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Geotechnical Aspects of Dike Construction Using Soil-Ash Composites

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Abstract

An analysis of using of anthropogenic materials, mainly ashes from Coal Combustion Products (CCP), for dike construction is shown. Perspectives of anthropogenic materials application in geotechnical engineering and their advantages in sense of the carbon dioxide reduction are discussed. According to regulations of Kioto Protocol 2005 and EU agreement „Energy Roadmap 2050" recycled materials have higher usage priority than natural ones. General remarks about constructions using soil-ash composites are given with discussion about their properties and laboratory investigation. Finally the full-scale experiment within the DREDGDIKES Project (www.dredgdikes.eu) is described, which is focused on the new technology with the usage of dredged and anthropogenic materials for construction of dikes.

Keywords: dike construction, dike experiment, green geotechnics, anthropogenic materials, Emission Trading System.

1. Introduction

The global ecological consciousness leads to changes in human mentality, and the way of thinking. Many man-made materials such as by-products of coal combustion (CCP), once recognized as an industrial waste, is regarded as a valuable raw material nowadays (e.g. for the road construction or production of building materials) [1, 2]. On the other hand, the facts prove that not only in Poland but also in many other European countries, there is still a number of barriers - mental, social and administrative – hinder the development of products based on secondary resources. It is important to look at the benefits of using them in a broader context – the so-called "Green Geotechnics" [3, 4], which aims to promote environmentally friendly activities in the framework of geoengineering. Environmentally friendly aspect is here understood multivalent, e.g. a reduction in the amount of solid waste (reuse of anthropogenic aggregates), CO_2 reduction (use of low-emission materials) and reducing energy consumption (use of materials available near the construction site). One of possible areas of CCPs implementation is construction and renovation of dikes using soil-ash composites [5].

2. Emission regulations

On 17 December 2008, an agreement on adoption of legislative measures aimed at controlling and reducing greenhouse gas emissions in the European Union, known as the Climate and Energy Package was confirmed. The main objective of the regulations contained in the package is to achieve by 2020 a 20% reduction in greenhouse gas emissions compared to emissions in 1990 in the EU. Two key elements of the package adopted, defining the legal framework for the management of greenhouse gas emissions and establishing the emission limits for individual EU Member States are quite important:

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1. The Directive of the European Parliament and the Council 2009/29/EC of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the trading system for greenhouse gas emissions (i.e. Directive EU ETS – Emissions Trading System) – the goal is to reduce greenhouse gas emissions in the sectors covered by the EU ETS (i.e. power and most industries) in 2020 by 21% compared to the level of emissions in 2005.
2. The Decision of the European Parliament and the Council Directive 2009/406/EC of 23 April 2009 about the efforts made by Member States, aiming to reduce greenhouse gas emissions to meet the Community's 2020 commitments to reduce emissions of greenhouse gases (non-ETS decision) – it assumes 10% reduction in greenhouse gas emissions in the 2005–2020 period sectors not covered by the EU ETS, such as transport and construction, agriculture, institutions, trade, services, waste, emissions of volatile fuels, municipal and household sector and also some industrial processes and the burning of fuels.

In case of Poland CO_2 emissions are estimated to about 210 million tonnes in the ETS, and 200 million tonnes in the non-ETS per year. Additionally Poland produces more than 100 million tonnes of mineral wastes annually. Power plants produce more than 15 million tonnes of fly ash and slag per year. In the case of the latter, i.e. CCP, the industry re-uses up to 70%, or more than 11 million tonnes per year. They are used both in the production of cement and hydraulic binders and injection as well as lightweight aggregates, i.e. to stabilize the road base courses. The balance, however, falls to a negative for the environment – there collected billions of tonnes of material in landfills already!

Poland's economy uses more than 200 million tonnes of natural aggregates, 17 million tonnes of cement and nearly 8 million tonnes of calcium annually. Simple calculation shows that the increased use of man-made mineral permits a double benefit: first, reduction of the amount of waste deposited in the environment (the ideal would be a negative balance – reducing the volume of waste dumps and landfills), and secondly reduction of CO_2 emissions. What is true in the area of non-EU ETS reduction target has been varied and some Member States might even increase their emissions in the period 2013–2020 (for example, Poland has the ability to increase emissions in non-ETS sectors by 14%), but keep in mind that legislative work in the EU tends to include the successive sectors of the economy in connection with the search for alternative low-carbon technologies which should become an important priority. About this fact the European Commission adopted on 15 December 2011 the so-called Energy Roadmap 2050.

The development of civilization in the XXI century world, basically based on consuming energy, is facing serious conflicting impulses. On the one hand, there must be provided increased access to energy as a result of population growth (intensity) and economic development of countries and the need to align the existing inequalities in access to energy. On the other hand, reliance on traditional fossil fuels threatens the greenhouse effect and environmental degradation. In this way, every day as a result of human activity, the amount of anthropogenic attributes is increased, and this growth unfortunately can be considered as an exponential progress.

3. Soil-ash composites – their advantages and laboratory investigation

The application of anthropogenic (in other words secondary) materials, like e.g. fly-ash in geotechnical practice can bring a lot of benefit both in ecological framework, as well as in the economical one. Besides of the CO_2 reduction the main advantages of CCPs in engineering sense are: good granularity, pozzolan and hydraulic properties, high strength, low volumetric density (about 1.1–1.3 kg/dm^3), which among other can reduce the transport cost by about 40%, what is the crucial component of application budget[3]. What is more – there is also wide availability of the CCPs in Poland and other EU countries. The gain on emission reduction can be easily evaluated. There are in literature examples of such calculations based on so-called emission ratio, defined as a mass of CO_2 emitted by an unit volume of construction, taking into account emission from materials and technological processes [4].

An important property of CCPs (fly-ash in particular) is possibility to create the soil-ash composites with desired mechanical properties [6]. The soil part in composite can be e.g. dredged sand from river bed – this source is very important from the flood protection viewpoint. In many parts of the rivers a steady dredging effort is applied to allow unrestricted flow of floes and the flood prevention. The huge amount of dredged material, extracted during this process, can be used e.g. as a granulate in the road embankments or to construct, rebuilt or renovate the existing dikes [2, 5]. The uniform granularity of river sand can be substantially diverged by ash addition, causing much better densification properties.

The investigations of soil-ash composite before large-scale application should be focused on wide aspect of parameters:

- physical,
- mechanical,
- strength,
- hydraulic,
- environmental investigation of water probes.

In Table 1 there are presented sample results of research on first four groups of parameters listed above, i.e. physical, mechanical, strength and hydraulic ones. The measured properties and parameters of soil-ash composite were obtained for different ratios of constituents (sand and ash). The experiments were made at the Gdansk University of Technology, within the Dredgdikes Project. There are selected results presented in the Table 1, for mixtures of 60/40, 50/50 and 40/60 parts of sand and ash, respectively.

Table 1. Sample results of soil-ash composite investigation for different sand/ash ratio.

Investigation	Unit	60/40	50/50	40/60
Optimal moisture	[%]	18,9	20,0	26,3
Max. dry density	[g/cm^3]	1,61	1,48	1,42
Permeability coeff.	[m/s]x10^{-5}	19,0	5,54	0,32
Uniformity coeff.	[-]	3,1	8,12	22,6
Oedometric mod. of prim. compress.	[MPa]	24,6	25,3	14,0
Oedometric mod. of sec. compress.	[MPa]	59,6	50,6	49,0
Internal frict. angle	[^{o}]	36	35	33
Cohesion	[kPa]	2,4	4,4	5,1
Vol. density of composite	[g/cm^3]	1,55	1,44	1,46

There were also environmental study of soil-ash composite performed. The samples were tested on wide set of chemical properties closely related to environmental indicators and water purity indictors. Some results, related to heavy metal content in soil-ash component are presented in Table 2. As a comparison the value of acceptable content (occupational exposure limit) is also presented – the value is mandatory for most strict requirements of soil subjected to environmental protection and drinkable water resources, and it is fulfilled by a large margin of safety for this material.

Table 2. Sample results of environmental investigation of soil-ash composite measured per kilogram of dry mass. Results compared with regulations of polish law in most strict case of soil – subjected to environmental protection

Heavy metal content	Unit	Result	Acceptable content
Lead (Pb)	[mgPb/kg]	<0.05	50
Cadmium (Cd)	[mgCd/kg]	<0.005	1
Copper (Cu)	[mgCu/kg]	<0.06	30
Mercury (Hg)	[mgHg/kg]	0.01	0.5

The scope presented can be regarded as essential one and a base for further, detailed investigation.

4. Aapplication of soil-ash composites – planning of the large-scale experiment in Poland

There is a wide interest in application of soil-ash composites in road construction engineering [3]. Application of ash-based materials in road construction is regulated by norms in several EU countries (e.g. Poland, Estonia, Germany, ...). The values of geotechnical parameters indicated in the Table 1 and safe environmental parameters, such as presented in the Table 2, clearly indicates numerous possibilities of soil-ash composites use in dikes construction.

To verify the feasibility of an ash-soil composite to build the dikes it is necessary to collect experimental data, preferably from large-scale model. The validation should include:

- slope stability,
- erosion control,
- environmental issues (possible water pollution),
- hydraulic issues (permeability, suffusion).

All these measurements should be conducted under control of meteorological conditions, where environmental background (humidity, rainfall, wind, solar radiation) cannot be neglected.

As a verification of described methodology an experimental dike section in the bank of the Vistula river has been constructed by Gdansk University of Technology. The experiment is realized within the Dredgdikes Project, in cooperation of partners from Germany and Poland. While in Poland the investigation is focused on sand-ash composites application in dikes construction, the German partner institutions are investigating ripened fine-grained organic dredged materials in combination with geosynthetics for flood protection constructions [7, 8, 9].

The Fig. 1. presents the general view of the experimental dike near Gdansk – after completion. The dike body forms the composite material consisting of 70% ash and 30% sand. The mixture was carefully chosen after the series of the laboratory tests, in procedure as described above. The total dimensions of the dike are: height 3 m, width 15 m, length: 24 m, with slopes inclined by ratio 1:2. The cross-section of the construction is presented in the Fig. 2.

Fig. 1. The view of the experimental dike in Poland

There is a separated section of 5 m width (by sheet-pile wall) in the dike (see Fig. 1, also Fig. 5b), for simulating the water table changes and flooding. To ensure the separation also from the underlying soil (to create a controlled experimental section) a 0.5 m thick clay liner is constructed as a base layer (see Fig. 2). The body of the dike is monitored using moisture sensors (EC-2 sensors with wireless signal transmission) and water level sensors (pressure cells with GSM signal transmission) – see Fig. 3. The placement of sensors in the dike body is indicated in the Fig. 2. All measurements are to be synchronized with meteorological data obtained from installed weather station.

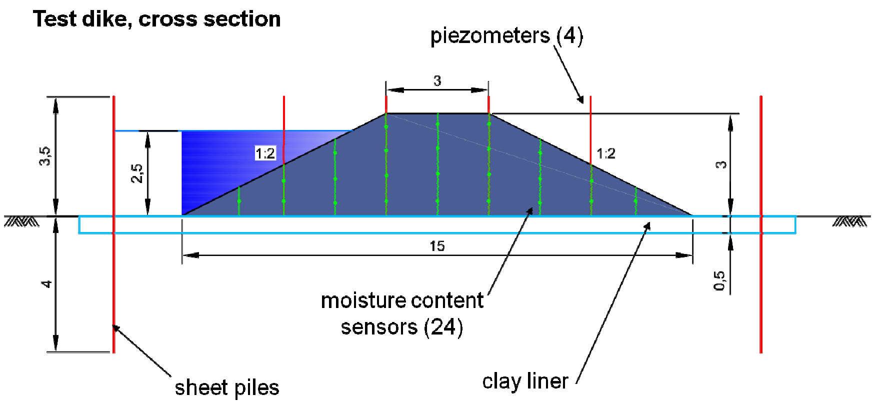


Fig. 2. The cross-section of the experimental dike in Poland with sensors placement

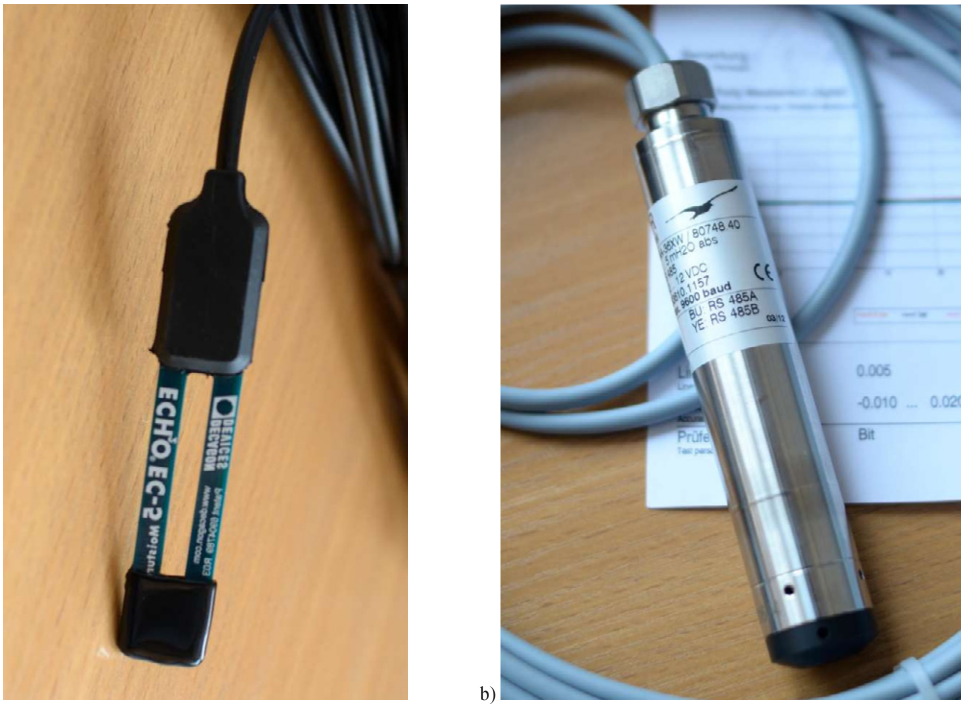
a) b)


Fig. 3. The sensors installed in the dike body: moisture sensor (a) and water level sensor (b)

The construction stages should be carefully planned and verified. After preparation phase – removal of unnecessary organic and soft layers of soil (Fig. 4a), one of important aspects is compaction control of the dike body during construction. In Fig. 4b one can see early stage of the dike construction and a classical technology of compaction – in case of small structures. It is clear that in case of larger structures one will use proper, heavy equipment [10]. Each layer of the construction needs to be controlled and the compaction verified (see Fig. 5a). In this case one can see clearly advantages of used composite – even heavy machines make no visible deformation of the dike body (see Fig. 5a). The last step is to create the bio-surface of the dike, the greening can be achieved by hydroseeding or other techniques; the final view of experimental dike is presented in the Fig. 1.

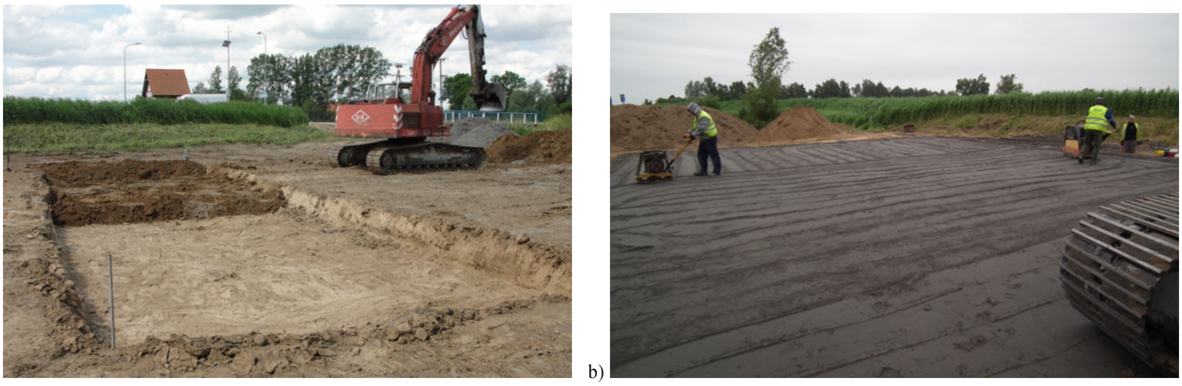
a) b)


Fig. 4. Construction stages: (a) preparation – removal of soft soil (b) compaction of single layer of dike body

An identification of the mechanical and hydraulic properties of the soil-ash composite, as well as the stability of the construction in function of time will be investigated in series of experiments. The time factor in sense of ageing of soil-ash composite (possible cementation) will be also studied following [2]. There are chosen several hydraulic loading scenarios considered, which are closely related to real life states of lowland rivers on the Baltic coast.

(a) (b)

Fig. 5. Construction stages: (a) compaction verification – plate loading test (b) installation of sheet-pile wall

One of the first experiments will simulate the flood rise of water level 0.5 m below the dike top with duration of one week and then its subsequent decrease. After the analysis of the first experiments, subsequent scenarios will be deployed. Some overflowing experiments are planned as well in the end of project – to ensure the stability of the dike and to estimate the erosion processes [11].

5. Numerical modeling & simulations

The results of large-scale experiment are valuable source of data for numerical modeling: both for model validation and its verification. This is necessary from scientific point of view – to understand in detail the properties of soil-ash composite and to study effects of interaction of solid parts with water. The scope of numerical simulations will include evolution of moisture within the dike body caused by high water table level. Unsaturated soil model will require laboratory determination of soil-water characteristic curve. Calibration of moisture parameters will allow for extended study of mechanical behavior of soil-ash composite, in this case the slope stability in unsaturated conditions. The effective stress principle in the analysis should be considered in following form:

$$\boldsymbol{\sigma}' = \left(\boldsymbol{\sigma} + p^a \mathbf{I}\right) + \chi\left(p^a - p^w\right)\mathbf{I} \tag{1}$$

where $\boldsymbol{\sigma}'$ is the effective stress tensor, $\boldsymbol{\sigma}$ denotes total stress tensor, p^a is air pressure in soil and p^w is pore water pressure. The χ coefficient in simplest case of Bishop's formulae is equal to saturation ratio S_r, but in general one should consider the extended sense:

$$\chi = +\chi_0 + \chi_1 + \chi_2 + \chi_3 \tag{2}$$

where each part of formulae (2) relates to different soil phenomena: χ_0 refers to soil structural strength and cementation forces, χ_1 is "classical" Bishop coefficient and is dependent on saturation, χ_2 depends on surface tension of water and χ_3 is connected with osmotic suction in soil [12]. The extended formulae for χ coefficient should be considered in case of soil-ash composites due to expected cementation phenomena developing in time.

The numerical simulations of dike equilibrium should also take into account material non-linearity, thus using nonlinear constitutive equations is necessary (e.g. Hardening Soil model). Solving the slope stability problem in such a case is a non-trivial one, because of material nonlinearity and unsaturated conditions. The problem worth investigation is also an above-mentioned environmental impact on water and measurements of diluted elements and chemicals from the dike body (see Table 2).

All described scientific problems are assigning new research directions, because of 'non-standard soil', such as soil-ash composite. The results of experiment and numerical analysis will be subject for future publications.

6. Conclusions

The popularization of anthropogenic materials in geoengineering is very relevant in today's world. The ecological benefits are obvious, but in Europe we have to obey the political decisions. The latest regulations about greenhouse gases emissions (Energy Roadmap 2050) poses very strict reduction goals for UE nations: namely 80–95% reduction in 2050 comparing to the year 1990. In the near future the Emission Trade System will become everyday practice and those technologies, which are less CO_2 emissive will be the winners.

As laboratory tests has shown, the CCPs have good mechanical parameters, comparable with mineral soils, e.g. silts. Mixing the fly-ash with mineral soil, such as dredged sand, fairly improves the parameters of such a composite, comparing to the constituents. Another benefit of soil-ash composites is their low cost. Depending on the ash source location, the cost of dike construction using soil-ash composites should be comparable to classical technologies.

The technology with anthropogenic materials are also very attractive opportunities for extensive scientific research. Numerous problems are queued for investigation, e.g. ash grain size evolution, chemical and mineralogical analysis of soil-ash composite, optimization of the composites, constitutive modeling and computer modeling of constructions build form soil-ash composites and others.

Finally, the use of man-made materials in construction, according to the authors, it is not some distant "future song" but it is an urgent task for today. It's not up to pushing environmental aspect, because that's the fierce discussions can take place, but the hard reality that the political arrangements impose on us. Recent findings regarding the reduction of greenhouse gas emissions (Energy Roadmap 2050) tend to be quite excessive reduction targets for 2050 for the countries of the European Union: it is the size of the order of 80–95% reduction in emissions compared to 1990! In the near perspective emissions trading market will become commonplace and the technologies that will save real money on reducing CO_2 emissions will be the priority. The only logical step for geotechnical community is to participate in the research of anthropogenic materials.

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