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Selected aspects of application of cohesive soils from SW Poland in sealing barriers

Abstract

The role of sealing barriers in a broad sense is recently increasing due to widespread pollution of the soil and groundwater environment, contamination of aquifers and a hazard of flooding. The notion of the sealing barriers is often limited in literature to liners for landfills of municipal or industrial waste, and radioactive waste deposition sites. In addition to these applications, the paper draws the attention to the use of sealing properties of cohesive soils in the construction and rehabilitation of flood embankments. The sealing properties of cohesive soils are related to the presence of clay minerals characterized by high hydrophilicity, well developed specific surface area, sorption properties and low permeability. These properties make them useful in the broadly defined environmental protection. The Neogene and Pleistocene sediments of SW Poland that contain clay minerals may be used both for the construction of flood embankments and as liners of municipal solid waste landfills. Their occurrences are evenly distributed; they have often been extracted as a material for building ceramics, and may represent the overburden or an accompanying mineral, which considerably facilitates their exploitation.

Streszczenie

W dzisiejszych czasach powszechnego zanieczyszczenia środowiska gruntowo-wodnego, skażenia poziomów wodonośnych, zagrożeń powodziami, wzrasta ranga szeroko rozumianych barier izolacyjnych. Pojęcie barier izolacyjnych często jest w literaturze zawężane do uszczelnień składowisk odpadów — komunalnych, przemysłowych, radioaktywnych. W przedstawionym artykule zostanie również zwrócona uwaga na wykorzystywanie właściwości izolacyjnych gruntów spoistych przy budowie i modernizacji wałów przeciwpowodziowych. Właściwości izolacyjne gruntów spoistych wynikają z obecności minerałów ilastych, które odznaczają się dużą hydrofilnością, rozwiniętą powierzchnią właściwą, właściwościami sorpcyjnymi i niską przepuszczalnością. Powoduje to, że mogą być wykorzystywane w szeroko pojętej ochronie środowiska. Występujące na terenie SW Polski neogeńskie i plejstoceńskie osady zawierające minerały ilaste mogą być wykorzystywane zarówno do budowy wałów przeciw powodziowych, jak i do uszczelnień składowisk odpadów komunalnych. Ich wystąpienia są dość równomiernie zlokalizowane, często były eksploatowane jako surowiec do produkcji ceramiki budowlanej, stanowią nadkład lub kopalinę towarzyszącą, co zdecydowanie ułatwia ich pozyskanie.

Keywords: flood embankment, waste landfills

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1. Introduction

In the times of widespread soil and groundwater pollution, aquifer contamination and flood hazard, the importance of sealing barriers is growing fast. Sealing barriers should prevent migration of pollutants from various sources, such as solid waste landfills, industrial plants, fuel storage and distribution centres. They may also be used to stop the dispersion of pollution formed as a result of breakdowns, catastrophes or natural disasters. Another role of the sealing barriers consists in protection against pollution of environmentally important areas, such as protected areas, peat bogs or Main Groundwater Reservoirs. Another important role played by these barriers in a broadly understood environmental protection is the prevention against flooding. When built in the form of flood embankments, they keep water within polders, thus protecting houses, infrastructure and the human life. Simultaneously, the barriers prevent spreading of pollutants washed away from flooded industrial plants, waste landfills, cemeteries or animal farms. The construction of sealing barriers and of flood embankments in particular, consumes immense volumes of material. Therefore, the significance grows of barriers that are made from natural materials, available in large quantities at a small distance from the future project site. Examples of such materials are sedimentary rocks that did not undergo diagenetic alteration and contain at least a dozen or so per cent of clay fraction, in which clay minerals prevail.

The uniqueness of clay minerals is related to their high hydrophilicity, great specific surface area, sorption properties and very low water permeability. A particularly high hydrophilicity is typical of smectite group minerals, in which the liquid limit may range between ca. 200% (e.g. Ca-montmorillonite from Turoszów) and 600% in pure Na-montmorillonite (e.g. from Wyoming). Owing to their structure, minerals of this group have also very high values of the swell and expansion potential (Grim 1968; Chen 1988). Much lower values of the liquid limit are typical of illites (up to ca. 70%), while the lowest values are connected with kaolinites. The swell and expansion potential of illites and kaolinites are considerably below the values that characterize the smectite group minerals.

A very well developed specific surface area of smectite group minerals and their sorption properties are related to very weak bonds between the layer units. The specific surface area of montmorillonite amounts to 600–800 m^2/g, and its ion exchange capacity (characterizing the sorption properties) is also high, i.e. around 70–130 cmol/kg (Grim 1968).

The structure of illite is identical with that of smectites, but following to the presence of K^+ ions between the layer units, bonds between them are considerably stronger and therefore, the specific surface area of this mineral is smaller (50–200 m^2/g) and chiefly represented by the exterior area; moreover, its sorption properties are much worse (20–50 cmol/kg).

Kaolinites, following to strong bonds between the layer units, have lowest values of the specific surface area (1–40 m^2/g) and poorest sorption properties (3–15 cmol/kg) of all clay minerals (Grim 1968).

The water permeability of pure, compacted clay minerals is very low and amounts to ca. 10^{-12} m/s for kaolinite and 10^{-14} m/s for compacted montmorillonite (Pusch 1994).

Following to such properties of clay minerals, even a presence of a dozen or so per cent of these minerals in sedimentary rocks may predispose them for application as sealing barriers.

The soils require, however, adequate compaction. Compaction is one the oldest methods for improving building soil properties. The effect of compaction is an increase in the dry density of solid particles at a given moisture content. As part of compactability investigations, the maximum dry density of solid particles and the optimum moisture content are determined for the specified test method. The Proctor Compaction Test is commonly used. The compaction of soils leads to improvement of their strength parameters, decreases soil compressibility and reduces the coefficient of permeability value that is so important for sealing properties of the sediment (Daniel 1993; Pisarczyk 2004).

Within the area of SW Poland, shallow lying clay deposits were formed chiefly during the Neogene and Pleistocene. They include, most of all, Poznań Formation clays and overlying glacial clays. Ice-marginal lake deposits are present locally. These deposits are accompanied by widespread eolian sediments, e.g. loesses within the Trzebnica Hills. In areas of volcanic activity dating back to the Miocene, there occur well known and partly documented weathering mantles composed of smectite and halloisite, formed as a result of weathering of volcanic eruption products.

Most of the Neogene and Pleistocene sedimentary rocks have been extracted for a long time as a raw material for ceramic building materials production. In numerous deposits, the material meeting parameters for such products was already completely exploited. The remaining material could, on the other hand, be used in the sealing barriers construction, as a decisive role in their construction is played by the presence of large quantities of materials at a close distance to the project site. It is easier to use clay sediments for sealing barriers, when procedures for their extraction and sale are in place, and the adequate extraction and haulage plant exists already at the location.

Surface rocks of the Earth's crust that form the subbase for civil structures or represent material for earthfill structures, are called building soils. Those created as a result of the economic activity of man, are referred to as the man-made fills. The ones formed by natural, geological processes are, on the other hand, called natural soils. Within the latter group, cohesive soils are distinguished, containing over 2% of clay fraction (PN-86/B-02480).

Cohesive soils to be used as sealing barriers shall have certain physical and physico-chemical properties, as well as specific mineral composition. Different properties are required from soils to be used for flood embankments, than from the ones to be used as liners for municipal or industrial waste landfills. Still other properties are important in the case of liners for radioactive waste disposal sites.

The notion of the sealing barriers is often limited to the liners for municipal or industrial waste landfills or radioactive waste disposal sites (Rowe et al. 1995; Daniel 1993; Pusch 1994). Apart from this application, the paper draws the attention to the utilization of sealing properties of cohesive soils in the construction and rehabilitation of flood embankments.

2. Application of cohesive soils in the flood embankment construction

In relation to major flooding of Poland's areas in the recent years (centennial or millennial floods), activities were accelerated in order to increase the rate of construction and rehabilitation of flood embankments, both in the Odra and Vistula river basins. The scale of devastation caused by the flood of 1997 in the Upper Odra basin and in the Lubusz Land is well known (Kołodziejczyk 2002). The devastation would be considerably smaller or none, if new flood embankments were systematically built and the old ones, constructed in the years 1905–1920, were properly maintained and rehabilitated. The flood protection system dating back to the early 20th century, performed well during floods of the 1930s, 1977 and 1985.

Flood embankments, like other hydro-engineering structures, are included in one of four importance classes I, II, III and IV. The highest one is class I (Regulation of the Minister of the Environment, Journal of Laws no. 86, item 579). Depending on the flood embankment importance class, areas of defended zones and the construction of the embankment are planned (Table 1).

Table 1. Flood embankment importance classes (as per the Regulation of the Polish Minister of the Environment, Journal of Laws no. 86, item 579, 20.04.2007)

Flood embankment importance class	Defended area (km^2)	Elevation of the embankment crest above the maximum water level
I	>300	1.5 m
II	150–300	1.0 m
III	150–10	0.7 m
IV	≤10	0.5 m

Construction of new embankments, which gained pace in the early 21st century, requires huge quantities of earthfill. According to the Regulation of the Polish

Minister of the Environment dated 20 April 2007 (Journal of Laws no. 86, item 579), the erection of hydro-engineering structures shall be executed with the use of native mineral soils and man-made fills. With regard to cohesive soils, the following parameters are required:

— clay fraction content below 30%,
— soft or stiff state,
— content of organic matter below 2%,
— calcium carbonate concentration up to 10%,
— absence of any chemical contaminants,
— dry density of solid particles over 1.500 g/cm^3.

These requirements are met by most boulder clays of the South Poland and Middle Poland Glaciations present very close to the ground surface or at a low depth in several areas of SW Poland. In many cases, they were extracted for the purpose of production of ceramic building materials. In general, however, their occurrences are not regarded as a source of valuable ceramic raw material, following to the quite specific properties of these clays. They commonly comprise significant quantities of sand and gravel fraction, and very often contain angular boulders. The presence of such components precludes application of most boulder clays from this area in the ceramics production. They are, however, beneficial with regard to application in the construction of flood embankments, as they facilitate proper compaction. The content of coarser gravel grains (over 5 mm) should not exceed several per cent in this case. The boulder clays occur chiefly in a soft or stiff condition, and the dry density of solid particles is much greater than 1.500 g/ cm^3. A certain problem may be posed by the considerable calcium content, which in deeper parts may be as high as 10% of $CaCO_3$. The fact that in most cases the near-surface layers contain no calcium down to 2–3 m below ground level, is very beneficial.

Layers incorporated in the embankment are 0.2–0.4 meter thick (depending on the compaction plant being at the disposal of the earthworks contractor). On completion of placement and compaction of each layer, compaction is checked, for instance by determining the degree of compaction (Is).

The degree of compaction (Is) is a ratio of the dry density of solid particles determined for the compacted soil layer and the maximum dry density of solid particles obtained using the Proctor Compaction Test (Myślińska 2010; Pisarczyk 2001, 2004).

Depending on the flood embankment class, the degree of compaction (Is) shall have the following values:

— new embankments — class I and II: Is = 0.92–0.95

class III and IV: Is = 0.90–0.92

— rehabilitated embankments: Is = 0.85–0.92.

Main elements of a flood embankment are presented in Figure 1.

The embankment height is assumed chiefly on the basis of maximum water levels that occur once in 100 years. In SW Poland, it is between 2 and 7 meters.

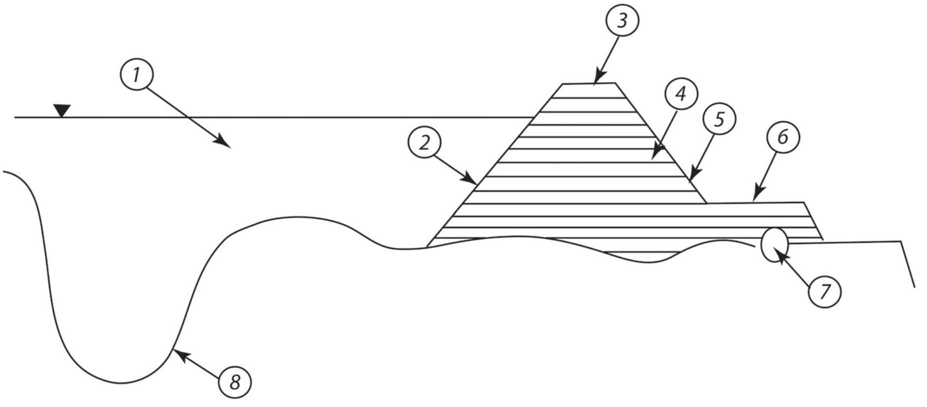

Figure 1. A flood embankment scheme (Kołodziejczyk 2002)
Explanations: 1 — high water channel, 2 — water side face, 3 — crest, 4 — body (cohesive soils), 5 — dry side face, 6 — berm, 7 — drainage, 8 — river bed.

The embankment crest width (between 3 and 5.5 m) facilitates traffic. The slope of sides shall ensure their stability and enable maintenance. Dry side faces are additionally strengthened with 1.5–2.0 meter wide berms that facilitate discharge of rainwater.

One of numerous components of the Wrocław flood protection system is a completed project under a title "The Kotowice polder — Siechnice-Groblice embankments, St. Katarzyna Commune." In the construction of these flood embankments, boulder clays of the Odra glaciation were used that occur in the overburden of the "AWIDA" Sand Pit in Bystrzyca, Oława Municipality. In the pit, varigrained sand, sandy gravel and gravel are extracted. The overburden boulder clay layer, stripped away in the course of exploitation, is collected and dumped on heaps. In spite of a small thickness of the boulder clay (no more than 2–3 meters), its storage poses a serious problem. Therefore, the use of the boulder clay and its incorporation in earthfill structures, such as e.g. flood embankments, is of a great importance. The boulder clay is gray-yellow and gray-brown in colour, rich in sand fraction and contains 2–4% of gravel fraction. The content of clay fraction ranges between 11% and 18%.

Soils from the overburden of the "AWIDA" Sand Pit in Bystrzyca, used to construct embankments in 2005–2007, have the following properties:

— sandy loam, silt loam, less frequently loam or loamy sand,
— natural moisture content: 8%–15%,
— liquid limit moisture content: 16%–26%,
— plastic limit moisture content: 8%–12%,
— condition: stiff, close to soft,
— maximum dry density of solid particles: 1.920–2.035 g/cm^3,
— optimum moisture content: 9%–15%.

As can be seen, these boulder clays met requirement set out for soils used to construct flood embankments. With regard to adequate compaction of these soils, similar values of their natural and optimum moisture content were important. As the optimum moisture content is the value at which the maximum dry density of solid particles is obtained, than if the value is close to the natural moisture content, the soil hauled directly from a deposit can be laid without preliminary drying or moistening.

This example proves, that in-depth research of sediments present at shallow depths, particularly when occurring in the zone of extraction, facilitates their rational use. Simultaneously, it prevents commencement of exploitation in another location.

3. Application of cohesive soils at municipal solid waste landfills

According to the Regulation of the Polish Minister of the Environment dated 24 March 2003 (Journal of Laws of 2003, no. 61, item 549), in the soil subbase of a planned municipal solid waste landfill, there shall exist a natural, geological barrier with a horizontal extent greater than the footprint of the structure and whose coefficient of permeability amounts to $k \leq 1.0x10^{-9}$m/s. If such a barrier is non-existent, then a liner from cohesive soil shall be installed.

These conditions are set forth to protect the soil and groundwater environment against contaminated leachate that forms as a result of rainwater penetration through the waste landfill. In uncontrolled municipal solid wastes, in the course of deposition lasting several tens of years, various processes and reactions take place under changing Eh and pH conditions and in the presence of the landfill gas. As a result of these processes, the chemical composition of leachate and its environmental impact are difficult to predict. Therefore, construction is necessary of a mineral liner that will eliminate or minimize contamination of water and soil.

Lining of the bottom and slopes of a landfill with cohesive soils is intended to:
— reduce migration of pollutants from leachate to the minimum,
— retard their dispersion in the environment,
— be prone to alterations caused by chemical compounds,
— have adequate bearing capacity and be resistant to unacceptable deformations.

Cohesive soils are also used as covers to seal the landfill surface, in order to:
— reduce rainwater infiltration into the waste mass,
— facilitate discharge of rainwater outside of the landfill,
— prevent dusting and uncontrolled escape of the landfill gas,
— prevent erosion of the landfill.

In order to be used for solid waste landfill liners, cohesive soils shall meet certain specific conditions. The main condition is a low value of the coefficient of permeability: $k \leq 1.0x10^{-9}$m/s. This value is accepted in most regulations and by the majority of authors involved in the research of this issue (Daniel 1993; Wysokiński 1995; Garbulewski 2000). Moreover, soils used in the solid waste landfill liners shall have the following properties:

— clay fraction content above 20%,
— no stone and gravel fraction,
— sand fraction content below 60%,
— plasticity index above 20%,
— liquid limit above 30%,
— content of organic matter up to 2%,
— calcium carbonate concentration up to 10%.

The Poznań Formation clay (Neogene) and boulder clays (Pleistocene) present in SW Poland meet these conditions and may be used for landfill liners. These deposits occur at shallow depths, almost at the terrain surface, and were frequently extracted for the purpose of ceramic building material production. In many instances, the extraction was abandoned, when the work front reached poor quality material. The Poznań Formation clay occurs in numerous localities within the Lubusz Land, e.g. deposits in Gozdnica, Jasień, Lubsko, in the area of Wrocław, e.g. in Pogalewo Małe and Pogalewo Wielkie, Krańsk near Brzeg Dolny, Strzelin and Sośnica near Kąty Wrocławskie. During Neogene, thick clay beds (exploited near Rusko and Jaroszów) and clays present within lignite in the Turów Lignite Mine were formed (Figure 2).

The Pleistocene boulder clays were exploited in numerous places, e.g. in Trzebnica, near Milicz and Kłodzko towns. The even distribution of deposits, where clay materials meeting conditions for liners were identified and researched, shall facilitate construction of mineral liners for modern municipal solid waste landfills (Figure 3).

Attaining adequate sealing properties by cohesive soils, expressed by the coefficient of permeability $k \leq 1.0x10^{-9}$m/s, is largely dependent on the granulometric compositions and the adequate compaction of the liner. According to numerous studies (Daniel, Benson 1990), the best sealing properties are revealed by soils compacted when their moisture content is 2–3% above the optimum moisture content value. It is assumed, that lowest values of the coefficient of permeability are achieved for this range of moisture content values. A separate issue that appears when discussing permeability of cohesive soils used to construct liners is the impact of landfill leachate chemical composition on variations in the coefficient of permeability. Organic and inorganic chemical compounds present in the leachates have impact on the width of the double electric layer, surface charges, pH values and simultaneously impact on the flocculation or peptization, and the increase or decrease in the coefficient of permeability value. It should be stressed, that leachates from municipal solid waste landfills are suspensions containing certain quan-

Figure 2. Locations of cohesive soils occurrences in Poland (Choma-Moryl 2004)

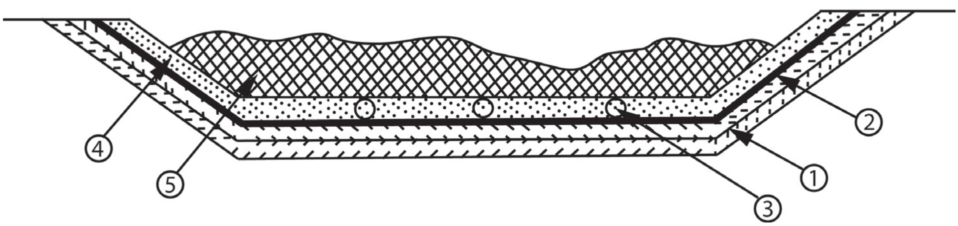

Figure 3. Liners for the bottom and slopes of a municipal solid waste landfill (Choma-Moryl 2004)

Explanations: 1 — mineral liner (cohesive soils), 2 — geomembrane, 3 — drain, 4 — drainage layer, 5 — wastes.

tities of solids which may lead to silting up of the liner and to the following, considerable decrease in the value of the coefficient of permeability.

Beside low values of the coefficient of permeability possible to achieve for cohesive soils, another important feature are their sorption properties. They are related to the presence of clay minerals, which occur chiefly in the clayey granulometric fraction. The sorption of pollutants by clay minerals provides significant protection of environment against pollution with leachates. The sorption properties may be assessed using simple methods, on the basis of the cation exchange capacity (CEC) and the specific surface area (S), i.e. properties which depend mostly on the mineral and granulometric composition. According to research, a 20–30 centimetre thick mineral liner intercepts heavy metals such as cadmium, lead and zinc (Wagner 1993). The research of sorption of cadmium and lead ions by cohesive soils of SW Poland implied that for concentrations present in most leachates, the soils will create a barrier against heavy metal migration (Choma-Moryl, Rinke 2005). The majority of Poznań Formation clays, as well as the clay accompanying lignite from the Turów Lignite Mine, clays from Rusko-Jaroszów area, and certain boulder clays display good compactability, the required value of the coefficient of permeability and good sorption properties. Examples of values for selected outcrops are listed in Table 2.

Table 2. The concentration of clayey fraction ≤ 2 μm, the dry density of solid particles (Pd_{max}), the optimum moisture content (W_{opt}), the coefficient of permeability ($k_{sat.}$), the cation exchange capacity (CEC) and the specific surface area (S) for selected outcrops

Outcrop location	Concentration of ≤ 2 μm fraction	Compactability		$k_{sat.}$ m/s	CEC-cmol/kg	S x10^3 m^2/kg
		P_{dmax} Mg/m^3	W_{opt}%			
Gozdnica	41–55	1.80–1.83	9.2–15.1	3.8×10^{-10}	20.5	120
Pogalewo Małe	50–65	1.72–1.77	16.2–20.1	3.1×10^{-10}	18.5	125
Jaroszów	75–90	1.57–1.65	19.2–26.6	3.6×10^{-12}	28.5	70
Trzebnica	20–25	1.95–1.99	7.5–15.3	1.8×10^{-10}	11.0	14

4. Conclusions

The protection of environment in which our civilisation has been created and is thriving, represents a task of an utmost importance that fortunately is being presently put into practice. The task is a complex one, and the paper deals with two aspects, i.e. the flood protection and the protection of the soil and groundwater environment against pollution. In these both instances, a proper use of natural materials, i.e. cohesive soils, is important. Flood embankments represent a major technical measure reducing the extent of flooding and the active profile of high water during flood periods. The first flood embankments were built on the area of Poland already in the 13th century. One of numerous aspects of embankment construction is obviously the economic aspect. According to this point of view, we build flood embankments, when the increased value of the defended areas offsets costs of their construction, or when the cost of embankment construction will be lower than that of losses caused by flooding. Therefore, identification and research of the highest possible number of occurrences of sediments that can be used for flood embankment construction is of an utmost importance. A particular attention should be paid to occurrences located at a short distance from river beds. Glacial clays, related to the activity of ice-sheets of the South Poland and Middle Poland Glaciations occur at shallow depths and in places directly under the topsoil. This facilitates greatly the extraction process. Glacial clay incorporated in the flood embankments represents most of all material present in the overburden of the main mineral, clay that is unfit for production of the ceramic building materials or was gained from deep cuts made for large civil structures. Properties of these sediments (particle size distribution, consistency, organic matter content and calcium carbonate content) are analysed for the purpose of preparation of a geological documentation of a mineral deposit, an engineering-geological report, as well as a geotechnical opinion and report. This enables allocation of soils according to a given class of embankments to be constructed. Following to conditions set forth in the design and the valid standards compaction of layers being placed should be controlled during construction of a given embankment. This requires assessment of the degree of compaction I_s based on the determination of the optimum moisture content and the dry density of solid particles in the Proctor compaction device.

In SW Poland, the number of such occurrences is large, and as it was shown on the example of the use of boulder clays from the "AWIDA" Sand Pit, it is frequently possible to utilize the overburden or sediments that accompany the main mineral.

Cohesive soils to be used for construction of liners at municipal solid waste landfills shall meet much stricter requirements than those for soils used to build flood embankments. Main features of such soils are a low value of the coefficient of permeability and a presence of sorption properties that should protect the soil and groundwater environment against migration of pollutants. According to the previous studies (Choma-Moryl 2004), the Poznań Formation clays, clays that accompany lignite deposits, fire clays that occur in the SW Poland reach the required value of the coefficient of permeability $k \leq 1.0x10^{-9}$ m/s. Sorption capacity of these soils prevents the spreading of contaminated leachate from municipal solid waste landfills. The location and availability of these soils enables their application in the construction of new landfills. Flood embankments perform their main role once every several or a dozen or so years, during several or less often a dozen or so days, and seldom for a longer time. Mineral liners of solid waste landfills, on the other hand, are to protect the environment for several tens of years under changing physico-chemical conditions. Municipal solid wastes contain remains of objects used by people in their everyday life, which come into reaction with one another, and products of such reactions are leached by rainwater. Following to such a hazard, the main requirement set out for modern waste landfills is the prevention of their negative impact on the environment. A majority of Neogene and Pleistocene sediments from SW Poland that contain over 30% of clayey fraction meet conditions for soils used in liners and sealing barriers. Their distribution is quite even; they frequently represent a material not useful for the production of ceramics, but that may become suitable for the construction of mineral liners of municipal solid waste landfills.

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