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Fluidised Fly-Ash Cement-Bentonite Cut-off Walls in Flood Protection

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Abstract

Vertical barrier walls are widely used in environmental control systems to restrict the lateral spreading of liquid or gaseous contaminants and for seepage control through and beneath levees. The barrier walls are constructed in single or two phases using slurry composed mainly of bentonite, cementitious materials and water to maintain the trench stability and finally low hydraulic conductivity of barrier. A turning point in the development of slurry technology arose from research demonstrating the positive effects of blast furnace slag or fly-ashes on slurry properties in terms of reduced hydraulic conductivity. This paper presents the implementation of an experimental section of cut-off wall in the subsoil of a modernised flood embankment along the Vistula River and the results of controlling analyses of applied hardening slurry with an admixture of activated fluidal ashes from hard coal. The results of tests confirm the possibility of practical application of fluidal ashes as active components to hardening slurry and obtaining – depending on the suspension composition – of favourable technological and exploitation properties of this material.

Key words: cut-off walls, slurry properties, fluidised fly-ash, flood protection

List of Symbols

d – diameter of the filter [m],
F – flow factor [m],
l – filter length [m],
p_0 – initial system pressure [m H_2O],
p_t – pressure at time t [m H_2O],
u_0 – static pore pressure [m H_2O],

V_0 – initial gas volume [m^3],
t – time [s].

1. Introduction

Hardening slurries applied in the construction of vertical trench cut-off walls are most commonly mixtures of cementitious material, bentonite and water, which in proper proportions of the compounds, enables us to obtain required conditions of fluidised and hardened slurry (Evans 1993, Sharma and Levis 1995). Besides these compounds, slurry comprises also additional binding agents, mineral filling-materials and chemical admixtures. The additional components influence properties of the cut-off material, enabling the achieving of the assumed parameters. Admixtures added to hardening slurries include furnace waste, particularly fly-ashes (Evans and Dawson 1999). This mineral material with binding properties may thus not only act as filling material, but also as additional binding agent. The fly-ashes can improve the resistance of cut-off materials to chemical (e.g. sulphate) attack; the unburned carbon content may usefully absorb organic materials and so retard their migration through the wall (Specification... 1999). Favourable anticorrosion properties of hardening slurry with fly-ash admixture have already been observed (Kledyński 2004). This is of crucial meaning when the vertical barrier cut-off walls are used to separate groundwater from pollution sources (Daniel and Koerner 1995, Daniel and Choi 1999).

The dominating power industry in Poland based on coal burning forces the seeking of such technologies of burning, purification of waste gases and management of combustion wastes, which are favourable to the natural environment. Fluidal combustion belongs to such modern technologies. Combustion wastes differ from those from conventional furnaces (Jarema-Suchorowska 2002), and the features which characterise the products of fluidal combustion compared with ashes and slag from conventional furnaces include:

- higher content of calcium compounds, determined as CaO, which in the case of ashes from burning coal attains from several to almost 30%, where free calcium oxide reaches several percent;
- higher content of sulphur compounds in the form of sulphides, which reach over a dozen percent; in some cases sulphites are also present;
- higher content of mass change during burning, reaching from several to almost 30%, which is caused by the presence of carbon and surplus of the sorbing agent;
- relatively lower content of the remaining elements typical of the chemical composition of ashes and slag from coal burning;
- a lower concentration of natural radioactive elements;
- a different crystal system – lack of sinters and glass phases;

– lower fill density and higher specific surface.

Due to the expected increase of their volume, such waste is subject to investigations with respect to potential utilisation in construction material technology and geo-technology. The problems associated with the application of raw fluidal ashes induced searching for ways of their conditioning. One of the conditioning methods applied for fluidal ashes is mechanic activation using the EMDC method (Patent no. 180380) without chemical admixtures. This activation induces physical changes of the ash grains, which prevents the destruction of the structure of concrete made with the admixture of fluidal ashes, and as such, affords an industrial application for the waste. Volatile fluid ash activated using the EMDC method is known by the trade name Flubet©. One of the most important reasons for conducting investigations on the application of Flubet© in geo- and hydro-technology is the growing demand for hardening slurry, used in constructing seepage-proof cut-off walls for modernising and reconstruction of flood embankments as well as in environment protection objects (sealing of landfills).

The paper presents the implementation of an experimental section of a seepage-proof cut-off wall in the subsoil of a modernised Vistula levee and the results of control tests of the applied hardening slurry with the admixture of activated fluidal ashes from hard coal.

2. Implementation of the Experimental Section of the Cut-off Wall

The requirements in relation to the hardening slurry specified in the project (Design of flood... 2002) were as follows:

- unconfined compression strength after 28 days of hardening – not less than 0.3 MPa;
- hydraulic conductivity after 28 days of hardening – not more than 1×10^{-8} m/s;
- density of fluid slurry – not less than 1.12 g/cm^3.

Based on many laboratory tests, the following slurry composition was worked out: water – 1000 kg; bentonite – 40 kg; Flubet© – 260 kg; cement CEM I 32.5 – 140 kg and properties indicated in Table 1.

The location of the experimental section of the cut-off wall is presented in Fig. 1. Its selection was induced by the proceeding activities linked with the implementation of a several metre sealing of the left bank flood embankment subsoil in the Vistula River. The section was located in an extremely difficult setting for an experimental application, because in this part of the valley the bank and convex flood embankment lie at a distance of only several tens of meters. The cut-off wall was thus shafted in difficult soil-water conditions, with intense influence of

Table 1. Parameters of hardening slurry with admixture of activated volatile fluid ashes from hard coal

Parameter		Value
density of fluid slurry – ρ_c		1.28 g/cm^3
viscosity ratio – L		39 s
24h water settling – Od		4.0 %
density of hardened slurry – ρ_c	after 14 days	1.21 g/cm^3
unconfined compression strength – R_c	after 14 days	1.51 MPa
hydraulic conductivity – k_{10}	after 14 days	7.23 × 10^{-9} m/s

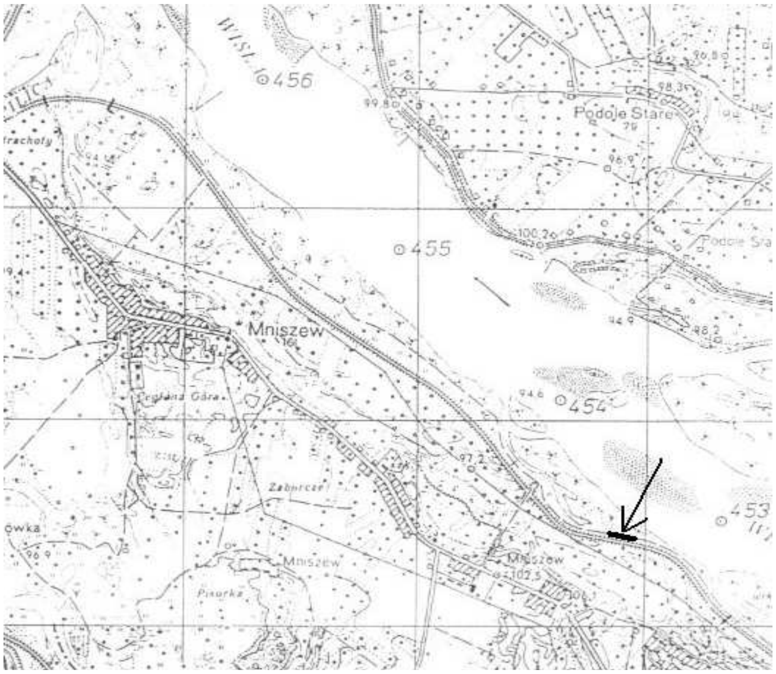

Fig. 1. Location of the experimental section of the cut-off wall

groundwater. The studied section was located at ca. 400 m from the slurry production site, which caused difficulty and decrease of the viscosity of the applied material due to the use of sackcloth pipelines (Ø 75 mm) for pumping and lack of an intermediate pump. The slurry was generated by filling a container with 20 dm^3 of water, its pumping in a cycling system and gradual addition of the solid components through a charge funnel located in the pressure part of the cycling pipeline. Besides mixing induced by the pump action, two stirrers with vertical axes, working at over 100 movements per minute, were installed in the container. Bentonite was added by weight (in sacks), whereas cement, Flubet© and water were added by volume. Dosing was the weakest element of the slurry production, and its correctness mainly depended on the experience of the crew and the intuition of the engineering supervision. Bentonite was added in the first place. Because of variable soaking time, the viscosity of the bentonite slurry with the beginning of cement dosing was different in each case. In order to prevent further problems with slurry pumping, the doses of cement and ash were limited to a level at which the maximal viscosity was not too high (viscosity ratio above 60–70 s). Twice, due to exceeded viscosity of the bentonite slurry, the content of bentonite had to be reduced by the admixture of water. During the following days of the experiment, 2, 3, and 3 batches of slurries, respectively, each with a volume of over 20 m^3, were generated to produce a 55 m experimental cut-off wall section. During the preparation of the following slurry batches, controlling measurements of viscosity and slurry density were made to correct the dosing of components. Excluding the first part of the cut-off wall, where the dosing of ash was restricted to ca. 75 kg/1000 kg of water for a purpose, in the remaining cases the dosing of cement and ash was carried out up to 10% of the planned values. When the mixing was terminated and the slurry reached the expected parameters, the shafting of the trench along with slurry pumping were conducted.

The trench was shafted by an undershot excavator down to the selected depth of ca. 6.15 m from the surface level. At the same time the upper surface of the hardening slurry was supposed to stabilise at ca. 1.15 m below area surface, which resulted from the need to connect the cut-off wall with the GCL (Bentomat) on the upstream side of the embankment – Fig. 2. Thus the final, static cut-off wall height should have reached ca. 5 m. The width of the excavator bucket was 34 cm. During trench shafting, its depth was continuously monitored by a plummet sounder. By the end of each day, the trench was filled with slurry with surplus with regard to the planned level of the cut-off wall upper surface, as before concentration the cut-off wall penetrated the surrounding soil, thus its level in the trench decreased. Significant water release from the slurry was not observed on its surface. The slurry underwent strong sanding up, to ca. 25% weight. Sieve analysis of soil collected from trench indicated the presence of strongly saturated medium-grained sands with interbeddings of clay (alluvia). Independently of simultaneous parameter analyses of the fluid slurry, samples were made for further

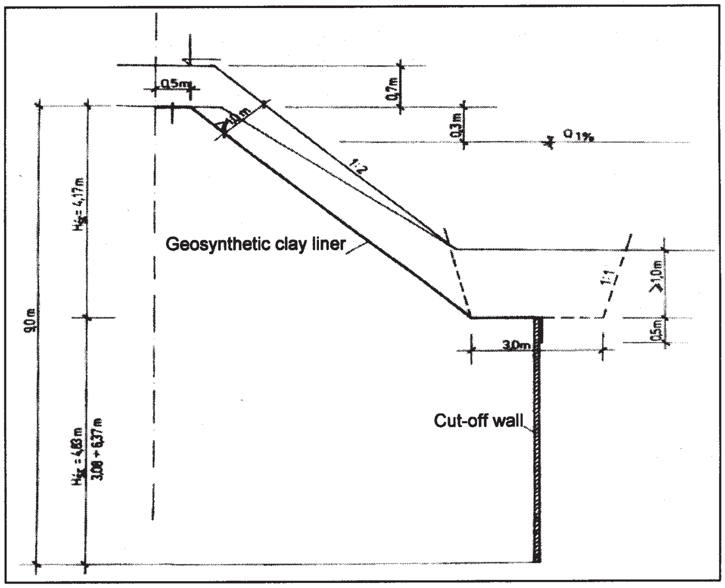

Fig. 2. Cross-section through the subsoil and flood embankment after modernisation

laboratory tests after production of slurry. The samples were made from slurry collected in the production site and from the shafted trench. The latter samples were identified in relation to the cross-section and depth.

Three fragments of the experimental section made during the following three days can be distinguished, because slurries inserted into the trench on a particular day were not mixed with each other. During the night the slurry hardened and its mixing with slurry added the next day was not possible.

3. Analyses of Slurry During Production and on Samples Collected During Cut-off Wall Construction

During production of slurry, its viscosity and density were analysed. When these parameters reached the assumed values, samples of slurry were collected from the mixing plant for further laboratory analyses. Samples were subject to 28 days of curing in water, after which the density, compression strength and hydraulic conductivity were tested. Laboratory hydraulic conductivity of the cement-bentonite slurry was determined using a falling-head (variable-head) permeameter consisting of a vertical test cylinder of cross-sectional area (A) equal 4.4×10^{-3} m^2. To the test cylinder there is attached a vertical, transparent tube of constant cross-sectional area equal 4×10^{-5} m^2. The hydraulic conductivity test involves the application of a total head drop across a slurry specimen and calculation of k

from Darcy's law. It was analysed at a changeable, stepwise increasing hydraulic gradient (from 5 to 45), assuming as the reliable value the directional coefficient in the relationship: initial hydraulic gradient – hydraulic conductivity (k).

All the determined parameters and properties were approximated for three parts of the experimental section referring to the three working days. This was based on the observation that the portions of slurry incorporated in the cut-off wall on each day underwent mixing (approximation). Approximated data for each of the subsections are presented in Tab. 2. It presents the results of analyses of particular properties of the fluid slurry (density, viscosity and 24h water settling) and slurry hardened after 28 days of curing in water in laboratory conditions (density, compression strength and hydraulic conductivity k_{10}). Analyses presented in Tab. 2 refer to slurry samples collected in the mixing plant.

Table 2. Properties of slurry collected in the production site

No.	Subsection	Properties of fluid slurry			Properties of hardened slurry		
		ρ_c [g/cm^3]	L [s]	Od [%]	ρ_c [g/cm^3]	Rc [MPa]	k_{10} [m/s]
1	I	1.26	65	2.0	1.245	0.93	7.95×10^{-9}
2	II	1.27	56	2.0	1.201	0.94	2.16×10^{-8}
3	III	1.24	56	3.5	1.184	0.49	4.51×10^{-8}

Table 3 presents the summary properties for samples collected from the trench during excavation.

Table 3. Properties of slurry samples collected from the trench

No.	Subsection	Properties of fluid slurry			Properties of hardened slurry		
		ρ_c [g/cm^3]	L [s]	Od [%]	ρ_c [g/cm^3]	Rc [MPa]	k_{10} [m/s]
1	I	1.50	–	–	1.532	1.27	1.84×10^{-8}
2	II	–	–	–	1.656	2.25	3.18×10^{-9}
3	III	1.24	67	2.0	1.194	0.53	2.91×10^{-8}

4. In Situ Tests of Hardened Slurry

Control tests of the experimental section of the cut-off wall were carried out after 30 days of its construction. They included the determination of:

- hydraulic conductivity (k) of slurry in cut-off wall within three sections at three depths;
- cone resistance (q_c) of Cone Penetration Test (CPT) in three sections of the cut-off wall.

The location of the control tests is presented in Fig. 3, a view of the experimental section of the cut-off wall is shown in Fig. 4.

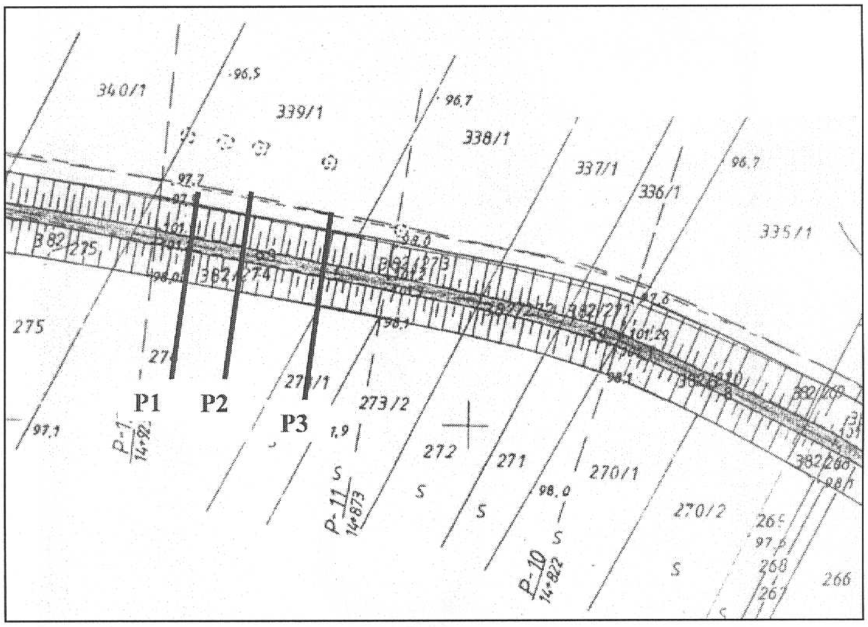

Fig. 3. Location of the control tests

Fig. 4. View of the experimental section

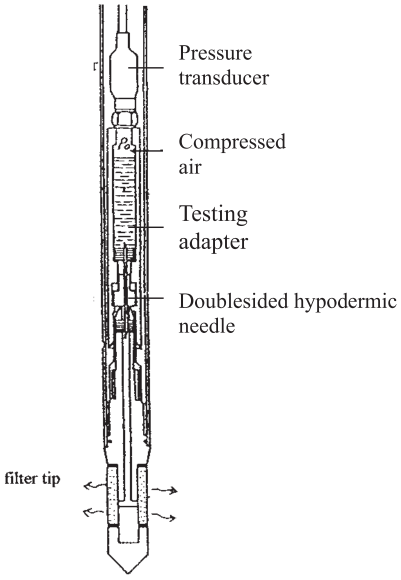

Fig. 5. Layout of the BAT system for *in situ* hydraulic conductivity tests

Hydraulic conductivity tests were made with the BAT probe (Fig. 5) and CPT soundings using a mechanical Begeman cone. The BAT Ground Water Monitoring System (Torstensson 1984) is an integrated system for, among others, in situ hydraulic conductivity tests. The key element in the system is the BAT Piezometer installed in the ground. During the hydraulic conductivity tests for BAT Piezometer installation the CPT rig (HASON 25 kN) of van den Berg has been used. The standard tip is furnished with a reinforcing core of Teflon-coated stainless steel and filter made of porous plastic (polypropylene). The permeability of the filter is less than 10^{-6} m/s. The tip is sealed with a prestressed disc of synthetic rubber. The BAT piezometer is mounted at the end of the steel pipe and then installed at the desired depth. The internal diameter of the rod should be greater than 1 inch to enable the lowering of test adapter onto the filter tip to check performance. The system arrangement for *in situ* measurements of hydraulic conductivity comprises a test adapter equipped with a double-sided hypodermic needle and gas/water container. The pressure in the container is measured with the aid of an electronic pressure transducer. The tests were carried out as an "outflow test". In the former case the gas/water container is completely gas-filled at the start of the test. In an outflow test the container is partly filled with water and partly with compressed gas. The initial pressure in the gas/water container and the equilibrium pore pressure in the soil are denoted p_0 and p_1 respectively. When the adapter is lowered on the nozzle the gas/water container is automatically connected to the tip with the aid of a double-sided hypodermic needle. The pressure change in the test adapter is similar to the falling-head test, is recorded and analysed by the falling-head theory. The hydraulic conductivity (k) is calculated according to Eqs. 1 and 2 (Torstensson 1984):

$$k = \frac{p_0 V_0}{Ft}\left[\frac{1}{u_0 p_0} - \frac{1}{u_0 p_t} + \frac{1}{u_0^2}\ln\frac{p_t(p_0 - u_0)}{p_0(p_t - u_0)}\right], \tag{1}$$

$$F = \frac{2\pi l}{\ln\left[\frac{l}{d} + \sqrt{1 + \left(\frac{l}{d}\right)^2}\right]}. \tag{2}$$

The value of hydraulic conductivity for a period equal to 30 minutes after the start of the test has been assumed reliable as values obtained during the beginning of the test in a partially saturated medium have been rejected.

In regular engineering practice, CPT is carried out in order to assess subsoil conditions. In the case of the bentonite barrier, the tests are aimed at determination of barrier homogeneity and undrained shear strength τ_{fu} estimation on the basis of the measured cone resistance q_c (Koda and Skutnik 2003).

In each Section the tests were made according to the following scheme:

I – anchoring the HASON 25 kN device by drilling two round anchors in soil;

II – CPT sounding to a level 0.1-0.2 m shallower than the planned level of BAT tets;

III – exchange of rod with CPT cone for rod with BAT probe and inserting rod into slurry (0.1–0.2 m below bottom of borehole made by CPT);

IV – hydraulic conductivity test using BAT probe;

V – exchange of rod with BAT probe for rod with CPT probe and continuation of CPT sounding to the next level planned.

Hydraulic conductivity tests of slurry in the cut-off wall were made in the P1 subsection at a level of 1.5, 3.0 and 4.2 m, and in subsections P2 and P3 – at 1.3 and 2.8 m. The graph presenting changes of the hydraulic conductivity of the slurry during the experiment is presented in Fig. 6. Table 4 presents the values of hydraulic conductivity 30 minutes after commencing the analyses; these were considered reliable to evaluate the tightness of the slurry *in situ*.

Examples of CPT soundings in the form of different distribution of cone resistance q_c in subsections P1, P2 and P3 are presented in Fig. 7. A similar pattern as for subsection P2 was obtained in the case of subsection P1, i.e. ca. 3.5–4.5 MPa at 0.5 m and ca. 18.5–20.0 MPa at 4.0 m. Subsection P3 registered lower resistance values – from 4.0 MPa at 0.5 m to ca. 10 MPa at 3.0 m. Based on the

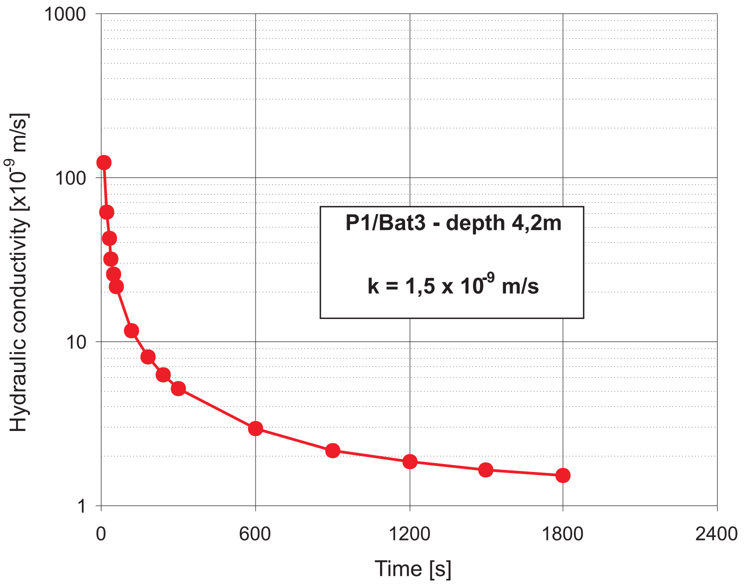

Fig. 6. BAT hydraulic conductivity test results; subsection P1/BAT3 – depth 4.2 m

Table 4. Values of hydraulic conductivity of the slurry in the cut-off wall. BAT tests

No.	Analysed subsection					
	P1		P2		P3	
	depth [m]	hydraulic conductivity *k* [m/s]	depth [m]	hydraulic conductivity *k* [m/s]	depth [m]	hydraulic conductivity *k* [m/s]
1	1.5	2.5×10^{-9}	1.3	2.4×10^{-9}	1.3	1.5×10^{-9}
2	3.0	1.9×10^{-9}	2.8	2.2×10^{-9}	2.8	1.0×10^{-9}
3	4.2	1.5×10^{-9}	–	–	–	–

CPT results obtained, it can be concluded that cone resistance (q_c) values increase with depth, and there is no abrupt changes of the q_c distribution. This means that the cut-off wall is homogeneous.

5. Analysis of the Results Obtained

Results obtained in laboratory conditions for the initial composition of hardening slurry (Tab. 1) and applied slurry (Tab. 2) are similar. Only the values of viscosity obtained in field samples were distinctly higher. This results mostly from the technology of dosing. Analysing the results of slurry produced in the mixing plant (Tab. 2 and Tab. 3), it can be observed that slurry in the last subsection of the cut-off wall was the weakest, which is confirmed by analyses of fluid slurry (lowest viscosity and 24h water settling), as well as strength analyses on samples collected

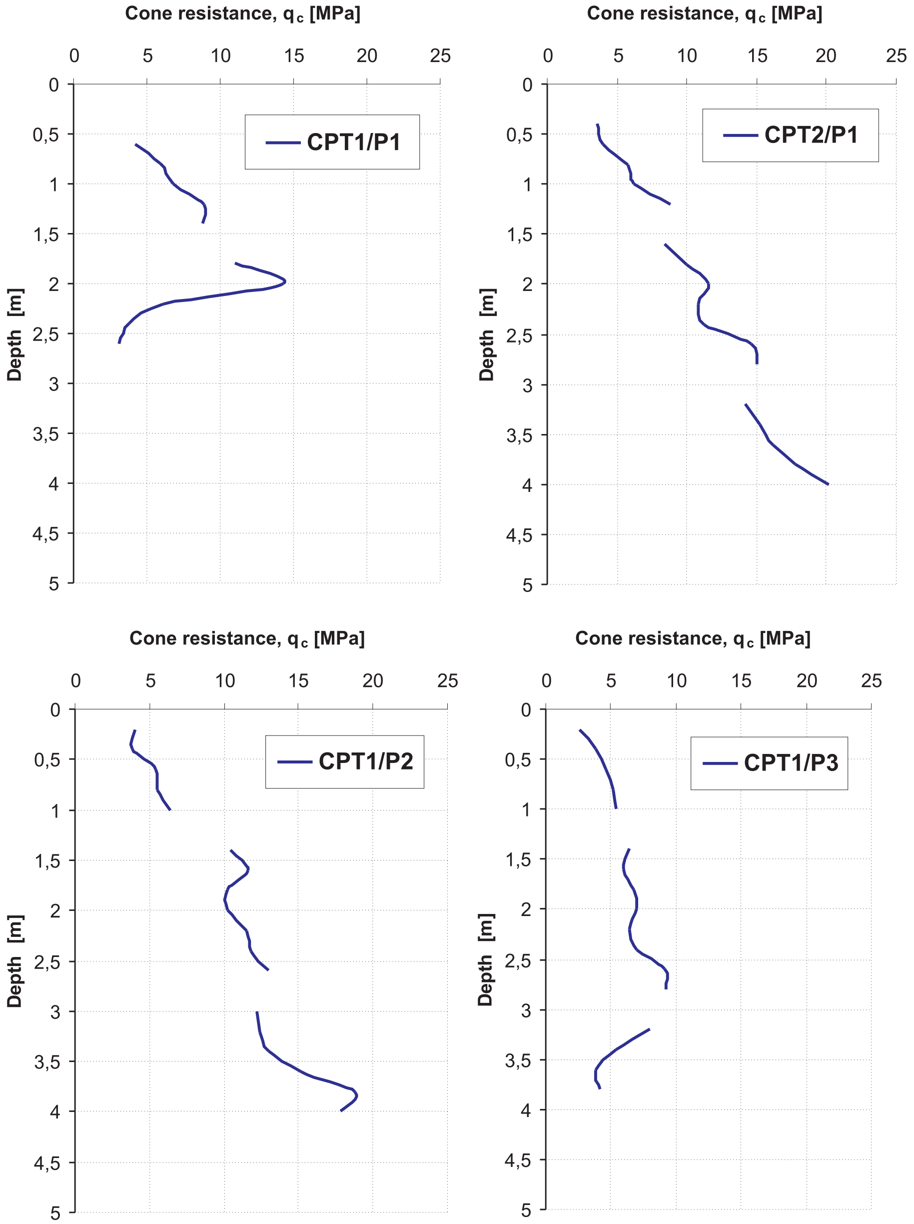

Fig. 7. CPT tests results in subsections: P1 (two tests CPT1/P1 and CPT2/P1), P2 (one test CPT1/P2) and P3 (one test CPT1/P3)

from mixing plant and trench. The same relations are noted between the results of cone resistance analysis q_c in *in situ* slurry tests.

Samples from the trench (Tab. 3) are stronger than those collected from the mixing plant (Tab. 2), which results from the sanding of slurry. The values of cone resistance q_c are much higher than those of unconfined compression strength, which results from differences in analysis conditions (free lateral deformations at unconfined compression of laboratory sample and complex stress on surface of cone inserted in slurry within the cut-off wall).

The hydraulic conductivity of slurry calculated on samples collected at the mixing plant are of the order of 10^{-8}–10^{-9} m/s and are generally similar to samples collected from the trench (despite sanding of slurry). In turn, the coefficients determined *in situ* are of the order 10^{-10}–10^{-9} m/s. This means that the slurry within the cut-off wall is tighter than that added. At the same time, indistinct changes of the hydraulic conductivity of the slurry at the cut-off wall level can be observed. The obtained results point to the stability of the slurry and its resistance to various influences of the technology applied and soil-water conditions in the experimental site.

6. Conclusions

Results of analyses confirm the possibility of practical application of fluidal ashes as active components to hardening slurry and obtaining – depending on the slurry composition – favourable technological and exploitation properties of this material.

Application of field methods for hydraulic conductivity determination (pressure dissipation tests) of slurry allows confirming its parameters in effective conditions of forming and maturing and after different intervals of cut-off wall activity.

The comparison of results of the hydraulic conductivity for slurry obtained in laboratory conditions and *in situ* indicates their high convergence; the differences observed result mainly from the actual differences of the material properties (admixture of sand, different maturation conditions, etc.).

CPT sounding in narrow cut-off walls (ca. 30 cm of width) is extremely difficult; even small deviations from vertical in the initial phase cause that in several meters of depth the BAT end-piece or CPT cone may move beyond the cut-off wall margin.

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