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Content

List of symbols

α – water retention curve fitting parameter, cm^{-1};

Δt – time duration required for lowering water level from h_1 to h_2, s;

θ_r – residual volumetric water content, assumed θ_r,=0, $m^3\ m^{-3}$;

θ_s – saturated volumetric water content, $m^3\ m^{-3}$;

μ – dynamic viscosity of water, kg $m^{-1}\ s^{-1}$;

ρ_s – density of soil, kg m^{-3};

ρ_w – density of water, kg m^{-3};

τ – dimensionless tortuosity factor;

$\o$ – dimensionless porosity;

ψ – soil water potential, cm;

a – water standpipe cross section area, m^2;

a_r – dimensionless anisotropy ratio, assumed constant for saturated and unsaturated conditions;

A – water retention curve fitting parameter, m^{-1};

A_s – soil sample cross section area, m^2;

clay – clay fraction content, %;

COLE – dimensionless coefficient of linear extensibility;

$\frac{dh}{dl}$ – pressure head gradient;

e – void ratio;

EV_a – actual daily evapotranspiration mm, day^{-1};

g – gravity vector, m s^{-2};

h – water pore pressure head, m;

h_1, h_2 – water level heights, m;

h_i – initial height of substrate specimen, after molding, before saturation, m;

h_s – height of swelled sample, m;

h_s – soil suction pressure, cm H_2O;

h_w – difference of water table height between reservoir of the permeameter and cylinder containing soil sample, m;

I – daily interception, mm day^{-1};

k – dimensionless constant equal to 3.6 10^{-5};

K_1 – maximum value of saturated hydraulic conductivity, m s^{-1};

$\boldsymbol{K}_{ij}$ – hydraulic conductivity tensor, i, j = 1, 2, m s^{-1};

K_s – saturated hydraulic conductivity, m s^{-1};

l – fitting parameter, l = 0.5;

L – soil sample height, m;

L_d – length of the dry soil bar, dried at 105 C degree, m;

LL – liquid limit, %;

LS – linear shrinkage indicator, %;
L_w – length of the wet soil bar, m;
n, m – dimensionless water retention curve fitting parameters, $m = 1\text{-}n^{-1}$;
P_{corr} – corrected daily precipitation, mm day^{-1};
PI – plasticity index, %;
PL – plastic limit, %;
Q – sink or source term, s^{-1};
q – water volumetric flow rate, m^3 s^{-1}, q=V/t, V – volume read from burette, m^3, t – time, s;
q_d – daily water flux, mm day^{-1};
q_D – Darcy unit flux, m s^{-1};
$\boldsymbol{q}_i$ – groundwater flux vector, m s^{-1};
q_{runoff} – daily surface runoff, mm day^{-1};
r_s – dimensionless geometry factor;
S – potential swell, %;
S_a – actual degree of saturation;
S_e – dimensionless effective saturation;
SL – shrinkage limit, %;
S_r – residual degree of saturation;
S_s – saturated degree of saturation;
S_s – specific surface area, m^2 kg^{-1};
t – time, s;
V_d – dry soil specimen volume, m^3;
V_s – saturated soil specimen volume, m^3;
z_d – dry soil specimen height, m;
z_s – saturated soil specimen height, m.

1. Preface

Landfilling, limiting the pressure of residual waste on the natural environment, public health, numerous social and economic issues, is the final stage of sustainable municipal solid waste management. The number of active landfills and relative volume of deposited waste vary in different countries of the world. Despite the fact that developed countries limit their application and increase the share of waste reuse and volume reduction processes, landfills are, and will be for many decades, a dominant cost-effective method of final deposition of municipal solid waste in medium- and low-income developing countries.

Landfilling is a manner of final waste deposition inside a trench equipped with various techniques of isolation of the waste body from the surrounding environment: soil, water and atmosphere. Thus, the sustainable landfill, according to the popular definition, should allow the safe disposal and subsequent degradation of waste in the shortest possible time-span, by the most financially efficient method available, and with the minimal damage to the environment. Potential impacts of goods consumption during landfill operation were reported to be from low to marginal in relation to the remaining environmental impacts of landfill. The damage to the environment may comprise contamination of surface water and groundwater through leachate, pollution of soil by direct contact with wastes or leachate percolation, air pollution by products of waste burning, spreading of diseases and odors as well as uncontrolled methane release. Therefore, a sustainable landfill, from the ecological and environmental point of view, should pose zero or minimal risk to the environment of being the source of several possible pollution streams, during its operational phase and long after the closure. The protection of the natural environment and the limiting the threats caused by sustainable landfill should cover the minimization of leachate generation and infiltration as well as the prevention of uncontrolled migration of landfill gas and odors for the entire period of waste disposal.

The main threats to water, soil and groundwater are posed by leachate, the liquid of different composition, which takes the constituents from the solid waste body, undergoing aerobic and anaerobic decomposition, through which it flows. The generation of landfill leachate is triggered by the presence of the surface water, which originates usually from precipitations and melting snow and percolates to the waste body through the top cover of the landfill. So, water inflow to and outflow from the deposited waste body should, in general, be prevented by both the top and bottom liners. Both liners are commonly constructed of natural materials of appropriate permeability and are often additionally supported by plastic or geosynthetic membranes, geotextiles etc. etc. However, application of the sophisticated sealing materials and techniques is often limited in developing countries of low- and medium-income, due to their high costs, possible social unacceptability and necessary transfer of know-how, services and technical support provided by the qualified staff and the applied monitoring system. Thus, in many cases in the developing countries, application of geomembranes, geotextiles and geosynthetics may fail to meet the principles and requirements of the social and economic pillars of the sustainable development.

Therefore, compacted clay liners (CCLs), despite their disadvantages, are still a worthwhile option, especially in the developing countries of medium or low incomes. The compacted clay liners are relatively easy in installation and maintenance, they can be applied in various local conditions and may utilize local mineral materials, equipment, workmanship and technologies.

On the other hand, compacted clay liners, prepared from various types of clayey substrates, of different particle composition and mineralogy, and of various plasticity, molded at variable water contents may present different properties, from general, through geotechnical to hydraulic. With the proper compactive effort applied, it is relatively easy to obtain the relatively low saturated hydraulic conductivity, far below the commonly required $K_s \leq 1 \cdot 10^{-9}$ m s^{-1}. Yet, compacted clays present some characteristics negatively affecting the long-term sealing performance of liners, thus affecting the sustainability of the landfill. These are the swell-shrinkage characteristics connected with the possibility of desiccation cracking and the ability of substrate to sustain its hydraulic conductivity after cyclic changes of saturation.

High plasticity clays, according to numerous criteria of earthen material selection are commonly advised as the proper choice for material of CCLs. But high plasticity clays are commonly characterized by high fines contents, high or very high shrinkage potential, high value of plastic limit, below which desiccation cracking may appear and very low resistance to cycling swelling and shrinkage, so that the reported increase in the hydraulic conductivity reached in some cases several orders of magnitude. As a result, long term sustainability of CCL is in this case at least doubtful. On the other hand, there are low plasticity clays, allowing comparable K_s after compaction, containing significant sand particles content, presenting clearly lower shrinkage potential and greater ability to sustain the relatively low hydraulic conductivity after cyclic changes of saturation. But these materials are quite often discouraged as the appropriate substrates for CCLs construction.

The additional doubts are connected with the multilayered, inclined top cover system suggested by several legal standards, including the Polish Journal of Laws from 2013 item 523, combining compacted clay layer of $K_s \leq 1 \cdot 10^{-9}$ m s^{-1}, additionally (in some cases optionally) supported by plastic of geosynthetic membranes, and coarse drainage layer of significantly greater saturated hydraulic conductivity, from range $1 \cdot 10^{-4}$–$1 \cdot 10^{-3}$ m s^{-1}. Such arrangement of neighborhooding layers in the top cover system may result in a significant lateral flow down slope, which allows to clearly reduce infiltration downward, towards waste body and helps to collect infiltration water by drainage pipes, thus limiting generation of leachate. However, on the other hand, increased flux downslope at the border between two substrates of K_s which differed by several orders of magnitude, even up to nine, may result in a limited possibility of rewetting the desiccated compacted clay liner. So, the even partially dried CCL, e.g. according to prolonged draught combined with possible influence of elevated temperature resulting from decomposition processes occurring inside the waste body, may have limited chances for resaturation to the secure water content above the plastic limit, receding possibility of desiccation cracking. Therefore, the sustainability of the compacted clay liner installed as a part of a multilayered cover system without the possibility, or with the limited possibility, of rewetting by infiltration of water from the drainage layer may be questioned.

The aim of this monograph was to determine the influence of various parameters of the selected clayey materials, all sampled in Wyzyna Lubelska, Poland, on the sustainability of compacted clay liner as a part of the top and bottom sealing of the municipal waste landfill. The presented analyses were based on literature review which made it possible to discuss the problem of sustainable landfilling and its requirements and impacts on the natural environment. The literature review based on peer reviewed publications, books, monographs, technical guidelines and standards allowed to present the role of landfilling in the sustainable municipal waste management, to discuss the advantages and disadvantages of compacted clay liners, present the most popular requirements and suggestions for assessment of material applicability for the compacted liner construction and to identify the most crucial determinants of liners sustainability. The work identified factors influencing long-term ability of sustaining the hydraulic conductivity of compacted clays including the swell and shrinkage properties, often leading to irreversible cracking, as well as resistance to cyclic drying and rewetting. The intensity of phenomena decreasing the long-term sustainability of compacted clay liner were related to the particle composition, mineralogy, plasticity (generally Atterberg limits) of the applied substrates and the compaction conditions, mainly the water content.

The presented analyses of factors influencing the sustainability of compacted clay liner as well as the construction of both bottom and top liners of landfill, were based on the determined basic characteristics, strength parameters, Atterberg limits, saturated hydraulic conductivity and water retention characteristics, swell and shrinkage potentials, including linear and volumetric shrinkage and, finally, hydraulic conductivity after several cycles of drying and rewetting. The applied tests were performed under the natural conditions of researched substrates and for specimens compacted at various water contents, according to several standards, Polish and international, including the British and American ones. The performed laboratory tests were supported by the numerical calculations of hydraulic efficiency of the top and bottom sealings of municipal waste landfill based on compacted clay liners utilizing tested substrates, formed wet and dry of optimum. Numerical simulations of top liner efficiency reflected twelve variants of liners (six compacted wet of optimum and six formed dry of optimum), constructed according to the actual Polish national standard and reflecting the shape of the selected existing experimental landfill in Rastorf, Germany. Time duration of the simulation covered one hydrologic year 2012. The performed field and laboratory measurements allowed to determine the various characteristics of the tested substrates, allowing to determine their behavior after compaction and under various saturation, directly influencing the sustainability of compacted clay liner. Numerical modeling allowed to assess the sealing capabilities of numerically tested CCLs as well as performance of the whole multilayered liner, including drainage and recultivation layers.

The performed analyses showed that all the tested clay substrates allowed achievement of required $K_s \leq 1 \cdot 10^{-9}$ m s^{-1} after compaction, both wet and dry of optimum. However, it was also observed, as it was expected, that the usually preferable high plasticity clays showed significant shrinkage potential and very low resistance to cyclic drying and rewetting. In several cases the final observed values of K_s were at the level of values presented by sandy materials. On the other hand, low plasticity substrate showed definitely the lower shrinkage potential and quite significant resistance to cyclic swelling and shrinkage. Numerical calculations showed the satisfactory sealing capabilities of all the tested liners, bottom and top. However, in some cases of the top cover CCLs compacted dry of optimum, moisture content lower than value of the plastic limit was observed, thus, desiccation cracking, in case of further drying, was highly possible. Results of numerical calculations showed also in most cases the constant saturation of modeled CCLs. Liners were not drying during the time duration of simulation, but the possibility of CCLs rewetting by water infiltration from inclined drainage layer was limited.

The performed analyses allowed to present the proposal for a simplified collection of criteria allowing to assess the applicability of clayey substrates in the construction of sustainable compacted clay liners. The summary, conclusions drawn and plans for future research were also presented.

2. Literature review

2.1. Landfilling as a part of sustainable waste management system

The concept of sustainable development defined by Our Common Future report (WCED, 1987) presents the idea of development guaranteeing the needs of the current generation as well as of the generations to come, instead of focusing on the needs of the current generation for the unlimited consumption and resources usage. The idea of sustainable development assumes existence and progress of the current generation in which the appropriate living conditions and usage of the natural resources do not affect the sustainability of the natural system, thus, allowing the future generations to have their needs met. The concept of sustainable development is usually considered in the three independent but linked areas: environmental (ecological), social and economic (e.g. Harris et al., 2001; Harding, 2006; Pawłowski 2009). According to Pawłowski (2006) these three basic pillars of sustainable development may be additionally supported by technical, legal, moral and political aspects. Integration of the all circles of sustainability mentioned above allows the development of complicated and complex strategies of mindful and directed sustainable development respecting the nature and intergenerational justice.

Meeting the needs of the current and future generations, considering the provision of necessary resources and ensuring the intact quality of the natural environment in the exploited ecosystems may be attained by the rational resources and wastes management (partial or total limiting of resources flow together with implementation of resources of lower environmental harmfulness) application of clean and energy efficient technologies of production, use of by-products and recycling of wastes (e.g. Kozłowski, 2000; Masternak, 2009). The important contribution in the realization of technical, ecological (environmental) and social aspects of the sustainable development should comprise on preservation, conservation and usage of inner and outer human environment to, among others, fresh water supply for domestic and industrial purposes, assuring the proper quality of air, soil and water (surface and groundwater) by e.g. limiting the anthropogenic pressure on the natural environment caused by various wastes (solid, liquid and gaseous) as by-products of the existence of our industrial and urbanized civilization (e.g. Bhamidimarri and Butler, 1998; Pawłowski, 2010). Preventing the increasing degradation of the natural environment, leading to pollution and deterioration of the actually available and possible to use in future, air, water and arable soil resources, is one of the basic research and application tasks for environmental engineering, because the amount and quality of limited air and water resources of ecosystems are directly connected to gasses emission, precipitation, surface and underground inflows as well as the discharge of sewages and leakage seepage of various origin and of anthropogenically modified quality (Palme et al., 2005; Marialokas, 2007; Palme and Tillman, 2008). Thus, the execution of intergenerational justice will depend on the proper management of non-renewable energy carries, sewerage and wastes, as well as on the availability of water of the proper quality required for domestic, municipal and industrial demands (e.g. Pawłowski and Pawłowski, 2008).

Improper handling of municipal solid wastes (MSW) during the whole process chain of waste management may seriously affect the sustainable development of the region and society due to the contamination of water, soil and atmosphere leading to negative changes in the ecosystem, the reduction of biodiversity, limiting the economic development and posing a major threat to public health (e.g. Batool and Ch, 2009; Sharholy et al., 2008; Al-Khatib et al., 2010; Othman et al., 2013). Rapid urbanization, related to economic progress, the increasing number of urbanized area populations, as well as the growing consumption may have detrimental effects on the urban population, because the generation of wastes is directly related to the urbanization degree, thus the application of the sustainable development concept to waste management in cities may improve the local ecosystems and the quality of life of urban residents (Jim, 2013; Mesjasz-Lech, 2014). As it was reported by Zaman and Lehmann (2013) cities take approx. 2% of global space, but consume 70% of global resources and generate 70% of total wastes. Thus, the system of sustainable management of solid wastes becomes a major priority of social, legal, economical and, last but not least, ecological/environmental concern, especially in urbanized areas where large amounts of solid wastes are generated (Huang and Chang, 2003; Erses Yay, 2015).

The proper sustainable municipal solid wastes management may minimize negative ecologic and environmental effects of wastes generation, transport, treatment and final disposal, supporting also the social and economic pillars of sustainability (Mesjasz-Lech, 2014). Briefly, public health may be influenced by the system of waste collection and transport, environment may be impacted by the wastes treatment and disposal, resource management may be supported by reduction, reusage and recycling, the other social and economic issues may be influenced by the financial sustainability, inclusivity, sound and coherent institutions as well as proactive public policies (Widomski et al., 2015d; Wilson et al., 2015).

The sustainable waste management system, according to Allen (2000) should encompass the following principles: i) reduction in generation of waste, ii) waste streaming at source, iii) recycling and reuse of waste, iv) treatment of waste in order to reduce its quantity and volume, v) landfilling of residual waste, vi) aftercare and rehabilitation of closed landfills, vii) each generation deals with its own wastes.

The sustainable solid waste management system (see Fig. 2.1) includes all essential activities related to the operational units of wastes collection, shipping and transport, treatment, recycling and final disposal (e.g. Pires et al., 2011; Zhang et al., 2014). According to Wilson (1985) a municipal solid waste management consisting of multiple waste collection, transport and disposal centers and facilities, including various activities and processes, has environmental, social and economic implications, which in turn may affect its sustainability. The generation of wastes and the ability of the society to engage in waste separation may be related to public/community wealth, social development, environmental and ecological awareness and knowledge (Shekdar, 2009; Guerrero et al., 2013; Widomski et al., 2015d). Transport of wastes from the producers to the treatment plants or locations of final disposal may be performed by various available means; generally road transport being dominant (Eres Yay, 2015). Then wastes, according to assumed type and manner of management may undergo various processes of material and energy recovery and/or volume reduction (e.g. Shekdar, 2013) which may include reuse, recycling, composting, biofuels production, incineration, pyrolysis, gasification etc. etc. (e.g. Santibanez-Aguilar et al., 2013). The final step of municipal solid waste management of remaining wastes, which cannot be processed by any other measures, is their final disposal by landfilling (e.g. Pires et al., 2011; Othman et al., 2013; Shekdar, 2013; Ozbay, 2015).

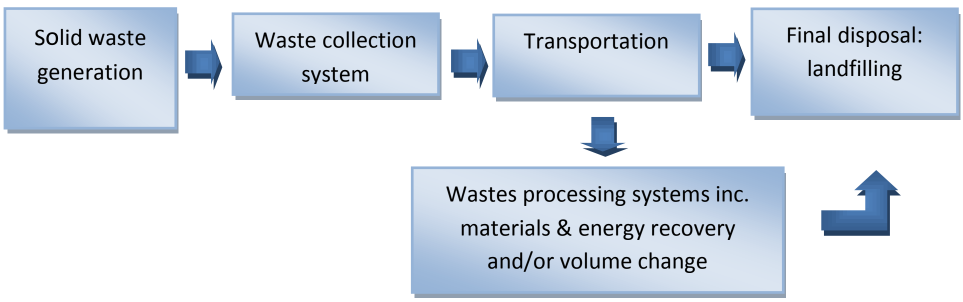

Fig. 2.1. Scheme of typical solid waste management system, modified after Shekdar (2009)

The developed countries of high incomes from various continents present generally sustainable attitude towards municipal solid wastes management, however, the applied practices vary from country to country or even, from region to region (e.g. Eres Yay, 2011; Pires et al., 2011; Marshall and Farahbakhsh, 2013). Sustainable development in high income countries is based on several important drivers: public health, environment, resource scarcity and value of wastes, climate change and public concern and awareness (Marshall and Farahbakhsh, 2013). In the European Union, the New Waste Directive 2008/98/EC (EU, 2008), is a common base for municipal solid waste management systems, despite the notable differences among member countries. European municipal solid waste management systems generally cover all typical stages: collection, transport, treatment, recycling/reuse and disposal which are tied to policies, institutional services, finances, proper technology selection, stakeholders participation and public awareness and their aim is to improve public health, protect the environment, promote the reuse and recycling of wastes, enhance waste separate collection etc. (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.

Developing countries of various parts of the world, with their rapidly increasing population, rapid urbanization, developing economies and growing standards of life are the regions suffering from a very high municipal waste generation. As a result, municipal solid waste management becomes a major issue for national governments, municipalities, corporations and individuals. However, in many cases, due to numerous reasons, sustainable MSW management systems do not operate properly in many developing countries and regions or cities (e.g. Shekdar, 2009; Zhang et al., 2010; Guerrerro et al., 2013; Marshall and Farahbakhsh, 2013; Sukholthaman and Shirahada, 2015). The main reasons of the lack of sustainable systems of MSW management in developing countries, from the general point of view, were summarized and categorized by Marshall and Farahbakhsh (2013) as: i) urbanization, inequality and economic growth; ii) cultural and socio-economic aspects; iii) policy, governance and institutional issues; iv) international influence.

According to Permana et al. (2015) the most serious and hardest to handle challenges encountered by municipal authorities in developing countries are: the high increase in the wastes generation, low municipal budget available, insufficient infrastructure, insufficient quality and technical capacity of technical personnel, high costs of MSW management, lack of understanding of several factors affecting various stages of MSW management system. These are the reasons for the pending system of MSW management in many locations in Indonesia, which may be, in the view of Permana et al. (2015), characterized as “collect, transport and forget”, without any links to sustainability. Analyses of the MSW management system in the city of Maputo, Mozambique reported by des Muchangos et al. (2015) suggested that the performed attempt of wastes management failed due to uncoordinated or ad hoc efforts and inadequate investments, combined with economic, administrative and technological weakness. The most important barriers for MSW management system in Maputo were recognized and grouped in several groups including: lacking or reduced and ineffective legislation and regulation, week support for stakeholders involvement and voluntary agreements, lack or improper economic instruments, week and ineffective education and the influence of communities behavior change, lacking or unreliable monitoring information and performance assessment, even including conflicts of interest and corruption, inappropriate choice of technology, and lacking, reduced or ineffective community linkages (des Muchangos et al., 2015). Similarly, Al-Khatib et al. (2010) reported several weaknesses of the local MSW management systems for selected regions of Palestine, including founding constrains, week law enforcement considering wastes collection, transport, treatment and disposal, lack of expertise, and lack of appropriate technologies or facilities.

The similar problems were also reported for the various regions of China, witnessing a very high population increase (including urbanized population), and as a result, increased amounts of solid wastes. The MSW management system in China, generally, reflects the structure presented in Fig 2.1, consisting of collection, transport, treatment, recycling/reuse and disposal. The most notable problems related to the applied MSW management in China covered: waste collection divided into formal and informal, low waste separation and recycling ratio, unsatisfactory quality of sanitary landfill (including locations of landfills, significant amount of open dumps, leachate control, landfill gas emission etc.), underdeveloped incineration and discharge/levying fees system (Zhang et al., 2010).

Thus, the simple and clear transfer and application of technical and technological solutions from the developed regions to the undeveloped or developing countries will not help to solve the problems related with the inefficient system of MSW management, posing serious threats to the public health and the natural environment. Since the European or North American practical solutions directly applied in developing countries may be too expensive, too complex and complicated, and may require additional energy consumption, qualified services and workmanship as well as experienced technical stuff, social and governmental mobilization and support, public awareness etc. etc.

Final disposal of municipal solid waste, as the optimal stage of MSW management systems in the developing countries of medium- and low-income is generally based on landfilling and open-dumping sites; the second method is being commonly recognized as the main source of environmental pollution (e.g. Ngoc and Schitzer, 2009; Shekdar, 2009; Zhang et al., 2010; Guerrero et al., 2013). According to data reported by Ngoc and Schitzer (2009) the amount of wastes disposed in open dumping sites in Southeast Asian countries varied between approx. 50% for Malaysia to 80% in Myanmar and Cambodia. The values of openly dumped wastes for the Philippines, Vietnam, and Brunei varied between 70% and 75%. At 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 30% for Malaysia. In contrast to the above, the example of Singapore may be quoted, where 2% of wastes were in 2009 disposed to open dumping sites and 2% were landfilled – 70% were incinerated (Ngoc and Schitzer, 2009). Moreover, open dumping sites are in low- or medium-income countries commonly localized in environmentally sensitive locations such as low, wetland areas, close to water bodies or at forest edges, along the roadsides, without any or with limited measures of operation control, protection at the bottom by clay liners or geo-membranes and gases treatment (Shekdar, 2009; Ngoc and Schitzer, 2009; Okot-Okumu and Nyenje, 2011; Oakley and Jimenez, 2012; Guerrero et al., 2013). Additionally, sanitary landfills are often located a considerable distance from urbanized areas, while uncontrolled open dumping sites are commonly within municipal limits, close to waste generators. Thus, transport costs and disposal fees may discourage the municipal residents from organized waste collection and landfilling, and as a result the residents may be attracted to uncontrolled open dumping sites (Ngoc and Schitzer, 2009)

Sanitary landfills, despite the fact that they are frequently being discouraged in the developed countries due to leachate seepage and gasses emissions, scarcity of land etc. (Othman et al., 2013), as the necessary final stage of solid waste management hierarchy, are in contrast to common practice of the uncontrolled dumping of wastes in developing countries (Oakley and Jimenez, 2012). Landfilling, from the historical point of view, was and nowadays remains a dominant cost-effective method of final deposition of municipal solid waste (Allen, 2000; Wagner, 2011).

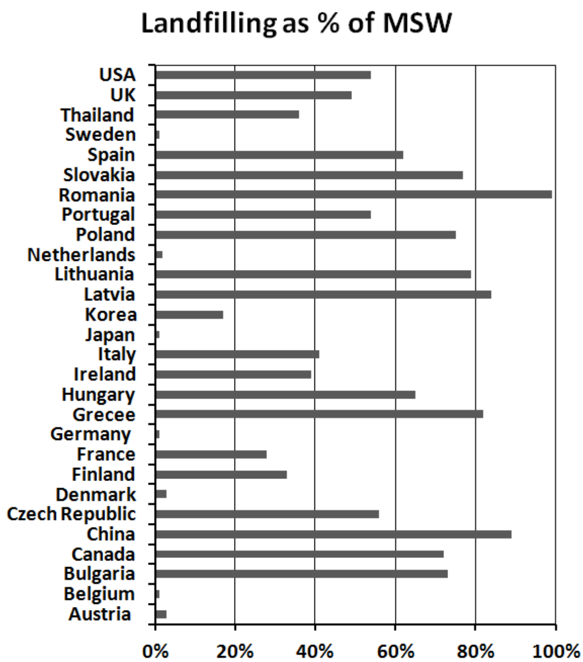

Fig. 2.2. Percentage of landfilled wastes as total MSW during last decade, developed after Zhang et al. (2010), Othman et al. (2013), Yang et al. (2014), Eres Yay (2015) and Ozbay (2015)

The approximate percentage share of landfilling in MSW managements systems of various countries during the last decade was presented in Fig. 2.2. Data presented in Fig. 2.2 show that countries of systematic and sustainable MWS management systems have their share in landfilling from 1 to 3%. The remaining volume of waste undergoes variable processes of recycling, reuse, energy and materials recovery and finally volume change, including incineration. There was also a visible reduction in the volume of waste deposited in landfills in the EU countries (Ireland, Czech Republic, Slovenia, Poland, Norway, UK, Denmark, Finland and Austria) during the recent years (Brennan et al., 2015), combined with the reduction of illegal landfills and improvement of waste acceptance practices by societies of member countries.

On the other hand, landfilling, despite its usefulness in limiting waste impacts on the environment and society, may be in some cases, for some communities, expensive in construction (significant amounts of clay, sand and gravel, plus additionally PEHD membranes, geomembranes, geotextiles etc.) and education, problematic and hard to maintain, especially in developing countries due to numerous processes occurring inside the waste body. It is also directly connected to greenhouse gases emission. In the developing countries landfills are commonly not properly constructed (with ineffective isolation by liners), poorly operated and the best practices are unknown or misunderstood, i.e. biogas is not significantly recovered, leachate is not treated, or if landfills are equipped in leachate collection and treatment systems, the quality of pollution control is insufficient due to careless operation and maintenance (Rissane and Naarajarvi, 2004; Zhang et al., 2010). Okot-Okumu and Nyenje (2011) reported the following operational and environmental problems of landfills observed in developing country: i) location on wetlands, close to rivers or 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. According to Ngoc and Schnitzer (2009) in developed countries of SE Asia, like Singapore, landfilling is not a difficult problem nowadays, due to lower population and application of sophisticated technologies and materials, supported by composting, recycling, incineration and anaerobic fermentation of wastes. On the other hand, in medium- and low-income countries of the regions, environmental pollution from unsustainable and insufficient landfills is openly complained.

2.2. Sustainable landfilling

According to Wagner (2011) the sustainability of solid wastes landfilling, as a historically dominant and nowadays still important and significant in foreseeable future method of the final waste management (including municipal, hazardous and radioactive) is crucial in the processes of transaction of goods, understood inter alia as availability of resources, availability between the generations, present and future.

Sustainable landfilling, according to Allen (2000) 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”.

Zurbrüg et al. (2012) discussed various determinants of sustainability in the solid waste management presented as a set of sustainable development indicators (SDIs), from which several may be connected to landfilling as a final disposal method. As for as the technical functionality of a sanitary landfill, the following SDIs were mentioned: level of local skills for design, construction, operation and maintenance, usage of local materials, level of performance considering expected goods and finally, adaptability. It is visible that the technical sustainability was related in this case to the availability of suitable local materials (including spare parts) and technologies, skills, services etc. Health and environmental impacts were characterized by the general level of community-related health protection, compliance with environmental legislation, meeting biding limits of emission, efficiency of natural resources and energy consumption. Thus for the environmental aspect, the sustainability of landfilling was related to its preventive measures to community health, avoidance and/or prevention of pollution, odors, insects, rodents etc. by the properly applied measures, compliance with local environmental standards and regulations concerning emissions to the atmosphere, water, soil and groundwater. In the field of economic sustainability SDIs for landfilling covered mainly cost efficiency and costs recovery, while the social aspect of final waste disposal was based on the levels of social commitment, acceptance and support (including institutional), demands, interactions and inclusion.

As it was expressed before, the sustainability of landfilling may be considered in most of the circles of sustainable development, including ecologic, social and economics. However, potential impacts of capital goods consumption during a landfill operation were reported to be from low to marginal in relation to the remaining environmental impacts of landfill, understood as direct and indirect emissions (e.g. Brogaard et al., 2013). Thus, 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 of this monograph.

Landfilling impacts on the environment may be categorized according to e.g. Ngoc and Schintzer (2009) and Othman et al. (2013) as: i) contamination of surface water and groundwater through 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 in landfill area and vi) uncontrolled release of methane by anaerobic decomposition of landfilled wastes.

So, a sustainable landfill, from the ecological and environmental point of view, poses zero or minimal risk to the environment through several possible streams of pollution, during its operational phase and long after the closure.

As it was already noted, landfilling of municipal wastes for a significant period of time, even several hundreds of years, may pose a major threat to the environment, resulting from biological, chemical and physical processes occurring in the waste body. The threat is caused by the long-lasting and mainly unpredictable possible migration of various pollutants to soil, water and air due to the unknown composition of the waste itself. Thus, the protection of the natural environment and limiting the threats caused by sustainable landfills should cover the minimization of leachate generation and infiltration, prevention of uncontrolled migration of landfill gas (containing greenhouse gases like methane and carbon dioxide) (Lou and Nair, 2009) 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, which takes the constituents from the solid waste body, undergoing aerobic and anaerobic decomposition, through which it percolates (Chofi et al., 2004; Mukherjee et al., 2014; Brennan et al., 2015). Municipal solid waste landfills produce leachate during their operation life and also several hundreds years after their closure, so the negative impacts of landfills are possible throughout all of this time duration (Brennan et al., 2015). And so, meeting the final principles of a sustainable landfill presented by Allen (2000) and discussed earlier is very difficult, and problematic, if possible at all.

During landfilling and site construction, the open waste body is vulnerable to atmospheric impacts by wind, precipitation and melting snow, and poses a significant threat to the environment. Thus, during the transition time up to the final rigid sealing, temporary landfill isolation is desirable to avoid odor emission, deflation of light waste fractions and excessive infiltration of precipitation water into the waste material and to minimize the discharge of leachate generation and percolation. Biogas collection is also possible during the early phases of waste body settlement. After the consolidation of waste, the temporary cover can be removed and replaced by the long-term coverage, which has to fulfill statutory requirements. However, such replacement is very expensive. In order to reduce the costs and efforts a temporary system partially or fully able to meet the requirements for long-term coverage or to be used as a basis, was developed and is being tested in Rastorf, Germany (Widomski et al., 2015b).

The possible future landfill emissions were tested by Laner et al. (2011) for the experimental landfill in Brietnau, Austria with the capacity 95 000 tones disposed in the period of 1987–88. The disposed wastes were compacted in layers and covered with layers of gravels and sandy silt, which were removed in 2009 and replaced by two 0.25 m layers of compacted mineral liner (saturated hydraulic conductivity K_s equal to $1\cdot10^{-9}$ m s^{-1}) supported with HDPE membrane, coarse gravel drainage layer of 0.5 m and 0.5 m soil layer. Bottom liner consisted of 1.7 m thick clay liner (K_s=$1.7\cdot10^{-9}$ m s^{-1}) and HDPE membrane. The reported predictions of future landfill performance for 300 hundreds years were based on emission parameters estimated experimentally and performed for three variants: continuous emission without changes in landfill conditions, gradual deterioration of containment system and complete failure of containment system. For the first variant, only 1% of emissions loads were released to subsurface, thus the emissions were not considered as a threat to the groundwater. In case of the second model, the time-variable loads of emissions to subsurface were comparable to the other anthropogenic sources, such as chloride emissions from deicing salts at 1 km of road, or nitrogen leaching from the arable area similar to the landfill area. The third variant, the sudden collapse of sealing system, showed the most disastrous results for soil and groundwater environment because all emission loads were flushed to the subsurface during the first decades of tested time span. Du et al. (2009) assessed the long-term performance of two general types of bottom liners applied in China, (based on natural clay barrier and compacted clay liner), with comparison to standard liner of German regulations according to the maximum leachate head, leakage rate, peak concentration of the target contaminant in aquifer below the landfill location and total mass per unit area of the contaminant discharged to the aquifer. The modeled issues of liner efficiency showed visible difference between both, Asian and German, types of liner assessed. The first, constructed according to Chinese regulations, in case of the liner based on natural clay deposit performed less effectively, which resulted in e.g. exceeding the allowable values of contaminant concentration for many years (up to approx. 60 years).

All the above shows the importance of the cover and liner system capable of sustaining their sealing properties for an extended period of time, thus isolation of landfills should be long-term and self-sustainable (e.g. Horn and Stępniewski, 2004; Laner et al., 2012), especially the permanent one, but the temporary solutions may also be included (e.g. Widomski et al., 2015b).

The generation of landfill leachate is triggered by the presence of surface water, which originates usually from precipitations and melting snow and percolates to the waste body through top cover of the landfill (Koerner and Soong, 2000). Thus, water inflow to and outflow from the deposited waste body should, in general, be completely prevented by the top liner, as well as by the bottom one. Both liners are often constructed of natural materials of appropriate permeability and capillary barrier systems and are often additionally supported by plastic or geosynthetic membranes (Bagchi, 1990; Simon and Müller, 2004; Laner et al., 2011, 2012; Aldaeef and Rayhani, 2014). The natural materials like clays, supported by geosyntetic clay liners, geomembranes, geonets and geotextiles are commonly used for the construction of liner in 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; Yang et al., 2014; Ozbay, 2015).

In the European Union, the required saturated hydraulic conductivity (K_s) for the mineral sealing liners, is lower than $1\cdot10^{-9}$ m s^{-1} (EU, 1999). Various types of clays are natural materials of a very low hydraulic conductivity, commonly applied to the construction of sealing liners of the landfills (Daniel and Wu, 1993; Bello, 2013). Application of clays as construction materials for landfill liners should be verified with regard to their compliance to the local legal standards (e.g. Journal of Laws from 2013 item 523; EU, 1999), as well as the technical engineering guidelines, commonly focused on the particle size distribution, saturated hydraulic conductivity, linear shrinkage and 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 may be reduced by an additional compaction. These are the cases when the natural materials for bottom liner *in situ* present values higher than the required or when the extraction of the clay material and its transport are necessary or when a compacted clay liner (CCL) for the final top cover of landfill closure is considered (e.g. Benson and Trast, 1995; Simon and Müller, 2004; Zhang et al., 2006).

Compaction of clayey substrates for CCL is usually suggested to be performed for water content wet of optimum, for density equal or greater than 95% of the maximum Proctor density (e.g. Fodged and Baumann, 1999; Wysokiński, 2007).

Generally, the construction of mineral landfill bottom liner and surface top cover, involving the application of compacted clay liner, is similar and comparable in many countries. For example, Polish national standard (Journal of Laws from 2013 item 523) requires for landfill of municipal waste the bottom sealing based on the natural geological barrier of thickness ≥1.0 m and saturated hydraulic conductivity $K_s \leq 1\cdot10^{-9}$ m s^{-1}. If natural barrier is incapable to sustain such requirements, the artificial barrier of thickness ≥0.5 m, with possible support of geomembranes or geotextiles, assuring $K_s \leq 1\cdot10^{-9}$ m s^{-1} is allowable. The bottom drainage system should have thickness ≥0.5 m and $Ks \geq 1\cdot10^{-4}$ m s^{-1}. The final top cover (capping sealing) should include sealing layer of mineral material of thickness ≥0.5 m and $K_s \leq 1\cdot10^{-9}$ m s^{-1} supported with the synthetic membrane, sand drainage layer of ≥0.5 m and $K_s \geq 1\cdot10^{-4}$ m s^{-1} supported with drainage pipes and recultivation layer of ≥1.0 m thickness allowing vegetation cover development.

Next, German landfill ordinance (DepV, 2009), for municipal wastes landfilling (landfill category DK I), describes requirements for the bottom liner as geological barrier of thickness ≥1.0 m and saturated hydraulic conductivity $K_s \leq 1\cdot10^{-9}$ m s^{-1}, of liner produced of mineral constituents of thickness ≥0.5 m lower saturated hydraulic conductivity, $K_s \leq 0.5 \cdot 10^{-10}$ m s^{-1}, and supported by the mineral drainage layer. If plastic sealing liners are to be used, they should be at least 2.5 mm thick. Surface sealing liner of municipal waste deposit, according to the German landfill ordinance (DepV, 2009), should consist of a sealing layer of thickness ≥0.5 m, with possible support of geomembranes or geotextiles, assuring $K_s \leq 5 \cdot 10^{-9}$ m s^{-1}, the supporting plastic membranes, if used, should have thickness of 2.5 mm, drainage layer of thickness ≥0.3 m and $K_s \geq 1 \cdot 10^{-3}$ m s^{-1} and recultivation/technical functional layer.

Similarly, the American Environment Protection Agency's standards (EPA, 1993) for bottom liner require at least two feet (approx. ≥0.66 m) of compacted clay liner of saturated hydraulic conductivity $K_s \leq 1 \cdot 10^{-9}$ m s^{-1} which may be supported by a flexible membrane of minimal thickness of 30 mils (0.08 mm) or 60 mils (approx. 1.5mm) for HDPE membranes. Bottom liner may be supported by drainage layer of 12 inches (approx. 0.30 m) and $K_s \geq 1 \cdot 10^{-5}$ m s^{-1} and leachate collection pipes. The requirements for American final cover design suggest that minimization of infiltration should be assured by 18 inches (approx. 0.45 m) of earthen material of permeability less or equal to the bottom liner, but no greater than $1 \cdot 10^{-7}$ m s^{-1}. If geomembrane is to be used as top part of the top liner it should have at least 20 mils (approx. 0.5 mm) of thickness, or 60 mils (1.5 mm) for HDPE membrane. The top of landfill should be covered by a minimum 6 inches (0.15 m) of earthen erosion control and vegetation layer. Obviously, the more complicated alternative designs of final top cover are possible and acceptable.

Initially commonly used as hydraulic barriers compacted clay liners (CCL) reaching a very low saturated hydraulic conductivity, far below $1 \cdot 10^{-9}$ m s^{-1}, even reaching values of $1 \cdot 10^{-12}$ m s^{-1} and significant water holding capacities (pF value of 2.0–4.2) were assumed to be the most versatile type of liners for containment of landfills as probably more durable, easier to maintain and cheaper than the synthetic liners (e.g. Allen, 2000; Finsterwalder, 2003; Aldaeef and Rayhani, 2015). It was assessed by Foged and Baumann (1999) that compacted clay liner of saturated hydraulic conductivity from range $1 \cdot 10^{-9}$–$1 \cdot 10^{-10}$ m s^{-1} normally was able to retain 75–95% of leachate, while K_s of $1 \cdot 10^{-11}$–$1 \cdot 10^{-12}$ m s^{-1} allowed reaching the value of >99% leachate retained. CCLs consisting of clay minerals of low swelling capabilities were not prone to problems of reaction with municipal solid waste leachate. The decrease in hydraulic conductivity of the compacted clays was also observed due to pores clogging by sediments and developed biomass (Farquahar and Parker, 1989; Allan, 2000; Francisca and Glatstein, 2010).

Efficiency of sealing properties of CCLs is directly related to the efficiency of compaction as a shear process depending on the applied compaction energy and the molding conditions, including the water content (Benson and Trast, 1995; Osinubi and Nwaiwu, 2005; Cuisinier at al., 2011; Whalley et al., 2012; Bello, 2013;

Widomski et al., 2015a, 2015e). Generally, clays were (and are) suggested to be compacted at water contents greater then optimum (e.g. Allen, 2000; Simon and Müller, 2004; Wysokinski, 2007). However, clays containing significant amounts of swelling minerals (e.g. unstable illites and smectities) are prone to swelling, shrinkage and cracking (which are to be discussed below, later in the text). The popular bentonite clays, consisting mainly of expansive minerals of smectite groups are susceptible to severe desiccation cracking due to low water content and elevated temperatures (Allen, 2000). Moreover, in the case of direct contact with leachate, due to chemical reactions between organic substances and bentonite, increase in the permeability is possible (Alther, 1987). The performance of the other natural compacted clay liners may also be limited by chemical interactions with leachate, but in the case of failure, the attenuation properties of clays can, to some extent, mediate groundwater contamination by percolating leachate (Allen, 2000).

Strength properties of compacted clay liners are also directly dependent on the actual water content. The ductility (ability to significant deformations when loaded) of CCL increases and its strength decreases alongside the increase in water content (Mukunoki et al., 2014). However, application of landfills based on CCLs in developing countries, principally constructed of local clayey materials (where possible), may achieve social acceptance and become economically affordable for local communities/governments.

The above described common designs of top cover for the municipal waste landfill combining both highly permeable drainage layer and nearly impermeable compacted clay liner, commonly divided by geomembrane or geotextile, often inclined may significantly affect hydraulics of the capping. The difference in hydraulic conductivity of the two adjoining layers reaching five orders of magnitude causes a significant resistance to vertical infiltration flow and directs the velocity vector horizontally. Thus, the achieved efficiency of drainage layer in redirecting infiltration water and its removal by installed drainage pipes may be significant. But, the greater the inclination of the liner slope, the lower the possibility for water flowing down slope through the drainage layer to infiltrate the compacted clay liner. The above mentioned situation is not a serious problem in case of saturated clay sealing compacted wet of optimum, at water content greater than plastic limit (*PL*), which is not prone to shrinking and cracking. However, in the case of clay sealing barriers compacted dry of optimum, at low water contents, or utilizing substrates of high *PL*, or dried due to exposure to atmospheric conditions, limited infiltration may result in problems connected with the rehydration of the barrier. The time duration of water retention in a sandy drainage layer, may be insufficient to enable the infiltration into clay layer. This makes shrinkage, cracking and the increase in the saturated hydraulic conductivity of the clay sealing highly possible (e.g. Widomski et al., 2015a).

Artificial liners, used solely or as the support for natural mineral liners, were originally, at the last decade of XXth century, treated as of uncertain and unproven long-term performance. Their service lifetime was assessed as maximum 100 years (Finsterwalder, 2003; Simon and Müller, 2004). The durability of synthetic membranes subjected over the long time periods to corrosive effects of leachate and increased temperatures resulting from exothermic processes occurring inside waste body was questioned (e.g. Allen, 2000; Finsterwalder, 2003). Additionally, HDPE membranes were proved to be prone to stress cracking and damage, particularly due to unsuitable dumping practices or failure of the membranes near welded seams (Rollin et al., 1991; Artieres and Delmas, 1995). The extreme care and favorable weather conditions during synthetic liner installation were also underlined (Allen, 2000).

However, the opinions changed diametrically during the first decade of XXIth century, when it was determined that sealing properties of certified and properly installed HDPE-GMs are able to sustain aging processes for a significantly longer time. The oxidation degradation of certified HDPE-GM was estimated as at least lasting several hundred years (Simon and Müller, 2004). Simultaneously, it was reported that a single CCL supported with the drainage and recultivation layer may undergo cracking formation due to desiccation processes and can be penetrated by roots and animals (Melchior et al., 2001; Simon and Müller, 2004). Thus, geomembranes are considered as a part of the multilayered liners of the importance comparable to, or greater, than CCLs. The properly installed HDPE geomembrane would pose an absolute barrier for water and gas flow, the pollutant transport would be only possible due to the process of diffusion. However, it was also noted that geomembrane may become pervious, to some extent, to flow of water and gas, due to faults resulting from material itself, preparation of the base, workmanship in geomembrane installation, following earth-works, waste loads, piping installation etc. (Simon and Müller, 2004). Thus, the rather costly certified installation of geomembranes is sensitive to damages. The appropriate protection, workmanship and state-of art technology are required because the future performance of HDPE lining depends directly on them.

Influence of HDPE geomembranes application as landfill sealing to landfill gas production and extraction was also tested. It was observed that the applied solely welded geomembrane layer increased gas flow in the gas uptake pipe by 25% versus the flow observed for a case in which HDPE membranes were not welded. However it was also assessed that low heat isolation of HDPE membrane may seriously affect the landfill gas generation in cold weather, especially in shallow landfills (Chen et al., 2011). Experiments referring to the application of HDPE as a partial temporary cover over worked-out landfill sections reported by Capaccioni et al. (2011) suggested some negative effects derivable from geomembrane cover, including lateral migration and concentration of gas emissions through adjacent active section of the landfill, resulting in increased landfill gas flux velocities through landfill soil cover, allowing the methane emission without a significant oxidation.

Basnett and Bruner (1993) as well as Hewitt and Philip (1999) observed another dangerous issue related with the HDPE membrane presence over the CCL – desiccation of compacted clay liner and cracks formation below HDPE geomembrane, resulting from elevated temperature and restrained rewetting by infiltration water. However, for in-situ test site conditions of the CCL covered by various geotextiles but without waste body below (no heat generation), geotextile cover proved ability to significantly reduce cracking (Safari et al., 2014).

Another popular technique of lining, especially in developed countries, is application of geosythetic clay liners (GCLs) consisting of a bentonite layer placed between two geotextile layers. According to Bouazza (2002) as well as to Simon and Müller (2004) GCL membranes are used as cost-effective and space saving alternatives for CCLs, due to their easy transportation and installation, but their applicability is confronted with three design issues affecting their long-term behavior: cracking due to desiccation, long-term shear strength on steep slopes and limited resistance to roots penetration. In some conditions, under the proper load applied (15–20 kN m^{-2}) GCL presents the ability to reduce the cracks when rewetted, due to significant swelling potential of bentonite (Heerten, 2002). Thus, the increased permeability of GCL during the dry season, may be, to some extent, reduced during the wet season of high precipitation or snow melting. Bentonite has a very low value of shear stress, so GCL systems need reinforcement by stitching and/or needle punching. Long-term stability of GCL is therefore dependent on the stability of reinforcing fibers, which, in fact may be affected by polymer aging, degradation or environmental stress cracking (Simon and Müller, 2004).

Unfortunately, the modern alternative methods of liner construction, supporting CCLs, may affect the stability of the liner as an engineering, multilayer construction. The stability of the multilayered liner, consisting of several layers of various mineral materials, including compacted fine soils in the sealing layer, sand or gravel in the drainage layer and various types of soil as the recultivation layer, plus additionally synthetic geomembranes, is controlled by the shear stress of each component and the various interfaces between components in the system (Stark et al., 2012). On landfill slopes GCL membranes are permanently exposed to shear stress caused by the component of gravity force triggered by the recultivation and drainage layers, above the geosynthetics. Thus, sliding stability of the cover system depends on friction forces between GCL and other mineral components of the liner and the internal shear stress inside GCL (Müller et. al, 2008). There were reported cases of slope instability resulting form week geosynthetic interfaces (eg. Mitchell et al. 1990; Stark and Poepel, 1994; Stark et al., 1998; Chang, 2005; Benson et al., 2012) usually related to low shear resistance of geomembrane and geosynthetic interface, significantly lower than the resistance of interface between soil layers (Stark and Poepel, 1994; Dove and Frost, 1999; Stark and Choi, 2004; Dixon et al., 2006; Eid, 2011; Benson et al., 2012; Qian and Koerner, 2015; Stark et al., 2015), especially in cases of high saturation of sodium bentonite (Müller et al., 2008). Additionally, strength parameters of the material may be changed in the long period of operation due to aging (of physical or chemical nature), including environmental stress cracking. Moreover, Müller et al. (2008), undermined the extrapolation, based on visco-elastic behavior, of previously preformed field (up to 10 years) and laboratory creep tests (up to 10000 hours) of GCL performance in the long-term time duration, e.g. 100 years. The performed long-term shear behavior test at elevated temperatures of several tested GCLs showed sensitivity to testing medium (deionized and tap water) for which failure cases were observed.

Similarly, interface between various artificial liner layers may cause landfill liner failure. There are known cases of failure of liner based on 1 mm thick PVC geomembrane, needle-punched fabric supported GCL with nonwoven geotextile on its upper side, where PVC membrane ripped along the slope several weeks after installation and PVC-GCL interface was a landslide interface (Thiel, 2009) or slide occurring along the interface between LLDPE (linear low-density polyethylene) geomembrane and geosynthetic clay liner consisting of geonet with non-woven needle-punched geotextiles (Benson et al., 2012). Although, there are known examples of liner failures where sliding interface occurred not between geomembrane/compacted low permeability soil liner but between a soil – soil interface. Thus, such situations should be avoided by the proper compaction manner of soil liner layers, for which each lift is kneaded into the lower lift and molding water content should be controlled for each particular case and applied material (Stark et al., 2012).

Taking all the above into consideration, one may state that compacted clay liners (CCLs), alone or combined with artificial membranes, despite their drawbacks, are still a worthwhile option, especially in developing countries of medium or low incomes. The CCLs are easier in installation and maintenance, can be adopted in various local conditions, may utilize local mineral materials, equipment, workmanship and technologies. In the case of application of certified artificial liners based on geomembranes, geotextiles etc. etc. in less developed countries, transfer of know-how, technical support, qualified staff and monitoring system is necessary to install a liner of required quality and to allow its long-term performance, also after the closure of the landfill. However, it is visible that in many cases the requirements for the successful application of geomembranes of GCLs may not fit the principles of sustainable landfilling.

2.3. Material selection recommendation

There is no unified and comprehensive international legal regulation assessing the applicability of mineral material for use in the construction of a compacted clay liner. Generally, legal regulations of several countries refer only to the saturated hydraulic conductivity and structure of mineral liner composition. For instance, regulations of the European Union and the Republic of Poland specify the maximum allowable value of coefficient of saturated hydraulic conductivity for the sealing layer of a multilayered mineral liner as lower than $1 \cdot 10^{-9}$ m s^{-1} (EU, 1999; Journal of Laws from 2013 item 523). Similarly, German landfill ordinance (DepV, 2009) presents various required values of K_s for different types of landfills and particular liners. So, for DK I landfill type (quite inert municipal waste) maximum allowable K_s for geological barrier was determined as $\leq 1 \cdot 10^{-9}$ m s^{-1}, while for the first mineral liner component it was set as $5 \cdot 10^{-10}$ m s^{-1}. The K_s for surface sealing system liner component of DK I was described as $5 \cdot 10^{-9}$ m s^{-1}. The allowed maximum values for geological barrier and two mineral liner components for DK II (municipal solid wastes) as well as the top cover mineral sealing were determined also as $1 \cdot 10^{-9}$ m s^{-1}, $5 \cdot 10^{-10}$ m s^{-1} and $5 \cdot 10^{-9}$ m s^{-1}, respectively.

More developed technical standards and guidelines allowing the assessment of substrates applicability to compacted clay liner construction are also available, from simple regulations covering only the basic characteristics like the K_s, particle size distribution (clay content or fine particles content) and the selected Atterberg limits, usually the plasticity index (e.g. EPA, 1993) to fully developed sets of indicators consisting of particle size distribution, mineralogy, strength parameters, Atterberg limits, forming characteristics etc. (e.g. Wysokinski, 2007). The selected interesting threshold values of various technical manuals of landfill liner construction for mineral substrates usability are presented in Tab. 2.1.

Tab. 2.1 presenting threshold values of several parameters of clay substrates allowing to assess the usefulness of mineral materials to CCLs construction shows some interesting values. All the presented regulations and guidelines consider some general parameters, such as: clay (or fine) particles content, the plasticity index and saturated hydraulic conductivity K_s. The three mentioned main characteristics are supported, in some cases, by clay minerals content, liquid limit, plastic limit, swell and shrinkage index or selected strength parameters. The required values of clay or fine (clay+silt) particles content suggest that soils of significant clay content are required to assure low value of saturated hydraulic conductivity within the range 10^{-9}–10^{-10} m s^{-1}. The suggested values of applied Atterberg limits, based mainly on the plasticity index and liquid limit allow to classify possible clayey soils or substrates according to the plasticity chart (ASTM D2487-11; Ladd and Lambe, 1961; Bain, 1971; Chen, 1988) presented in Fig. 2.3.

Tab. 2.1. Comparison of various exemplary regulations or guidelines concerning threshold values of substrates applicability for CCL construction, developed after (Bagchi, 1990; Daniel and Koener, 1995; EPA, 1993; Rowe et al., 1995; Arch, 1998; NRA, 1995; Manitoba Government, 2007; Majer, 2007; Wysokinski, 2007)

	Bagchi (1990)	Daniel and Koener (1995)	EPA (1993)	Rowe et al. (1995)	Arch (1998)	NRA (1995)	Manitoba Gov. (2007)	Majer (2007)	ITB Wysokiński (2007)
Clay content (%)	≥25	≥10 –20	-	min. 15–20	>10	>10	≥20	≥20 ≥25 pref.	≥20
Clay + silt content (%)	≥50	≥30 –50	≥30	-	>30	-	≥50	≥50	≥60
Clay minerals content (%)	-	-	-	min. 15–20	-	-	-	≥20	≥20
Plastic limit (%)	-	-	-	-	-	-	-	-	25–45
Liquid limit (%)	≥30	-		-	<90	≤90	≥30	≥30	40 –115
Plasticity index (%)	≥15	≥7 –10	≥10 –30	≥7	10-30	≥6–12 ≤65	≥20	≥15 ≥30 pref.	15–70
Linear shrinkage (%)	-	-	-	-	-	-	-	-	≤17
Swelling index (%)	-	-	-	-	-	-	-	≥5	≥4
K_s ($m\ s^{-1}$)	$\leq 1 \cdot 10^{-9}$	$\leq 1 \cdot 10^{-9}$	$\leq 1 \cdot 10^{-9}$	$1 \cdot 10^{-9}$ – $1 \cdot 10^{-10}$	$\leq 1 \cdot 10^{-9}$	$\leq 1 \cdot 10^{-9}$	$\leq 1 \cdot 10^{-9}$ $\leq 5 \cdot 10^{-10}$	$1 \cdot 10^{-10}$	$\leq 1.0 \cdot 10^{-9}$
Modulus of primary compre-ssibility M_0 (MPa)	-	-	-	-	-	-	-	-	≥5
Internal friction angle (deg)	-	-	-	-	-	-	-	-	≥3

Liquid limit (*LL*) for fine grained soils reflects shearing resistance of approx. 1.7–2.0 kPa and pore water pressure of approx. 6.0 kPa (Mitchell and Soga, 2005). All clays essentially have similar surface structures, so the forces between these surfaces and absorbed water should be the same. Thus, liquid limit for the same group of clay substrates, consisting of the same or similar minerals (in our case clayey soils consisting of significant amount of clay minerals) should be the same because the amount of water absorbed per unit area of surface corresponding to 6 kPa soil water pressure should be similar. So, the greater the specific surface, the greater amount of water is required to reduce the strength of the material, thus the greater value of the liquid limit (Mitchell and Soga, 2005). Increase in the liquid limit value reflects the increase in the swelling potential of soil/substrate.

The plasticity index (*PI*), referring to a difference between the liquid limit and plastic limit (plastic limit is the minimum amount of water necessary to make clay plastic/cohesive, below it, soil is prone to cracking) is a measure of plasticity of soil, understood as irreversible deformation of materials' shape due to the applied forces (Mitchell and Soga, 2005; Baumgartl, 2006). Thus, the plasticity index of soils reflects the size of the range water content for which soil demonstrates the plastic properties (Mitchell and Soga, 2005). Increase in the plasticity index results not only in plasticity increase but also reflects increase in the shrinkage potential.

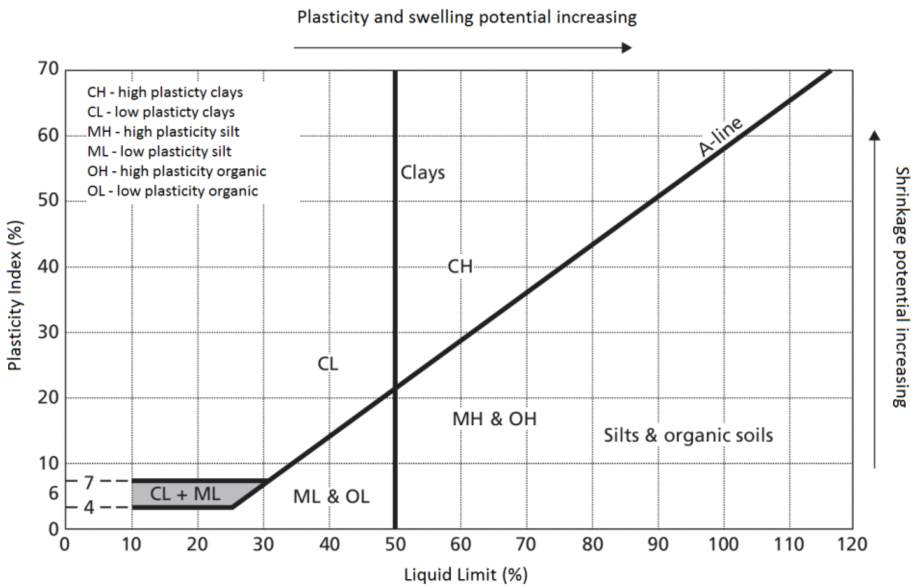

Fig. 2.3. Plasticity chart of USCS (BS 1377–2: 1990), modified after Knappett and Craig (2007)

The required threshold values of plasticity index presented in Tab. 2.1 vary between 6–15% as the bottom threshold to 70% as the upper boundary, while the suggested liquid limits are in the range from 30% to 115%. Thus, depending on the values of suggested *PI* and *LL*, low and high plasticity clays are treated as suitable for CCLs construction. Substrates of lower threshold values i.e. *LL*≥30% and *PI* ≥6–

20% may be recognized as CLs (low plasticity clays) or in case of *PI*=6%, as it is visible in Fig. 2.3, CL+ML (low plasticity silt). On the other hand, substrates for the upper boundary thresholds, i.e. *PI*≤65–75% and *LL*≤90–115% are commonly recognized as high plasticity clays. The main difference between the two discussed groups of clay materials is their behavior when saturated. High plasticity clays are characterized by high and very high swelling potential and medium, high or very high shrinkage potential. Thus, extensive shrinkage, vertical or/and horizontal, for such substrates may be expected, combined with commonly irreversible cracking, drastically increasing permeability of clays. So, application of high plasticity clays to construction of CCLs may pose some risks of shrinkage and cracking, leading to the loss of isolation properties of the liner. Additionally, the high plasticity clays, of *PI*≥30%, may cause some difficulties during liner construction in the field conditions due to formation of hard clods when dry and sticky clods when saturated (e.g. EPA, 1993).

2.4. Determinants of liner sustainability

If a sustainable landfill is understood as safe disposal of wastes, obtained with the most financially efficient method available and with the minimal damage caused to the environment in a prolonged period after the closure of the landfill, the sealing capabilities of the bottom and top liners, based on CCLs, should be sustained. Thus, the long-term performance of a sustainable landfill liner, assuring limitation of environmental impacts related to pollution streams to water, groundwater and soil, depends on three interrelated properties of the applied soil/substrate, i.e. hydraulic conductivity in natural conditions and after compaction, swell-shrinkage properties and resulting cracking as well as, finally, ability of soil/substrate to sustain its hydraulic conductivity after cyclic changes of saturation, commonly understood as several cycles of drying and rewetting or shrinkage and swelling.

2.4.1. Hydraulic conductivity of compacted clays

Saturated hydraulic conductivity K_s of soils or particle substrates depends on, among others, particle size distribution (K_s usually decreases with the increase in fine particles content), void ratio (or porosity), pore sizes (pore diameters), specific surface area, swelling, mineralogy and ion exchange capabilities (e.g. Lambe, 1954; Mitchell and Jaber, 1990; Benson and Trast, 1995; Foged and Baumann, 1999; Egloffstein, 2001; Stępniewski et al., 2011).

The saturated hydraulic conductivity for laminar flow through pours media may be expressed by the Kozeny-Carman equation (e.g. Whalley et al., 2012):

$$K_s = \tau \frac{1}{S_s} \frac{\rho_w^2 g}{\mu \rho_s^2} \frac{e^3}{1+e}$$

where:

K_s – saturated hydraulic conductivity, m s^{-1};

S_s – specific surface area, m^2 kg^{-1};

τ – tortuosity factor;

ρ_w – density of water, kg m^{-3};

ρ_s – density of soil, kg m^{-3};

g – gravity vector, m s^{-2};

μ – dynamic viscosity of water, kg m^{-1} s^{-1};

e – void ratio which is calculated as:

$$e = \frac{\o}{1-\o}$$

where:

$\o$ – dimensionless porosity.

The 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), however during the bottom liner or top capping construction compaction is commonly, due to numerous reasons, necessary. Compaction, as a result of shear processes, is a deformation process causing increase in the bulk density and decrease in the porosity caused by internal or external loads, which cause rearrangement of soils particles. Soils as porous media undergo transformations when external stress exceeds the internal soil strength defined by the pre-compression stress value (e.g. Horn et al., 1995; Yavuzcan et al., 2005), rearranging spatial distribution of clods, aggregates and particles as well as removing fluids from the porous media. Thus, soil compaction causes changes in pore shapes and diameters/size distribution, directly affecting resultant value of hydraulic conductivity, which, in turn, is controlled by the size, shape and connectivity of microscale pores modified during the compaction process (Ebina et al., 2004).

However, the effects of the compaction process on hydraulic properties (including hydraulic conductivity) of clays are not uniform. There were numerous cases reported in which the resultant saturated hydraulic conductivity after compaction varied, even by several orders of magnitude, in relation to clay soil composition and molding conditions (e.g. Lambe, 1954; Mitchell et al., 1965; Benson et al., 1994; Benson and Trast, 1995; Rowe et al., 1995; Zhang et al., 2006; Whalley et al., 2012; Bello, 2013; Widomski et al., 2015a).

It was observed that the saturated hydraulic conductivity of compacted clay soils/substrates depends greatly on the compaction effort, molding water content and dry bulk density achieved during compaction (Benson et al., 1994; Benson and Trast, 1995). The specimens compacted at higher initial water content/saturation reach lower value of saturated hydraulic conductivity. Benson et al. (1994) reported, which was proved in numerous publications, that hydraulic conductivity is sensitive to the values of Atterberg limits and particle size distribution. Soils and substrates of high clay or fine (clay+silt) particles and clay minerals content and more plastic, of higher liquid limit or plasticity index achieve lower hydraulic conductivity. Values of the Atterberg limits are related to the clay content and mineralogy of tested soil, so increase in the clay content or presence of active clay minerals led to decrease the size of microscale pores, thus reduction of hydraulic conductivity should be expected (Benson and Trast, 1995). Specimens compacted at high water contents, wet of optimum (reflecting maximum bulk density after compaction), on the "wet" side of Proctor curve, where water flow is controlled by microscale pores show lower hydraulic conductivity than samples compacted at lower initial saturation, on the left, "dry" side of Proctor curve, dry of optimum, due to greater remolding of clogs, elimination of large interclod voids and preferential reorientation of clay particles (e.g. Lambe, 1958; Mitchell et al., 1965; Benson and Trast, 1995). So, in short, specimens compacted dry of optimum would have greater hydraulic conductivity than specimens of the same substrate, compacted wet of optimum, which would present relatively low hydraulic conductivity (Bello, 2013). Compaction affects also water retention characteristics of soil, as water retention curves are more sensitive to compaction effort than to variable molding water content, however strong field variations are possible (Miller et al., 2002; Zhang et al., 2006). Therefore, saturated hydraulic conductivity should be correlated with other natural properties of clays by proper and careful selection of molding water content, due to different results of compaction and unstable behavior of clays in relation to variable saturation, thus, design of the sustainable CCL should be based on the data collected for each particular type of tested soil or substrate.

After landfill construction, CCLs in contact with chemical leachate and during prolonged exposure to elevated temperatures should provide an adequate hydraulic performance. Aldaeef and Rayhani (2014) found that landfill temperature has a noticeable effect on hydraulic performance of CCL, because after 75 days of exposure to constant heat of 55 C degree (comparable to temperatures noted inside waste body, see Hanson et al. (2010) or Rowe and Yu (2010)), hydraulic conductivity of tested CCLs specimens increased by 2 or 3 times due to the decrease in permeating liquid viscosity. On the other hand, during the same experiment it was observed, that after initially increased hydraulic conductivity of CCLs versus leachate, the prolonged time of exposure to 75 days resulted in the decrease in saturated hydraulic conductivity, reaching even one order of magnitude for room temperature, probably due to clogging of pore voids in the soils (Aldaeef and Rayhani, 2014).

2.4.2. Swell-shrink properties

Fine textured soils/substrates like clays, and also 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; Izdebska-Mucha and Wójcik, 2013). Expansive soils are able to increase their volume or to swell when saturated and to reduce their volume, or to shrink, when dewatered (Basma et al., 1996). Thus, clays undergo intense swelling and shrinkage processes resulting in non-rigid volume conditions caused by change in effective stress (e.g. Jones and Hobbs, 2005; Gebhardt et al., 2012). Volume change of clays is controlled by physic-chemical properties of constituent clay minerals (Taylor and Smith, 1986). Both swelling and shrinkage are generally correlated to plasticity of clays and, in addition to soil characteristics, mineral composition, particle size distribution and type of cations in clay matric (e.g. Kalkan, 2011; Izdebska-Mucha and Wójcik, 2013).

Swelling, as the capability to increase soil specimens volume, was related to properties of clay minerals, among which, the greatest ability to swell was observed for Na-smectite (up to 1400–1600%) and Ca-smectite (65–145%). The remaining clay minerals groups showed less susceptibility to swelling, i.e. illites 60–120% of free swell and kaolinite 5–60% (Taylor and Smith, 1986). Swelling clays consist of negatively charged aluminosilicate layers bonded together by cations. The ability to absorb water between the layers is the most characteristic property of the expansive clays, resulting in significant repulsive forces and clay expansion (Hensen and Smit, 2002). The molecules of absorbed water are positioned in the center of the clay minerals interlayer, and water oxygen orientates towards counterion, for example sodium, while the water hydrogen atoms are bonded to the clay surface oxygen atoms. Thus, due to the increase in water vapor pressure the clay swells. Further, water molecules position themselves in favorable position versus counterions for full hydration in the interlayer plane (Hensen and Smit, 2002). Swelling may be divided into three stages including: i) absorbing of water and expanding, initially at the surface of the clay, ii) accelerated swelling due to large suction matrix and iii) slow swelling, with pores gradually filled with water (Lu et al., 2013).

Swelling of clays is dependent on several factors including mineral composition, particle distribution, Atterberg limits etc. Under the same compaction effort the final swelling of clays decreases with increased molding water content (e.g. Lu et al., 2013; Widomski et al., 2015a).

Generally, despite the fact that both swelling and shrinkage phenomena are mutually dependent, especially in cases of clays of significant illites content, shrinkage poses greater threat than swelling (Chen, 1988). The same may be stated about the influence of swelling on landfill durability.

Shrinkage, the decrease of expansive soil or substrate specimen volume, is caused by subjecting the soil specimen to dehydration (Peng et al., 2006). Drying of soils, resulting in shrinkage, is caused by the evaporative flux from soil surface and most of the drying strains occur in the saturated, initial phase of drying. The mechanism of shrinkage is based on the suction-induced contraction of the pore vessels and the rate of water removal and rate of shrinkage is controlled by evaporative and permeability properties (Hu et al., 2013). The process of water evaporation from soil specimens, leading to shrinkage was divided by Tang et. al (2011b) into three parts: i) a constant rate of water loss from specimen remaining saturated, ii) falling rate zone initiated by air entry pressure, iii) final, stabilized zone, where desiccation does not result in any further water loss.

Shrinkage may be divided into four stages: i) structural shrinkage with strongly increased rigidity of the soil pore system, ii) normal (proportional) shrinkage caused by desiccation when small voids are being drained and the considerable volume loss is proportional to water loss, iii) further desiccation leading to residual shrinkage of lesser volume loss, iv) zero shrinkage, close to complete dehydration (e.g. Reeve and Hall, 1978). Generally, volumetric shrinkage depends on numerous characteristics of soils, including mineralogical composition, particle size distribution, texture and structure, available exchangeable cations and range of water content (and equivalent soil suction) for which shrinkage takes place. The critical water content is in the range between the upper limit less than full saturation and lower limit less then shrinkage limit (e.g. Izdebska-Mucha and Wójcik, 2013; Habib, 2013). Thus, on the whole, soils of high plasticity are highly prone to shrinkage (Puppala et al., 2013). Moreover, shrinkage properties of compacted fine soils, including clays, are also highly dependent to molding water content (Tay et al, 2001; Habib, 2013; Lu et al., 2013; Widomski et al., 2015a). For the same compaction effort and the same soil or substrate specimens, the increase in molding water content results in the increased shrinkage. Shrinkage is definitely larger for specimens compacted wet of the optimum of Proctor curve (e.g. Tay et al., 2001; Puppala et al., 2013; Widomski et al., 2015a), thus specimen compacted close to saturated conditions may be expected to show the greatest magnitude of shrinkage. The explanation of the above was presented e.g. by Lu et al. (2013). The thickness of the hydrated soil film and spacing between soil particles increases with increased water content, thus ample space for soil shrinkage is provided. The adhesive forces between clay particles and the effective stress of soil decreases with the increase in water content, thus allowing it to shrink. Additionally, various molding water contents result in different microscopic structures of compacted clay.

Shrinkage of non-rigid soils may be divided into two types or components, horizontal and vertical. Vertical shrinkage results in soil subsidence, while horizontal shrinkage component produces cracks, highly dangerous for the sustainability of sealing capabilities of the compacted clay liner (Peng et al., 2006). Vertical shrinkage is usually dominant during the first phases of structural shrinkage. Then, in relation with further dehydration of clay specimen, isotropic shrinkage is being observed. Finally, in many cases, due to extending desiccation, the dominant horizontal shrinkage appears (e.g. Peng et al., 2006; Gebhardt et al., 2012). Most of the shrinkage induced cracks appear during the phase of constant evaporation loss, when soil/substrate specimen is still saturated (Tang et al., 2011b).

Due to the transformed pore system, accompanied by desiccation cracks created during shrinkage, the physical and hydraulic properties are affected, including pore size distribution, water retention capabilities and saturated and unsaturated hydraulic conductivity (Gebhardt et al., 2012). Hydraulic conductivity of soils with cracks may be greater even by several orders of magnitude in relation to uncracked soils of the same type (e.g. Boyton and Daniel, 1981; Albrecht and Benson, 2001). For example, He et al. (2015) reported for K_s measured for tap water 25-fold increase for compacted natural clay and 5.7-fold increase for the bentonite modified clay liner, both compacted at wet of optimum and then dried, before the experiments.

Reduction in overall compacted soil/substrate strength and stability, increase in its compressibility and created pathways for fluids transport are the main negative results of cracking for compacted clay liner (e.g. Yesiller et al., 2000).

Despite the fact that according to Mitchell (1993) cracking is controlled by the amount and type of clay minerals present in drying soil or substrate, water is an important factor in the stress changes of clays, because water phase plays the role of stabilizer for soil particles by water menisci forces between them (Baumgartl et al., 2004). The pressure of pore water affects, through the rearrangement of particles in the clay layer, the resulting effective stress and the long-term internal rigidity, as well as the hydraulic and pneumatic impermeability of the mineral liners. Water also changes friction forces among soil particles, affecting the stability of the system. In the case of unsaturated water conditions, the effective stress resulting from the water potential may be defined as tensile stress (Baumgartl et al., 2004), which increases with the decreasing water potential. When the tensile stress is greater than the tensile strength of the clay material, movement of the soil particles is possible and cracks appear, as the result of water loss to the atmosphere from the solid mass of soil specimen (Corte and Higashi, 1960). Cracks, significantly affecting soil strength and hydraulic properties, appear at the end of the saturation stage, or during an early stage of desaturation (Chertkov, 2007; Hu et al., 2013). Presence of cracks significantly modifies transport processes in soil, leading to preferential flow and faster movement of gas, water, including increased infiltration rate, as well as solutes and particles (Bronswijk, 1990; Jameson et al., 2001; Allaire et al., 2009; Tang et al., 2011). Cracking can also influence evaporation during the dry periods, as inner layer of soil is being exposed to air (Tang et al., 2011).

Generally, intensity of cracking is affected by content of fine (clay+silt) particles in the shrinking soil/substrate creating pores of small dimensions leading to significant suction and water content and resulting in negative water suction pressure. The greater value of fines content and the greater water content applied, the higher value and changes of water suction pressure and higher amounts of cracking may be observed. On the contrary, with the decreased fine particles content, lower cracking appears (Holtz and Kovacs, 1981; Mitchell, 1993; Yesiller et al., 2000). To avoid intense cracking the clays were also sometimes suggested to be compacted at low water contents, dry of the optimum of Proctor curve, where shrinkage potential is definitely lower – however intense swell may be expected for the low values of molding water content (e.g. Daniel and Wu, 1993; Yesiller et al., 2000; Tay et al., 2001; Widomski et al., 2015a). Due to mineralogy of natural clays, presence of highly active minerals such as smectite and vermiculite increases the intensity of cracking. Intensity of cracking may be reduced by addition of coarse-grained material to soil/substrate, however it may, to some extent, change the other hydraulic and engineering properties of soil (Klepke and Olson, 1985; Yesiller et al., 2000). The tests of hydraulic conductivity of various mixed clay-sand compacted specimens performed by Ebina et al. (2004), covering local Japanese sands mixed with 16 different clays (including purified bentonite, montmorillonite, ion-exchange bentonite, mica-montmorillonite and Ca-montmorillonite), showed in most cases the possibility of reaching considerably low values of K_s by these substrates, i.e. in the range 10^{-10}–10^{-12} m s^{-1}. Thus, it is possible to obtain the clayey substrate of the required sealing capabilities, and, due to coarse particles content, limited shrinkage.

2.4.3. Cyclic drying and wetting

Swelling and shrinkage are irreversible processes, soils or substrates specimens once swelled or shrinked are generally unable to return to their initial characteristics (Holtz and Kovacs, 1981). Cyclic swelling/shrinkage involves the continuous process of clays swelling when saturated, then shrinking (partially or fully) when desiccated, than again being wetted to swell, dehydrated to shrink etc. etc. (Basma et al., 1996). According to numerous studies, each cycle of drying and rewetting changes swelling and shrinkage properties of clays and the state of equilibrium is being achieved after 3^{rd} – 5^{th} cycle, when changes in expansivity of clays are being stopped (e.g. Chen et al., 1985; Basma et al., 1996; Baumgartl et al., 2004; Dörner et al., 2009; Tang et al., 2011a; Fernandes et al., 2015; Widomski et al., 2015a). Both the swelling pressure and swelling potential decreases with the increasing number of wetting-drying cycles (Kalkan, 2011). Cracks, once established, usually in locations of low cohesion, are always present in the specimen, even after rewetting and swelling of soil (cracks in many cases may be closed due to well known self-healing phenomenon, but the structure of soil is weakened), as long as no dynamic energy is introduced to the soil structure and no additional molding takes place (Yesiller et al., 2000; Baumgartl et al., 2004; Tang et al., 2008). Shrinkage caused by drying during the first cycle causes irreversible changes in clay fabric (Yesiller et al., 2000; Tang et al., 2008) because particles bonds may be permanently broken, significantly weakening the soil. Rewetting causes further weakening of the rearranged structure of soil by addition of water, than subsequent drying will cause another changes related to shrinkage. Each drying and wetting cycle, especially in case of high plasticity clays, deepen the cracked zone leading to progressive reduction of bulk shear strength of the clay and affecting the hydraulic conductivity (Othman et al., 1994; Rayhani et al., 2008). The surface of soil undergoing cyclic wetting and drying becomes more fragmentarized and covered by the increasing short crack segments with the increase in the swell and shrinkage cycles. Surface desiccation cracks become also more and more irregular and coarse (Tang et al., 2008).

Propagation of desiccation cracks for clay specimens was described in details by Tang et al. (2008, 2011a). During the first drying stage water evaporation was composed of a constant rate zone and decreasing rate zone, the final observed cracks pattern, after reaching the shrinkage limit, was dominated by polygon clods and smooth cracks network. Then, during the second wetting phase, added water resulted in sudden collapse of the clods and the desiccation cracks from the previous drying stage were closed but the network of new microcracks appeared on the surface and divided the clods into smaller aggregates. The second wetting stage generally led to irreversible and significant rearrangement of clay particles and pore network. After the second drying phase, the observed specimens' homogeneity decreased, shapes of clods were more irregular with large amounts of inter-aggregate pores and cracks were also more ragged. As a result, the bonds between new aggregates were broken very quickly during the following wetting stage, without the creation of new microcrakcs. The equilibrium stage was achieved during the following several cycles, the influence of the next wetting-drying cycles on cracks development was insignificant (Tang et al., 2008, 2011a). According to Tang et al. (2008) the geometrical structure of cracks is dependent on temperature, thickness of soil layer, wetting-drying cycles and soil/substrate particle distribution, especially fine particles content.

According to fundamental studies reported by Basma et al. (1995) cyclic swelling of clays results in a gradual destruction of the original contacts in clay structure and reconstruction and reorientation of structure of large micro-scale aggregates by their disorientation. Thus, change in the expansion behavior in relation to increased number of drying and wetting cycles is observed. The character and value of changes in expansivity depend on the initial structure of the clay and the character of its structural bonds. Moreover, decrease in expansive behavior and reduced water retention capability after several cycles of drying and rewetting were observed when clays were alternately wetted and partially dried to the partial shrink (e.g. air dry). On the contrary, an increase in swelling characteristics was observed when clay specimens were cyclicly wetted and fully dried to full, maximum shrink, in this case a horizontal clay particles orientation was noted. The above may be connected with decrease and increase in voids in partially and fully dried clay specimens (Basma et al., 1995).

Swelling and shrinkage processes also results in cracking and changes in unsaturated and saturated hydraulic conductivity. The relation between number of drying-rewetting cycles was reported. Number and size of cracks as well as hydraulic conductivity of specimens increase with the growing number of swell-shrink cycles.

The increase in cracking and resultant increase in the hydraulic conductivity of cracked compacted clays are also related to molding water content (e.g. Baumgartl et al., 2004; Lu et al., 2013; Widomski et al., 2015a). Each cycle of drying, due to reduced water potential, is moving soil particles to position of lower inner energy to stabilize the soil structure by higher friction forces and contact bonds between soil particles. Thus, each cycle of drying and rewetting causes decrease in the void ratio and increase in the bulk density as well as increase in hydraulic conductivity due to cracking and destruction of initial structure of compacted clays as specimens of high well-shrink capabilities (Baumgartl et al., 2004; Gebhardt et al., 2012). So, drying and rewetting, cyclic, partial or total, which is possible during the long-term performance of liners exposed to variable atmospheric conditions, may also change the ability of the clay to undergo vertical and volumetric deformations (e.g. Tripathy and Rao, 2009), as well as considerably affect its hydraulic properties, (Baumgartl et al., 2004; Pires et al., 2005; Seguel and Horn, 2006).

Generally, significant changes of hydraulic properties may be expected after several cycles of drying and wetting. According to Albrecht (1996) large increase in the K_s was observed for high plasticity fine soils compacted wet of optimum after wetting and drying cycles. On the contrary, lower changes after several shrink-swell cycles were noted for specimens compacted at dry of optimum water contents. The difference was assessed as the result of significant desiccation cracking for specimen compacted wet of optimum. The hydraulic conductivity before drying-wetting tests for low plastic clays tested was at a similar level for both dry and wet sides of Proctor curve, while after the first drying and wetting cycle it increased and remained nearly constant (Albrecht, 1996). Hydraulic conductivity of cyclically dried and wetted compacted clay specimens was strictly correlated with cracks formation development (Omidi et al., 1996) and according to Brian and Benson (2001) the increase in the K_s value could reach even the value of three orders of magnitude. In case of low plasticity clay substrates limited changes in hydraulic conductivity (up to 10 or 20 times for soils of plasticity index of the range 15–35%) were related to almost total absence of cracks, or their limited number, cracks with tight opening, prone to closure, also by clogging by particles eroded during permeation (Rayhani et al., 2008).

Yesiller et al. (2000) reported on the collection of previous observations of drying crackings of compacted clay liners operating in various conditions in the field and exposed to natural cycles of drying and wetting. The noted significant cracking cases were observed during landfill construction, on in-situ test plots and at the operating landfills. The reported cracks varied from 13–25 mm in width and 0.3 m depth for a liner during construction, over 10 mm and 0.3 m for an operating landfill and up to 13 mm width and 0.2–0.25 m for testing plots. There were even cracks reaching the depth of 1.0 m reported, the entire thickness of CCL (Yesiller et al., 2000).

During the construction of a liner, or as the result of multilayered liner failure, CCL may be exposed to the direct daily thermal changes causing increased desiccation. Aldaeef and Rayhani (2015) during the performed tests observed that increase in hydraulic conductivity of up to one order of magnitude was noted for CCL utilizing low plasticity clays (PI<10%) after 30 cycles of simulated thermal changes (8 h heating in 55 C deg, 16 h cooling in 22 C deg.). The studied substrates of higher plasticity (PI=25% and PI=37.5%) did not show the significant changes of hydraulic conductivity. However, the performed tests showed that overlaying the CCL with soil cover layer minimized the effects of the applied daily thermal cycles and the tested compacted clay liners were able to sustain their hydraulic conductivity even after exposure to 60 applied thermal cycles. It was also found that application of geomembranes to temporarily cover CCL during the construction period, in order to avoid influence of wetting-drying cycles was problematic due to the dark color of geomembrane, enhancing the effects of solar radiation (Aldaeef and Rayhani, 2015).

Thus, the long-term self-sustainability of a clay sealing layer may be questionable, as it is either exposed to atmospheric conditions or threatened by desiccation, caused by the low water retention capacity of drainage or cultivation layers, as well as a significant slope inclination that results in considerable lateral flows. There are still unanswered questions considering relations between the most important hydraulic and geotechnical properties of clayey soils and substrates and sustainability of compacted clay liners allowing the proper selection of mineral material for compacted earthen liner leading to its long-term sustainability.

2.5. Summary of literature review

The performed literature review, based on over 150 peer reviewed publications, technical manuals, national and international guidelines and standards, showed the significance of sustainable landfilling problem in the contemporary sustainable municipal solid waste management all over the world. Despite the fact that there is a clear increase in recycling and re-use of wastes as well as in the other methods of waste volume and mass reduction, including incineration, landfilling remains and will remain a significant method of final municipal wastes disposal. Landfilling in the developed, high income countries is being reduced to numbers required by the amount of residual wastes, which cannot be disposed by other methods. As it was presented before, in the mid-income countries, even including Europe and selected members of the European Union, landfilling, has still a significant share in the total final disposal of municipal solid wastes.

However, in the low income developing countries of many continents, suffering significant health, environmental and social threats related to unsatisfactory municipal waste management and encountering several serious problems with implementing sustainable waste management, including safe final disposal of wastes, landfilling seems to be the most suitable option due to its long-term sealing capabilities, limited impacts on the environment and public health, relatively inexpensive and simple construction, which may be based, partially or totally, on the local materials, workmanship, technologies, services and know-how. Thus, sustainable landfilling means the safe disposal and subsequent degradation of waste within a landfill, in the shortest possible time-span, with minimal damage to the environment and local societies, by the most financially efficient method available.

In the developed high-income countries of North America, Europe and Asia, where modern technologies, services and know-how are available, also financially for disposal sites, landfills, based on compacted clay liners, supported with geomembranes, geotextiles and geosynthetics, with social support, are orientated towers sustainability. In developing countries of low economic income, where there are no organized productive municipal waste management systems, covering collection, transport, treatment and disposal, where uncontrolled waste dumping poses direct threats to public health and environment, direct application of materials and methods from the developed countries would not ensure introduction of sustainable waste management and sustainable disposal in landfills.

However, as it was discussed, modern materials of landfill sealing which require careful installation by skilled workers, with full observance of the precise technical requirements and know-how to present their full capabilities, may pose threats to landfill sealing in case of improper installation and may affect slope stability in case of inaccurate landfill design and may be too expensive (as the investments and operation control cost) for local communities from developing countries from all around the world. Thus, their application in many cases may be questionable from the point of view of sustainability. So, in many cases compacted clay liners, inexpensive, relatively easy in construction and utilizing local materials, technologies and workmanship may fulfill the idea of sustainable landfilling.

Compacted clay liners, as a sealing element of the multilayered liner, constructed of clayey soils or substrates, containing significant amounts of clay minerals, such as smectites, illites, kaolinites or chlorities, allow to achieve a very low hydraulic conductivity after compaction, far below commonly required $1 \cdot 10^{-9}$ m s^{-1}. Such a low hydraulic conductivity is required to prevent contamination of surface water and groundwater through leachate, and pollution of soil by direct contact with wastes or leachate in the long-term horizon of landfill operation time duration, reaching even hundreds of years. However, the results of compaction as a shear process depend on the applied compaction energy and the molding conditions, including the water content. Thus, for compaction of the same substrate, of constant particle size distribution and mineralogy the resultant saturated hydraulic conductivity may be distinctly different, even by several orders of magnitude. Generally, the higher applied molding water content, the lower final hydraulic conductivity of compacted clay material. Thus, several guidelines suggest application of compaction wet of Proctor optimum for CCL construction, for molding water content greater than optimum, allowing to obtain the maximum density after compaction.

However, clays are expansive mineral materials, showing a tendency to changing their volume as the effect of changes in moisture content. During water content increase they swell, while during dewatering (desiccation) they shrink. Swelling and shrinkage potentials of compacted clays are directly related to the applied molding water content. Swelling potential decreases with the increase in molding water content. Shrinkage potential, to the contrary, increases in relation to increasing molding water content. Thus, for mineral soils/substrates compacted wet of optimum swelling potential is decreasing but the shrinkage capabilities are significant.

Shrinkage of expansive clays, containing significant amounts of swelling clay minerals, is connected with cracking, which in turn affects their physical and hydraulic properties, including pore size distribution, water retention capabilities as well as saturated and unsaturated hydraulic conductivity. Moreover, swelling and shrinkage, caused by consequent cycles of wetting and drying of compacted clay liners are irreversible and after several repetitions may cause the destruction of compacted particles structure, significantly increasing the hydraulic conductivity of CCL, thus, drastically reducing its sealing capabilities. Swelling-shrinkage characteristics, cracking and behavior under cyclic drying and rewetting are related to particle distribution, mineralogy, compaction effort and water content and, last but not the least, plasticity of clays. High plasticity clays, containing significant share of fines particles, reaching very low K_s values after compaction, demonstrate significant shrinkage characteristics and are clearly prone to desiccation cracking, especially after several cycles of swelling and cracking. The greater fines particles content and the greater molding water content applied, the higher cracking may be observed, also after subsequent cycles of swelling and shrinkage. Thus, again, increase in saturated hydraulic conductivity, caused by drying and rewetting, is specially significant on the “wet” side of Proctor curve, wet of optimum, where clayey soils or substrates are frequently suggested to be compacted.

Meanwhile, numerous guidelines presenting more or less simplified or developed criteria for clay material selection, applicable for compacted clay liner constructions, generally allow, or even in some cases favor, high plasticity clays of significant content of fine (clay+silt) particles. Such soils or substrates allow to obtain a very low hydraulic conductivity after compaction but they also present a significant shrinkage potential and are prone to increase in saturated hydraulic conductivity after cycling swelling and shrinkage. Thus, the long-term sustainability of compacted clay liners utilizing high plasticity clays is at least questionable. In this situation, there arise reasonable doubts concerning limited (according to numerous guidelines) applicability of low plasticity clayey materials containing more coarse particles in compacted clay liner constructions. Such materials should make it possible to obtain the required low value of saturated hydraulic conductivity after compaction, at the same time presenting lower shrinkage potential and higher resistance to cyclic drying and rewetting. It is also interesting to note how available guidelines for clayey materials selection approach the present described disadvantages of expansive materials, possibly reducing sustainability of landfill liners. Concerns also refer to the practical performance, i.e. hydraulic efficiency, of CCLs of top cover of both, temporal or final, top covers of landfill capping and bottom liners utilizing various types of clayey materials, compacted at both sides of Proctor curve, dry of optimum and wet of optimum. Such analyses should answer the question how hydraulic characteristics of clay materials influence the sustainability of compacted clay liners.

3. Aim and scope of dissertation

The main aim of this dissertation was to determine the influence of various parameters of the selected clay substrates on the sustainability of a compacted clay liner as a part of the top and bottom sealings of a municipal waste landfill.

Additionally, the set of criteria allowing the selection of earthen material for construction of a sustainable compacted clay liner for municipal waste landfill was developed.

The scope of the dissertation covered several objectives, allowing to achieve the previously described aim of the studies: i) field and laboratory measurements of general properties of the tested clayey substrates, strength and geotechnical parameters, Atterberg limits, hydraulic conductivity in natural conditions and after compaction at various water contents, swelling, linear and volumetric shrinkage and hydraulic conductivity after several cycles of drying and rewetting; ii) numerical modeling of hydraulic performance for multi-layered top cover of municipal waste landfill meeting requirements of the Polish national standards, presented in Journal of Laws from 2013 item 523, and utilizing the tested clay substrates of various plasticity, compacted wet and dry of optimum; iii) assessment of the hydraulic efficiency of bottom liner meeting the national Polish standards and utilizing six tested clays, compacted wet and dry of optimum; iv) development of criteria proposal for earthen material selection for compacted clay liner construction focused on liner sustainability.

4. Materials and methods

The presented studies covered measurements of saturated hydraulic conductivity, retention and swell-shrink characteristics, as well as geotechnical properties of six clay materials of Lublin Upland (Wyzyna Lubelska) compacted according to the standard Proctor method at various water contents, both wet and dry of optimum. The studies were supported by the numerical assessment of hydraulic efficiency of compacted liners constructed of the tested clays, according to Polish and European standards. The performed investigations covered i) the determination of the basic characteristics of the six considered clay materials, including physicochemical and geotechnical characterization of both; ii) measurements of their saturated hydraulic conductivity *in situ*; iii) laboratory measurements of saturated hydraulic conductivity of the materials compacted by the standard Proctor method at various water contents; iv) measurement of water retention characteristics for six tested substrates under natural conditions and after compaction; v) assessment of swelling and shrinkage potential of the materials following Proctor compaction at various water contents; vi) measurements of saturated hydraulic conductivity of the considered materials following one, two, and three cycles of drying and wetting; vii) numerical assessment of the hydraulic efficiency of a sustainable liner constructed of the tested clay materials.

The tested clay materials used in the presented studies were sampled in the six locations, including Bychawa, Lazek Ordynacki, Pawlow, Mejznerzyn, Markowicze and Gawlowka, all Lublin Voivodeship, SE part of Poland. The precise locations of all sampling sites were as follow:

- Bychawa, approx. 30 km S from Lublin, 51°00′57″N 22°31′58″E;
- Lazek Ordynacki, munipalicity Janów Lubelski, approx. 90 km S from Lublin, 50°38′19″N 22°17′10″E;
- Pawlow, munipalicity Rejowiec Fabryczny, approx. 50 km E from Lublin, 51°08′46″N 23°12′44″E;
- Mejznerzyn, munipalicity Michow, approx. 50 km N from Lublin, 51°33′07″N 22°17′56″E;
- Markowicze, munipalicity Ksiezpol, approx. 100 km S from Lublin, 50°26′21″N 22°44′33″E;
- Gawlowka, munipalicity Michow, approx. 50 km N from Lublin, 51°31′27″N 22°24′53″E.

As far as it is known, neither of the clays were previously used or considered to be used as a material for hydro-isolation. The tested materials were sampled from the existing open cast mining pits, from the depth of approx. 0.6–1.0 m. They were subjected *in situ* to macroscopic description.

4.1. Field and laboratory measurements

4.1.1. General and geotechnical characteristics

The determination of basic and geotechnical characteristics of the tested six clay materials was performed within the frame of the Polish Ministry of Science and Higher Education project No. NN 523 755040.

The particle size distribution of the tested substrates was determined with the standard sedimentation method (PN-B-04481:1988). The particle size distribution following the saturated hydraulic conductivity tests was measured with the laser diffraction method, by means of Mastersizer 2000 laser diffractometer, manufactured by Malvern, UK. The application of the two different methods for the measurement of particle size distributions was dictated by the fact that the obtained results differed significantly one from another (e.g. Ryżak and Bieganowski, 2010; Bieganowski et al., 2013). Therefore, the sedimentation method was used to determine the particle size distribution of the investigated materials, whereas the laser diffraction method allowed to show the subtle differences in the particle size distribution (which was impossible in the sedimentation method). Quantification of subfractions of clay particles were also possible due to application of the laser diffraction method.

Solid particle density was measured in le Chatelier flask and by the air pycnometer according to Langer, Eijkelkamp, The Netherlands, while the gravimetric water content was obtained with the standard weight method (ASTM C566-13).

The microscopic analyses of the tested materials' structure were performed within NN 523 755040 project with the Quanta SEM 200 FEG scanning electron microscope by FEI, USA. Qualitative mineralogical composition of tested materials was determined by x-ray diffraction (XRD) method using Panalytical X'Pert APDm Netherlands with PW 3020 goniometer and Cu lamp with graphite monochromator. Semi-quantitative composition of the raw sample and of the clay fraction was determined with the differential thermal analysis (DTA) method using TG-DTA/DSC Setsys 16/18 thermobalance, produced by Setaram, France. Specific surface area of the particles and micropores area were measured through the nitrogen adsorption method, using the ASAP 2020 Physisorption Analyzer by Micrometrics, USA. Cation exchange capacity (CEC) values were determined with the use of $BaCl_2$ and the atomic absorption spectrometry (ASA), as described by Derkowski et al. (2006).

The Atterberg limits, such as plastic limit and liquid limit of the studied six clay materials, were determined within the frame of No. NN 523 755040 project through standard procedures (PKN-CEN ISO/TS 17892-12).

Plasticity index was calculated as difference between the liquid limit and plastic limit:

$$PI = LL - PL$$

where:
PI – plasticity index, %;
LL – liquid limit, %;
PL – plastic limit, %.

Shrinkage limit was calculated according to formula (Wysokiński, 2007):

$$SL = 0.34 \cdot PL(1 + clay)$$

where:
SL – shrinkage limit, %;
$clay$ – clay fraction content, %.

The potential swell S, in %, based on Atterberg limits was calculated as follows (Seed et al., 1962; Bentley and Carter, 1991):

$$S = 60 \cdot k \cdot PI^{2.44}$$

where: k – dimensionless constant equal to $3.6\ 10^{-5}$.

Measurements of modulus of primary and secondary compressibility were performed within NN 523 755040 project in the 26-W70302 oedometer by Wykeham Farrance, ITL, India, according to PKN-CEN ISO/TS 17892-5 standard. Internal friction angle and cohesion were measured in DIGISHEAR shearing test apparatus by Wykeham Farrance, India, according to PKN-CEN ISO/TS 19892-10. Measurements were conducted in 60x60x60 mm boxes under consolidated drained test conditions, with undisturbed samples of natural water content, after preliminary sample consolidation, without the water outflow during the test (consolidated undrained test).

Soil resistance to penetration was determined within NN 523 755040 project by the field penetrometer Penetrologger, by Eijkelamp, The Netherlands. The 60 deg. cones of 3.3 cm^2 and 1 cm^2 area were used during the penetration tests. The penetrometer was calibrated for measurement depth of 0-20 cm and load of 0-100 kg. Accuracy of applied equipment was ±1%.

4.1.2. Proctor tests and hydraulic conductivity measurements

The *in situ* saturated hydraulic conductivity of the tested materials was measured by the GeoN falling head field permeameter for fine grained soils, made by Geo Nordic, Stockholm, Sweden. The applied permeameter is advised to be used for soils of hydraulic conductivity lower than $1 \cdot 10^{-7}$ m s^{-1}, while the lower limit of BAT probe applicability is $1 \cdot 10^{-12}$ m s^{-1} (BAT, 2006). The outflow falling head method of measurements for unsaturated soils conditions was applied. The probe was inserted at the depth of 50–70 cm below soil surface level, into exposed layer of the tested clay (see Fig. 4.1.). Measurements were repeated in three points for each testing location.

Fig. 4.1. *In situ* K_s measurements with GeoN falling head field permeameter applied at various test sites

Saturated hydraulic conductivity of the six tested clays materials in laboratory conditions was measured in falling head permeameter specially constructed for this purpose in the NN 523 755040 project. The applied permeameter is presented in Fig. 4.2. The measuring unit allows simultaneous permeability tests for the four 100 cm^3 soil samples in standard steel cylinders.

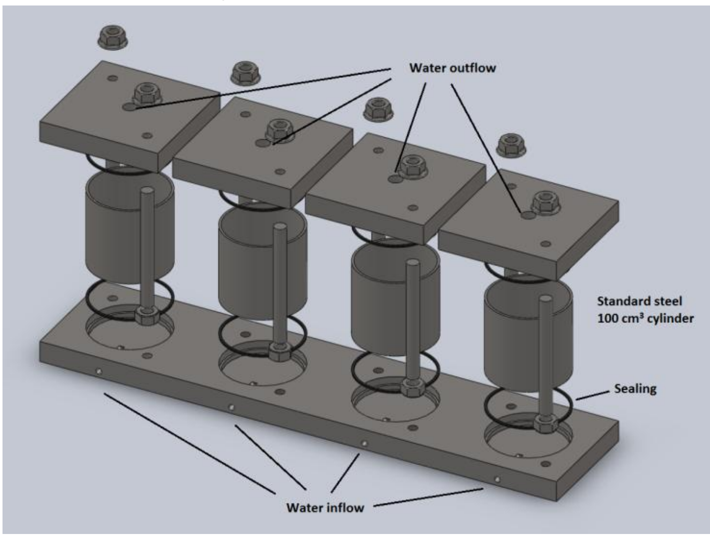

Fig. 4.2. Falling head water permeameter for 100 cm^3 steel cylinders of undisturbed samples

The main laboratory measurements of saturated hydraulic conductivity of the studied clay materials compacted by standard Proctor method at various water contents were performed in H-4145 falling head permeameters (see Fig. 4.3.) for compacted soils by Humboldt Mfg. Co, USA, according to ASTM D5856-95. The applied rigid wall compaction permeameter had diameter of 101.6 mm and height of 116.4 mm.

The tested materials were molded with the following water contents:

- Bychawa clay: 0.13, 0.15, 0.16, 0.17, 0.20, 0.22, 0.23, 0.25, 0.26 and 0.27 kg kg^{-1};
- Lazek Ordynacki clay: 0.14, 0.16, 0.17, 0.19, 0.20, 0.21, 0.22, 0.23 and 0.25 kg kg^{-1};
- Pawlow clay: 0.12, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.20, 0.22, 0.23, 0.24 and 0.26 kg kg^{-1};
- Mejznerzyn clay: 0.14, 0.17, 0.19, 0.20, 0.21, 0.22, 0.23, 0.24, 0,26, 0.27, 0.29 and 0.30 kg kg^{-1};
- Markowicze clay: 0.12, 0.13, 0.14, 0.15, 0.16, 017, 0.19, 0.20, 0.24 and 0.25 kg kg^{-1};
- Gawlowka clay: 0.08, 0.10, 0.11, 0.13, 0.14, 0.15, 0.18, 0.19 and 0.20 kg kg^{-1}.

Samples of the tested soils were prepared and compacted according to standards PN-B-04481:1988 and ASTM D698-12e2. The applied standard Proctor test with 24.5 N rammer dropped from a height of 305 mm allowed to obtain a compactive effort of 600 kJ m^{-3}. Three molds were formed for the each applied initial water content. None of the tested portions of clay materials was used again after compaction.

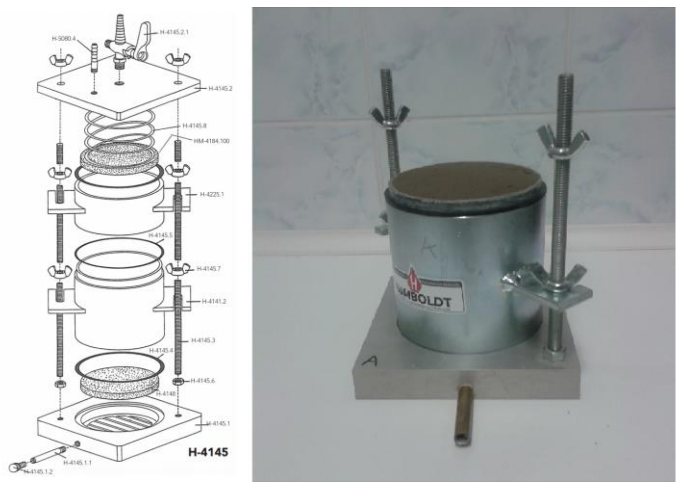

Fig. 4.3. Scheme and picture of H-4145 permeameter for compacted soils (manufacturer’s resources and own photograph)

According to permeameter operation manual, H-4145 construction, presented in Fig. 4.3. location of water stub pipes and air relief valve, the applied measurement units were supplied with water from top, according to the scheme presented below, accessible in literature and several standards (e.g. FM 5-513, 2000; Assaad and Harb, 2013) – see Fig. 4.4.

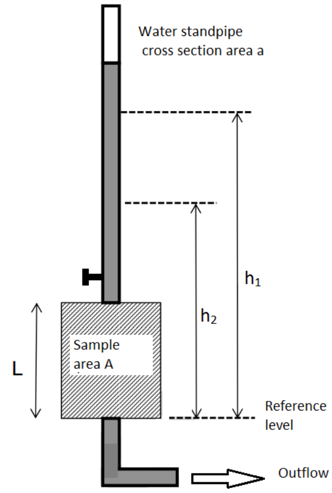

Fig. 4.4. Scheme of H-4145 laboratory application, modified after Assaad and Harb (2013)

The following equation was used to calculate saturated hydraulic conductivity for tested clay materials during the falling head method measurements (e.g. FM 5-513, 2000):

$$K_s = \frac{a \cdot L}{A_s \cdot \Delta t} \ln \frac{h_1}{h_2}$$

where:

K_s – coefficient of saturated hydraulic conductivity, m s^{-1};

a – water standpipe cross section area, m^2;

A_s – soil sample cross section area, m^2;

L – soil sample height, m;

h_1, h_2 – water level heights, m;

Δt – time duration required for lowering water level from h_1 to h_2, s.

Saturated hydraulic conductivity measurements in the rigid wall permeameters were performed until observation of the constant value of K_s.

4.1.3. Swell and shrink characteristics of compacted clays

After the laboratory measurements of saturated hydraulic conductivity, the swelling and shrinkage characteristics of compacted clays were determined in order to assess the swelling and shrinking potential of the tested compacted clays. Swelling characteristics were measured for saturated samples following the saturated hydraulic conductivity tests, directly in the applied molds of permeameter for compacted soils. The height of the sample for calculation of the swelling was measured using vernier caliper at 10 regularly distributed locations for each sample. Swelling index, *SI* in %, was calculated as follows:

$$SI = \frac{h_s - h_i}{h_i} \cdot 100\%$$

where:

h_s – height of swelled sample, m;

h_i – initial height of substrate specimen, after molding, before saturation, m.

Shrinkage of natural and compacted clays was measured in 100 cm^3 cylindrical samples, taken directly in situ or from the compaction molds, according to the methodology similar to that of Peng et al. (2007), Dörner et al. (2009) and Gerbhardt et al. (2012). Shrinkage of the cylindrical samples was measured by a vernier caliper with the accuracy of 0.05 mm in 8 selected locations (as repetitions), both for the diameter and the height. Afterwards, the measured dimensions were used to calculate two dimensionless shrinkage indicators, r_s and *COLE* (Grossman et al., 1968; Bronswijk, 1990), according to the following formulas:

$$r_s = \frac{\ln \frac{V_d}{V_s}}{\ln \frac{z_d}{z_s}}$$

where:

r_s – dimensionless geometry factor;

V_d, z_d – dry specimen volume, m^3 and height, m;

V_s, z_s – saturated specimen volume, m^3 and height, m;

$$COLE = \left(\frac{V_s}{V_d}\right)^{\frac{1}{3}} - 1$$

where:

COLE – dimensionless coefficient of linear extensibility;

V_d – dry specimen volume, m^3;

V_s – saturated specimen volume, m^3.

Dimensionless geometry factor r_s for vertical deformation should be equal to 1.0. The values between 1.0 and 3.0 are typical for the predominant vertical deformation, r_s=3.0 is for isotropic deformation, whereas the values of r_s greater than 3.0 are typical if the horizontal deformation is predominant. The values of the coefficient of linear extensibility (*COLE*) lower than 0.03 indicate a low shrinkage potential. The values between 0.03 and 0.06 are related to a moderate shrinkage potential. The values from 0.06 to 0.09 are typical for a high potential and the values greater than 0.09 indicate a very high shrinkage potential (Parker et al., 1977; Gebhardt et al., 2012).

Shrinkage and swelling potentials for all the applied values of molding water contents were also calculated as the differences between dry bulk density after compaction and dry bulk density following swelling and shrinkage (e.g. Bauer et al., 2001; Horn and Stępniewski, 2004).

Linear shrinkage tests for compacted clay materials were based on the popular standard bar linear shrinkage test method (e.g. BS 1377-1:1990; Kampala and Horpibulsuk, 2013). However, the method was modified to allow measurements of linear shrinkage of clay substrates compacted at various molding water contents. No shrinkage molds were used. The samples were cut directly from the compaction molds and cuboid slogs were formed (e.g. Dasog et al., 1988; Hu et al., 2013). Three slogs were cut from one mold. The linear dimensions of cut slogs were measured by the vernier caliper with the required several repetitions, the gravimetric water content was determined by weighing the sample. Then, the tested samples were allowed to air dry, first in room temperature approx. 20 C degree, next outdoors samples were exposed to the direct sunlight (Dasog et al., 1988), finally, they were dried in the oven in 105 C degree (e.g. Peng et al., 2007). The linear shrinkage (%) was calculated as follows:

$$LS = \frac{L_w - L_d}{L_w} \cdot 100\%$$

where:

L_w – length of the wet soil bar, m;

L_d – length of the dry soil bar, dried at 105 C degree, m.

4.1.4. Hydraulic conductivity after drying and wetting cycles

Additionally, in order to assess the sustainability of all tested clay materials which are likely to be used for liner construction, the compacted and saturated materials were sampled in standard 100 cm^3 steel cylinders, one cylinder was sampled from one compaction mold. All the samples were air dried at room temperature, approx. 20 C degree, and rewetted through capillary saturation. After each of the three cycles of drying and wetting, additional saturated hydraulic conductivity measurements were performed with constant or falling head method, see Fig. 4.5, (depending on the value of the measured parameter, above $K_s = 1 \cdot 10^{-5}$ m s^{-1} the constant head method was used) in a laboratory permeameter, produced by the former IMUZ (Instytut Melioracji i Uzytkow Zielonych), Lublin, Poland.

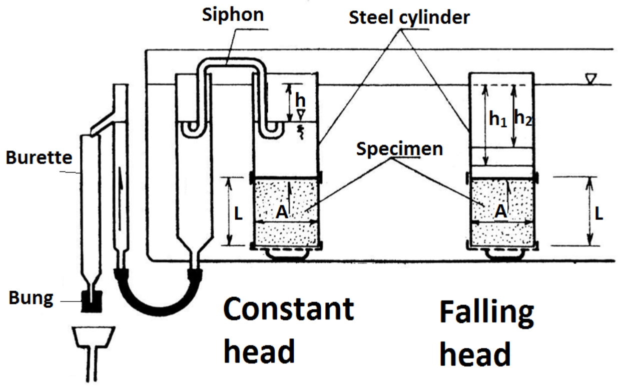

Fig 4.5. Scheme of constant and falling head method application in IMUZ permeameter, modified after Zawadzki and Olszta (1981)

The coefficient of saturated hydraulic conductivity was calculated in falling head method according to the following formula (Wit, 1967; Zawadzki and Olszta, 1981):

$$K_s = \frac{L}{\Delta t} \ln \frac{h_1}{h_2}$$

while K_s measured by the constant head method was calculated as follows:

$$K_s = \frac{L}{A} \cdot \frac{q}{h_w}$$

where:
q – water volumetric flow rate, $m^3\ s^{-1}$, $q=V/t$, V – volume read from burette, m^3, t – time, s;
h_w – difference of water table height between reservoir of the permeameter and cylinder containing soil sample, m.

4.1.5. Water retention characteristics

Water retention capabilities of the compacted clay materials were tested in pressure range to 1500 kPa (15 bar, 150 m H_2O) by the standard sand box (IMUZ, Lublin, Poland) and pressure chambers with ceramic plates by Soil Moisture, Santa Barbara, USA. The following pressure values were applied to the performed tests: 1, 2, 5, 7, 10, 50, 100, 500, 1000 and 1500 kPa. Changes in specimens volumes caused by dewatering were included in further calculations.

The results of water retention curve measurements were fitted in Stastistica, Statsoft, USA and verified by SWRC model (Seki, 2007) to the standard van Genuchten's formula (1980):

$$\theta = \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^m} + \theta_r$$

where:

θ_s – saturated volumetric water content, $m^3\ m^{-3}$;
θ_r – residual volumetric water content, assumed θ_r,=0, $m^3\ m^{-3}$;
ψ – soil water potential, cm;
α – water retention curve fitting parameter, cm^{-1};
n, m – dimensionless water retention curve fitting parameters, $m = 1\text{-}n^{-1}$.

Assumption of residual water content θ_r,=0, $m^3\ m^{-3}$, was based on SWRC calculations and several fundamental literature reports (e.g. Greminger et al., 1985; Wösten and van Genuchten, 1988; Wessolek et al., 1994) showing zero or very small residual water content for clays.

4.2. Materials and methods applied to numerical modeling

4.2.1. Input data

Numerical modeling of hydraulic efficiency of a top cover mineral liner constructed of the compacted tested clay materials, including water balance, lateral flows and seepage, was performed by FEFLOW, WASY-DHI, Germany modeling software (Diersch and Kolditz, 2002; Mazzia and Putti, 2006; Trefry and Muffels, 2007; Widomski et al., 2010, 2013). The developed two dimensional model represented a 10 m long section of mineral liner of 2 m thickness, developed according to the requirements of the up-to-date Polish and European standards (Journal of Laws from 2013 item 523; EU, 1999), consisting of three layers, from the bottom: the compacted clay sealing layer of 0.5 m thickness, the sand drainage layer of 0.5 m and the soil recultivation layer of thickness equal to 1.0 m. The size of developed model reflected the dimensions of commonly applied test sites or domains for field and modeling experiments (e.g. Yesiller et al., 2000; Wysokiński, 2007; Widomski et al., 2010; Narejo, 2013; Widomski et al., 2013; Safari et al., 2014).

To fully numerically test the hydraulic sustainability of the compacted clay liner, geomembrane between CCL and sand drainage liner was not included in the model, because its installation is usually optional, not obligatory, according to various national standards (e.g. EPA, 1993; EU, 1999). It was omitted also according to suggestions by IBT (Wysokiński, 2007).

The applied slope shape reflected the morphology of the selected part of the top cover of the experimental municipal waste landfill liner in Rastorf, Germany (Widomski et al., 2015b, 2015c). Soil of the recultivation layer in the developed model reflected the real materials sampled in recultivation layer tested in Rastorf.

The top surface of the modeled liner was assumed to be covered with perennial grass mixture. The prepared model consisted of 5965 nodes and 11549 elements. The developed finite elements mesh was presented in Fig 4.6.

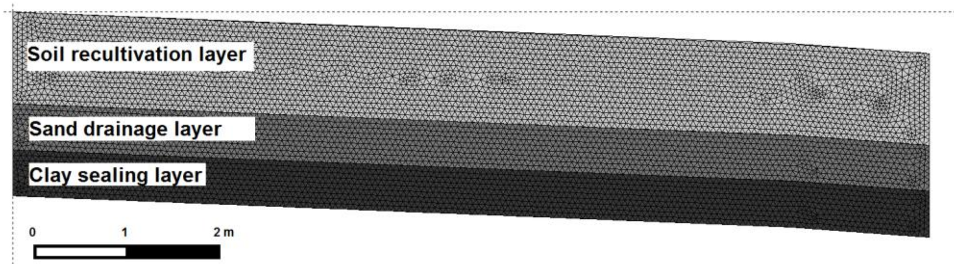

Fig. 4.6. Developed model of the selected section of municipal landfill top liner, modified after Widomski et al. (2015c)

Modeling in FEFLOW was adopted to this work concerning compacted clay substrates despite the fact that this software allows numerical calculations of rigid systems. The previous studies concerning water balance of landfill top cover system, both monitoring the soil moisture and pore water pressure as well as numerical calculations (e.g. Widomski et al., 2015b, 2015c), showed that a compacted liner normally performs in conditions of significant saturation or close to the state of full saturation, thus its water content may be similar to, or greater then, the suggested molding water content from the range $w_{opt}<w_f<1.2w_{opt}$. Moreover, numerical calculations were applied in this work not to authoritatively assess its sealing capabilities in the full range of saturation variability, including droughts, landslides, liner exposure to direct atmospheric conditions etc. etc., but to assess its hydraulic capabilities during the standard, typical, hydrologic year of weather characteristics close to mean for the selected relation.

Numerical calculations of the two dimensional water flow in porous media of variable saturation in FEFLOW were based on the standard forms of Darcy's and Richards' equations (Richards, 1931; Raats, 2001; Diersch, 2009):

$$\boldsymbol{q}_i = -\boldsymbol{K}_{ij} \frac{\partial h}{\partial x_j}$$

$$\frac{\partial h}{\partial t} = -\frac{\partial \boldsymbol{q_i}}{\partial x_i} \mp Q$$

where:

$\boldsymbol{q}_i$ – groundwater flux vector, m s^{-1};

h – water pore pressure head, m;

t – time, s;

$\boldsymbol{K}_{ij}$ – hydraulic conductivity tensor, i, j = 1, 2, m s^{-1};
Q – sink or source term, s^{-1}.

Mathematical description of water retention curve applied to simulations in FEFLOW was based on the model by van Genuchten (1980) in the form:

$$S_a = \frac{S_s - S_r}{[1 + (Ah)^n]^m} + S_r$$

where:
S_a – actual degree of saturation;
S_s – saturated degree of saturation, S_s=1;
S_r – residual degree of saturation, $S_r = 0$;
h – water pore pressure head, m;
A – fitting parameter, m^{-1};
n, m – dimensionless fitting parameters: $m = 1 - n^{-1}$.

Hydraulic conductivity of unsaturated soils K was calculated in the presented model according to formula by van Genuchten (1980):

$$K = K_s {S_e}^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2$$

where:
K_s – saturated hydraulic conductivity, m s^{-1};
l – fitting parameter: l = 0.5 (van Genuchten, 1980; Diersch, 2009; Iwanek et al., 2010);
S_e – dimensionless effective saturation defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}.$$

According to FEFLOW input data requirements, the maximum value of saturated hydraulic conductivity K_s (e.g. horizontal or vertical), the anisotropy factor as relation of lower to greater value of conductivity and the rotation angle are required (Diersch, 2009). Thus, the applied anisotropy ratio defines the value of the second element of the diagonal matrix presented below:

$$\boldsymbol{K}_{ij} = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix},$$

$$K_2 = a_r \cdot K_1$$

where:
a_r – dimensionless anisotropy ratio, assumed constant for saturated and unsaturated conditions;
K_1 – maximum value of saturated hydraulic conductivity.

Time duration of the performed simulation for each applied variant reflected the 365 days of hydrological year 2012, November 1, 2011 until October 31, 2012. The presented calculations were performed with the time step of variable length, automatically controlled by forward Euler/backward Euler time integration scheme with the maximum time step length limited to 0.01 day. The assumed convergence error applied to FEFLOW's Euclidian integral Root Mean Squared Error norm was equal to 0.001, while the adaptive mesh error was equal to 0.01.

Characteristics of the sand of the drainage layer and material of the recultivation layer assumed in the modeling, after Wildenshild et al. (1997) and Widomski et al. (2015b) are presented in Table 4.1. The isotropic hydraulic characteristics of clay and sand soil were established in the performed calculations due to previous reports considering hydraulic conductivity of compacted clays (e.g. Boynton and Daniel, 1985; Sadek et al., 2007) and the developed small scale model (e.g. Widomski et al., 2013).

Table 4.1. Substrate characteristics for drainage and cultivation layers assumed in the modeling

	Recultivation layer	Sand drainage
Saturated hydraulic conductivity (m s^{-1})	$2.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-4}$
Saturated water content θ_s (m^3 m^{-3})	0.29	0.37
Residual water content θ_r (m^3 m^{-3})	0	0.11
Water retention curve parameter A (m^{-1})	7.65	2.30
Water retention curve parameter n (-)	1.10	7.70
Anisotropy ratio α (-)	0.17	1
Anisotropy rotation angle ϕ (deg)	90	0

4.2.2. Initial and boundary conditions

Numerical modeling of water infiltration through the mineral liner required assumption of the necessary initial and boundary conditions. The initial conditions for time duration t=0 days were assumed as follows: saturation for compacted clay liner resulting from applied molding water content within the range $w_{opt}<w_f<1.2\ w_{opt}$ and 95% of Proctor density, saturation of sand drainage layer as S_a=0.1 and finally saturation of soil recultivation layer as S_a=0.88, based on pore pressure measurements performed in Rastorf on November 1, 2011.

The necessary boundary conditions for the developed model covered the bottom, top and side conditions. The bottom (see Fig. 4.6) boundary condition was assumed to be the constant gradient type Neumann condition of value equal to the saturated hydraulic conductivity of the soil in the sealing layer. This type of boundary condition reflects the undisturbed free water drainage, e.g. gravitational seepage to the lower domain. Zero flux boundary condition was assigned to the left boundary of the model, which reflected in reality the side border of the tested catchment – the top of the landfill's capping slope. The gradient type Neumann boundary condition was also applied to the right side of the modeled domain to reflect lateral drainage trough the right boundary of the model.

The Neumann type (second type) top boundary condition was assigned to the upper limit of the model to reflect the water flux entering and/or leaving the modeled liner profile section. The calculated and assumed as boundary condition daily values of water flux were based on four components, measured and calculated, daily precipitation, interception, evapotranspiration and surface runoff for municipal landfill in Rastorf, Germany for 2012 hydrologic year (Widomski et al., 2015b, 2015c). The values of precipitation and runoff measurements applied to calculations were obtained by the local weather station and the system of surface runoff measurement, while evapotranspiration and interception were based on calculations supported by meteorological measurements. All the measurement equipment used in Rastorf to evaluate water balance components was previously described by Widomski et al. (2015b). Measured values of daily precipitation were corrected in accordance to Richter correction method, in order to exclude the possible measurement errors of the weather station (e.g. evaporation and wind loss) (Richter, 1995).

Reference daily evapotranspiration was calculated according to the standard Penman-Monteith formula (Allen et al., 1994; ATV-DVWK-M 504, 2002), on the basis of the measured weather data and assumed data. Plant cover data (LAI, leaf area index) and assessment of daily interception were performed according to Mitchell et al. (1998) and the formula by Hoyningen-Huene (1983). The assumed LAI for perennial grass mixture covering the top surface of landfill capping was in the range from 3.0 to 5.0, for the winter and summer part of the year, respectively. The observed precipitation in the 2012 hydrological year was equal to 754 mm (compared to 890 mm in 2011). From June to August, the highest rainfall resulted in up to 30 mm per day. The mean annual temperature was 7.8 °C. The average precipitation in Kiel, Germany is equal to 752 mm with a mean temperature of 8.9 °C, so the meteorological data for selected time of simulation may refer to mean weather data for Kiel/Rastorf.

The developed top boundary condition is presented in Fig. 4.7. The values of daily water flux through the top boundary of the modeled domain were obtained by the following formula (Widomski et al., 2015b, 2015c):

$$q_d = -P_{corr} + EV_a + I + q_{runoff}$$

where:

q_d – daily water flux, mm day^{-1};

P_{corr} – corrected daily precipitation, mm day^{-1};

EV_a – actual daily evapotranspiration mm, day^{-1};
I – daily interception, mm day^{-1};
q_{runoff} – daily surface runoff, mm day^{-1}.

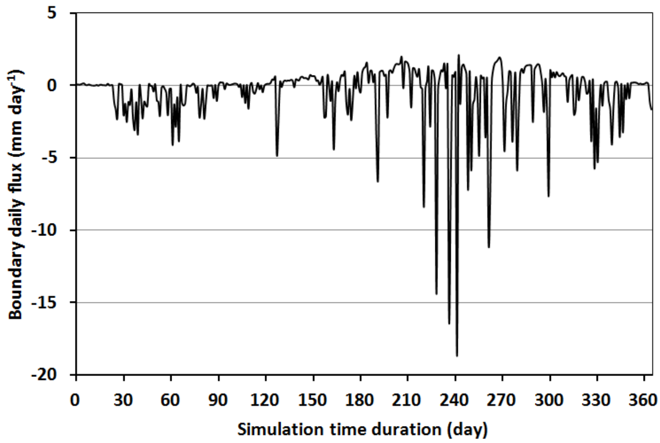

Fig. 4.7. Assumed top boundary condition, negative values mean infiltration, positive evapotranspiration, after Widomski et al. (2015b, 2015c)

4.2.3. Model calibration and sensitivity analysis

The presented model is a modification of a model previously developed for the temporary landfill top cover located in Rastorf, Germany (Widomski et al., 2015b) and was already subjected to calibration and sensitivity analysis. Model calibration, in details described by Widomski et al. (2015b) covered the modification of modeling input parameters, based on comparing the mean daily calculated and measured values of volumetric water content for selected locations on the slope. Generally, the performed model calibration was based on adjustment of daily values of upper boundary condition by application of variable coefficient allowing determination of the actual evapotranspiration in relation to the reference values obtained from the standard Penman-Monteith formula. The values of constant actual evapotranspiration coefficient in range from 0.4 to 0.5 were tested. The best fit was observed for the coefficient of actual evapotranspiration equal to 0.42 (Widomski et al., 2015b).

The obtained water retention parameter n of the van Genuchten's model in many cases for tested compacted clay substrates indicated values below 1.1–1.2. According to the known literature reports, these low values can cause some difficulties and uncertainties in predicting unsaturated hydraulic conductivity near full saturation (Vogel at al., 2001; Ippisch et al., 2006). As it was advised by Vogel et al. (2001), due to $n<1.3$, the low value of air entry pressure equal to 0.01 m was assumed to the presented numerical calculations. In addition, the previously performed sensitivity analysis (Widomski et al., 2015b) was aimed to check the reactions of the developed model concerning small changes in the input parameters of the van Genuchten's model as crucial input data in the numerical model (Baroni et al., 2010). The van Genuchten's *n* parameter was selected for sensitivity analysis also due to its importance as pore size distribution index affecting the shape of water retention curve and resultant water retention characteristics. Several sets of *n* parameter of the van Genuchten's model were applied to the numerical calculations, increased or decreased versus the original values obtained from the retention data. The results of numerical modeling with the applied *n* values were validated by the standard procedures including coefficients of determination for p=0.05, Nash – Sutcliffe coefficient (NSE) and RMSE, normalized RMSE (NRMSE) as well as ratio of RMSE to standard deviation of measured data (RSR) (Moriasi et al., 2007; Pollacco and Mohanty, 2012). The sensitivity analyses performed by Widomski et al. (2015b) for the variable van Genuchten's parameter *n* showed that the increase and decrease of the tested parameter value did not result in a better performance of the model. The observed decrease of model accuracy was related to the applied increase or decrease in the *n* value, leading to underestimated or overestimated calculated values of soil moisture. The increased *n* value, lowering the deflection angle of water retention curve, led to the increased seepage of drainage water. On the other hand, the decreased pore size distribution index reduced the water retention capabilities of soil. Thus, the assumption to modeling of the values of van Genuchten's parameter *n* directly from retention data fitting was reasonable despite their low value (Widomski et al., 2015b).

4.2.4. Bottom liner seepage

Assessment of bottom liners efficiency was determined for the assumption of its operation at saturated, or very close to saturated, conditions (Widomski and Stępniewski, 2014). Thus, the standard form of Darcy equation used for seepage flux determination for 1 m^2 of liner area:

$$q_D = K_s \frac{dh}{dl}$$

Where:
q_D – Darcy unit flux, m s^{-1};
$\frac{dh}{dl}$ – pressure head gradient.

Calculations were performed in MS Excel, for the assumed thickness of bottom compacted clay liner equal to 1 m and variable pressure head from range 0.25–1.0 m (Widomski and Stepniewski, 2014).

5. Results and discussion

The results of performed analyses covered *in situ* and laboratory measurements of general characteristics, strength parameters, Atterberg limits, saturated hydraulic conductivity (both under natural conditions and after compaction at variable water content), swell-shrinkage characteristics, also in relation to molding water content and, finally, saturated hydraulic conductivity after several cycles of drying and wetting. The above mentioned researches were supported by numerical studies of hydraulic performance of compacted clay liner utilizing tested substrates, formed both wet and dry of optimum.

5.1. Results of field and laboratory studies

5.1.1. General characteristics

The tested clay materials, sampled in Lublin Voivodeship were recognized as Miocene, Pliocene and Oligocene sediments. Macro photos and SEM images of studied materials in natural conditions, taken during Polish Ministry of Science and Higher Education project NN 523 755040, are presented in Fig. 5.1.

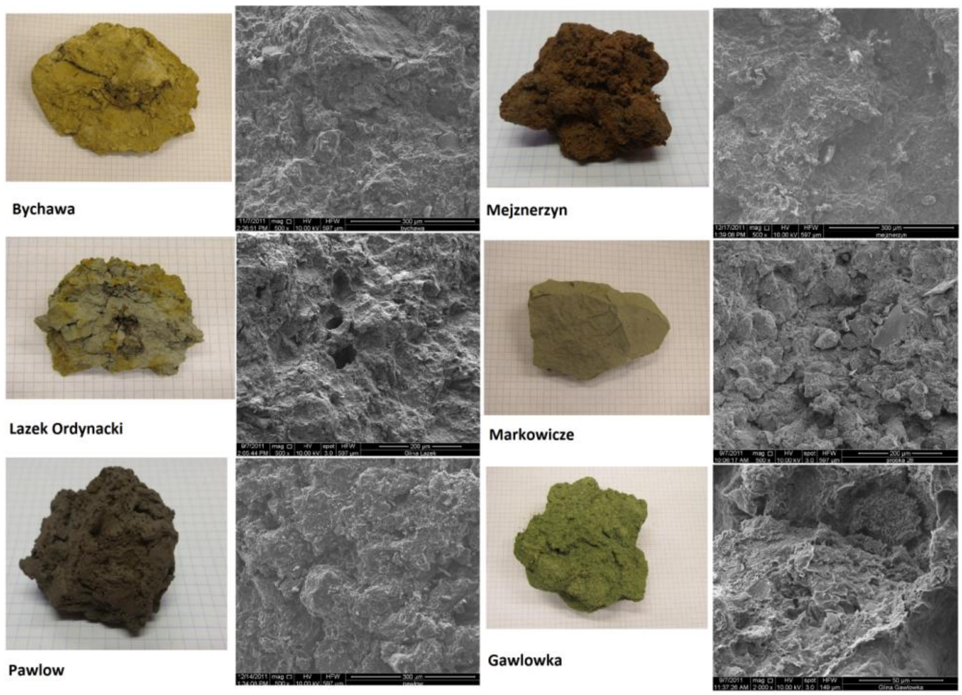

Fig. 5.1. Macro photos and SEM images (500 x) of tested substrates, modified after Stępniewski et al. (2015) and Widomski et al. (2015a)

5.1.1.1. Particle size distribution

The determined particle size distribution of the tested clay substrates and recognized soil texture type according to popular USDA classification are presented in Tab. 5.1.

Table 5.1. Particle size distribution of tested clay materials, modified after Stępniewski et al. (2015)

Substrate	Particles size content (%)				Soil USDA texture type
	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay <0.002 mm	Silt + clay	
Bychawa	12	46	42	88	Silty clay
Lazek Ordynacki	4.5	51	44.5	95.5	Silty clay
Pawlow	11	37	52	89	Clay
Mejznerzyn	13	35	52	87	Clay
Markowicze	25	37	38	75	Clay loam
Gawlowka	66	3	31	34	Sandy clay loam

Results of particle size distribution presented in Tab. 5.1 allowed to determine the substrates texture type, according to USDA regulations, as clays for two substrates and silty clays for the another two. The remaining were recognized as clay loam and sandy clay loam. The clay fraction content, as significantly influencing geotechnical properties, water conductivity and retention properties, varied between 31% and 52%. The content of the sum of clay and silt fractions for all tested substrates varied between 34% for Gawlowka and 95.5% for Lazek Ordynacki. All tested substrates met the popular requirements concerning clay fraction content, i.e. clay fraction content is greater than threshold value, mostly of range >10–25% (e.g. Bagchi, 1990; Daniel and Koerner, 1995; Rowe et al., 1995; Arch, 1998; Wysokiński, 2007). In most cases, including Bychawa, Lazek Ordynacki, Pawlow, Mejznerzyn and Markowicze, the observed sum of silt and clay fraction also met the reported variable suggested values of range >30–60%. The Gawlowka substrate showing sum of clay and silt particles fraction equal to 34% met thresholds of limited threshold values, i.e. reported by Daniel and Koener (1995) and Arch (1998).

Fig. 5.2. presents the percentage distribution of clay sub-fractions of all the tested clay materials obtained during laser diffraction tests. The total sum o clay particles, <2 μm was divided into four ranges: below 0.5, 0.5–1.0, 1.0–1.5 and 1.5–2.0 μm. Three of the tested substrates presented similar distribution of clay particles. On the other hand, material sampled in Gawlowka showed a significantly higher content of

particles of diameters below 0.5 µm, between <0.5 and 1.0 µm and visibly lower content of clay particles in range 1.5–2.0 µm. The lowest numbers of particles below 0.5 µm were observed for Mejznerzyn and Markowicze substrates.

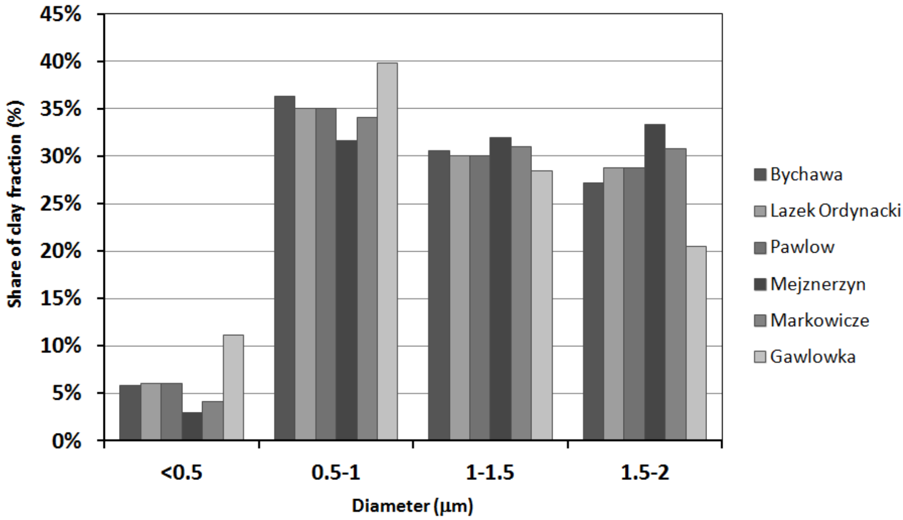

Fig. 5.2. Distribution of clay sub-fractions for all tested materials

5.1.1.2. Particle density, field bulk density, total porosity and field water content

Measured particle density, in situ bulk density and in situ gravimetric water content of the studied clayey materials were presented in Tab. 5.2.

Tab. 5.2. Particle density, in situ bulk density, total porosity and water content for tested substrates, partially modified after Stępniewski et al. (2015)

Substrate	Particle density (Mg m^{-3})	*In situ* bulk density (Mg m^{-3})	Total porosity *in situ* (m^3 m^{-3})	Water content *in situ* (kg kg^{-1})
Bychawa	2.72	1.64	0.40	0.26
Lazek Ordynacki	2.68	1.70	0.37	0.21
Pawlow	2.61	1.67	0.36	0.18
Mejznerzyn	2.79	1.37	0.51	0.28
Markowicze	2.76	1.97	0.29	0.14
Gawlowka	2.86	1.95	0.32	0.18

Measured particle density of all tested substrates was in range of 2.68–2.86 Mg m^{-3} which are typical values for soils containing significant amounts of heavy minerals. Only one of the tested materials had *in situ* bulk density lower than 1.5 Mg m^{-3} and porosity greater than 0.50 m^3 m^{-3}. Two of the tested materials, Markowicze and Gawlowka, containing the greatest sand fraction content, showed the highest *in situ* bulk density, greater than 1.9 Mg m^{-3} and low porosity, approx. 0.30 m^3 m^{-3}. The remaining clay materials presented bulk density in the range of 1.6–1.7 Mg m^{-3} and porosity between 0.36 and 0.40 m^3 m^{-3}.

5.1.1.3. Mineral characteristics

Determined mineral composition of tested materials, covering mass percentage of clay minerals content, swelling (illities and smectities, I+S) and non-swelling minerals (kaolinites and chlorites, K+Ch), ratio of non-swelling versus swelling minerals (K+Ch)/(I+S), FeOOH and $CaCO_3$ content were presented in Tab. 5.3.

Tab. 5.3. Mineral characteristics of tested clay substrates, modified after Stepniewski et al. (2015)

Substrate	Clay minerals content (%)	Swelling minerals content (I+S) (%)	Non-swelling minerals content (K+Ch) (%)	(K+Ch) /(I+S) (-)	FeOOH content (%)	$CaCO_3$ content (%)	Quartz and feldspars content (%)
Bychawa	90	81	9	0.11	8	0	2
Lazek Ordynacki	60	54	6	0.11	5	10	25
Pawlow	70	48	22	0.45	0.5	0	29.5
Mejznerzyn	80	52	28	0.55	1	7	12
Markowicze	50	40	10	0.25	0	10	40
Gawlowka	50	30	20	0.66	0	0	50

All of the tested substrates presented clay minerals content equal to or higher than 50%. The highest values were observed for Bychawa silty clay (90% of clay minerals) and Pawlow clay (80%). The results of swelling (illites and smectities) and non-swelling minerals (kaolinite and chlorites) mass contents measurements as well as the ratio of non-swelling versus swelling minerals contents, (K+Ch)/(I+S), suggest, that due to significant content of swelling minerals (up to 81% of weight in Bychawa substrate) evident high plasticity and significant swell and shrinkage potentials may be expected. Lower swell and shrinkage capabilities may be expected in case of substrates presenting the highest ratio of non-swelling minerals versus swelling minerals contents and low value of clay minerals and high content of quartz and feldspars, i.e. substrates sampled in Gawlowka and Markowicze. The content of clay minerals greater than 20% in all tested substrates met requirements reported by Wysokiński (2007). Additionally, $CaCO_3$ content in all the studied materials, in range of 0–10%, was lower than the maximum suggested allowable value, i.e. 15% (Wysokiński, 2007).

5.1.1.4. Physical and chemical properties

Table 5.4 presents selected physical and chemical properties of the tested substrates affecting its water related properties, i.e. water permeability and water retention characteristics.

Tab. 5.4. Selected physical and chemical properties of tested clay materials, modified after Stępniewski et al. (2015)

Parametr	Bychawa	Lazek Ordynacki	Pawlow	Mejznerzyn	Markowicze	Gawlowka
Single point surface area (m^2 g^{-1})	47.1	33.7	31.5	44.9	17.4	25.0
BET surface area (m^2 g^{-1})	48.1	34.3	32.1	45.8	17.7	25.4
Langmuir surface area (m^2 g^{-1})	65.4	46.6	43.5	62.2	24.1	34.6
t-Plot micropore area (m^2 g^{-1})	9.46	6.15	7.96	7.84	3.21	1.40
t-Plot external surface area (m^2 g^{-1})	38.6	28.2	24.1	37.9	14.5	24.0
Mean particle diameter (nm)	125	175	187	131	338	236
Mean mesopores radius (nm)	7.27	9.65	7.83	9.73	11.83	11.14
CEC (cmol(+) kg^{-1})	36.1	31.8	42.2	36.3	36.8	23.6

The characteristics of tested substrates presented in Tab. 5.4 describing the structure of the tested materials show some interesting relations. Materials of high clay fraction and low sand fraction contents, such as substrates sampled in Bychawa, Lazek Ordynacki, Mejznerzyn and Pawlow, were characterized by higher surface (single point, BET and Langmuir), t-plot external surface area and micropore area. On the other hand these substrates presented lower mean particle diameter and mean mesopores radius. Materials containing significant share of sand fraction and in result, quartz and feldspars and limited clay fraction and clay minerals content, such as Gawlowka and Markowicze were characterized by lower surface area, external surface area and micropores area. Similarly, the mean particle diameter and mesopores radios were grater in this case. All the above may significantly influence hydraulic properties of the tested materials.

5.1.2. Strength parameters

Table 5.5 presents measured values of the internal friction angle, cohesion as well as resistance to penetration, measured modules of primary and secondary compressibility for the six tested clay substrates. The observed values of internal friction angle, cohesion and resistance to penetration in natural conditions were typical for cohesive soils. Values of the primary and secondary compressibility modulus show that tested soils are less compressible during the secondary load. Internal friction angle of all tested substrates was greater than 3 deg. required by Wysokinski (2007) as a criterion of clay material applicability for liner construction. Measured value of cohesion in several cases is lower than 35 kPa required by Wysokiński (2007), i.e. in the case of Pawlow, Mejznerzyn, Markowicze and Gawlowka.

Tab. 5.5. Internal friction angle, cohesion, resistance to penetration, modules of primary and secondary compressibility for tested clay materials, modified after Stępniewski et al. (2015)

Substrate	Internal friction angle (deg)	Cohesion (kPa)	Resistance to penetration (MPa)	Modulus of primary compressibility M_0 (MPa)	Modulus of secondary compressibility M (MPa)
Bychawa	8	61	0.47	5	9
Lazek Ordynacki	8	41	1.02	5	12
Pawlow	23	11	0.90	3	8
Mejznerzyn	18.7	31	0.66	3	7
Markowicze	24	21	6.00	27	79
Gawlowka	23	28	4.22	3	17

5.1.3. Atterberg limits and plasticity chart

The obtained Atterberg limits for the six tested clay materials were presented in Table 5.6. The measurement results presented in Tab. 5.6 show that five of the tested substrates (Bychawa, Lazek Ordynacki, Pawlow, Mejznerzyn, Markowicze) presented similar values of *LL* (over 50%, range of 51–66%), *PL* and *PI* – over 20%, range of variability 23–28% and 24–38%, respectively. Only one material, sandy clay loam sampled in Gawlowka, showed significantly lower (approx. 50%)

values of Atterberg limits, with *LL* equal to approx. 27%, *PL* aprox. 15% and *PI* close to 12%. According to BS 5930 soil classification, taking into account *LL* value, most of the tested substrates may be classified as of high plasticity, *LL*=50–70%. Only Gawlowka material was classified as clay of low plasticity, with *LL*<35%.

Tab. 5.6. Atterberg limits observed for tested clay substrates, partially modified after Stępniewski et al. (2015)

Substrate	Liquid limit *LL* (%)	Plastic limit *PL*(%)	Plasticity index *PI* (%)	Shrinkage limit *SL* (%)	Potential swell *S* (%)
Bychawa	52	25	27	12	12
Lazek Ordynacki	59	24	35	12	20
Pawlow	53	23	30	12	14
Mejznerzyn	66	28	38	15	26
Markowicze	51	27	24	13	8
Gawlowka	27	15	12	7	2

The shrinkage limit, calculated from the obtained Atterberg limits, shows the value of water content below which the soil specimen is not shrinking. Again, five of the tested materials of high and medium plastic properties presented a similar value of *SL*, between 12–15%, thus their shrinkage potential may be accordingly similar. Sandy clay loam sampled in Gawlowka showed value of *SL* significantly lower i.e. *SL*=7%, than the remaining tested substrates. Thus, its shrinkage potential may be expected to by clearly lower then presented by the remaining tested materials.

The highest calculated swelling potential was observed for Mejznerzyn substrate (25.9%), while the lowest, equal to 2% was calculated for Gawlowka material. According to the classification of potential swell presented by Bentley and Carter (1991) Gawlowka substrate was classified as presenting a moderate potential swell, while the remaining materials presented high and very high (Mejznerzyn) potential swell.

To better illustrate relations between the selected Atterberg limits and their effects on swell and shrink characteristics of clay material, the plasticity chart was presented in Fig. 5.3 (ASTM D2487-11; Ladd and Lambe, 1961; Bain, 1971; Chen, 1988).

All the tested substrates are located at plasticity chart above A-line (equation $PI=0.73\cdot(LL-20)$), separating clayey materials from silts and below the U-line

(PI=0.9·(LL–8)) the upper limit of *PI* and *LL* for known soils, inside the area typical for clays (eg. Bain, 1971; Holtz and Kovacs, 1981; Mitchell and Soga, 2005).

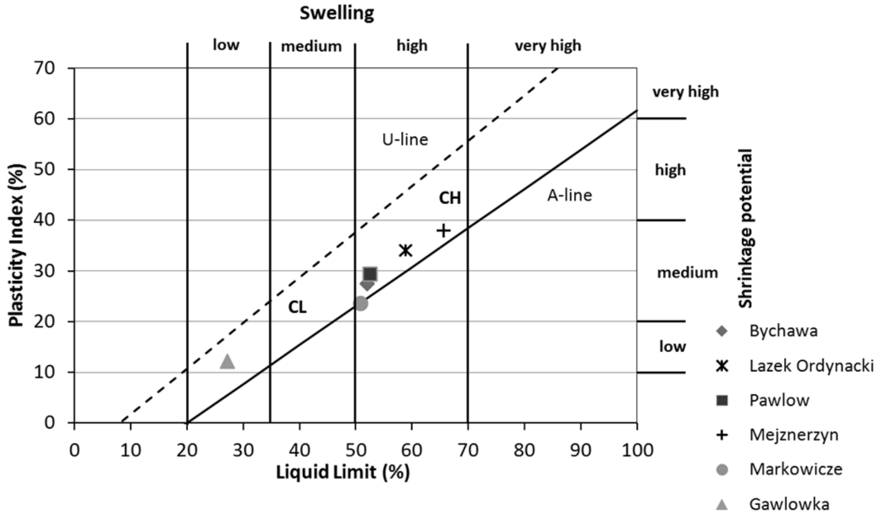

Fig. 5.3. Plasticity chart for tested clay materials, according to USCS classification; CL – low plasticity clays, CH – high plasticity clays

Most of the tested substrates, except the one sampled in Gawlowka, can be recognized as high plasticity clays, while Gawlowka was recognized as low plasticity clay. Similarly, shrinkage and swelling potentials for most samples except Gawlowka were determined as medium and high, respectively, according to the classification adopted after e.g. Ladd and Lambe (1961) and Chen (1988). The Gawlowka substrate was located in the zone of low swelling and low shrinkage potential. Although, there are also visible differences among the remaining five substrates belonging to the group of high swell and shrinkage materials. The substrates sampled in Lazek Ordynacki and Mejznerzyn, recognized as silty clay and clay according to USDA, containing over 50% of swelling minerals showed the highest values of the liquid limit and plasticity index, which can have a significant influence on the sustainability and performance of these materials, including type of shrinkage and subsequent desiccation cracks development, as construction materials for natural compacted barriers.

According to the Polish requirements concerning plasticity of clays presented by Wysokinski (2007) suggesting *PI* of materials applicable for liner construction should be in the range of 15–70%, most of the tested materials can be recognized as suitable or very suitable. Only Gawlowka substrate of *PI*=12% can be assigned to materials inappropriate without additional treatment. Although, its applicability is possible when taking into account the different available selection of criteria, for example of EPA (1993) or Rowe et al. (1995), suggesting usability of clays when *PI* is greater than 10% and 7%, respectively. Studies presented by Benson and Trast (1995) also reported successful liner formation of clays characterized by *PI* in range 11–14%. All tested substrates showed the plasticity index below 40%. However, materials of *PI* in range of 30% to 40%, such as substrates sampled in Lazek Ordynacki and Mejznerzyn, *PI*=34.3% and *PI*=38.1%, respectively, are cohesive and sticky so they become hard to be processed in the field because they may tend to form hard clods when dry and sticky clods when saturated (EPA, 1993; EPA, 1996).

5.1.4. Hydraulic conductivity under natural conditions

Tab. 5.7 presents results of saturated hydraulic conductivity measurements of tested substrates under natural conditions with application of field permeameter and in falling head laboratory permeameter for 100 cm^3 undisturbed samples.

Tab. 5.7. Measured natural saturated hydraulic conductivity of tested substrates, partially modified after Stępniewski et al. (2015)

Substrate	In situ measurements		Laboratory measurements	
	K_s (m s^{-1})	SD	K_s (m s^{-1})	SD
Bychawa	$2.75 \cdot 10^{-10}$	$7.79 \cdot 10^{-12}$	$7.78 \cdot 10^{-10}$	$3.35 \cdot 10^{-10}$
Lazek Ordynacki	$1.37 \cdot 10^{-10}$	$3.54 \cdot 10^{-12}$	$4.30 \cdot 10^{-10}$	$4.24 \cdot 10^{-10}$
Pawlow	$2.51 \cdot 10^{-10}$	$1.36 \cdot 10^{-11}$	$2.74 \cdot 10^{-10}$	$8.27 \cdot 10^{-11}$
Mejznerzyn	$2.05 \cdot 10^{-10}$	$1.56 \cdot 10^{-10}$	$8.04 \cdot 10^{-10}$	$4.86 \cdot 10^{-10}$
Markowicze	$1.00 \cdot 10^{-10}$	$1.98 \cdot 10^{-10}$	$4.86 \cdot 10^{-9}$	$2.13 \cdot 10^{-10}$
Gawlowka	$4.73 \cdot 10^{-10}$	$1.50 \cdot 10^{-10}$	$2.25 \cdot 10^{-9}$	$4.89 \cdot 10^{-10}$

The results of measurements presented in Tab. 5.7 show that all the six studied substrates tested in situ, directly in clayey material layer presented saturated hydraulic conductivity lower than the value of $1.0 \cdot 10^{-9}$ m s^{-1} required by several standards, such as e.g. Journal of Laws from 2013 item 523; Council Directive 99/31/EC, EPA 530-R-93-017 or suggested by several technical guidelines (e.g. EPA, 1996; EPA, 2015) or literature reports (Bagchi, 1990; Daniel and Koerner, 1995; Rowe et al., 1995; Arch, 1998; Wysokinski, 2007). Thus, municipal landfills could be directly located on natural layers of the tested clay substrates, after assuring their required thickness. Although, the results of measurements performed in laboratory with 100 cm^3 standard cylinders sampled in situ showed, in the most studied cases, the grater values of K_s than observed during in situ measurements. In the two cases of the clay materials from Markowicze and Gawlowka K_s measured in laboratory conditions had values greater than $1.0 \cdot 10^{-9}$ m s^{-1}. However, these substrates are likely to be successfully used after molding. On the other hand, there are known literature reports presenting the above as the standard and typical phenomenon, when results of K_s measurements in laboratory conditions are different, even by one order of magnitude than results obtained by field methods *in situ* (e.g. Shackelford and Javed, 1991; Fredlund and Rahardjo, 1993; Allen, 2001; Sobolewski, 2005).

5.1.5. Water retention curves of tested materials under natural conditions

Water retention, repellency and drainage outflow may play an important role in water management, water balance, including infiltration, drainage of gravity water and leachate seepage of the bottom and top sealing compacted clay liner of municipal wastes landfill (see e.g. Widomski et al., 2015b) when the discussed layer is only partially or variably saturated. Thus, knowledge about water retention curve of clay material proposed for sealing the construction seems to be reasonable. Fig. 5.4 presents water retention curves (pF curves) for all the tested clayey materials in the natural conditions, separately for the processes of specimen watering and dewatering allowing to assess the hysteresis of water retention curve.

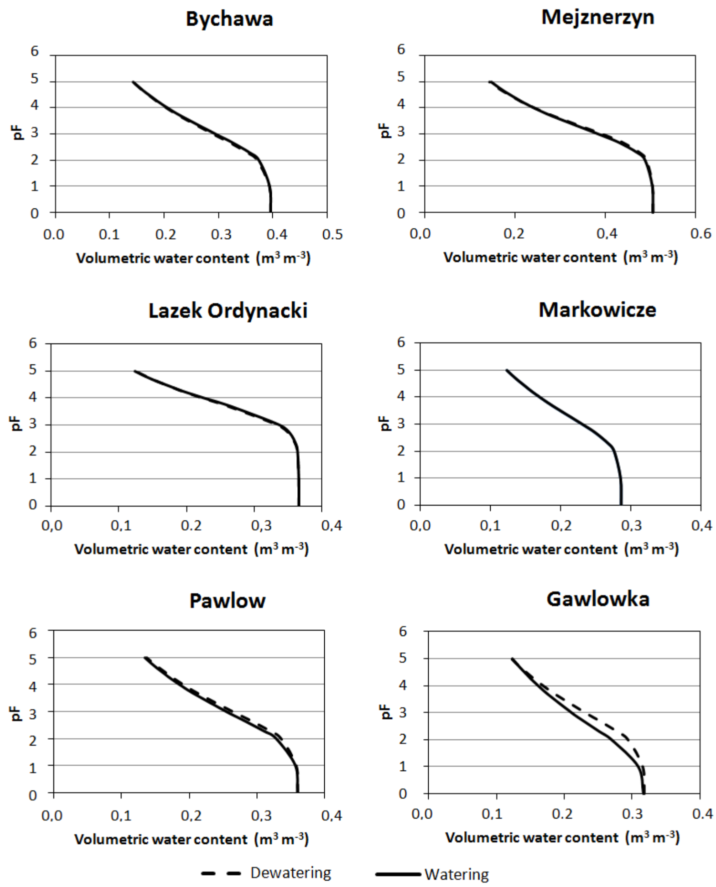

Fig. 5.4. Water retention characteristics of tested materials, presented as pF curves

Water retention characteristics in Fig. 5.4. were presented as the pF curves, according to the equation:

$$\mathrm{pF} = \log h_s$$

Where:

h_s – soil suction pressure, cm H_2O.

Table 5.8 contains water retention data of tested substrates under their natural conditions fitted to the popular van Genuchten's model (1980) of water retention curve, together with the fitting data assessment by coefficient of determination, R^2, for p=0.05.

Tab. 5.8. Van Genuchen's parameters for water retention characteristics of tested materials, R^2 for p=0.05

Substrate	Process	θ_s ($m^3\ m^{-3}$)	α (m^{-1})	n (-)	R^2
Bychawa	Dewatering	0.397	0.65	1.159	0.977
	Watering		0.55	1.162	0.975
Lazek Ordynacki	Dewatering	0.366	0.06	1.262	0.996
	Watering		0.05	1.274	0.982
Pawlow	Dewatering	0.360	0.78	1.145	0.970
	Watering		1.10	1.140	0.973
Mejznerzyn	Dewatering	0.505	0.23	1.231	0.994
	Watering		0.28	1.219	0.994
Markowicze	Dewatering	0.286	0.39	1.141	0.990
	Watering		0.38	1.142	0.996
Gawlowka	Dewatering	0.318	0.92	1.140	0.999
	Watering		3.28	1.117	0.996

The fitting data presented in Tab. 5.8 show values typical for clayey soils (see e.g. Zand-Parsa and Sepaskhah, 2004; Schaap and van Genuchten, 2006), with typical low values of *n* dimensionless fitting parameter describing pore size distribution index (Vogel at al., 2001; Ippisch et al., 2006) which may cause some uncertainties during modeling of water flow in conditions close to full saturation.

Fig. 5.4 shows considerable water retention capacity of all tested materials, pF in range 2.0–4.2, and relatively low amount of water capable to leave the soil profile due to the gravity force (pF 0–2.0) and to form the seepage to deeper layers. Thus, in relation to water holding capacities (see Tab. 5.9) of tested materials under their natural conditions, they may be recognized as appropriate for isolation liner construction.

Tab. 5.9. Water holding capabilities (pF 2.0–4.2) for tested clay materials

Substrate	Process	Water holding capacity (m^3 m^{-3})	Mean water holding capacity (m^3 m^{-3})
Bychawa	Dewatering	0.180	0.181
	Watering	0.181	
Lazek Ordynacki	Dewatering	0.297	0.297
	Watering	0.297	
Pawlow	Dewatering	0.134	0.125
	Watering	0.116	
Mejznerzyn	Dewatering	0.172	0.172
	Watering	0.173	
Markowicze	Dewatering	0.161	0.160
	Watering	0.159	
Gawlowka	Dewatering	0.115	0.115
	Watering	0.115	

5.1.6. Characteristics of tested materials after compaction

Table 5.10 presents the obtained maximum dry bulk density of tested clayey materials combined with the optimal molding water content and their saturated hydraulic conductivity observed at the optimal water content.

Tab. 5.10. Effects of compaction process for the tested clay substrates, modified after Stępniewski et al. (2015)

Substrate	Maximum Proctor density (Mg m^{-3})	Optimal molding water content w_{opt} (kg kg^{-1})	Saturated hydraulic conductivity at w_{opt} (m s^{-1})
Bychawa	1.71	0.22	$2.75 \cdot 10^{-11}$
Lazek Ordynacki	1.72	0.21	$2.09 \cdot 10^{-11}$
Pawlow	1.78	0.19	$5.66 \cdot 10^{-11}$
Mejznerzyn	1.56	0.26	$2.86 \cdot 10^{-11}$
Markowicze	1.83	0.16	$9.35 \cdot 10^{-11}$
Gawlowka	1.99	0.13	$4.42 \cdot 10^{-10}$

Results of laboratory measurements presented in Tab. 5.10 show that, despite the different observed densities and saturated hydraulic conductivity values, during in situ and laboratory tests, all six tested materials after standard Proctor compaction at optimal water content were able to achieve value of K_s significantly below the usually required maximum value of $1.0 \cdot 10^{-9}$ m s^{-1}. The observed values of K_s were in range between approx. $4.4 \cdot 10^{-10}$–$2.10 \cdot 10^{-10}$ m s^{-1}, one and two orders of magnitude lower than the required threshold. The lowest values were achieved for the high plasticity clays, the materials containing significant amount of clay fraction and huge percentage of clay minerals, i.e. the substrates sampled in Bychawa, Lazek Ordynacki, Mejznerzyn and Markowicze. The highest value of K_s at w_{opt} was observed for the sandy substrate sampled in Gawlowka. Similarly, the observed optimal water content, between 0.13 and 0.26 kg kg^{-1}, also reflects the particle size and mineral composition of the involved substrates (the detailed correlations among various characteristics of the tested materials and effects of compaction will be presented in further part of this manuscript). Generally, the higher clay and the lower sand fraction content, the higher optimal water content is obtained after compaction.

In order to better understand the influence of molding water content on characteristics of clay material after compaction and its behavior affected by presence of water the detailed graphs containing Proctor curve, dry bulk density after swelling and shrinkage as well as value of saturated hydraulic conductivity related to molding water content are presented in Fig. 5.5.

The compaction characteristics for Bychawa (see Fig. 5.5) clayey material showed the typical shape of Proctor curve with maximum density 1.71 Mg m^{-3} observed at molding water content of 0.22 kg kg^{-1}. The minimum applied molding water content of 0.13 kg kg^{-1} allowed to obtain bulk density equal to 1.49 Mg m^{-3}, while the highest molding water content of 0.27 kg kg^{-1} resulted in bulk density 1.56 Mg m^{-3}.

The maximum Proctor density for Lazek Ordynacki substrate was quite similar, 1.72 Mg m^{-3} for molding water content of 0.21 kg kg^{-1}. The lowest applied molding water content equal to 0.14 kg kg^{-1} resulted in bulk density of 1.49 Mg m^{-3}, while for the maximum applied water content during compaction 0.25 kg kg^{-1}, the dry bulk density was equal to 1.62 Mg m^{-3}.

The compaction curve for the Pawlow substrate had a different shape than for the two materials discussed above. It was flatter and more symmetric and gained maximum density of 1.78 Mg m^{-3} at w_{opt} of 0.19 kg kg^{-1}. The lowest bulk density after compaction was equal to 1.57 Mg m^{-3} and was obtained for the maximum applied water content, i.e. 0.26 kg kg^{-1}. The lowest applied molding water content 0.12 kg kg^{-1} in case of the material sampled in Pawlow resulted in dry bulk density after compaction of 1.71 Mg m^{-3}.

The compaction curve obtained for the Mejznerzyn substrate was quite similar in shape to the one observed in case of the Bychawa material but it was definitely flatter. It gained the maximum Proctor density of 1.56 Mg m^{-3} at molding water content of 0.26 kg kg^{-1}, which was the highest observed w_{opt}. The maximum applied water content equal to 0.30 kg kg^{-1} allowed to achieve bulk density of 1.52 Mg m^{-3} while the lowest water content, 0.14 kg kg^{-1}, resulted in bulk density after compaction equal to 1.40 Mg m^{-3}.

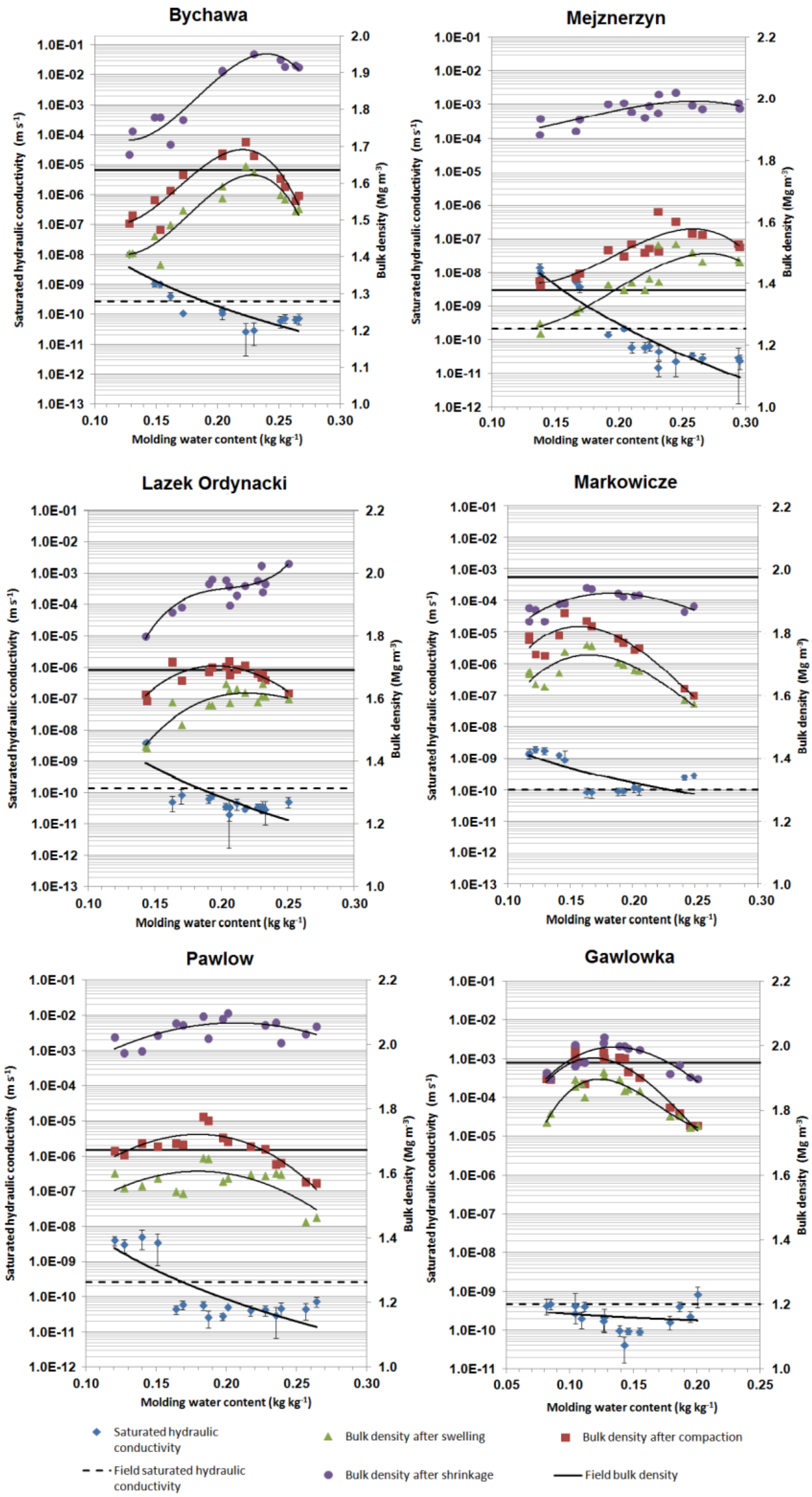

Fig. 5.5. Compaction characteristics of tested substrates (error bars for K_s – SD)

The two remaining Proctor density curves, for the Markowicze and Gawlowka substrates, containing significant amount of sand particles fraction had a very similar shape, rapidly decreasing after gaining their maximum, the value of which was quite high, i.e. 1.83 Mg m^{-3} and 1.99 Mg m^{-3} at quite low molding water contents, 0.16 kg kg^{-1} and 0.13 kg kg^{-1} for Markowcze and Gawlowka, respectively.

The changes in saturated hydraulic conductivity related to molding water content are also clearly visible in Fig. 5.5. The obtained hydraulic conductivity decreased due to increase in applied molding water content. The observed K_s in most cases of applied variable water contents reached the values lower than commonly required $1.00 \cdot 10^{-9}$ m s^{-1}. The minimal obtained values due to compaction were compared to K_s for the optimal water content in Tab 5.11.

Tab. 5.11. Minimum measured saturated hydraulic conductivity of compacted tested substrates

Substrate	Minimum K_s (m s^{-1})	w_f at min K_s (kg kg^{-1})	Relation vs. K_s at w_{opt}
Bychawa	$2.75 \cdot 10^{-11}$	0.22	=
Lazek Ordynacki	$2.09 \cdot 10^{-11}$	0.21	=
Pawlow	$2.63 \cdot 10^{-11}$	0.19	<
Mejznerzyn	$1.53 \cdot 10^{-11}$	0.23	<
Markowicze	$4.17 \cdot 10^{-11}$	0.17	<
Gawlowka	$1.53 \cdot 10^{-11}$	0.14	<

Comparing the data presented above in Tab. 5.11 it may be stated that in the several cases (Pawlow, Mejznerzyn, Markowicze and Gawlowka) the observed lowest values of K_s were obtained at molding water contents different than w_{opt}.

However it is worth to note that the lowest applied molding water contents for many sampled substrates disallowed to reduce saturated hydraulic conductivity to values lower than the commonly required $1.00 \cdot 10^{-9}$ m s^{-1}. For Bychawa substrate water contents of 0.13 and 0.15 kg kg^{-1} led to K_s values above $1.00 \cdot 10^{-8}$ m s^{-1} and $1.10 \cdot 10^{-9}$ m s^{-1}, respectively. For Lazek Ordynacki 0.14 kg kg^{-1} resulted in $3.93 \cdot 10^{-9}$ m s^{-1}. Applied molding water contents of range 0.12–0.15 kg kg^{-1} for material sampled in Pawlow resulted in K_s in range from $2.98 \cdot 10^{-9}$ m s^{-1} to $5.06 \cdot 10^{-9}$ m s^{-1} while, similarly, in case of Mejznerzyn clay the applied molding water content of range 0.14–0.17 kg kg^{-1} allowed to reach values of $1.10 \cdot 10^{-8}$–$5.33 \cdot 10^{-9}$ m s^{-1}. Test of saturated hydraulic conductivity for Markowicze material showed that the required value of K_s was achieved only for molding water contents greater than 0.15 kg kg^{-1}, for water contents between 0.12 and 0.15 kg kg^{-1}, the observed values of K_s were in range of $1.24 \cdot 10^{-9}$–$2.53 \cdot 10^{-9}$ m s^{-1}. Thus, the Gawlowka material, characterized by significant share of sand fraction, was the only studied clay substrate for which the required value of saturated hydraulic conductivity was achieved at all applied molding water contents (0.08–0.2 kg kg^{-1}). The maximum K_s observed after compaction was equal to $8.55 \cdot 10^{-10}$ m s^{-1}. This property may be very useful in practical application of the Gawlowka substrate to CCL construction because it allows greater margin of error in preparation of initial saturation of the applied substrate.

As for the suggested compaction water content (Wysokinski, 2007) allowing to obtain 95% of the Poroctor density requested during construction of compacted clay liner, i.e. molding water content equal to 1.0–1.2 of w_{opt}, wet of optimum, on the right side of the Proctor curve, the values of K_s obtained for forming water content (w_f) at range of $w_{opt} \leq w_f \leq 1.2 w_{opt}$ were presented in Tab. 5.12. Thus, all the tested clay materials presented sufficient isolating properties required to construct a successfully operation compacted clay liner.

Tab. 5.12. Saturated hydraulic conductivity for water content $w_{opt} \leq w_f \leq 1.2 w_{opt}$

Substrate	K_s at 95% Proctor bulk density wet of optimum $w_{opt} \leq w_f \leq 1.2 w_{opt}$ (m s^{-1})	w_f (kg kg^{-1})
Bychawa	$6.15 \cdot 10^{-11}$	0.25
Lazek Ordynacki	$5.20 \cdot 10^{-11}$	0.25
Pawlow	$4.17 \cdot 10^{-11}$	0.22
Mejznerzyn	$2.46 \cdot 10^{-11}$	0.30
Markowicze	$1.17 \cdot 10^{-10}$	0.20
Gawlowka	$9.45 \cdot 10^{-11}$	0.15

Fig. 5.5 also shows changes of substrates' dry bulk density caused by swelling and shrinkage. The difference of density for compacted material and material after swelling decreased with the increase in molding water content. The relation between bulk density of compacted material and after shrinkage had different direction, it increased with the increase in molding water content. In all tested cases the difference between curves showing bulk dry density after swelling and after shrinkage were clearly visible. Measured bulk densities of tested substrates after swelling reached values of 1.38–1.65 Mg m^{-3} for Bychawa, 1.44–1.65 Mg m^{-3} for Lazek Ordynacki, 1.45–1.65 Mg m^{-3} for Pawlow, 1.24–1.53 Mg m^{-3} for Mejznerzyn, 1.57–1.76 Mg m^{-3} for Markowicze and 1.75–1.92 Mg m^{-3} for Gawlowka. Thus, changes of density related to swelling process were in the relative range of 2.8–11.5%, 1.1–10.1%, 1.6–8.9%, 3.3–11.0%, 1.6–6.7% and 0.0–7.0%, respectively.

The observed difference between bulk density for compacted and swelled material compacted at high water contents was in the most cases relatively small, max to approx. 3%, although in the case of Gawlowka substrate the value of 0.0 Mg m^{-3} was noted, which means than no swelling was observed.

Fig. 5.5 presents also shrinkage characteristics of compacted substrates, the crucial determinant of compacted clay liner sustainability. It is clearly visible that dry bulk density after shrinkage for tested clay substrates compacted at various water contents was in most cases clearly higher then density indicated by the Proctor curve. Measured bulk densities of the shrinked tested clay materials were in range of 1.68–1.95 Mg m^{-3} for Bychawa, 1.8–2.03 Mg m^{-3} for Lazek Ordynacki, 1.97–2.10 Mg m^{-3} for Pawlow, 1.89–2.02 Mg m^{-3} for Mejznerzyn, 1.83–1,94 Mg m^{-3} for Markowicze and finally, 1.9–2,03 Mg m^{-3} for Gawlowka substrates. Thus, the observed increase in the bulk density after shrinkage for the tested substrates and for all molding water contents applied was in range of 8.0–23.6%, 9.2–25.5%, 14.5–31%, 19.5–38.9%, 1.6–17.8% and 0.1–8.6%, respectively for all the tested sampling locations. The highest increase in density after shrinkage was observed for high initial water contents applied during the compaction of high plasticity clays, the materials containing significant amount of clay fraction. On the other hand, the lowest bulk density increases were noted for substrates sampled in Gawlowka and Markowicze, containing significant amount of sand fraction and the lowest share of clay particles.

The above may be better illustrated by Fig. 5.6 presenting graphically swelling and shrinkage potentials, understood after Horn and Stępniewski (2004), as differences between dry bulk density after compaction and after swelling and shrinkage, related to values of applied molding water content. In the most cases of the tested substrates the observed shrinkage potential was in all the ranges of water content higher than the swelling potential. The only exceptions may be observed for substrates containing significant amounts of sand fraction, i.e. materials sampled in Markowicze and Gawlowka, for which, for selected water contents lower than w_{opt} the observed shrinkage potential was lower than the swelling potential at the same molding water content. In all the tested cases there was a visible tendency of decrease in the swell potential according to changes in the molding water content. The maximum observed swelling potentials for the minimal applied water content during compaction were similar in the most cases, 0.11 Mg m^{-3} for Bychawa samples, 0.16 Mg m^{-3} for Lazek Ordynacki, 0.15 Mg m^{-3} for Pawalow, 0.15 Mg m^{-3} for Mejznerzyn, 0.13 Mg m^{-3} for Markowicze and 0.13 Mg m^{-3} for Gawlowka. On the other hand, the minimum swelling potential was in all cases noted for the maximum applied water content during compaction and varied between 0.0 Mg m^{-3} for Gawlowka, 0.02 Mg m^{-3} for Lazek Ordynacki, 0.03 Mg m^{-3} for Bychawa, Pawlow and Markowicze as well as 0.05 Mg m^{-3} for Mejznerzyn. Additionally, swelling potential was significantly lower at wet of optimum, at the right side of the Proctor curve for the tested water contents greater than w_{opt}.

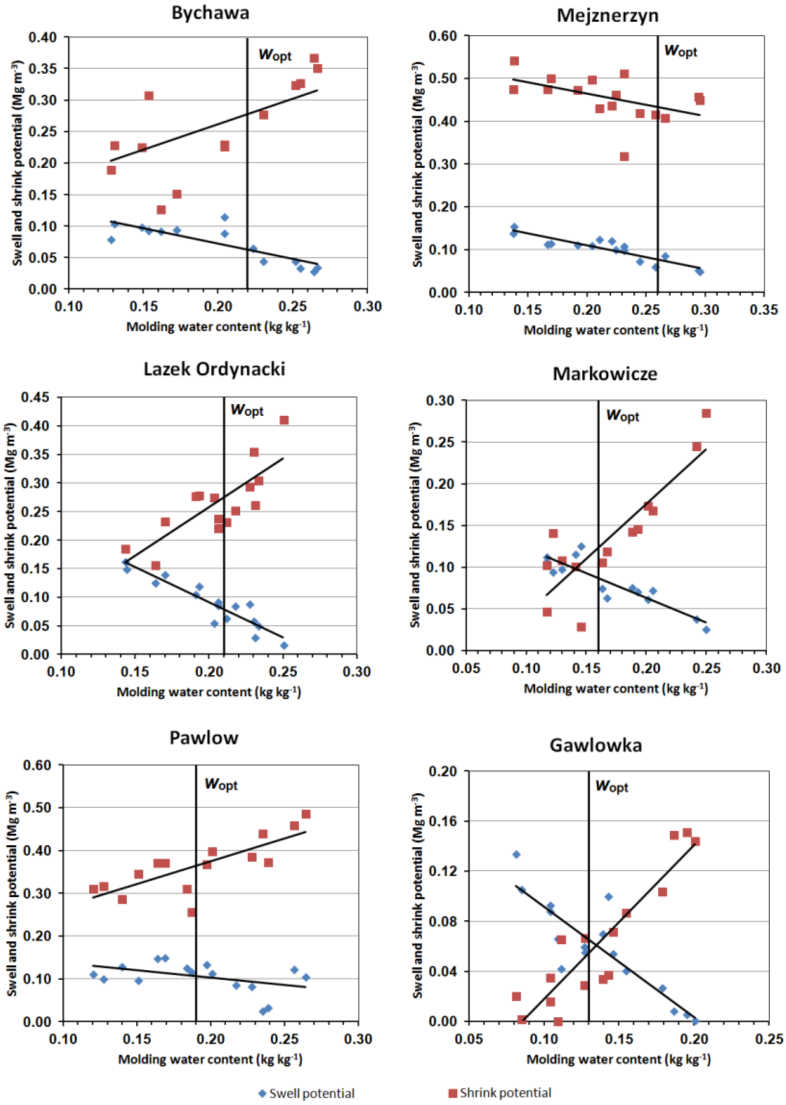

Fig. 5.6. Relations of swell and shrink potential of tested substrates to applied molding water content

In the case of five of the tested materials (Bychawa, Lazek Ordynacki, Pawlow, Markowicze and Gawlowka) a significant increase in the shrinkage potential related to the increase in molding water content was observed. The maximum shrinkage potentials equal to 0.37 Mg m^{-3}, 0.41 Mg m^{-3}, 0.49 Mg m^{-3}, 0.28 Mg m^{-3} and 0.15 Mg m^{-3} for Bychawa, Lazek Ordynacki, Pawlow, Markowicze and Gawlowka, respectively, were observed for the highest applied water content during compaction. On the other hand, the lowest shrinkage potentials were in most cases noted for the lowest values of molding water contents, i.e. starting from 0.0 Mg m^{-3} for Gawlowka substrate, through 0.03 Mg m^{-3} for Markowicze (both containing significant amounts of sand fraction), 0.13 Mg m^{-3} for Bychawa, 0.16 Mg m^{-3} for Lazek Ordynacki, 0.26 Mg m^{-3} for Pawlow and finally 0.28 Mg m^{-3} for Markowicze. The only noted exception was observed for the substrate sampled in Mejznerzyn, clay of high plasticity, for which even slightly opposite tendency was observed – decrease of shrinkage potential with the increase in molding water content. The lowest applied water content during forming resulted in 0.54 Mg m^{-3} shrinkage potential while the highest value of molding water content allowed 0.32 Mg m^{-3}.

Additionally, it was visible that in most cases the values of calculated shrinkage potential were higher on the right side of Proctor curve, for water contents higher than w_{opt}. Thus, to avoid serious shrinkage and resultant cracking, compaction should be probably performed for moisture content close to the optimal moisture or even, in some cases, dry of optimum, on the left, “dry” side of the Proctor curve. However, it should be noticed that in case of the studied materials, in several cases (see Tab. 5.13) compaction on the left side of Proctor curve allowing to obtain suggested 95% of Proctor’s density resulted in K_s higher than acceptable $1.00 \cdot 10^{-9}$ m s^{-1}.

Tab. 5.13. Saturated hydraulic conductivity for water content from rage $w_f < w_{opt}$

Substrate	K_s at 95% Proctor density dry of optimum $w_f < w_{opt}$ (m s^{-1})	w_f (kg kg^{-1})
Bychawa	$1.11 \cdot 10^{-10}$	0.20
Lazek Ordynacki	$8.43 \cdot 10^{-11}$	0.19
Pawlow	$5.06 \cdot 10^{-09}$	0.15
Mejznerzyn	$2.20 \cdot 10^{-10}$	0.20
Markowicze	$1.91 \cdot 10^{-9}$	0.12
Gawlowka	$4.40 \cdot 10^{-10}$	0.08

For the two substrates, Pawlow and Markowicze, which failed to meet the requirements at 95% of the Proctor density, the required value of $K_s \leq 1.00 \cdot 10^{-9}$ m s^{-1} were obtained dry of optimum, $w_f < w_{opt}$, for molding water content equal to 0.16 and 0.15 kg kg^{-1}, respectively.

Values of swelling index (*SI*) for tested substrates related to the applied molding water content were presented in Fig. 5.7. In all of the tested cases, for all studied clay materials, the decrease in *SI* versus increase in water content during compaction was observed. The measured *SI* values varied (decreased) in range of 6.5–2.1% for Bychawa, 10.9–1.1% for Lazek Ordynacki, 11.6–3.4% for Mejznerzyn, 7.0–0.8%

for Pawlow, 6.3–1.6% for Markowicze and finally, 6.7–0.3% for Gawlowka. Clearly, the increase in molding water content resulted in the reduction of swelling capabilities of the tested materials for liner construction. However, not all the materials at the all applied molding water contents met the requirements of *SI* ≥4% suggested by Wysokiński (2007). The suggested minimal value of *SI* was not achieved for molding water contents greater than approx. 0.21 kg kg^{-1} for Bychawa, 0.22 kg kg^{-1} for Lazek Ordynacki, 0.24 kg kg^{-1} for Pawlow, 0.29 kg kg^{-1} for Mejznerzyn, 0.19 kg kg^{-1} for Markowicze and 0.12 kg kg^{-1} for Gawlowka. Some of these molding water content values are lower than the optimal water content w_{opt}, i.e. Bychawa, Markowicze and Gawlowka. In the cases of the remaining three substrates, i.e. Lazek Ordynacki, Pawlow and Mejznerzyn, molding water content for *SI*=4% was greater than w_{opt}, precisely in range between w_{opt} and 1.2 w_{opt}, or ever greater than 1.2 w_{opt}. However, according to Wysokiński (2007) the swelling index measurement should be treated as secondary.

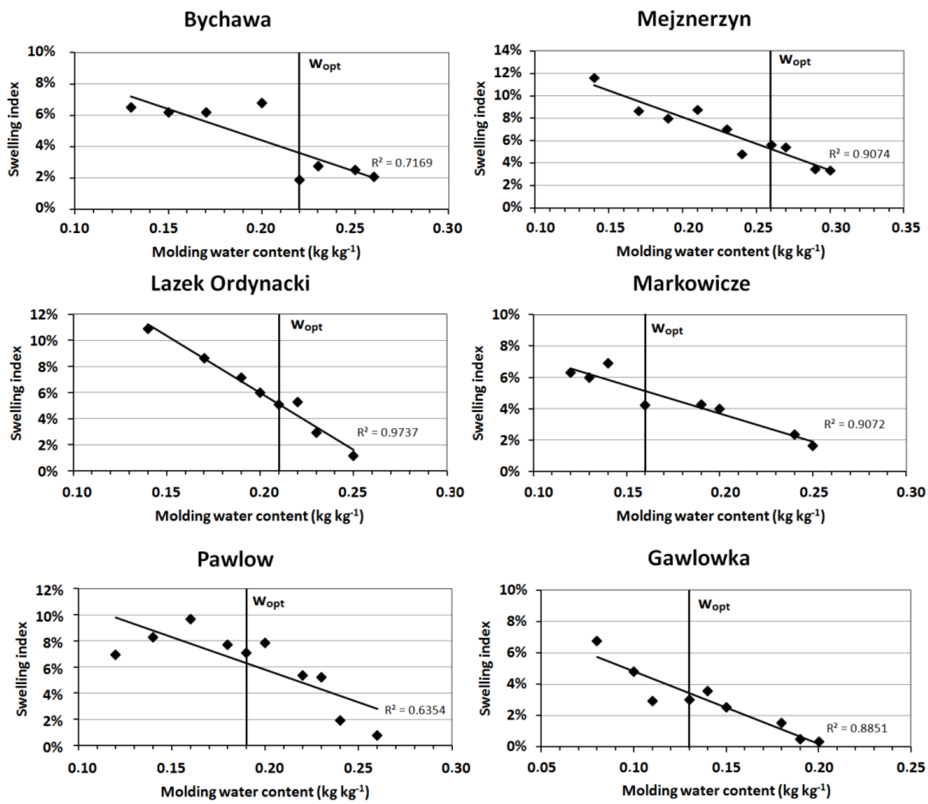

Fig. 5.7. Swelling index for all tested clay substrates

Characteristic values of the swelling index (*SI*) were summarized in Tab. 5.14.

Tab. 5.14. Characteristic values of swelling index for tested materials

Substrate	Mean swelling index (%)	Max swelling index (%)	Min swelling index (%)	SD
Bychawa	4.4	6.8	1.9	0.022
Lazek Ordynacki	5.9	10.9	1.1	0.031
Pawlow	6.7	11.6	3.4	0.026
Mejznerzyn	6.1	9.7	0.8	0.028
Markowicze	4.5	6.9	1.6	0.019
Gawlowka	2.9	6.7	0.3	0.020

5.1.7. Shrinkage characteristics of compacted clay materials

5.1.7.1. Linear shrinkage

Mean values of linear shrinkage indicator (*LS*) obtained during the bar test for compacted mineral materials were presented in Tab. 5.15 along with mean *COLE* for tested samples. According to suggestions of Jones and Hobbs (2005) no decimals for *LS* percentage values were presented.

Tab. 5.15. Linear shrinkage and *COLE* observed during shrinkage bar test

Substrate	Mean *LS* (%)	SD	Shrinkage type (Altmayer,1956)	*COLE* (-)	SD	Shrinkage potential (Parker et al., 1977)
Bychawa	7	1.7	Marginal	0.077	0.022	High
Lazek Ordynacki	7	1.7	Marginal	0.055	0.026	Moderate
Pawlow	6	1.6	Marginal	0.067	0.020	High
Mejznerzyn	6	2.7	Marginal	0.066	0.043	High
Markowicze	5	1.7	Marginal	0.052	0.026	Moderate
Gawlowka	3	0.8	Non-critical	0.044	0.044	Moderate

The observed mean *LS* varied between 7% and 3%, thus on the basis of the shrinkage behavior classified by Altmayer (1956), it may be described generally as marginal. The only exception was noted for the Gawlowka substrate presenting mean *LS*=3% and classified as non-critical. The *COLE* shrinkage potential indicator values calculated for samples from the bar test varied between 0.044 and 0.077 (the lowest value again for sandy Gawlowka), thus shrinkage potential of the studied bars was recognized as from moderate to high.

5.1.7.2. Volumetric shrinkage

Results of volumetric shrinkage tests of the studied clayey substrates, covering *COLE* and r_s dimensionless shrinkage indicators are presented in Fig. 5.8.

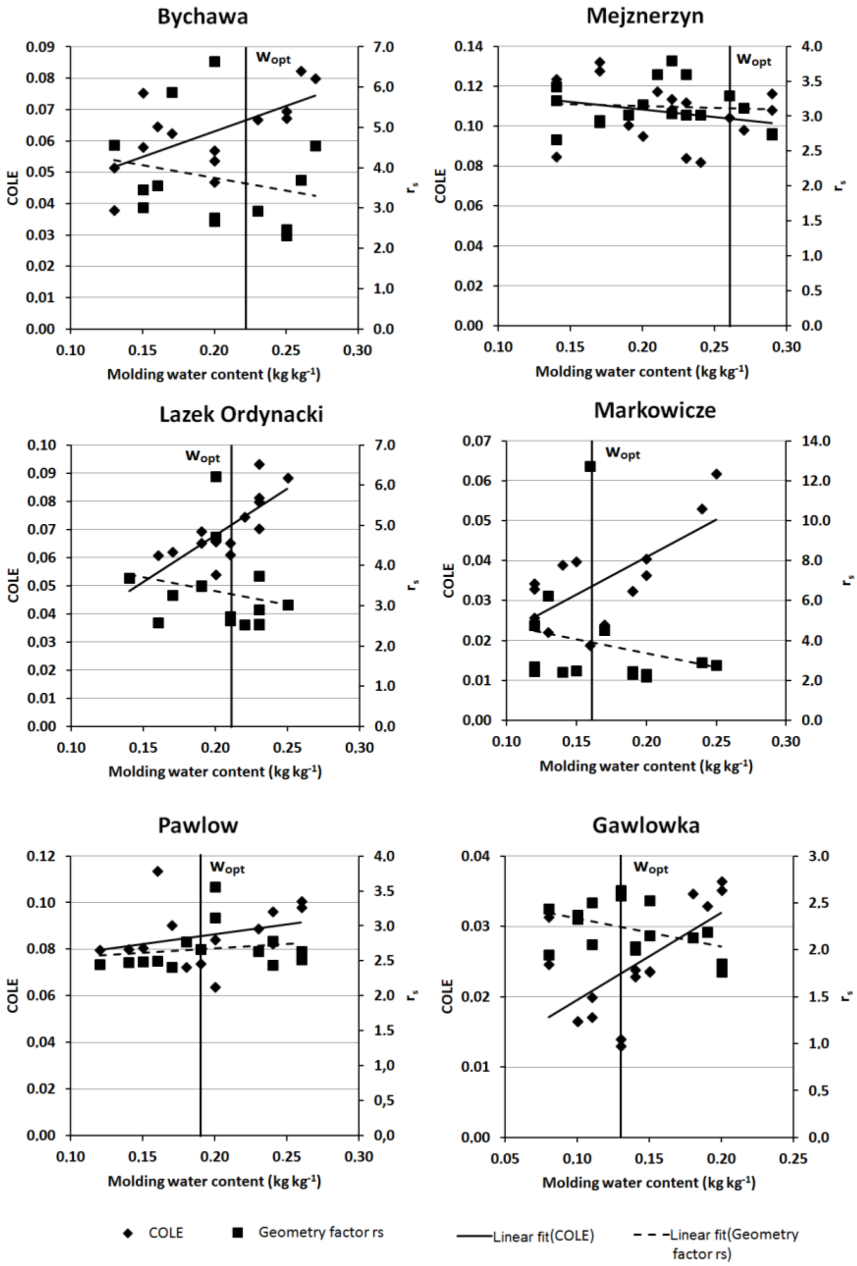

Fig. 5.8. Volumetric shrinkage characteristics of the tested clayey materials

Analysis of Fig. 5.8 allows to assess the shrinkage potential and shrinkage type for all tested substrates, in relation to the applied variable molding water content. Linear fits of *COLE* values for the subsequent water contents reflect the shapes of shrinkage potential discussed earlier. In most cases, excluding Mejznerzyn substrate, there were visible clear tendencies of increase in *COLE* value related to the increase in molding water content. Obviously, the inclination of the curve and values of its coordinates were different.

The *COLE* values for Bychawa substrate increased from 0.038 to 0.082 for range of molding water content from 0.13 to 0.27 kg kg^{-1}, so its shrinkage potential can be described as from moderate to high. Similar description of shrinkage potential (from moderate to high) was noted for Lazek Ordynacki, but slightly higher values of *COLE* were observed, i.e. from 0.054 to 0.093. Furthermore, shrinkage potentials from high to very high was determined for two substrates, Pawlow and Mejznerzyn. Values of *COLE* observed for Pawlow varied between 0.064 and 0.114, while values noted for Mejznerzyn were in range of 0.082–0.132.

On the other hand, two of the tested substrates showed significantly lower values of *COLE* and classified shrinkage potential in the range from low to moderate or high. Thus, *COLE* for Markowicze was in the range from 0.019 to 0.062, allowing to classify its potential as from low to high for the range of molding water content 0.12–0.25 kg kg^{-1}.

The lowest *COLE* values were observed for the substrate sampled in Gawlowka, low plasticity clay, 0.013–0.036, which allowed to classify its shrinkage potential in range of low – moderate. Thus, it is clearly visible that despite the fact that required value of K_s, below $1.00 \cdot 10^{-9}$ m s^{-1} is available at a wide range of soil water content, the proper selection of water content during material forming may be crucial which is due to significant increase in shrinkage potential endangering the self-sustainability of the compacted clay liners.

In most of the tested cases, presented in Fig. 5.8, the value of the dimensionless geometry factor r_s decreased with the increase in the applied molding water content. Analysis of r_s value allowed to recognize the type of shrinkage that occurred. There was a decreasing tendency of r_s observed for Bychawa and Mejznerzyn for which the linear fit presented in Fig. 5.8 was in the range of predominant horizontal deformation. In case of the Lazek Ordynacki and Markowicze substrates there were observed tendencies of moving deformation type from predominant horizontal to predominant vertical. The generally vertical deformation caused by shrinkage was observed for Pawlow and Gawlowka substrates.

Thus, according to the presented observations, the type of shrinkage that occurred may be connected with the type of substrate and content of sand, silt and clay fraction (or coarse and fines). The greater amount of sand fraction resulted in predominant vertical deformation, on the other hand, increased clay content led to horizontal deformation, and it usually resulted in desiccation cracking (e.g. Peng et al., 2006; Gebhardt et al., 2012). The mean values of *COLE* and r_s for the tested substrates are presented in Tab. 5.16.

Tab. 5.16. Mean values of *COLE* and r_s for the six tested substrates

Substrate	Mean *COLE* (-)	SD	Shrinkage potential (Parker, et al. 1977)	Mean r_s (-)	SD	Shrinkage deformation (Bronswijk, 1990)
Bychawa	0.062	0.013	High	3.7	1.30	Predominant horizontal
Lazek Ordynacki	0.071	0.011	High	3.3	1.00	Predominant horizontal
Pawlow	0.085	0.013	High	2.7	0.31	Predominant vertical
Mejznerzyn	0.107	0.015	Very high	3.1	0.32	Predominant horizontal
Markowicze	0.035	0.012	Moderate	3.8	2.84	Predominant horizontal
Gawlowka	0.024	0.008	Low	2.2	0.27	Predominant vertical

In case of the studied materials applications as materials for compacted clay liner formed at suggested molding water content, i.e. $w_{opt} \leq w_f \leq 1.2 w_{opt}$ and 95% Proctor density, (Wysokiński, 2007) the resulting effects presented in Table 5.17 are possible.

Tab. 5.17. Determined shrinkage characteristics for $w_{opt} \leq w_f \leq 1.2 w_{opt}$ and 95% Proctor density

Substrate	w_f (kg kg^{-1})	*COLE* (-)	Shrinkage potential (Parker, et al. 1977)	r_s (-)	Shrinkage deformation (Bronswijk, 1990)
Bychawa	0.25	0.07	High	3.3	Predominant horizontal
Lazek Ordynacki	0.25	0.08	High	3.3	Predominant horizontal
Pawlow	0.22	0.085	High	2.7	Predominant vertical
Mejznerzyn	0.30	0.102	Very high	3.1	Predominant horizontal
Markowicze	0.20	0.04	Moderate	3.5	Predominant horizontal
Gawlowka	0.15	0.025	Low	2.2	Predominant vertical

Thus, as it is visible in Tab. 5.17, the forming of the tested substrates during compacted liner construction at w_f suggested by the Polish guidelines (Wysokiński, 2007), wet of optimum, resulted in shrinkage potential in the range of “very high –

high” for high plasticity materials containing significant amounts of clay fraction and clay minerals, i.e. Bychawa, Lazek Ordynacki, Pawlow and Mejznerzyn.

On the other hand, compaction performed dry of optimum, on the left “dry” side of Proctor curve, allowed to obtain shrinkage characteristics presented in Tab. 5.18. It is visible that in most cases, except Mejznerzyn substrate, the observed values of *COLE* for 95% of Proctor density and $w_f<w_{opt}$ were lower than the results noted for $w_{opt}\leq w_f\leq 1.2w_{opt}$, but the recognized shrinkage potential type remained the same.

Tab. 5.18. Determined shrinkage characteristics for $w_f<w_{opt}$ and 95% Proctor density

Substrate	w_f (kg kg^{-1})	*COLE* (-)	Shrinkage potential (Parker, et al. 1977)	r_s (-)	Shrinkage deformation (Bronswijk, 1990)
Bychawa	0.20	0.062	High	3.8	Predominant horizontal
Lazek Ordynacki	0.19	0.062	High	3.5	Predominant horizontal
Pawlow	0.16	0.082	High	2.6	Predominant vertical
Mejzerzyn	0.20	0.11	Very high	3.2	Predominant horizontal
Markowicze	0.12	0.025	Low	4.2	Predominant horizontal
Gawlowka	0.08	0.018	Low	2.4	Predominant vertical

There was only one significant exception noted, reduction of shrinkage potential classification, from moderate to low, for Markowicze substrate. However this material, as it was mentioned before, at w_f=0.12 kg kg^{-1} (95% of the Proctor density) failed to meet the popular $K_s\leq 1.0\cdot 10^{-9}$ m s^{-1} requirements.

5.1.8. Water retention curves of compacted materials

Results of measurements of water retention characteristics for all the tested substrates after compaction at variable water contents are presented in Fig. 5.9 where pF curves for drying (dewatering) and selected molding water contents were presented.

The results of the measured water retention characteristics fitted to the standard van Genuchten’s model (van Genuchten, 1980) are presented in Tab. 5.19 – 5.24. The data presented cover both curves, watering and dewatering (drying) related to the observed water retention curve hysteresis.

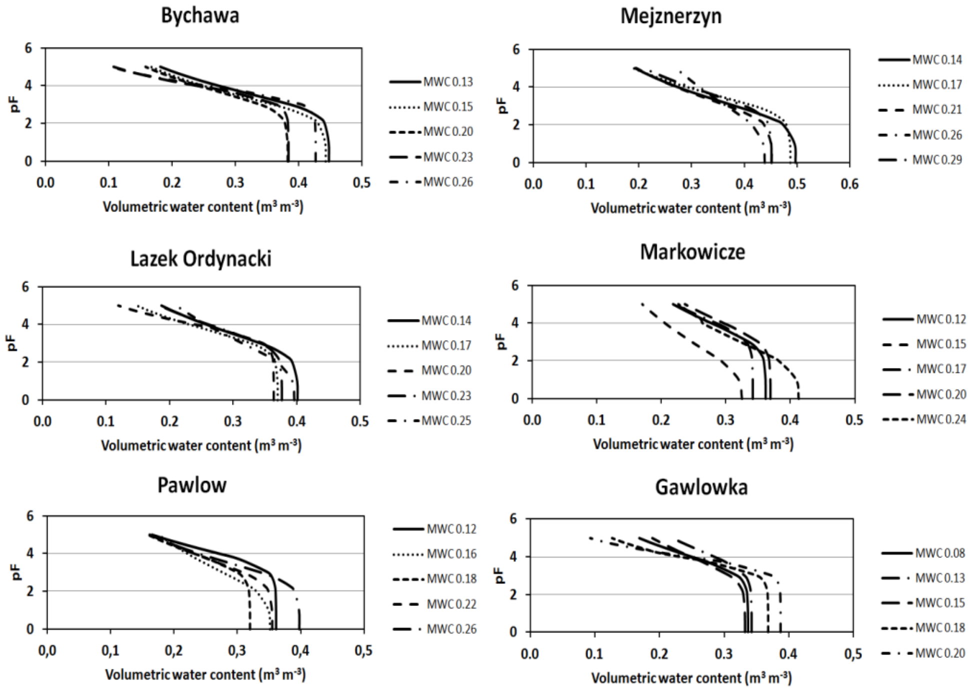

Fig. 5.9. Water retention curves (pF curves) for the tested substrates compacted at different water contents, MWC – molding water content, kg kg^{-1}

Tab. 5.19. Determined van Genuchten's parameters for compacted Bychawa substrate

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.13	Dewatering	0.447	0.148	1.180	0.985
	Watering		0.112	1.190	0.982
0.15	Dewatering	0.443	0.254	1.177	0.992
	Watering		0.271	1.174	0.992
0.20	Dewatering	0.383	0.110	1.188	0.984
	Watering		0.112	1.187	0.984
0.22	Dewatering	0.370	0.075	1.236	0.985
	Watering		0.081	1.229	0.985
0.23	Dewatering	0.384	0.031	1.370	0.974
	Watering		0.032	1.370	0.975
0.25	Dewatering	0.411	0.209	1.167	0.991
	Watering		0.203	1.167	0.991
0.26	Dewatering	0.426	0.031	1.408	0.979
	Watering		0.033	1.387	0.978

Tab. 5.20. Determined van Genuchten's parameters for compacted Lazek Ordynacki substrate

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.14	Dewatering	0.401	0.228	1.141	0.990
	Watering		0.570	1.118	0.991
0.17	Dewatering	0.37	0.105	1.197	0.989
	Watering		0.104	1.197	0.990
0.19	Dewatering	0.368	0.928	1.123	0.992
	Watering		0.997	1.120	0.993
0.20	Dewatering	0.364	0.031	1.325	0.979
	Watering		0.046	1.257	0.972
0.21	Dewatering	0.363	0.675	1.116	0.994
	Watering		0.830	1.113	0.996
0.22	Dewatering	0.363	0.849	1.113	0.992
	Watering		0.894	1.112	0.992
0.23	Dewatering	0.376	0.100	1.155	0.981
	Watering		0.119	1.149	0.983
0.25	Dewatering	0.396	1.274	1.089	0.983
	Watering		1.405	1.082	0.990

Tab. 5.21. Determined van Genuchten's parameters for Pawlow substrate

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.12	Dewatering	0.361	0.028	1.233	0.900
	Watering		0.039	1.210	0.906
0.14	Dewatering	0.352	0.453	1.106	0.994
	Watering		0.738	1.100	0.998
0.16	Dewatering	0.351	1.004	1.100	0.986
	Watering		1.380	1.099	0.990
0.18	Dewatering	0.320	0.060	1.171	0.991
	Watering		0.063	1.168	0.991
0.20	Dewatering	0.347	0.029	1.215	0.956
	Watering		0.042	1.189	0.983
0.22	Dewatering	0.355	0.185	1.144	0.987
	Watering		0.165	1.147	0.986
0.24	Dewatering	0.376	0.096	1.132	0.995
	Watering		0.104	1.130	0.995
0.26	Dewatering	0.398	0.187	1.172	0.987
	Watering		0.142	1.182	0.979

Tab. 5.22. Determined van Genuchten's parameters for Mejznerzyn substrate

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.14	Dewatering	0.497	0.486	1.153	0.993
	Watering		0.544	1.151	0.994
0.17	Dewatering	0.487	0.148	1.189	0.993
	Watering		0.169	1.183	0.995
0.19	Dewatering	0.458	1.031	1.081	0.992
	Watering		1.344	1.079	0.946
0.20	Dewatering	0.465	0.554	1.102	0.995
	Watering		0.607	1.100	0.995
0.21	Dewatering	0.451	0.340	1.144	0.996
	Watering		0.332	1.144	0.996
0.22	Dewatering	0.458	0.294	1.137	0.998
	Watering		0.294	1.137	0.998
0.23	Dewatering	0.460	0.287	1.079	0.994
	Watering		0.394	1.074	0.997
0.24	Dewatering	0.425	0.017	1.179	0.856
	Watering		0.019	1.179	0.889
0.26	Dewatering	0.439	1.452	1.067	0.988
	Watering		1.599	1.067	0.999
0.27	Dewatering	0.441	0.507	1.086	0.993
	Watering		0.441	1.087	0.992
0.29	Dewatering	0.451	0.135	1.156	0.995
	Watering		0.173	1.149	0.997

Fig. 5.9 and data presented in Tab. 5.19 – 5.24 show that compaction did not drastically change the shape of pF curves for all the tested clayey substrates. For most applied molding water contents, the observed water retention curves had the typical shape for clayey soils, i.e. very low gravitational water content below field capacity (between pF 0.0 and 2.0) because of the nearly vertical curve at this range. The slightly increased drainage water, of approx. few vol. % water was observed only for several pF curves for Markowicze, Mejznerzyn and Lazek Ordynacki. Then, inclination of obtained retention curves in the range of available water was quite similar for all the tested cases – see Fig. 5.10.

Thus, water holding capacity values (pF=2.0–4.2) for the following tested substrates were in the range: Bychawa 0.154–0.204 m^3 m^{-3}, Lazek Ordynacki 0.118–0.152 m^3 m^{-3}, Pawlow 0.101–0.166 m^3 m^{-3}, Mejznerzyn 0.083–0.216 m^3 m^{-3}, Markowicze 0.074– 0.209 m^3 m^{-3} and Gawlowka 0.082–0.174 m^3 m^{-3}.

Tab. 5.23. Determined van Genuchten's parameters for compacted Markowicze clay

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.12	Dewatering	0.362	0.114	1.107	0.963
	Watering		0.487	1.086	0.992
0.13	Dewatering	0.376	0.081	1.135	0.968
	Watering		0.233	1.109	0.991
0.14	Dewatering	0.353	0.032	1.311	0.986
	Watering		0.025	1.339	0.970
0.15	Dewatering	0.326	2.799	1.082	0.968
	Watering		4.909	1.072	0.976
0.16	Dewatering	0.336	0.037	1.139	0.914
	Watering		0.065	1.128	0.908
0.17	Dewatering	0.342	0.038	1.121	0.917
	Watering		0.075	1.110	0.911
0.19	Dewatering	0.359	0.166	1.100	0.978
	Watering		0.032	1.180	0.966
0.20	Dewatering	0.369	0.078	1.101	0.946
	Watering		0.151	1.090	0.965
0.24	Dewatering	0.4130	1.550	1.089	0.980
	Watering		2.450	1.077	0.983
0.25	Dewatering	0.422	0.133	1.461	0.995
	Watering		0.102	1.494	0.993

Tab. 5.24. Determined van Genuchten's parameters for Gawlowka substrate

Molding water content (kg kg^{-1})	Process	θ_s (m^3 m^{-3})	α (m^{-1})	n (-)	R^2
0.08	Dewatering	0.337	0.045	1.181	0.918
	Watering		0.083	1.157	0.934
0.10	Dewatering	0.310	0.102	1.142	0.964
	Watering		0.568	1.103	0.938
0.11	Dewatering	0.330	0.019	1.255	0.974
	Watering		0.061	1.150	0.974
0.13	Dewatering	0.311	0.011	1.361	0.954
	Watering		0.026	1.218	0.976
0.14	Dewatering	0,314	0.109	1.221	0.995
	Watering		0.158	1.207	0.986
0.15	Dewatering	0.332	0.098	1.123	0.945
	Watering		0.207	1.107	0.964
0.18	Dewatering	0.368	0.030	1.371	0.989
	Watering		0.067	1.254	0.989
0.19	Dewatering	0.373	0.018	1.549	0.968
	Watering		0.041	1.318	0.975
0.20	Dewatering	0.387	0.023	1.456	0.992
	Watering		0.019	1.510	0.990

Data presented in Tab. 5.19 – 5.24 and Fig. 5.9 show also movement of water retention curve origination along the horizontal coordination axis due to changes of porosity and water capacity at pF=0 for each applied molding water content.

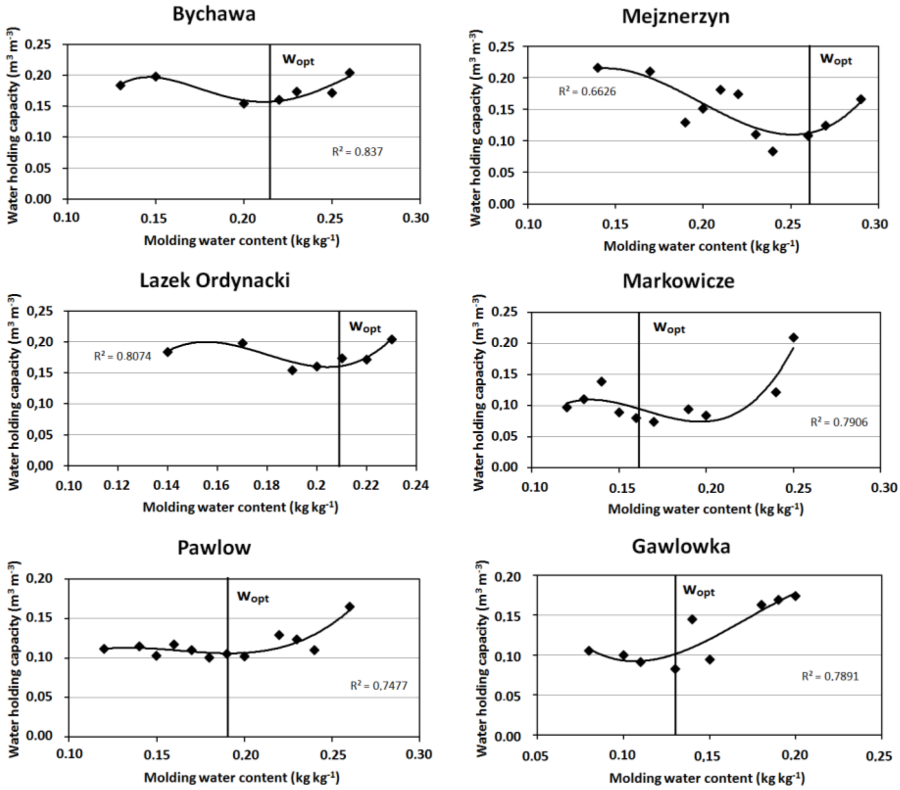

Fig. 5.10. Water holding capacity (volumetric water content between pF 2.0 and 4.2) for all tested substrates after compaction

The shape of water retention curve also allows to assess the content of macro-, meso- and micropores in the tested porous material. The threshold values of pF for equivalent pore diameters were assumed as pF=2.0 for 30 μm diameter (border between macropores and mesopores) and pF 4.2 for 0.2 μm diameter as threshold value for micropores (e.g. Paivanen, 1973; Walczak et al., 2002; Witkowska-Walczak et al., 2004). The observed distributions of macropores, mesopores and micropores for selected tested molding water contents of all substrates under study are presented in Fig. 5.11.

In most of the cases presented in Fig. 5.11 the shares of particular pore types were comparable. The only significant exception was observed for the Markowicze substrate compacted at high water contents, where for e.g. 0.25 kg kg^{-1} the evident increase in mesopores was noted.

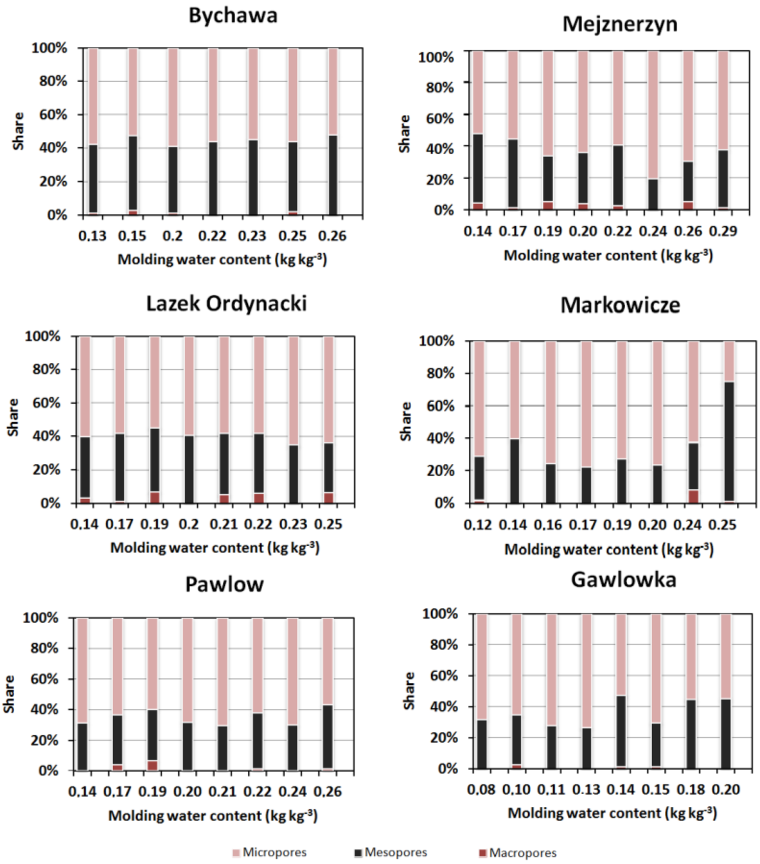

Fig. 5.11. Pore size distribution for the tested clay materials

The generally dominating pore size for all tested samples was classified as micropores, the share of which varied between approx. 52–59% for Bychawa, 55–65% for Lazek Ordynacki, 57–70% for Pawlow, 52–80% for Mejznerzyn, 25–78% for Markowicze and, finally, 53–75% for Gawlowka. Contrarily, the largest pores, i.e. macropores had the lowest share of total porosity in all tested substrate samples and for all applied molding water contents. The observed ranges of macropores quota for studied compacted materials were 0.2–2.8% for Bychawa, 0.3–7.0% for Lazek Ordynacki, 0.3–6.9% for Pawlow, 0.1–5.6% for Mejznerzyn, 0.2–8.1% for Markowicze and 0.1–2.4% for Gawlowka.

Fig. 5.12 presents mean pore size distribution for all the tested clay substrates and all applied values of molding water content.

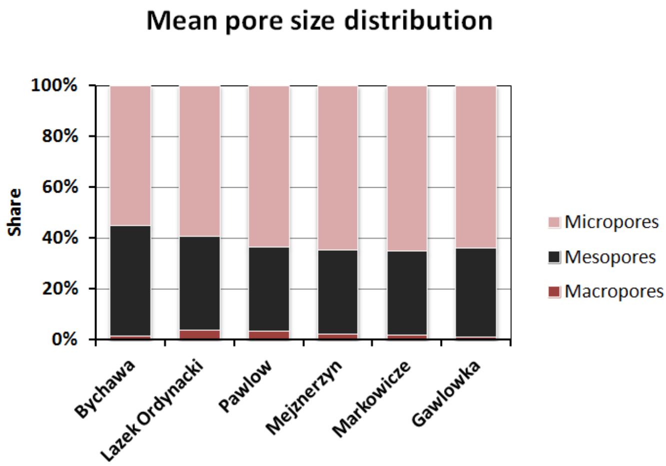

Fig. 5.12. Mean pore size distribution for compacted clay materials

Fig. 5.12 shows that the mean share of macropores was the lowest for the Bychawa and Gawlowka substrates, 1.2% and 0.8%, respectively and the biggest in case of Pawlow and Lazek Ordynacki, 3.2% and 3.8%. The mean share of mesopores was similar for most of the tested substrates and varied between 32.9% for Markowicze and 36.6% for Lazek Ordynacki. The greatest mean share of mesopores was noted for Bychawa compacted clay, i.e. 43.4%. Thus, the dominant pore size were the micropores whose share varied between 55.3% for Bychawa and 65.4% for Markowicze.

5.1.9. Saturated hydraulic conductivity of compacted clays after drying and rewetting

The crucial assessment of compacted clay liners' long-term hydraulic sustainability and resistance to external conditions, understood as cyclic drying and rewetting causing cyclic shrinkage and swelling, was based on the measurements of the saturated hydraulic conductivity of clays, compacted at different water contents, air dried and rewetted in the three subsequent cycles.

Fig. 5.13 presents results of the saturated hydraulic conductivity measurements conducted for all the six tested substrates and variable molding water contents and three subsequent cycles of air drying and rewetting. The results of K_s measurements presented in Fig. 5.13 show that in all the tested cases the drying and rewetting of substrates' samples resulted in the loss of their sealing capabilities. No tested sample, regardless of its particle size composition, mineralogy and the applied molding water content was able to sustain the required K_s=1.0·10^{-9} m s^{-1}.

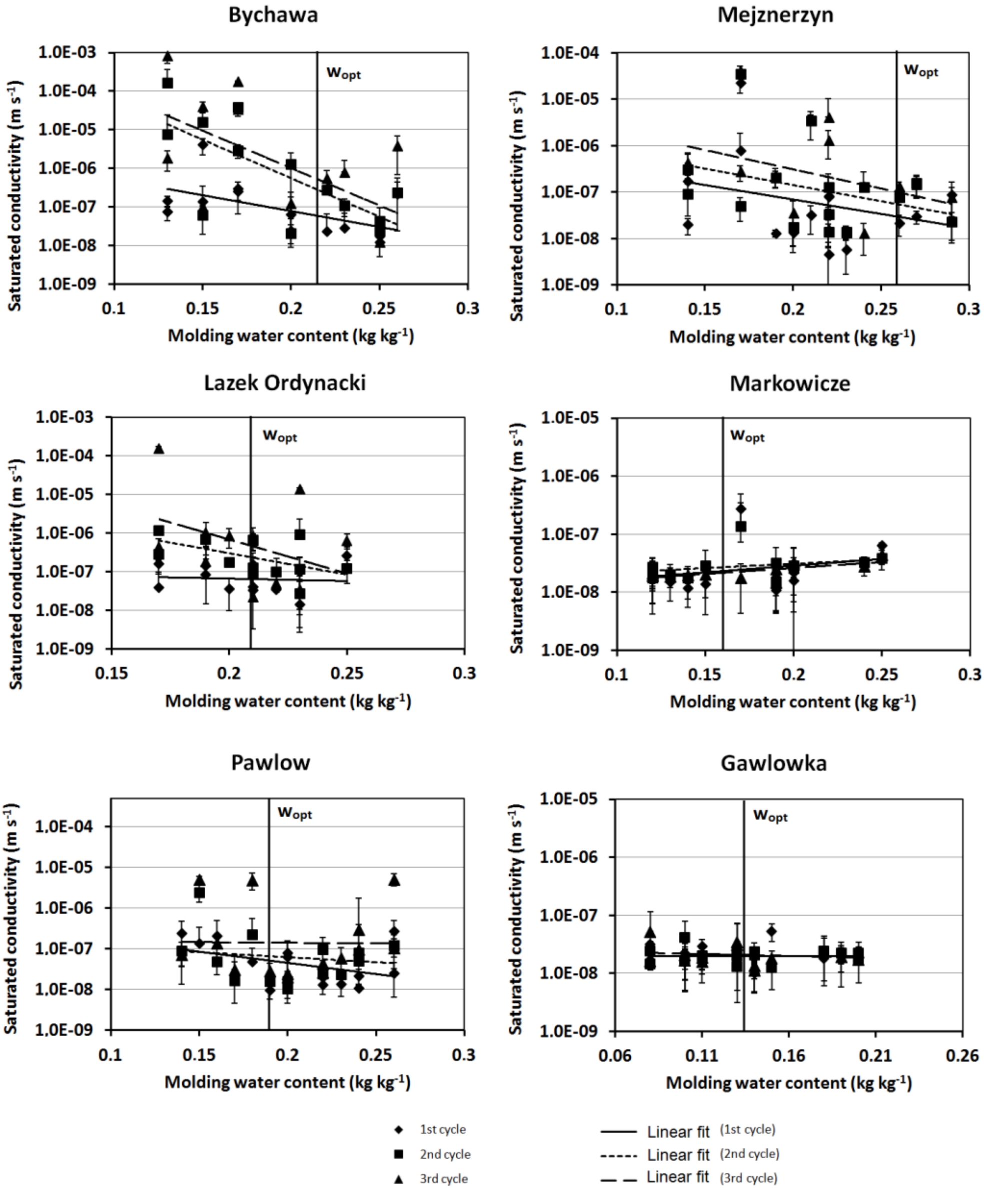

Fig. 5.13. Saturated hydraulic conductivity of tested clays, compacted at various water contents, after three cycles of air drying and wetting, error bars – SD

In many cases the increase in K_s value to the level of 10^{-4}–10^{-5} m s^{-1} was observed. As an example, the following maximum values of K_s were observed for the tested substrates at 1st, 2nd and 3rd drying and rewetting cycle (for variable molding water contents), respectively: Bychawa – $4.1 \cdot 10^{-6}$ m s^{-1}, $1.66 \cdot 10^{-4}$ m s^{-1} and $8.45 \cdot 10^{-4}$ m s^{-1}; Lazek Ordynacki – $2.17 \cdot 10^{-7}$ m s^{-1}, $1.19 \cdot 10^{-6}$ m s^{-1}, $1.59 \cdot 10^{-4}$ m s^{-1};

Pawlow – $2.78 \cdot 10^{-7}$ m s^{-1}, $2.52 \cdot 10^{-6}$ m s^{-1}, $5.19 \cdot 10^{-6}$ m s^{-1}; Mejznerzyn – $2.23 \cdot 10^{-5}$ m s^{-1}, $3.44 \cdot 10^{-5}$ m s^{-1}, $3.99 \cdot 10^{-5}$ m s^{-1}; Markowicze – $2.79 \cdot 10^{-7}$ m s^{-1}, $1.35 \cdot 10^{-7}$ m s^{-1}, $4.37 \cdot 10^{-8}$ m s^{-1}; Gawlowka – $5.33 \cdot 10^{-8}$ m s^{-1}, $4.16 \cdot 10^{-8}$ m s^{-1}, $5.21 \cdot 10^{-8}$ m s^{-1}. Thus, the highest noted maximum values of K_s, typical for various sandy soils were observed for the Bychawa, Lazek Ordynacki and Mejznerzyn substrates, while the lowest results were noted for Markowicze and Gawlowka.

Despite the scattered data points representing the obtained results, the additional linear fits presented also in Fig. 5.13 are useful to establish the general tendency for the studied phenomenon. In most of the cases, i.e. for Bychawa, Lazek Ordynacki, Pawlow and Mejznerzyn, the following findings were observed: i) the growing number of drying and rewetting cycles resulted in the increased value of measured coefficient of saturated hydraulic conductivity; ii) for each drying and wetting cycle the increase in the molding water content resulted in lower increase in the K_s value; iii) the increase in saturated hydraulic conductivity for each cycle was greater for high plasticity substrates compacted at low water contents.

In the case of the substrates sampled in Markowicze and Gawlowka, containing significantly greater amount of the coarse sand fraction, the clearly different behavior of soil samples was observed. There was no observed clear and significant increase in the measured K_s value caused by cyclic drying and rewetting noted for the compacted Markowicze and Gawlowka clays and the relation between applied molding water content and the increase in the coefficient of saturated hydraulic conductivity was also imperceptible. In the case of both discussed substrates the measured K_s values for each drying-rewetting cycle were in the limited range i.e. approx. 10^{-8}–10^{-7} m s^{-1}. The fitted linear trend lines were almost horizontal (in case of Gawlowka) or presented an even slightly ascending tendency (Markowicze). Thus, we may state that according to the presented results of K_s measurements, both discussed clay materials of medium and low plasticity showed limited susceptibility to increase in saturated conductivity after several cycles of air drying and wetting. Moreover, no significant influence of the applied molding water content on the increase in K_s value after subsequent cycles of drying and rewetting was observed, in relation to data obtained for previously discussed results in the case of which the increase by several e.g. 6 or 7 orders of magnitude versus K_s after compaction, before the first desiccation, was observed.

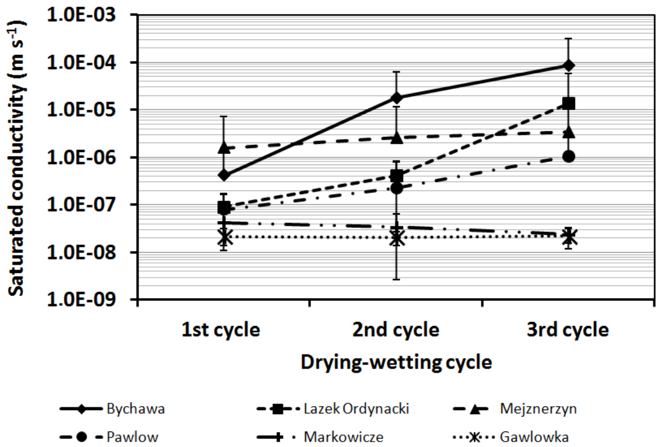

Fig. 5.14. Mean saturated hydraulic conductivity for all tested clay materials after one, two and three cycles of drying and wetting, error bars – SD

To better illustrate the above discussed changes of saturated hydraulic conductivity of compacted clay materials after several cycles of air drying and rewetting until the full saturation, the mean values of K_s for each material and drying and wetting cycle were presented in Fig. 5.14. It is clearly visible that in all the cases the tested compacted clays were unable to sustain the required level of K_s lower than $1.0{\cdot}10^{-9}$ m s^{-1}. For some studied substrates, including Bychawa, Lazek Orydnacki and Pawlow, there was visible a considerable increase in mean K_s value for the subsequent cycles of drying-wetting. The discussed increase between the first and the final, third cycle was equal approx. two orders of magnitude for Bychawa and Lazek Ordynacki, and one order of magnitude for Pawlow. The mean K_s for the substrate sampled in Mejznerzyn was equal to $1.59{\cdot}10^{-6}$ m s^{-1}, $2.60{\cdot}10^{-6}$ m s^{-1}, $3.37{\cdot}10^{-6}$ m s^{-1} for the 1st, 2nd ant the 3rd cycle, respectively. Thus, in this case more than 100% of K_s increase was noted. On the other hand, the Markowicze and Gawlowka clay materials presented the nearly constant mean value of K_s measured after the consecutive drying-wetting cycle. In the case of Gawlowka substrate, the measured mean values of coefficient of saturated hydraulic conductivity for the three cycles varied between $2.15{\cdot}10^{-8}$ m s^{-1} and $2.22{\cdot}10^{-8}$ m s^{-1}. The Markowicze clay presented even slight decrease in measured mean K_s for the following cycles ($4.28{\cdot}10^{-8}$ m s^{-1}, $3.38{\cdot}10^{-8}$ m s^{-1}and $2.37{\cdot}10^{-8}$ m s^{-1}, respectively). Thus, these two clay substrates, containing considerable share of coarse sand fraction, presented substantial resistance to the increase in K_s value caused by repeated air drying and wetting resulting in full saturation. So, despite the fact, that after the first cycle of drying and wetting their saturated hydraulic conductivity increased to the level of approx. $2.0{\cdot}10^{-8}$–$4.0{\cdot}10^{-8}$ m s^{-1}, greater than the required standardized value, the further increase in K_s, leading to rapid deterioration of compacted clay liner sealing capabilities allowing increased infiltration of surface water into the waste body, was not observed. This feature of compacted clay liners utilizing materials from Markowicze and Gawlowka, may considerably sustain or increase the sustainability of top capping systems in variable atmospheric conditions, during possible failures, landslides, exposition of clay liner to direct atmospheric conditions including sunlight, wind etc. Moreover, in both cases the resultant values of K_s after the third cycle of shrinkage and swelling for Markowicze and Gawlowka, was lower than value of $1 \cdot 10^{-7}$ m s^{-1} for compacted earthen liner required by EPA technical manual (EPA, 1993).

5.1.10. Correlations between selected characteristics of tested substrates

Analyses of the results presented above referring to different measurements covering inter allia physical, geotechnical and hydraulic characteristics of the six tested clay materials prone to be used in construction of compacted clay liners allowed to observe several important and statistically significant correlations between varying studied properties of clays.

First, the relations between the basic characteristics of studied clay substrates, including particle size composition, mineral characteristics, FeOOH and $CaCO_3$ contents and values of obtained Atterberg limits were studied. There were observed no statistically significant correlations between mineral characteristics, including clay minerals, swelling and non-swelling minerals, (K+Ch)/(I+S) ratio, FeOOH and $CaCO_3$, quartz and feldspars contents and Atterberg limits. The remaining obtained coefficients of correlation are presented in Tab. 5.25.

Tab. 5.25. Correlation coefficients between particle size fractions of the tested clays and obtained Atterberg limits; underlined values are statistically significant at $p<0.05$

	Liquid limit *LL*	Plastic limit *PL*	Plasticity index *PI*	Shrinkage limit *SL*	Potential swell *S*
Sand 2–0.05 mm	<u>-0.915</u>	<u>-0.822</u>	<u>-0.898</u>	<u>-0.874</u>	-0.773
Silt 0.05–0.002 mm	<u>0.827</u>	0.803	0.780	0.801	0.629
Clay <0.002mm	<u>0.833</u>	0.624	<u>0.880</u>	0.770	<u>0.845</u>

Tab. 5.25 shows strong, positive or negative, statistically significant correlations between: i) sand content and liquid limit, plastic limit, plasticity index and shrinkage limit; ii) clay content and liquid limit, plasticity index and potential swell. The potential swell was introduced to the above presented analysis because its value is based on the Atterberg limits (Seed et al., 1962; Bentley and Carter, 1991). The negative correlations between sand fraction content and the mentioned Atterberg

limits show that reduction in the sand fraction share should increase values of *LL*, *PL*, *PI* and *SL*, on the other hand increase in the sand fraction content reduces values of Atterberg limits. On the other hand, increase in clay content increases values of Atterberg limits, for which strong statistically significant correlations were observed in the cases of *LL*, *PI* and the potential swell. Additionally, numerous significant correlations were observed for clay minerals (positive correlations) as well as quartz and feldspars (negative correlations) contents and single point surface area, BET surface area, t-Plot micropore and external surface area, mean particle diameter and mean mesopores radius.

Analysis of correlations between general characteristics discussed above and strength parameters including internal friction angle, cohesion, moduli of primary and secondary compressibility M_o/M and resistance to penetration showed nearly no statistically significant correlations. There were only three strong significant correlations for $p<0.05$ noted. R=-0.948 for relation between FeOOH content and internal friction angle, R=0.914 for again FeOOH content and cohesion and finally, R=-0.814 between clay minerals content and resistance to penetration.

Then relations between general characteristics of the tested substrates and results of compaction including Proctor density, w_{opt}, K_s at w_f, K_s at w_f (for $w_{opt}<w_f<1.2\ w_{opt}$) and K_s after the third cycle of drying and rewetting were studied.

According to the results of linear regression presented in Tab. 5.26 there were several strong statistically significant correlations observed for particle size fractions and compaction effects, i.e. R=0.81 between sand fraction content and maximum Proctor's density, R=0.985 for relation between sand fraction content and K_s at w_{opt}, R=-0.951 for silt fraction content and K_s at w_{opt}, R=-0.813 for clay fraction content and R=-0.855 for clay content and K_s a w_f. If the weaker correlations (below R=0.81) should be added to the consideration, we may state that increase in sand content resulted in increased value of the Proctor density and saturated hydraulic conductivity for the optimal water content. On the other hand, increase in silt and clay content resulted in lower Proctor's density and K_s at optimal and forming water content. Interestingly, the contents of swelling minerals and FeOOH showed strong correlation, R=0.90 in both cases, with saturated hydraulic conductivity after three cycles of air drying and rewetting. Quartz and feldspar content showed positive correlation (R=0.841) with maximum Proctor density and negative (R=-0.887) with optimal water content. In case of the factors influencing the value of optimal water content, its value was increased with the increase in clay fraction and clay minerals content and reduced with the sand fraction as well as quartz and feldspars content.

Tab. 5.26. Correlations between general characteristics of the tested clays and compaction effects; underlined values are statistically significant at $p<0.05$

	Maximum Proctor density	Optimal water content	K_s at w_{opt}	K_s at w_f	Max K_s after 3rd cycle
Sand 2–0.05 mm	0.812	-0.772	0.985	0.600	-0.295
Silt 0.05–0.002 mm	-0.697	0.652	-0.951	-0.392	0.415
Clay <0.002mm	-0.813	0.795	-0.771	-0.855	-0.037
Clay minerals content	-0.728	0.800	-0.586	-0.700	0.707
Swelling minerals content (I+S)	-0.608	0.664	-0.669	-0.441	0.901
Non-swelling minerals content (K+Ch)	-0.164	0.187	0.223	-0.442	-0.455
(K+Ch)/(I+S)	0.287	-0.257	0.649	-0.063	-0.598
FeOOH content	-0.363	0.442	-0.453	-0.259	0.900
$CaCO_3$ content	-0.342	0.220	-0.402	0.117	-0.358
Quartz and feldspars content	0.841	-0.887	0.743	0.664	-0.721

There were also observed the positive correlations between optimal water content and single point surface area, BET surface area, Langmuir surface area and t-Plot micropore area. K_s at w_f was also positively correlated to the mean particle diameter.

Results of correlations analysis between the earlier discussed general characteristics of the tested substrates and swell-shrink characteristics are presented in Tab. 5.27.

Tab. 5.27. Correlations between general characteristics of tested substrates and swell-shrink characteristics; underlined values are statistically significant at $p<0.05$

	Mean *LS*	*COLE* at w_{opt}	r_s at w_{opt}	Mean *COLE*	Mean r_s	Mean swell index
Sand 2–0.05 mm	-0.956	-0.822	-0.724	-0.734	-0.621	-0.830
Silt 0.05–0.002 mm	0.955	0.643	0.841	0.521	0.771	0.654
Clay <0.002mm	0.683	0.954	0.275	0.960	0.133	0.952
Clay minerals content	0.678	0.700	0.262	0.677	0.309	0.378
Swelling minerals content (I+S)	0.823	0.516	0.534	0.416	0.608	0.948
Non-swelling minerals content (K+Ch)	-0.355	0.293	-0.563	0.446	-0.620	0.220
(K+Ch)/(I+S)	-0.742	-0.158	-0.804	0.001	-0.826	-0.171
FeOOH content	0.713	0.276	0.449	0.141	0.530	0.016
$CaCO_3$ content	0.237	0.143	0.676	0.101	0.530	0.268
Quartz and feldspars content	-0.830	-0.741	-0.520	-0.682	-0.538	-0.430

Data presented in Tab. 5.27 show that the content of sand fraction, concerning strong significant (for $p<0.05$) but also weaker correlations had a reducing effect on swell and shrink characteristics. Increase in the sand fraction content reduced mean linear shrinkage (*LS*), *COLE* and mean swell index statistically significant. On the other hand, silt and clay content showed the strong and statistically significant positive correlations with mean *LS* (R=0.955) and r_s at w_{opt} (R=0.841) as well as *COLE* at w_{opt} (0.954), mean *COLE* (R=0.960) and mean swell index (R=0.952), respectively. Thus, gain of silt and clay content increases the swell and shrink characteristics of the tested substrates. No statistically significant correlations were observed for the clay minerals content, but the swelling minerals content showed correlation of R=0.823 with the mean linear shrinkage and R=0.948 with the mean swell index. Additionally, the (K+Ch)/(I+S) ratio showed the negative correlation equal to R=-0.826 with the mean r_s, so increasing the ratio of non-swelling versus swelling minerals contents decreases the value of the dimensionless shrinkage geometry factor, moving its value from the range of predominant horizontal towards isotropic and vertical deformation. As it should be expected, a negative correlation was also observed between the quartz and feldspar content and the mean linear shrinkage. Thus, to reduce the value of swell and shrink processes the substrates of appropriate sand fraction content should be selected as materials for compacted clay liner construction because, as it was noted, sand presence in clay material, reduces the linear shrinkage, shrink potential, and swell index. Mean *LS*, mean *COLE* and *COLE* for w_{opt} were also positively correlated to the t-Plot micropore area.

Analysis of relations between general characteristics and pore size distribution showed that among the tested materials the swelling minerals content showed a positive correlation with the mesopores share (R=0.815) and a negative one with micropores (R=-0.861). Similar observations were noted for FeOOH content and mesopores (R=0.926) and micropores (R=-0.98).

The most interesting remaining correlations between mean pore size distribution obtained from the water retention curves for compacted substrates and other tested characteristics were presented in Tab. 5.28.

Tab. 5.28. Correlation between pore size distribution and selected strength, swell and hydraulic parameters; underlined values are statistically significant at $p<0.05$

	Internal friction angle	Cohesion	Mean swell index	Max K_s after 3rd cycle
Macropores	-0.260	-0.240	<u>0.824</u>	-0.277
Mesopores	-0.790	<u>0.916</u>	-0.291	<u>0.965</u>
Micropores	<u>0.894</u>	<u>-0.875</u>	0.055	<u>-0.914</u>

The number of macropores, as it is visible in Tab. 5.28, was related to the increase in the mean swell index for the tested clay materials. Presence of mesopores was correlated to the increased cohesion (R=0.91) and maximum K_s after the third cycle of air drying and rewetting. Finally, the share of micropores was related to the internal friction angle increase (R=0.894) and decrease of cohesion (R=-0.85) and maximum obtained value of K_s after three cycles of air drying and rewetting (R=-0.914).

Next, the links between Atterberg limits and compaction results were studied and the obtained correlations are presented in Tab. 5.29.

Tab. 5.29. Correlations between Atterberg limits and compaction effects for tested substrates; underlined values are statistically significant at p<0.05

	Maximum Proctor density	Optimal water content	K_s at w_{opt}	w_f at 95% Proctor density
Liquid limit *LL*	<u>-0.942</u>	<u>0.883</u>	<u>-0.934</u>	<u>0.931</u>
Plastic limit *PL*	-0.798	0.694	<u>-0.901</u>	0.768
Plasticity index *PI*	<u>-0.947</u>	<u>0.917</u>	<u>-0.885</u>	<u>0.947</u>
Shrinkage limit *SL*	<u>-0.896</u>	<u>0.813</u>	<u>-0.930</u>	<u>0.871</u>
Potential swell *S*	<u>-0.937</u>	<u>0.921</u>	-0.754	<u>0.942</u>

Tab. 5.29 shows numerous strong and statistically significant correlations, positive or negative, between the obtained Atterberg limits and the effects of compaction performed for all the tested substrates. Including both the strong and weak correlations, its visible that during the researches performed an increase in Atterberg limits values was accompanied by a decrease in maximum Proctor density(R value up to -0.947) and saturated hydraulic conductivity after compaction at w_{opt} (R value to -0.934). On the other hand, the increased values of obtained Atterberg limits caused an increase in optimal water content (value of R up to 0.921) and forming water content at 95% of Proctor's density (R up to 0.947).

Finally, the relations between the obtained Atterberg limits and swell-shrink characteristics of all tested substrates were studied, see Tab. 5.30.

Tab. 5.30. Correlations between Atterberg limits and swell-shrink characteristics of tested clay materials; underlined values are statistically significant at p<0.05

	Mean *LS*	*COLE* for w_{opt}	r_s for w_{opt}	Mean *COLE*	Mean r_s	Mean swell index
Liquid limit *LL*	<u>0.826</u>	<u>0.873</u>	0.720	<u>0.831</u>	0.585	<u>0.821</u>
Plastic limit *PL*	0.706	0.614	<u>0.887</u>	0.571	<u>0.804</u>	0.620
Plasticity index *PI*	<u>0.828</u>	<u>0.942</u>	0.584	<u>0.904</u>	0.431	<u>0.865</u>
Shrinkage limit *SL*	0.760	0.771	0.792	0.739	0.686	0.743
Potential swell *S*	0.707	<u>0.933</u>	0.449	<u>0.919</u>	0.282	<u>0.815</u>

Again, several strong statistically significant positive correlations were observed for comparison of the Atterberg limits and swell-shrink characteristics of the tested compacted clay substrates. The mean linear shrinkage of compacted clays showed correlations with the liquid limit and plasticity index, the value of obtained R was equal to 0.826 and 0.828, respectively (the remaining limits allowed correlation in the range 0.706–0.76). *COLE* for w_{opt} and mean *COLE* for all applied molding water contents correlated with the liquid limit (*LL*), plasticity index (*PI*) and potential swell (*S*). Shrinkage geometry factor r_s showed correlation with the plastic limit (R=0.887). Finally, there were three significant correlations noted for the mean swell index, with liquid limit (R=0.821), plasticity index (R=0.865) and potential swell, as calculated according to Atterberg limits (R=0.815). Thus, the above shows than swelling and shrinkage potential, as it was presented on plasticity chart, increases with the growing values of Atterberg limits. So, in order to reduce the swell and shrinkage potentials, the materials presenting high values of *LL*, *PL* and *PI* should be avoided.

5.1.11. Verification of applicability according to ITB national criteria

As the final part of the experimental part of the presented studies which were to examine the various characteristics of clayey substrates affecting the sustainability of compacted clay liners constructed of tested materials, the applicability of studied clays to CCL forming was analyzed according to the most developed Polish national guidelines proposed by ITB, Instytut Techniki Budowlanej (Wysokiński, 2007).

Tab. 5.31 contains the summarized selected measured parameters of the six studied clay substrates affecting their applicability as material for a compacted clay liner, according to ITB guidelines (Wysokiński, 2007). The main requirement demanded from clays, not only by ITB guidelines but also by various European and national standards (e.g. Journal of Laws from 2013 item 523; Council Directive 99/31/EC; EPA 530-R-93-017), refers to the maximum allowable value of saturated hydraulic conductivity lower than $1.0 \cdot 10^{-9}$ m s^{-1}. Despite the fact, that two of the tested clay substrates during laboratory experiments showed *in situ* hydraulic conductivity greater that the required value, all the clays tested in field conditions presented K_s value lower than the required $1.0 \cdot 10^{-9}$ m s^{-1}. Finally, and perhaps most importantly, all the tested substrates showed the satisfyingly low K_s (from range of 10^{-10}–10^{-11} m s^{-1}) after compaction, both at optimal water content and suggested forming water content from range w_{opt}<w_f<1.2 w_{opt}. Thus, the sealing properties of the tested clays are suitable for the construction of a fully operational compacted clay liner.

All the tested materials also presented clay fraction share content greater than values required by ITB (≥30%) and several other guidelines, presenting different thresholds, e.g. EPA (>10%), Rowe at al. (1995) as well as Daniel and Koerner (1995), (≥20%). The requirements expressed by the ITB in relation to clay minerals and CaCO3 content, ≥20% and ≤15%, respectively, were also met. The substrate sampled in Gawlowka failed to meet the threshold value of clay+silt fraction share (required ≥60%) due to the observed 34%. However, such a value would conform with the American requirements presented in EPA's 530-R-93-017 technical manual where the minimal value of the discussed parameter was set as 30%.

Tab. 5.31. Comparison of obtained characteristics of studied substrates and threshold criterion values according to ITB guidelines (Wysokiński, 2007)

	Threshold value (Wysokiński 2007)	Bychawa	Lazek Ordynacki	Pawlow	Mejznerzyn	Markowicze	Gawlowka
Clay content (%)	≥20	42	44,5	52	52	38	31
Slay + silt content (%)	≥60	88	95,5	89	87	75	34
Clay minerals content %	≥20	90	60	70	80	50	50
$CaCO_3$ content (%)	≤15	0	10	0	7	10	0
Plastic limit (%)	25-45	25	24	23	28	27	15
Liquid limit (%)	40-115	52	59	53	66	51	27
Plasticity Index (%)	15-70	27	35	30	38	24	12
Mean linear shrinkage (%)	≤17	7	7	6	6	5	3
Mean swelling index (%)	≥4	4.4	5.9	6.7	6.1	4.5	2.9
K_s in situ field (m s^{-1})	$\leq 1.0 \cdot 10^{-9}$	$2.75 \cdot 10^{-10}$	$1.37 \cdot 10^{-10}$	$2.51 \cdot 10^{-10}$	$2.05 \cdot 10^{-10}$	$1.00 \cdot 10^{-10}$	$4.73 \cdot 10^{-10}$
K_s in situ laboratory (m s^{-1})	$\leq 1.0 \cdot 10^{-9}$	$7.78 \cdot 10^{-10}$	$4.30 \cdot 10^{-10}$	$2.74 \cdot 10^{-10}$	$8.04 \cdot 10^{-10}$	$4.86 \cdot 10^{-9}$	$2.25 \cdot 10^{-9}$
Ks at w_{opt} (m s^{-1})	$\leq 1.0 \cdot 10^{-9}$	$2.75 \cdot 10^{-11}$	$2.09 \cdot 10^{-11}$	$2.63 \cdot 10^{-11}$	$1.53 \cdot 10^{-11}$	$4.17 \cdot 10^{-11}$	$1.53 \cdot 10^{-11}$
Ks at w_f (m s^{-1})	$\leq 1.0 \cdot 10^{-9}$	$6.15 \cdot 10^{-11}$	$5.20 \cdot 10^{-11}$	$4.17 \cdot 10^{-11}$	$2.46 \cdot 10\text{-}^{11}$	$1.17 \cdot 10^{-10}$	$9.45 \cdot 10^{-11}$
$\mathbf{M_0}$ (MPa)	≥5	5	5	3	3	27	3
Internal friction angle (deg)	≥3	8	8	23	18.7	24	23

A more complicated situation was observed when the applicability of the tested clay materials to compacted liner construction was studied in relation to their Atterberg limits. In several cases, the values of the plastic limit (i.e. Lazek

Ordynacki, Pawlow and Gawlowka), liquid limit, plasticity index and swelling index (in all cases of the Gawlowka substrate) are below the threshold values presented by ITB. In this case, the most important and popular seems to be the assessment of the plasticity index. The bottom threshold value proposed by ITB was equal to 15%, so *PI* of the Gawlowka substrate equal to 12% fails to meet the requirements. However, again, the various guidelines and technical manuals present different threshold values, e.g. *PI*=10% as requested by EPA technical manual (1993) or even *PI*=7% proposed as the bottom threshold by Rowe at al. (1995). Additionally, some earlier mentioned studies published by Benson and Trast (1995) reported successful liner formation and operation where clays characterized by *PI*=11%–14% were applied as material for CCL construction. The discussed Polish national requirements suggested *PI* value of 70% as the upper limit of clays applicability. However, it was reported that soils of *PI* greater than 30%, like Lazek Ordynacki and Mejznerzyn, may cause some difficulties during liner construction under the field conditions due to formation of hard clods when dry and sticky clods when saturated (e.g. EPA, 1993). The values of the remaining characteristics of the compacted clays tested and presented in Tab. 5.31, including the mean linear shrinkage, the mean swelling index, M_0 and the angle of internal friction are generally in accordance with ITB requirements. The visible exceptions are the mean swell index for Bychawa lower than 4% and the modulus of primary compressibility M_0=3 MPa for Pawlow, Mejznerzyn and Gawlowka, which was lower than the required 5 MPa. However, the above does not significantly affect the hydraulic sustainability of compacted clay liners but may influence selected constructional issues.

5.2. Results of numerical modeling

Numerical modeling performed to assess the hydraulic efficiency of a landfill capping system based on compacted clay liners utilizing all tested substrates allowed to determine the sealing capabilities of liners and their hydraulic performance for two applied different molding water contents, wet and dry of optimum, at the “wet” and “dry” side of the Proctor curve. The calculated annual seepage, degree of saturation and velocity of flow components at selected reference points as well as saturation and velocity distribution were applied to the presented analyses.

5.2.1. Hydraulic efficiency of liner compacted at $w_{opt}<w_f<1.2w_{opt}$

The first part of the presented numerical modeling was performed for the six tested substrates, compacted at $w_{opt}<w_f<1.2w_{opt}$ for 95% of Proctor density. The input data describing the applied compacted substrates characteristics (see Tab.

5.32.) were based directly on laboratory measurements, which methodology and results were extensively discussed in the previous parts of this dissertation.

Tab. 5.32. Input data for modeling calculations considering tested materials compacted at $w_{opt}<w_f<1.2w_{opt}$ to 95% of Proctor density

Substrate	Molding water content (kg kg^{-1})	K_s (m s^{-1})	θ_s (m^3 m^{-3})	A (m^{-1})	n (-)	Initial saturation (-)	Remarks
Bychawa	0.25	$6.15\cdot10^{-11}$	0.411	0.209	1.167	0.961	Dewatering
				0.203	1.167		Watering
Lazek Ordynacki	0.25	$5.20\cdot10^{-11}$	0.396	1.274	1.089	0.953	Dewatering
				1.405	1.082		Watering
Pawlow	0.22	$4.17\cdot10^{-11}$	0.355	0.185	1.144	0.819	Dewatering
				0.165	1.147		Watering
Mejznerzyn	0.29	$2.46\cdot10^{-11}$	0.451	0.135	1.156	0.958	Dewatering
				0.173	1.149		Watering
Markowicze	0.20	$1.17\cdot10^{-10}$	0.369	0.078	1.101	0.935	Dewatering
				0.151	1.090		Watering
Gawlowka	0.15	$9.45\cdot10^{-11}$	0.332	0.098	1.123	0.917	Dewatering
				0.207	1.107		Watering

The calculated accumulated annual seepage through the bottom of compacted clay liner constructed of all tested materials is presented in Fig. 5.15.

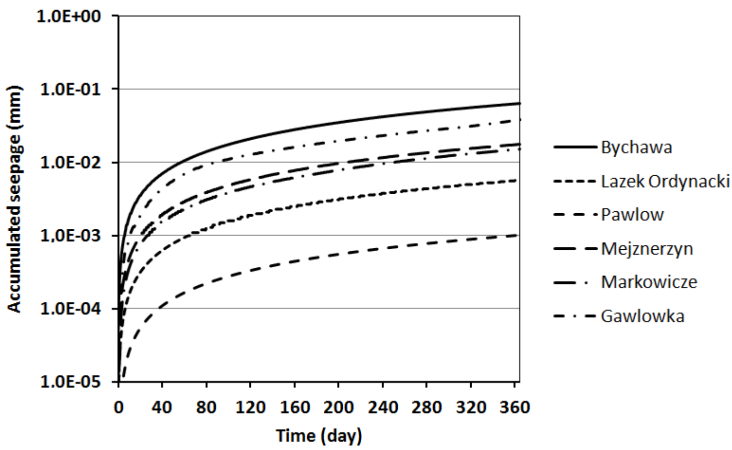

Fig. 5.15. Calculated accumulated seepage for top landfill capping utilizing clay liners constructed of tested substrates compacted $w_{opt}<w_f<1.2w_{opt}$

The calculated accumulated annual seepage through the CCL of the top cover system for all the tested substrates showed a very good sealing performance of compacted clay liners. In all the tested cases the accumulated seepage was clearly lower than 1 mm. Thus, the modeled sealing layer, prepared of the tested substrates, compacted at $w_{opt}<w_f<1.2w_{opt}$ and to 95% of the Proctor density, may be treated as nearly impermeable, for all the tested clay materials. Obviously, there are visible differences in the calculated seepage for the all tested substrates, i.e. the lowest seepage values were observed for Pawlow and Lazek Ordynacki, while the greatest for Gawlowka and Bychawa.

Fig. 5.17 presents time variable saturation in the reference points, presented in Fig. 5.16 for all applied layers i.e. recultivation, drainage and sealing of tested liners.

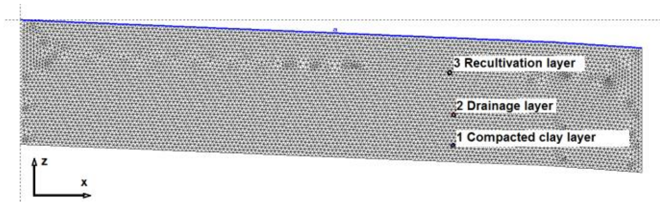

Fig. 5.16. Location of reference points in modeled section of capping liner

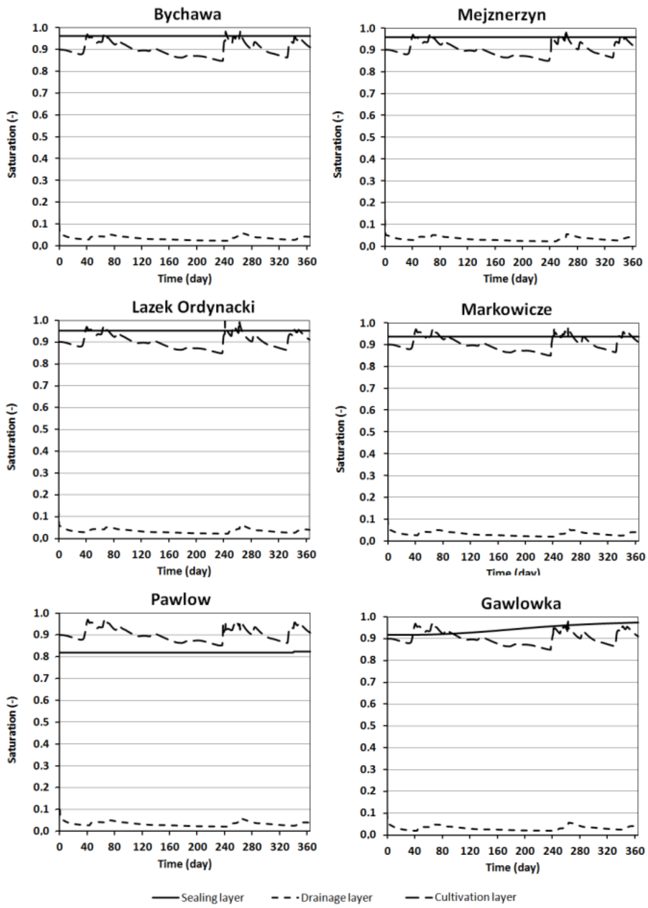

Fig. 5.17. Time-variable water saturation of tested top landfill capping layers based on CCL compacted at $w_{opt}<w_f<1.2w_{opt}$

All the tested and modeled liners presented in Fig. 5.17 performed similarly. During the hydrological year 2012 the saturation of the modeled recultivation layer varied between approx. 0.85–0.97, reacting directly to the boundary conditions stemming from atmospheric conditions and vegetation grass cover activity. On the other hand, the sand drainage layers, due to their high drainage water content (pF<2.0), presented very low saturation, of range approx. 0.02–0.10. But the slight reactions on changes in the upper boundary condition, especially during thaw and extensive precipitation, are also visible. Fig. 5.17 shows also the satisfying performance of the modeled compacted clay liners. The modeled sealing layers of CCLs were able to sustain the molding water content applied as the initial condition for numerical modeling, the observed variations were in range of 0.005–0.01. In the case of Pawlow and Gawlowka substrates even the increase in saturation over the value of initial saturation from molding water content was observed. The maximum increase in compacted clay liner saturation was observed for Gawlowka substrate containing the greatest share of sand fraction and was equal to 0.058.

The presented numerical calculations allowed to asses also the possibility of compacted clay liner cracking after desiccation. We may assume that for the water contents between liquid limit and plastic limit the strength of soil/substrate varies slightly due to the moisture changes and the material remains plastic. However, at water contents below the plastic limit even the slight decrease in the saturation of specimen may result in cracking (e.g. Mitchell and Soga, 2005; Baumgartl, 2006; Sadek et al., 2007). Accordingly, the comparison of the calculated gravimetric water contents at reference point inside the modeled CCL with the value of determined *PL* should allow to assess the risk of cracking. Simulated gravimetric water contents for the modeled time duration of 12 months for Bychawa, Lazek Ordynacki, Mejznerzyn and Gawlowka were higher than the value of their *PL*. As no decrease in the water content was observed during time duration of simulation for CLLs made of Bychawa, Lazek Ordynacaki, Mejznerzyn clay materials and increase in saturation was noted for CCL based on the Gawlowka substrate, these liners should avoid cracking and remain in the plastic zone. In the case of liners utilizing Pawlow and Markowicze substrates the modeled time related water contents in reference point were more or less below values of *PL* for these substrates. Thus desiccation of CCL may result in cracking, however the decrease of water content was not observed for the applied time of saturation.

Therefore, taking the above into consideration, the proper construction of landfill capping meeting the requirements of the Polish standards, utilizing the tested clay substrates compacted wet of optimum, at $w_{opt}<w_f<1.2w_{opt}$, operating without failures, landslides etc. etc. in most cases ensured the appropriate saturation of the compacted clay material during the modeled period of time. However special attention should be paid to the selection of molding water content above the plastic limit, because the increase in the CCL saturation was observed only for one case, i.e. CCL utilizing compacted Gawlowka substrate.

The nearly impermeable and inclined compacted clay liner should result in an increased flux of infiltration water inside the drainage layer. Figures 5.18 – 5.23 present saturation and velocity vectors' module distribution for all the tested liners and selected exemplary time step, t=300 day.

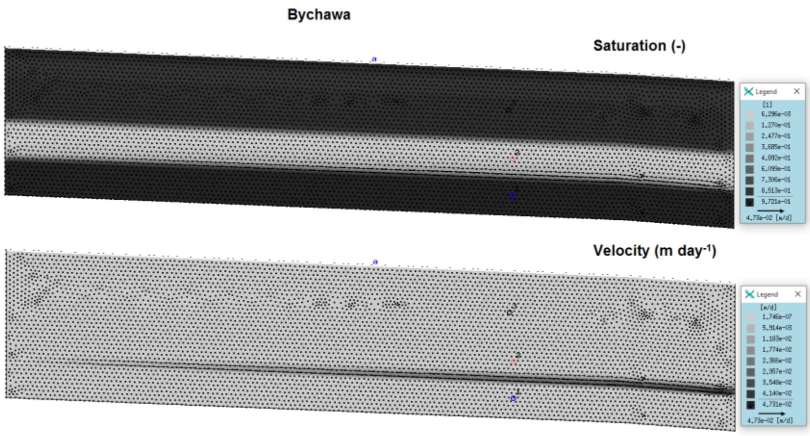

Fig. 5.18. Saturation and velocity field for liner based on Bychawa clay, compacted at $w_{opt}<w_f<1.2w_{opt'}$, t=300 day

The maximum saturation observed at t=300 day in the case of CCL using the substrate sampled in Bychawa (Fig. 5.18) reached the value of approx. 0.97. Saturation of recultivation layer varied between approx. 0.84–0.94. The maximum modeled field of dominant lateral flux velocity was observed in the drainage layer, directly above the compacted clay liner and reached the value of $4.73 \cdot 10^{-2}$ m day^{-1}.

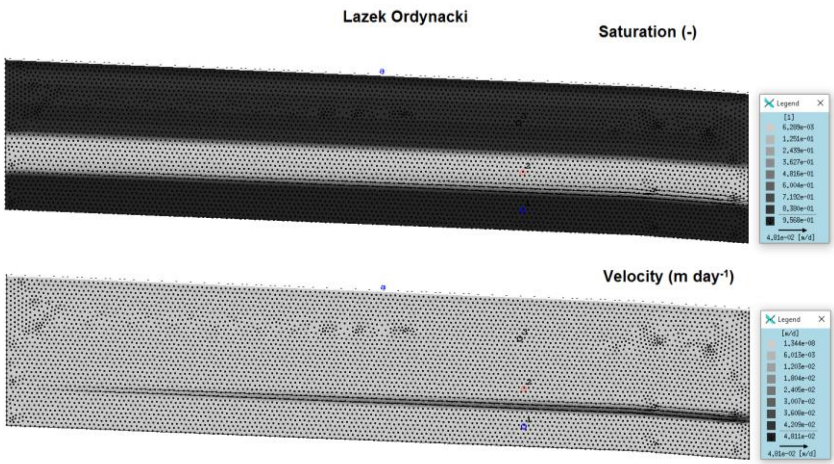

Fig. 5.19. Saturation and velocity field for liner based on Lazek Ordynacki clay, compacted at $w_{opt}<w_f<1.2w_{opt'}$, t=300 day

Soil saturation distribution in a multilayered liner based on the Lazek Ordynacki substrate (see Fig. 5.19) is similar to the previous one. The observed (at t=300 day) saturation of CCL constructed of the discussed substrate reached the value of approx. 0.96, while saturation of the recultivation layer varied between approx. 0.85–0.96. The maximum velocity of the lateral water flow observed directly over the compacted clay liner reached the level of $4.81 \cdot 10^{-2}$ m day^{-1}.

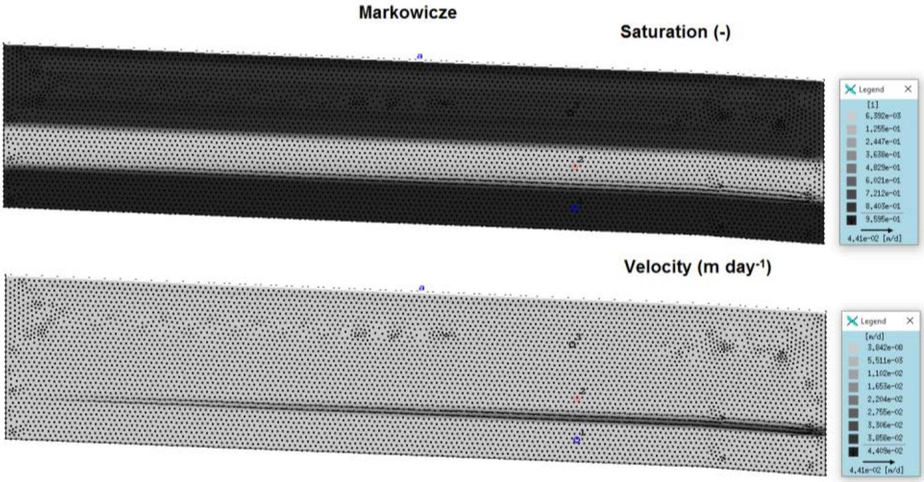

Fig. 5.20. Saturation and velocity field for liner based on Markowicze substrate, compacted at $w_{opt}<w_f<1.2w_{opt}$', t=300 day

Again, the general spatial distribution of soil saturation in the cross section of the landfill capping utilizing the Markowicze substrate for compacted clay liner construction, repeats the previously discussed ones – see Fig. 5.20. The saturation of sealing layer was equal to approx. 0.96 and the saturation of the recultivation layer varied in the range of approx. 0.85–0.96. The maximum calculated velocity of the lateral water flow observed directly over compacted clay liner reached the level of $4.41 \cdot 10^{-2}$ m day^{-1}.

Similarly, the maximum observed, calculated at time duration equal to 300 days, saturation of compacted clay liner constructed of the substrate sampled in Mejznerzyn (Fig. 5.21) reached the value of approx. 0.96. The soil saturation of the recultivation layer varied between approx. 0.85–0.93. The maximum calculated field of dominant lateral flux velocity was observed in the drainage layer, directly above the compacted clay liner. The modeled velocity of flow reached the value of $4.73 \cdot 10^{-2}$ m day^{-1}.

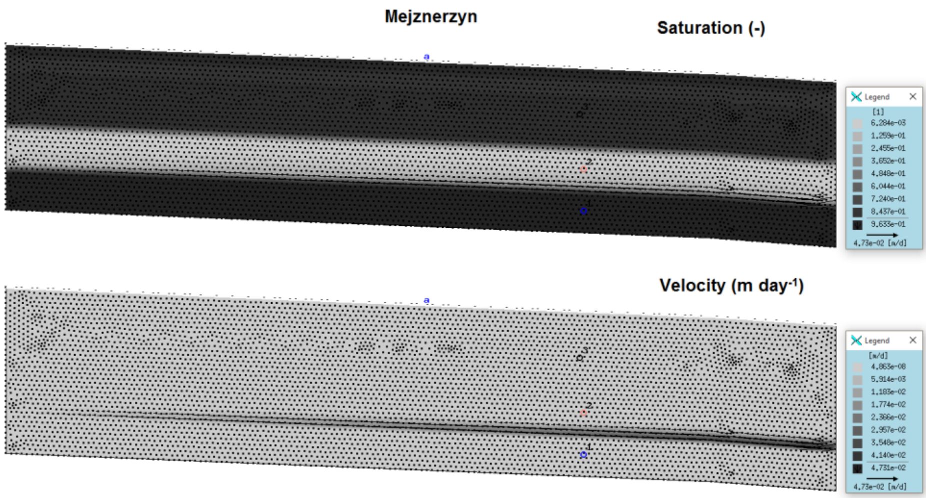

Fig. 5.21. Saturation and velocity field for liner based on Mejznerzyn substrate, compacted at $w_{opt}<w_f<1.2w_{opt}'$, t=300 day

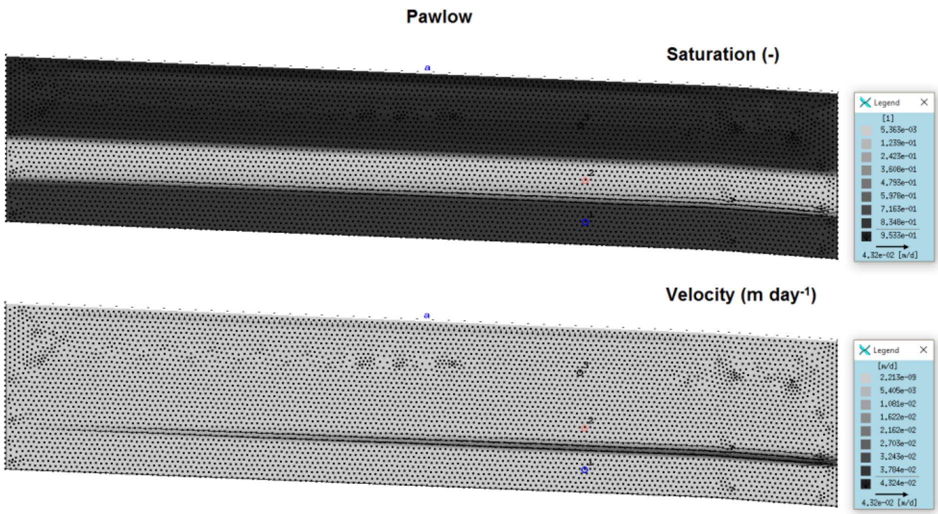

Fig. 5.22. Saturation and velocity field for liner based on Pawlow substrate compacted at $w_{opt}<w_f<1.2w_{opt}$, t=300 day

The observed, calculated at t=300 day, saturation of the compacted clay liner constructed of the Pawlow substrate reached the value of approx. 0.95 (see Fig. 5.22). The recultivation layer was saturated between approx. 0.85–0.95. The maximum value of modeled field of the dominant lateral flux velocity equal to $4.32\cdot10^{-2}$ m day^{-1} was again observed in the drainage layer, directly above the compacted clay liner.

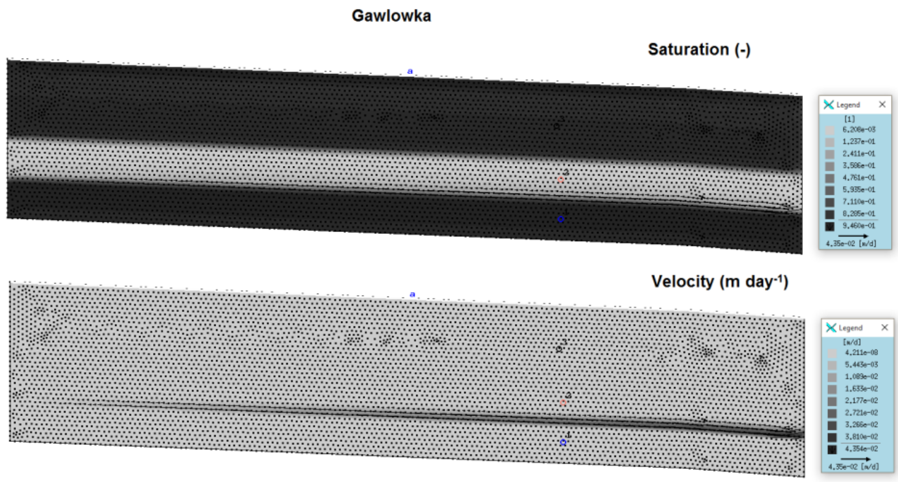

Fig. 5.23. Distribution of saturation and velocity vector for liner based on Gawlowka substrate, compacted at $w_{opt}<w_f<1.2w_{opt}$', t=300 day

Finally, the soil saturation distribution in the profile of the mineral liner utilizing compacted material sampled in Gawlowka, presented in Fig. 5.23 showed for t=300 day the degree of saturation of compacted clay liner in range of 0.92–0.95 and soil saturation in recultivation layer between approx. 0.85 and 0.93. The maximum value of the modeled dominant lateral flux velocity field was again observed in the sand drainage layer, directly above the compacted clay liner. Vectors of flow velocity reached the level of maximum $4.35 \cdot 10^{-2}$ m day^{-1}.

Thus, Figures 5.18 – 5.23 show that all the tested materials, despite some differences in their particle composition, general characteristics and geotechnical properties, applied to the construction of multilayer landfill capping liner performed very similarly during the discussed, selected time step of the numerical simulation. The calculated values and spatial distribution of the soil saturation and velocity field of water flow as well as the values of saturation in reference points were almost identical in all the compared cases. Additionally, the performance of the recultivation and saturation layers in all the tested six cases of various clay materials used for sealing layer construction, is nearly identical, which may be represented by correlation matrices for mean daily soil saturation calculated in reference points inside recultivation and drainage layers for the whole period of simulation, presented in Tables 5.33 – 5.34.

Calculated coefficients of correlation, statistically significant for p=0.05, varied between 0.975–0.998 for the degree of saturation of recultivation layer and 0.958–0.998 for the saturation of drainage layer. Thus, the observed correlations among time dependant saturation of all tested variants of recultivation and drainage layers of the modeled top covers of a municipal landfill were strong. So, one may state that none of the six applied materials for compacted clay liner, molded at $w_{opt}<w_f<1.2w_{opt}$ to 95% of the Proctor density had a significant influence, negative or positive, on the other layers of the liner's capping hydraulic performance.

Tab 5.33. Correlation matrix for saturation of drainage layers for all tested cappings, p=0.05

	Bychawa	Lazek Ordynacki	Markowicze	Mejznerzyn	Pawlow	Gawlowka
Bychawa	-	0.997	0.995	0.977	0.998	0.958
Lazek Ordynacki	0.997	-	0.996	0.985	0.996	0.959
Markowicze	0.995	0.996	-	0.986	0.996	0.962
Mejznerzyn	0.977	0.985	0.986	-	0.978	0.951
Pawlow	0.998	0.996	0.996	0.978	-	0.957
Gawlowka	0.958	0.959	0.962	0.951	0.957	-

Tab. 5.34. Correlation matrix for saturation of recultivation layers for all tested cappings, p=0.05

	Bychawa	Lazek Ordynacki	Markowicze	Mejznerzyn	Pawlow	Gawlowka
Bychawa	-	0.998	0.996	0.983	0.985	0.994
Lazek Ordynacki	0.998	-	0.992	0.989	0.983	0.997
Markowicze	0.996	0.992	-	0.979	0.993	0.992
Mejznerzyn	0.983	0.989	0.979	-	0.975	0.995
Pawlow	0.985	0.983	0.993	0.975	-	0.988
Gawlowka	0.994	0.997	0.992	0.995	0.988	-

To better understand the hydraulic similarities or differences among all the tested liners utilizing studied substrates the values of horizontal and vertical components of water flow velocity, calculated for the applied reference points (see Fig. 5.17) presented in Fig. 5.24 should be discussed.

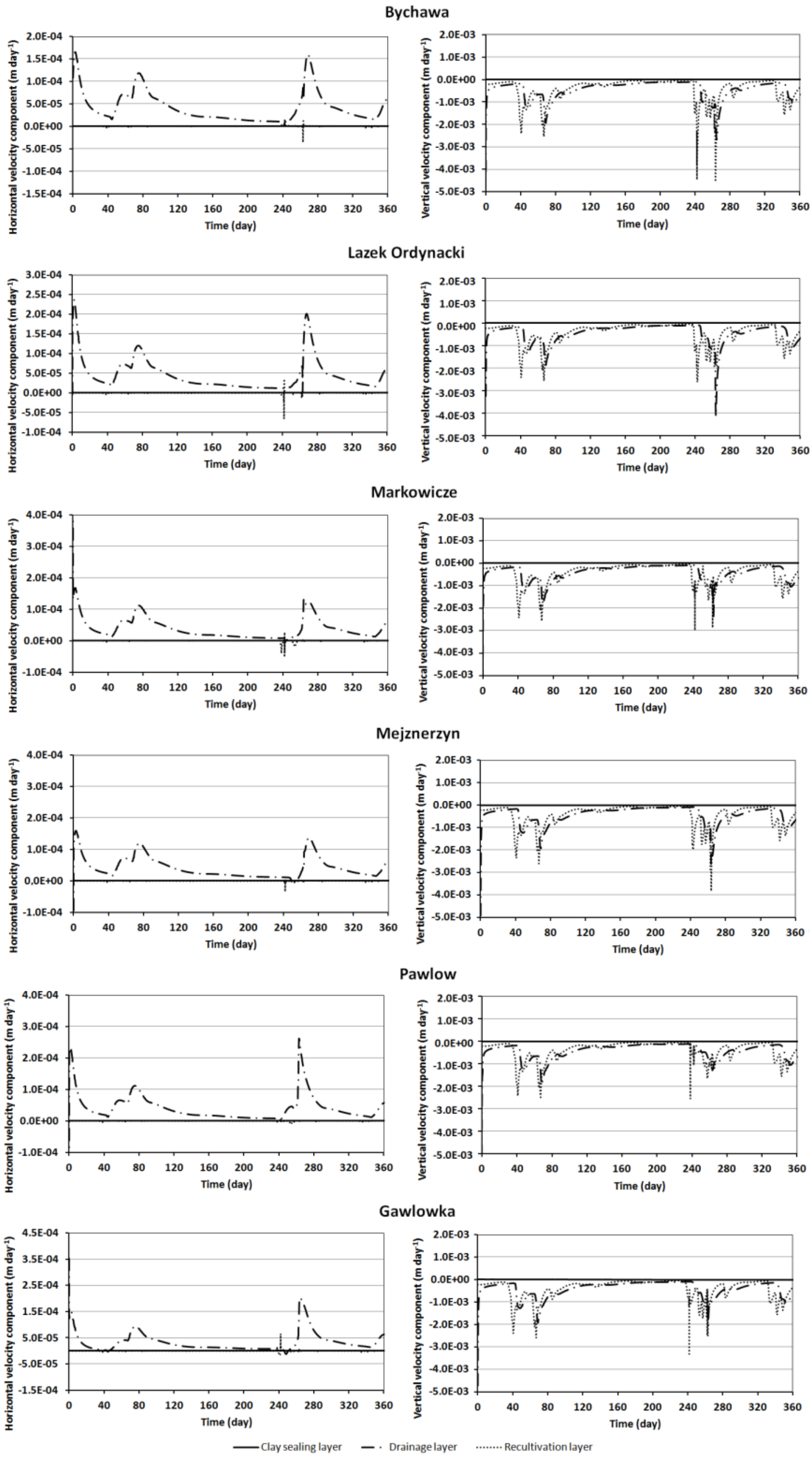

Fig. 5.24. Vertical and horizontal components of velocity vectors at reference points

The results of numerical calculations of components of velocity vector of soil water flow at three selected reference points for all six studied variants of liner showed similar values. In all the cases vertical infiltration was dominant inside the top recultivation layer and middle drainage layer – the negative value of vertical component of water flow vector was observed for the whole applied time duration of the simulation. On the other hand, the dominant, significant horizontal component of water flow velocity was also observed in all the cases for the sand drainage layer. The obtained value of the horizontal component of flow velocity vector had a positive sign, thus, according to the coordination system applied (see Fig. 5.16) the flow of water was directed downslope the drainage layer.

The above presented results of numerical calculations of the hydraulic efficiency of six hypothetical covers for municipal waste landfill meeting the requirements of European and Polish standards and several technical and engineering guidances (e.g. Bagci, 1990; EPA, 1993; Danel and Koener, 1995; Arch, 1998; EU 1999; Journal of Laws from 2013 item 523) showed that all the tested clay substrates proved their hydraulic usefulness in landfill construction. Their sealing capabilities were comparable, nearly reducing the infiltration water seepage to zero (bellow 0.1 mm per year), despite their different geophysical and geotechnical properties resulting from various particle fraction distribution, mineral characteristics etc. etc. Thus, according to results of modeling calculations, compaction at $w_{opt}<w_f<1.2w_{opt}$ and to 95% of Proctor density, suggested by the Polish guidelines (Wysokiński, 2007) allowed to form a successful compacted clay liner of materials containing more than 30% of clay fraction. In all the tested cases, the remaining layers of the modeled landfill's top cover systems performed similarly. However, taking into account the limited possibilities of additional saturation of inclined CCL (K_s from the range 10^{-10}–10^{-11} m s^{-1}) by water from drainage layer ($K_s \geq 1.0 \cdot 10^{-4}$ m s^{-1}) molding water content should be selected very carefully, not to allow a decrease of water below *PL* value, in order to avoid the possibility of cracking (e.g. Mitchell and Soga, 2005; Baumgartl, 2006; Sadek et al., 2007).

Comparison of soil saturation for the whole period of simulation in reference points located inside recultivation and drainage layers showed very strong correlations, thus their performance in all the cases was almost identical, regardless the applied clay substrate for compacted clay liner construction. Spatial distribution of saturation and shape of velocity fields for the tested soil profiles were also similar in all studied variants. Additionally, there were no significant differences observed in the hydraulic performance of the recultivation and drainage layers, assessed by analysis of components of vectors of soil water flow velocity. The recultivation layer was in all cases the location of the dominant vertical flow related to infiltration of surface water. On the other hand, the soil water velocity flow vector in the drainage layer was strongly deviated horizontally, towards the inclination of the slope. Thus, the hydraulic efficiency of a top liner construction utilizing substrates compacted at $w_{opt}<w_f<1.2w_{opt}$ was not dependant on differences in range 10^{-10}–10^{-11} m s^{-1} among K_s values of compacted clay substrates.

Fig. 5.25 presents assessment of unit seepage through fully saturated bottom liner of 1 m thickness consisting of the tested substrates compacted at $w_{opt}<w_f<1.2w_{opt}$. Calculations of seepage were performed for one year time and variable water pressure head, i.e. 0.10, 0.25, 0.50 and 1.0 m.

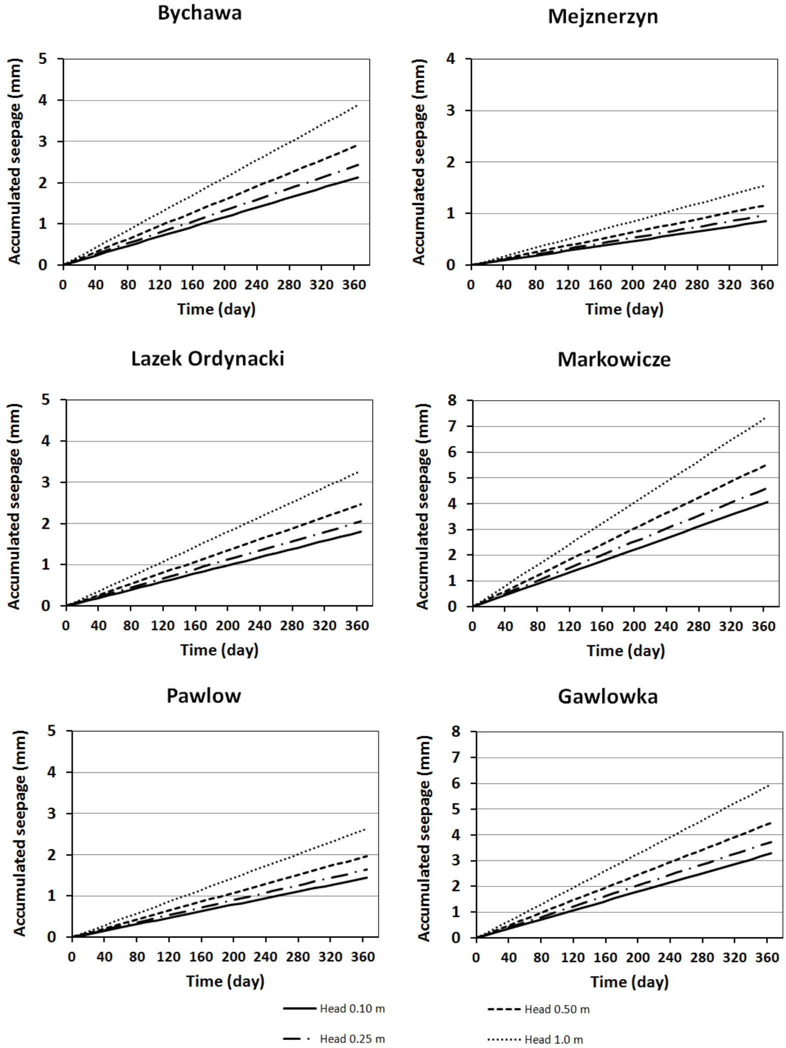

Fig. 5.25. Calculated cumulative unit seepage for bottom liners of 1 m thickness constructed of tested clay materials and compacted at $w_{opt}<w_f<1.2w_{opt}$

The calculated values of annual accumulated unit seepage for variable values of water pressure heads showed satisfactory sealing capabilities of the studied bottom liners. In all the tested cases, for the significant water/leachate head (1.0 m) in the drainage layer and waste body above the top boundary of the liner the accumulated seepage was assessed as from less than 2 mm per year for Mejznerzyn substrate to above 7 mm for material sampled in Markowicze (the annual precipitation was equal to 754 mm). Such huge values of leachate head are rare, the usually permitted maximum head over drainage system is 300 mm (0.3m), the greater values were reported only for failure situations for landfills where the drainage system was clogged (eg. Koerner and Soong, 2000). The discussed sealing capabilities of the tested compacted clays, combined with the successful leachate drainage should be sufficient in preventing pollutants migration to the natural soil and water environment.

5.2.2. Hydraulic efficiency of clay liner compacted at $w_f<w_{opt}$

The second part of the presented numerical modeling was performed for the six tested substrates, compacted at $w_f<w_{opt}$ and to 95% of the Proctor density. In the two cases, for Pawlow and Markowicze, the resultant K_s for compacted clay materials at 0.95 of optimum density was greater than allowed $1.0\cdot10^{-9}$ m s^{-1}. Thus, in these cases, the molding water contents from range $w_f<w_{opt}$ as close as possible to 95% of Proctor density and allowing K_s lower than $1\cdot10^{-9}$ m s^{-1} were selected for the further numerical studies. The input data describing the applied compacted substrates characteristics (see Tab. 5.35) were based directly on laboratory measurements, which methodology and results were already discussed in this paper.

Tab. 5.35. Input data for modeling calculations for tested materials compacted at $w_f<w_{opt}$

Substrate	w_f (kg kg^{-1})	K_s (m s^{-1})	θ_s (m^3 m^{-3})	A (m^{-1})	n (-)	Initial saturation (-)	Remarks
Bychawa	0.20	$1.11\cdot10^{-10}$	0.383	0.110	1.188	0.854	Dewatering
				0.112	1.187		Watering
Lazek Ordynacki	0.19	$8.43\cdot10^{-11}$	0.368	0.928	1.123	0.794	Dewatering
				0.997	1.120		Watering
Pawlow	0.16	$4.43\cdot10^{-11}$	0.351	1.004	1.100	0.681	Dewatering
				1.380	1.099		Watering
Mejznerzyn	0.20	$2.20\cdot10^{-10}$	0.465	0.554	1.102	0.650	Dewatering
				0.607	1.100		Watering
Markowicze	0.15	$8.75\cdot10^{-10}$	0.326	2.799	1.082	0.772	Dewatering
				4.909	1.072		Watering
Gawlowka	0.08	$4.40\cdot10^{-10}$	0.337	0.045	1.181	0.416	Dewatering
				0.083	1.157		Watering

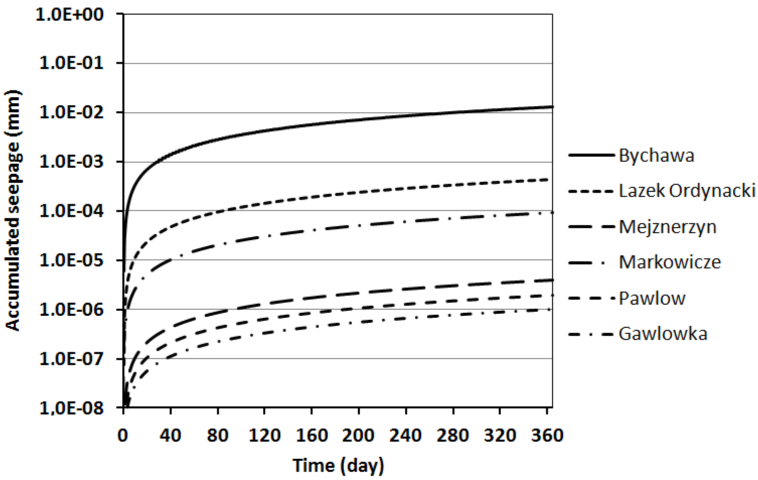

Fig. 5.26. Calculated accumulated seepage for top landfill capping utilizing clay liners constructed of tested substrates compacted at $w_f<w_{opt}$

The calculated accumulated annual seepage for all the tested substrates, compacted at dry of optimum, at $w_f<w_{opt}$, presented in Fig. 5.26, showed a very good sealing capabilities of the sealing clay liners. In all the tested cases the accumulated seepage was significantly lower than 1 mm. Obviously, there were again visible differences in the calculated seepage for the all tested substrates, i.e. the lowest seepage values were observed for Gawlowka and Mejznerzyn, while the greatest for Bychawa and Lazek Ordynacki. Thus, the modeled sealing layer, prepared of the tested substrates, compacted at $w_f<w_{opt}$ should be treated as nearly impermeable, for all the tested clay materials. Moreover, the numerical calculations of seepage showed that the tested clay materials compacted at lower water contents (lower than w_{opt}) presented in the most cases significantly lower annual seepage than the same substrates compacted at $w_{opt}<w_f<1.2w_{opt}$. The above phenomenon may be explained so that clays of significant water holding capacity (available water content), compacted at low water content showed the low value of the initial soil saturation, i.e. approx. 0.42–0.85. Thus, the available water retention was greater than in the case of substrates with initial saturation in the range 0.82–0.96. So, a greater volume of water infiltrating from the capping surface through the recultivation and drainage layers, may be retained in a compacted clay sealing liner, at least in its upper part.

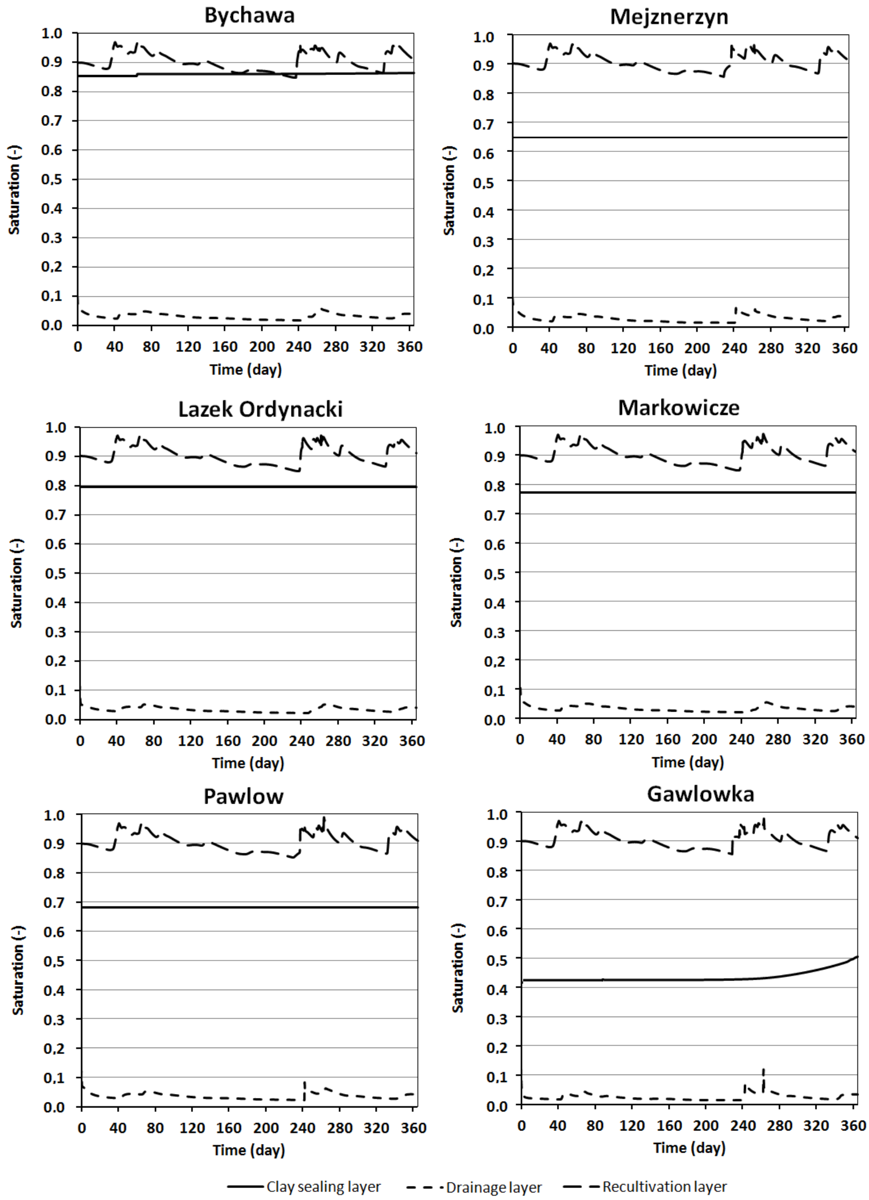

Fig. 5.27. Time-variable saturation degree of tested top landfill capping layers compacted at w_f<w_{opt}

All modeled liners utilizing the six tested clays compacted at w_f<w_{opt} performed similarly – see Fig. 5.27. During the modeled time duration of hydrologic year 2012, the calculated saturation of the recultivation layer varied in range approx. 0.85–0.99 reacting directly to the boundary conditions resulted from atmospheric conditions and grass cover water uptake. The values of time variable saturation were close to saturation of the recultivation layers tested previously.

A similar situation was observed in case of the sand drainage layers in liners using clays compacted at $w_f<w_{opt}$. The saturation of drainage layer, observed in the reference points, was in all cases in range of 0.015–0.12. But the slight reactions on changes in the upper boundary condition, especially during days of thaw and extensive precipitation, were also visible. Fig. 5.27 also presents the hydraulic performance of compacted clay liners formed at $w_f<w_{opt}$. Interestingly, in most of the tested cases (i.e. Bychawa, Lazek Ordynacki, Mejznerzyn, Markowicze and Pawlow), the modeled compacted clay substrates were able to sustain the constant saturation, equal to initial, or slightly different, in the reference point. The only notable different situation was observed for the compacted clay liner utilizing the substrate sampled in Bychawa, showing the lowest value of seepage. In this case, material compacted at quite low water content, dry of optimum, with the degree of saturation 0.42 increased its saturation during twelve months to the value of 0.50.

However, the analysis of the time variable water contents observed at reference points in the modeled CCLs showed that despite the fact that no dehydration of clay layers was observed, the water content values were below the plastic limit. Thus, resistance of clayey material to changes in stress caused by desiccation becomes minimal and cracks may appear (e.g. Mitchell and Soga, 2005; Baumgartl, 2006; Sadek et al., 2007). Only in the case of a CCL based on the sandy clay loam sampled in Gawlowka the design of modeled top cover capping allowed to increase, to some extent, the saturation of CCL. However, water content in the reference point was still below the plastic limit. Accordingly, the application of the clayey substrates compacted dry of optimum to inclined CCL overlaid with a drainage layer consisting of coarse material, taking into account their lower shrinkage potential, should be considered in relation to their plastic limit and compaction conditions.

Thus, the proper construction of a landfill capping meeting the requirements of the Polish standards (Journal of Laws from 2013 item 523), utilizing the tested clay substrates compacted dry of optimum, at $w_f<w_{opt}$, sustained the initial saturation of compacted clay material during the modeled period of time, no drying of the sealing layer was observed. Water content of the studied CCLs remained below the *PL* values so cracking was possible. Additionally, in the case of four substrates, sampled in Lazek Ordynacki, Markowicze, Mejznerzyn and Pawlow, no increase in value of saturation was also observed.

Figures 5.28 – 5. 33 present saturation and velocity vectors fields for all tested liners utilizing substrates compacted at $w_f<w_{opt}$ and for the selected exemplary time step t=300 day, during the wet period of the simulation duration time.

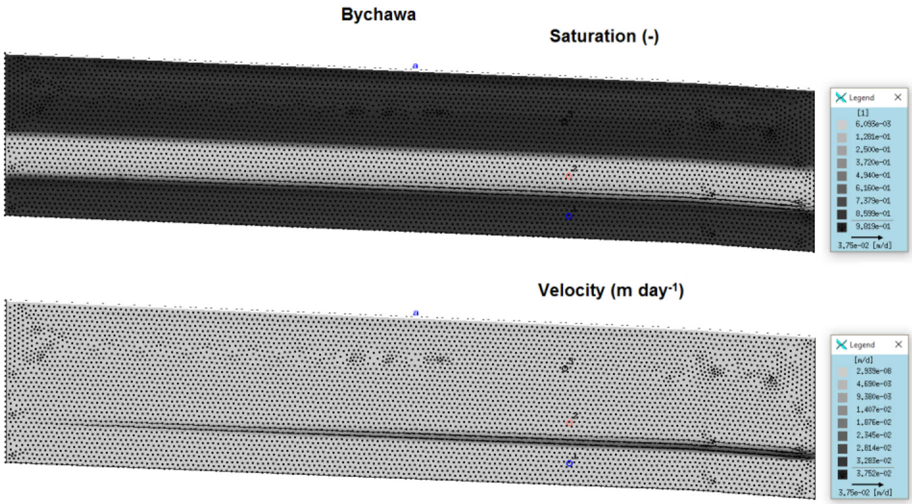

Fig. 5.28. Saturation and velocity field for liner based on Bychawa substrate compacted at w_f<w_{opt}, t=300 day

The observed at t=300d saturation of the compacted clay liner constructed of the substrate sampled in Bychawa and compacted at w_f<w_{opt} (Fig. 5.28) varied between 0.87 and 0.92. The saturation of the recultivation layer varied between approx. 0.85–0.95. The maximum modeled field of dominant lateral flux velocity was observed in the drainage layer, directly above the compacted clay liner and reached the value of $3.75 \cdot 10^{-2}$ m day^{-1}.

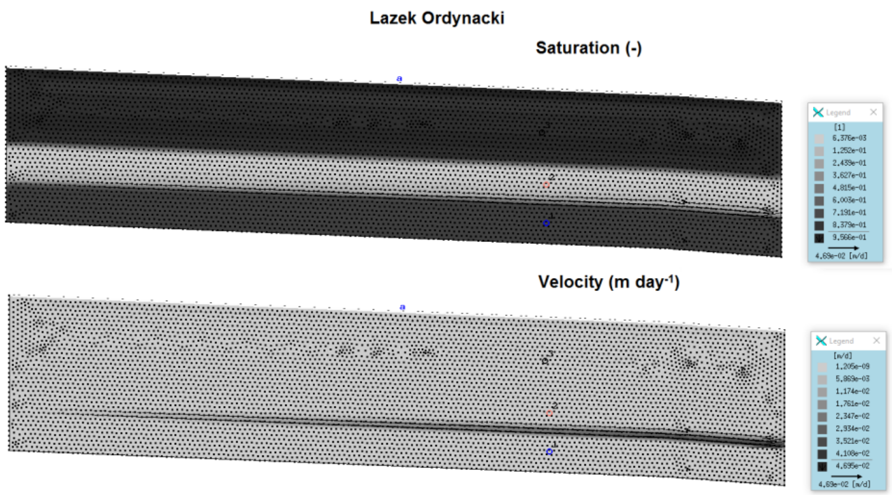

Fig. 5.29. Saturation and velocity field for liner based on Lazek Ordynacki substrate compacted at w_f<w_{opt}, t=300 day

The spatial distribution of soil saturation in the liner based on Lazek Ordynacki substrate compacted at w_f<w_{opt} presented in Fig. 5.29 is similar to the ones previously discussed. The observed at t=300 day saturation of the compacted clay liner constructed of the discussed substrate reached the uniform value of approx. 0.79. Saturation of the recultivation layer for the same time step varied between approx. 0.85–0.96. The maximum velocity of the lateral water flow observed directly over the compacted clay liner reached the level of $4.69 \cdot 10^{-2}$ m day^{-1}.

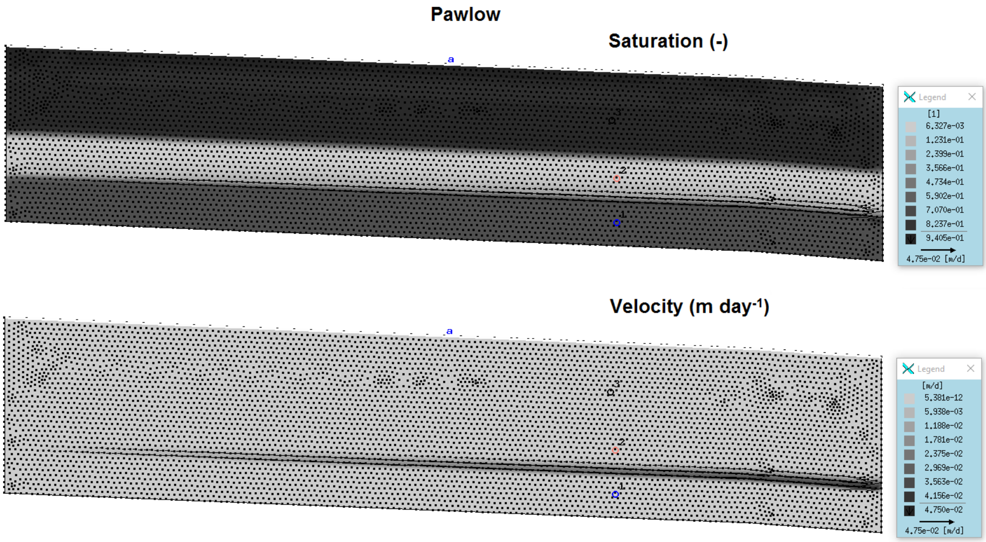

Fig. 5.30. Saturation and velocity field for liner based on Pawlow substrate compacted at w_f<w_{opt}, t=300 day

The observed for the time duration t=300 day the calculated saturation of CCL constructed of the Pawlow substrate formed dry of optimum reached values in the range of approx. 0.68–0.73 (see Fig. 5.30). The recultivation layer was saturated between approx. 0.86 and 0.94. The maximum value of the modeled dominant lateral flux velocity equal to $4.75 \cdot 10^{-2}$ m day^{-1} was again observed directly above the compacted clay liner in the drainage layer.

A similar situation was observed in the case of saturation distribution at the time step t=300 day for the liner utilizing substrate sampled in Mejznerzyn and compacted at w_f<w_{opt}. The saturation of the compacted clay liner presented in Fig. 5.31 reached the level of approx. 0.65–0.69.

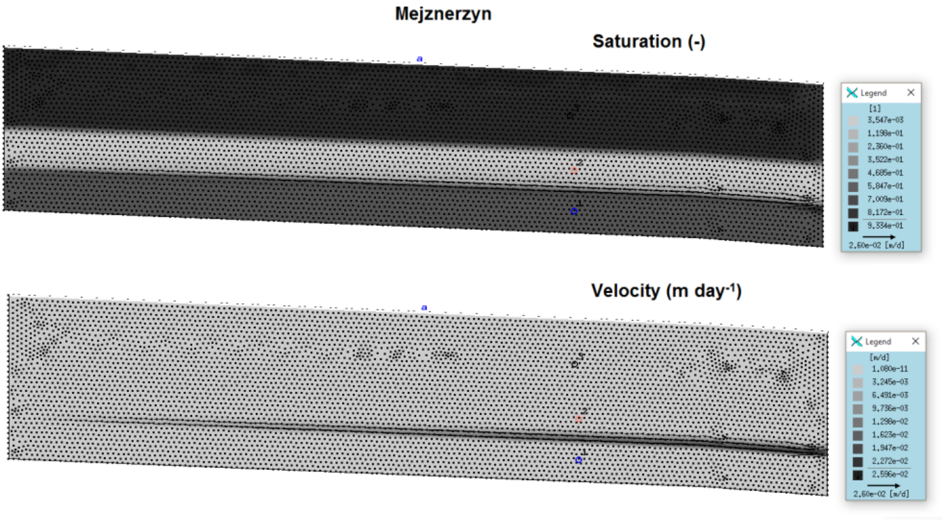

Fig. 5.31. Saturation and velocity field for liner based on Mejznerzyn substrate compacted at w_f<w_{opt}, t=300 day

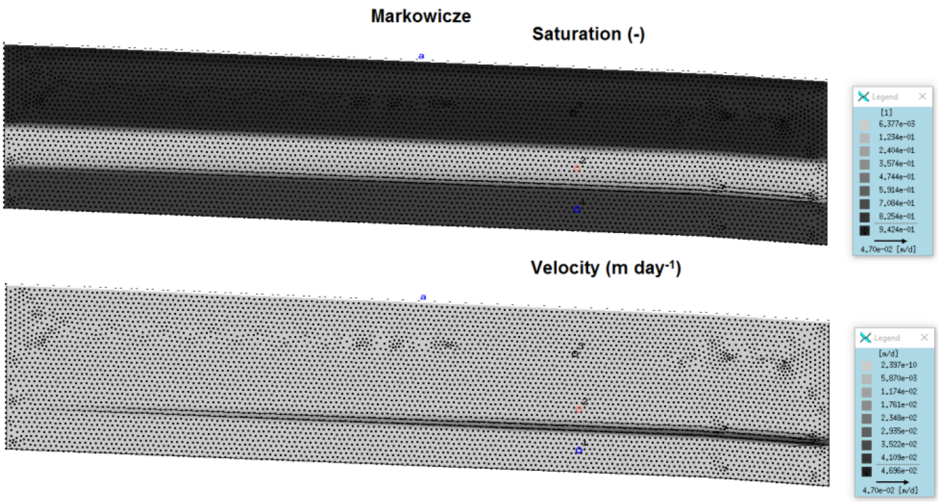

Fig. 5.32. Saturation and velocity field for liner based on Markowicze substrate compacted at w_f<w_{opt}, t=300 day

The soil saturation of recultivation layer varied between approx. 0.86–0.90. The maximum modeled field of dominant lateral flux velocity was observed in the drainage layer, directly above the compacted clay liner and reached the value of $2.60 \cdot 10^{-2}$ m day^{-1}.

The general spatial distribution of soil saturation at time duration t=300 day in the cross section of the landfill capping utilizing in CCL the Markowicze substrate molded dry of optimum, at $w_f<w_{opt}$, visible in Fig. 5.32, repeats the previously discussed ones. The saturation of the sealing layer was equal to approx. 0.79 and saturation of the recultivation layer varied in the range of approx. 0.85–0.94. The maximum calculated velocity of lateral water flow was again observed directly over the compacted clay liner and reached the level of $4.70 \cdot 10^{-2}$ m day^{-1}.

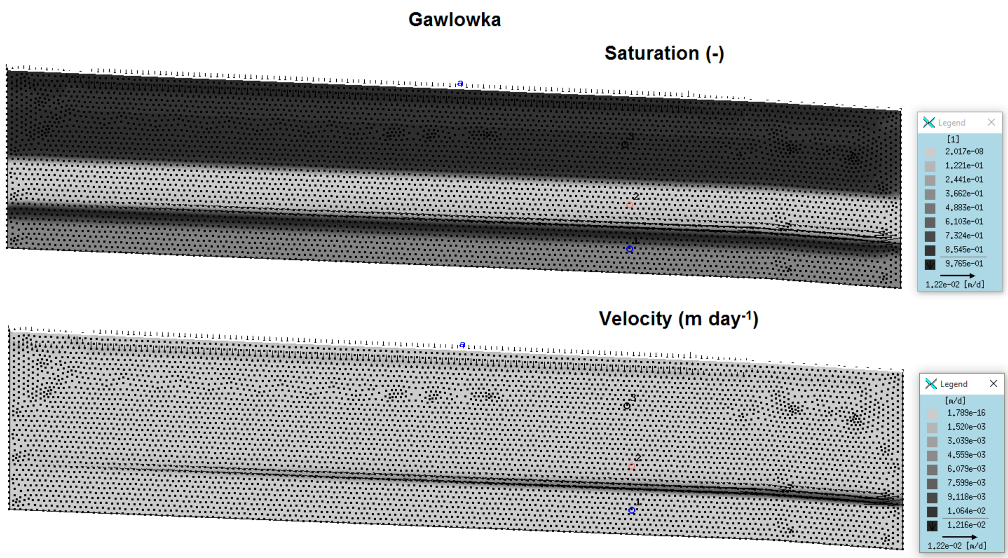

Fig. 5.33. Saturation and velocity field for liner based on Gawlowka substrate compacted at $w_f<w_{opt}$, t=300 day

Finally, the soil saturation distribution in the profile of the mineral liner utilizing the clay material sampled in Gawlowka compacted at $w_f<w_{opt}$, presented in Fig 5.33, showed for analyzed time duration t=300 day, the degree of saturation of compacted clay liner in the range of 0.42–0.45 and soil saturation in the recultivation layer in range of approx. between 0.86 and 0.94. There is a visible differentiation of saturation in the compacted clay liner, with higher saturation in the area close to boundary with the sand drainage layer, indicating watering of the clay layer by infiltration water. The maximum value of the modeled dominant lateral flux velocity was again observed in the sand drainage layer, directly above the compacted clay liner and reached level of $1.22 \cdot 10^{-2}$ m day^{-1}.

To conclude, Figs 5.28 – 5.33 show that all the tested materials, compacted at dry of optimum, i.e. at water content lower than the optimum, $w_f<w_{opt}$, and applied to the construction of a multilayered top landfill capping, again performed similarly at the selected, exemplary time step of the numerical simulation. The calculated values and spatial distribution of soil saturation and velocity field of soil water flow as well as the values of saturation in reference points were almost identical in all the compared

cases. The only noticeable difference was observed for the Gawlowka substrate compacted at a relatively low water content, resulting in low initial saturation, allowing infiltration and retention of water from the layers located above. However, in most cases, excluding Lazek Ordynacki and Markowicze, there were visible differences in saturation distribution in the modeled CCLs. Some part of water from the drainage layer percolated to CCL and was sustained, due to significant water holding capacity of the compacted clayey substrates discussed previously, inside the upper part of the sealing layer. The observed differences for time step t=300 day were in range up to 5% (0.05) of saturation degree by water.

Additionally, the performance of the recultivation and saturation layers in the most of tested six cases of various clay materials used for sealing layer construction, is nearly identical, which may be represented by correlation matrices for mean daily soil saturation calculated in reference points inside the recultivation and drainage layers, presented in Tab. 5.36. and 5.37.

Tab. 5.36. Correlation matrix for saturation of drainage layers for all tested cappings consisting of compacted clay liner formed at $w_f<w_{opt}$, p=0.05

	Bychawa	Lazek Ordynacki	Markowicze	Mejznerzyn	Pawlow	Gawlowka
Bychawa	-	0.981	0.984	0.866	0.877	0.712
Lazek Ordynacki	0.981	-	0.995	0.821	0.850	0.671
Markowicze	0.984	0.995	-	0.830	0.855	0.649
Mejznerzyn	0.866	0.821	0.830	-	0.987	0.874
Pawlow	0.877	0.850	0.855	0.987	-	0.873
Gawlowka	0.712	0.671	0.649	0.874	0.873	-

Presented in Tab. 5.36 and Tab. 5.37 the calculated coefficients of correlation, statistically significant for p=0.05, varied between 0.905–0.996 for saturation of the recultivation layer and 0.671–0.995 for saturation of the drainage layer. Thus, the observed correlations among time dependant saturation of most of the tested variants of recultivation and drainage layers of the modeled top covers of municipal landfill were strong.

The weakest correlations, in range of 0.671–0.874 were observed for the drainage layer in capping based on the Gawlowka substrate compacted below optimal water content, thus saturation in that layer differs slightly. Again, even taking into account the weaker correlations observed for Gawlowka substrate, the six materials applied for a compacted clay liner, molded at $w_f<w_{opt}$ and close to 95% of the Proctor density had no significant influence, negative or positive, on the hydraulic

performance of the other layers of the capping. Thus, no matter what the applied dry of optimum molding water content was, in all the cases, even including Gawlowka, the hydraulic performance of recultivation and drainage layer was comparable.

Tab. 5.37. Correlation matrix for saturation of recultivation layers for all tested cappings consisting of compacted clay liner formed at $w_f < w_{opt}$, p=0.05

	Bychawa	Lazek Ordynacki	Markowicze	Mejznerzyn	Pawlow	Gawlowka
Bychawa	-	0.991	0.984	0.976	0.988	0.935
Lazek Ordynacki	0.991	-	0.996	0.957	0.974	0.915
Markowicze	0.984	0.996	-	0.947	0.965	0.906
Mejznerzyn	0.976	0.957	0.947	-	0.989	0.982
Pawlow	0.988	0.974	0.965	0.989	-	0.955
Gawlowka	0.935	0.915	0.906	0.982	0.955	-

The results of numerical calculations of the components of velocity vector of soil water flow at three selected reference points for all six studied variants of a liner utilizing the tested substrates compacted dry of optimum showed similar values. In all the studied cases vertical infiltration was dominant for the top recultivation layer and middle drainage layer. The negative value of the vertical component of the water flow vector was observed for the whole time duration of the simulation. On the other hand, the dominant, significant horizontal component of water flow velocity was also observed in all the cases for the sand drainage layer. The obtained value of the horizontal component of flow velocity vector had a positive sign, thus, according to the coordination system applied (see Fig. 5.34) the flow of water was directed down slope the drainage layer of the studied capping scheme.

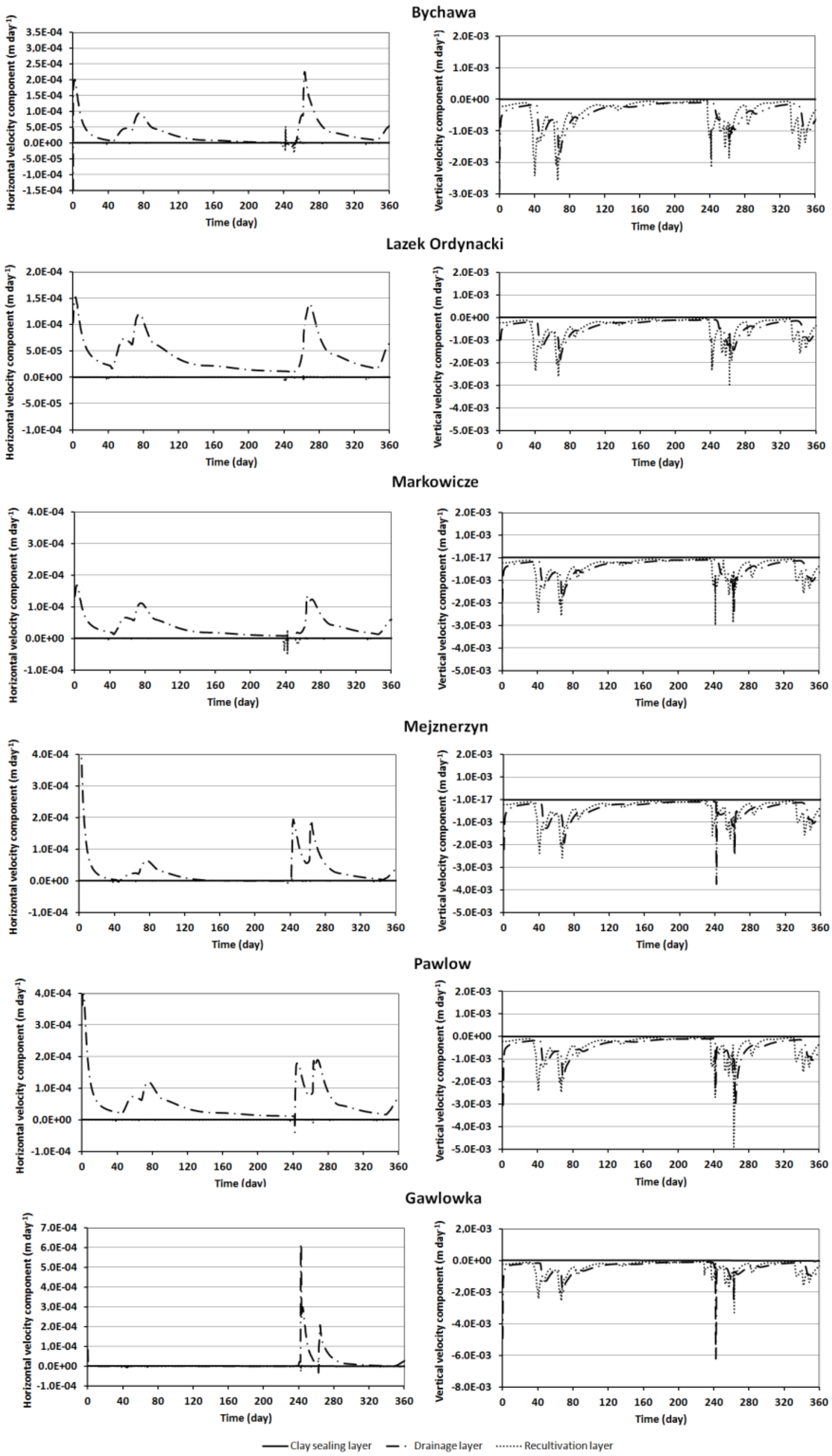

Fig. 5.34. Vertical and horizontal components of velocity vectors at reference points

The assessment of unit seepage through the fully saturated bottom liner of 1 m thickness consisting of the tested substrates compacted at $w_f<w_{opt}$ was presented in Fig. 5.35. Calculations of seepage were again performed for one year time and variable water pressure head, i.e. 0.10, 0.25, 0.50 and 1.0 m over the top surface of the sealing liner.

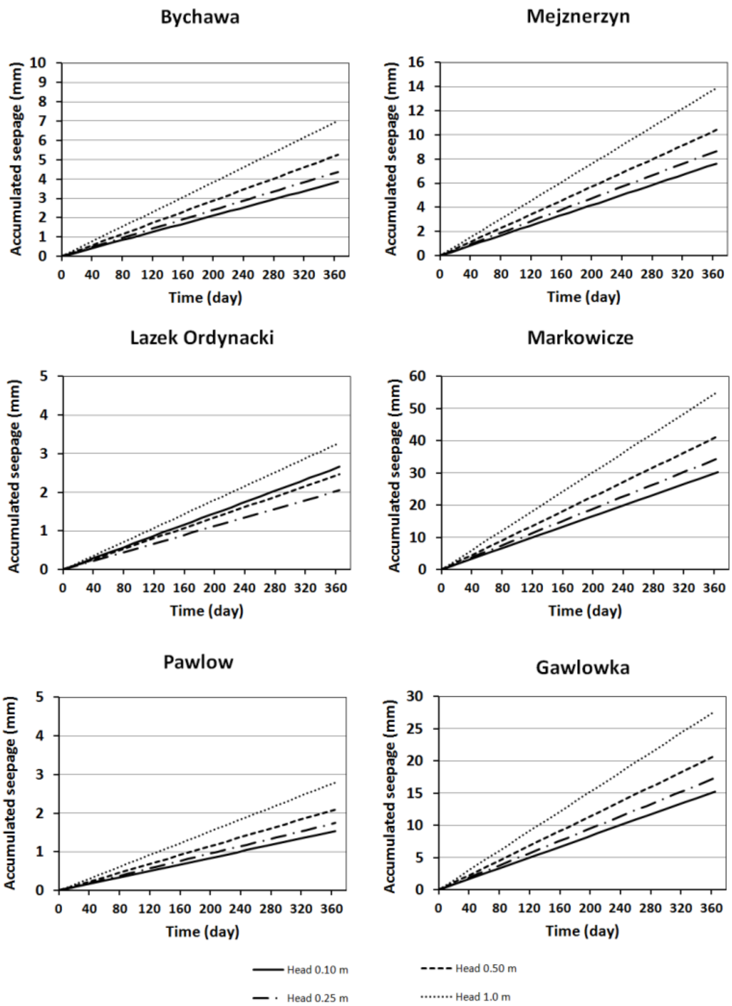

Fig. 5.35. Calculated cumulative unit seepage for bottom liners of 1 m thickness constructed of tested clay materials and compacted at $w_f<w_{opt}$

Calculated values of annual accumulated unit seepage for the bottom clay liners compacted at dry of optimum (at $w_f<w_{opt}$) and variable values of water pressure heads showed higher values than the seepage assessed for clay materials compacted wet of optimum, at $w_{opt}<w_f<1.2w_{opt}$. In all the tested cases, for the significant water head (1.0 m) above the top surface of the compacted liner the accumulated seepage, as it was expected in relation to applied K_s value, seepage was assessed as from less than 3 mm per year for the Pawlow substrate to above 55 mm for the material sampled in Markowicze. As it was mentioned before, according to literature (e.g. Koerner and Soong, 2000) huge values of leachate head, reaching 1.0 m, are rare, usually the maximum leachate head over the drainage system does not exceed 300 mm (0.3 m), while greater values were observed for landfills where the drainage system was clogged. However, the obtained results of sealing capabilities of studied compacted clays, combined with successful leachate drainage should be sufficient in preventing pollutants migration to the natural soil and water environment. Thus, in the both tested variants of forming water content, below and above the optimum, the tested clays used in the compacted mineral bottom liners showed sufficient sealing capabilities.

In summary, the sealing capabilities and hydraulic performance of the modeled section of a top landfill cover based on the compacted clay sealing liners, utilizing six different clay materials sampled in the region of Lublin Voivodeship, Poland and compacted at water contents from two ranges, $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$, corresponding to the right and left, or “dry” and “wet”, side of the Proctor curve were numerically tested. In all the tested cases the sealing capabilities of the compacted clay liner may be assessed as satisfactory, the annual unit seepage for each tested substrate and applied molding water content, was below 1 mm per year. The above was directly connected to a very low permeability of the compacted tested clay materials, their significant water holding capacity (available water retention) and initial saturation.

Additionally, the observed calculated velocity of soil water flow inside the sand drainage layer, of significant hydraulic conductivity, even seven orders of magnitude higher than the compacted clays, combined with inclination of the modeled slope resulted in the significant lateral flows and horizontally diverted vectors of water flow velocity. Thus, as it was expected, the calculated increase in the compacted clay liner saturation by water infiltrating from the sand drainage layer was limited. In several cases of the applied clays compacted at different water contents, from both sides of the Proctor curve, dry and wet of optimum, the saturation in reference points remained constant through the whole time duration of the simulation, i.e. during the hydrologic year of 2012.

The only clear exceptions were observed for both variants of capping modeling including the substrate sampled in Bychawa, compacted for both $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ where the slight increase in clay liner saturation, by less than 0.1, was observed during the period of simulation. Thus, the above may be understood in two ways: i) results of modeling indicate that construction of the top capping according to the Polish standards, combining permeable sand and nearly impermeable clays, prevents, in most cases, changes of the compacted clay liner saturation, which is not

drying or wetting; ii) in case of capping construction failures, landslides, or even forming of the clay liner at incorrect, too low water content the possibility of natural, self-rewatering of compacted material is limited and was observed in modeling only for the material containing significant amount of coarse sand fraction. In the selected cases for molding water content from range $w_{opt}<w_f<1.2w_{opt}$ and in all the cases from $w_f<w_{opt}$ the observed water contents at reference points inside CCL were lower than value of the plastic limit so in case of the further desiccation below the molding water content occurrence of cracks was possible. The observed lack of calculated water content decrease was probably related to the facts that all the substrates were compacted below their water field capacity (pF=2.0) and the CCL was covered with 1.5 m of drainage and recultivation layer, which clearly limited the possibility of liner evaporation.

In all the tested cases the hydraulic operation of the recultivation and drainage layers was similar, for all the applied clay materials and molding water contents for the sealing layer construction. The calculated components of water flow velocity vector for reference points located inside the sand drainage layer showed presence of two notable vectors, horizontal and vertical, redirecting lateral water flux along the slope between the drainage and the clay sealing layer. The vertical component of velocity vector was dominant in recultivation layer, so according to changes in the boundary conditions, reflecting, among others time-variable precipitation, interception and evapotranspiration, the discussed layer was mainly the location of downwards infiltration. The observed saturation values in reference points located in drainage layer were in most cases similar, for the same material compacted at two water contents, $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$.

The calculated coefficients of correlation, statistically significant for p=0.05, varied between 0.728–0.991 for 365 values of mean daily saturation calculated for liner utilizing clays compacted for both sides of the Proctor curve, dry and wet of optimum. The obtained values of R for saturation in the drainage layer were as follows: Bychawa – 0.987, Lazek Ordynacki – 0.987, Pawlow – 0.901, Mejznerzyn – 0.812, Markowicze – 0.991, Gawlowka – 0.728. Thus, in the most cases strong correlations were observed. Fig. 5.36 presents linear correlations for mean daily saturation values in reference point at the top recultivation layers, calculated for all liners using the clays compacted wet and dry of optimum. i.e. $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$. The calculated values of R for 365 values of saturation in recultivation layer were as follows: Bychawa – 0.990, Lazek Ordynacki – 0.997, Pawlow – 0.983, Mejznerzyn – 0.934, Markowicze – 0.986, Gawlowka – 0.916. Further statistical analysis, based on the non-parametric Wilcoxon signed-rank test (used as an alternative for the t-Student test) for the daily mean saturation at reference points located in the drainage and recultivation layers of capping utilizing the clay substrates compacted at $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ showed that in most cases the

discussed series were not identical, there were observed statistically significant differences between mean values for each group. The only exception was noted in the case of the recultivation layer in the liner based on the compacted Markowicze clay. According to the Wilcoxon signed-rank test no statistically significant differences between the mean ranks were observed. Thus, we may state that in the six presented cases, molding water content applied to the same clay material during construction of top cover systems for municipal wastes landfill, meeting the requirements of the Polish national standards (Journal of Laws from 2013 item 523) had nearly no influence on their hydraulic operation, i.e. water content, saturation and flow velocity inside recultivation layer of the capping.

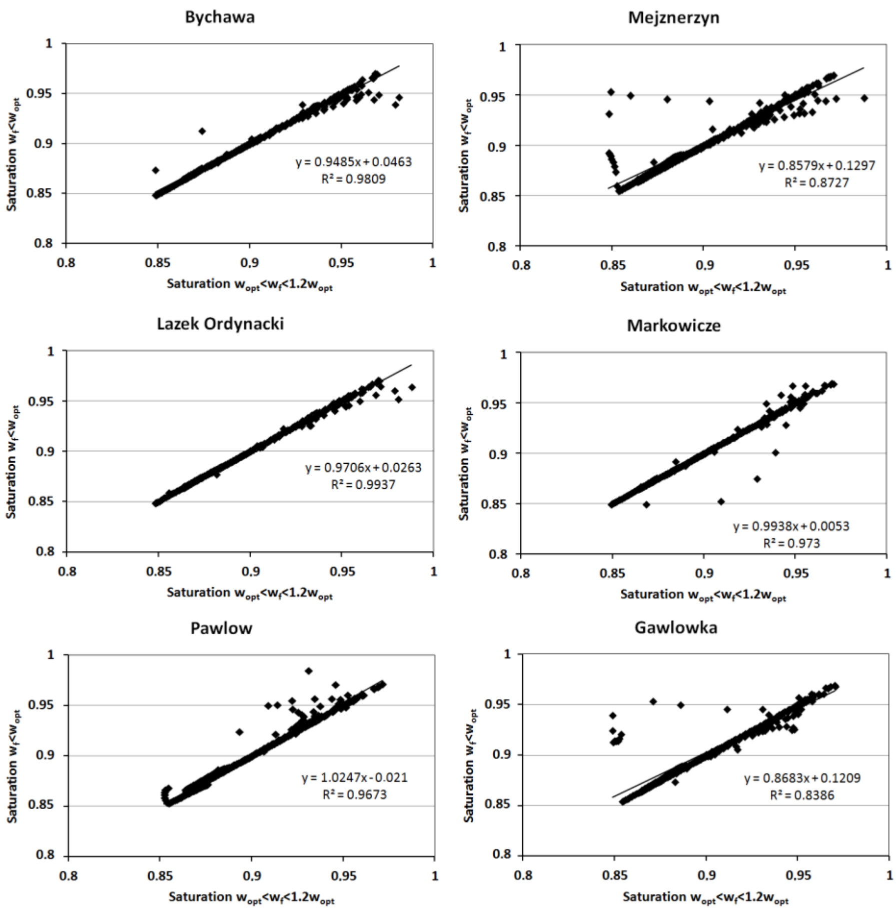

Fig. 5.36. Linear correlation of mean daily saturation calculated for reference point in recultivation layer of capping utilizing clays compacted at $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$

5.3. Proposal of material selection criteria for sustainable CCL

Finally, on the basis of the literature studies and the results of the Author's researches covering field and laboratory measurements and numerical modeling, a simplified, preliminary proposal of a set of criteria for material selection for sustainable compacted clay liner was suggested in Tab. 5.38.

Tab. 5.38. Proposal of criterion allowing selection of substrates for sustainable compacted clay liner construction

Parameter	Unit	Suggested value
Clay content	%	≥25
Fines content	%	≥30
Sand content	%	≤70
Plastic limit	%	Preferable approx. 15–25
Plasticity index	%	Preferable 10–30
Shrinkage potential (Parker et al., 1977)	-	Low to moderate, *COLE*≤0.06
Shrinkage deformation (Bronswijk, 1990)	-	Vertical or predominant vertical, $r_s \leq 3.0$
K_s in situ	$m\ s^{-1}$	$\leq 1 \cdot 10^{-9}$
K_s after compaction	$m\ s^{-1}$	$\leq 1 \cdot 10^{-9}$
K_s after compaction and three cycles of swelling-shrinkage	$m\ s^{-1}$	$\leq 1 \cdot 10^{-7}$

As it is visible, Tab. 5.38 contains a set of basic, general, easy to measure and determine, characteristics of clayey substrates affecting the sustainability of compacted clay liners. All indicators mentioned in the discussed table are related to the long-term sealing properties of a compacted clay liner endangered by the behavior of the compacted clay in contact with water. Resultant compaction effects, including K_s and shrinkage are related, beside molding water content, to clay, fines (clay+silt) and sand particles contents as well as the plasticity of clays. The applied values of Atterberg limits trigger a possibility of desiccation cracking (plastic limit) and, as related to plasticity, the general behavior after compaction and cyclic swelling and shrinkage (e.g. Mitchell and Soga, 2005; Baumgartl, 2006; Sadek et al., 2007).

Dimensionless indicators of shrinkage potential and deformation, *COLE* and r_s were selected as directly based on shrinkage measurements. The presented choice was also based on easy-to-understand formulas and clear threshold values (Parker et al., 1977; Bronswijk, 1990). Finally, the allowable value of K_s after three cycles of air drying and rewetting was selected according to the EPA's requirements for maximum saturated hydraulic conductivity of a compacted earthen liner of a municipal landfill top cover (EPA, 1993).

However, it should be clearly underlined that the criteria set presented in Tab. 5.38 should be treated as preliminary, as the base for the discussion, and after the future studies, covering a greater numbers of clay substrates may be developed, the applied threshold values may also be changed.

Tab. 5.39 contains attempt of determination of compatibility of tested clay substrates compacted at $w_{opt} \leq w_f \leq 1.2w_{opt}$ and 95% Proctor density to criteria presented in Tab. 5.38.

Tab. 5.39. Characteristics of tested substrates, compacted wet of optimum, validated according to sustainability criteria set presented in Tab. 5.38

	Bychawa	Lazek Ordynacki	Pawlow	Mejznerzyn	Markowicze	Gawlowka
Clay content (%)	42	44,5	52	52	38	31
Slay + silt content (%)	88	95,5	89	87	75	34
Sand content(%)	12	4.5	11	13	25	66
Plastic limit (%)	24.6	24.5	23.1	27.5	27.2	14.9
Plasticity index (%)	27.5	34.3	29.5	38.1	23.7	12.3
Shrinkage potential (Parker et al., 1977) *COLE* (-)	0.07 high	0.08 high	0.085 high	0.102 very high	0.04 moderate	0.025 low
Shrinkage deformation (Bronswijk, 1990) r_s (-)	3.3 Predom. horizontal	3.3 Predom. horizontal	2.7 Predom. vertical	3.1 Predom. horizontal	3.5 Predom. horizontal	2.2 Predom. vertical
K_s in situ m s^{-1}	$2.75 \cdot 10^{-10}$	$1.37 \cdot 10^{-10}$	$2.51 \cdot 10^{-10}$	$2.05 \cdot 10^{-10}$	$1.00 \cdot 10^{-10}$	$4.73 \cdot 10^{-10}$
K_s after compaction (m s^{-1})	$6.15 \cdot 10^{-11}$	$5.20 \cdot 10^{-11}$	$4.17 \cdot 10^{-11}$	$2.46 \cdot 10^{-11}$	$1.17 \cdot 10^{-10}$	$9.45 \cdot 10^{-11}$
K_s after compaction and three cycles of swelling-shrinkage (m s^{-1})	$8.51 \cdot 10^{-5}$	$1.37 \cdot 10^{-5}$	$1.03 \cdot 10^{-6}$	$3.37 \cdot 10^{-6}$	$2.37 \cdot 10^{-8}$	$2.32 \cdot 10^{-8}$

Data presented in Tab. 5.39 for the substrates compacted wet of optimum show that only one of the six tested soils met all of the suggested indicators of a sustainable clay material for construction of a sustainable compacted clay liner. All the presented threshold values were met by the sandy clay loam sampled in Gawlowka, presenting low shrinkage potential, predominant vertical deformation after shrinkage (less prone to cracking), sufficiently low hydraulic conductivity under natural conditions and after compactions and, finally, at least partial sealing capabilities after several cycles of drying and rewetting.

6. Summary

The main purposes of each sustainable waste management system are to minimize negative ecologic, environmental, social and economic effects of waste generation, transport, treatment and final disposal. Landfilling in the sustainable waste management system allows to isolate the final residual volume of waste, which is generally unsuitable to be further reduced, reused or recycled. Sustainable landfilling is a final, but crucial, part of sustainable municipal waste management allowing the safe disposal of waste within a landfill, and its subsequent degradation in the shortest possible time duration, by the most financially efficient method available, and with the minimal damage to the environment. Dumped wastes and processes occurring inside the waste body of a landfill are significant sources of pressure on the natural ecosystems. The main environmental impacts of landfills are related to the contamination of surface water and groundwater through leachate, possible pollution of soil by the direct contact with wastes or leachate percolation, air pollution, bad odors, spreading of diseases by birds, insects and rodents and uncontrolled release of methane. Thus, a sustainable landfill should be effectively isolated from the natural environment for the prolonged time of full decomposition of the collected and dumped waste.

Despite the rapid development and clear advantages of polymer-based sealing materials (geomembranes, geotextiles and geosythetics) the compacted clay liners are commonly used as sealing elements, or the sole sealing element, of mineral liners applied worldwide to landfills construction, especially in the undeveloped and developing countries of low and medium economic incomes and undeveloped local technologies and lacking professional workmanship. Therefore environmental sustainability of a landfill depends on the sustainably of its liners, including the subject of this paper, compacted clay liners which means then they should be able to contain pollutants migration to soil, water and air, for the prolonged time of landfill after closure. Ergo, sustainability of compacted clay liners is related to the ability of the liner to maintain its sealing capabilities, which in turn are dependent on the hydraulic conductivity, swell-shrink characteristics, and resistance to cyclic drying and rewetting. The abilities of CCLs to sustain their functions for a prolonged time are related to several factors: particle size composition, mineralogy, plasticity and compaction conditions.

The discussed technical guidelines for compacted clay liner material selection usually favor substrates of high clay and fines (clay+silt) content, significant clay mineral share and high plasticity, i.e. with a relatively high plastic limit and plasticity index, usually compacted wet of optimum at the right side of Proctor curve to obtain a very low hydraulic conductivity, far below 10^{-9} m s^{-1}. Nonetheless, such high plasticity clay substrates are typically characterized by the high shrinkage potential, irreversible desiccation cracking appearance after water content drops below the plastic limit and week resistance to cyclic drying and rewetting, which causes the increase in hydraulic conductivity by several orders of magnitude.

On the other hand, there are low plasticity clays, containing significant share of coarse sand fraction, and presenting the lower shrinkage potential, lower *PL* and *PI* as well as better resistance to cycles of drying and rewetting. Low plasticity clays show also the weaker relations between conditions of compaction and the resultant K_s, swell and shrinkage characteristics, sensitivity to cyclic drying and rewetting etc. etc. But despite the fact that the appropriate value of K_s may be achieved, these substrates, as it was presented, are often discouraged from application in the construction of CCLs.

This monograph was focused on studies concerning the influence of the characteristics of clays, hydraulic, geotechnical etc., on the sustainability of a compacted clay liner. The presented studies covered the field and laboratory measurements of general characteristics of the six tested substrates, their Atterberg limits, compaction characteristics at several variable water contents, saturated hydraulic conductivity and water retention curve before and after compaction, swelling, linear and volumetric shrinkage as well as hydraulic conductivity after three cycles of swelling and shrinkage. Additionally, the presented studies were supported by the numerical modeling of hydraulic efficiency of a multilayered top capping of a municipal landfill based on a compacted clay liner as a sealing layer, compacted both wet and dry of optimum, meeting requirements of Polish national standards. The shape of a section of an existing municipal landfill and the real weather conditions were applied to modeling. The hydraulic efficiency of bottom liners meeting the Polish and EU standards and utilizing the six tested substrates, compacted wet and dry of optimum, was also tested.

The presented *in situ* and laboratory measurements of numerous properties of the tested clay substrates, both under natural condition and after compaction at variable water contents as well as numerical calculations of the hydraulic efficiency of compacted clay liners utilizing the studied materials were performed to allow the assessment of sustainability of the CCL according to the presented introduced by the Author set of sustainability indicators.

According to the USDA regulations tested substrates were classified as clays, silty clays, clay loam and sandy clay loam, all contained more than 30% of clay fraction and presented clay minerals content equal to or higher than 50%.

The main general and commonly sole requirement (e.g. in several governmental standards) allowing the legal applicability of clays in the construction of the municipal landfills' capping sealing layer is the ability of the substrate to reduce its saturated hydraulic conductivity below the required $K_s=1.0\cdot10^{-9}$ m s^{-1}, was met by the tested substrates after the compaction, on both sides of Proctor curve, wet and dry of optimum, i.e. at $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$. Hydraulic conductivity in the range 10^{-10}–10^{-11} m s^{-1} was achieved after compaction at water contents from the both discussed ranges for all the six tested clay substrates.

The ability to reduce K_s after compaction to a very low value is commonly related to the clay fraction content which in all the tested cases was greater than 30%. The other reported criterion is based on the sum of clay and silt fractions, which in case of the tested materials was in most cases significant, from 75% to approx. 96%. The only exception was observed for the Gawlowka substrate, for which clay+silt content was equal only to 34%. However, the above had no negative influence on the compaction effects for the Gawlowka substrate, K_s values at optimal water content and suggested forming water content were similar to the values observed for the remaining tested clay substrates.

Swell-shrinkage characteristics and changes of saturated hydraulic conductivity of the compacted clays after several cycles of drying and rewetting are commonly related to the particle size composition of soils and resultant Atterberg limits. Generally, according to the USCS soil classification (after ASTM D2487-11) the studied clayey materials were classified as the high plasticity clays (CH) and low plasticity clays (CL). As CH were recognized Bychawa, Lazek Ordynacki, Pawlow, Mejznerzyn and Markowicze, the sole substrate representing low plasticity clays was the Gawlowka material. High plasticity clays, despite the fact that they allow to obtain a very low saturated hydraulic conductivity after compaction, present several disadvantages from the practical point of view and the further sustainability of compacted clay liner. Clays of plasticity index greater than 30–40%, such as sampled in Lazek Ordynacki and Mejznerzyn, may pose serious difficulties during field forming; when dry they form hard rocky clogs. On the other hand, when saturated they become sticky and adherent, as a result, hard to form. High plasticity clays are usually characterized by the significant swell and shrink potentials, which was confirmed during the laboratory test included in the presented studies. Swell and shrinkage characteristics read from plasticity chart allowed to assess the tested CHs as presenting high swelling and medium shrinkage potentials. Next, laboratory researches performed for the clays compacted at variable water contents showed that the significant increase in shrinkage potential related to the increase in molding water content was observed. The applied bar shrinkage test showed mean linear shrinkage for CHs in the range 5–7% and average value of dimensionless *COLE* 0.052–0.077, which according to classification by Parker et al. (1977) allowed to assess the shrinkage potential from moderate to high. The results of volumetric shrinkage tests showed mean values of *COLE* as 0.035–0.107 which means shrinkage potential from moderate to very high (Parker et al., 1977). For forming water content from the range $w_{opt}\leq w_f\leq 1.2w_{opt}$ and 95% Proctor density, *COLE* values for the studied high plasticity clays were in the range 0.04–0.102, i.e. the shrinkage potential was determined as from moderate to very high. Similarly, *COLE* value for molding water content from the range 0.025–0.11 represented shrinkage potential from low to very high. In all the discussed cases of the tested CHs, shrinkage characteristics reaching the upper limits were observed for Lazek Ordynacki, Mejznerzyn, Bychawa and Pawlow, i.e. substrates containing significant part of clay+silt fraction, while the lower limit was permanently observed for the Markowicze substrate, containing grater (25%) sand fraction content. Additionally, swell index for the studied CHs reached the range of 4.4–6.7%.

On the other hand, substrate sampled in Gawlowka, recognized, according to the USCS soil classification, as a low plasticity clay, showed 3% of linear shrinkage and *COLE* equal to 0.044 during the bar shrinkage test, which allowed the classification of its shrinkage potential as moderate according to Parker et al. (1977). The mean value of *COLE* obtained during the volumetric shrinkage test for the material sampled in Gawlowka was equal to 0.024, which resulted in the classification of its shrinkage potential as low. Measurements of shrinkage for $w_{opt} \leq w_f \leq 1.2 w_{opt}$ and $w_f < w_{opt}$ and 95% of the Proctor density resulted in *COLE* equal to 0.025 and 0.018 respectively, again classifying the shrinkage potential of the Gawlowka substrate as low in the both applied cases. The measured swell index of the Gawlowka samples was also lower than in the case of the above presented CHs, and was equal to 2.9%.

Analysis of the dimensionless shrinkage geometry factor r_s showed that the tested substrates performed differently. For compaction performed for both wet and dry of optimum, $w_{opt} \leq w_f \leq 1.2 w_{opt}$ and $w_f \leq w_{opt}$, four materials showed predominant horizontal deformation, commonly related to the possibility of desiccation cracking, i.e. Bychawa, Lazek Ordynacki, Markowicze and Mejznerzyn. The predominant vertical deformation, safer for CCL sustainability, was observed for Pawlow and Gawlowka.

Thus, all the above showed that if one takes into account the possible significant shrinkage of compacted clay liner, resulting commonly in cracking which drastically decreases the sealing capabilities of CCL, clayey substrates presenting high values of plasticity index should be avoided. It was observed that in the case of the tested clay materials increase in the plasticity index resulted in increased swell-shrink characteristics. Positive correlations between the *PI* value and swell index, linear shrinkage, *COLE* value for w_{opt}, as well as mean *COLE* were observed. Therefore, the increased possibility of swelling, shrinkage and subsequent cracking, seriously endangering the sustainability of a clay liner is triggered by high values of *PI*.

The Atterberg limits, including the already discussed plasticity index are commonly linked to the particle size distribution of the applied substrates, therefore the influence of sand and clay fractions on characteristics affecting CCLs sustainability should be also considered.

Two of the six tested substrates showed noticeable amount of sand fraction, i.e. the clay loam sampled in Markowicze 25% and the sandy clay loam from Gawlowka 66% (both contained 50% mass of clay minerals). Both of the tested substrates presented significantly low liquid limit (51% and 27%, respectively) and plasticity index, 27% and 12%, respectively. *PI* for the Bychawa substrate was below applicability limit according to the guidelines by ITB (Wysokiński, 2007), however there were reported successful liners utilizing clays of *PI*<15% (EPA, 1993; Rowe at al., 1995; Benson and Trast, 1995). The substrate sampled in Gawlowka was recognized as a low plasticity clay and in Markowicze as high plasticity clay, however the *LL* value for this substrate was located close to the border line between CLs and CHs, the difference versus threshold value was lower than 1% of liquid limit. The swelling potential of the two discussed substrates was assessed according to the plasticity chart as high for Markowicze (again nearly at the threshold line) and low for Gawlowka, while shrinkage potential at plasticity chart was assessed as medium for Markowicze and low for Gawlowka. As it was mentioned earlier, the substrate sampled in Gawlowka, recognized as CL was characterized by the lowest of the observed values of swell index, linear shrinkage and *COLE* determined during the bar shrinkage test as well as mean *COLE* and *COLE* for both tested ranges of molding water content $w_{opt} \leq w_f \leq 1.2 w_{opt}$ and and $w_f < w_{opt}$ both 95% of the Proctor density.

All the above mentioned swell and shrinkage characteristics allowed to assess the shrinkage potential of the Gawlowka material generally as low (moderate shrink potential was observed only for *COLE* analysis and bar shrinkage test). This material also presented the lowest, of all the six tested, swell and shrink potentials, determined according to Stępniewski and Horn (2004) for the full range of the applied molding water contents. Shrinkage characteristics for the Markowicze substrate was determined during the bar and volumetric shrinkage tests as generally moderate. Low shrinkage potential was observed only for the material compacted at $w_f < w_{opt}$ and 95% Proctor density. Additionally, analysis of relations between the sand fraction content and compaction effects and swell-shrinkage characteristics showed that increase in the sand content slightly increases the saturated hydraulic conductivity and obtained Proctor density as well as reduces the mean linear shrinkage, *COLE* at w_{opt} and mean swelling index. Thus, it is visible that in the case of the tested substrates, sand content, without any significant increase in the obtained K_s value after compaction at suggested water contents, reduced the characteristics negatively affecting the sustainability of a compacted clay liner.

On the other hand, the tested substrates, including Bychawa, Lazek Ordynacki, Pawlow and Mejznerzyn, containing significant amount of clay (42–55%) and clay+silt (87–95.5%) fraction were characterized by high swelling and medium shrinkage potentials read from the plasticity chart. Tests of linear and volumetric shrinkage allowed to determine their shrinkage potential generally as high and very high. Moderate shrinkage potential was observed only for Lazek Ordynacki during the bar shrinkage test. On the other hand, shrinkage potential for the Mejznerzyn substrate (52% of clay fraction) was in all the tested cases of volumetric shrinkage tests determined as very high. According to the analyzed results of laboratory measurements, clay content decreased saturated hydraulic conductivity at w_f and the Proctor density and increased all important swell and shrinkage potential indicators, such as the swell index and *COLE*, both at w_{opt} and mean for all applied molding water contents. Thus, clay and clay+silt content, while on the one hand allowing to obtain slightly better compaction results, including K_s at w_{opt} and w_f, on the other hand increased swell and shrinkage characteristics, negatively affecting the sustainability of a compacted liner.

The sustainability of a compacted clay liner may also be affected by the endurance of the liner material during variable saturation cycles, for which the most drastic examples are the air drying and rewetting cycles. Unfortunately, the performed laboratory measurements showed that none of the tested compacted clay materials, with meaningless molding water content, was able to sustain the K_s at w_f after one, two and three cycles of drying and wetting. However, some interesting tendencies, significant for liner sustainability assessment were observed. For most of the tested high plasticity clays (including the Bychawa, Lazek Orydnacki, Pawlow and Mejznerzyn substrates), containing low sand and high clay+silt contents, the subsequent cycles of drying and rewetting led to the significant increase in saturated hydraulic conductivity. As it was mentioned before, even values of K_s from the level of 10^{-4} m s^{-1} were observed for the high plasticity clays. Additionally, decrease in the molding water content resulted in the increase in the measured K_s after each cycle of drying and wetting. Finally, analysis of mean values of K_s for each tested high-plasticity clay showed an increase in the observed value for each subsequent cycle of air drying and wetting. Thus, application of high-plasticity clays containing significant share of clay and silt fractions may be connected with the considerable risk of partial or total loss of CCL’s sealing capabilities. Partially or totally dried and rewetted, according to several possible exploitation mistakes or failures, compacted tested CHs were unable to limit the infiltration of surface water into the sealing layer, and, subsequently, into the wastes body.

On the other hand, despite the fact that compacted tested substrates containing considerable amount of sand fraction, i.e. the low plasticity clay sampled in Gawlowka and the high plasticity clay from Markowicze, were also unable to sustain the K_s value below 10^{-9} m s^{-1}, their saturated hydraulic conductivity after subsequent cycles of drying and rewetting was different then in the cases of the previously discussed high plasticity clays. Both discussed clay materials showed limited susceptibility to increase in their saturated conductivity after three cycles of air drying and wetting. Moreover, no significant influence of the applied molding water content on the increase in K_s value after the subsequent cycles of drying and rewetting was observed, in relation to data obtained for previously discussed high-plasticity clays. Thus, according to the discussed results, two studied clayey materials, after drying and rewetting were able to provide at last partial sealing properties, significantly better (several orders of magnitude) than in the case of the remaining four researched substrates of high plasticity clays. Therefore, application of low plasticity substrates allowing to retain at least partial sealing capabilities should improve the sustainability of a compacted clay liner.

The performed numerical modeling of the hydraulic efficiency of top capping systems utilizing the tested substrates in compacted clay liner (sealing layer) and meeting requirements of the actual national standards of Poland, showed that all modeled cappings performed similarly. For the both applied forming water contents $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ the sealing capabilities assessed as related to annual unit seepage were comparable and satisfactory, reducing infiltration to waste body to negligible values lower than 1.0 mm. In nearly all cases, for clays compacted at both sides of Proctor curve, at variable water content, the clay liners sustained their initial saturation without regard for its value (observed fluctuations reached maximum level of approx. 1.0%).

The only notable exceptions from the mentioned above were observed for the modeled CCL utilizing the Gawlowka substrate, compacted at, both $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ water contents. In this case, the visible increase in compacted liner saturation versus its initial saturation was observed, up to even approx. 0.06 for $w_{opt}<w_f<1.2w_{opt}$ and 0.08 for $w_f<w_{opt}$. Thus, despite the fact, that numerical modeling showed significant lateral water flow downslope through the sand drainage layer, caused by the inclination of slope and a very high difference between saturated hydraulic conductivity in the drainage and compacted sealing layers, the CCL based on the Gawlowka substrate presented tendency to moistening due to partial infiltration by the water flux from the drainage layer. The above may result in the risk of desiccation cracking in case of the decrease in water content for the selected substrates compacted at $w_{opt}<w_f<1.2w_{opt}$ and for the all molded at $w_f<w_{opt}$ because the modeled water content in the tested CCL dropped below the value of plastic limit for the tested substrates. Thus, the proper selection of the molding water content seems to be crucial, not only in relation to the required value of saturated hydraulic conductivity but also taking into account the swell-shrink potential and plastic limit value, to avoid significant shrinkage and cracking.

Moreover, the hydraulic performance of two top layers, i.e. recultivation and drainage, gauged by time variable saturation as well as velocity vectors directions and values was comparable in all the tested cases, no matter which clayey material was applied to the construction of compacted clay liner and which value of the molding water content was applied, from wet and dry of optimum. Thus, each tested CCL allowed the comparable and appropriate performance of the drainage and recultivation layers, allowing to redirect water flux downslope in the drainage layer and sustain the saturation of the recultivation layer significantly above the level of 0.8 (80%) assuring water available for plants growing at the capping surface and strengthening the land surface by roots, thus allowing to limit soil erosion by water (splash, sheet, rill and inter-rill erosion).

All the above shows that the hydraulic sustainability of CCLs constructed of clayey substrates is not affected directly in the normal, standard, operational conditions by the variable particle and mineral composition of the materials used. Nonetheless, the sustainability of compacted clay liners may be endangered, i.e. their operational functionality and sealing capabilities may be reduced in the case of various failure issues, designing and construction errors etc. Thus, the sustainability of compacted clay liners should be, in my opinion, after assuring the required K_s after compaction, studied in relation to swell and shrink characteristics and changes in their hydraulic conductivity after several cycles of drying and rewetting.

According to the developed set of sustainability criteria for mineral materials, only one substrate, the low plasticity sandy clay loam sampled in Gawlowka met all the required thresholds. However, the presented set of criteria for material selection should be further developed and discussed.

Therefore, to summarize, the performed studies showed that despite the fact that all the tested substrates were generally in agreement with the popular local or international technical requirements for applicability of clay materials to CLL construction, not always the sustainability of the liner was obvious. The set of sustainability indicators for material selection support was developed and tested on the studied clayey materials. High plasticity clays, favored by several technical manuals and guidelines, presented during the performed studies significantly high values of the plastic limit and plasticity index, high or very high shrinkage potential, predominant horizontal deformation during shrinkage (related to possible desiccation cracking). CHs were also unable to sustain their sealing capabilities after several cycles of swelling and shrinkage, the increase in K_s reached even six orders of magnitude, in relation to values obtained after compaction. On the other hand, the low plasticity clay tested presented lower values of the plastic limit and plasticity index, low shrinkage potential, predominant vertical deformation, and at least partial ability to sustain sealing properties after several cycles of drying and rewetting. Thus, in my opinion, sustainability of a CCL, understood as its ability to sustain the most important hydraulic sealing properties during the long-term operation after the closure of the landfill, constructed of low plasticity clay is clearly more probable than in the case of high plasticity clay application. The above opinion is based on the lower durability of the compacted high plasticity clays to external impacts related to water. Moreover, the discussed weakening processes limiting the sealing properties of CHs increase their intensity due to increase in the molding water content, especially for the high initial saturations, wet of optimum. Finally, substrates of various plasticity, particle size distribution and mineralogy etc. etc. showed comparable and generally satisfactory strength parameters. The applied numerical modeling showed that multilayered top cover systems and bottom liners based on the tested substrates performed similarly.

The presented studies will be continued and will cover:

- Introduction of other types of clayey materials of various particle size distribution and mineral composition and different plasticity to the research;
- Introduction of the landfill leachate as permeating liquid in the measurements of the hydraulic conductivity of a compacted clay liner;
- Numerical modeling of several possible implementations of a multilayered top cover of a landfill, including terracing, embankments and capillary barriers etc.etc. orientated towards the increased saturation of a CCL by infiltration water.

7. Conclusions

The following conclusions related to the properties of clays and the sustainability of a compacted clay liners may be presented after discussion of the results obtained by field and laboratory measurements as well as by the performed numerical calculations:

- According to USCS soil classification (after ASTM D2487-11) the studied clayey materials were classified as high plasticity clays (CH, 5 types) of high swelling and medium shrinkage potentials and low plasticity clays (CL, one type) of low swelling and shrinkage potential;
- All six studied substrates characterized *in situ*, directly in clayey material layer presented saturated hydraulic conductivity lower than the usually required value of $1.0 \cdot 10^{-9}$ m s^{-1}; compaction wet and dry of the optimum, at $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ allowed to achieve the hydraulic conductivity in the range 10^{-10}–10^{-11} m s^{-1};
- For most of the tested substrates the low applied molding water contents dry of optimum disallowed to reduce saturated hydraulic conductivity to the values lower than $1.0 \cdot 10^{-9}$ m s^{-1}; the only exception was observed for the low plasticity Gawlowka material, for which the required value of K_s was achieved in the case of all applied molding water contents;
- According to the analyses of swelling and shrinkage potentials the observed results were generally related to values of applied molding water content; the swell potential decreased due to increase in water content while the shrinkage potential increased due to increase in water content, and in most of the cases the observed shrinkage potential reached its highest values for specimens compacted wet of optimum;
- Volumetric shrinkage tests of the studied high plasticity clays showed the shrinkage potential from moderate to a very high, while the low shrinkage potential was observed for the low plasticity clay;
- Analysis of the dimensionless shrinkage geometry factor r_s showed that the tested substrates behaved differently, for compaction performed both wet and dry of optimum; four materials (Bychawa, Lazek Ordynacki, Markowicze and Mejznerzyn) showed predominant horizontal deformation, related to the possibility of desiccation cracking, while the safer for a CCL sustainability predominant vertical deformation was observed for the Pawlow and Gawlowka substrates;
- Laboratory measurements showed that none of the tested compacted clay materials, with meaningless applied molding water content, was able to sustain the K_s at w_f after one, two and three cycles of drying and wetting;

- For most of the tested high plasticity clays (including Bychawa, Lazek Orydnacki, Pawlow and Mejznerzyn substrates) the subsequent cycles of drying and rewetting led to a significant increase in the saturated hydraulic conductivity, even by several orders of magnitude, thus a considerable risk of partial or total loss of sealing capabilities by the CCL is present;
- Two substrates containing significant share of coarse sand fraction, i.e. Bychawa and Markowicze, showed limited susceptibility to the increase in saturated conductivity after three cycles of air drying and wetting; moreover, no significant influence of the applied molding water content on the increase in the K_s value after subsequent cycles of drying and rewetting was observed;
- The performed numerical modeling of the hydraulic efficiency of the top capping systems utilizing the tested substrates in a CCL and meeting the requirements of the actual national Polish standards, showed that all the modeled covers performed similarly;
- Both applied molding water contents $w_{opt}<w_f<1.2w_{opt}$ and $w_f<w_{opt}$ allowed the comparable and satisfactory sealing capabilities assessed on the basis of the modeled annual unit seepage.
- In nearly all the cases, for clays formed at variable water content at both sides of the Proctor curve, the modeled CCLs sustained their initial saturation regardless its value, the only notable exceptions were observed for liner utilizing the Gawlowka substrate, for which a visible increase in compacted liner saturation was observed;
- Numerical modeling showed a significant lateral water flow downslope through the sand drainage layer, caused by the inclination of the slope and a very high difference between saturated hydraulic conductivity of the drainage and compacted sealing layers, thus additional saturation of the CCL was limited;
- The modeled water content in the tested CCLs for selected substrates compacted wet of optimum and for all substrates compacted dry of optimum was below the value of plastic limit, which may result in the desiccation cracking in case of decrease in water content;
- The hydraulic performance of the two top capping layers, i.e. the recultivation and drainage one, assessed by time variable saturation as well as velocity vectors directions and values was comparable in all the tested cases, no matter which material was applied in the construction of the compacted clay liner and what was the value of molding water content applied, wet and dry of optimum;
- Comparable and appropriate performance of the drainage and recultivation layers was observed for the all CCLs tested, allowing to redirect the water

flux downslope in the drainage layer and sustain the saturation degree of the recultivation layer significantly above the level of 0.8 (80%) ensuring water available for the plants growing at capping surface and strengthening the soil surface by roots.

Thus, to ensure the construction of a sustainable compacted clay liner several crucial issues resulting from the presented studies should be underlined:

- High plasticity clays, containing a dominant share of fine particles and high clay minerals content presenting high plastic limit and plasticity index, prone to desiccation cracking and shrinkage, should be avoided and if possible replaced by substrates containing coarse fraction and presenting lower plasticity;
- Application of the low plasticity substrates or high plasticity materials with the significant share of sand may allow to retain at least partial sealing capabilities and should improve the sustainability of the compacted clay liner;
- Practical application of the proposed criteria set for the earthen material selection should help to improve the sustainability of compacted clay liners;
- Molding water content should be very carefully selected because it triggers the future behavior of the compacted clay liner e.g. defines not only the saturated hydraulic conductivity and retention characteristics, but also the swell and shrink potentials and resistance against cycles of drying and wetting;
- Molding water content should also be assessed in relation to the plastic limit of the applied clay substrate; in the case of water content drop below the value of the plastic limit desiccation cracking may be triggered, in case of further decrease in saturation;
- High inclination of the top cover liner should be avoided because it allows the dominant lateral water flow downslope which significantly limits the infiltration from coarse drainage layer to the subjacent compacted clay liner, clearly reducing the possibility of its resaturation.

8. Bibliography

1. **Albrecht B.A., 1996.** Effect of desiccation on compacted clays. MSc. Thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI.
2. **Albrecht B.A., Benson, C.H., 2001.** Effect of desiccation on compacted natural clay. Journal of Geotechnical and Geoenvironmental Engineering 127 (1), 67–75.
3. **Aldaeef A.A., Rayhani M.T., 2014.** Hydraulic performance of Compacted Clay Liners (CCLs) under combined temperature and leachate exposures. Waste Management, 34, 2548–2560.
4. **Aldaeef A.A., Rayhani M.T., 2015.** Hydraulic performance of compacted clay liners under simulated daily thermal cycles. Journal of Environmental Management, 182, 171–178.
5. **Al-Khatib I.S., Monou M., Abu Zahra A.S.F., Shaheen H.Q., Kassinos D., 2010.** Solid waste characterization, quantification and management practices in developing countries. A case study: Nablus district – Palestine. Journal of Environmental Management, 97,1131–1138.
6. **Allaire S.E., Roulier S., Cessna A.J., 2009.** Quantifying preferential flow in soils: a review of different techniques. Journal of Hydrology 378, 179–204.
7. **Allen A., 2000.** Containment landfills: the myth of sustainability. Engineering Geology, 60, 3–19.
8. **Allen R.G., Smith M., Perrier A., Pereira L.S., 1994.** An update for the definition of reference evapotranspiration. ICID Bull, 43, 1–34.
9. **Alther G.R., 1987.** The qualification of bentonite as a soil sealant. Engineering Geology, 23, 177–191.
10. **Altmeyer W.T., 1956**. Discussiom following paper by Holtz and Gibbs. Transactions of the American Society of Civil Engineers. 2814 (2), 666–669.
11. **Arch J., 1998.** Clay barriers in landfills. In: Environmental interactions of clays. Clays and environment. (Eds A. Parker, J.E. Rea.), Springer, Berlin, Germany.
12. **Artieres O., Delmans P., 1995.** Puncture resistance of geotextile-geomembranne lining systems. In: Christensen T.H., Cossau R., Stegmann R. (Eds.) Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, 213–224.
13. **Assaad J., and Harb J., 2013.** Use of the Falling-Head Method to Assess Permeability of Freshly Mixed Cementitious-Based Materials. J. Mater. Civ. Eng., 25(5), 580–588.
14. **ASTM C566-13, 2013.** Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying. ASTM International, West Conshohocken, PA, USA.
15. **ASTM D2487-11**. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System).

16. **ASTM D5856-95, 2007**. Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall Compaction-Mold Permeameter. ASTM International, West Conshohocken, PA, USA.
17. **ASTM D698-12e1**. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m^3)). ASTM International, West Conshohocken, PA, USA
18. **ATV-DVWK-M 504, 2002.** Verdunstung in Bezug zu Landnutzung, Bewuchs und Boden. DWA, Hennef, Germany.
19. **Bagchi A., 1990.** Design, construction and monitoring of sanitary landfill. John Wiley & Sons, New York, USA.
20. **Bain J.A., 1971.** A plasticity chart as an aid to the identification and assessment of industrial clays. Clay Minerals, 9.1.
21. **Baroni G., Facchi A., Gandolfi C., Ortuani B., Horeschi D., van Dam J. C., 2010.** Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity. Hydrol. Earth Syst. Sci., 14, 251–270.
22. **Basma A.A., Al-Homoud A.S., Malkawi A.I.H., Al-Bashebsheh M.A., 1996.** Swelling-shrinkage behavior of natural expansive clays. Applied Clay Science, 11, 211–227.
23. **Basnett C., Bruner R., 1993.** Clay desiccation of a single-composite liner system. Geosynthetics 93 Conference, Vancouver, 1329–1334.
24. **BAT, 2006**. In situ permeability measurement with the BAT Permeameter, BAT Geosystems AB, Vallentuna, Sweden.
25. **Batool S.A., Ch. M.N., 2009.** Municipal solid waste management in Lahore city district, Pakistan. Waste Management, 29, 1971–1981.
26. **Bauer B., Taubner H., Tippkötter R., 2001.** The measurement of mechanical and hydraulic consolidation of clayey substrates using an improved Proctor method (in German). Wasser und Boden, 53, 27–29.
27. **Baumgartl T., 2006.** Atterberg limits. In: Lal R. (Ed.), Encyclopedia of Soil Science, CRC Press.
28. **Bello A.A., 2013.** Hydraulic conductivity of three compacted reddish brown tropical soils. KSCE Journal of Civil Engineering, 17(5), 939–948.
29. **Benson C., Zhai H., Wang X., 1994.** Estimating the hydraulic conductivity of compacted clay liners, Journal of Geotechnical Engineering, 120, 366–387.
30. **Benson C.H., Edil T.B., Wang X., 2012.** Evaluation of a final cover slide at landfill with recalculating leachate. Geotextiles and Geomembranes, 35, 100–106.
31. **Benson C.H., Trast J.M., 1995**. Hydraulic conductivity of thirteen compacted clays. Clays and Clay Materials, 46 (6), 669–681.
32. **Bentley S.P., Carter M., 1991.** Correlation of soil properties, Pentech Press, London.
33. **Bhamidimarri R., Butler K., 1998.** Environmental engineering education at the millennium: An integrated approach. Water Science and Technology, 38(11), 311–314.

34. **Bieganowski A., Chojecki T., Ryżak M., Sochan A. and Lamorski K. 2013.** Methodological aspects of fractal dimension estimation on the basis of PSD. Vadose Zone Journal, 12.
35. **Bouazza A., 2002.** Geosynthetic clay liners. Geotextiles and Geomembranes, 20, 3–17.
36. **Boynton S.S., Daniel D.E., 1985.** Hydraulic conductivity tests on compacted clay. ASCE Journal of Geotechnical Engineering 111 (4), 465–478.
37. **Brennan R.B., Healy M.G., Morrison L., Hynes S., Norton D., Clifford E., 2015.** Management of landfill leachate: The leacy of European Union Directives. Waste management. In press.
38. **Brian A.A., Benson C.H., 2001.** Effect of desiccation on compacted natural clays. Journal of Geotechnical and Geoenvironmental Engineering 127, 67–75.
39. **Brogaard L.K., Stentsoe, S., Willumsen, H.C., Christensen T.H., 2013.** Quantifying capital goods for waste landfilling. Waste management Resources 31, 555–598.
40. **Bronswijk J.J.B., 1990**. Shrinkage geometry of a heavy clay soil at various stresses. Soil Science Society of America Journal, 54 (5), 1500–1502.
41. **BS 1377-1, 1990.** Methods of tests for soils for civil engineering purposes. General requirements and sample preparation.
42. **BS 1377-2: 1990.** Methods of test for soils for civil engineering purposes. Classification tests.
43. **BS 5930: 1999.** Code of practice for site investigations.
44. **Butt T.E., Lockley E. and Oduyemi K.O.K., 2008.** Risk assessment of landfill disposal sites – State of the art. Waste Management, 28, 952–964.
45. **Capaccioni B., Caramiello C., Tatano F., Viscione A., 2011.** Effects of temporary HDPE cover on landfill gas emissions: Multiyear evaluation with the static chamber approach at an Italian landfill. Waste Management, 31, 956–965.
46. **Chang F.H., 1988.** Foundations on expansive soils. Elsevier Science Publishers, Amsterdam, The Netherlands.
47. **Chang M., 2005.** Three-dimensional stability analysis of the Kettleman Hills landfill slope failure based on observed sliding-block mechanism. Computers and Geotechnics, 32, 587–599.
48. **Chen F.D., 1988.** Foundations of Expansive Soils. Elsevier Science Company Inc.
49. **Chen X.Q., Lu Z.W., He., X.F., 1985.** Moisture movement and deformation of expansive soils. 11th Int. Conf. Soil Mech. Found. Eng., 4, San Francisco, 2389–2392.
50. **Chen Z., Gong H., Zhang M., Wu W., Liu Y., Feng J., 2011.** Impact of using high-density polyethylene geomambrane layer as landfill intermediate cover on landfill gas extraction. Waste Management, 31, 1059–1064.
51. **Chofi A., Younsi A., Lhadi E.K., Mania J., Mudry J., Veron A., 2004.** Environmental impact of an urban landfill on a costal aquifer (El Jadida, Morocco). J. African Earth Sci., 39 (3-5), 509–516.

52. **Corte A., Higashi A., 1960.** Experimental research on desiccation cracks in soil. Research report 66, U.S. Army Snow Ice and Permafrost Research Establishment. Wilmette, Illinois.
53. **Cuisinier O., Auriol J.C. and Le Borgne T., 2011.** Microstructure and hydraulic conductivity of a compacted lime-treated soil. Eng Geol., 123 (3),187–193.
54. **Daniel D.E. and Koerner R.M. 1995.** Waste containment facilities. Guidance for Construction, Quality Assurance and Quality Control of Liner and Cover Systems. ASCE Press, New York, USA.
55. **Daniel D.E., Wu Y.K., 1993.** Compacted clay liners and covers for arid sites. Journal of Geotechnical Engineering, ASCE, 119 (2), 223–237.
56. **Dasog G.S., Acton D.F., Mermut A.R., De Joung E., 1988.** Shrink-swell potential and cracking in clay soils of Saskatchewan. Can, J. Soil. Sci., 68, 251–260.
57. **DepV, 2009.** German landfill ordinance, Deponieverordnung – DepV: Degree on landfills (ordinance to simplify the landfill law) – Germany, in the form of the resolution of the Federal Cabinet dated April 27th 2009.
58. **Derkowski A., Franus W., Beran E. and Czimerova A., 2006.** Properties and potential applications of zeolitic materials produced from fly ash using simple methods of synthesis. Powder Technology, 166/1, 47–54.
59. **Diersch H.J.G., 2009.** FEFLOW, finite element subsurface flow and transport simulation system reference manual. DHI-WASY Ltd. Berlin, Germany.
60. **Diersch H.J.G., Kolditz O., 2009.** Variable-density flow and transport in porous media: approaches and challenges. Advances in Water Resources, 25, 899–944.
61. **Dixon N., Jones D. R. V., Fowmes G. J., 2006.** Interface shear strength variability and its use in reliability-based landfill stability analysis. Geosynthetics International, 13(1), 1–14.
62. **Dörner J., Dec D., Peng X., Horn R., 2009.** Change of shrinkage behavior of an Andisol in southern Chile: Effects of land use and wetting/drying cycles. Soil & Tillage Research, 106(1), 45–53.
63. **dos Muchangos L.S., Tokai A., Hanashima A., 2015.** Analyzing the structure of barriers to municipal solid waste management policy planning in Maputo city, Mozambique. Environmental Development, 16, 76–89.
64. **Dove J.E., Frost, J. D., 1999.** Peak friction behavior of smooth geomembrane–particle interfaces. Journal of Geotechnical and Geoenvironmental Engineering, 125(7), 544–555 .
65. **Ebina T., Minja J.A., Nagase T., Onodera Y., Chattereje A., 2004.** Correlation of hydraulic conductivity of clay-sand compacted specimens with clay properties. Applied Clay Science, 26, 3–12.
66. **Egloffstein T.A., 2001.** Natural bentonites–influence of the ion exchange capacity and partial desiccation on permeability and self–healing capacity of bentonites used in GCLs. Geotextiles and Geomembranes, 19, 427–444.

67. **Eid H.T., 2011.** Shear strength of geosynthetic composite systems for design of landfill liner and cover slopes. Geotextiles and Geomembranes, 29 (3), 335–344.
68. **EPA, 1993.** Solid waste disposal facility criteria. Technical manual 530-R-93-017. US Environmental Protection Agency.
69. **EPA, 1996.** Environmental Guidelines: Solid Waste Landfills**.** US Environmental Protection Agency.
70. **EPA, 2015.** Draft Environmental Guidelines: Solid Waste Landfills, Second Edition. US Environmental Protection Agency.
71. **Erses Yay A.S., 2015.** Application of life cycle assessment (LCA) for municipal solid waste management; a case study of Sakarya. Journal of Clearer Production, 94, 284–293.
72. **EU, 1999.** Council Directive 99/31/EC of 26 April 1999 on the landfill of waste, Brussels, Council of the European Union; 1999.
73. **EU, 2008.** Directive 2008/98/EC of The European Parliament and of The Council of 19 November 2008 on waste and repealing certain Directives
74. **Farquhar G.J., Parker W., 1989.** Interactions of leachates with natural and synthetic envelops. In: Bacconi P. (Ed.), Lecture Notes in Earth Sciences, vol. 20, The Landfill, Reactor and Final Storage, Springer, Berlin, 174–200.
75. **Fernandes M., Denis A., Fabre R., Lataste J.F., Chretien M., 2015.** In situ study of the shrinkage of a clay soil cover over several cycles of drought-rewetting. Engineering Geology. 192, 63–75.
76. **Finsterwalder K., 2003.** Bemessung der Sicherungssysteme von Deponien und Altlasten unter Einbeziehung der stochastischen Natur der Variablen (Design of barrier systems for landfills and the remediation of contaminated sites taking into account the stochastic nature of the variables). In: Schulz, H. (Ed.), Neue Entwicklungen bei Oberflächenabdichtungen von Deponien. Universität der Bundeswehr, München.
77. **FM 5-513, 2000.** Coefficient of Permeability - Falling Head Method. Florida Department of Transportation.
78. **Foged N., Baumann J., 1999.** Clay membrane made of natural high plasticity clays: leachate migration due to advection and diffusion. Engineering Geology, 54, 129–137.
79. **Francisca F.M., Glatstein D.A., 2010.** Long term hydraulic conductivity of compacted soils permeated with landfill leachate. Applied Clay Science 49. 187–193
80. **Fredlund D.G., Rahardjo H., 1993.** Soil Mechanics for Unsaturated Soils. John Wiley & Sons.
81. **Gebhardt S., Fleige H. and Horn R., 2012.** Anisotropic shrinkage of mineral and organic soils and its impact on soil hydraulic properties. Soil & Tillage Research, 125, 96–104.
82. **Greminger P.J., Sud Y.K., Nielsen D.R., 1985.** Spatial variability of field-measured soil water characteristics. Soil Sci. Soc. Am. J., 49: 1075–1082.
83. **Grossman, R.H., Brasher, B.R., Franzmeier, D.P., Walker, J.L., 1968.** Linear extensibility as calculated from natural-clod bulk density measurements. Soil Sci. Soc. Am. Proc. 32, 570–573.

84. **Guerrero L.A., Maas G., Hogland W., 2013.** Solid waste management challenges for cities in developing countries. Waste Management, 33, 220–232.
85. **Hanson, J.L., Yesiller, N., Oettle, N.K., 2010.** Spatial and temporal temperature distributions in municipal solid waste landfills. J. Environ. Eng. 136 (8), 1095–1102.
86. **Harding R., 2006.** Ecologically sustainable development: origins, implementation and challenges, Desalination, 187, 229–239.
87. **Harris J.M., Wise T.A., Gallagher K.P., Goodwin N.R, 2001.** A Survey of Sustainable Development, Social and Econo Dimensions, Island Press, Washington, Covelo, London 2001.
88. **He J., Wang Y., Li Y., Ruan X.C., 2015.** Effects of leachate infiltration and desiccation cracks on hydraulic conductivity of compacted clay. Water Science and Engineering, 8, 151–157.
89. **Heerten G., 2002.** Geosynthetic clay liner performance in geotechnical applications. In: Zanzinger, H., Koerner, R.M., Gartung, E. (Eds.), Clay Geosynthetic Barriers. A.A. Balkema Publishers, Lisse, The Netherlands, 3–19.
90. **Hensen E.J.M., Smit B., 2002.** Why clays swell. J. Phys. Chem. B., 106, 12664–12667.
91. **Hewitt P.J., Philip L.K., 1999.** Problems of clay desiccation in composite lining systems. Engineering Geology, 55, 107–113.
92. **Holtz R.D., Kovacs W.D., 1981.** An introduction to geotechnical engineering, Prentice Hall, Englewood Cliffs, NJ, USA
93. **Horn R. and Stępniewski W., 2004.** Modification of mineral liner to improve its long-term stability. Int. Agrophysics, 18, 317–323.
94. **Horn R., Domzal H., Slowinska-Jurkiewicz A., van Quwerkerk C., 1995.** Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Tillage research, 35, 23–26.
95. **Hoyningen-Huene J.F.V., 1983.** Die Interzeption des Niederschlags in landwirtschaftlichen Pflanzenbeständen. Schriftenreihe des Deutschen Verbandes für Wasserwirtschaft und Kulturbau, 57, 1–53.
96. **Hu L.B., Peron H., Hueckel T., Laloui L., 2013.** Mechanism of critical properties in drying shrinkage of soils: experimental and numerical parametric studies. Can. Geotech, J., 50, 536–549.
97. **Huang G.H., Chang N.B., 2003.** The perspectives of environmental informatics and system analysis. Journal of Environmental Informatics 1(1), 1–7.
98. **Ippisch O., Vogel H.-J., Bastian P., 2006.** Validity limits for the van Genuchten–Mualem model and implications for parameter estimation and numerical simulation, Adv. Water Res., 29(12), 1780–1789
99. **Iwanek M., Krukowski I., Widomski M.K., Olszta W. 2010.** Effect of van Genuchten model tortuosity parameter on hydraulic conductivity calculations. 447–454, in Pawłowski L., Dudzińska M. & Pawłowski A. (eds), Environmental Engineering III, Taylor & Francis, London

100. **Izdebska-Mucha D., Wójcik E., 2013.** Testing shrinkage factors: comparison of methods and correlation with index properties of soils. Bull Eng Geol Environ, 72, 15–20.
101. **Jamieson R.C., Gordon R.J., Sharples K.E., Stratton G.W., Madani A., 2002.** Movement and persistence of fecal bacteria in agricultural soils and subsurface drainage water: a review. Canadian Biosystems Engineering 44, 1.01–1.09.
102. **Jim C.Y., 2013.** Sustainable urban green strategies for compact cities in developed and developing economies. Urban Ecosystems, 16, 741–761.
103. **Jones L.D., Hobbs P.P.R., 2005.** The shrinkage and swelling behavoiur of UK soils: the clays of the Lambeth Group. Research Report RR/04/001, British Geological Survey, Keyworth, Notingam.
104. **Journal of Laws from 2013 item 523, 2013**. Regulation of the Minister of Environment of 30 April 2013 about landfilling of wastes (in Polish). Sejm of the Republic of Poland, Warsaw, Poland.
105. **Kalkan E., 2011.** Impact of wetting-drying cycles on swelling behavior of clayey soils modified by silica fume. Applied Clay Science, 52, 345–352.
106. **Kampala A., Horpibulsuk, S. 2013.** Engineering Properties of Silty Clay Stabilized with Calcium Carbide Residue. J. Mater. Civ. Eng., 25(5), 632–644.
107. **Kleppe J.H., Olson R.E., 1985.** Desiccation cracking of soil barriers. In: Johnson, A.I., Frobel, R.K., Cavalli, N.J., Pettersson, C.B. (Eds.), Hydraulic Barriers in Soil and Rock, ASTM STP 874. ASTM, West Conshohocken, 263–275.
108. **Knappett J.A, R.F. Craig, 2012.** Craig's Soil Mechanics, Eighth Edition, CRC Press.
109. **Koerner R.M., Soong T.Y., 2000.** Leachate in landfills: the stability issues. Geotextiles and Geomembranes, 18, 293–309.
110. **Kozłowski S., 2000.** Ekorozwój – wyzwanie XXI wieku, Warszawa.
111. **Ladd C.C., Lambre T.W., 1961.** The identification of behavior of compacted expansive clays. Proceedings of 5th International Conference in Soil Mechanics and Foundation Engineering, Paris, Vol.1, 201–205.
112. **Lambe T.W., 1954.** The permeability of compacted fine-grained soils. Special Technical Publication No. 163, American Society of Testing and Materials, 56–67.
113. **Lambe T.W., 1958.** The structure of compacted clay. Journal of Soil Mechanics and Foundation Division, 84, 2-34.
114. **Laner D., Crest M., Schraff H., Morris J. W. F. and Barlaz, M. A., 2012.** A review of approaches for the long-term management of municipal solid waste landfills. Waste Management, 32, 498–512.
115. **Laner D., Fellner J. and Brunner P. H., 2011.** Future landfill emissions and the effect of final cover installation – A case study. Waste Management, 31, 1522–1531.
116. **Lou W.F., Nair J., 2009.** The impact of landfilling and composting on greenhouse gas emission – A review. Bioresource Technology, 100, 3792–3798.

117. **Lu H., He W., Liao Z.W., Chen W., 2013.** The swelling, shrinkage and cracking properties of compacted clay. EJGE, 18, 1037–1044.
118. **Majer E., 2007.** Methodology of assessment of soil for designing af compacted clay liners (CLLs) in landfills, (in Polish). Geologos 11, 239–252.
119. **Mariolakos I., 2007.** Water resources management in the framework of sustainable development. Desalination, 213(1-3), 147–151.
120. **Marshall R.E., Farahbakhsh K., 2013.** Systems approaches to integrated solid waste management in developing countries. Waste Management, 33(4), 988–1003.
121. **Masternak J., 2009.** Manners of sustainable development realization in industry (in Polish). Problems of Sustainable Development, 4(2), 107–113.
122. **Mazzia A., Putti M., 2006.** Three-dimensional mixed finite element-finite volume approach for the solution of density-dependent flow in porous media. Jour. Comp. and Appl. Math. 185, 347–359.
123. **Mesjasz-Lech A., 2014.** Municipal waste management in context of sustainable urban development. Procedia – Social and Behavioral Sciences, 151, 244–256.
124. **Miller C.J., Asce M., Yesiller N., Asce A.M., Yaldo K., Mereyyan S., 2002.** Impact of soil type and compaction conditions on soil water characteristics. J. Geotech. Geoenviron. Eng., 128, 733–742.
125. **Mitchell J., Hooper D., Campanella R., 1965.** Permeability of compacted clay. Journal of Soil Mechanics and Foundation Division, 91, 41–65.
126. **Mitchell J., Seed R., Seed, H., 1990.** Kettleman Hills Waste Landfill Slope Failure. In: Liner-System Properties. J. Geotech. Engrg., 116(4), 647–668.
127. **Mitchell J.K., 1993.** Fundamentals of soil behavior. Wiley, New York.
128. **Mitchell J.K., Jaber M., 1990.** Factors controlling the long-term properties of clay liners. Waste containment systems: construction, regulation and performance. ASCE. Geotechnical Special Publication 26, 84–105.
129. **Mitchell J.K., Soga K., 2005.** Fundamentals of soil behavior, 3rd Edition. John Wiley & Sons, Hoboken, NJ, USA.
130. **Mitchell R.B., Mosser L.E., Moore K.J., Redfearn D.D., 1998**. Tiller demographics and Leaf Area Index of four perennial pasture grasses. Agron. J., 90, 47–53.
131. **Moriasi D.N., Arnold J.G., Van Liew M.W., Binger R.L., Harmel R.D., Veith T.L., 2007.** Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50, 885–900.
132. **Mukherjee S., Mukhopadhyay S., Hashim M.A., Sen Gupta, B., 2014.** Contemporary environmental issues of landfill leachate: assessment and remedies. Crit. Rev. Environ. Sci. Technol., 45 (5), 472–590.
133. **Müller W., Jakob I., Seeger A., Tatky-Gerth R., 2008.** Long-term shear strength of geosynthetic clay liners. Geotextiles and Geomembranes, 26, 130–144.

134. **Narejo D., 2013.** Finite element analysis experiment on landfill cover drainage with geosynthetic drainage layer. Geotextiles and Geomembranes, 38, 68–72.
135. **Ngoc U.N., Schnitzer H., 2009.** Sustainable solutions for solid waste management in Southeast Asian countries. Waste Management, 29, 1982–1995.
136. **NRA, 1995.** Earthworks to landfill sites. National Rivers Authority North West Region.
137. **Oakley S.M., Jimenez R., 2012.** Sustainable sanitary landfills for neglected small cities in developing countries: The semi-mechanized trench method from Villanueva, Honduras. Waste Management, 32, 2535–2551.
138. **Omidi G.H., Thomas J.C., Brown K.W., 1996.** Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner. In: Water Air and Soil Pollution vol. 89. Kluwer Academic Publishers, Netherlands, 91–103.
139. **Osinubi K.J., and Nwaiwu Ch. M. J., 2005.** Hydraulic Conductivity of Compacted Lateritic Soil. Geotech Geoenviron Eng., 131(8),1034–1041.
140. **Othman M.A., Benson C.H., Chamberlain E.J., Zimmie T. F., 1994.** Laboratory testing to evaluate changes in hydraulic conductivity in compacted clays caused by freeze –thaw. In: Daniel, D.E., Trautwein, S.J. (Eds.), Hydraulic Conductivity and Waste Contaminant Transport in Soil. ASTM STP 1142. Philadelphia, 227–253.
141. **Othman S.N., Noor Z.Z., Abba A.H., Yusuf R.O., 2013.** Review of life cycle assessment of integrated solid waste management in some Asian countries. Journal of Cleaner Production, 43, 251–262.
142. **Ozbay I., 2015.** Evaluation of municipal solid waste management practices for an industrialized city. Pol. J. Environ. Stud., 24 (2), 637–644.
143. **Paivanen J., 1973.** Hydraulic conductivity and water retention in pit soils. Acta Forestslia Fennica, 129, 1–70.
144. **Palme U., Lundin M., Tillman A.M., Molander S., 2005.** Sustainable development indicators for wastewater systems – researchers and indicator users in a co-operative case study. Resources, Conservation and Recycling, 43(3), 293–311.
145. **Palme U., Tillman A.M., 2008.** Sustainable development indicators: how are they used in Swedish water utilities. Journal of Cleaner Production, 16(13), 1346–1357.
146. **Parker J.C., Amos D.F., Kaster D.L., 1977.** Evaluation of several methods of estimating soil volume change. Soil Sci. Soc. Am. J., 41(6): 1059-1064.
147. **Pawłowski A., 2006.** Multidimensionality of sustainable development. Problems of Sustainable Development, 1, 23–32.
148. **Pawłowski A., 2009.** Revolution of sustainable development. Problems of Sustainable Development, 4 (1), 65–76.
149. **Pawłowski A., 2010.** The role of environmental engineering in introducing sustainable development. Ecological Chemistry and Engineering S, 17(3), 264–278.

150. **Pawłowski A., Pawłowski L., 2008.** Sustainable development in modern civilization. Part 1. Environment and sustainable development. Problems of Sustainable Development, 3(1), 53–65.
151. **Peng X., Horn R., Peth S., Smucker A., 2006.** Quantification of soil shrinkage in 2D by digital image processing of soil surface. Soil & Tillage Research 91, 173–180.
152. **Peng X., Horn R., Smuckjer A., 2007.** Pore shrinkage dependency of inorganic and organic soils on wetting and drying cycles. Soil Sci. Soc. Am. J. 71 (4), 1095–1104.
153. **Permana A.S., Towolioe S., Aziz N.A., Ho C.S., 2015.** Sustainable solid waste management practices and perceived cleanliness in a low income city. Habitat International, 49, 197–205.
154. **Pires A., Martinho G., Chang N.-B., 2011.** Solid waste management in European countries: A review of system analysis techniques. Journal of Environmental Management, 92, 1033–1050.
155. **Pires L.F., Bacchi O.O.S., Reichardt K., 2005.** Gamma ray computed tomography to evaluate wetting/drying soil structure changes. Nuclear Instruments and Methods in Physics Research, B 42, 857–863.
156. **PKN-CEN ISO/TS 17892-12. 2009.** Geotechnical investigation and testing. Laboratory testing of soil. Part 12: Determination of Atterberg limits (in Polish). Polish Committee for Standardization, Warsaw, Poland.
157. **PKN-CEN ISO/TS 17892-5. 2009.** Geotechnical investigation and testing. Laboratory testing of soil. Part 5: Incremental loading oedometer test (in Polish). Polish Committee for Standardization, Warsaw, Poland.
158. **PKN-CEN ISO/TS 19892-10. 2009.** Geotechnical investigation and testing. Laboratory testing of soil. Part 10: Direct shear tests (in Polish). Polish Committee for Standardization, Warsaw, Poland.
159. **PN-B-04481:1988.** Soils. Researches of soil samples (in Polish). Polish Committee for Standardization, Warsaw, Poland.
160. **Pollacco J.A., Mohanty B.P., 2012.** Uncertainties of Water Fluxes in Soil-Vegetation-Atmosphere Transfer Models: Inverting Surface Soil Moisture and Evapotranspiration Retrieved from Remote Sensing, Vadose Zone J. 11(3).
161. **Puppala A.J., Manosuthikij T., Chittoori B.C., 2013.** Swell and shrinkage characterizations of unsaturated expansive clays from Texas. Engineering Geology, 164, 187–194.
162. **Qian X., Koerner R., 2015.** Critical interfaces of multilayer geosynthetic liner systems. Environmental Geotechnics, 10.1680/envgeo.13.00103, 118–126.
163. **Raats P. A. C., 2001.** Development in soil-water physics since the mid-1960s. Geoderma 100, 355–387.
164. **Rayhani M.H.T., Yanful E.K., Fakher A., 2008.** Physical modeling of desiccation cracking in plastic soils. Engineering Geology, 97, 25–31.
165. **Reeve M.J., Hall D.G.M., 1978**. Shrinkage in clayey subsoils of contrasting structure. Journal of Soil Science, 29 (3), 315–323.

166. **Richards L.A., 1931**. Capillary conduction of liquids through porous mediums. *Physics* 1, 318–333.
167. **Richter D. 1995.** Ergebnisse methodischer Untersuchungen zur Korrektur der systematischen Meßfehler des Hellmann-Niederschlagsmessers. Berichte des Deutschen Wetterdienstes 194. Offenbach am Main: DWD.
168. **Rissane J., Naarajarvi T., 2004.** China Waste Management. Working Paper for Streams Technology Programme.
169. **Rollin A., Mlynarek J., Lafleur J., Znaescu A., 1991.** An investigation of a seven years old HDPE geomembrane used in a landfill. In: Christensen T.H., Cossau R., Stegmann R. (Eds.) Proceedings Sardinia 91, Third International Landfill Symposium. CISA, Cagliari, 667–678.
170. **Rowe R.K., Quigley R.M., Booker J.R., 1995.** Clayey barrier systems for waste disposal facilities. E & FN SPON, London, UK.
171. **Rowe R.K., Yu Y., 2010.** Factors affecting the clogging of leachate collection systems in MSW landfills. In: Proc. of 6th International Congress on Environmental Geotechnics, Tata McGraw Hill Education, New Delphi, India, November 2010, 3–23.
172. **Ryżak M., Bieganowski A., 2010.** Determination of particle size distribution of soil using laser diffraction - comparison with areometric method. Int. Agrophysics, 24, 177–181.
173. **Sadek S., Ghanimeh S., El-Fadel M., 2007.** Predicted performance of clay-barrier landfill in arid and semi-arid environments. Waste Management, 27, 572–583.
174. **Safari E., Ghazizade M.J., Abduli M.A., Gatmiri B., 2014.** Variation of crack intensity factor in three compacted clay liners exposed to annual cycle of atmospheric conditions with and without geotextile. Waste Management, 34, 1408–1415.
175. **Santibanez-Aguilar J.E., Ponce-Ortega J.M., Gonzalez-Campos J.B., Serna-Gonzalez M., El-Halwagi M.M., 2013.** Optimal planning for the sustainable utilization of municipal solid waste. Waste Management, 33, 2607–2622.
176. **Schaap M.G., van Genuchten M.Th., 2006.** A modified Mualem-van Genuchten Formulation for improved description of the hydraulic conductivity near saturation. Vadose Zone Journal, 5, 27–34.
177. **Seed H.B., Woodward R.J., Lundgren R., 1962.** Prediction of swelling potential for compacted clays. Journal of Soil Mech. Found. Div. Am. Soc. Civil Eng. 88, 53–87.
178. **Seguel O., Horn R., 2006.** Structure properties and pore dynamics in aggregate beds due to wetting and drying cycles. Journal of Plant Nutrition and Soil Science, 169, 221–232.
179. **Seki K., 2007.** SWRC fit - a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. Hydrol. Earth Syst. Sci. Discuss., 4: 40–437.
180. **Shackelford C.D., Javed F., 1991.** Large-scale laboratory permeability testing of a compacted clay soil. Geotechnical Testing Journal, 14(2), 171–179.

181. **Sharholy M., Ahmad K., Mahmood G., Trivedi R.C., 2008.** Municipal solid waste management in Indian cities – a review. Waste Management, 28(2), 459–467.
182. **Shekdar A.V., 2009.** Sustainable solid waste management: an integrated approach for Asian countries. Journal of Waste Management, 29, 1438–1448.
183. **Simon F.G., Müller W.W., 2004.** Standard and alternative landfill capping design in Germany. Environmental Science & Policy, 7, 277–290.
184. **Sobolewski M., 2005.** Various methods of the measurement of the permeability coefficient in soils - possibilities and application. Electronic Journal of Polish Agricultural Universities, 8(2).
185. **Stark T. D., Choi, H., 2004.** Peak versus residual interface strengths for landfill liner and cover design. Geosynthetics International, 11(6), 491–498.
186. **Stark T. D., Poeppel A.R., 1994.** Landfill liner interface strengths from torsional ring shear tests. Journal of Geotechnical Engineering, 120(3), 597–615.
187. **Stark T., Niazi F., Keuscher T., 2015.** Strength Envelopes from Single and Multi Geosynthetic Interface Tests. Geotechnical and Geological Engineering, 10.1007/s10706-015-9906-4, 1351–1367.
188. **Stark T.D., Choi H., Lee C., Queen B., 2012.** Compacted soil liner interface strength importance. Journal of Geotechnical and Geoenvironmental Engineering, 138 (4), 544–550.
189. **Stark T.D., Williamson T.A., Eid H.T., 1996.** HDPE geomembrane/geotextile interface shear strength. Journal of Geotechnical Engineering, 122 (3), 197–203 .
190. **Stępniewski W., Pawłowska M., Gazda L., Widomski M.K., Franus M., Depta M., 2015.** Cohesive soils of Lublin region suitable for mineral sealing lines and other engineering applications. Wyd. Politechniki Lubelskiej, Lublin.
191. **Stępniewski W., Widomski M.K., Horn R., 2011.** Hydraulic Conductivity and Landfill Construction. In: Developments in Hydraulic Conductivity Research, Dr. Oagile Dikinya (Ed.), 249–270, InTech.
192. **Sukholthaman P., Shirahada, K., 2015.** Technological challenges for effective development towards sustainable waste management in developing countries: Case study of Bangkok, Thailand. Technology in Society, in press.
193. **Surmann R., Pierson P., Cottour F., 1995.** Geomembrane liner performance and long term durability. In: Christensen T.H., Cossau R., Stegmann R. (Eds.) Proceedings Sardinia 95, Fifth International Landfill Symposium, vol. 2. CISA, Cagliari, 405–414.
194. **Tang C.S, Shi B., Liu C., Zhao L., Wang B., 2008.** Influencing factors of geomertical structure of surface shrinkage cracks in clayey soils. Engineering Geology 101, 204-217.
195. **Tang C.S., Cui Y.J., Shi B., Tang A.M., Liu C., 2011a.** Desiccation and cracking behaviour of clay layer from slurry state under wetting-drying cycles. Geoderma, 166, 111–118.

196. **Tang C.S., Shi B., Liu C., Suo W.B., Gao L., 2011b.** Experimental characterization of shrinkage and desiccation cracking in this clay layer. Applied Clay Science, 52, 69–77.
197. **Tay Y.Y., Stewart D.I., Cousens T.W., 2001.** Shrinkage and desiccation cracking in bentonite-sand landfill liners. Engineering geology, 60, 263–274.
198. **Taylor R.K., Smith T.J., 1986.** The engineering geology of clay minerals: swelling, shrinkage and mudrock breakdown. Clay Minerals, 21, 235–260.
199. **Thiel R., 2009.** Post-construction landfill liner failure and lessons learned. Geosynthetics 2009, February 25–27 2009, Salt Lake City, Utah.
200. **Trefry M. G., Muffels C., 2007.** FEFLOW: A finite-element ground water flow and transport modeling tool. Ground Water, 45, 525–528.
201. **Van Genuchten MTh., 1980.** A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892–898.
202. **Vogel T., van Genuchten M.Th., Cislerova M., 2001.** Effect of the shape of the soil hydraulic functions near saturation on variably-saturated flow predictions, Adv. Water Res., 24 (2), 133–144.
203. **Wagner J., 2011.** Incentivizing sustainable waste management. Ecological Economics, 70, 585–594.
204. **Walczak R., Rovdan E., Witkowska-Walczak B., 2002.** Water retention characteristics for peat and sand mixtures.Int. Agrophysics, 16, 161–165.
205. **WCED, 1987.** Our Common Future, World Commission of Environment and Development Oxford University Press 1987.
206. **Wessolek G., Plagge R., Leij F.J., van Genuchten M.Th., 1994**. Analysis problems in describing field and laboratory measured soil hydraulic properties. Geoderma, 64, 93–110.
207. **Whalley W.R., Matthews G.P., Ferraris S., 2012.** The effect of compaction and shear deformation of saturated soil on hydraulic conductivity. Soil & Tillage research, 125, 23–29.
208. **Widomski M. K., Iwanek M., Stępniewski W., 2013.** Implementing anisotropy ratio to modeling of water flow in layered soil. Soil Sci. Soc. Am. J., 77, 8–18.
209. **Widomski M. K., Sobczuk H., Olszta W., 2010.** Sand-filled drainage ditches for erosion control: Effects on infiltration efficiency. Soil Sci. Soc. Am. J., 74, 213–220.
210. **Widomski M.K., Beck Broichsitter S., Zink A., Fleige H., Horn R., Stępniewski W., 2015b.** Numerical modeling of water balance for temporary landfill cover in North Germany. Journal of Plant Nutrition and Soil Science, 178, 401–412.
211. **Widomski M.K., Gleń, P., Łagód G., Jaromin-Gleń K., 2015d.** Sustainable development of one of the poorest province of the European Union: Lublin Voivodeship, Poland – attempt of assessment. Problems of Sustainable Development, nr 2, vol. 10, 137–149

212. **Widomski M.K., Stępniewski W., 2014.** Molding water content of clay soils and hydraulic properties of mineral liners of waste landfills. Proceedings of Ecopole, 1(8), 95–102.
213. **Widomski M.K., Stępniewski W., Horn R., 2015c.** Modeling studies of hydraulic efficiency of compacted waste landfill clay liner. Ecol Chem Eng A., 22 (3), 381–392.
214. **Widomski M.K., Stępniewski W., Horn R., Bieganowski A., Gazda L., Franus M., Pawlowska M., 2015a.** Shrink-swell potential, hydraulic conductivity and geotechnical properties of two clay materials for landfill liner construction. Int. Agrophys., 29, 365–375.
215. **Widomski M.K., Stępniewski W., Polakowski C. 2015e.** Molding water content of clay soils and hydraulic properties of mineral liners of waste landfills. Ecol Chem Eng A., 22 (2), 251–263.
216. **Wildenschild D., Jensen K.H., Hollenbeck K.J., Illangasekare T.H., Znidarcic D., Sonnenborg T., Butts M.B., 1997.** A two-stage procedure for determining unsaturated hydraulic characteristics using a syringe pump and outflow observations. Soil Sci. Soc. Am. J., 61, 347–359.
217. **Wilson D.C., 1985.** Long-term planning for solid waste management. Waste Management & Research, 3 (3), 203–216.
218. **Wilson D.C., Rodic L., Cowing M.J., Velis C.A., Whiteman A.D., Scheinberg A, Vilches R., Masterson D., Stretz J., Oelz B., 2015.** “Wasteware” benchmark indicators for integrated sustainable waste management in cities. Waste Management, 35, 329–342.
219. **Wit K.E., 1967.** Apparatus for measuring hydraulic conductivity of undisturbed soil samples. Inst. For Land and Water Management Research Tech. Publ. 52. Wageningen, The Netherlands.
220. **Witkowska-Walczak B., Walczak R., Sławiński C. 2004.** Determination of water potential-moisture characteristics of soil porous media. IA PAS, Lublin, Poland.
221. **Wösten J.H.M. van Genuchten M.Th., 1988.** Using texture and other soil properties to predict the unsaturated soil hydraulic functions. Soil Sci. Soc. Am. J., 52: 1762–1770.
222. **Wysokiński L. (ed.), 2007.** Principles of assessing the suitability of cohesive soils of Poland for the construction of mineral insulating barriers (in Polish). ITB, Ministry of Environment, Warsaw, Poland.
223. **Yang N., Damgaard A., Lu F., Shao L.M., Brogaard L.K.S., He P.J., 2014.** Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study. Waste Management, 34, 929–937.
224. **Yavuzcan H.G., Matthies D., Aurenhammer H., 2005.** Vulnerability of Bavarian silty loam soli to compaction under heavy wheel traffic: impacts of tillage method and soil water contnet. Soil & Tillage Research, 84, 200–215.
225. **Yesiller N., Miller C.J., Inci G., Yaldo K., 2000.** Desiccation and cracking of three compacted landfill liner soils. Engineering Geology, 57, 105–121.

226. **Zaman A.U., Lehmann S., 2013.** The zero waste index: a performance measurement tool for waste management systems in a ’zero waste city’. Journal of Cleaner Production, 50, 123–132.
227. **Zand-Parsa Sh., Sepaskhah A.R., 2004.** Soil hydraulic conductivity function based on specific liquid-vapor interfacial area around the soil particles. Geoderma, 119, 143–157.
228. **Zawadzki S., Olszta W., 1981.** Modified Wit apparatus for laboratory measurements of hydraulic conductivity of soils, (in Polish). Wiadomości IMUZ, vol. XIV.2.
229. **Zhang D.Q., Tan S.K., Gersberg R.M., 2010.** Municipal solid waste management in China: Status, problems and challenges. Journal of Environmental Management, 91, 1623–1633.
230. **Zhang S. L., Grip H, Lovdahl L., 2006.** Effect of soil compaction on hydraulic properties of two loess soils in China, Soil Tillage Res., 90, 117–125,
231. **Zhang Y., Huang G.H., He L., 2014.** A multi-echelon supply chain model for municipal solid waste management system. Waste Management, 34, 553–561.
232. **Zurbrüg C., Gfrerer M., Ashadi H., Brenner W., Küper D., 2012.** Determinants of sustainability in soild waste management – The Gianyar Waste Recovery Project in Indonesia. Waste Management, 32, 2126–2133.