was the most common method of waste management worldwide (Vaverková, 2019). In the 1960s and 70s, waste was deposited in field conditions such as ravines and it was believed that leachate from landfills was self-cleaning in the soil by diluting contaminants in groundwater. During this time, waste collection was also done in an uncontrolled manner. Legal landfill owners operated landfills without keeping proper documentation (Porowska, 2019). Landfills did not have adequate protection against toxic leachate infiltrating the ground. Old landfills were located on permeable soils with high groundwater levels and unfavourable geotechnical conditions (Koda, 2011). Over the years, it has been shown that soil cannot neutralise all infiltrating contaminants no matter how high the ion exchange capacity of the soil is and how thick the non-aqueous zone of the subsoil is (Wysokiński, 2009) and the construction of a landfill should take

into account topographic, geological, geotechnical and hydrogeological aspects (Jessberger, 1993). Landfill leachates which contain large amounts of organic matter, ammonium, heavy metals, in the present day, poses a threat to the soil and water environment around the landfill and are considered to be one of the main sources of heavy metals discharged into the environment (Vaverková et al., 2019; Singh & Chandel, 2022).

Taking into account the construction process, landfills have been considered as one of the most technically difficult facilities, due to the fact that they are facilities with huge areas, capacities and thicknesses up to several tens of meters and must have maximum containment, and at the same time are obliged to have the least possible impact on the environment (Ważny, 2015). In the construction of the above-mentioned facilities, it is necessary to take into account a number of construction requirements, safety plan and, above all, it is necessary to have extensive knowledge of groundwater flow paths, aquifers located and their hydraulic

properties (Jessberger, 1993). Landfills are also susceptible to mechanical deformation due to the stresses, thickness and technology of the landfill, so this aspect must be considered in their construction (Manassero, Van Impe & Bouazza, 1996). According to Manassero, Benson and Bouazza (2000), for a landfill to function properly, it is necessary to optimise the location, construct highly efficient sealing and cover systems, optimise storage, monitor, and be able to reuse the area after closure.

Currently, if a landfill does not meet legal requirements in Poland the Voivodship Inspectorate of Environmental Protection (Wojewódzki Inspektorat Ochrony Środowiska – WIOŚ) can order its closure. Nevertheless, the closure itself does not close the problem related to its toxic impact on the environment, as the mere “cleaning up” of such areas and covering the landfill with a layer of random soil, creates an environment conducive to the migration of toxic substances (Koda, 2011). Remediation procedures are necessary here to stop further spreading of contamination. To perform them extensive geotechnical or hydrogeological knowledge is needed to verify the site and select appropriate methods. Nowadays, it can be seen that the approach to landfill waste management systems is moving towards sustainable waste disposal (Adelopo, Haris, Alo, Huddersman & Jenkins, 2017). The public has become aware that municipal waste management is a major factor that has a significant impact on the environment (Behrooznia, Sharifi, Alimardani & Mousavi-Avval, 2018). The introduction of appropriate legal conditions and the conduct of reclamation works have contributed to the improvement of the environmental situation related to waste disposal. The Local Data Bank of the Statistics Poland (Bank Danych Lokalnych – BDL) estimated that there were twice as less landfills in 2018 than there were in 2008 (Główny Urząd Statystyczny [GUS], 2022). In contrast, US Environmental Protection Agency (EPA) estimated that there were 2.5 times fewer municipal landfills in the USA in 2018 than in 1995 (Statista, 2022).

In this paper, a review about past and present methods of technical reclamation of landfills from selected regions was done, thanks to which the environment is improved and the number of exploited municipal waste landfills gradually decreases.

TECHNICAL METHODS OF LANDFILL BASE SEALING AND RECLAMATION COVER SYSTEM IN POLAND

In Poland, for quite a long time, there was not proper legal act concerning the construction and location of landfills (Jamróz, 2012). The development of waste management can be confidently divided into two periods. The first to the period before Poland’s accession to the European Union and the second one to the period after the accession, i.e. after 1 May 2004 (Mamak & Kicińska, 2016). An exception to the legal act regulating the construction of landfills was the Regulation of the Minister of Economy of 21 October 1998 (Rozporządzenie Ministra Gospodarki z dnia 21 października 1998 r. w sprawie szczegółowych zasad usuwania, wykorzystywania i unieszkodliwiania odpadów niebezpiecznych), which was issued on the basis of the already repealed Act of 27 July 1997 on waste (Ustawa z dnia 20 lipca 2017 r. Prawo wodne). It mainly concerned hazardous waste, which in terms of quantity were not the biggest problem. All technical conditions related to the construction of landfills were defined in the development conditions and in subsequent building permits (Jamróz, 2012). This resulted in the so-called free hand in land development after the construction of the landfill. The landfills did not have adequate ground protection (Fig. 1) and leachate infiltrated polluting the groundwater in the vicinity.

It was not until 2003 that the situation began to improve. At that time, the Regulation of the Minister of the Environment of 24 March (Rozporządzenie Ministra Środowiska z dnia 24 marca 2003 r. w sprawie szczegółowych wymagań dotyczących lokalizacji, budowy, eksploatacji i zamknięcia, jakim powinny odpowiadać poszczególne typy składowisk odpadów) came into force. The regulation sets guidelines for locating landfills on a natural geological barrier not less than 1 m thick with a filtration coefficient $k \leq 1.0 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$ for landfills of non-hazardous and inert waste and not less than 5 m thick with a filtration coefficient $k \leq 1 \cdot 10^{-9} \text{ m} \cdot \text{s}^{-1}$ for landfills of hazardous waste in both supplemented with synthetic insulation (usually HDPE geomembrane). In places where the natural barrier does not meet the conditions, it was recommended to apply an artificial geological

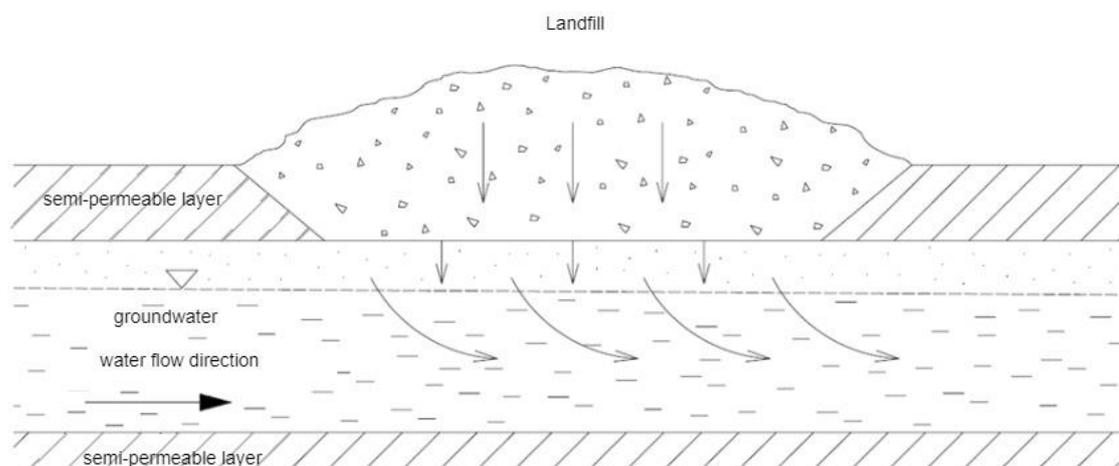


Fig. 1. Scheme of unsealed landfill with aquifer and deep natural isolation layer (acc. Koda, 2011)

barrier with a thickness of at least 0.5 m, possibly supplemented with synthetic insulation (HDPE or PVC). Following the introduction of new legislation, reclamation work was carried out on old unsealed landfills in Poland. Slurry walls enclosing the landfill like vertical cut-off barriers were a remedial solution to the degraded site to minimise environmental risk (Koda, 2012; Koda and Osinski, 2017).

Sealing the base of the landfill is necessary to enable collection and drainage of leachate water not allowing them to infiltrate into the ground (Ważny, 2015). According to Wysokiński (2009), substrate sealing can be divided into natural (clays, sandy loams), artificial (polyethylene or polypropylene geomembranes, or PVC foils) or mixed (clays or loams with plasticizers, asphalt materials or bentonite-synthetic composites). Figure 2 shows base landfill sealing schemes divided into: single mineral (a), single composite mineral-synthetic (b), double synthetic (c), double composite (d). The selection of an appropriate seal depends on the volume of the landfill and geological conditions. For small objects with favourable geological conditions sealing (a) is recommended, whereas for large objects with unfavourable geological conditions sealing (c) or (d) should be chosen (Wysokiński, 2009).

When a landfill site ends its operation, it must be properly recultivated. The legal requirement to perform reclamation of landfills in Poland was imposed by the two most important legal acts in this regard: Art. 146

of the Law of 14 December 2012 on waste (Ustawa z dnia 14 grudnia 2012 r. o odpadach) and the Regulation of the Minister of Environment of 30 April 2013 on landfills (Rozporządzenie Ministra Środowiska z dnia 30 kwietnia 2013 r. w sprawie składowisk odpadów). Next to strictly defined technical condition, in new regulation guidelines concerning the necessity of conducting monitoring during the pre-operational, operational and post-operational (30 years after the end of operation) phases of the project were appeared. According to the above-mentioned regulation, the first stage of reclamation is cleaning and protecting the landfill against wind and water erosion by creating a reclamation cover with a structure depending on the waste properties. In case of landfills for non-hazardous and neutral waste, its thickness should make it possible to maintain the so-called permanent vegetation cover. However, in case of hazardous waste landfills, according to the above-mentioned regulation, the owner of the landfill is obliged to cover the facility with a special screening layer containing impermeable synthetic insulation (HDPE), followed by a top layer of soil of at least 1 m thickness with a fertile layer of soil allowing for proper plant development.

Environmental criteria (including the design of the trough of the reclaimed landfill, the degree of environmental hazard, the direction of reclamation, or the required time to perform reclamation procedures) and economic criteria (including capital costs, operating

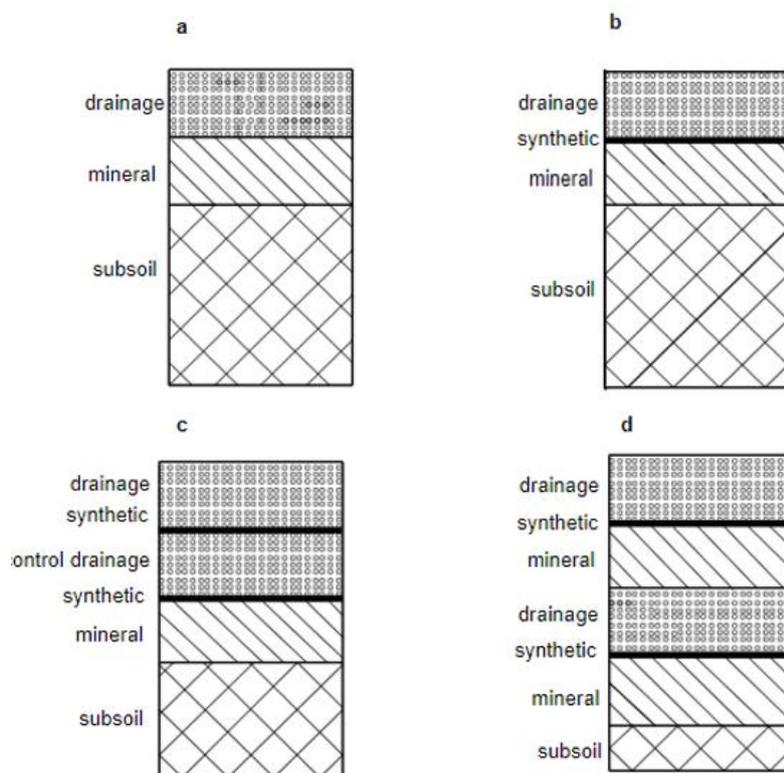


Fig. 2. Modified landfill base sealing schemes: a – single mineral barrier; b – single composite mineral-synthetic barrier; c – double synthetic; d – double composite barrier (acc. Wysokiński, 2009)

costs, and the use value of the land) should be taking into account during selecting a technical reclamation method (Mamak & Kicińska, 2016).

Figure 3 shows an example of proper surface cover for a non-hazardous landfill using a mineral seal for the reclamation process. Cohesive soils can be used for mineral sealing in landfills provided that, among other things, they have a clay fraction content of 20% for municipal landfills, 30% in hazardous landfills; at least 60% of the material should be smaller than the sand fraction (< 0.05 mm) and are characterised by the absence of coarser fractions (> 2 mm), calcium carbonate content < 10%, and organic matter < 2%. By using a mineral seal, a small amount of moisture infiltrates into the waste pile, which supplements the oxygen deficiency and at the same time speeds up the aerobic fermentation processes. This layer can also supplement the reclamation layer with vegetation after a long time (Koda, 2011). According to the technical

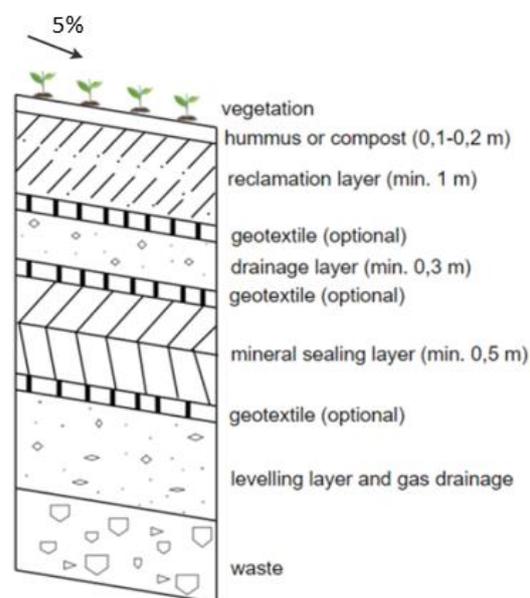


Fig. 3. Proposed landfill remediation cover systems (acc. Koda, 2011)

conditions, the permeability coefficient of the mineral seal should be less than $10^{-9} \text{ m}\cdot\text{s}^{-1}$ (Wysockiński, 2009). The inclination of the remediation cover surface should be greater than 5%.

TECHNICAL METHODS OF LANDFILL BASE SEALING AND RECLAMATION IN THE UNITED STATES AND RECOMMENDED BY THE INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

In the past, natural soils were used as liners (Fig. 4a), but this practice quickly became uncommon because it was difficult to prove that natural liners were free of zones with high hydraulic conductivity (Fig. 4b) or secondary features such as the potential for fissure or crack formation (Daniel, 1993). Vertical cut-off barriers shown on Figure 4c were used occasionally in conjunction with natural liners. However, this practice is uncommon for new sites, and was instead used more frequently for older sites as part of site remediation. A more typical situation is Figure 4b in which an engineered liner is used to control migration of contaminants out of the landfill area. For hazardous waste landfills a double liner of geomembrane (GM) is used with a drainage layer located above the first liner and a leak detection layer located between the two liners. For non-hazardous waste sites a single liner is used.

According to the Resource Conservation and Recovery Act (RCRA), regulations related to non-hazardous waste management are found in Section 239–259. New facilities should have a liner created from two parts: the upper part in the form of a 0.76 mm GM liner, and the lower part from at least a 2 m layer of compacted soil with a hydraulic conductivity of no more than $1\cdot 10^{-9} \text{ m}\cdot\text{s}^{-1}$. The material must provide adequate abrasion resistance to the top and bottom interfaces to prevent material movement on slopes. Geosynthetics such as GM are now widely used in both liners and covers of modern municipal landfills and provide an effective barrier to leachate water and infiltration (Chen, Gao, Zhu & Chen, 2008). An example of a seal consistent with current legislation in the US is shown in Figure 5a. The lowest level of the mineral seal must be able to resist erosion and leachate infiltra-

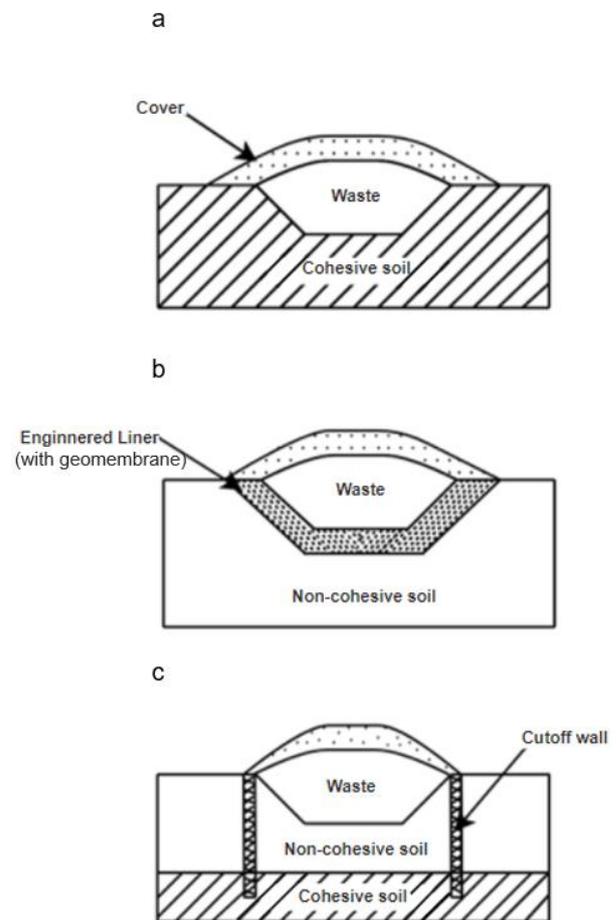


Fig. 4. Sealing layers on the landfill: a – natural soil; b – engineered liner; c – vertical cut-off walls (acc. Daniel, 1993)

tion thus minimising the occurrence of seepage. The next lined GM layer must be characterised by the lack of settlement susceptibility associated with its stress–strain characteristics and provide long-term prevention against leakage of undesirable substances (Christiansen, Cossu & Stegmann, 1994). A protective layer using geotextile is laid over the GM to properly distribute the stresses concentrated in the GM, and then there is a drainage system that stores and removes leachate from the waste. This solution prevents the accumulation of leachate above the sealing system. This solution prevents the accumulation of leachate above the sealing system. An optional layer between the drainage and the waste is a transition level, which

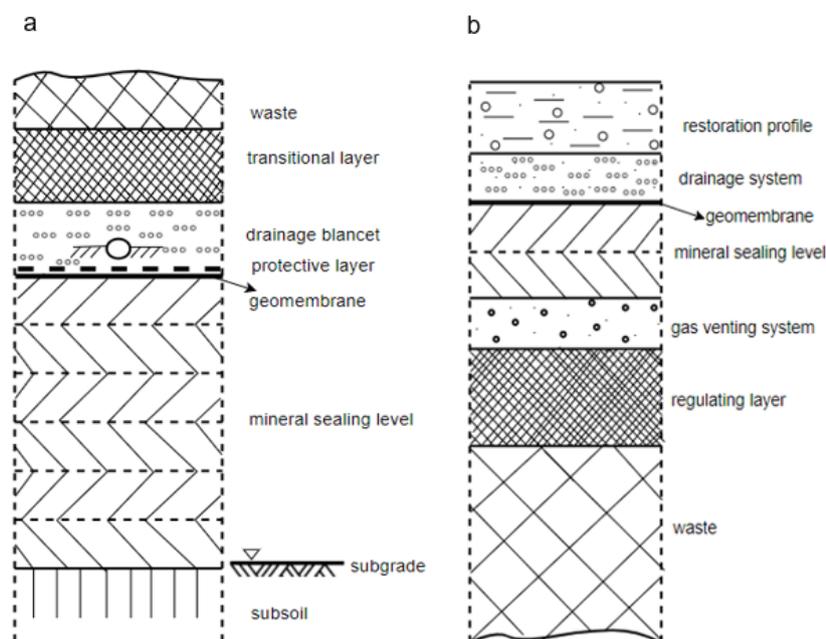


Fig. 5. Landfill seal layers using the base liner system (a) and landfill cover system with geomembrane (b) (acc. Jessberger, 1993)

prevents drain blockage if fine-grained waste were recommended by International Society for Soil Mechanics and Geotechnical Engineering – ISSMGE (Jessberger, 1993).

In accordance with the Part 257 Subpart D, § 257.102 of the RCRA, a landfill reclamation final cover design must be completed before work. The permeability of the final cover must be less than or equal to the permeability of the bottom liner system or natural subsoils present or a permeability of no more than $1 \cdot 10^{-7} \text{ m} \cdot \text{s}^{-1}$. Infiltration of liquids through the closed facility must be minimised by using an infiltration layer with a thickness of 45.7 cm or more of earth material. However, the final reclamation layer that forms the plant substrate must contain at least 15.2 cm of soil material to support plant growth. Figure 5b shows an example schematic of reclamation layer placement. The first layer of waste and regulation is to maintain the stability of the waste pile and prevent the migration of the mineral seal material to the waste surface. The gas venting system improves the pressure in the control layer of the landfill and, most importantly, provides safety against unwanted landfill gas accumulation. The higher mineral sealing layer minimizes

the formation of leachate, and on top of it the GM with its high chemical resistance separates the waste pile from the reclaimed part. Geomembrane is also resilient due to weight and stress strains, which is even more important than chemical resistance (Christiansen et al., 1994). A drainage system located just above GM minimizes hydrostatic pressure under the drainage layer. Meanwhile, the final component, the final restoration profile located at the top of the landfill, is intended to prevent erosion through vegetation (and protects against root penetration into subsequent layers) and is intended to protect the mineral layer from freezing (Jessberger, 1993).

TECHNICAL METHODS OF LANDFILL BASE SEALING AND RECLAMATION IN THE CZECH REPUBLIC

The requirements related to closure and reclamation of landfills in Czech Republic is based on standard ČSN 83 8035 from 1996 (Český normalizační institut [CNI], 1996). In 2018, there were changes in the technical conditions for landfills in the Czech Republic.

The main change in ČSN 83 8035 from 2018 (CNI, 2018) compared to the previous version of the above-mentioned standard was the detailing of the performance of levelling layers, the definition of the properties of the sealing layers and the reclamation layer. The maximum thickness of each sealing layer was estimated at 0.5 m or up to 1.5 m in justified cases (Ministerstvo životního prostředí, 2019). The updated 2018 standard has changed the grouping of waste into inert (S-IO), other waste (S-OO) and hazardous waste (S-NO). The division is in line with the Directive 1999/31/EC, which defines other waste (S-OO) as waste that will not decompose or burn, such as gravel, sand or stones. The rehabilitation of S-IO landfills does not require the closure of the facility with an impermeable cover as is the case for S-OO and S-NO landfills. The Czech landfill reclamation treatments include seven layers. A levelling layer (0.25 m thick) is laid on top of the waste pile, followed by a degassing layer with geotextile. The next element is an insulating layer made of GM HDPE. Geotextile is laid on top of this layer to protect it from physical factors. The last element is a drainage layer made of gravel with a thickness of 0.5 m and a layer of soil on top of it, which serves as a substrate for plants (Adamcová, 2019).

The protective reclamation layer is designed to protect the closed landfill from meteorological and

biological impacts, but is also capable of storing large quantities of water, preventing infiltration into the landfill (Božek, Filip & Kotovicová, 2006).

The ČSN 83 8035 standard from 1998 (amended from 2002) had relatively low requirements for the reclamation layer. The only recommendation was a layer thickness of at least 1 m, which would ensure protection of the landfill seal from damage. The updated ČSN 83 8035 standard from 2018 has introduced slightly broader restrictions on this layer. Before performing reclamation works, it is necessary to perform a project in which the stability of the proposed reclamation method is accurately calculated. In order to strengthen the stability for landfills with slopes steeper than 1 : 3, it is recommended to make an additional strengthening element to the whole layer. If the slopes of the landfill are only covered with grass or planted with bushes with shallow root systems, the thickness of the layer according to the updated ČSN 83 8035 standard should vary between 80 and 90 cm (including the drainage layer). However, if tall tree vegetation is used, the thickness of the layer should be increased accordingly to a maximum of 3 m. At least the upper part of the above layer should contain fertile soil with a thickness of not less than 0.1 m. In the case of S-IO landfills, where impermeable closure is not required, the thickness of the above-mentioned reclamation layer depends only on

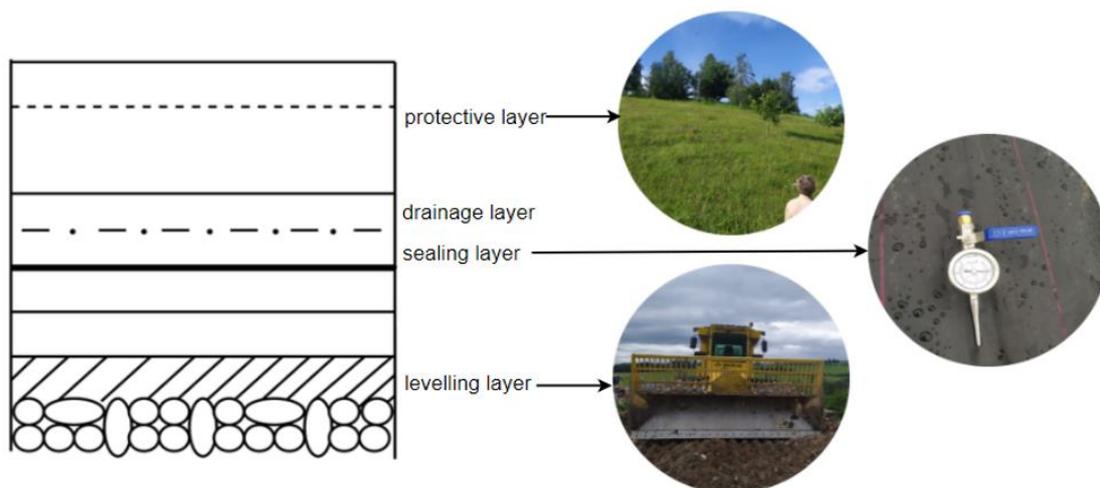


Fig. 6. Example of technical reclamation of landfill S-OO according to ČSN 83 8035 standard (acc. Božek, Filip & Kotovicová, 2006)

further needs related to subsequent use (Ministerstwo środowiska, 2019).

A simplified and generalised diagram of the technical reclamation of the S-OO landfill is shown in Figure 6.

CONCLUSIONS

Closure and reclamation of landfills is a very important process in the proper functioning of the environment. Reclamation must be preceded by a project and work plan that takes into account the legislation of a given country. The most important objective of reclamation is to minimize the potential hazards related to the negative environmental impact of landfill sites. Improper reclamation of the landfill in the long-term spectrum may be the reason for the occurrence of an ecological risk, which is mainly based on the migration of dangerous and indestructible heavy metals that pollute the soil or the groundwater in surrounding.

Despite many similarities in landfill remediation techniques around the world, differences between them are still visible. The use of impermeable landfill covers in reclamation is still rejected in some countries.

As an argument against the use of GM, the problem of maintaining the stability of the remaining layers and the slowing down of biogas production is shown. On the other hand, the problem related to the stability of the layers above the GM mainly concerns old landfills with steep slopes. Mineral seals or bentonite mats, which are used in Poland thanks to their permeable properties, provide a small amount of moisture to the deposit, which makes up for the oxygen deficiency and then contributes to the acceleration of aerobic fermentation. This highlights the need for further research to find a uniform solution that will give guidance on how landfill remediation should be carried out nowadays.

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PRZEGLĄD TECHNICZNYCH METOD USZCZELNIANIA I REKULTYWACJI SKŁADOWISK ODPADÓW NA ŚWIECIE

STRESZCZENIE

Składowiska odpadów, nawet prawidłowo zaprojektowane, wykonane i eksploatowane, są obiektami, które w przyszłości są potencjalnym źródłem zanieczyszczeń wód powierzchniowych i podziemnych oraz powietrza atmosferycznego. Stare składowiska odpadów komunalnych z powodu braku odpowiednich regulacji prawnych często powstawały w nieodpowiednich warunkach gruntowo-wodnych, co w znacznym stopniu przyczyniało się do uwalniania toksycznych odcieków do gruntu. Rekultywacja terenów zdegradowanych jest rodzajem ratunku dla obszarów zanieczyszczonych. W niniejszym opracowaniu przedstawiono przegląd metod uszczelniania i rekultywacji składowisk odpadów na przestrzeni lat w różnych krajach na świecie.

Słowa kluczowe: odpady, rekultywacja składowisk, syntetyki, odcieki