



Utilization of municipal solid waste incineration bottom ash and cement kiln bypass dust in modified cement mortars

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Abstract

The study evaluated the feasibility of using two industrial by-products: municipal solid waste incineration bottom ash (MSWI-BA) and cement kiln bypass dust (CBPD), as partial replacements of conventional constituents in cement mortars. MSWI-BA was used as a replacement for standard sand (5, 10, 15, and 20%, introducing a volumetric adjustment to the weight of the norm sand), while CBPD was used as a replacement for cement (2.5 and 5.0%); both materials were introduced either individually or in combination. The flow of fresh mortars, water absorption and dry bulk density, flexural and compressive strengths at 7 and 28 days, and resistance to freeze - thaw cycling (25 cycles) were investigated. The incorporation of the by-products reduced consistency (from 2.2 to 30.6%) and increased water absorption by 11.1 - 18.5% relative to the reference mix. All modified series showed lower mechanical strength than the reference mortar; among the mixes incorporating a single by-product, the highest 28-day compressive strength was obtained for 5% MSWI-BA (≈ 44 MPa), whereas the combined mix MIX 5/2.5 reached 37.1 MPa. After freeze - thaw cycling, the modified mortars exhibited lower mass loss (0.07 - 0.36%) than the reference series (0.82%). The results suggest that incorporating MSWI-BA and CBPD at low substitution levels can be a practical step towards more sustainable, circular-economy-oriented mortar production, combining reduced landfilling of waste materials with a lower demand for virgin raw materials.

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1. Introduction

One of the most widely used materials in the construction sector is cement. In 2024, global cement production reached 4.2 billion metric tons and was similar to 2023 (Statista, 2026). Cement production affects the environment not only through high CO₂ emissions but also due to the generation of by-products, including dust from the rotary kiln dedusting system (cement kiln dust, CKD) and, where applied, dust from the bypass system (cement bypass dust, CBPD). Their physical and chemical properties depend on raw materials, fuel type, and production technology. CKD is generated in all cement plants, whereas CBPD occurs only when a bypass system is implemented (e.g., in cement production using alternative fuels) to reduce chlorine and alkali levels (Al-Jabri et al., 2002, 2006). Cement dust waste is classified in the 10 13 06 waste group (Directive EU 2018/851). Compared with CKD, CBPD contains substantially higher chlorine, K₂O, and SO₃, which may limit its utilisation. By-products may account for 0.25-2% of

clinker mass depending on technology and inputs; in practice, CBPD is approximately 2% of clinker weight on average (Hanein et al., 2020). Consequently, the utilisation of cement-production dusts is increasingly considered. CKD is currently applied, for example, in cement and glass production (Aydin et al., 2019), road and highway construction and soil stabilisation (Keerthi et al., 2013; Yoobanpot et al., 2017; Peethamparan et al., 2008; Buczynski & Iwanski, 2017), and it has also been investigated for building-material production in laboratory studies (Abdel-Gawwad et al., 2019; Udoeyo & Hye, 2002). The literature also reports studies on the application of CBPD in the production of construction materials (Borek et al., 2023; Ahmed et al., 2023; Nocun-Wczelik & Stolarska, 2019; Wojtacha-Rychter et al., 2022; Owsiak et al., 2020). Al-Aghbari et al. (2009) demonstrated that the highly alkaline nature of CBPD enables its use as an activator for binder systems applied to soil stabilisation in geotechnical engineering. Borek et al. (2023) showed that CBPD can fully replace the binder in autoclaved calcium - silicate products, such as bricks



composed of 92% sand and 8% quicklime, resulting in a 5% increase in compressive strength and a 5.3% reduction in bulk density. Tkaczewska (2019) reported that small additions of CBPD (0.05–5.00% of binder mass), provided that the free CaO content is below 10%, can enhance the compressive strength of autoclaved materials. Therefore, within a circular-economy framework, it is worth considering CBPD as a secondary raw material for building materials, used either independently or synergistically with other waste streams.

In the production of concrete and cement mortars, numerous studies have demonstrated the feasibility of using waste-derived materials as partial substitutes for natural aggregates, including ceramic wastes (Ray et al., 2021; Ulewicz & Halbiniak, 2016), glass cullet (Adhikary et al., 2021), polymer wastes (Rashad, 2016; Sharma & Bansal, 2016; Tavakoli et al., 2018; Ulewicz et al., 2024; Bassam et al., 2020; Helbrych, 2019; Czajkowska et al., 2023; Pietrzak & Ulewicz, 2023; Ulewicz & Pietrzak, 2021), and hemp fibre (Šadzevičius et al., 2023). Recycled aggregates obtained from cement mortars and concrete, as well as slag, have also been successfully applied for this purpose (Kalinowska-Wichrowska et al., 2022; Collivignarelli et al., 2020; Ebubekir et al., 2020). The mechanical performance of mortars and concretes is likewise not adversely affected when approximately 20% of the aggregate is replaced with materials such as biomass fly ash and silica dust (Ulewicz & Jura, 2021; Popławski, 2020) or with wastes from the steel industry (Lis & Nowacki, 2022; Ulewicz et al., 2024a). Similarly, small additions of ash originating from the incineration of municipal solid waste and sewage sludge (up to approximately 20%) can serve as substitutes for natural aggregates without deteriorating mechanical properties (Saikia et al., 2015; Kalak et al., 2023; Pietrzak & Ulewicz, 2025). Currently, increasing attention is being paid to the management of waste generated during the thermal treatment of municipal waste, because the thermal treatment process is becoming an increasingly important method of managing such waste. In 2023, the amount of municipal waste generated in the European Union was 511 kg per capita (Eurostat, 2025), and the reported treatment structure included recycling (48%), landfilling (22.5%), and incineration (25.2%). This situation means that waste streams originating from thermal conversion are produced on a large scale, which highlights the need to identify cost effective, safe, and resource efficient methods for managing such waste. Municipal solid waste incineration bottom ash (MSWI-BA) is classified under waste code 19 01 12 in the European Waste Catalogue (2000/532/EC).

Recent literature reports highlight the potential for using an MSWI-FA/MSWI-SW mixture (fly ash and solid waste from flue gas treatment, i.e., by-products of municipal solid waste incineration plants) as a secondary raw material in binder-based material technologies, as an alternative to a portion of conventional constituents (Pietrzak et al., 2025). Moreover, several studies have investigated the use of MSWI-BA as a component of concrete or mortars, mainly as an aggregate to improve mechanical performance and durability (Kalak et al., 2023; Bawab et al., 2021; Saikia et al., 2015; Malaiškienė et al., 2023). Properly processed MSWI-BA can partially replace natural aggregates, reducing the consumption of primary raw

materials and limiting the landfilling of this waste. In addition, cement kiln bypass dust (CBPD), which has been studied as a separate by-product of the cement industry, may also be used in cement-based materials. However, these two waste streams have been investigated mainly separately, and the literature lacks reports on their simultaneous use in cementitious composites. Therefore, the present study analyses cement mortars modified with MSWI-BA and CBPD, applied both individually and in combination in various proportions, in order to assess their effective utilisation in the production of cement mortars, consistent with a circular-economy approach.

2. Materials

The following materials were used to test cement mortars: Portland cement CEM I 42.5R (Table 1), meeting the requirements of the PN-EN 197-1 standard, standard quartz sand (Kwarcmix) of 0-2 mm fraction complying with the PN-EN 196-1 standard, water from the Czeszochowa water mains (meeting the PN-EN 1008:2004 standard).

Table 1. Technical parameters of Portland cement CEM I 42.5R

Technical parameters	Test results	Standard requirements PN-EN 197-1
Specific surface area according to Blaine, [cm ² /g]	4124.00	-
Beginning of binding, [min.]	184.00	≥ 60
End of binding, [min.]	242.00	-
Volume change, [mm]	1.00	≤ 10
Compressive strength – early (after 2 days), [MPa]	30.10	≥ 20.0
Compressive strength – standard (after 28 days), [MPa]	60.20	≥ 42.5 ≤ 62.5
Contents SO ₃ , [%]	2.95	≤ 4.0
Chloride content, [%]	0.09	≤ 0.1
Soluble content Cr(VI), [ppm]	0.18	≤ 2.0
Insoluble residue, [%]	0.57	≤ 5.0
Loss on ignition, [%]	3.33	≤ 5.0

The average content of nitrates in the water was 37.0 mg/dm³, chlorides 31.5 mg/dm³ and sulphates 53.8 mg/dm³. The following types of waste were used in the study: bottom ash (MSWI-BA) from the incineration of municipal waste (waste code 19 01 12) and cement bypass dust (CBPD) from a cement kiln bypass system (waste code 10 13 06). MSWI-BA was collected from the Thermal Waste Treatment Plant in Krakow, Poland. Cement kiln bypass dust (CBPD) was obtained from the local market (Silesian Voivodeship) in Poland. The chemical composition of the waste used in the study was determined using the fluorescence spectroscope (SPECTRO, Poland) and is presented in Table 2. The determined specific density of the used waste, according to PN-EN 196-6, was 2.32 g/cm³ for the once-ground bottom ash and 2.63 g/cm³ for the dust. The bottom ash was ground once using the M400

impact mill (Zielona Góra, Poland) to a 0-2 mm fraction (Figure 1).



Fig. 1. Waste used in the study: a) bottom ash obtained from the incinerator, ground once in the mill (MSWI-BA); b) CBPD

Table 2. Chemical composition of the used waste

Chemical composition, [% (m/m)]	Waste	
	MSWI-BA	CBPD
CaO	16.74	29.02
SiO ₂	17.35	5.46
SO ₃	5.17	9.35
Al ₂ O ₃	12.04	2.41
Cl ⁻	1.24	9.52
MgO	18.83	1.60
Fe ₂ O ₃	2.84	1.08
P ₂ O ₅	1.19	-
K ₂ O	0.60	14.71
Other	24.00	26.85

TGA-DTA thermal analysis was performed of the waste used in the study, with the use of the SDT 650 thermal analyser (TA Instruments, USA). Thermograms were recorded in a synthetic air atmosphere at a heating rate of 10°C/min to 1000°C. The results of thermogravimetry (TG), differential thermogravimetry (DTG) and differential thermal analysis (DTA) are shown in Figures 2 and 3.

Based on the obtained TG/DTA curves for bottom ash, a slight weight loss was observed in the range of 0-400°C, which may be related to the loss of physical and chemically bound water. That temperature range (approx. 300-400°C) may also cause the decomposition of magnesium carbonate (MgCO₃), which, according to the literature data, decomposes in the range of 170-330°C. However, no endothermic peak was observed on the DTA curve to confirm the carbonate decomposition reaction. In contrast, an endothermic peak was observed on the DTA curve in the range of 600-800°C, associated with the decomposition of calcium carbonate, which coincides with the mass loss on the TG curve in that temperature range. Based on the literature data, calcium carbonate decomposition is observed in the range of 550-825°C. In the TG curve, mass loss was observed in three temperature ranges, approx. 300-400°C, 500-700°C and above 800°C. The first of the above ranges coincides with the endothermic peak on the DTA curve. This is related to water loss. Dust is a highly hygroscopic material. The 500-700°C temperature range is related to the decomposition of calcium carbonate and the third range is related to mass loss, which is not represented on the DTA curve (no peak), suggesting the evaporation or thermal decomposition of potassium

compounds, which can occur in the form of salts (chlorides, carbonates and sulphates).

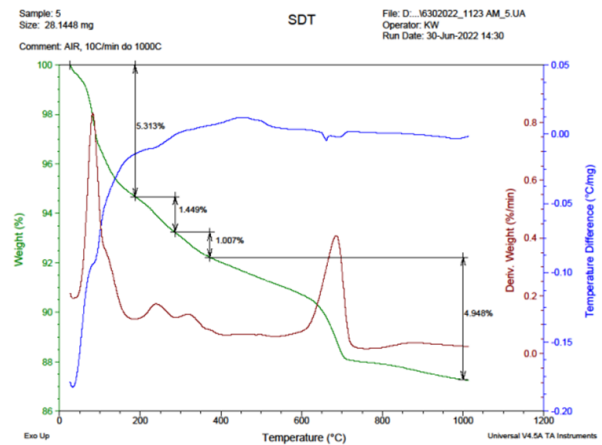


Fig. 2. TGA-DTA thermogram for MSWI-BA

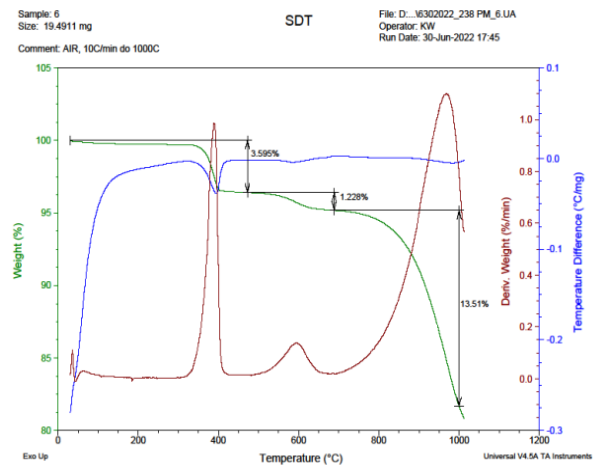


Fig. 3. TGA-DTA thermogram for CBPD

3. Methods

A control standard mortar and 14 series of mortars modified with the "MSWI-BA" and/or "CBPD" waste were prepared. Waste MSWI-BA was added in the amount of 5, 10, 15 and 20% of the cement mass as a sand substitute (introducing a volumetric adjustment to the weight of the norm sand), and CBPD was used as a cement replacement in the amount of 2.5 and 5.0% of the cement mass. The waste material was dosed into the mortars separately and as a mixture (in different proportions). The composition of the designed mortars is shown in Table 3.

Compressive and flexural strength tests were conducted using the MMC-3742.FPR testing machine, in accordance with the EN 196-1 standard, employing beams with dimensions of 40x40x160 mm. Tests for compressive and flexural strength were performed after 7 and 28 days of sample curing. For the flexural strength test, 3 beams were tested by increasing the load at a rate of 50 ± 10 N/s until failure occurred. Compressive strength tests were carried out on 6 half-beams, with the load uniformly increased at a rate of 2400 ± 200 N/s.

Table 3. The composition of the designed mortars

Mortar series	Ingredients				
	Cement	Sand	Water	MSWI-BA	CBPD
	[g]	[g]	[cm ³]	[g]	[g]
MS	450	1350.0	225	-	-
MSWI-BA 5	450	1324.3	225	22.5	-
MSWI-BA 10	450	1298.6	225	45.0	-
MSWI-BA 15	450	1272.9	225	67.5	-
MSWI-BA 20	450	1247.3	225	90.0	-
CBPD 2.5	428.7	1350.0	225	-	11.25
CBPD 5	427.5	1350.0	225	-	22.50
MIX 5/2.5	438.75	1324.94	225	21.94	11.25
MIX 5/5	427.50	1325.58	225	21.38	22.50
MIX 10/2.5	438.75	1298.60	225	43.90	11.25
MIX 10/5	427.50	1298.60	225	42.75	22.50
MIX 15/2.5	438.75	1274.83	225	65.81	11.25
MIX 15/5	427.50	1276.75	225	64.13	22.50
MIX 20/2.5	438.75	1247.30	225	87.70	11.25
MIX 20/5	427.50	1247.30	225	87.70	22.50

MIX = MSWI-BA/CBPD

The absorption of mortars was tested using the soaking method in accordance with PN-B-04500:1985. The test was conducted after 28 days of sample curing. For the test, three beams with dimensions of 40 mm × 40 mm × 160 mm were prepared from each mortar type.

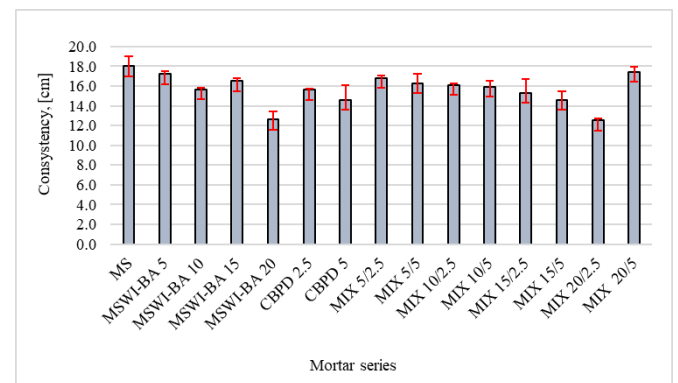
Freeze-thaw resistance test, performed in accordance with PN-B-04500:1985, using the Toropol K-010 chamber (Toropol, Warsaw, Poland). For the test, 12 beams with dimensions of 40 mm×40 mm×160 mm were prepared using each type of mortar. The samples were subjected to 25 freeze-thaw cycles and the remaining samples were left as reference. Consistency of fresh cement mortar testing using a flow table, following the PN-EN 1015-3 standard. Bulk density of cement mortar in the dry state testing, in accordance with PN-EN 1015-6:2000.

4. Results and discussion

4.1. Effect of MSWI-BA and CBPD on fresh mortar consistency

The consistency of fresh mortars was determined using the flow table method (Figure 4). The reference mortar (MS) reached a flow of 18.0 cm, whereas the waste-modified mixes exhibited lower values, ranging from 12.5 to 17.6 cm. The largest reduction ($\approx 30\%$ relative to the reference) was observed for the 20% MSWI-BA as a sand replacement and for

the series MIX 20/2.5 mix (combined MSWI-BA and CBPD). In contrast, the series MSWI-BA 5 and MIX 20/5 mixes showed flow values comparable to the reference, while the remaining mixes exhibited an average decrease of approximately 14%. These results indicate that the incorporation of MSWI-BA and especially CBPD reduces mortar consistency at a constant water dosage, implying an increased water demand (or the need for plasticizing admixtures) to maintain a standard consistency. A comparable decrease in flow ($\approx 22\%$) following the addition of 10% CBPD was reported by Didamony et al. (1992). The observed reduction in consistency can be attributed primarily to the higher fineness of CBPD compared with Portland cement, which increases the specific surface area and, consequently, the water demand of the binder system.

**Fig. 4.** Consistency of the individual cement mortar series

4.2. Physical properties of hardened cement mortars modified with waste

Water absorption of hardened mortars was determined after 28 days (Figure 5). The reference samples (MS) exhibited a water absorption of 8.1%. All waste modified mortars showed higher values (ranging from 9.0 to 9.6%), which corresponds to an increase of approximately 11.0 - 18.5% relative to the reference. Mixes incorporating a single waste stream (only MSWI-BA or CBPD) reached 9.0 - 9.4%, whereas the combined MSWI-BA/CBPD mixes exhibited slightly higher absorption (9.2 - 9.6%). The increased absorption indicates a higher open porosity and/or more pronounced capillary network in the modified mortars, may contribute to the observed reductions in mechanical strength.

The next stage of the study was to determine the dry bulk density for the cement mortars (Figure 6) in accordance with PN-EN 1015-6. The reference mortar (MS) exhibited a dry bulk density of 2169 kg/m³. The highest value was obtained for the series CBPD 2.5 (2176 kg/m³), indicating that a low-level cement replacement with CBPD did not reduce density. In contrast, mortars containing MSWI-BA showed a decrease in dry bulk density relative to the reference, and the lowest value was recorded for the MIX 20/2.5 series (2000 kg/m³), i.e., approximately 7.8% lower than the MS mortar. For all the series MIX, the dry bulk density was generally lower than that of the reference mortar, which may indicate a higher open porosity and/or less effective particle packing. This trend is

consistent with the increased water absorption observed for waste-modified mortars.

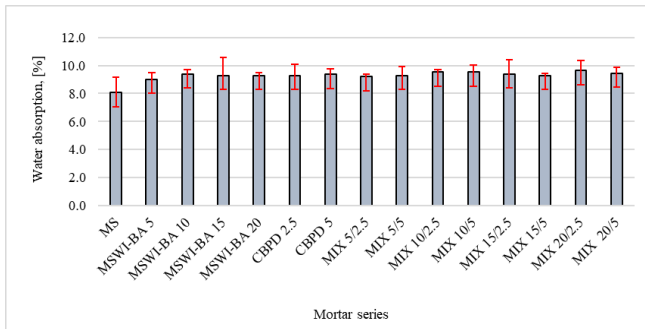


Fig. 5. Absorption of individual cement mortar series

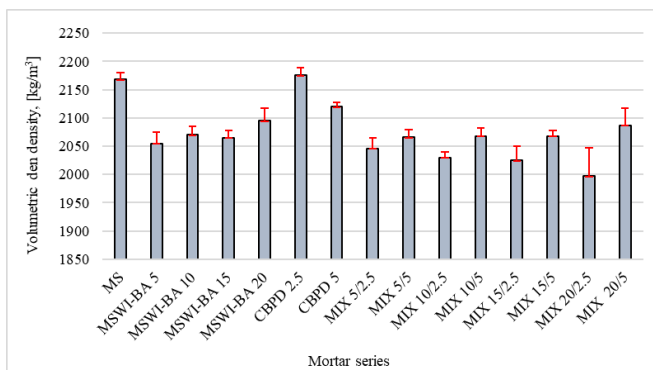


Fig. 6. Bulk density of the individual cement mortar series

4.3. Mechanical performance of mortars incorporating post-production waste

The flexural strength of the mortars was determined after 7 and 28 days of curing (Figure 7). The reference mortar (MS) achieved 7.5 MPa after 7 days and increased to 8.9 MPa after 28 days. All waste-modified mortars exhibited lower flexural strength at both ages. After 7 days, the largest reduction (34.7% relative to MS) was recorded for the MIX 20/2.5 series, i.e., the mortar containing 20% ground MSWI-BA as a sand replacement and 2.5% CBPD as a cement replacement. The remaining modified series also showed a noticeable decrease in early flexural strength (typically about 27% compared with the reference). After 28 days, the modified mortars remained weaker than the control, with the reduction ranging from 24.7% to 36%. A comparable trend was reported by Didamony et al. (1992), who observed that replacing cement with 10% CBPD reduced flexural strength by approximately 30% compared with the control mortar. Overall, the decrease in flexural strength is consistent with the reduced consistency (Figure 4) and the increased absorption (Figure 5), suggesting that the waste additions may promote a more porous and less effectively packed microstructure.

Subsequently, compressive strength was evaluated after 7 and 28 days of curing (Figure 8). After 7 days of curing, the reference mortar (MS) reached an average compressive strength of 38.9 MPa, increasing to 51.2 MPa after 28 days. All waste-modified mortars exhibited lower compressive strength at both ages. After 7 days, the reduction relative to MS ranged from 24.4% to 42.9%. After 28 days, the decrease ranged from 13.7% to 57.2% compared with the reference. Mortars modified with MSWI-BA (5 - 20% sand replacement)

achieved 26.7 - 34.0 MPa at 7 days and 36.5 - 44.2 MPa at 28 days, whereas mortars containing CBPD (2.5 - 5% cement replacement) and MSWI-BA/CBPD combinations showed 22.2 - 27.5 MPa at 7 days and 29.2 - 37.1 MPa at 28 days. Although strength increased with curing time, none of the modified mortars reached the strength of the control. The observed reduction in compressive strength is consistent with the reduced consistency (Figure 4), increased water absorption (Figure 5), and decreased dry bulk density (Figure 6), suggesting that the waste additions may promote a more porous and less effectively compacted microstructure. In addition, the chemical characteristics of CBPD (high CaO content) may influence hydration and microstructure development, which can further affect strength. Similarly, Al-Harthi et al. (2003) reported that compressive strength generally decreased with increasing bypass dust content; however, they noted that a 5% replacement level did not necessarily impair compressive strength

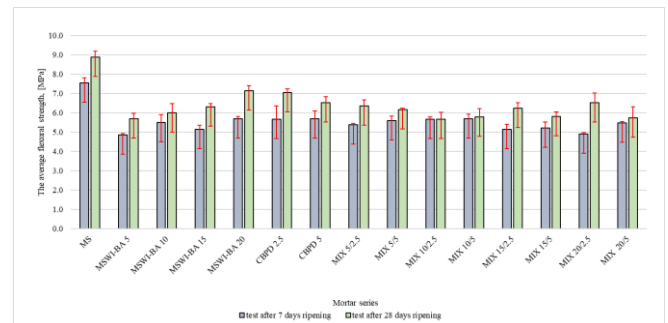


Fig. 7. Average flexural strength after 7 and 28 days of the sample maturation

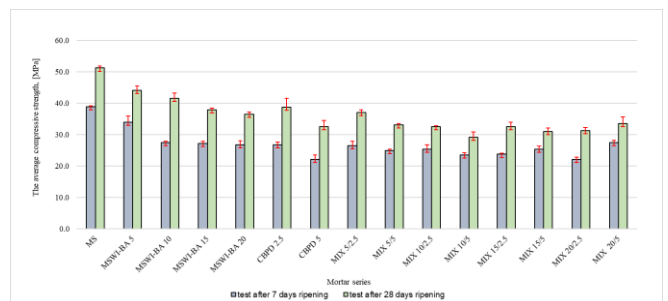


Fig. 8. Average compressive strength after 7 and 28 days of the sample maturation

4.4. Durability of waste modified mortars under freeze-thaw cycles

Following the freeze-thaw exposure, the reference mortar exhibited a decrease in compressive strength (-6.4%) and a pronounced reduction in flexural strength (-32.8%) compared with the companion specimens not subjected to cycling. Mortars containing MSWI-BA generally showed smaller losses of mechanical performance than the mortars modified solely with CBPD. In the series of mortar with CBPD, flexural strength decreased by more than 18% and compressive strength by more than 20%, indicating a less favourable response to cyclic freezing and thawing. Notably, the combined MSWI-BA/CBPD mixes exhibited a beneficial interaction:

the change in compressive strength after freeze - thaw ranged from (+1.3%) to (-16.2%), i.e., markedly lower than that observed for the series with only CBPD. In particular, MIX 5/2.5 showed a slight increase in compressive strength (+1.3%), whereas MIX 10/5 achieved the smallest change in flexural strength (-0.1%). In terms of surface scaling, the mass loss of the control mortar was 0.82%, while for all waste-modified mortars it remained substantially lower (0.07 - 0.36%), confirming improved resistance to material loss under the applied freeze - thaw regime. Overall, the results indicate that appropriate proportioning of MSWI-BA and CBPD can mitigate freeze - thaw-induced deterioration of mechanical properties while simultaneously reducing mass loss.

Table 4. Frost resistance test results for individual mortar series

Mortar series	Frost resistance		
	Average decrease (-) / increase (+) in compressive strength (%)	Average decrease (-) / increase (+) in flexural strength (%)	Average weight loss (%)
MS	(-) 6.4	(-) 32.8	0.82
MSWI-BA 5	(+) 1.4	(-) 7.8	0.15
MSWI-BA 10	(+) 3.3	(-) 8.3	0.18
MSWI-BA 15	(+) 2.1	(-) 6.7	0.28
MSWI-BA 20	(+) 0.7	(-) 7.5	0.15
CBPD 2.5	(-) 20.7	(-) 18.4	0.15
CBPD 5	(-) 21.0	(-) 19.2	0.05
MIX 5/2.5	(+) 1.3	(-) 5.4	0.36
MIX 5/5	(-) 14.3	(-) 5.2	0.19
MIX 10/2.5	(-) 15.4	(-) 15.2	0.24
MIX 10/5	(-) 16.2	(-) 0.1	0.28
MIX 15/2.5	(-) 3.5	(-) 9.5	0.34
MIX 15/5	(-) 5.8	(-) 10.1	0.17
MIX 20/2.5	(-) 6.2	(-) 11.3	0.07
MIX 20/5	(-) 4.9	(-) 6.4	0.21

4.5. Resource efficiency and environmental implications

In Table 5, a recommendation matrix covering all analysed mortar series was prepared to facilitate data interpretation and to identify the most promising material solutions. The matrix converts the experimental results into a simple qualitative rating (++ , + , - , --) based on predefined performance thresholds expressed as percentages of the reference mix, enabling rapid comparison of variants in terms of strength, water absorption, and freeze-thaw durability. This approach supports the selection of mixes that provide the best compromise between mechanical performance and durability, which is particularly important for the sustainable design of construction materials. As indicated by the matrix analysis, low replacement levels (especially MSWI-BA 5 and selected MIX combinations) offer the most balanced performance, whereas higher replacement levels and some MIX combinations are less favourable due to simultaneous reductions in strength- and durability-related

indicators. Accordingly, the MIX 5/2.5 variant was selected for the economic assessment because it maintains acceptable strength parameters relative to the reference mortar, even after frost resistance testing, while enabling partial substitution of both cement (by CBPD) and natural sand (by MSWI-BA).

Table 5. Recommendation matrix for all mortar series

Mortar series	Assessment of compressive strength	Assessment of flexural strength	Assessment of water absorption	Assessment of frost resistance
MSWI-BA 5	+	+	+	++
MSWI-BA 10	+	++	+	++
MSWI-BA 15	+	+	-	++
MSWI-BA 20	+	+	-	++
CBPD 2.5	+	+	+	--
CBPD 5	+	-	-	--
MIX 5/2.5	+	+	-	++
MIX 5/5	+	+	--	-
MIX 10/2.5	+	+	-	++
MIX 10/5	+	+	--	-
MIX 15/2.5	-	+	-	+
MIX 15/5	-	+	-	+
MIX 20/2.5	-	-	--	-
MIX 20/5	-	-	--	+

++ tested property > 90% of the reference value
 + tested property 70–90% of the reference value
 - tested property 50–70% of the reference value
 -- tested property < 50% of the reference value

To complement the selection of the MIX variant, the material savings, the embodied CO₂ reduction associated with cement substitution, and the gross economic effects of the selected variant were quantified. The use of cement kiln bypass dust (CBPD) and municipal solid waste incineration bottom ash (MSWI-BA) as partial replacements of conventional constituents in cement mortars may provide both economic and environmental benefits. The environmental benefits include reduced consumption of primary raw materials (especially natural aggregates), a potential decrease in CO₂ emissions due to a lower cement content (for which the literature reports an order of magnitude of approximately 0.66 - 0.82 kg CO₂ per kg of cement), and reduced landfilling of by-products (MSWI-BA).

Therefore, the potential material savings and gross economic effects were estimated for MIX 5/2.5 using the standard mortar proportion (cement:sand:water = 1:3:0.5 by mass) and local unit prices. For the standard mortar composition, even a low combined substitution level (2.5% CBPD as cement replacement and 5% MSWI-BA as sand replacement; MIX 5/2.5) results in measurable material and economic effects. Expressed per 1 tonne of mortar, this corresponds to replacing approximately 33.33 kg of natural sand and approximately 5.56 kg of cement. Assuming a CEM I cement price of 174-214 EUR/t, the cost saving associated with cement reduction alone is approximately 0.97 - 1.19 EUR per tonne of mortar. In addition, based on local washed sand prices (19.02 - 20.20 EUR/t) and the disposal (landfilling) fee for waste code 19 01 12 (5.89 EUR/t), the gross economic benefit related to sand

substitution and avoided disposal is approximately 0.83 - 0.78 EUR/t of mortar. Overall, this yields approximately 1.79 - 2.06 EUR of gross savings per 1 tonne of mortar, excluding the costs of material processing and quality control. Although these unit savings may appear modest, they could become more significant at production scale, depending on local market and operational conditions, and may support manufacturing aligned with the principles of sustainable development and the circular economy. However, the overall economic balance will depend on the full costs of waste processing (e.g., waste grinding, separation, and quality control) and associated logistics. Even where the net economic benefit is limited, the use of these by-products can still be justified by environmental gains, including reduced demand for virgin raw materials and decreased landfilling. Therefore, further efforts to optimise mortar production technologies incorporating these materials are justified, as the potential environmental benefits and long-term cost effectiveness of such solutions can be substantial.

5. Summary and conclusion

This study evaluated cement mortars modified with municipal solid waste incineration bottom ash (MSWI-BA) used as a partial replacement of standard sand (5 - 20%) and cement kiln bypass dust (CBPD) used as a partial replacement of cement (2.5 - 5%), introduced both individually and in combination. Based on the obtained results, the following conclusions can be drawn:

- both flexural and compressive strengths at 7 and 28 days were lower for all modified series compared with the reference mortar (MS). Among the waste-modified mortars, the highest 28-day compressive strength was achieved by MSWI-BA 5 (≈ 44 MPa), whereas CBPD 2.5 reached ≈ 39 MPa and the combined mix MIX 5/2.5 reached ≈ 37 MPa. These strength reductions are consistent with the trends observed for flow, water absorption, and dry bulk density.
- After 25 freeze - thaw cycles, the reference mortar showed a 6.4% loss in compressive strength and a 32.8% loss in flexural strength. Mortars with only CBPD exhibited more pronounced deterioration ($\approx 21\%$ loss in compressive strength), whereas mortars with MSWI-BA showed only minor changes in compressive strength. For the combined MSWI-BA/CBPD mixes, the compressive strength change ranged from +1.3% to -16.2%, while mass loss remained lower (0.07 - 0.36%) than for the reference series (0.82%), indicating limited surface scaling under the applied test conditions.

In summary, low replacement levels, particularly mix: MIX 5/2.5 (5% MSWI-BA and 2.5% CBPD) represent a practical compromise between mechanical performance and resistance to freeze - thaw cycling, while also supporting resource efficiency by partially reducing the consumption of virgin raw materials and valorising industrial by-products.

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