CTU Journal of Innovation and Sustainable Development
ISSN 2588-1418 | e-ISSN 2815-6412

DOI:10.22144/ctujoisd.2025.015

Evaluating municipal incinerated bottom ash as a sand replacement in foamed mortar: Effects of air foam and silica fume modification

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Article info.

Received 26 Dec 2023
Revised 8 Jan 2024
Accepted 8 Aug 2024

Keywords

Controlled low-strength mixtures (CLSM), foamed flowable mortar, municipal incinerated bottom ash, silica fume, waste utilization

ABSTRACT

This study presents an investigation into the feasibility of utilizing municipal incinerated bottom ash (MIBA) as a substitute for sand in foamed flowable mortar, with a specific focus on its applicability as flowable fill materials. Employing a mix design strategy with a fixed cement content of 180 kg/m³, the research systematically varies air foam (AF) percentages (15-20% by volume), MIBA replacement levels (0-40%), and introduces silica fume (SF) at a fixed rate of 12% by weight of fine aggregate. The study assesses flowability, setting times, and compressive strength under diverse curing conditions, including normal and H_2SO_4 (3%) curing. H_2SO_4 was employed to simulate harsh curing conditions in an acidic environment, providing insights into the mortar's behavior under more aggressive circumstances. Remarkably, at 40% bottom ash and 20% air foam, flowability experiences a significant 29.3% reduction, reaching 163.4 mm. Setting times prolong with increasing MIBA percentages, showing a substantial 64.7% increase at 40% replacement. Silica fume demonstrates its positive impact, revealing approximately 16% enhanced compressive strength in mixtures with air foam under normal curing conditions. Under H_2S0_4 curing, the mixture with 15% air foam and 12% silica fume experiences a slight reduction in compressive strength, showing a 13.7% decrease from 0.73 MPa under normal curing to 0.63 MPa. This research unveils the intricate interplay of variables, providing valuable insights for optimizing sustainable mortar formulations. Consequently, it contributes to environmentally conscious construction practices by bolstering the mechanical properties of the mortar.

1. INTRODUCTION

The synthesis of recent research on sustainable construction materials reveals significant quantitative findings. Hwang and Huynh (2017) experiments illustrate that higher ground granulated blast-furnace slag (GGBFS) content in alkali-activated controlled low-strength material (CLSM) reduces flowability and increases compressive strength. Huynh et al. (2022) quantified the positive effects of a 15% circulating fluidized bed combustion ash (CFA) ratio on compressive strength, dynamic moduli, ultrasonic pulse velocity, and reduced drying shrinkage in eco-cements, while a 30% CFA ratio leads to a 16% decrease in compressive strength. Al-Ejji et al. (2023) detailed percentage reductions (ranging from 70% to 90%) in heavy metal concentrations achieved through innovative surface treatment of municipal incinerated bottom ash

(MIBA). Fan et al. (2022, 2023) highlighted a more than 6-fold increase in the mechanical strength of eco-friendly mortar after 7 days of hydration, with fly ash proving more beneficial than GGBFS. Li et al. (2023) emphasize the ability of artificial lightweight aggregate concrete from municipal solid waste incinerator bottom ash (MSWIBA) to enhance the interfacial transition zone and reduce chloride ion penetration. Lynn et al. (2016) quantitatively analyzed the impact of MIBA on various properties, indicating reductions in consistency, compressive strength, and other parameters in mortars, with potential improvements in concrete performance. Zhang et al. (2021) provided quantitative data illustrating enhancements in early-age cement hydration and pozzolanic reactivity, as well as the superior strength of dry-cast concrete with 20% bottom ash from municipal solid waste incineration (MSWI-BA) replacement compared to ordinary Portland cement (OPC) reference samples. These quantitative insights form a robust foundation for comprehending the performance of waste by-products in construction applications.

In recent studies, scientists have delved into various aspects of concrete performance, investigating its physical characteristics, chemical makeup, mechanical properties, workability, and durability when incorporating municipal solid waste (MSW). Siddique highlights MSW's inherent pozzolanic activity, making it a promising addition to concrete (Siddique, 2010). Conventional concrete, with its hydration byproduct $Ca(OH)_2$, often faces challenges like water solubility and reduced strength, affecting overall quality. However, MSW's pozzolanic nature dynamically transforms $Ca(OH)_2$ during hydration into secondary calcium silicate hydrate and calcium aluminate hydrate gel. This transformation effectively alters larger, detrimental pores in concrete into gel pores (Lin & Lin, 2006), contributing to an enhanced material density. The focus narrows down to MIBA and its potential as a sustainable substitute for construction sand in foamed flowable mortar (Le et al., 2021), especially in CLSM formulation (Le et al., 2018).

Existing literature highlights the importance of sustainable alternatives (Ho et al., 2022), yet the current state of research exhibits limitations, with a scarcity of comprehensive assessments on MIBA's application in foamed flowable mortar. Recognizing this research gap, this study endeavors to provide a nuanced understanding of MIBA's feasibility as a substitute for sand, introducing a novel perspective to the domain of controlled low-strength mixtures.

While previous research has made commendable strides in exploring sustainable alternatives (Cheng et al., 2023), a critical evaluation reveals limitations in terms of general applicability and depth of investigation. This study focused on addressing the research gap regarding MIBA in foamed flowable mortar, particularly in conjunction with air foam (AF) and silica fume (SF). Focused on its potential in CLSM, our systematic experimentation provides a detailed analysis of flowability, setting times, and compressive strength under various conditions. Keeping cement content constant at 180 kg/m³, AF ranged from 15% to 20% by volume, assessing its impact. Systematic sand replacement by MIBA (0%, 10%, 20%, 30%, and 40%) allowed for a comprehensive examination. SF, consistently at 12% by weight, contributed to supplementary material content. This mixture design strategy explores the interplay of variables, offering insights into MIBA's influence on foamed flowable mortar performance. The overview of the research is presented in the following Figure 1.

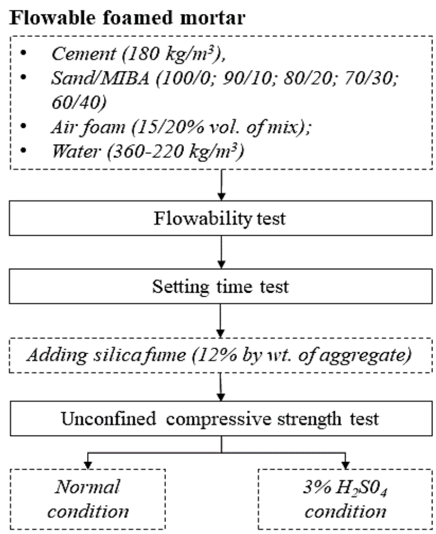


Figure 1. Research flowchart

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. General materials

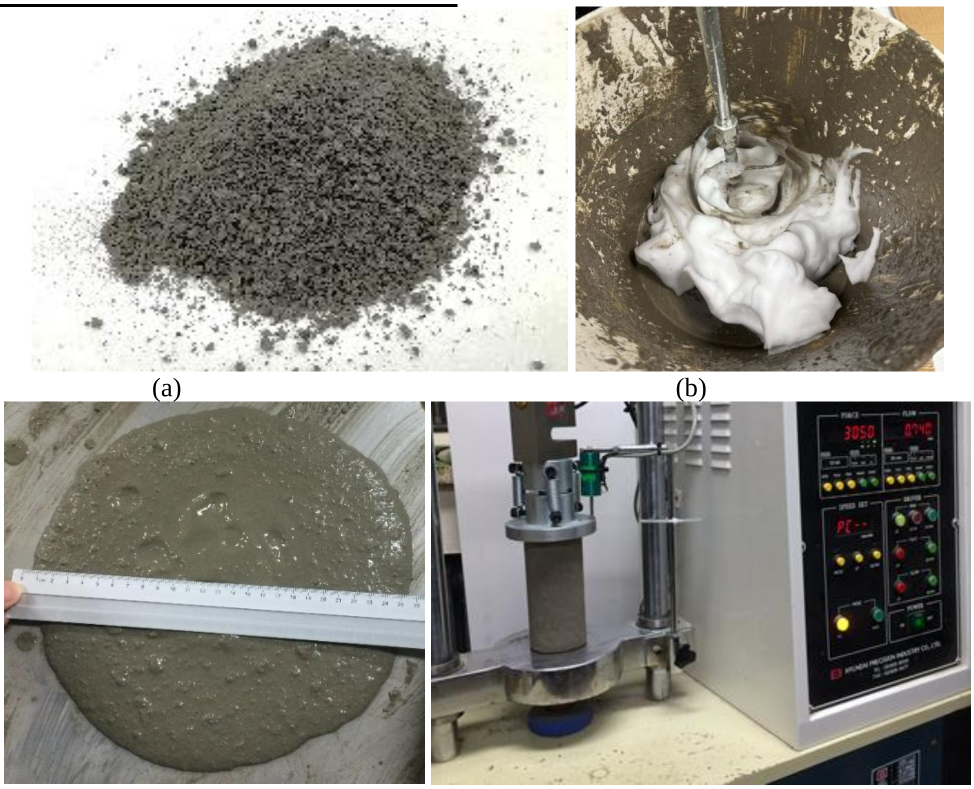
The materials employed in this study included Portland cement type II, construction sand, and MIBA. SF, an amorphous pozzolanic material, was utilized as an additive. Additionally, AF was generated to introduce aeration into the mortar mixtures. The overview of the gradation of aggregate and mix design is presented in Table 1 and Table 2, respectively. Compared to sand, MIBA exhibits a coarser texture and lower percentages pass through larger sieve sizes. While both MIBA and sand show 100% passing at the 4.75 mm sieve size, distinctions become evident in finer sieves. This assessment suggests that MIBA possesses a broader particle size distribution, potentially influencing the workability and performance of mortar or concrete mixtures when utilized as a sand substitute.

Table 1. Gradation of MIBA and sand

Sieve size (mm)	Passing (%)	
	MIBA	Sand
4.75	100	100
2.36	86	87
1.18	75	78
0.6	33	42
0.3	12	16
0.15	3	4

2.1.2. MIBA

MIBA was a key component in the experimental investigation (Figure 2a). MIBA was obtained from municipal waste incineration facilities and served as a partial replacement for traditional construction sand in the foamed flowable mortar mixtures (Liu et al., 2023). Understanding the characteristics of MIBA was essential for evaluating its potential influence on the mechanical properties of the mortar. MIBA is defined by a particle size distribution spanning 0.1 to 10 mm, a specific gravity of 2.2, and a bulk density ranging from 800 to 1000 kg/m³ (Kim et al., 2023). The moisture content falls between 1.5% and 3%. The chemical composition, presented as a percentage by weight, includes SiO_2 (20-30%), Al_2O_3 (5-10%), Fe_2O_3 (10-20%), CaO (15-25%), MgO (1-3%), $Na_2O + K_2O$ (3-5%), and other constituents (<5%).



(a) (b) (c) (d)

Figure 2. (a) MIBA materials, (b) foaming mix, (c) flowability test, and (d) UCS test

2.1.3. Air-foaming agent

To enhance the workability of the fresh foamed flowable mortar, AFA type II, a commercially available air-foaming agent, was added at a volume content of 10%. This agent introduced controlled air voids, improving flowability and handling characteristics during placement (Le et al., 2018). The generated AF is shown in Figure 2b. As shown in Table 2, the deliberate adjustment in water content aligns with the systematic modulation of air foam percentages in the mix design strategy. Higher levels of air foam contribute to improved flowability in foamed mortar. Consequently, the reduction in water content was introduced in response to increased foaming levels, ensuring optimal workability while adhering to the principles of controlled low-strength mixtures. This approach aims to strike a balance between the benefits of higher air foam content for enhanced flowability and the need for a controlled water-to-cement ratio. Additional clarification on this adjustment has been incorporated into the methodology section to elucidate the rationale behind the variation in water content.

2.2. Mixing and curing process

Foamed flowable mortar with varying MIBA percentages replacing sand was prepared, testing different AF concentrations (15% and 20%) and including 12% SF by weight of cement in specific mixtures. The three-stage mixing process ensured uniformity, starting with dry ingredients at 60 rpm for 3 minutes, followed by a 2-minute wet mix at 60 rpm with water, and the gradual addition of the air-foaming agent over 2 minutes. This controlled process ensured consistent, workable foamed flowable mortar across all batches. The curing conditions for the foamed flowable mortar specimens were carefully controlled to optimize their mechanical properties. Specimens were subjected to a standard curing regime, maintained at a temperature of 23°C and relative humidity of 50% for 28 days.

Table 2. Mix design of the MIBA mixture

Mix. Code	Cement (kg/m^3)	Sand (kg/m^3)	MIBA (kg/m^3)	SF (kg/m^3)	AF (vol.%)	Water (kg/m^3)
A0-M00	180	800	0	0	0	360
A0-M10	180	720	80	0	0	360
A0-M20	180	640	160	0	0	360
A0-M30	180	560	240	0	0	360
A0-M40	180	480	320	0	0	360
MS00	180	634	0	86.4	15%	240
MS10	180	562	72	86.4	15%	240
MS20	180	490	144	86.4	15%	240
MS30	180	418	216	86.4	15%	240
MS40	180	346	288	86.4	15%	240
MS00	180	605	0	82.6	20%	220
MS10	180	537	69	82.6	20%	220
MS20	180	468	138	82.6	20%	220
MS30	180	399	206	82.6	20%	220
MS40	180	330	275	82.6	20%	220

2.3. Testing method

Flowability tests, conducted following ASTM D6103 (2017), assessed the workability of mortar mixtures by measuring the spread diameter on a flat surface, providing crucial insights into flow characteristics as presented in Figure 2c. Setting times were determined following ASTM D4832 (2023), evaluating initial and final setting times using the Vicat apparatus. The impacts of varying MIBA percentages, AF conditions, and SF addition on setting times were systematically analyzed. As shown in Figure 2d, UCS tests at both 7 and 28 days utilized cylindrical specimens (diameter: 70mm, height: 140mm) with 3 replicates (ASTM D4832, 2023). These specimens were cured under different conditions, including normal and H_2SO_4 (3%) curing. The loading rate for UCS tests was set at 1 mm/min, offering a comprehensive exploration of curing methods' influence on the mechanical properties of the foamed flowable mortar. The utilization of a 3% sulfuric acid (H_2SO_4) solution in the curing process aims to simulate harsh conditions, emulating an acidic environment.

3. RESULTS AND DISCUSSION

3.1. Flowability test results

Figure 3 depicts flowability test results for foamed flowable mortar, examining the influence of MIBA as a substitute for construction sand at varying percentages. The control mixture, with 0% bottom ash and 0% AF, exhibits the highest flowability at 232.3 mm. Results show a consistent trend of decreasing flowability with increasing MIBA percentages, indicating a negative impact on mortar flow. The control mixture serves as the benchmark, with specific deviations highlighted for each bottom ash and AF combination. For example, at 40% bottom ash replacement and 20% AF, flowability reduces by 29.3% in comparison to the control. This reduction is attributed to the water absorption characteristics of MIBA particles, hindering smooth flow by limiting available water content for lubrication.

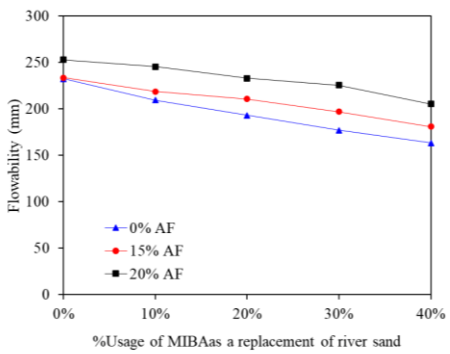


Figure 3. Flowability test results

3.2. Setting time test results

Figure 4 illustrates the influence of MIBA as a sand substitute in foamed flowable mortar on setting times under different AF conditions. The control mixture (0% MIBA, 0% AF) has the shortest setting time at 14.112 hours. Increasing MIBA percentages extend setting times, with 15% and 30% replacements causing increases of 21.4% (3.024 hours) and 42.7% (6.024 hours), respectively. This trend continues with 30% and 40% replacements, resulting in increases of 57.7% (8.1405 hours) and 64.7% (9.108 hours). Mixtures with 20% AF generally exhibit longer setting times than those with 15% AF. The findings suggest that MIBA incorporation significantly affects foamed flowable mortar setting times, possibly due to specific characteristics of bottom ash particles impacting cement hydration kinetics.

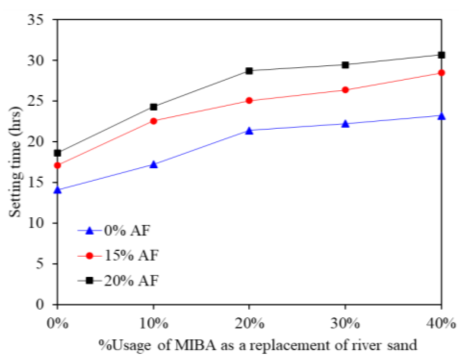


Figure 4. Setting time test results

3.3. UCS test results

3.3.1. 7 days strength

Figure 5 shows clear trends in the 7-day unconfined compressive strength of cement mortar with varying percentages of MIBA replacing construction sand. The control mix (0% MIBA) exhibits the highest early-age strength at 0.43 MPa, while the introduction of MIBA results in a consistent decrease in compressive strength. For instance, at 15% MIBA replacement, the compressive strength drops to 0.40 MPa, and further reductions are observed with increasing MIBA content. Additionally, the incorporation of AF exacerbates this decline in strength across all mixtures. The detrimental impact of MIBA on early-age strength is evident when compared to the control, emphasizing the need for meticulous mix design adjustments to balance the sustainability benefits of MIBA with the essential requirement of maintaining compressive strength in cement mortar applications.

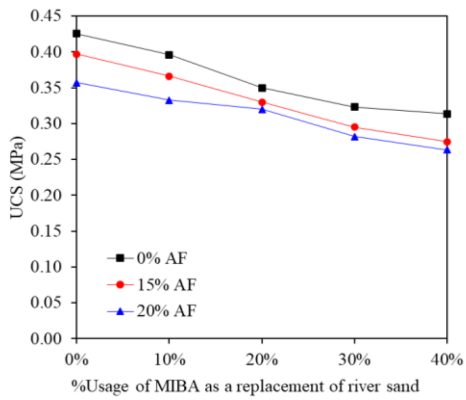


Figure 5. 7-day-UCS test results

3.3.2. 28 days strength

Figure 6 presents the unconfined compressive strength results at 28 days for foamed flowable mortar formulations incorporating varying percentages of MIBA as a substitute for construction sand. The control mix, featuring 0% MIBA and a standard composition, exhibits the highest compressive strength at 0.89 MPa. However, as the percentage of MIBA increases, there is a discernible trend of decreasing compressive strength, potentially attributed to differences in particle characteristics and reactivity between MIBA and traditional sand. Notably, the addition of AF appears to further reduce compressive strength, highlighting a potential trade-off between increased workability and decreased strength. Interestingly, the mixtures with supplementary SF (20% AF + 12% SF and

15% AF + 12% SF) show improvements in compressive strength, suggesting that SF may counteract the negative impact of AF under specific conditions.

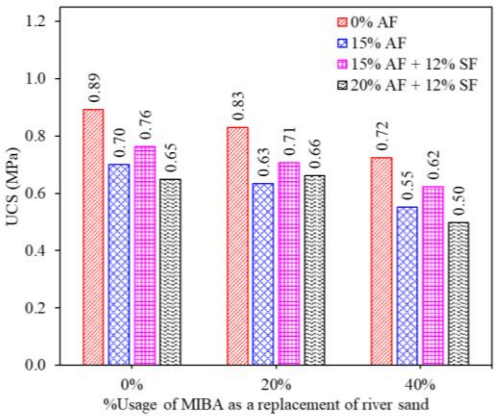


Figure 6. 28-day-UCS test results

3.3.3. *Impact of curing conditions*

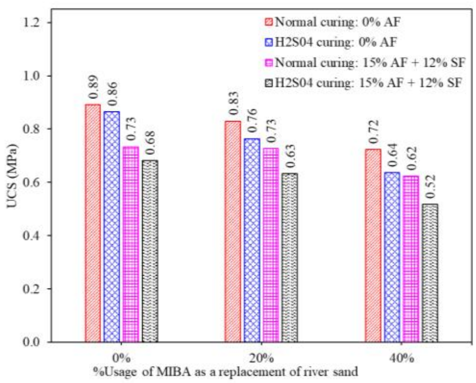


Figure 7. Impact of curing conditions

In Figure 7, UCS at 28 days for mortar with MIBA replacing construction sand is illustrated, revealing critical insights under various curing conditions. The control mix (0% MIBA) demonstrates the highest compressive strength at 0.89 MPa under normal curing, and slightly reduced under H_2SO_4 curing. Notably, the mixture with 15% AF and 12% SF experiences a significant reduction in compressive strength under H_2SO_4 curing, registering 0.63 MPa compared to 0.73 MPa under normal curing. The addition of SF proves beneficial, resulting in approximately 16% better compressive strength under normal curing conditions. This enhancement is attributed to SF's pozzolanic properties, fostering denser microstructures and improved particle binding, thereby mitigating the adverse effects of AF and enhancing overall compressive strength.

4. CONCLUSION

In summary, flowability, setting times, and compressive strengths are influenced by both the percentage of replacement and additional factors like AF and SF. The incorporation of MIBA in foamed flowable mortar leads to a gradual decrease in flowability, with higher MIBA percentages resulting in more pronounced reductions. Notably, at 40% bottom ash and 20% AF, flowability drops to 163.4 mm, representing a 29.3% reduction compared to the control and offering specific insights into the influence of bottom ash on mortar flow. With increasing MIBA percentages, setting times extend, indicating potential delays in mortar hardening. Compared to the control, setting times increased by 21.4% (3.024 hours) at 15% MIBA replacement and by 42.7% (6.024 hours) at 30% MIBA replacement. Higher MIBA percentages result in a consistent decrease in UCS at 7 days. The addition of AF further diminishes early-age strength. The control mix with 0% MIBA exhibits the highest compressive strength under normal curing conditions. H_2SO_4 curing introduces variability in strengths, emphasizing the need for tailored curing approaches. SF proves beneficial, showing approximately 16% better compressive strength in mixtures with AF under normal curing conditions. SF emerges as a crucial additive for enhancing compressive strength, showcasing its potential to mitigate the adverse effects of certain variables in the mortar mix. These findings provide valuable insights for optimizing sustainable mortar formulations, paving the way for environmentally conscious construction practices with improved mechanical properties.

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