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BINDING CAPABILITY OF ASHES AND DUSTS FROM MUNICIPAL SOLID WASTE INCINERATION WITH SALT BRINE AND GEOTECHNICAL PARAMETERS OF THE CEMENTED SAMPLES

BADANIA ZDOLNOŚCI WIĄZANIA PYŁÓW I POPIOŁÓW PO SPALANIU ODPADÓW KOMUNALNYCH Z SOLANKOWĄ WODĄ ZAROBOWĄ I GEOTECHNICZNE PARAMETRY SCALONYCH PRÓBEK

Based on laboratory tests of selected properties of secondary waste (ashes and dusts) from municipal waste incineration plants, the possibility of recovering some properties of waste in the process of filling the post-mining voids in the salt mine was assessed. The furnace bottom ash and the waste from the flue gas treatment from one of the national incineration plants were examined. The grain curves of dry waste and the density of the prepared mixtures were characterized. Twelve variants of the compositions of ash-based mixtures with varying proportions of the individual components were considered, taking into account both fresh water and brine. For each variant of the composition, the amount of redundant liquid appeared as well as the time of solidifying of the mixture to a certain strength and the compressibility values obtained. Considering the possibility of transporting mixtures in mines by means of pipelines at relatively long distances, and allowing the filling of large salt chambers to be filled and evenly filled, flow parameters were determined. In addition, the permeability of solidified waste samples was investigated, showing the potential for reducing the strength of the waste mass due to the action of water or brine. The technical feasibility of eliminating redundant liquid in the binding process has been confirmed, which is particularly important in salt mines. Preliminary values for the amount of binder (5%÷10%) to be added to the mixtures to obtain the specified strength properties of the artificially formed mass at $Rc = 0.5$ MPa. Attention was paid to the important practical aspect resulting from the rapid increase of this type of waste in the comming years in Poland and at the same time vast potential for their use in salt mining, where we have a huge capacity of salt chambers available.

Keywords: municipal waste, salt chambers, ashes, hardening backfill

Na podstawie przeprowadzonych laboratoryjnych badań wybranych właściwości odpadów wtórnych (popiołów i pyłów), pochodzących ze spalarni odpadów komunalnych, oceniono możliwości odzysku niektórych właściwości odpadów w procesie wypełniania pustek poeksploatacyjnych istniejących w kopalni

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soli. Zbadano popioły paleniskowe oraz odpady z oczyszczania spalin, pochodzących z jednej z krajowych spalarń. Scharakteryzowano krzywe składów ziarnowych suchych odpadów oraz gęstości sporządzonych mieszanin. Badaniom poddano 12 wariantów składów mieszanin na bazie popiołów ze zmiennym udziałem poszczególnych składników, uwzględniając zarówno ciecz zarobową słodką jak i solankę. Dla każdego wariantu składu określono ilość pojawiającej się cieczy nadosadowej, jak również czasy tężenia mieszanin do uzyskania określonej wytrzymałości oraz uzyskane wartości ściśliwości. Mając na uwadze możliwości transportu mieszanin w kopalni za pomocą rurociągów na stosunkowo duże odległości, oraz umożliwienie szczelnego i równomiernego wypełniania dużych komór solnych wyznaczono parametry rozlewności. Ponadto przeprowadzono badania rozmakalności zestalonych próbek odpadów pokazując potencjalne możliwości obniżenia wytrzymałości masywu odpadowego wskutek działania wody lub solanki. Potwierdzone zostały techniczne możliwości wyeliminowania nadmiarowej cieczy zarobowej w procesie wiązania, co jest szczególnie ważne w kopalni soli. Podano wstępne wartości ilości spoiwa (5%÷10%), które należy dodać do mieszanin w celu uzyskania określonych właściwości wytrzymałościowych sztucznie wytworzonego masywu, na poziomie wartości Rc = 0,5 MPa.

Zwrócono uwagę na ważny aspekt praktyczny wynikający z radykalnie wzrastającej ilości tego typu odpadów w nadchodzących latach w Polsce i jednocześnie olbrzymie potencjalne możliwości ich wykorzystania w górnictwie solnym, gdzie mamy do dyspozycji olbrzymie pojemności komór solnych.

Słowa kluczowe: odpady komunalne, komory solne, popioły, podsadzka utwardzana

1. Introduction

Effective use of all raw materials, reduction of waste generation in technological processes and recovery of the waste is a commonly accepted standard in the interest of the environment. In underground mining technologies some types of waste and their properties have been recovered for several years. For example, in order to prevent rock mass deformation and/or terrain surface subsidence, various methods of backfilling the post-mining voids with waste utilization (recovery) are used. Mixtures are introduced into the rock mass using, among others, hydraulic or paste filling technology with binders (Sheshpari, 2015). Particularly interesting for the filling of post-mining voids is the latest technology in which a mixture of industrial waste, water and binder are prepared. A paste backfill is especially used in underground metal ore mining methods to reduce volume of tailings stored on surface. Examples of mixtures of paste backfill mixtures in ore mines in Canada are shown in Figure 1. Particularly good conditions for the recovery of waste in underground filling technology may create some salt mines, due to the tightness of salt rock and large volumes of underground post-mining voids remaining after extraction (Korzeniowski et al., 2015). It is possible to manage a large amount of waste due to the geometry of the chambers: 15 heights, 15 width and from 100 to 400 meters in length. It seems advantageous to use mixtures that completely or nearly completely bind to the liquid and do not leave the leachate after binding. Rich experience in underground recovery of waste used to fill excavations was collected in German salt mines. One of the types of waste used here is waste from municipal waste incinerators. The problem of management of this waste is growing in Poland due to the ongoing development of such installations.

The subject of the research is secondary waste from one of the municipal waste incinerators in Poland, occurring as ashes and dusts. The purpose of laboratory tests is to determine the properties of mixtures prepared on the basis of these wastes, with a view to the initial assessment of their suitability, and thus for recovery, in hydraulic or paste filling of the unnecessary excavations in the salt mine. As important physical and geotechnical characteristics, the following are selected and determined from the point of view of obtaining suitable parameters: grain composition of

the waste, apparent density of the dry mixtures containing the waste and the binder, amount of redundant water in the waste mixture after solidification, slump flow rate of the mixtures, solidification time, uniaxial compressive strength, permeability and compressibility.

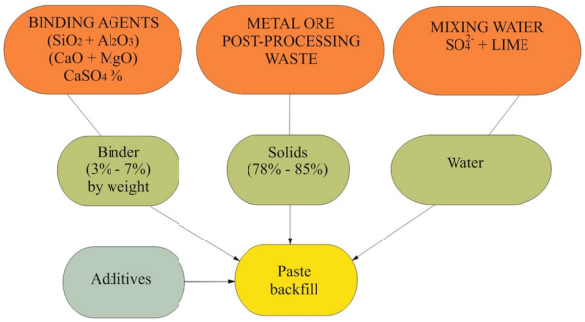

Fig. 1. Examples of paste fill components used in Canadian mines (according to: Belem & Benzaazoua, 2004)

2. Preparation of mixtures based on waste

The study was conducted for two types of waste (dust, ash) originating from one of the municipal waste incineration plants:

– for waste from flue gas treatment – type A,
– for furnace bottom ash – type B waste.

The mixtures are prepared by combining the ingredients (waste, mixing liquid, binder) in the proper proportions. The liquid was fresh water or saturated brine. The use of saturated brine is intended to prevent dissolution of the salt upon contact of the mixture with rocks of the salt deposit. Type A waste are Arabic numerals: 1,1s, 2, 2s, 3, 3s and type B waste with Roman numerals: I, Is, II, IIs, III and IIIs, where "s" represents brine as a liquid. The volumetric proportions of the individual components in the mixtures, with 2%, 5% and 10% of the binder respectively, are illustrated in Figure 2.

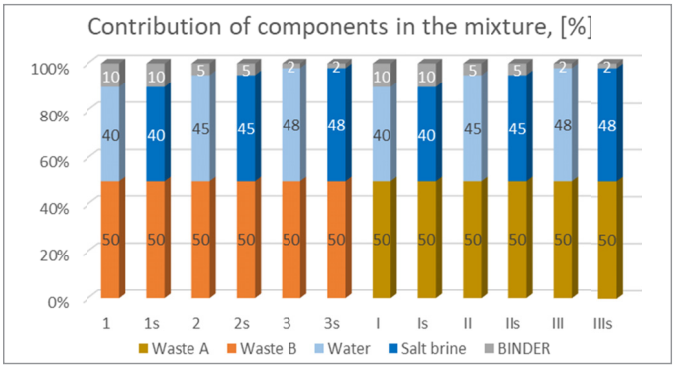

Fig. 2. Composition of tested mixtures

3. Determination of grain composition of waste

The average particle size study was performed on an Analyser 22 MicroTec Plus laser gauge (Fig. 3). The device enables rapid wet measurements of quantity and particle size from 0.08 to 2,000 µm. The measurement results are shown in Figures 4 and 5 and Tables 1 and 2.

Fig. 3. Laser instrument for measurement of particles – type „Analysette 22 MicroTec Plus

TABLE 1

Type A waste grains distribution

x [µm]	Q3(*x*) [%]	CV [%]	M605	M606	M607	dQ3(*x*) [%]
1	**2**	**3**	**4**	**5**	**6**	**7**
0.5	1.3	7.6	1.2	1.3	1.4	1.3
1	2.5	8	2.2	2.5	2.7	1.2
2	4.3	9.1	3.8	4.4	4.7	1.8
4	7	9.2	6.2	7.1	7.7	2.7
6	9.2	8.7	8.1	9.2	10.1	2.2
8	11.1	8.2	9.9	11.2	12.2	1.9
10	13	8.2	11.7	13.1	14.3	1.9
11	14	8.3	12.5	14.1	15.4	1
12	15	8.4	13.4	15.2	16.5	1
14	17.1	8.5	15.2	17.4	18.8	2.1
16	19.4	8.3	17.2	19.7	21.1	2.3
18	21.7	7.9	19.4	22.1	23.6	2.3
20	24.1	7.5	21.7	24.5	26.1	2.4
25	30.1	6.5	27.6	30.5	32.3	6
30	36.1	6.1	33.3	36.4	38.7	6
35	42.1	5.9	38.9	42.4	44.9	6
40	48	5.7	44.4	48.5	51.1	5.9
45	53.8	5.6	49.8	54.5	57.1	5.8
63	71.7	4.6	67.3	72.8	75	17.9
71	77.6	4	73.4	78.7	80.8	5.9

TABLE 1. Continued

1	2	3	4	5	6	7
80	82.7	3.5	78.8	83.8	85.6	5.1
90	86.9	2.9	83.4	87.9	89.3	4.2
100	89.7	2.4	86.8	90.6	91.8	2.8
120	92.9	1.8	90.6	93.6	94.4	3.2
140	94.3	1.4	92.4	95	95.5	1.4
160	95.2	1.2	93.5	95.8	96.2	0.9
180	96	1.1	94.5	96.5	96.9	0.8
200	96.8	0.9	95.6	97.2	97.7	0.8
250	98.7	0.4	98.1	98.9	99.2	1.9
300	99.7	0.1	99.5	99.8	99.9	1
350	100	0	100	100	100	0.3

x [µm] – particle class; Q3(*x*) % – average cumulative percentage contribution of particles in respective grain class; CV% – standard deviation from three measurements; M605, M606, M607– measurement numbers; dQ3(x)% – average percentage contribution of particles in respective grain class.

TABLE 2

Type B waste grains distribution

***x* [µm]**	**Q3(*x*) [%]**	**CV [%]**	**M611**	**M612**	**M613**	**dQ3(*x*) [%]**
0.5	2.8	24.6	2	2.7	3.7	2.8
1	5.6	27.3	3.9	5.3	7.6	2.8
2	10	21.8	7.5	9.7	12.9	4.4
4	19.8	15	16.3	19.7	23.6	9.8
6	32	11.2	27.7	31.8	36.4	12.2
8	44	8.5	39.5	43.9	48.7	12.0
10	54.5	6.9	50	54.4	59.2	10.5
11	59.1	6.4	54.5	59	63.8	4.6
12	63.1	6	58.5	63	67.8	4.0
14	69.7	5.5	64.9	69.9	74.4	6.6
16	75	5.2	70	75.4	79.6	5.3
18	79	4.9	74	79.5	83.5	4.0
20	82.2	4.6	77.3	82.7	86.6	3.2
25	87.7	3.8	83.7	87.7	91.8	5.5
30	91.3	3.1	88.2	90.6	95	3.6
35	93.9	2.5	91.5	93.1	97	2.6
40	96	1.9	94.2	95.4	98.4	2.1
45	97.6	1.3	96.2	97.4	99.3	1.6
63	99.9	0.1	99.7	100	100	2.3
71	100	0	100	100	100	0.1
80	100	0	100	100	100	0.0

x [µm] – particle class; Q3(*x*) % – average percentage contribution of particles in respective grain class; CV% – standard deviation from three measurements; M611, M612, M613 – measurement numbers; dQ3(*x*)% – average percentage contribution of particles in respective grain class

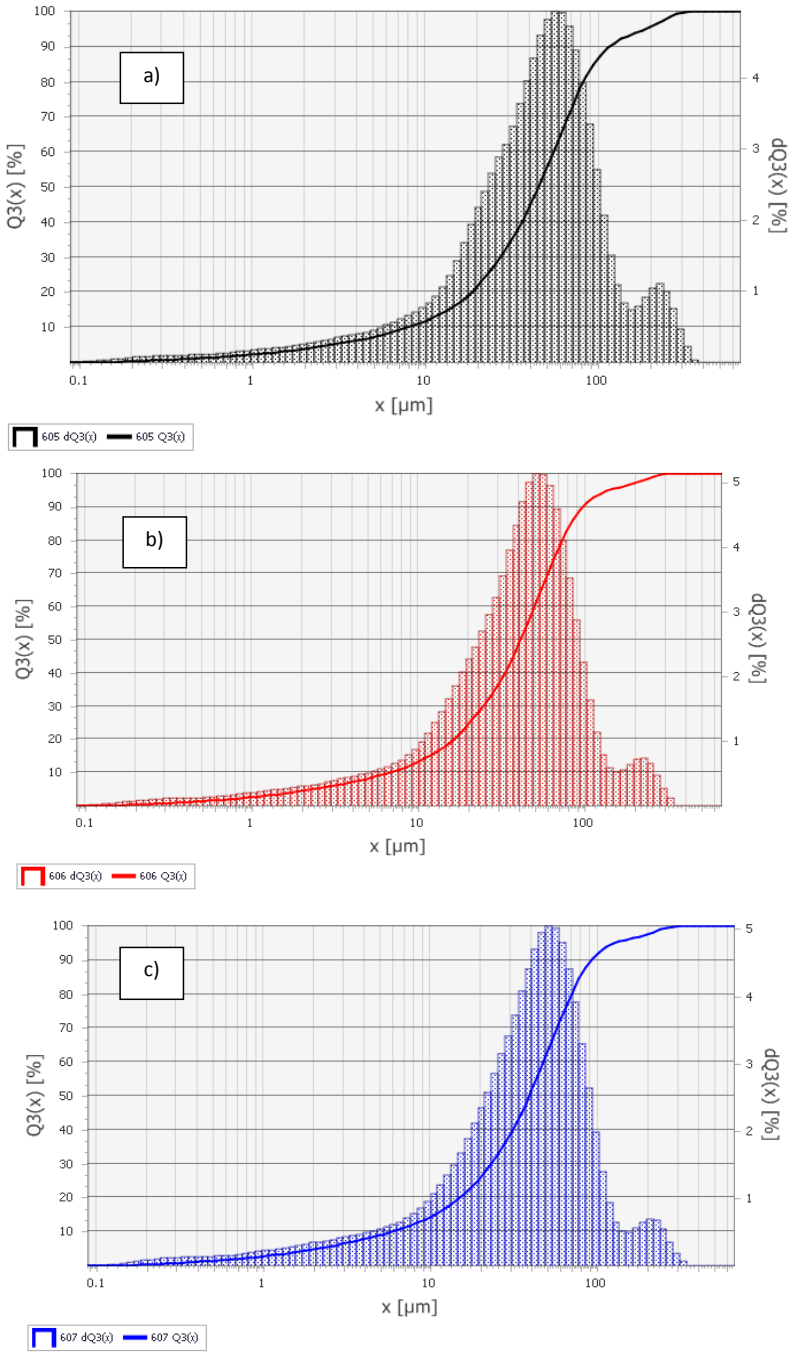

Fig. 4. Waste particles distribution curve, type A:
a) sample 605, b) sample 606, c) sample 607; Q3(x)% – grain composition – cumulative curve;
dQ3(x)% – average percentage contribution of particles in respective grain class

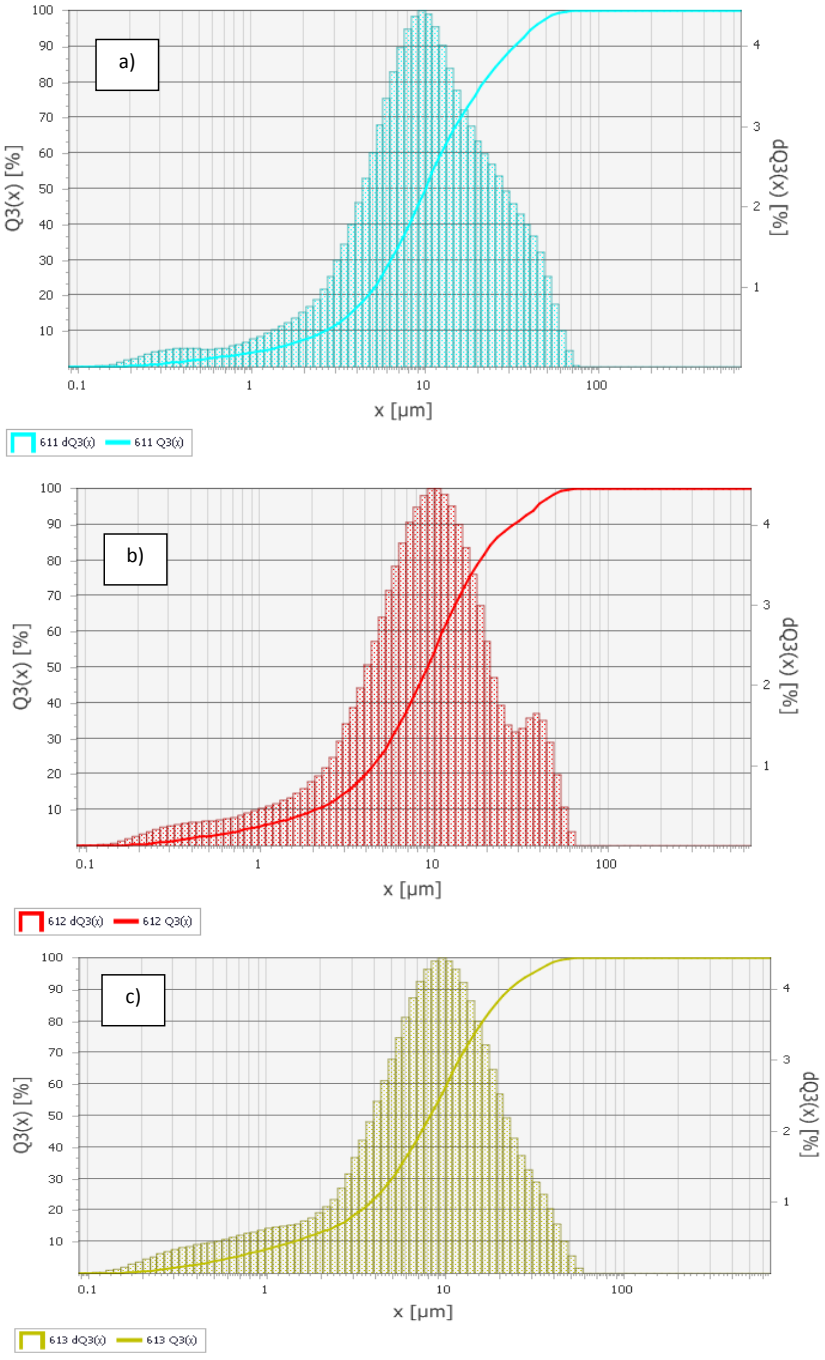

Fig. 5. Raw waste (type B) particles distribution curves.
a) sample 611, b) sample 612, c) sample 613; Q3(x)% – cumulative curve of grain composition; dQ3(x)% – average percentage contribution of particles in respective grain class.

4. Determination of apparent density of dry mixture

All samples were tested for mixtures of solid materials, i.e. mixtures of waste with a binder, without any liquid.

The method of determining the apparent density is the determination of the mass of the vented sample volume by the formula:

$$\gamma_0 = \frac{m - m_1}{V} \left[\frac{\text{g}}{\text{cm}^3} \right]$$

where:

m — sample mass with measuring vessel, [g],
m_1 — mass of dry measuring vessel, [g],
V — volume occupied by the sample in a measuring vessel, [cm^3].

Appropriate masses of materials were determined on a laboratory scale of "AJ1200CE VIBRA" with a precision of 0.01 g. The results are shown in Table 3.

5. Determination of amount of redundant water in mixtures

The principle of the method of determining the amount of redundant water is to measure the percentage of water that is accumulated above the mixture of the test material immediately after being placed in the cylinder. The study used cylinders with a diameter of 48 mm and a height of 72 mm. The research involved the use of an electronic slide caliper, for which the accuracy was 0.01mm. The results are shown in Table 3 and Fig. 6. The amount of redundant water N is expressed in percent from the formula:

$$N = \frac{h - h_1}{h} \cdot 100 \ [\%]$$

where:

h — total sample height after submersion, [mm],
h_1 — sample height after stabilization of the water table over the sample, [mm].

The measurements show that the amount of redundant water is dependent on the type of liquid (sweet water or salt brine) as well as the percentage of binder in the individual mixtures. During the test of mixtures with type A waste, practically no accumulation of redundant water/brine was observed, regardless of whether the solution was brine or fresh water, the N value was 0%.

In mixtures with B-type waste redundant water appeared in both fresh water as well as brine. In the first case, the amount of water N is 16% to 34%, in the second – the value N ranged from 4% to 36%, inversely proportional to the amount of added binder. It is noteworthy that with the 5% and 2% binder content in both fresh water and brine mixtures, the amount of redundant water is very close, while the content of 10% of the binder results in the amount of redundant water, in case of the brine, being four times smaller than for fresh water.

TABLE 3

Physical properties of waste samples with binding component and mixing liquid
(% – binder percentage; k.j. – „yogurt consistence")

Parameter		Sample type	Mixing liquid: fresh water			Mixing liquid: brine		
			I (10%)	II (5%)	III (2%)	Is (10%)	IIs (5%)	IIIs (2%)
			1 (10%)	2 (5%)	3 (2%)	1s (10%)	2s (5%)	3s (2%)
Density of dry mass [g/cm^3]		**B waste**	1.442	1.372	1.292	1.748	1.720	1.621
		A waste	1.293	1.277	1.246	1.471	1.443	1.355
Percentage of redundant water, N [%]		**B waste**	16	22	34	4	24	36
		A waste	0	0	0	0	0	0
Slump flow rate of the mixture	*Spreading diameter, D* [mm]	**B waste**	260	330	>340	240	280	340
	Hight of the cone, h [mm]		2	2	4	2	2	2
	Spreading diameter, D [mm]	**A waste**	125	170	210	65	100	200
	Hight of the cone, h [mm]		2	5	10	50	25	4
Solidification period, [day] *(until the needle penetrated less than 3 mm depth)*		**B waste**	16	21	29	17	32	34
		A waste	4	12	42	3	36	>60
Uniaxial compressive strength, R_c [MPa]		**B waste**	0.252	0.260	0.268	0	0	0
		A waste	0.672	0.269	0.238	0.530	0.240	0
Compressibility, [%] *(k.j.) – yogurt's consistency*		**B waste**	39.23	48.2	41.00	36.9	>50	>50
		A waste	48.1	No data (k.j.)	No data (k.j.)	22.3	No data (k.j.)	No data (k.j.)
Compressive strength of the sample after brine saturation – R_{cw} (after 24 hours), **[MPa]**		**B waste**	No data	No data	No data	No data	No data	No data
		A waste	0.507	No data	No data	0.31	No data	No data

Fig. 6. Samples of waste mixtures, type B, with redundant water (above), and without the redundant water, type A (below)

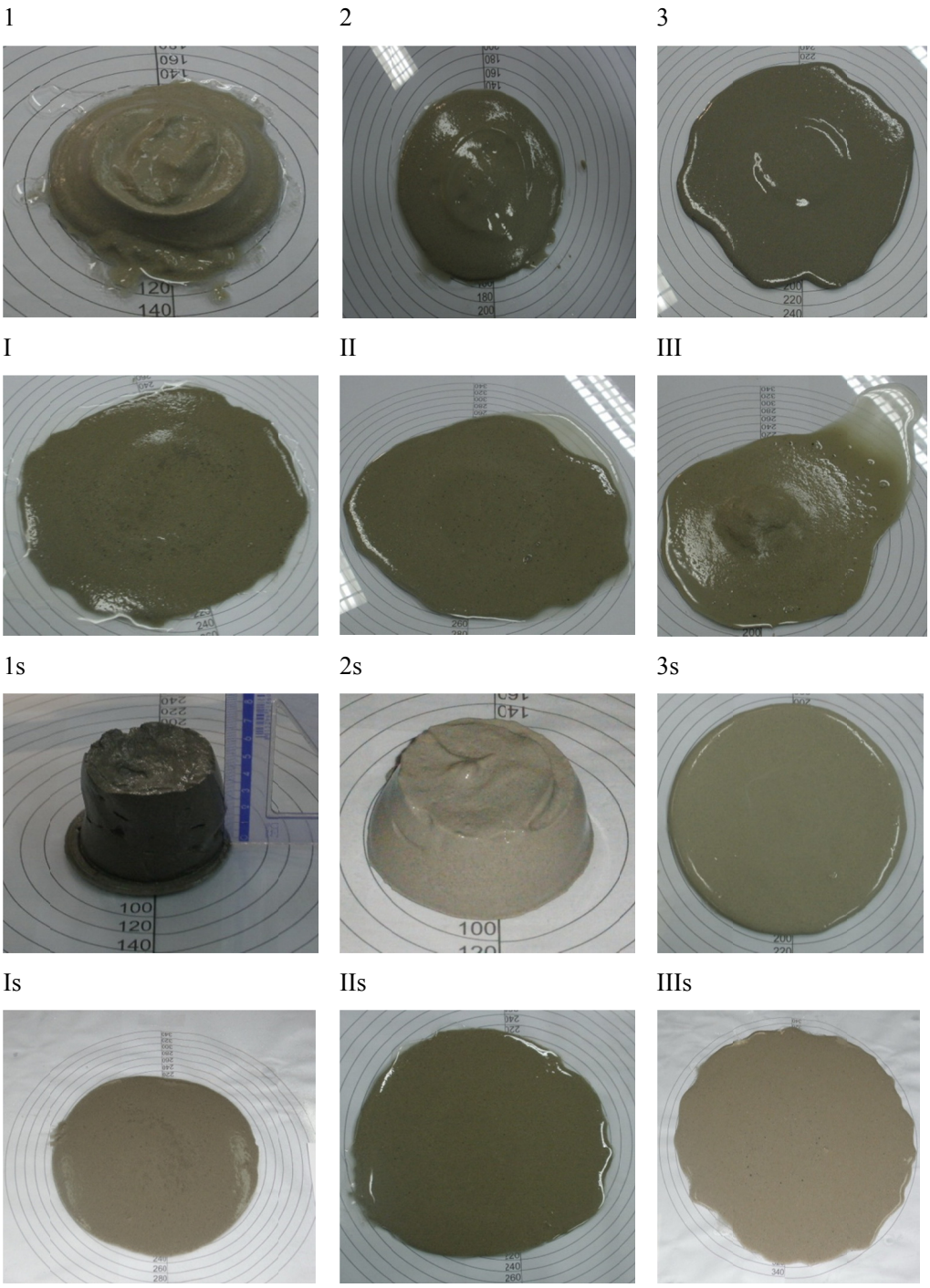

Fig. 7. Slump flow tests of the mixtures

6. Determining slump flow of mixtures

Slump flow is the ability of the mixture to spread (for example, in a filled excavation or sealed-up caving gobs) expressed by the diameter of the spilled mixture on a horizontal, smooth surface. In the study, a truncated cone shaped vessel with a height of 60 mm and a diameter of 63 mm at the base and an upper diameter of 38 mm was used. The research involved the use of an electronic slide caliper, for which the accuracy was 0.01 mm. The results are shown in Table 3 and Figure 7.

B-waste mixtures show a relatively high slump flow rate of 240 to 340 mm, with little variation between samples with brine and fresh water, as a liquid. Flow rates increase with decreasing binder content. The higher slump flow rate differentiation is characterized by mixtures with waste type A. In the case of fresh water, the rate is from 125 mm to 210 mm and in the case of brine from 65 mm to 200 mm and is inversely proportional to the binder content.

7. Determination of solidification time of mixtures

Determination of the solidification time of the mixture according to that described in PN-B-04300:1988, using the Vicat's apparatus and is based on the depth of immersion of the penetrator (needle) of the moving part of the apparatus. As the solidification time, the time taken to penetrate the depth of less than 3 mm is assumed. Research results are presented in Figures 8 and 9. The laboratory studies of solidification time of mixtures were carried out in a research laboratory, where the temperature corresponded to the mine conditions for underground salt mines. The temperature did not exceed 25°C. Periods of solidification of mixtures with type A waste vary from 3 to more than 60 days, and waste type B from 16 to 34 days, inversely proportionally to the binder content, table 3.

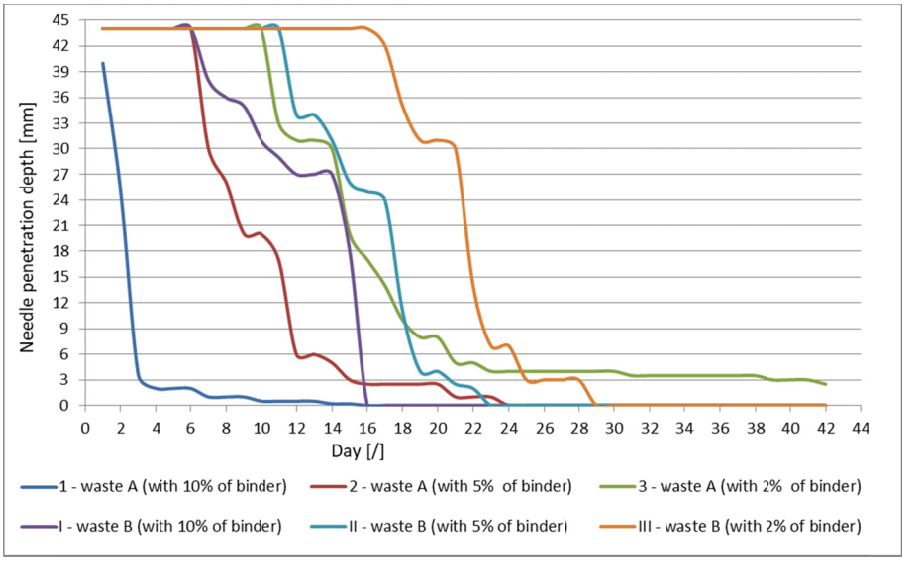

Fig. 8. Solidification of the mixtures in time (Vicat Needle Apparatus) – mixing liquid: fresh water.

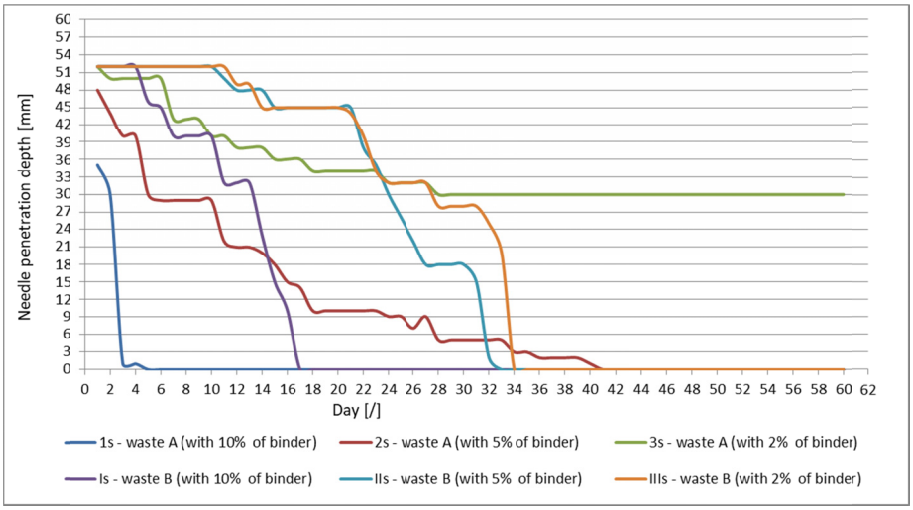

Fig. 9. Solidification of the mixtures in time (Vicat Needle Apparatus) – mixing liquid: brine

8. Determination of strength of solidified mixture samples on uniaxial compressive

Determination of strength for uniaxial compressive was carried out on cylindrical samples with a height of 100 mm and a diameter of 46 mm after 45 days of seasoning. Such a long period resulted from the fact that in shorter periods, i.e. after 28 days, the samples did not show

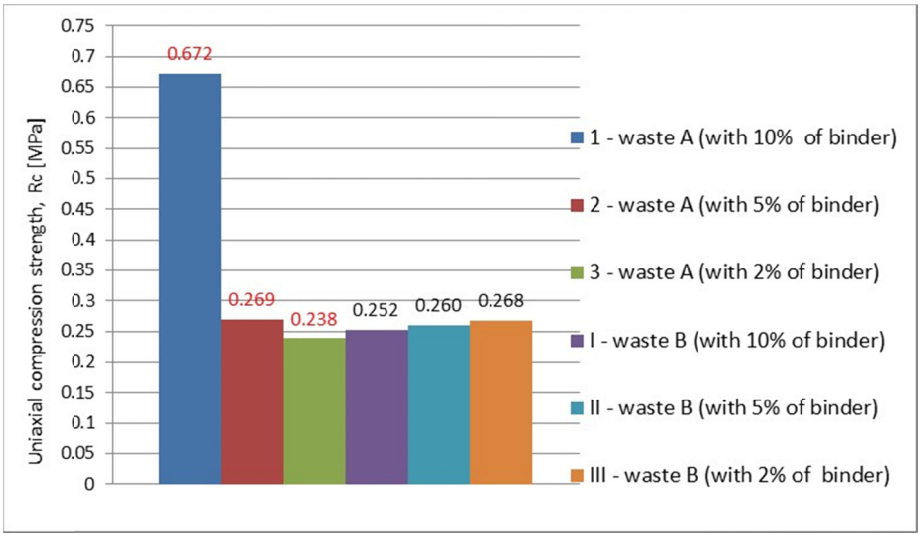

Fig. 10. Uniaxial compressive strength of solidified samples of mixtures – mixing liquid: fresh water

an adequate consistency to be tested. The strength of the solidified samples of the mixtures on uniaxial compressive was determined by the formula:

$$R_c = \frac{P}{F} \quad [\text{MPa}]$$

where:

P — maximum value of force before fracturing, [N],
F — area of the sample base on which the force is applied, [mm^2].

After 45 days of seasoning the samples were taken out of forms, weighed and subjected to a macroscopic structural assessment. Single-axis compressive testing was performed on a CONTROLS machine with a loading speed of 0.05 MPa/s. The results are shown in Figures 10-12. Seasoned samples of all tested mixtures have a low compressive strength of less than 1 MPa (0.238÷0.672 MPa). The highest strength R_c, over 0.5 MPa, showed samples of mixtures with the highest content of binder – 10%, both for water and brine as a mixing liquid (Figs 10 and 12). No compressive strength show all mixtures made from B type waste and brine, irrespective of binder content. Samples of the remaining mixtures have similar strengths of approximately R_c = 0.24-0.26 MPa.

Fig. 11. Examples of samples after compressive strength tests

9. Determination of the soakability of solidified samples of mixtures

Soakability is a change of compressive strength as the result of water action over a specified period of time. To determine the soakability of solidified mixtures considering the salt rock conditions, samples were immersed in saturated brine solution for 1 day. After 24 hours, the samples were drawn, measured and subjected to macroscopic evaluation, followed by a strength test on a CONTROL machine. The results are shown in Table 3.

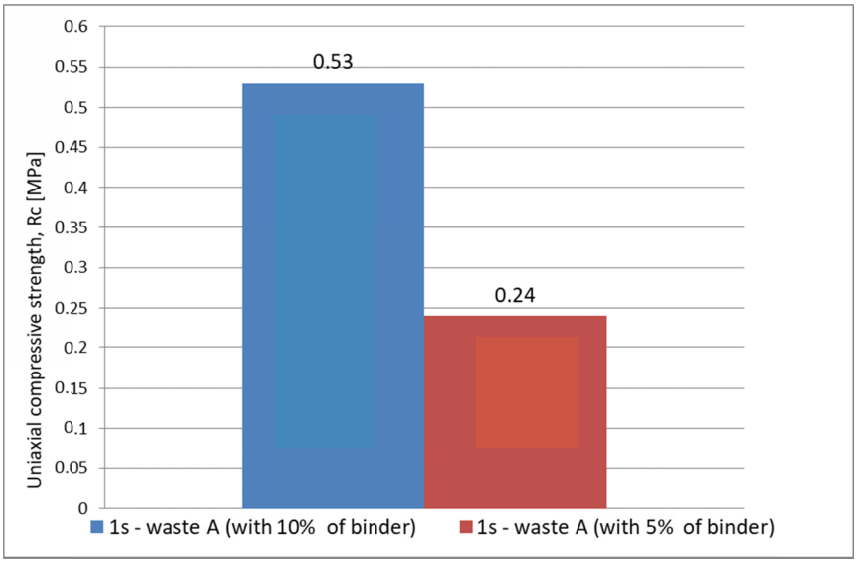

Fig. 12. Uniaxial compressive strength of solidified samples of mixtures – mixing liquid: brine

The characterization was calculated as a percentage from the formula:

$$K = 1 - \frac{R_{cw}}{R_c} \cdot 100 \ [\%]$$

where:

R_c — sample strength in air-dry condition, [MPa],
R_{cw} — sample strength after brine action, [MPa].

The soakability was determined only for two types of mixtures containing:

– waste type A, 10% binder and fresh water as a liquid,
– waste type A, 10% binder and brine as a liquid.

The above samples showed respectively: brine strength R_{cw}: 0.507 MPa and 0.31 MPa, K = 25% and 42%.

For all other samples, determination of the strength after wetting was impossible due to their spontaneous decomposition ($R_{cw} \approx 0$), so the theoretical value of their soakability was 100%.

10. Determination of compressibility of solidified samples of mixtures

The principle of the method consists in measuring the height of the sample (uniaxial strain) placed in the oedometer and subjected to a three-axis stress pattern, under pressure exerted axially on the upper surface of the sample according to PN-G-11011. The initial layer height of the mixture in the oedometer at 15 MPa loading was determined in the study, and the material samples

were then loaded up to 25 MPa. The compressibility at the specified pressure was calculated as a percentage by the formula:

$$S_p = \frac{H_0 - H_p}{H_0} \cdot 100$$

where:

H_0 — height of the mixture layer in the oedometer at a load of 15 MPa, mm,
H_p — height of the mixture layer in the oedometer at a load of 25 MPa, mm.

The study used oedometers with an internal diameter of 113.34 mm and a height of 130 mm. Preparation of samples required the creation of special forms that allowed the batch to be aged for 45 days. After this period the samples were placed in oedometers and then tested. The results shown in Table 3 show high compressibility from 36.9% to over 50%. In some cases, due to the loose consistency of the mixture, compressibility was not determined.

11. Conclusions

The paper presents the results of laboratory tests aimed at preliminary assessment of the possibility of applying of secondary waste (ashes and dusts) originating from municipal waste incineration plants, using the technology of filling voids with water-binding mixtures in salt mines. The amount of such waste will increase in Poland in the coming years due to the construction of new installations. The technology that makes it possible to recover these wastes using the already huge space created by regular chambers as a result of rock salt deposit exploitation in a sealed salt rock, will be beneficial to the environment. Two types of waste have been used for the study: furnace bottom ash and waste from the flue gas treatment (dust). The mixtures consisted of waste, binder and fresh water or brine in selected proportions. The most important physical and geotechnical characteristics were determined, which are important for obtaining the proper parameters of both the mixture in motion and its behaviour during and after the filling of the chambers. The results are summarized in Table 3. Among the investigated compositions of mixtures, it can be stated that for a given type of waste, the addition of a binding agent (binder) of 5÷10% gives a certain strength to the artificially formed massif. This allows for the recovery of the resilient properties of the waste material and, consequently, the strengthening and improvement of geomechanical stability of the rock mass. Studies have shown the possibility of developing a mixture recipe that virtually eliminates excess saline in the chamber – the brine will be completely consumed in the binding process to form an artificial massif with a compressive strength of approximately 0.5 MPa. Due to the variability of chemical compositions of ash from different incineration plants, individualized quantity and quality of the binder component are required. The results obtained are preliminary and confirm the technical feasibility of this recovery process.

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