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Original Research Article

ENERGY-EFFICIENT MORTAR WITH ADDITION OF ASH AND SLAG FROM MUNICIPAL WASTE INCINERATION

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A b s t r a c t

The increasing generation of waste and the need for sustainable construction materials have prompted research into the use of waste-derived by-products in concrete. This study investigates the potential of fly ash (MWI-FA) and bottom slag (MWI-BS) from municipal waste incineration (MWI) as cement mortar and concrete components. The materials were sourced from a thermal treatment plant in Poznań, Poland. The study involved substituting cement with MWI-FA, as well as fine/coarse aggregates with MWI-BS in varying proportions. The physical properties, consistency, and compressive/bending strength of the modified composites were evaluated. The results indicated that the addition of MWI-FA notably reduced mortar strength, with a 51% decrease in compressive strength observed at a 25% replacement level. The ash was also characterised by a low silica content and high chloride and sulphate contents. Conversely, MWI-BS showed potential as a fine aggregate substitute with no clear impact on strength (approx. -4% / 25% addition of BS). Concrete with 20% coarse aggregate replaced by MWI-BS exhibited slightly higher workability and slower strength gain (-7÷10%). The findings suggest that while MWI-FA poses challenges as a cement substitute, MWI-BS is a promising alternative for aggregates, particularly in mass concrete applications where slower strength gain is acceptable. The methods and discussion presented exemplify a simple approach to preliminary investigation into the use of a particular MWI ash in mortar/concrete. Further research is needed to assess long-term durability and performance in various environments.

Keywords: green mortar, municipal waste incineration, fly ash, bottom slag, aggregate

1. INTRODUCTION

The decreasing availability of natural resources, restrictions related to greenhouse gas emissions, and the growing volume of waste are some of the fundamental challenges posed worldwide by the rapid growth of civilization [1]. The construction industry is among those aiming, among others, to preserve natural deposits, transition from a linear to a circular economy (close material loops by utilizing waste), and reduce its carbon footprint [2]. Concrete is the world's most manufactured product, while cement

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production accounts for approx. 8% of global CO_2 emissions [3, 4]. Thus, understandably, urgent effort is made to create more sustainable, 'green concrete' [5].

Industrial by-products and waste have been used as supplementary material or substitutes for traditional components of concrete mix for many decades now, providing both ecological and economic benefits [6]. Their role in the concrete mix can be diverse, acting as a binder, additive, aggregate, or reinforcement [3, 6–8]. The properties of some by-products are well understood, advantageous, and standardized (e.g., fly ash from coal incineration [9]). Others, especially recently emerging, might pose challenges due to their properties. This group includes i.e., FBC (Fluidized Bed Combustion) fly ash [10], sewage sludge combustion ash [11], construction and demolition waste [3], by-products of water treatment [12], waste synthetic fibres [13], and wastepaper [14], to name just a few. Changing regulations regarding waste management impose an obligation on concrete manufacturers to utilize such materials by the principles of sustainable development [15].

The yearly generation of municipal waste continues to grow. In 2022 in Poland, an average of 357 kg was produced per capita, a 28% increase relative to 1995; for the entire EU, the value equals 513 kg, a 10% increase in the same period [16]. The increasing volume of municipal waste represents a notable problem, primarily due to its profound impact on the natural environment and economic cost (landfill fees). In line with current policies (e.g. [17, 18]), landfilling is limited, and waste is instead subjected to different types of treatment. Disposal by recycling and composting has increased in popularity in the EU by about 200% between 1995 and 2022, and the amount of waste incinerated has also been raised by almost 100% in the same period [16].

The incineration of municipal waste carries the environmental benefits of waste volume reduction and energy recovery, e.g., for district heating or electric power generation. Burning the so-called pre-RDF (Refuse Derived Fuel – a combustible fraction extracted from pre-treated municipal waste) results in lower carbon dioxide emissions (90–100 kg/MWh) compared to burning hard coal (approximately 110–120 kg/MWh) or biomass (approximately 100–120 kg/MWh) [19]. Europe has over 500 municipal waste incineration plants [20] and incinerates about 26% of municipal waste [16]. In Poland, as of 2024, there were eight operational incineration plants. However, according to the National Fund for Environmental Protection and Water Management (NFOŚiGW), 39 new facilities are planned over the next seven years [21–23].

The process of thermal treatment, in essence, converts one type of waste into another, as it produces fly ash (fine particles separated from the flue gas) and bottom slag (solid residue left after combustion). According to some estimates, roughly 0.02 Mg of ash and 0.30 Mg of slag are generated per 1 Mg of incinerated waste [24, 25]. One can thus roughly assume that, with 60 mln Mg of municipal waste incinerated in the EU yearly (2,8 mln Mg in Poland), 1,2 mln Mg of ash and 18 mln Mg of slag is generated (0,06 Mg and 0,8 mln Mg in Poland, respectively) [16, 26]. These large quantities of by-products raise the question of how to manage them effectively. The available research mentions, i.e., the possibility of slag application in glassmaking, ceramics, zeolite synthesis, and concrete [24, 27–31]. Fly ash is reported to have largely similar applications, including asphalt, cement, ceramics, glass, geopolymers manufactory, and synthesis of zeolites [25, 28, 32–34].

Several research papers regarding the use of slag and ash from municipal waste incineration in concrete and mortar are available. The authors of [35] replaced 30% cement with ground slag (from incinerated hospital waste) in mortars in parallel with similar specimens with a commonly used additive – ground granulated blast furnace slag (GGBFS). The effects of slag and GGBFS were similar in terms of consistency and compressive strength after 28 days (though it was 30% lower than pure cement specimens). The municipal waste slag caused a notably longer setting time. In [33], a post-treated mixture of ashes from waste incineration was used in mortars as partial cement replacement. Substitution of 20% cement did not affect compressive strength (but 40% was detrimental) after 28 days of curing.

After 90 days, however, the 20% replacement produced compressive strength increased by up to 10% relative to pure cement specimens. The research described in [27] involved sand fractions of slag replacing fine aggregate in mortars. The flexural and compressive strengths were comparable in 100% slag and 100% sand specimens after 28 days, but slag seemed to promote a greater strength after 365 days. The consistency was majorly affected, though – 100% slag caused very low plasticity compared to 100% sand (29 vs. 11 cm spreading diameter) [36].

One of the important aspects in the context of using ash and slag from municipal waste incineration in concrete is their microscopic analysis. This plays a key role in evaluating the use of slags and ash from waste incineration in concrete and mortars, as they allow for a detailed analysis of their structure and interactions with cement. Through microscopic techniques, such as electron microscopy, it is possible to examine the morphology of slag and ash particles, including their porosity, surface irregularities, and the distribution of mineral phases. SEM (scanning electron microscopy) enables the identification of structural inhomogeneities, the presence of amorphous glass, and crystalline mineral phases, which can influence chemical reactions in cement, such as pozzolanic reactions. Additionally, it helps detect possible contaminants that could negatively affect strength or corrosion resistance [37]. Based on some sources, it can also be observed that there is a correlation between grain size and the porosity of slag from municipal waste incineration [37]. The slag and ash tested in [37] showed through microscopic analysis that the specimens contain anthropogenic materials that didn't combust. Moreover, SEM used in [27] showed the influence of the irregularity and porosity of the slag on its adhesion to the cement paste.

The frequently reported issue of elevated heavy metal and organic pollutant contents, including dioxins, in ash and slag is met with several papers reporting a low or negligible leachability [27, 37, 38]. The slag and ash tested in [37] reportedly showed low concentrations of heavy metals and their strong binding to the solid phase. Leachates from mortars with the addition of slag contain increased total carbon, calcium, and nickel but not chlorides and sulphates [38]. Another report stated minor concentrations of zinc, lead, and iron in similar leachates, all below permissible limits according to the EPA TCLP test [27].

Various approaches can be chosen to include ash and slag from the incineration of municipal waste in a mortar or concrete mix, and the results vary from poor to advantageous. Pre-treatment or post-treatment, e.g., fraction separation, grinding, and sintering, might allow for control of some properties [37]. One should note that the composition of by-products of thermal treatment of waste varies widely over time and due to factors specific to the respective generation areas, such as the level of urbanization and industrialization. As a result, the ash and slag of each plant are unique to the location and cannot be considered comparable across different countries or regions [29]. It is thus necessary to investigate and regularly control the properties before assuming management methods for a particular by-product.

This study investigates the potential use of fly ash and bottom slag from a Polish municipal waste thermal treatment plant as components in cement mortar and concrete. Three approaches are tested – the substitution of binder by ash, as well as fine and coarse aggregate by separated fractions of slag. The role of the proportion of replacement is also evaluated. The scope includes basic physical properties of raw materials, as well as fresh mix consistency and strength of hardened composites after 28 days of curing (7,28, 56 for concrete specimens). Additionally, a notable portion of the paper is devoted to analysing and discussing the compositions of tested ashes in the context of the general population of municipal waste incineration by-products (based on a literature review). The problem of utilization of such ashes is complex, including numerous potential pretreatment methods, which complicate testing and economic calculation. This paper aims to show a relatively simple preliminary approach to analyse the feasibility of their application in mortar/concrete on a practical example.

2. MATERIALS AND METHODS

2.1. Fly ash and slag

The fly ash and bottom slag from municipal waste incineration were supplied by the Installation for Thermal Transformation of Municipal Waste in Poznań, Poland (ITPOK Poznań). The plant incinerates 210 000 Mg/year of mixed municipal waste, a fraction not subject to segregation and recycling (so-called residual) and without pre-treatment, waste code 20 03 01 [20, 39]. This installation has two combustion lines with a 13.5 Mg/h capacity. The thermal power of the plant is 34 MWt, and the electrical power is 15 MWe [40]. The temperature of the burned waste is more than 1000˚C [39]. The resulting by-product generation is approx. 57000 Mg/year of slag and 8400 Mg/year of fly ash [41]. The bottom slag has been at least partially used as aggregate in road construction, while the fly ash is deposited in controlled conditions (as hazardous waste) [41].

Tables 1-2 present the physical properties of ash (European Waste Code 19 01 07 - solid wastes from gas treatment, hereafter: MWI-FA) and slag (19 01 12, MWI-BS). Although it is common practice to use the test methods established for conventional coal combustion fly ash (siliceous or calcareous), it must be stressed that the ash under investigation here is a different material. The comparison of the MWI-FA with the requirements of EN 450-1 [42] is for indicative purposes only, as this standard applies to fly ash from the combustion of pulverized coal. Figure 1 presents the grain size distribution of MWI-BS obtained in sieve analysis. Both by-products come from incineration, so their water content is effectively 0%. MWI-BS was transported from the Poznań municipal waste incineration plant in buckets and spread on plastic sheeting to allow the water to drain. It was then stored in buckets. No additional treatment of the materials (e.g., washing, grinding, calcination) was used at any point of this research besides simple fraction separation of MWI-BS by sieve, as described further. The MWI-BS supplied by the municipal waste incineration plant was divided into two fractions: 0/8 mm and 8/20 mm. The maximum particle size of the investigated MWI-BS was confirmed to be 20 mm by sieve analysis. To investigate the physical properties of MWI-BS, the slag was divided into two fractions: 0/2 mm and 2/20 mm. The 0/2 mm fraction corresponds to the sand fraction, whereas the 2/20 mm fraction corresponds to the gravel fraction.

Table 1. Physical properties of MWI-FA. The standard requirements refer to siliceous fly ash and are provided for comparison

Properties	Unit	Result	Standard deviation	Test method	Requirements in norm
Grain density	$\frac{g}{cm^3}$	2,43	0,07	EN 1097-7 [43]	-
Specific surface area	$\frac{cm^2}{g}$	3677	218	EN 196-6 [44]	≥ 3000[1]
Water demand	%	94,7	0,7	EN 450-1 [42]	$\leq 95\%$
Fineness	%	27,72	0,55	EN 451-2 [45]	$\leq 40\%$ (category N)
Pozzolanic activity after 28 days	%	51	2	EN 450-1 [42]	$\geq 75\%$

[1] – requirement considering test (control) cement according to EN 450-1 [43]

Table 2. Physical properties of MWI-BS from the municipal waste incineration

Properties	Unit	Result	Standard deviation	Test method	Requirements in norm
Grain density of fraction 0-2 mm	$\frac{g}{cm^3}$	2,29	0,04	EN 1097-7 [43]	EN 1097-7 [43]
Bulk density of fraction 0-2 mm	$\frac{g}{cm^3}$	1,38	0,02	EN 1097-3 [46]	EN 1097-3 [46]
Bulk density of fraction 2-20 mm	$\frac{g}{cm^3}$	1,33	0,02	EN 1097-3 [46]	EN 1097-3 [46]
Voids of fraction 0-2 mm	%	48	-	EN 1097-3 [46]	EN 1097-3 [46]
Voids of fraction 2-20 mm	%	50	-	EN 1097-3 [46]	EN 1097-3 [46]

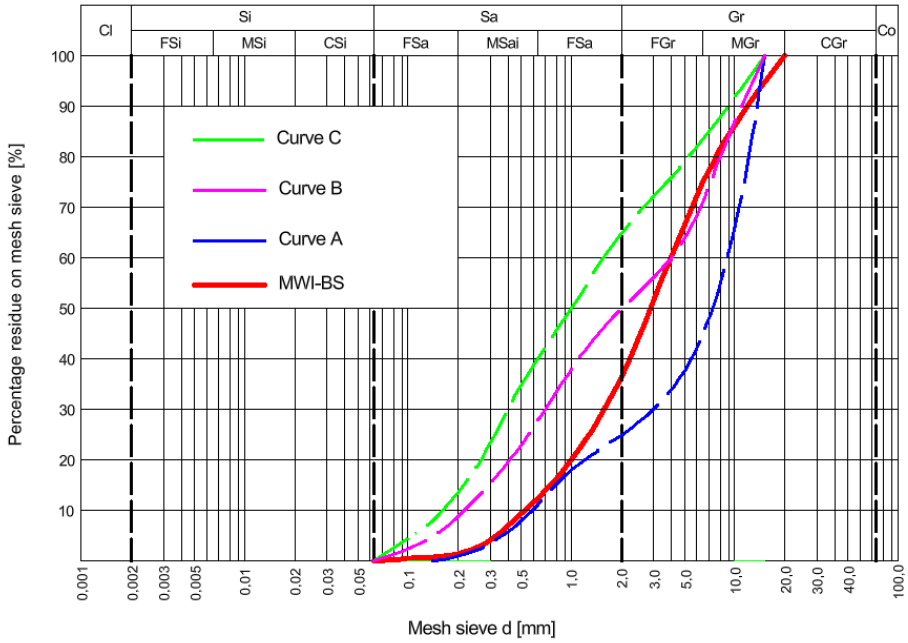

Fig. 1. Grain size distribution of MWI-BS according to EN 933-1 [47] and grain size limit curves (D_{max}=16 mm) according to PN-B-06265:2022-08 [48]. Range below curve A – coarse-grained; range between curve A and curve B – coarse-medium-grained; range between curve B and curve C – medium-fine-grained; range above curve C – fine-grained

Analyzing the test results presented in Table 1, the particle density of MWI-FA is generally consistent with typical values for mineral materials. The relatively low standard deviation indicates a stable material quality within the tested batch, especially considering its origin. MWI-FA has a high specific surface area (equivalent to cement), which suggests that the material has a potentially notable physicochemical activity and might influence chemical reactions in the hardening composite. Despite that, it exhibits an acceptable water demand, meaning that it should not adversely impact on the consistency of mortars. The fineness value indicates an amount of fine particles well corresponding with what is, for example, expected from conventional coal combustion fly ash. The results of the pozzolanic

activity test suggest a very low ability of MWI-FA to promote binding (e.g., react with calcium hydroxide) during the first 28 days of cement hydration.

The physical properties of MWI-BS presented in Table 2 indicate a relatively low bulk density in loose state, which might relate to its high porosity and void ratio. The suggestion that it contains a notable amount of space between the grains can be assessed in Fig. 1, where recommended gradation curves for coarse aggregate (D = 16mm) are displayed, which show a range of gradations ensuring low void ratios according to PN-B-06265:2022-08 [48]. The gradation curve is barely inside the coarse-medium range, with a low fine fraction content. The grain density of MWI-BS is lower than that of mineral materials, such as quartz and limestone, but within the range of normal weight aggregate.

Analyzing the graph in Fig. 1, it can be observed that the MWI-BS specimen contains a minimal amount of fine fractions—particles with a diameter below 0.1 mm account for 0.57%. It should be noted that MWI-BS was not washed prior to testing; therefore, fine particles generated during crushing may have remained on the surfaces of the coarser grains. The dominant fraction consists of particles with a diameter of 0.1–10 mm (85.69%). The material is a mixture with a varied grain size distribution, corresponding to the dimensions of sand and fine gravel, indicating potential applications in construction. Judging by the standard gradation curves, adding finer fractions or grinding might be beneficial in reducing voids and increasing bulk density.

Table 3. Chemical composition (wt. % oxides) of the MWI-FA. Range and average values provided in the literature, from reports provided by the plant operator in Poznań (ITPOK), and recommendations of the EN 450-1 standard regarding the siliceous fly ash (for comparison)

Oxides	**Literature** [25, 50, 59–68, 51, 69–78, 52, 79–87, 53–58]			**ITPOK Poznań**			Requirements in norm EN 450-1 [42]
	Min	Max	Average	Min	Max	Average	
CaO	7,40	58,79	**28,51**	29,00	37,80	**33,51**	≤ 10 (reactive)[1]
SiO_2	1,04	49,20	**15,64**	3,00	16,70	**9,69**	≥ 25,0 (reactive)
Cl	0,70	27,43	**13,55**	6,30	18,70	**13,61**	≤ 0,1
Na_2O	0,46	19,00	**7,43**	4,10	7,30	**5,69**	≤ 5,0
SO_3	1,39	23,60	**7,38**	3,00	15,60	**8,98**	≤ 3,0
Al_2O_3	0,51	17,20	**6,72**	1,60	7,50	**3,91**	-
K_2O	1,35	11,25	**5,26**	-	-	-	-
SrO	0,01	19,00	**3,60**	-	-	-	-
MgO	0,32	21,40	**2,38**	-	-	-	≤ 4,0
Fe_2O_3	0,30	6,77	**2,34**	1,20	3,20	**1,93**	-
P_2O_5	0,17	13,56	**1,69**	1,10	4,40	**2,43**	≤ 5,0
TiO_2	0,12	4,20	**1,27**	-	-	-	-
Mn_3O_4	0,08	1,67	**0,39**	-	-	-	-
BaO	0,10	0,22	**0,16**	-	-	-	-
LOI	0,22	25,72	**9,19**	1,00	4,40	**2,40**	≤ 5,0 (category A)
$SiO_2 + Al_2O_3 + Fe_2O_3$	1,75	60,24	**24,70**	5,80	27,40	**15,53**	≥ 70,0

1 – reactive CaO content above 10% is allowed according to EN 197-1 in the calcareous fly ash [88]

The grain homogeneity index of slag is Cu=7,55, and the index of curvature is Cc=1,24 [49]. Based on the homogeneity index, this MWI-BS can be classified as medium-grained material, while based on the curvature index, it can be classified as multi-fraction material.

Chemical compositions of MWI-FA and MWI-BS are presented in Tables 3 and 4, expressed as oxides, % of specimen mass. The range (min and max) and the average values were derived from selected published papers. The title 'ITPOK Poznań' refers to the plant of origin of the materials tested in this research, and it summarizes the results of regular properties control test conducted at the facility over a period of 21.03.2023-11.01.2024 with an interval of one month [unpublished]. The requirements according to selected standards, included in the righthand side column in Tables 3 and 4, refer to different materials widely utilized in the concrete industry – coal combustion fly ash and ground granulated blast furnace slag. These serve as a point of reference but are expected to differ notably from the by-products of MWI.

Table 4. Chemical composition (wt. % oxides) of the bottom slag (MWI-BS). Range and average values provided in literature, from reports provided by the plant operator in Poznań, and recommendations of the EN 15167-1 [89] standard regarding the ground granulated blast furnace slag (for comparison)

Oxides	**Literature** [24, 27, 91–100, 33, 35, 62, 79, 83–85, 90]			**ITPOK Poznań**			Requirements in norm EN 15167-1 [89]
	Min	Max	Average	Min	Max	Average	
SiO_2	18,00	64,80	**42,36**	28,50	55,90	**42,24**	-
CaO	10,40	42,30	**21,48**	3,20	15,00	**8,93**	-
Al_2O_3	2,90	23,30	**11,29**	5,20	12,80	**8,30**	-
Fe_2O_3	2,03	21,70	**6,92**	1,20	5,30	**2,94**	-
Na_2O	1,30	5,11	**2,29**	1,30	2,50	**1,83**	-
SO_3	0,61	12,80	**4,16**	-	-	-	≤ 2,5
MgO	0,06	2,43	**1,01**	0,83	11,30	**3,79**	≤ 18,0
P_2O_5	0,01	3,91	**1,28**	-	-	-	-
K_2O	0,01	2,20	**0,84**	-	-	-	-
TiO_2	0,01	3,12	**1,16**	-	-	-	-
BaO	0,12	0,14	**0,13**	-	-	-	-
Mn_3O_4	0,06	0,20	**0,12**	-	-	-	-
SrO	0,04	0,06	**0,05**	-	-	-	-
LOI	0,01	4,10	**1,15**	0,50	3,40	**1,30**	≤ 3,0
$CaO + MgO + SiO_2$	39,50	90,00	**64,85**	33,40	67,50	**54,95**	≥ 66,7
$\frac{CaO + MgO)}{SiO_2}$	0,20	2,21	**0,53**	0,17	0,37	**0,30**	≥ 1,0 [-]

The main components of MWI-FA (population-wise) are calcium oxides (CaO), silica (SiO_2), and chlorides (Cl). There are also notable amounts of sulfur oxides (SO_3), sodium oxides (Na_2O), aluminum oxides (Al_2O_3), as well as potassium oxides (K_2O). MWI-FA from the particular plant in Poznań seems to contain lower amounts of SiO_2 and Al_2O_3, as well as somewhat greater amounts of CaO and SO_3, relative to the broad average. If one compares the MWI-FA to coal combustion fly ash according to EN 450-1 [42], the fundamental difference lies in the very low total SiO_2, Al_2O_3, and Fe_2O_3 content. The reactivity of MWI-FA in cement composites, if any, might be questionable due to the low amount of

silica (and possibly excessive SO_3) but may be based on the high CaO content, suggesting possible similarities to calcareous fly ash [88]. Another group of by-products with similarly elevated CaO and SO_3 contents and a relatively low % of reactive silica stems from fluidized bed combustion [101]. In the case of MWI-FA, the most alarming, however, could be the high amounts of Cl and SO_3 in the context of corrosion, including in reinforced concrete.

Perhaps unintuitively, the oxide composition of MWI-BS differs notably from MWI-FA's. In the general population, the most notable components are SiO_2, CaO, Al_2O_3, and Fe_2O_3, with SiO_2 dominating and a notably lower CaO content than fly ash. In relation to that, the slag from the particular plant in Poznań has lower CaO, Al_2O_3, and Fe_2O_3 contents. MWI-BS is sometimes compared to ground granulated blast furnace slag, especially in those studies that assume grinding as pre-treatment [38]. Although MWI-BS does not meet the crucial requirements for GGBFS, it seems there is a closer similarity between them (and conventional fly ash) than in the case of MWI-FA, judging solely by the oxide composition. It can be expected that MWI-BS may exhibit some binding properties akin to those of the more traditional industrial by-products.

Figures 2 and 3 present X-ray diffraction (XRD) analysis of MWI-FA and MWI-BS. The research was carried out using a BRUKER D8 ADVANCE X-ray diffractometer. Based on the analysis, MWI-FA contains notable amounts of calcite, anhydrite, and sodium chloride. The dominant phases in MWI-BS include quartz and calcite. Some hydrates are present in the MWI-BS sample, despite it coming from the high-temperature process of MWI with no modification.

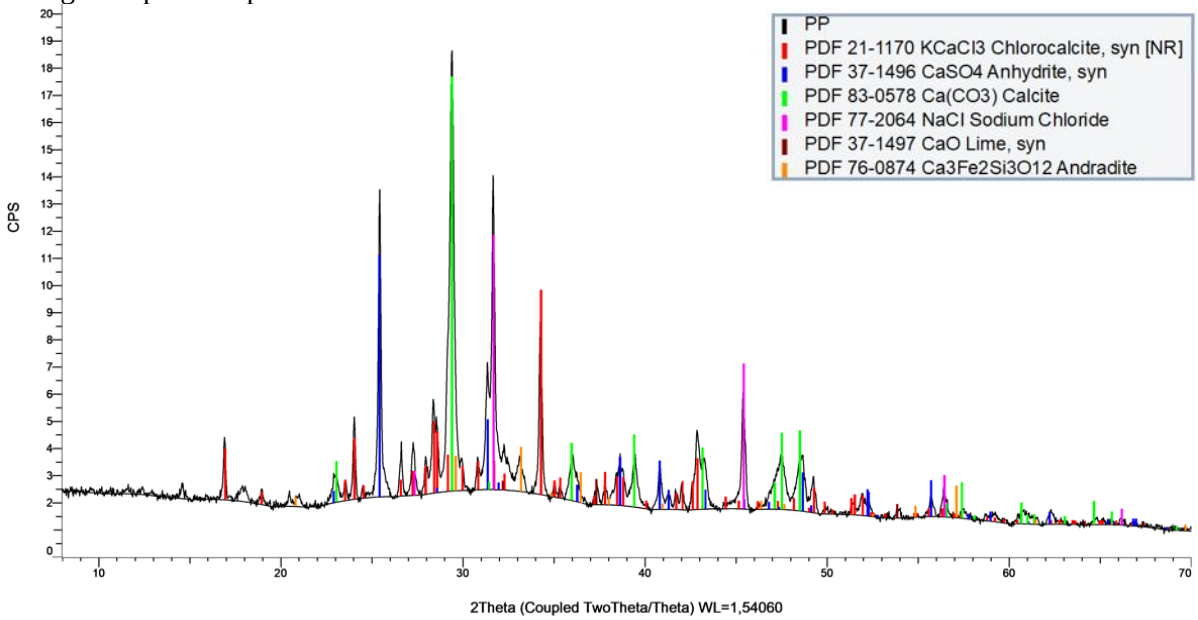

Fig. 2. X-ray diffraction (XRD) analysis of MWI-FA

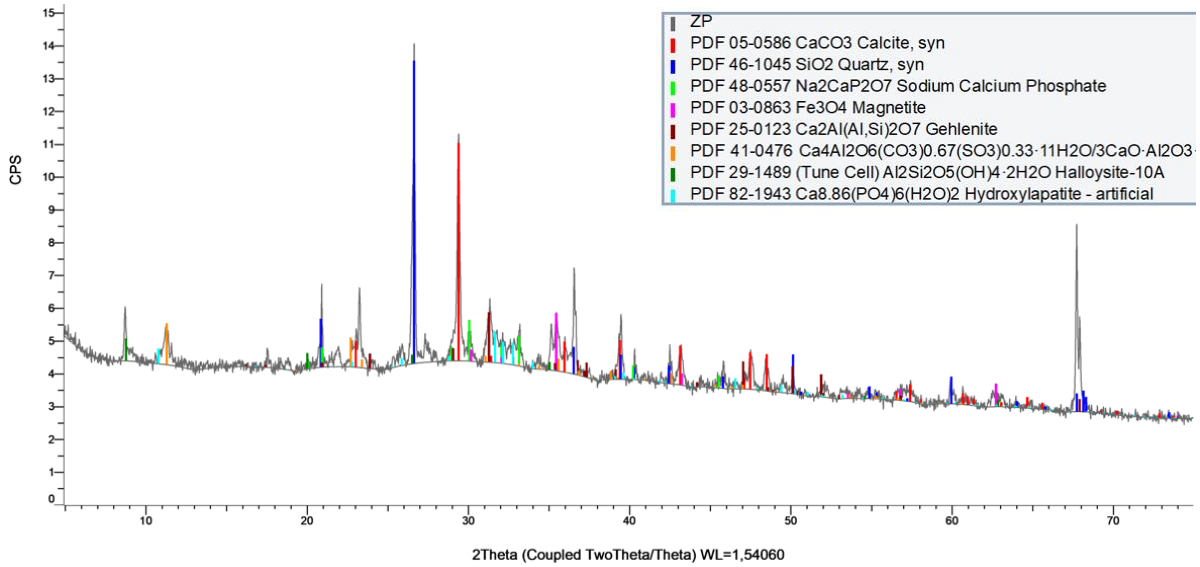

Fig. 3. X-ray diffraction (XRD) analysis of MWI-BS

Figure 4 presents SEM images of MWI-FA and MWI-BS along with EDS analysis. The research was carried out using a Hitachi TM3000 Scanning Electron Microscope. Characteristic spherical particles can be observed in the images showing the MWI-FA sample (Fig. 4a). Other individual spherical particles are characterized by a rough, irregular surface and a microporous structure. The presence of spherical particles may be indicative of the combustion temperature and cooling rate. Rapid cooling of MWI-FA leads to the formation of spherical (non-crystalline) particles [102, 103]. Based on EDS analysis, these particles predominantly contain Ca and Si. The elevated Cl content in the MWI-FA samples may be due to the presence of plastics in the incinerated waste [104–106].

In the images of MWI-BS, a high irregularity of particles and a porous surface can be observed. The visible particles vary in shape and size, which may indicate a heterogeneous chemical composition. Thin, irregular, sharp-edged shapes are visible, as well as plate-like elements. Fibrous structures were also observed [107]. Based on the chemical composition from the EDS analysis, it can be inferred that in Figure 4c, the fibrous and needle-like structures may contain anhydrite [108]. Anhydrite may be present in municipal waste or form during the combustion process because of the oxidation of sulfur and sulfur dioxide [108, 109]. This is supported by Table 5, where Ca and S account for more than half of the total composition [110, 111].

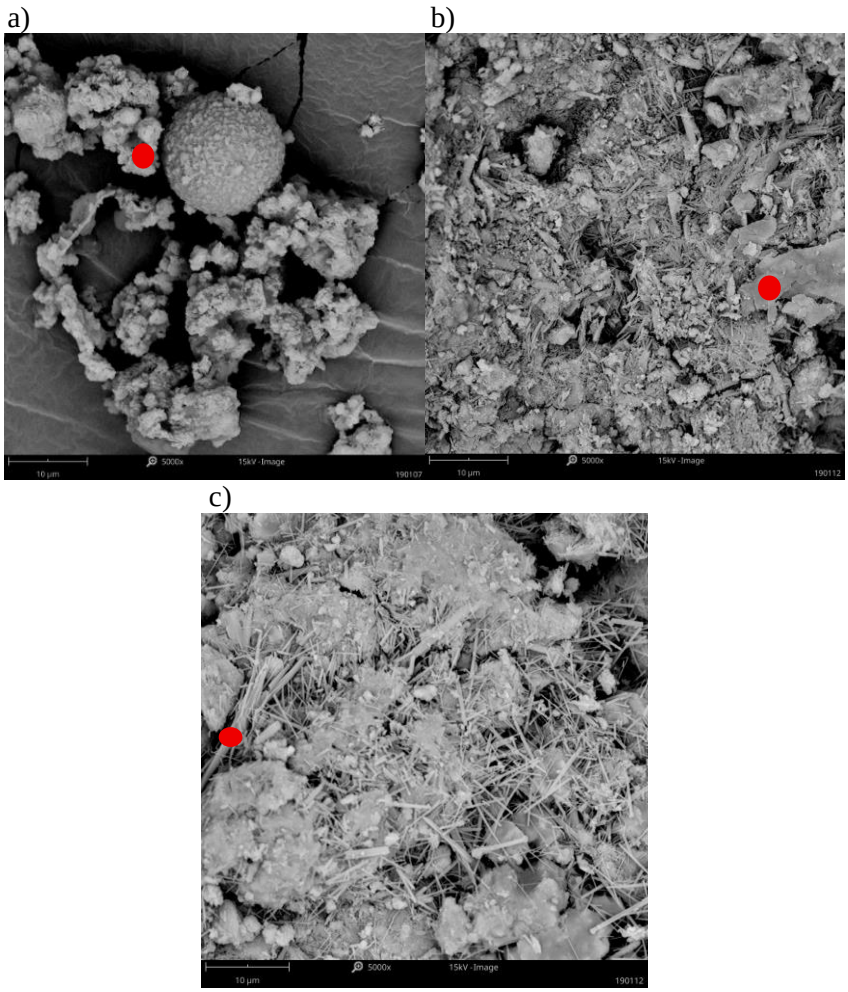

Fig. 4 a), b), c). SEM images of MWI-FA (a) and MWI-BS (b, c) at 5000× magnification

Table 5. Elemental composition based on EDS analysis

Oxide Symbol	Stoich. Conc. [%]		
	Figure 2a	Figure 2b	Figure 2c
Ca	34.76	41.26	42.25
Si	24.92	4.74	5.93
Al	9.69	18.18	22.02
S	7.17	-	11.12
Zn	6.98	-	-
Cl	6.34	10.54	-
K	1.81	-	-
Sr	1.46	-	-
Nb	-	7.58	8.66
Na	-	3.43	5.76

Additional testing was conducted to characterize the leaching characteristics of the MWI-FA and MWI-BS samples. Conductivity and pH were tested using CP-511 pH meter. Chlorides were tested using Chloride Test Method: titrimetric with dropping bottle MQuant. Sulfates were tested using MQuant Sulfate Test 110019.

Table 6. Selected test results on leachates from raw MWI-FA and MWI-BS, as well as cement grout incorporating MWI-FA; L/S=10 mg/kg of dry mass

Specimen	pH	Conductivity	Chlorides	Sulfates
	[-]	[mS/cm]	[mg/l]	[mg/l]
MWI-FA	12.6	32.4	14000	22000
MWI-BS	11.7	2.5	600	2000
Cement-FA grout[1]	12.7	6.1	1000	10000
Limit values [111]				
Inert waste	-	-	800	1000
Waste other than non-hazardous and inert	-	-	15000	20000

1 – binder: 75% cement, 25% MWI-FA; w/b = 0.5; 90-d curing time

Comparing MWI-FA and MWI-BS with the limit values specified in the regulation [112] for inert waste (Tab. 6), it can be observed that the concentrations of chlorides and sulfates for MWI-FA are notably exceeded. The values for MWI-BS are also exceeded; however, the difference is not as notable as in the case of MWI-FA.

Comparing MWI-FA and Cement FA grout, it is observed that chlorides have been immobilized in the cement paste, which is not true in case of sulfates.

2.2. Mortar preparation and testing

Standard cement mortar specimens were made according to EN 196-1 [113]. After the specimens were made, the molds were left for 24 hours. After 24 hours, the specimens were unmolded and submerged in tap water until strength testing.

The plan of the experiment included two mortar specimen series (Tab. 6). In the first one, a portion of cement was substituted by MWI-FA in varied proportions in the range of 5-25% of mass. Thus, a constant water to binder ratio (w/b) of 0.5 is maintained, treating MWI-FA as 100% binder. In the second specimen series, a part of sand was replaced by the 0-2 fraction of MWI-BS in the same % range. Here, slag is treated as pure aggregate, thus its addition does not change w/b (equal to 0.5).

The list of mortar specimens is presented in Table 7. The components used include in the first one (with MWI-FA) cement CEM I 42.5 R [113], standard sand [113], and tap water. In the second one (with MWI-BS) cement CEM I 42.5 R [113], quartz sand (0.5-1.4 mm) and tap water was used. Three specimens were prepared for each mortar mix.

Table 7. Mix design of mortar specimens. 'A' series involves the substitution of cement by MWI-FA; 'S' series involves the substitution of sand by the 0-2 fraction of. MWI-FA – municipal waste incineration fly ash, MWI-BS – municipal waste incineration bottom slag

Dosage of ingredients [g]						Substitution level [%]	
Specimen	Cement CEM I	Water	Sand 0-2 mm / 0.5-1.4 mm	MWI-FA	MWI-BS 0-2 mm	MWI-FA	MWI-BS 0-2 mm
NA	450,0	225,0	1350,0	-	-	-	-
A5	427,5	225,0	1350,0	22,5	-	5	-
A10	405,0	225,0	1350,0	45,0	-	10	-
A15	382,5	225,0	1350,0	67,5	-	15	-
A20	360,0	225,0	1350,0	90,0	-	20	-
A25	337,5	225,0	1350,0	112,5	-	25	-
NS	450,0	225,0	1350,0	-	-	-	-
S5	450,0	225,0	1282,5	-	67,5	-	5
S10	450,0	225,0	1215,0	-	135,0	-	10
S15	450,0	225,0	1147,5	-	202,5	-	15
S20	450,0	225,0	1080,0	-	270,0	-	20
S25	450,0	225,0	1012,5	-	337,5	-	25

The consistency of fresh cement mortar specimens was determined by flow table according to the standard [114]. Compressive and bending strength test was performed for each specimen after 28 days with means of hydraulic press, the rate of load increases equalled 0,5±0,2 MPa/s according to the requirements presented in the standard EN 12390-3 [115].

2.3. Concrete preparation

Standard concrete specimens were made according to EN 206-1 [9]. The ingredients of were selected to achieve a consistency of class S3 (according to [116]). The mix composition was designed according to the formula of B. Kopycinski [117]:

$$c + \dot{z} + p + w = 1, p = p_z(1 - \dot{z}), \dot{z} = \frac{1 - j_{\dot{z}}}{m_{\dot{z}}}, p_z = \frac{1 - j_p}{m_p}, \frac{c}{w} = \frac{f_{cm} + 0{,}5 \cdot A_1}{A_1 \cdot \rho_c} \qquad (2.1)$$

c – cement$[-]$, w - water$[-]$, ż - gravel $[-]$, p - sand$[-]$,

f_{cm} - average compressive strength of concrete$[MPa]$,

A_1 - coefficient depending on cement strength$[-]$,

ρ_c - cement density$\left[\frac{g}{cm^3}\right]$, $j_{\dot{z}}$ - voids of gravel$[-]$, j_p - voids of sand$[-]$,

$m_{\dot{z}}$; m_p - swelling index of gravel and sand dependent on grain size$[-]$.

At first fine and coarse aggregate was placed and distributed evenly in the mixer. Next, cement was added and then water was poured slowly. To form specimens, plastic moulds were used with dimensions 100x100x100 mm. Three specimens of each concrete mix were prepared for compressive strength testing. The fresh specimens were left for 24 hours in increased air humidity, after which they were unmoulded and submerged in tap water until compressive strength test.

This part of the experiment involved just two mix designs – the reference concrete and the one modified by replacing 20% (mass) of coarse aggregate with MWI-BS (Tab. 8). MWI-BS that was added had a fraction 8-20 mm. This fraction was used to investigate more precisely the influence of this specific MWI-BS fraction on the properties of concrete. The component proportions are presented in Table 8. The materials used included blastfurnace cement (CEM III according to EN-197-1 [88]), tap water, river sand and gravel with grain size 8-16 mm. Here, MWI-BS was treated as pure aggregate, the w/b ratio in the mix equals 0.59.

Table 8. Mix design of concrete specimens. MWI-BS – municipal waste incineration bottom slag

Dosage of ingredients $\left[\frac{kg}{m^3}\right]$						Substitution level [%]
Specimen	Cement CEM III	Water	Sand 0-2 mm	Gravel 8-16 mm	MWI-BS 8-20 mm	
C0	340	200	560	1275	-	-
C20	340	200	560	1020	255	20

The consistency of fresh concrete mix was tested by slump test according to EN 12350-2 [116]. The compressive strength test was performed after 7, 28, and 56 days, according to EN-206 [9], with means of hydraulic press, the rate of load increase equalled 0,5±0,2 MPa/s according to the requirements presented in the standard EN 12390-3 [115].

3. RESULTS

3.1. Mortars with MWI-FA

Table 9 presents the strength and consistency test results for mortars with the addition of MWI-FA. As observed, replacing part of the cement with MWI-FA in the mortar composition causes a decrease in strength compared to the strength of the standard mortar. This decrease is more notable the higher the MWI-FA content in the binder composition. Replacing 25% of the cement with MWI-FA results in a 49% decrease in strength, equivalent to a 51% activity index according to EN 450-1 [42]. Based on consistency tests, the flow of the mortars increases noticeably as the content of MWI-FA increases.

3.2. Mortars with MWI-BS

Analysing the results of the tests in Table 9, it can be observed that partial replacement of fine aggregate with MWI-BS does not notably affect the compressive or bending strength of the mortars with a maximum replacement rate of sand by slag of up to 20%. Mortars containing 25% slag replacement exhibit an average compressive strength that is 4% lower compared to the reference mortar. This result can be considered minor in view of the uncertainty. The consistency tests suggest a detrimental effect of slag addition. The larger the substitution of sand by MWI-BS, the smaller the flow of fresh mor-tar.

Table 9. Compressive strength of mortars with the addition of MWI-FA and MWI-BS as a substitute for cement and fine aggregate

Specimen	Consistency [mm]	Substitution level [%]:		Compressive strength after 28 days [MPa]		Bending strength after 28 days [MPa]		Percentage change of compressive strength [%]
		MWI -FA	MWI -BS	Result	Sample Stand. dev.	Result	Sample Stand. dev.	
NA	180,0	-	-	38,9	0,9	10,16	0,35	-
A5	183,5	5	-	25,4	1,3	8,35	0,07	-34,7
A10	187,0	10	-	25,7	0,7	7,52	0,57	-33,9
A15	186,5	15	-	24,6	1,4	6,11	0,65	-36,8
A20	197,5	20	-	22,2	0,9	6,20	0,05	-42,9
A25	194,0	25	-	19,9	0,2	5,20	0,04	-48,8
NS	145,0	-	-	31,0	0,8	5,88	0,08	-
S5	141,5	-	5	25,2	1,7	6,40	0,20	-18,7
S10	139,0	-	10	30,4	0,3	6,56	0,23	-1,9
S15	131,5	-	15	31,3	0,6	6,48	0,39	1,0
S20	122,5	-	20	31,1	0,7	6,00	0,10	0,3
S25	120,5	-	25	29,7	1,2	5,80	0,26	-4,2



a) reference specimen b) specimen with MWI-FA

Fig. 5. Image of the fracture surface of a cement mortar specimen without the addition of MWI-FA-NA (a) and with the addition of MWI-FA-A25 (b)

Figure 5 presents the fracture surface of the reference specimen (a) and the specimen with the addition of MWI-FA (b). The warped cracking surface of the specimen (b) (as opposed to a flat one in specimen (a) may indicate a heterogeneity of material strength, resulting in breaking along the weak sections.

3.3. Concrete with MWI-BS

The results presented in Table 10 reveal that concrete with 20% of coarse aggregate replaced with MWI-BS shows a slower increase in compressive strength relative to the reference concrete samples during 56 days of curing. For example, the compressive strength of modified concrete after 56 days is similar to that of plain concrete after 28 days. The impact of slag addition on consistency (in the slump test) is a minor shift towards more slump.

Table 10. Compressive strength of concrete with the addition of MWI-BS as a substitute for coarse aggregate (20% replacement)

Date for concrete compressive strength test	Compressive strength [MPa]						Percentage change of compressive strength [%]
	Reference concrete	Sample Stand dev.	Consistency [mm]	Concrete with MWI-BS	Sample Stand. dev.	Consistency [mm]	
7 days	22,85	0,04	150 (S3)	21,19	0,47	170(S4)	-7,1
28 days	35,10	0,59		32,51	0,45		-7,4
56 days	39,64	0,11		35,87	0,81		-9,5

4. DISCUSSION

The presented test results (Fig. 6-9), regarding the potential use of MWI-FA and MWI-BS in both mortars and concrete, indicate the conditional possibility of using these waste materials in these composites, but not without challenges (especially regarding MWI-FA). The results were estimated as the arithmetic mean of independent measurements. The expanded uncertainty of the mean was calculated as $U = t * \left(\frac{s}{n}\right)^{\frac{1}{2}}$, where s denotes the sample standard deviation (shown in Table 9 an 10), t - the coverage factor from Student's t-distribution corresponding to a two-sided 95% confidence level, and n - number of measurements.

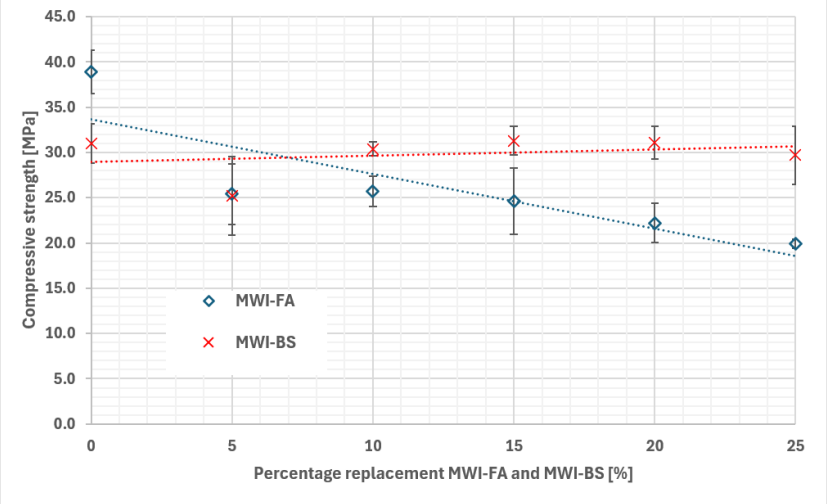

Fig. 6. Compressive strength of mortars after 28 days of curing, depending on the amount of MWI-FA and MWI-BS as % of replaced cement and sand (respectively)

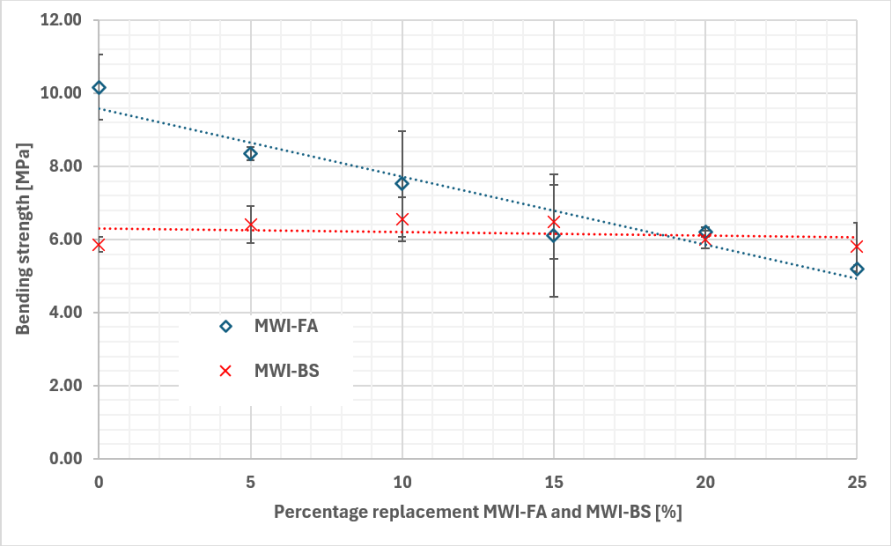

Fig. 7. Bending strength of mortars after 28 days of curing, depending on the amount of MWI-FA and MWI-BS as % of replaced cement and sand (respectively)

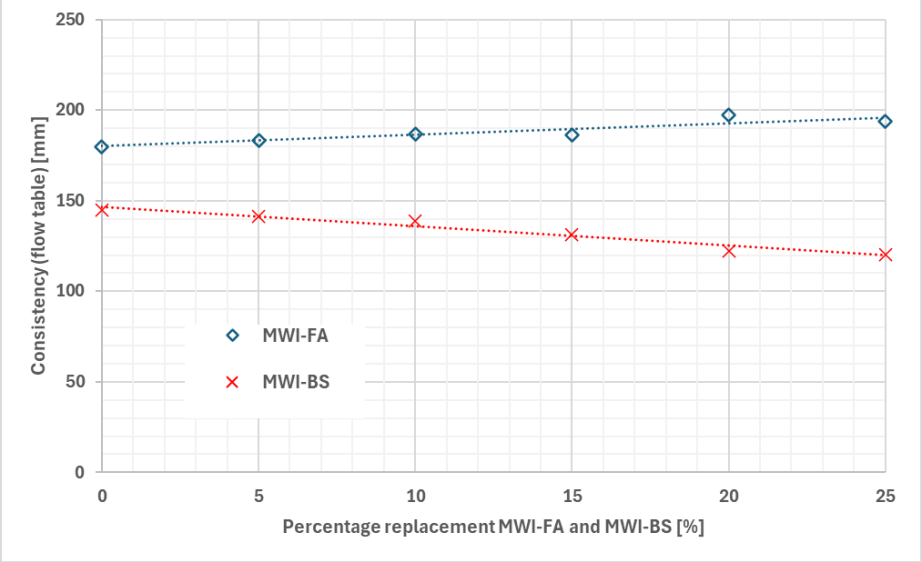

Fig. 8. Consistency (flow table) of fresh mortar depending on the amount of MWI-FA and MWI-BS as % of replaced cement and sand (respectively)

The replacement of 20% coarse aggregate by MWI-BS in concrete yields higher workability but causes a slight decrease in strength. This indicates some risks involved in this process, potentially related to the lowered quality and durability of the modified composite. The strength ratio of the modified vs. unmodified concrete after 7/28/56 days is 93/93/90%, which shows the necessity to investigate longer curing durations (also see Fig. 9).

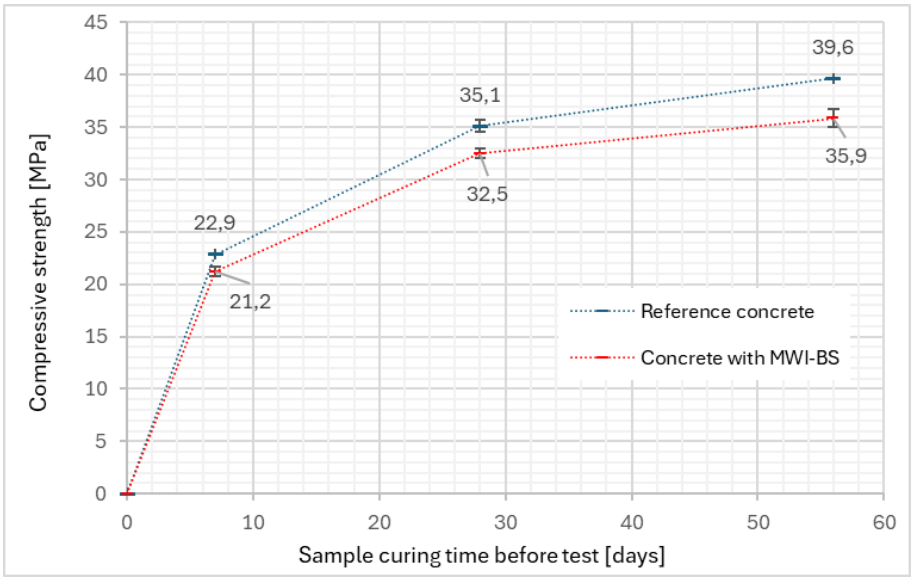

Fig. 9. Compressive strength development in time – reference concrete vs concrete with MWI-BS

According to the presented results, MWI-FA is a poor substitute for cement if no extra treatment is assumed. Even the smallest substitution of 5% of cement with MWI-FA is severely detrimental to the strength of mortar after 28 days, indicating poor binding properties and possibly negative interference with the cement binding process (Fig. 6 and 7). The desirable, relatively low water demand and higher flow in consistency tests do not matter much if one cannot solve this major problem. The results exemplify the risks due to the variability of properties in the population of MWI fly ashes. The general remark stating that they exhibit "good chemical and physical quality for the production of concrete mixtures" (found in [118]) or any general description regarding the entire population of MWI ashes is questionable. Individual analyses, such as this one, including, e.g., chemical composition and mechanical tests, seem necessary. The results also support the claim that the material is difficult to effectively utilize without some kind of pre-treatment [25]. The observed notable drop in mortar strength may be related to the properties of the MWI-FA itself, e.g., absorption of water necessary for cement binding, but is most likely a result of its chemical composition and reactivity. One hypothesis is that the causes of the observed result include very low silica and the total SiO_2 + Al_2O_3 + Fe_2O_3 content, especially compared to conventional fly ash used in concrete. Reactive silica is a primary reason for latent hydraulic properties of the latter, as it reacts with portlandite over time to form the C-S-H phase [119]. Additionally, the chloride content of MWI-FA is two orders of magnitude greater than what is expected from conventional fly ash. It has been established that it plays a multi-factor role in cement hydration [120] and is a notable risk for potential steel reinforcement due to corrosion. Another point worth mentioning is the elevated SO_3 content in MWI-FA, which is known to regulate the setting time (similar to Cl). Excessive sulfate contents also create the risk of delayed ettringite formation (DEF), reducing strength and durability [121]. It makes sense, however, to investigate the possible similarity between MWI-FA and coal combustion calcareous fly ash based on the elevated CaO and SO_3 content (although the low SiO_2 remains problematic). The calcareous fly ash can exhibit beneficial hydraulic and pozzolanic properties [122]. Based on the results obtained, the main advantage of using the tested MWI-FA in concrete might be the immobilization of pollutants.

The 0-2 fraction of MWI-BS is a potentially useful substitute for fine aggregate in mortars. Its addition impacts consistency to a small extent (decreases flow, Fig. 8), which might be caused, among

others, by the irregular particle shapes (Fig. 2c). The slag particles do not undergo a similar grinding process to those of, e.g., sand carried by rivers; hence, they are less spherical. On the other hand, mortar strength does not seem to be affected even for higher slag contents (25%), both compressive and bending (Figs 6 and 7). If the spread of results is ignored, one could assume a nonlinear relationship between the strength and dosage of MWI-BS (especially in bending strength, Fig. 7), with an optimum close to 15% sand replacement by MWI-BS. Based on that and the chemical composition (Table 6), it is advisable to investigate the reactivity potential of MWI-BS as a binder, not treating it as an inert aggregate, because of the high SiO_2, Al_2O_3, and Fe_2O_3 content relative to MWI-FA. However, tests of ground MWI-BS from the same plant as a 30% cement substitute in mortar specimens showed a drop in strength of even 60% [123]. This indicates fundamental differences between the two utilization approaches and may suggest that grinding alone is questionable as pre-treatment.

5. CONCLUSIONS

This paper can serve as a practical example for preliminary analyses of the feasibility of using MWI by-products in cement composites, including an overview of the variability in the chemical compositions and discussing their relationship to the mechanical properties of hardened specimens.

The main conclusions are as follows:

1. The chemical composition of waste incineration by-products varies greatly (based on a broad analysis of available papers). It notably differs from the composition of the combustion by-products traditionally used in the concrete industry (e.g., siliceous/calcareous fly ash, blast furnace slag).
2. The oxide composition of MWI-FA is problematic due to low SiO_2, Al_2O_3, and Fe_2O_3, as well as high Cl and SO_3 contents (relative to what is expected from other concrete additives). Its basic physical properties are within the norm for concrete fly ash (grain density, specific surface area, water demand, fineness).
3. Based on oxide contents only, MWI-BS is a much better fit in cement-based composites compared to MWI-FA. Its main constituents include SiO_2, CaO, Al_2O_3 and Fe_2O_3, with SiO_2 clearly dominating (> 40%).
4. The replacement of cement by MWI-FA in mortar specimens results in increased flow and a notable decrease in bending and compressive strength after 28 days, even with a 5% substitution (an 18% and 35% drop, respectively).
5. The replacement of sand by MWI-BS (separated 0-2 mm fraction) in mortar specimens decreases flow but does not noticeably impact the strength after 28 days, even for a maximum tested content of 25%. It is possible that slag is not inert and thus acts as a binder to some extent, which should be considered for the mix design.
6. The replacement of 20% of coarse aggregate in concrete by MWI-BS (8-20 mm) results in a slightly higher workability and a reduction in compressive strength of about 10% after 7, 28, and 56 days (a consistently lower rate of strength gain).

The presented research shows that while applying MWI-FA may be a notable challenge, MWI-BS is a promising substitute for aggregates. The chemical composition and mechanical properties indicate that the potential use of slag as a binder should also be investigated. It should be noted that the investigated materials were obtained from a single municipal waste incineration (MWI) plant. The results presented in this study should not be generalized to all types of MWI-FA and MWI-BS generated by similar processes. Further studies involving materials from different incineration plants are therefore necessary to assess the broader applicability of the findings. The slightly slower strength gain is specifically not an issue in the case of mass concrete, e.g., in hydraulic structures, where high early

strength and quick hardening are not required. However, further studies on heat evolution, thermal behavior, shrinkage, permeability, and long-term durability are necessary to determine whether concrete incorporating MWI-FA and MWI-BS is suitable for use in hydraulic structures. Alternatively, one can consider the addition of MWI-FA and/or MWI-BS in situations where lowering the built-in carbon footprint is deemed more important than the decrease in the material properties. Further study may investigate, i.e., longer curing periods (90-365 days) and durability in aggressive environments. As part of the planned research, the leaching of heavy metals from concrete incorporating MWI-FA and MWI-BS will also be investigated. Furthermore, the radioactivity of samples containing the by-products of municipal waste incineration will be determined.

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