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Influence of fly ash from the thermal treatment of municipal sewage sludge on chosen properties of hardening slurries

Wpływ popiołu z termicznego przekształcania komunalnych osadów ściekowych na wybrane właściwości zawiesin twardniejących

Abstract

Over recent years in Poland, there has been a rapid accumulation of sewage sludge – a by-product of the treatment of urban wastewater. This has come about as a result of infrastructure renewal, specifically, the construction of modern sewage treatment plants. As a consequence, the amount of fly ash resulting from the thermal treatment of municipal sewage sludge has grown significantly. The aim of this experiment was to evaluate the possibility of using the fly ash that results from municipal sewage sludge thermal treatment (SSTT) as an additive to hardening slurries. The article presents the technological and functional parameters of hardening slurries with the addition of fly ash obtained by SSTT. Moreover, the usefulness of these slurries is analysed on the basis of their basic properties. The mandated requirements for slurries employed in the construction of cut-off walls in flood embankments are listed as a criterion of usefulness. On the basis of this experiment, the usefulness of fly ash obtained through SSTT as an addition to hardening slurries was identified.

Keywords: hardening slurry, cut-off walls, fly ash from thermal treatment of municipal sewage sludge, hydraulic conductivity

Streszczenie

W ostatnich latach odnotowano dość szybki wzrost ubocznych produktów w procesie oczyszczania ścieków komunalnych – osadów ściekowych. Jest to pochodna rozwoju cywilizacyjnego Polski i budowy nowoczesnych oczyszczalni ścieków. W wyniku takich działań ilość powstałych lotnych popiołów po spaleniu komunalnych osadów ściekowych znacząco rośnie. Celem przeprowadzonego eksperymentu była ocena możliwości zastosowania lotnego popiołu z termicznego przekształcania komunalnych osadów ściekowych (TPKOŚ) jako dodatku do zawiesin twardniejących. W artykule zaprezentowano wyniki badań parametrów technologicznych i użytkowych zawiesin twardniejących z dodatkiem lotnego popiołu z TPKOŚ. Na podstawie oznaczonych wartości podstawowych właściwości (w stanie płynnym oraz po stwardnieniu) analizowano przydatność projektowanych zawiesin twardniejących. Jako kryterium porównawcze zastosowano wymagania w stosunku do zawiesin twardniejących stosowanych podczas realizacji przesłon przeciwfiltracyjnych w wałach przeciwpowodziowych. Na podstawie przeprowadzonego eksperymentu stwierdzono przydatność popiołu z TPKOŚ jako dodatku do zawiesin twardniejących.

Słowa kluczowe: zawiesina twardniejąca, lotny popiół z termicznego przekształcania komunalnych osadów ściekowych, przesłony przeciwfiltracyjne

1. Introduction

After the Polish accession to the European Union (EU), the criteria and procedures concerning the management of water and sewage, as well as waste, have been significantly tightened. The National Programme for Urban Wastewater Treatment involves the construction of modern sewage treatment plants. From 2004 to 2014, a more that 14% increase in the number of municipal sewage treatment plants was recorded – from 2875 in 2004 to 3288 in 2014 [3]. However, the rise in the number of highly efficient specialist facilities has resulted in a relatively fast increase in the amount of the major by-product of the sewage treatment process, namely municipal sewage sludge. According to the data from the Central Statistical Office of Poland [3], the amount of municipal sewage sludge produced in 2014 alone reached 556.0×10^6 kg d.m. Thus, the steady annual increase in the amount of municipal sewage sludge at around 2.0–2.5%, poses enormous problems with regard to its safe management. This data clearly indicates a decrease in the amount of sludge stored in landfills (from around 16% in 2008, to around 5% in 2014) and an increase in the amount of sludge processed thermally (from about 1% in 2008, to around 15% in 2014). The above trends also meet the goals set by the municipal sewage sludge management directives [22]. These are:

- reducing (or abandoning) sewage sludge storage;
- increasing the amount of municipal sewage sludge processed before re-introduction to the environment, as well as the amount of sludge recycled by thermal methods;
- maximising the use of biogenic substances contained in the sludge, while meeting all the requirements related to health and chemical safety.

Experts in the field of waste agree on the current absence of a clear strategy for municipal sewage sludge management in Poland, as well as on the need for development and investment in modern thermal treatment methods [13].

The sewage sludge thermal treatment technique (SSTT) makes it possible to change the chemical and biological composition of sludge, to reduce the heavy metal content, to neutralise pathogens and to significantly decrease the weight and volume of sludge. The thermal methods of dealing with municipal sewage sludge (MSS) include incineration, co-incineration and other processes such as wet oxidation, pyrolysis, gasification and vitrification [13]. Over recent years, the use of these methods has increased in Poland, and therefore, the amount of coal combustion products (CCP), such as ash, has also increased. Unfortunately, the sewage sludge incineration process does not eliminate the high content of phosphorous and heavy metals in sewage sludge. Therefore, research continues to develop effective, environmentally safe methods of managing/using ash from the thermal treatment of sewage sludge. A popular solution for the processing of fly ash from SSTT is their use in the ceramics industry or in construction, for example, in the solidification of concrete blocks or their sintering into a granulated form [10, 14, 20]. The main purpose of these methods is the safe and economical immobilisation of hazardous compounds within the obtained material structure.

This paper presents research on the possibility of using fly ash resulting from SSTT as a constituent of hardening slurries used for fabricating cut-off walls (anti-filtration barriers) in hydraulic structures and in environmental protection structures. It should be noted that research on hardening slurries containing other types of coal combustion products (e.g. conventional ash resulting from fluidised bed combustion) showed an improvement in the hydraulic conductivity of hardening slurries under both capillary and diffusive conditions [6].

2. Types and Properties of Hardening Slurries

In hydraulic structures, cut-off walls are normally constructed by way of narrow (trench) spatial excavations. The excavations are first lounged by the addition of bentonite and water slurries, and are then filled with cohesive soil, modified local soils, concrete and loam-concrete or so-called hardening slurries.

A hardening slurry is defined as a slurry which hardens over time and contains cement or another binder and additional materials, such as loam (bentonite), granulated blast furnace slag or fly ash, fillers and admixtures [19].

If chemical admixtures are excluded from the slurry compositions, the remaining components are of a mineral character; some of these are by-products of certain waste technology processes.

The slurries used or tested in Poland can be classified in terms of their components [8], these are:

- cement-bentonite-water;
- cement-bentonite-water with chemical admixtures;
- cement-bentonite-water with additives, such as sand, hard or lignite coal ash, hard or lignite coal fluidised bed combustion ash, blast furnace slag;
- bentonite-water with additives, such as lignite coal ash, hard coal ash, lime;
- cement-bentonite-water with additives, the so-called 'company mixes'.

Information on the properties of the above-mentioned slurries can be found in [2] and [8]. Information on the of ready mixes can be found in the approved technical specifications issued for these products [21].

The values of the selected properties of hardening slurries presented in Table 1 characterised by requirements for various methods of cut-off wall construction in flood embankments. In

Table 1. Selected properties of hardening slurries used in the fabrication of cut-off walls in flood embankments [2, 9]

No.	Properties	Unit	Value	Marked by
1	2	3	4	5
properties of hardening slurries in the liquid state (technological)				
1	density	[g/cm^3]		BN-90/1785-01 1990
2	deep soil mixing method (DSM)		1.30–1.50	
3	vibro injected thin-wall method (WIPS)		1.50–1.60	
4	narrow spatial excavation method		1.15 – 1.40	
5	conventional viscosity (the time of flow from Marsh funnel)	[s]	max. 50	BN-90/1785-01 1990
6	24h water setting	[%]	max. 4.0	PN-85/G-02320 1985

Tab. 1 cont.

1	2	3	4	5
7	structural strength after 10 min	[Pa]	1.4–10.0	BN-90/1785-01 1990
8				
properties of hardening slurries after hardening (functional)				
9	uniaxial compressive strength after 28 days of curing	[MPa]	0.5–2.0	PN-EN 12390-3 2011
10	hydraulic conductivity after 28 days of curing	[m/s]	≤ 10–8	the same laboratory methods as for cohesive soil

relation to sealings (cut-off walls) used in other specialised hydraulic structures (bunds in sewage treatment plants or in landfills), the requirements for this type of construction are specified individually, depending on the design requirements.

3. Characteristics of Ash from The Thermal Treatment of Sewage Sludge Used in the Experiment

Sewage sludge ash is produced by the incineration of sewage sludge at a high temperature (around 600–920°C), most often in the fluidised bed process. This process ensures a considerable reduction in the volume of material, while the yield of thermal energy results in ash with specific characteristics, not found among the by-products of coal combustion. The ash produced in the process has unique characteristics that are not found in other coal combustion products. Owing to the high content of organic substances in sewage sludge, ash from the thermal treatment of sewage sludge may contain 0.3–1.5% of phosphorus [11], which negatively affects the cement hydration process in concrete based on this additive by delaying it [12]. The relatively high content of heavy metals is also problematic, so it is necessary to immobilise them (e.g. in hardening slurries).

The ash examined here came from a large municipal sewage treatment plant equipped with a sewage sludge thermal utilization (SSTU) station. Sewage sludge mixed with screenings and fats is pumped onto a fluidised bed of sand, where it is incinerated. The by-products of this process are slag, ash and the products of dry flue gas cleaning.

The test results presented in literature [4, 7, 10, 14, 20] indicate a very limited suitability of SSTT ash for the construction industry, and particularly for modern concrete technology. Moreover, the high water demand and low pozzolanic activity of this ash preclude its use as an additive in concrete. However, these properties open up the possibility of using it in hardening slurries, in which the ratio of w/s (water/dry ingredients) and the resulting strength are subject to other assessment criteria.

4. Formulae of Hardening Slurries

The hardening slurries used in this study were prepared from tap water, sodium bentonite, Portland cement CEM I 32.5R and SSTT fly ash.

Table 2 shows the composition of these slurries (the content of component kg/m^3 of the slurry), for each formulae (from R1 to R4), the water/cement ratio (w/c) and water/dry ingredients ratio (w/s) are listed.

Table 2. Formulae of hardening slurries (the content of component kg/m^3 of the slurry)

No.	Formula	Water	Bentonite	Ash	Cement	*w* to *c*	*w* to *s*
1	2	3	4	5	6	7	8
1	R1	806	32	363	145	5.56	1.49
2	R2	771	31	455	154	5.00	1.20
3	R3	746	22	373	336	2.22	1.02
4	R4	740	15	370	370	2.00	0.98

5. Scope of testing

5.1. Tests of Technological Properties

Tests were performed to determine the density (ρ) of the liquid slurries, their conventional viscosity ratio (L), 2h and 24h water settings (O_d) and structural strength (t).

The volumetric density (ρ) of the slurries was tested by Barroid's balance [1], and their conventional viscosity (L) was measured with a viscometer (*Marsh's funnel*) [1]. The 2h and 24h water setting (O_d) test determines the percentage share of the volume of spontaneously separating water in 1.0 dm^3 of liquid slurry after the slurry had remained in a measuring cylinder for two hours and one day [15]. Finally, the structural strength (τ) of the slurries was tested by Szirometer apparatus [1]. The readings of structural strength (in [Pa]) were carried out at one and ten minute intervals.

5.2. Preparation of Samples for Testing after Hardening

Hardening slurry test cylinders were prepared in PVC and steel cylindrical moulds with a diameter of 8.0 cm and a height of 8.0 cm. Before the slurry set, the samples were kept under a foil covering in the laboratory. After 2–3 days, the samples were submerged in water at a temperature of +18°±2°C. They were left under water until being measured.

5.3. Tests of Functional Properties

5.3.1. Density of hardened slurry

The volumetric density of the hardened slurry ro was determined for cylindrical samples made in steel moulds [18]. These tests were performed after 28 days of slurry maturation. After a sample was removed from the water-filled container, it was left to dry for several minutes. It was then weighed, and its diameter and height were measured. After the volume of the sample had been calculated, the following formula was used to determine its density (Eq. 1):

$$\rho_o = \frac{m}{V} \ [\mathrm{kg/m^3}] \tag{1}$$

where:

ρ_o – volumetric density of the sample, [kg/m^3];
m – mass of the sample, [kg];
V – volume of the sample, [m^3].

5.3.2. Hydraulic Conductivity Tests

The hydraulic conductivity of hardening slurries is very low (similar to that of cohesive soils); therefore, the time needed to obtain the balance of supply and outflow of water from the sample in tests with a constant hydraulic gradient is quite low. In such cases, conductivity tests are performed with a variable hydraulic gradient. This method consists of determining, at specific times (t_1, t_2, etc.) the values of water pressure (h_1, h_2, etc.) in the supply tube of cross-sectional area a during the flow of the liquid through the sample of length (height) L and cross-sectional area A. In this case, hydraulic conductivity is calculated using the following formula (Eq. 2):

$$k_T = \frac{a \cdot L_p}{A \cdot \Delta t} \ln \frac{h_1}{h_2} \ [\mathrm{m/s}] \tag{2}$$

where:

k_T – hydraulic conductivity at temperature T, [m/s];
a – cross-sectional area of the supply tube, [m^2];
L – length (height) of the sample, [m];
A – cross-sectional area of the sample, [m^2];
Δt – time between pressure measurements h_1 and h_2, $\Delta t = t_2 - t_1$, [s];
$h_{1,2}$ – values of water pressure at times t_1 and t_2, [m].

The main advantage of this testing method is the possibility it offers for measuring minute water flow, as well as the forcing of high water pressures. The hydraulic conductivity tests with tap water were conducted using apparatus specially built from chemical-resistant plastic (plexiform and polyvinyl chloride) [5]. The action of the infiltrating medium (tap water) on the tested sample was of a gravitational nature, and the measurements were performed with a decreasing initial hydraulic gradient. All tests were performed after 28 days of slurry maturation. The hydraulic conductivity calculated by Eq. 2 does not take into account the influence of the temperature of the infiltrating liquids. The k_T values obtained during the tests (at temperature T) were recalculated into k_{10} values corresponding to a temperature of +10°C. The following formula (Eq. 3) was used:

$$k_{10} = \frac{k_T}{0.7 + 0.03T} \text{ [m/s]} \tag{3}$$

where:

- k_{10} – hydraulic conductivity at temperature +10°C, [m/s];
- k_T – hydraulic conductivity at temperature T, [m/s];
- T – temperature of the infiltrating liquids, [°C].

5.3.3. Compressive strength tests

Compressive strength values f_c were determined for cylindrical samples made in steel moulds [16]. The tests were performed after 28 days of slurry maturation. The samples were matured under laboratory conditions in tap water. After a sample had been taken out of the water-filled container, it was left to dry for several minutes. Its upper surface (and the lower if it was uneven) was then smoothed to fit the surface of the sample precisely to the heads of the testing machine. Compressive strength measurements were performed with a ZD 20 testing machine. Each sample was compressed with a stress gain of 0.04–0.06 MPa/s until destruction. Three samples were compressed in each series. The following formula was used to calculate the compressive strength (Eq. 4):

$$f_c = \frac{P}{A} \text{ [MPa]} \tag{4}$$

where:

- f_c – compressive strength, [MPa];
- P – stress force destroying the sample, [N];
- A – cross-sectional area of the cylindrical sample, [mm^2].

5.3.4. Tensile splitting strength tests

Tensile splitting strength values f_{ct} were determined for cylindrical samples made in steel moulds [17]. The samples were matured under laboratory conditions in tap water. After a sample was taken out of the water-filled container, it was left to dry for several minutes. The tests were performed after 28 days of slurry maturation. The tensile splitting strength measurements were performed with a ZD 20 testing machine. Each sample was placed on the cylinder surface (side surface) on a disc machine and then exposed to load-induced tension with a stress gain of 0.04–0.06 MPa/s until destruction. Three samples of the slurry were tested in each series. The following formula was used to calculate the tensile splitting strength (Eq. 5):

$$f_{ct} = \frac{2P}{\Pi d^2} \text{ [MPa]} \tag{5}$$

where:

f_{ct} – tensile splitting strength, [MPa];
P – stress force destroying the sample, [N];
d – diameter of the cylindrical sample, [mm^2].

6. Tests results for Technological Properties of Liquid Slurries

Tests results for the aforementioned technological properties of liquid slurries are shown in Table 3.

Table 3. Technological parameters of liquid slurries

No.	Parameter		R1	R2	R3	R4
1	2		3	4	5	6
1	density	[g/cm^3]	1.36	1.41	1.48	1.50
2	conventional viscosity	[s]	46	50	48	46
3	water setting (2h)	[%]	5.0	3.0	3.5	4.0
4	water setting (24h)	[%]	10.0	6.0	5.0	4.0
5	structural strength after 1 minute	[Pa]	2.00	1.60	1.70	2.70
6	structural strength after 10 minutes	[Pa]	2.00	1.90	3.30	4.10

7. Test Results for Functional Properties of Hardened Slurries

The averaged values of the functional properties after hardening are shown in Table 4. In brackets are shown as scatter of results from the average as a coefficient of variation (n in percentages). In addition, table 4 shows the values of brittleness.

Table 4. Functional parameters of hardening slurries after hardening

No.	Parameter	R1	R2	R3	R4
1	2	3	4	5	6
1	volumetric density ρ_o [kg/m^3]	1390 (2.5)	1430 (2.0)	1500 (1.0)	1520 (3.0)
2	hydraulic conductivity k_{10} [m/s]	6.50×10^{-7} (10.0)	2.20×10^{-7} (13.5)	3.90×10^{-8} (11.0)	1.50×10^{-8} (12.0)
3	compressive strength f_c [MPa]	0.29 (15.1)	0.35 (16.2)	1.12 (20.1)	1.30 (20.5)
4	tensile splitting strength f_{ct} [MPa]	0.09 (10.2)	0.13 (8.0)	0.22 (9.0)	0.32 (9.0)
5	brittleness f_{ct}/f_c [–]	0.31	0.37	0.20	0.25

8. Analysis of Test Results

The obtained values of the parameters were compared with the requirements for hardening slurries used in the fabrication of cut-off walls in flood embankments presented in Table 1. It should be noted that the density of all hardening slurries tested in this study (shown in Table 3) is sufficient to ensure drilling excavation stability. These slurries show a density increase in accordance with the theoretical assumptions of [8], as well as a decrease in the *w/c* and *w/s* ratios (Fig. 1).

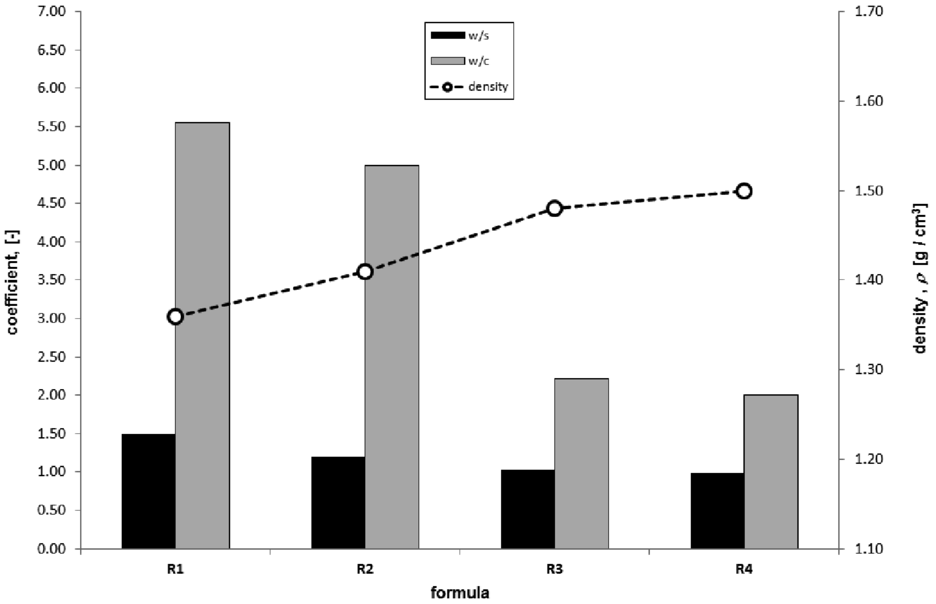

Fig. 1. Relationship between density and the *w/s* and *w/c* ratios

All tested formulas meet the limit values for conventional viscosity (estimated to be a maximum of 50 sec) because of the hydraulic transport of the slurry at the construction site, as well as its movement in the drilled excavation. Furthermore, there is no clear trend in the variability of the conventional viscosity values in relation to the *w/c* and *w/s* ratios (Fig. 2).

The values of water setting after two hours meet the assumed criteria (maximum 4.0%) for all the formulas except R1 (Fig. 3). However, in the case of water setting determined after 24 hours, the limit value was met only by the R4 formula (Fig. 3). It should be noted that a higher value of this parameter can result in the lack of uniformity of any wall made of such a slurry. The decrease in the value of water setting after 24 hours is proportional to the decrease in the *w/s* and *w/c* ratios.

The structural strength, also defined as the gel strength, describes the thixotropic properties of the slurry [8]. The appropriate structural strength value is conductive to the stability of excavation walls, as it protects them from soil particle run-in and ensures the required stability of slurries contaminated by excavated soil; therefore, soil particles remain suspended in the slurry weight and do not settle out. The values determined during the experiment (Fig. 4) meet the acceptable criteria (above 1.4 Pa as stated by [9]).

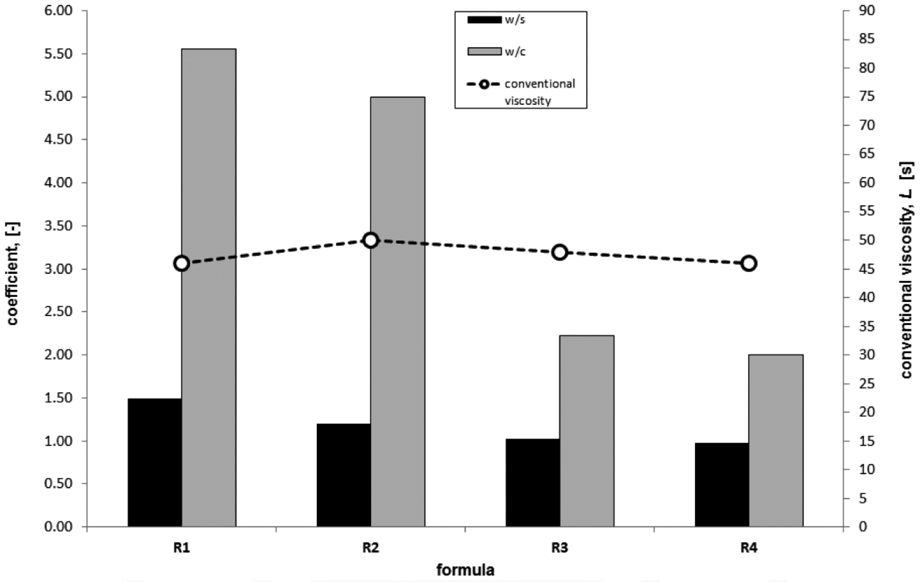

Fig. 2. Relationship between conventional viscosity and the *w/s* and *w/c* ratios

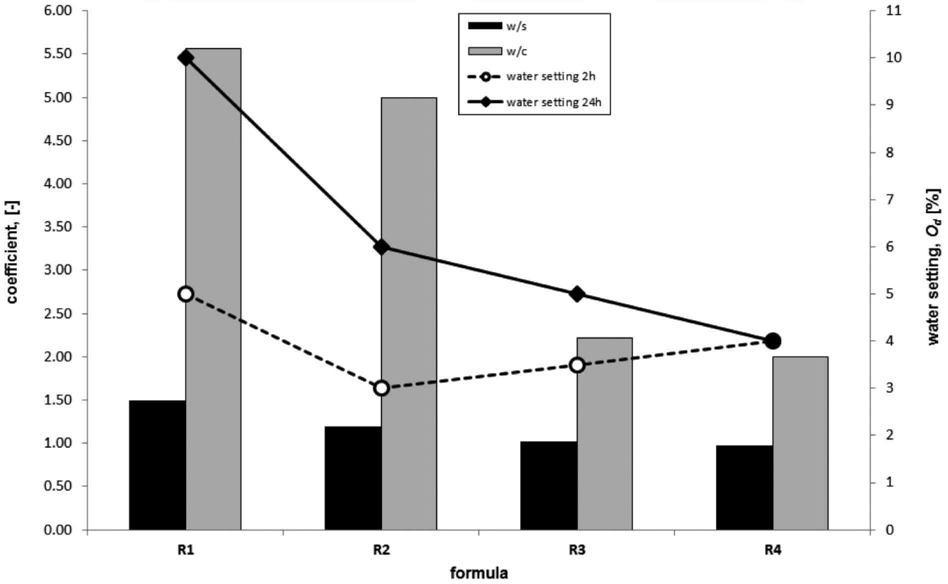

Fig. 3. Relationship between water setting and the *w/s* and *w/c* ratios

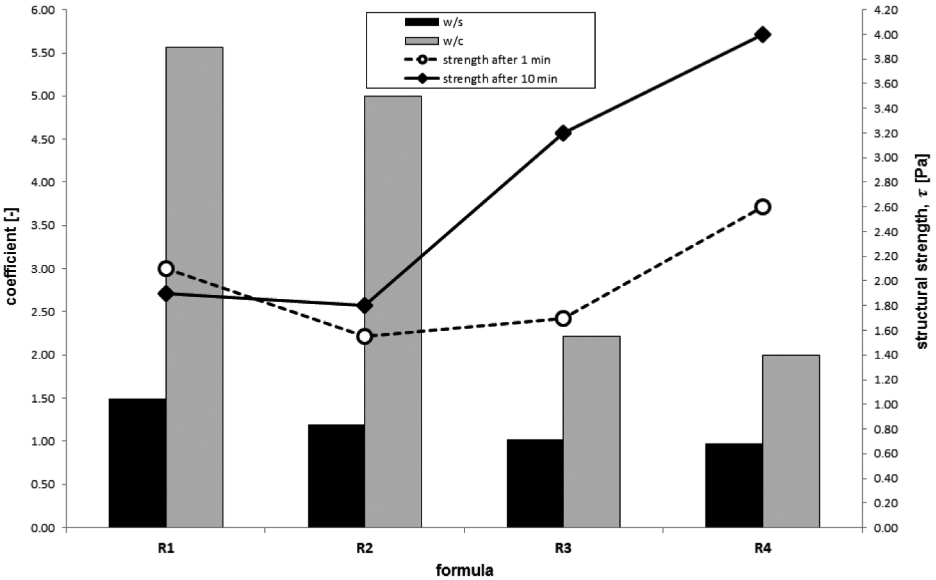

Fig. 4. Relationship between structural strength and the *w/s* and *w/c* ratios

The volumetric density values presented in Table 4 show that the volumetric density after hardening is at an acceptable level for all the formulas, and the increase in this parameter is (generally) inversely proportional to the increase in the *w/s* and *w/c* ratios.

The hydraulic conductivity of the slurries as a function of the *w/s* and *w/c* ratios is presented in Figure 5. The hydraulic conductivity limit value for hardening slurries used for fabricating cut-off walls in flood embankments is $k_{10} \leq 1.0 \times 10^{-8}$ (Table 1), which ensures an appropriate tightness of the flood embankment. For all hardening slurry formulas tested in this study, k_{10} values above the limit value were obtained. In the case of the R4 formula, the k_{10} value (1.50×10^{-8}) was only slightly above the limit value.

In the analysed hardening formulas, a clear correlation can be observed between the hydraulic conductivity values and the quantity of the binder (cement) and dry ingredients (Fig. 5).

With regard to hardening slurries used for fabricating cut-off walls in flood embankments, the compressive strength values are designed to be at a level of 0.5 to 2.0 MPa. It is worth noting that, because of the lacking hydraulic and pozzolanic properties of the ash used in this study, the binder (cement) affects the strength parameters. The compressive strength values of the slurries as a function of the quantity of the binder (cement) are therefore presented in Figure 6. The f_c values obtained during the tests confirm the usefulness of the R3 and R4 formulas.

Because of the need to maintain the continuity of any structure made of hardening slurries, it is necessary to know the appropriate f_{ct} tensile splitting strength. For the slurries investigated here, this value was about 30% of the compressive strength value [8]. The quotient of the tensile splitting strength (f_{ct}) and the compressive strength (f_c) are measures of the material's fragility. For the slurry formulas tested here, this parameter ranged from 0.20 to 0.37, which is over twice as high as the fragility of a mortar and cement concrete (below 0.125). This is due to the presence of bentonite as well as the high porosity and moisture of slurries, and consequently, it ensures the good cooperation of structures made from hardening slurries with their subsoil.

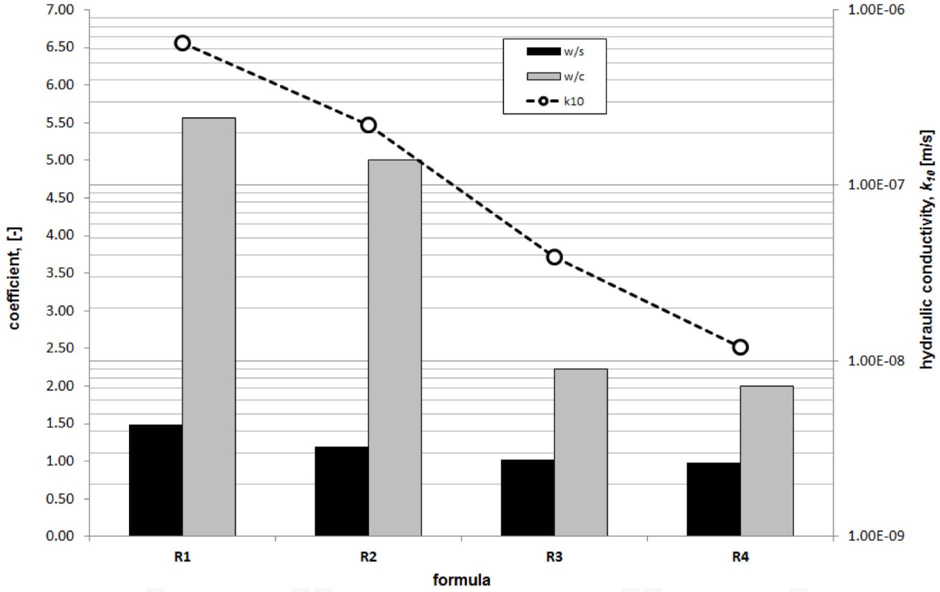

Fig. 5. Relationship between hydraulic conductivity and the *w/s* and *w/c* ratios

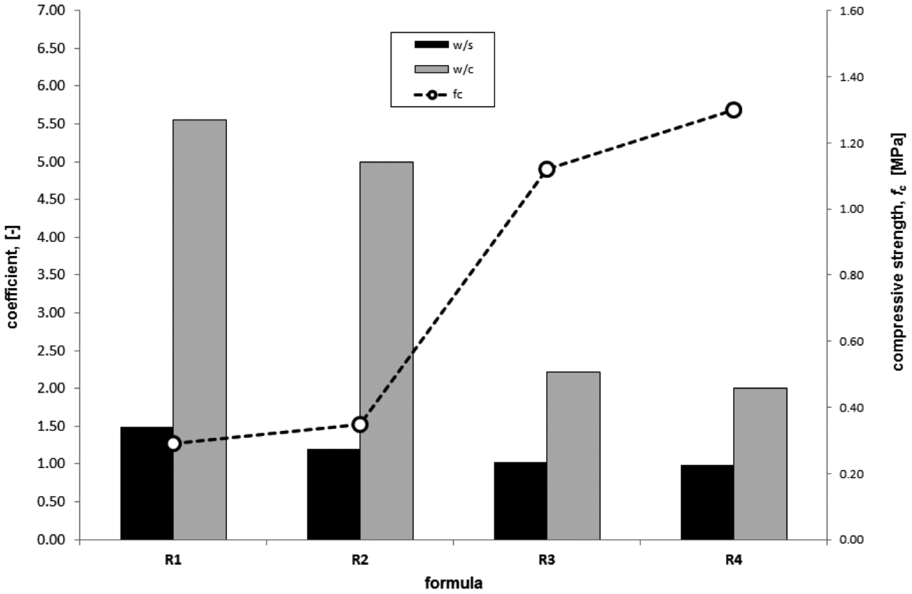

Fig. 6. Relationship between hydraulic conductivity and the *w/s* and *w/c* ratios

9. Conclusion

Considering all the technological and performance parameters analysed above, it should be noted that the R4 formula met most of the criteria which qualify hardening slurries as a material for cut-off walls in flood embankments. Only a slight excess of the acceptable hydraulic conductivity value was recorded ($k_{10} = 1.50 \times 10^{-8}$). It must be pointed out that, owing to the lack of hydraulic and pozzolanic properties in the ash utilised in this study, the proportion of the binder has to be increased to improve the slurry matrix tightness. This binder can be cement (as in this experiment) or another type of binder, e.g. ground blast furnace slag or fly ash resulting from the combustion of hard or lignite coal (additional coal combustion products).

The obtained results show the potential of the fly ash resulting from thermal treatment of municipal sewage sludge when used as an additive to hardening slurries. Such a utilisation of fly ash can constitute a new direction in the management of this type of industrial waste. The values of slurry properties recorded in this study confirm the safe bounding of ash in the slurry matrix. Tests for the leaching of heavy metals and other substances from the slurry matrix are the next stage in research on the safe use fly ash.

The proposed experiment in the direction of the use of fly ash from thermal treatment of municipal sewage sludge is part of a broader policy of sustainable development.

The test results presented in this paper form the basis of further studies on the potential use of ash from the thermal treatment of sewage sludge as a component of hardening slurries used in fabricating cut-off walls in environmental protection structures or in other civil structures, for example, for mining damage recovery and site restoration.

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