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Assessment of the impact of municipal solid waste incineration bottom ash used as partial cement replacement in cement mixture using bioassays

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Abstract: The paper is focused on the research of ecotoxicological properties of mortar prisms produced with partial cement replacement by ash from energy recovery of municipal waste. Two types of ash were used: ash from incineration and ash from municipal waste gasification. According to the Waste Catalogue, ash is considered other waste, which is non-hazardous and nowadays it is predominantly landfilled. Negative results of standardized biotests are inevitable precondition for the use of ash for construction products. The results from both biotests (acute toxicity test on aquatic organisms *Daphnia magna* and growth inhibition test of higher cultivated plants *Sinapis alba*) confirmed suitability of cement replacement by ash from energy recovery of municipal waste. Environmental safety of produced mortar prisms is different. Recommended replacement of cement with ash, obtained from municipal waste gasification, is 10% and with ash gained from incineration is 15%. The use of this type of waste in construction industry will lead to the decrease of landfilled waste. Due to the replacement of cement with waste (from industrial branches) natural resources of raw materials used in the process of cement production are saved.

Introduction

The current world is constantly changing and people increase environmental pressure. Sources of materials are gradually becoming reduced. Construction industry uses 50% more raw materials than any other economic activity. Therefore, it is regarded as unsustainable sector. The second important global problem is a sphere of waste management. In this sphere, the European Union (EU) focuses on the decrease of environmental and health impacts of waste and on the improvement of the efficiency of its use. In 2016 the total amount of waste produced by economic activities and households of all 28 member states was 2,533 million tons. It is the highest recorded amount in the EU-28 in the period from 2004 to 2016. Municipal waste represents only 10% of the total amount of produced waste. However, it has a high political profile due to its complex character, composition and distribution among many waste sources (Bień et al. 2014, Eurostat 2018, Rodrigues et al. 2017, Tiruta-Barna 2012). Despite the increasing amount of waste in the EU-28, total amount of landfilled municipal waste is being reduced thanks to the Council Directive 31/1999 on the landfill of waste (Directive No. 1999/31/CE). Decreasing the amount of landfilled municipal waste was reflected not only in higher rate of recycled municipal waste in the EU-28, but also in the increase of energy recovery of municipal waste (Eurostat 2019, Joseph et al. 2018).

Energy recovery of municipal waste is an efficient way to dispose municipal waste. By energy recovery, the volume of municipal waste is reduced by 75–80%. However, residues such as fly ash and ash result from energy recovery of landfilled municipal waste. It is necessary to use them to prevent repeated formation of landfills (Crillesen et al. 2006, Stiernström et al. 2014).

Suitable reuse of these residues from different industrial activities (e.g. fly ash from power plants, slag from iron production, foundry sand, calcium sulphate from desulphurised combustion products, silica fume from the ferrous alloys production, waste glass and ceramics, as well as construction waste) in the construction industry can significantly help to decrease environmental impact. This decrease can be manifested through the restriction of raw materials extraction, reduction of energy use, reduction of greenhouse gases emissions and restriction of landfilled waste production (Bálintová et al. 2015, Kobetičová et al. 2017, Tiruta-Barna 2012). Ecotoxicological properties of building materials and their leaches and biological degradability of organic substances in leaches belong to the characteristics to which basic requirement for buildings "Hygiene, Health and Environment" from the attachment 1 of the Regulation on construction products (Regulation (EU) No 305/2011) is related. Working group TC

351 – construction products deals with the solution of those basic characteristics, i.e. assessment of dangerous substances release, and focuses on the development of standardized methods concerning releasement of dangerous substances into indoors and into soil, underground and surface water. Nowadays, tests of leachability of construction products are available (CEN/TS 16637-2 2014, CEN/TS 16637-3 2017). Except for the leachability tests, the working group TC 531 created technical report on ecotoxicity and biological degradability (CEN/TR 17105 2017). The report deals with biological tests for aquatic and terrestrial environment. It includes recommendations for the individual tests and elimination of potential problems during the testing. Ecotoxicology is a relatively new branch of toxicology, dated back to the 1960s. The aim of ecotoxicology is to determine how the pollutants (usually of anthropogenic origin) behave in the natural environment and how they affect organisms in this environment (Sparling 2016, Sparling 2017). Therefore, this science can significantly contribute to the increase of sustainability of constructions, because it allows for the assessment of potential environmental risks related to the materials, which are to be integrated into the construction, without a necessity of using the LCA (Life Cycle Assessment) (Rodrigues et al. 2017). Monitoring the ecotoxicity of construction products is a new sphere. Nowadays there are only a few of scientific studies concerning this topic and due to the variety of materials used in construction industry (e.g. coatings, cements, concrete, plastering, PVC floors, polypropylene-wood composites and others) each of the studies deals with another material (Bandow et al. 2018, Gartiser et al. 2017a). In order to get reliable and comparable results, Bandow et al. (2018) recommend the use of standardized ecotoxicological methods with the focus on the standard CEN/TR 17105 (2017).

The aim of this experiment was to study environmental safety using biotests, i.e. by the determination of ecotoxicological properties of mortar prisms with partial cement replacement with ash from energy recovery of municipal waste. Effects of the used starting materials (cement, sand and bottom ash) and produced mortar prisms on the terrestrial (growth inhibition test of higher cultivated plants (*Sinapis alba*)) and aquatic (acute toxicity test on aquatic organisms (*Daphnia magna*)) trophic levels were studied.

Materials and methods

Materials

Portland cement Extracem 42.5 R (the CRH company, factory in Rohožník, Slovakia), with the clinker content of 95–100% was used for the samples preparation. Material that partially replaces clinker comes from two energetic facilities for the municipal waste recovery: from the gasification (G) of municipal waste and from incineration (I) of municipal waste. Gasification equipment consists of a grid mechanism and combustion with partial air access. The gasification reactor has a capacity of 500–1200 kg/h of separated waste. Separated municipal waste is processed into RDF (Refuse Derived Fuel). The fuel is fed into the gasification reactor. The temperature of the gasification process – the gasification zone consists of a drying zone (temperature approximately 300°C) and an oxidation zone (temperature approximately 800°C). The ignition temperature is 300°C. The bottom ash is transported into silo storage tanks by a grate device. The estimated bottom ash mass flow is 120 kg/h. Bottom ash from silo storage tanks is displaced to separate ferrous metals. Incineration equipment is used for heat treatment of MSW using heat generated during combustion. The boiler is single-drum, radiant, three-pass, with a vacuum combustion system on 6 pieces of "Dusseldorf" cylindrical grates, arranged in a row 30°. The boiler capacity is 8 000 to 10 000 kg/h MSW with combustion temperature min. 850°C. In the ash treatment area, the ash is cooled in a water bath, then deposited by a crane with a bucket grab onto a conveyor belt where the ferrous metal is separated magnetically. Sand (standard sand from the Filtrační písky company, the Czech Republic) was used in the mortar prisms, as well as water from a public water supply system. These components meet the requirements of CEN EN 196-1 (2016).

Determination of risk elements

Determination of risk elements (Cu, Zn, Al, Fe, Pb, Cd, Co, Ni, As, Mn) was performed by ISO 11885 Water quality. Determination of selected elements was done by inductively coupled plasma optical emission spectrometry (ICP-OES) (ISO 11885 2007) on the optical emission spectrometer OES-ICP VARIAN 725 ES. Aqueous extract was prepared according to EN 12457-4 Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Part 4: One stage batch test at a liquid to solid ratio of 10 L/kg for materials with particle size below 10 mm (without or with size reduction) (EN 12457-4 2006).

Mortar prisms

The experiments were performed with mortar prisms, produced with partial replacement of 0–20% of the clinker weight. The composition of mortar prisms is shown in Tab. 1. Eight types of mortar prisms and one mortar prism from standard cement mixture were produced. The dimensions of mortar prisms were 40 mm × 40 mm × 160 mm. They were produced in three repetitions. Tested mortar prisms were left to mature for the period of 28 days (EN 15002 2015).

Table 1. Mixture proportion of bottom ash from municipal solid waste incineration mortar prisms

Sample	STD[2]	SG5[3]	SI5[4]	SG10	SI10	SG15	SI15	SG20	SI20
Cement (g)	450.0	427.5	427.5	405.0	405.0	382.5	382.5	375.0	375.0
Sand (g)	1350.0	1350.0	1350.0	1350.0	1350.0	1350.0	1350.0	1350.0	1350.0
BA[1] (g)	–	22.5	22.5	45.0	45.0	67.5	67.5	75.0	75.0
Water (g)	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0

[1] BA – bottom ash, [2] STD – cement mixture (standard), [3] SG – sample with bottom ash from municipal solid waste gasification, [4] SI – sample with bottom ash from municipal solid waste incineration.

Determination of ecotoxicological properties

The following tests were used for the determination of ecotoxicity: terrestrial test – growth inhibition test of higher cultivated plants (*Sinapis alba*) and aquatic test – acute toxicity test on aquatic organisms (*Daphnia magna*). Selected biotests are ranged among standardized tests. In both cases the preliminary tests were carried out. Preliminary tests were carried out on raw materials used for the production of mortar prisms (cement, sand, ash G and ash I) and 8 produced mortar prisms containing ash from energy recovery of municipal waste (G and I) and standard (STD) (EN 14735 2006, STN 83 8303 1999, EN ISO 6341 2012, OECD 2004).

Leaching

Raw materials for the preparation of cement mixtures (sand, cement and bottom ash) were leached in demineralized water for 24 hours (stirred at 10 revolutions per minute; Heidolph Reach 200, Germany) at laboratory temperature (EN 14735 2006). The mortar prisms were leached in demineralized water. The period of leaching was 1 day and 7 days. This period was determined due to the proposal in the standard CEN/TR 17105 (2017). Leaching was performed by plunging a mortar prism into leaching fluid, keeping the condition of 2 mL of leaching fluid to 1 cm2 of surface of the tested unit. The leaching temperature was 22°C ± 2°C. Leaching was carried out in the air-conditioned laboratory. After the leaching, solid particles were separated by filtration (paper filters with the pores of 5 μm) (CEN/TR 17105 2017).

Prepared water leaches were treated by addition of 2.5 mL of stock solutions of salts into 1000 mL of water leach (Tab. 2). For the ecotoxicity tests the water leaches of solid materials and construction products were modified to pH 7.8 ± 0.2 and during the acute toxicity test on aquatic organisms the content of dissolved oxygen was monitored in the samples, too. All water leaches were compared to the control that was prepared from stock solutions (Tab. 2), namely by pipetting 10 mL of each of solutions 1–4, up to the volume of 1 liter (EN ISO 6341 2012).

The pH meter InoLab Terminal level 3 with use of pH SenTix 41 electrode (WTW, Germany) was used in the treatment of pH of water leaches. The dissolved oxygen was determined by the electrical and chemical method, using OXI 340i oximeter with StirrOX G membrane probe (WTW, Germany) after calibration.

Conditions of biotests

Acute toxicity test on aquatic organisms (Daphnia magna)

The test is performed on crustaceans from the subclass of *Phyllopoda*, water flea (*Daphnia magna*), from at least the third generation, obtained by acyclic partogenogenesis from laboratory breeding. Acute toxicity of materials for plankton organisms is determined, when % of immobilization of the exposed individuals is set (Table 3) (EN ISO 6341 2012, OECD 2004).

Growth inhibition test of higher cultivated plants (Sinapis alba)

The test is performed on the seed of higher cultivated plant, *Sinapis alba*, of the family *Brassicaceae* (Tab. 4). After

Table 2. Stock solution for the treatment of aqueous extract and preparation of reconstituted water (EN ISO 6341 2012)

Stock solution	Chemical substance	Concentration (g/L)
1	$CaCl_2 \cdot 2H_2O$, p.a.	117.6
2	$MgSO_4 \cdot 7H_2O$, p.a.	49.3
3	$NaHCO_3$, p.a.	25.9
4	KCl, p.a.	2.3

Table 3. Conditions of the acute toxicity test on aquatic organisms (*Daphnia magna*)

Test organism	*Daphnia magna*
Age of tested individuals	individuals younger than 24 hours since birth
Incubation temperature	20°C ± 2°C
Photoperiod	16 hours of light / 8 hours of darkness
Concentration of dissolved O_2	at the beginning of the test min. 7 mg/L / at the end min. 60%
Control sample	reconstituted water (Table 2)
Reference substance	$K_2Cr_2O_7$, $EC_{50,\ 48hours}$ = 0.74 mg/L (limit 0.3–1.5 mg/L)
Preliminary test	max. number of 20 individuals per a container and max. density of 5 individuals per 10 mL of solution and simultaneously under control (reconstituted water) conditions
Repetition	4
Test duration	48 h
Validity of the test	% of immobilised individuals in control = 5% (limit ≤ 10%)
Monitored response	% of immobilised individuals

germination, a simple root with a hypocotyl starts growing. Toxic effect of the substances comprised in water leach on the germination of seeds and root growth in initial periods of the plant development (period of 72 hours) was tested and compared to the control (STN 83 8303 1999).

Processing the results

The software STATISTICA 12 (Version 12, StatSoft Company, Tulsa, USA) was used to process the results. Averages and their standard deviations (SD) were calculated from the selected data sets in the extent of 4 measurements-repetitions.

Results and discussion

Before the mortar prisms production, ecotoxicological properties and content risk elements of used ash, cement and sand were controlled. Tests results are negative and shown in Table 5 and Table 6. Based on these results, it was possible to produce mortar prisms (see Table 1).

Monitored changes of physical and chemical properties of the starting raw materials and modified water leaches from the mortar prisms are stated in Table 7. It follows from them that the conditions for the validity of the acute toxicity test on

Table 4. Conditions of the test of growth inhibition of higher cultivated plants (*Sinapis alba*)

Test organism	*Sinapis alba*, colour: ochre yellow, size: 1.5 – 2.0 mm, germination of 97%
Number of seeds in Petri dish	30 seeds
Volume of the sample	10 mL
Repetition	4
Test duration	72 hours
Incubation	incubator TS 606 CZ/2-Var (WTW, Germany)
Incubation temperature	20°C ± 2°C
Control sample	reconstituted water (Table 2)
Validity of the test	germination in control sample = 97.8% (limit ≥ 90%)
Reference substance	$K_2Cr_2O_7$, $IC_{50,\ 72hours}$ = 51.80 mg/L (limit 4.1–85 mg/L)
Measuring root length	Steel calibrated measuring instrument
Preliminary test	30 seeds on the filter paper soaked in 10 mL of the undiluted sample / under the same control (reconstituted water) conditions
Monitored response	root growth inhibition compared to control, IC (%)

Table 5. Results of ecotoxicological tests of starting raw materials for the production of mortar prisms

Biotest	Cement	Sand	G-BA	I-BA
Growth inhibition of higher cultivated plants (*Sinapis alba*) [IC, %]	19.86	1.14	-25.10	-10.72
Acute toxicity test on aquatic organisms (*Daphnia magna*) [Immobilisation, %]	40.00	0.00	25.00	15.00

Table 6. Results content risk elements of starting raw materials for the production of mortar prisms

Indicator	Cement	Sand	G-BA	I-BA	*	**
			μg/L			
Copper	0.10	0.10	82.30	179	300	2.10^3
Zinc	2.90	1.50	4.11	54.00	300	900
Aluminum	9.60	451.0	31 922	4 636	–	2.10^6
Iron	1 626	1 480	6.20	216	–	–
Lead	0.20	1.80	7.30	5.27	50	200
Cadmium	1.50	0.90	2.28	3.05	5.0	100
Cobalt	1.50	1.70	0.40	2.58	–	100
Nickel	0.10	0.60	17.94	2.87	40	200
Arsenic	19.00	6.10	11.00	2.45	–	100
Manganese	3.16	2.05	0.30	1.60	–	–

Legend: * Decree of the German Government LAGA Merkblatt (1994), ** Decree of the Walloon Government, Belgium (2001).

aquatic organisms *Daphnia magna* were met. The temperature of samples was not monitored individually. The test was carried out in an air-conditioned laboratory at the temperature of 20°C ± 2°C. The acute toxicity test on aquatic organisms *Daphnia magna* proved that they react to larger amount of chemicals with higher sensitivity (Martins et al. 2007). Therefore, they form a suitable test unit.

Evaluation of acute toxicity test on aquatic organisms (Daphnia magna)

Results of the acute toxicity test on aquatic organisms (*Daphnia magna*), determined in the leaches from the mortar prisms containing replacement of the cement by ash (I and G) after one day and seven days of leaching, are graphically assessed and shown in Figure 1. Basic statistical characteristics are in Table 8.

Table 7. Physical and chemical indicators of adjusted water leaches of starting material and mortar prisms over the acute toxicity test on aquatic organisms (*Daphnia magna*) and growth inhibition test of higher cultivated plants (*Sinapis alba*)

		pH		Dissolved O_2 [mg/L]	
		0 hours	48 hours	0 hours	48 hours
Starting material	Cement	7.78	7.87	8.15	6.01
	Sand	7.90	7.93	7.77	6.95
	G-BA	7.68	7.75	9.36	7.54
	I-BA	7.81	7.90	9.11	8.20
1 day of leaching mortar prism	STD	7.82	7.86	7.72	5.61
	SG5	7.93	7.86	7.86	5.41
	SI5	7.90	7.80	7.89	5.45
	SG10	7.86	7.84	7.93	5.58
	SI10	7.86	7.83	7.90	5.53
	SG15	7.88	7.85	7.91	5.32
	SI15	7.79	7.80	7.82	5.68
	SG20	7.99	7.87	7.84	5.46
	SI20	7.97	7.82	7.83	5.21
7 days of leaching mortar prism	STD	7.70	7.75	8.46	7.87
	SG5	8.00	8.02	8.54	7.93
	SI5	7.80	7.91	8.47	8.10
	SG10	7.88	7.96	8.31	8.02
	SI10	7.73	7.88	8.27	8.01
	SG15	7.92	7.88	8.51	8.05
	SI15	7.85	7.93	8.39	8.05
	SG20	7.96	8.00	8.51	7.99
	SI20	7.65	7.72	8.35	7.89

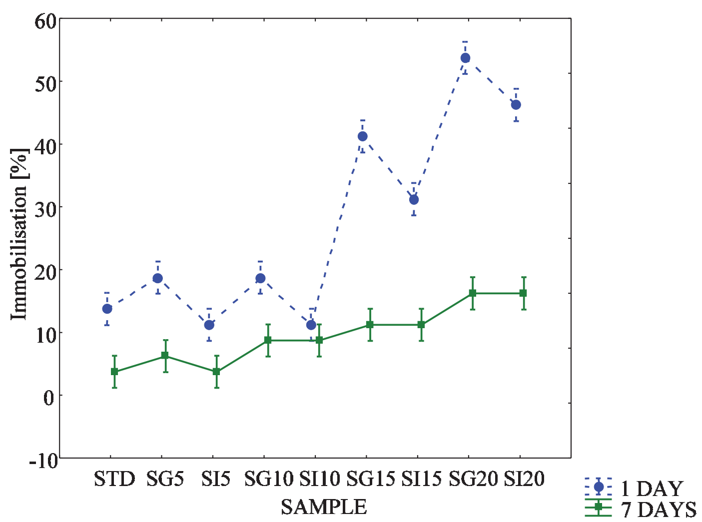

Fig. 1. Graphical assessment of the acute toxicity test on aquatic organisms (*Daphnia magna*)

The Duncan test was used in order to compare the conformity between the samples that were without cement replacement with ash (standard, STD) and the mortar prisms with partial cement replacement with ash (SG and SI). It follows from the results of the Duncan test (Tables 9, 10) that there is conformity of 19.26% in immobilization of *Daphnia magna* between the standard (STD) and the mortar prism of 5% cement replacement with ash from incineration (SI5), and conformity of 16.89% between STD and mortar prism SI10 after 1 day of leaching. After seven days of leaching the conformity of 100% was affirmed between STD and SI5. After 1 day of leaching there was no conformity affirmed between the standard and samples of mortar prisms of cement replaced with ash from gasification (G). After seven days of leaching the conformity of 16.89% was detected in the samples of STD and SG5.

In compliance with (CEN/TR 17105 2017, EN ISO 6341 2012, OECD 2004) the values were negative in the samples with cement replacement with ash (G, I) (≤ 50%) but sample SG20 was positive 51.25% after 1 day of leaching.

Results of growth inhibition test of higher cultivated plants (Sinapis alba)

Results of growth inhibition test of higher cultivated plants (*Sinapis alba*), determined in the leaches from mortar prisms with the replacement of cement with ash (I and G) after one day and seven days of leaching, are graphically assessed and shown in Figure 2.

Table 8. Statistical characteristics of acute toxicity test on aquatic organisms (*Daphnia magna*) after 48 hours

		Average [%]	Standard error [%]	Confidence Intervals	
				-95%	+95%
1 day of leaching mortar prism	STD	11.2500	2.3936	3.6326	18.8674
	SG5	16.2500	2.3936	8.6326	23.8674
	SI5	10.0000	2.0412	3.5039	16.4961
	SG10	16.2500	2.3936	8.6326	23.8674
	SI10	10.0000	2.0412	3.5039	16.4961
	SG15	40.0000	2.0412	33.5039	46.4961
	SI15	30.0000	2.0412	23.5039	36.4961
	SG20	51.2500	2.3936	43.6326	58.8674
	SI20	45.0000	2.0412	38.5039	51.4961
7 days of leaching mortar prism	STD	3.7500	1.2500	-0.2281	7.7281
	SG5	8.7500	2.3936	1.1326	16.3674
	SI5	2.5000	1.4434	-2.0935	7.0935
	SG10	10.0000	2.0412	3.5039	16.4961
	SI10	10.0000	2.0412	3.5039	16.4961
	SG15	10.0000	2.0412	3.5039	16.4961
	SI15	10.0000	2.0412	3.5039	16.4961
	SG20	15.0000	2.0412	8.5039	21.4961
	SI20	15.0000	2.0412	8.5039	21.4961

Table 9. Results of the Duncan test – acute toxicity test on aquatic organisms (*Daphnia magna*) after 1 day of leaching of mortar prisms

Sample	STD	SG5	SI5	SG10	SI10	SG15	SI15	SG20	SI20
Average	13.75	18.75	11.25	18.75	11.25	41.25	31.25	53.75	46.25
STD		0.00885	0.19256	0.01159	0.16886	0.00003	0.00006	0.00002	0.00003
SG5	0.00885		0.00046	1.00000	0.00038	0.00006	0.00006	0.00003	0.00003
SI5	0.19256	0.00046		0.00053	1.00000	0.00002	0.00003	0.00002	0.00002
SG10	0.01159	1.00000	0.00053		0.00046	0.00006	0.00014	0.00003	0.00006
SI10	0.16886	0.00038	1.00000	0.00046		0.00003	0.00003	0.00002	0.00002
SG15	0.00003	0.00006	0.00002	0.00006	0.00003		0.00015	0.00006	0.00885
SI15	0.00006	0.00006	0.00003	0.00014	0.00003	0.00015		0.00006	0.00006
SG20	0.00002	0.00003	0.00002	0.00003	0.00002	0.00006	0.00006		0.00036
SI20	0.00003	0.00003	0.00002	0.00006	0.00002	0.00885	0.00006	0.00036	

It follows from the graph (Fig. 2) that there was a stimulation effect in majority of the samples. The differences in stimulation depending on time of leaching were confirmed. The influence of leaching period brought about the decrease of the stimulation effect on the growth of *Sinapis alba* root in comparison with the control. A significant effect of the technology of municipal waste incineration was shown. More distinct stimulation effect was in the samples with the replacement of cement with ash, obtained through the gasification process (G). We suppose that stimulation of the growth of *Sinapis alba* root was caused by the presence of elements contained in used ash, as well as in other raw materials used for the production of mortar prisms. Some of them had stimulation effect on the plant growth. Roots of plants have a limited number of binding sites for metals. Binding sites are being fully saturated and other additions of metals do not lead to further increase of the content of these metals in plants (Page and Feller 2005). This was confirmed in our samples, too (Fig. 2). Copper, iron, manganese and zinc, which were determined in the water leach (Table 6), are known for their catalytic effect on the growth of plants (Paľove--Balang et al. 2006).

Basic statistical characteristics of the analyzed water leachates of mortar prisms tested with the growth inhibition tests of higher cultivated plants *Sinapis alba* are shown in Table 11 and values of the Duncan test are in Tables 12, 13.

It follows from the results of the Duncan test that there is conformity of 21.97% in stimulation of *Sinapis alba* root between the standard (STD) and the mortar prism of 5% cement replacement with ash from incineration (SI5). After seven days of leaching the conformity of 85.43% was affirmed between these samples. After 24 hours of leaching there was no conformity affirmed between the standard and samples of mortar prisms of cement replaced with ash from gasification (G). After seven days of leaching the conformity of 6.90% was detected in the samples of STD and SG5. Higher replacement (in %) of ash from incineration (I) of municipal waste was confirmed experimentally in the production of mortar prisms in comparison with the ash obtained as waste from energy recovery of municipal waste by gasification (G).

It follows from the results of the growth inhibition test of *Sinapis alba* root that, after 24-hour-leaching of the samples, (STN 83 8303 1999) mortar prism with 15% cement

Table 10. Results of the Duncan test – acute toxicity test on aquatic organisms (*Daphnia magna*) after 7 days of leaching of mortar prisms

Sample	STD	SG5	SI5	SG10	SI10	SG15	SI15	SG20	SI20
Average	3.75	6.25	3.75	8.75	8.75	11.25	11.25	16.25	16.25
STD		0.16886	1.00000	0.01159	0.01383	0.00059	0.00053	0.00002	0.00002
SG5	0.16886		0.19256	0.16886	0.19256	0.01567	0.01383	0.00004	0.00004
SI5	1.00000	0.19256		0.01383	0.01567	0.00066	0.00059	0.00002	0.00002
SG10	0.01159	0.16886	0.01383		1.00000	0.20724	0.19256	0.00059	0.00053
SI10	0.01383	0.19256	0.01567	1.00000		0.19256	0.16886	0.00053	0.00046
SG15	0.00059	0.01567	0.00066	0.20724	0.19256		1.00000	0.01159	0.00885
SI15	0.00053	0.01383	0.00059	0.19256	0.16886	1.00000		0.01383	0.01159
SG20	0.00002	0.00004	0.00002	0.00059	0.00053	0.01159	0.01383		1.00000
SI20	0.00002	0.00004	0.00002	0.00053	0.00046	0.00885	0.01159	1.00000	

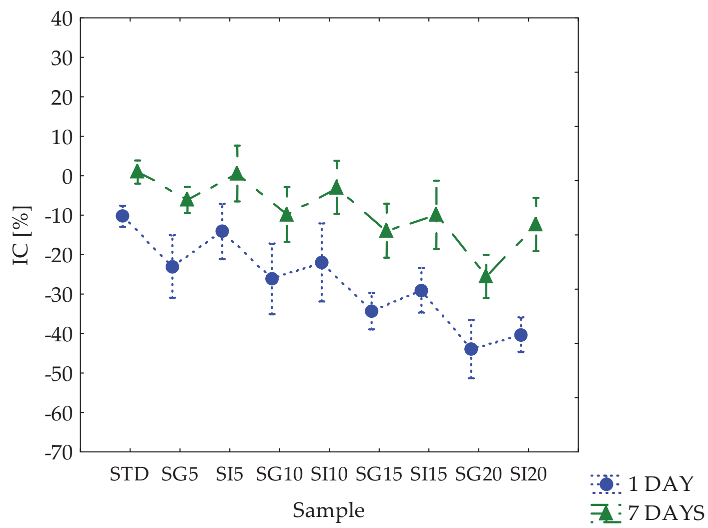

Fig. 2. Graphical assessment of the growth inhibition test of higher cultivated plants (*Sinapis alba*)

Table 11. Statistical characteristics of the growth inhibition test of higher cultivated plants (*Sinapis alba*)

		Average [%]	Standard Error [%]	Confidence Intervals	
				- 95%	+ 95%
1 day of leaching mortar prism	STD	-10.2817	0.8447	-12.9699	-7.5936
	SG5	-22.9603	2.5033	-30.9269	-14.9937
	SI5	-14.1217	2.2062	-21.1429	-7.1005
	SG10	-26.1217	2.8128	-35.0732	-17.1702
	SI10	-21.9894	3.1147	-31.9016	-12.0772
	SG15	-34.3122	1.4455	-38.9125	-29.7118
	SI15	-29.0622	1.7775	-34.7190	-23.4053
	SG20	-43.9762	2.3235	-51.3707	-36.5817
	SI20	-40.2276	1.3752	-44.6042	-35.8510
7 days of leaching mortar prism	STD	0.9378	0.9252	-2.0065	3.2200
	SG5	-6.1574	1.0491	-9.4961	-2.8187
	SI5	0.5542	2.2219	-6.5170	7.5400
	SG10	-9.8413	2.1860	-16.7982	-2.8844
	SI10	-2.9458	2.1157	-9.6787	3.7200
	SG15	-13.9376	2.1496	-20.7786	-7.0966
	SI15	-9.9246	2.7186	-18.5767	-1.2725
	SG20	-25.5291	1.7158	-30.9895	-20.0687
	SI20	-12.3836	2.1189	-19.1270	-5.6402

Table 12. Results of the Duncan test – of growth inhibition test of higher cultivated plants (*Sinapis alba*) after 1 day of leaching of mortar prisms

Sample	STD	SG5	SI5	SG10	SI10	SG15	SI15	SG20	SI20
Average	-10.28	-22.96	-14.12	-26.12	-21.99	-34.31	-29.06	-43.98	-40.23
STD		0.00057	0.21967	0.00007	0.00101	0.00002	0.00003	0.00002	0.00002
SG5	0.00057		0.00996	0.31007	0.75321	0.00166	0.06849	0.00003	0.00004
SI5	0.21967	0.00996		0.00098	0.01594	0.00003	0.00012	0.00002	0.00002
SG10	0.00007	0.31007	0.00098		0.21226	0.01624	0.34448	0.00004	0.00020
SI10	0.00101	0.75321	0.01594	0.21226		0.00088	0.04159	0.00002	0.00003
SG15	0.00002	0.00166	0.00003	0.01624	0.00088		0.09729	0.00525	0.06349
SI15	0.00003	0.06849	0.00012	0.34448	0.04159	0.09729		0.00012	0.00157
SG20	0.00002	0.00003	0.00002	0.00004	0.00002	0.00525	0.00012		0.23052
SI20	0.00002	0.00004	0.00002	0.00020	0.00003	0.06349	0.00157	0.23052	

Table 13. Results of the Duncan test – of growth inhibition test of higher cultivated plants (*Sinapis alba*) after 7 days of leaching of mortar prisms

Sample	STD	SG5	SI5	SG10	SI10	SG15	SI15	SG20	SI20
Average	-0.94	-6.09	-0.30	-9.841	-2.95	-13.94	-9.94	-25.53	-12.38
STD		0.06901	0.85428	0.00744	0.29292	0.00054	0.00782	0.00002	0.00154
SG5	0.06901		0.08707	0.28108	0.36621	0.04722	0.29831	0.00004	0.10176
SI5	0.85428	0.08707		0.00997	0.34975	0.00079	0.01077	0.00002	0.00219
SG10	0.00744	0.28108	0.00997		0.06559	0.28362	0.98081	0.00023	0.48961
SI10	0.29292	0.36621	0.34975	0.06559		0.00717	0.07069	0.00002	0.01805
SG15	0.00054	0.04722	0.00079	0.28362	0.00717		0.27735	0.00228	0.65279
SI15	0.00782	0.29831	0.01077	0.98081	0.07069	0.27735		0.00022	0.47774
SG20	0.00002	0.00004	0.00002	0.00023	0.00002	0.00228	0.00022		0.00097
SI20	0.00154	0.10176	0.00219	0.48961	0.01805	0.65279	0.47774	0.00097	

replacement with ash obtained from incineration (I) and with 10% of ash gained from the gasification (G) of municipal waste, were convenient. After seven days of leaching of these samples, the stimulation effect decreased.

Gartiser et al. (2017b) carried out and assessed European round robin test according to the standard ISO 5725-2. The aim was to determine the inter-laboratory variability of the overall process for the ecotoxicological characteristics of construction products in eluates and bioassays. It was found out that the reproducibility of ecotoxicity tests from different eluates is acceptable and it is possible to differ between highly ecotoxical construction products and unecological ones. Direct testing of water leaches from construction products is a very promising approach to the assessment of the release of dangerous substances from construction products into the environment (Gartiser et al. 2017b).

Conclusions

The paper brings the results of research of environmental safety of mortar prisms, which were produced with partial cement replacement with ash from energy recovery of municipal waste (to 20%). The ash was obtained as waste from incineration of municipal waste (I) and from the gasification process of municipal waste (G). Produced mortar prisms containing ash complied with the indicators according to (EN 196-1 2016).

Ecotoxicity was tested in starting raw materials (cement, sand, ash I and ash G), in mortar prisms produced with the replacement of cement with ash (I and G) and from standard cement mixture (STD). Two ecotoxicity tests were performed – terrestrial test of growth inhibition of higher cultivated plants (*Sinapis alba*) and the acute toxicity test on aquatic organisms (*Daphnia magna*) (EN 14735 2006, STN 83 8303 1999, EN ISO 6341 2012, OECD 2004).

Results of ecotoxicological tests of starting raw materials were negative and suitable for the production of mortar prisms. Biotests confirmed suitability of partial replacement of cement with ash from energy recovery of municipal waste. However, the obtained results are different. Recommended partial replacement of cement with ash obtained from the gasification of municipal waste (G) is 10%, and with ash from incineration (I) is 15%. Higher replacements require further research, focused predominantly on the optimization of incineration process.

According to the Waste Catalogue, ash is considered other waste (Notice No. 365/2015). Nowadays, ash from energetic facilities for municipal waste disposal is landfilled. The use of this kind of waste in construction industry will decrease the amount of landfilled waste. Replacement of cement with residues (from industry branches) can also save natural resources of raw materials used for the cement production.

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