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Foam-based eco-lightweight controlled low-strength material for high-volume utilization of municipal solid waste incineration bottom ash

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Abstract: The increasing scarcity of natural aggregates, coupled with the growing environmental burden associated with municipal solid waste incineration (MSWI) residues, poses a dual challenge for sustainable urban construction. Previous studies have primarily investigated MSWI bottom ash (IBA) or foam-modified mortars in isolation; however, the combined effects of IBA, fly ash, and pre-formed foam on controlled low-strength material (CLSM) have not yet been systematically evaluated. This study develops an integrated, waste-valorized CLSM system and systematically investigates the fresh-state, hardened, durability, and eco-mechanical performance of fifteen mixtures incorporating 0–40% IBA, 0–20% fly ash, and 0–20% pre-formed foam. Cylindrical specimens were tested in accordance with relevant ASTM standards to evaluate flowability, bleeding, setting time, water absorption, 3–28-day compressive strength, and durability under simulated acid rain and seawater immersion, supported by a normalized multi-criteria assessment (MCA) and eco-mechanical indicators (relative carbon emission [RCE] and relative energy consumption [REC]). The results indicate that increasing IBA content reduced flowability from 170 mm to 130 mm and increased water absorption by up to 49%, whereas foam incorporation significantly enhanced flowability to a maximum of 270 mm, albeit with an associated increase in water absorption to 5.44–5.91%. The 28-day compressive strength decreased from 3.213 MPa in the control mixture to 2.187 MPa at the highest combined waste and foam content; nevertheless, all mixtures exceeded the minimum 1 MPa requirement for CLSM applications. Durability losses ranged from 4.77% to 10.51% under acid rain exposure and from 8.34% to 16.61% under seawater immersion, with high-porosity mixtures being the most adversely affected. Despite these trade-offs, mixtures with moderate waste contents—particularly M5 (10% IBA, 10% fly ash, and 10% foam)—exhibited a well-balanced performance, achieving an MCA score of 0.66, a 28-day compressive strength exceeding 2.5 MPa, a flowability of approximately 210 mm, and 85–88% strength retention under aggressive environments. Overall, the findings

Abstract: (continued) indicate that the combined use of IBA, fly ash, and pre-formed foam can produce lightweight CLSM with a favorable balance between engineering performance and strength-normalized environmental efficiency, making it promising for non-structural applications such as coastal and municipal backfilling.

Keywords: Controlled low-strength material, municipal solid waste incineration bottom ash, fly ash, foam concrete, eco-efficiency, durability.

1. Introduction

The rapid pace of urbanization has significantly intensified the demand for natural aggregates such as river sand and limestone, leading to critical resource depletion and ecological degradation in many regions. In response, the concept of a circular economy has gained increasing attention within civil engineering, promoting the reuse of industrial by-products and waste-derived materials as alternatives to virgin resources [1]. Beyond conserving natural capital, this approach also provides a sustainable pathway for managing the growing volumes of municipal and industrial waste generated worldwide. Among the available waste streams, municipal solid waste incineration bottom ash (IBA) represents a substantial yet still underutilized secondary resource. Although incineration can reduce municipal waste volumes by up to 90%, the resulting ash residues require careful management due to their heterogeneous composition and potential environmental risks [2].

The utilization of IBA in cementitious composites is governed by a critical balance between replacement level and mechanical performance. Numerous studies have demonstrated that relatively low replacement ratios, typically between 5% and 10%, can yield favorable mechanical properties. For instance, Yan et al. [3] reported compressive strengths exceeding 127 MPa in ultra-high-performance mortars incorporating IBA at these levels, while Avudaiappan et al. [4] observed an 8.15% increase in flexural strength at 10% replacement. In contrast, higher substitution ratios generally lead to mechanical degradation. Avudaiappan et al. [4]

also documented a 28% strength reduction at 30% replacement, and Alnezami et al. [5] reported tensile capacity losses of up to 80% when the replacement level reached 55%. Nevertheless, for applications with lower structural demands or specific rheological requirements, higher IBA utilization has proven feasible. Li et al. [6] and Zhang et al. [7] successfully incorporated 30–40% IBA in self-compacting and pervious geopolymer mortars while maintaining compressive strengths between 37 and 55 MPa. Similarly, Zhang et al. [8], Liu et al. [9], and Ding et al. [10] identified optimal replacement ranges of 20–50% for 3D-printing and shotcrete applications, balancing buildability with compressive strengths of 25–53 MPa. To further improve performance at elevated replacement levels, Zheng et al. [11] and Shah et al. [12] demonstrated that advanced compaction and optimized mixing strategies could partially recover elastic modulus and enhance structural build-up.

To address the inherent porosity and expansion risks associated with metallic aluminum in IBA, considerable attention has been devoted to pretreatment techniques and durability evaluation. Chemical pretreatments have shown particular effectiveness: Caprai et al. [13] reduced pore volume by a factor of 2.5 through waterglass impregnation, Qian et al. [14] achieved 10.7% CO₂ sequestration via semi-dry carbonation, and Liu et al. [15], together with Saikia et al. [16], demonstrated that alkaline treatments can stabilize volumetric expansion and enable safe utilization. From a durability perspective, Yao et al. [17] and Kim et al. [18] reported improved resistance of IBA-based mortars to sulfate and chloride attack, while Yao et al. [19] observed up to a nine-fold increase

in corrosion resistance coefficients at high replacement levels. Moreover, Chu et al. [20] and Gu et al. [21] confirmed effective immobilization of heavy metals within cementitious matrices, ensuring compliance with leaching regulations. Environmental assessments further support IBA valorization; life cycle analyses by Gu et al. [21], Liu et al. [22], and Yan et al. [23] revealed that optimized IBA mixtures can reduce energy consumption by approximately 7.8%, lower global warming potential by 4.9–10.5%, and decrease production costs by 17–32%, providing a strong incentive for large-scale implementation.

Despite these advantages, the direct use of IBA as a fine aggregate replacement presents notable challenges. Although its sand-like gradation makes it attractive for this role, IBA is characterized by high porosity, angular particle morphology, and elevated water absorption, which collectively increase water demand and compromise mechanical stability. To mitigate these effects, fly ash is commonly incorporated to improve fresh-state flowability through its spherical “ball-bearing” effect and to enhance long-term strength via secondary C–S–H formation [20]. In parallel, pre-formed foam has gained increasing attention for producing lightweight cellular matrices that reduce density and improve workability, particularly when waste aggregates stiffen the mixture [24]. However, the additional porosity introduced by both IBA and foam inevitably reduces strength, and the interactions among flowability, bleeding, and absorption are often highly non-linear. Although each of these components has been extensively studied individually, no prior research has systematically optimized CLSM mixtures that simultaneously incorporate IBA, fly ash, and pre-formed foam, leaving a clear gap in the development of sustainable CLSM systems that balance fresh-state performance, hardened strength, and durability.

This study addresses this gap by conducting

a systematic experimental evaluation and multi-criteria comparison of CLSM mixtures incorporating IBA, fly ash, and pre-formed foam. The primary objective is to evaluate the combined effects of these constituents and to identify mixture compositions that provide a practical balance among fresh-state behavior, mechanical performance, durability, and strength-normalized environmental efficiency. An experimental program comprising fifteen mixtures was designed, in which natural fine aggregate was replaced by IBA at levels of 0%, 10%, 20%, 30%, and 40%, while fly ash and pre-formed foam were simultaneously incorporated at 0%, 10%, and 20%. The mixtures were evaluated in terms of fresh properties (flowability and bleeding), setting behavior, hardened performance (water absorption and 28-day unconfined compressive strength [UCS]), and durability under simulated acid rain and seawater exposure. Finally, MCA integrating these technical indicators with strength-normalized environmental metrics—relative carbon emission (RCE) and relative energy consumption (REC)—was employed to identify the optimal mixture that maximizes waste utilization while maintaining engineering reliability.

2. Materials and experimental methods

2.1. Materials

Blended Portland Cement was used as the primary hydraulic binder for all mixtures. The cement complies with TCVN 6260:2015 [25] and provides a minimum 28-day compressive strength of 40 MPa, making it suitable for both structural and non-structural cementitious applications. The fineness, determined in accordance with TCVN 13605:2023 [26], indicates that at least 85% of particles pass the 90 μm sieve, supporting adequate early-age hydration. Setting times measured following TCVN 6017:2015 [27] show an initial setting time of not less than 45 minutes and a final setting time not exceeding 375 minutes, ensuring sufficient workability for mixing, placement, and self-compacting CLSM operations.

Natural river sand was used as the fine aggregate in the control mixtures and satisfies the requirements of TCVN 7570:2006 [28]. The sand exhibits a fineness modulus ranging from 2.0 to 3.3, which is appropriate for high-flow cementitious materials such as CLSM. Its specific gravity is

approximately 2.65 g/cm^3 , while water absorption, measured according to TCVN 7572-4:2006 [29], does not exceed 2%, contributing to stable workability and predictable hydration behavior. The sand was sieved to retain particles within the 0.15–4.75 mm size range.



Fig. 1. (a) IBA; (b) generated foam; (c) mixing components; (d) casting foam into slurry; and (e) curing of specimens

IBA obtained from the Can Gio waste treatment plant was used as a partial replacement for natural sand (Fig. 1a). Compared to natural sand, IBA exhibits a lower specific gravity ranging from 1.80 to 2.30 g/cm^3 and a significantly higher water absorption of approximately 12%, attributed to its highly porous internal structure. Particle sizes range from 0.15 to 5.00 mm, with angular and

irregular morphologies that increase internal friction and influence fresh-state behavior. Chemical composition analysis indicates that the ash is mainly composed of SiO_2 (33.00%), CaO (16.50%), and Al_2O_3 (3.80%). The presence of CaO may contribute to cementitious interactions, while the silica- and alumina-bearing phases can potentially support limited pozzolanic activity within

the cementitious matrix. The reported Cr_2O_3 and CuO contents were 420 ppm and 190 ppm, respectively, while Hg, As, Pb, and Cd were not detected in the reported analysis. These

compositional results alone do not establish environmental safety or regulatory compliance; leaching assessment against applicable criteria is required before field application.

Table 1. Selected chemical composition of cement, fly ash, and IBA (major oxides in wt.% and selected trace metals in ppm).

Material	SiO_2 (%)	CaO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	$\text{Na}_2\text{O} + \text{K}_2\text{O}$ (%)	LOI (%)	Cr_2O_3 (ppm)	CuO (ppm)
Cement	21.0	63.0	5.0	3.0	2.0	2.5	0.8	3.0	-	-
Fly ash	55.0	4.0	25.0	8.0	1.0	1.0	2.5	4.0	-	-
IBA	33.0	16.5	3.8	-	-	-	-	-	420	190

Prior to mixing, the IBA was sieved to the target size range and used in an air-dry condition (i.e., not pre-saturated to SSD). Therefore, the batch water represents the added mixing water without SSD correction for IBA absorption. This approach was adopted to evaluate the coupled influence of IBA morphology/gradation and foam on fresh stability under a constant added-water condition.

The pre-formed foam was generated using a commercial synthetic foaming agent EABASSOC (origin: United Kingdom), imported and supplied in Vietnam by THT International. According to the supplier's technical information, the agent is water-soluble with a density of approximately 1.02 g/cm^3 and near-neutral pH (~ 6.7 in water). The foaming agent was diluted with water (typically 2.5–3.0% by volume) and processed through a foam generator to produce stable fine-bubble foam (Fig. 1b), which was incorporated immediately into the mortar to achieve the target foam volume fraction. Foam quality was controlled by checking foam density and short-term stability prior to mixing. The foam density was controlled within the range of 50–100 kg/m^3 , with a water retention capacity of at least 85%, ensuring adequate bubble stability during mixing. Bubble diameters ranged from 100 to 500 μm , producing a relatively uniform pore structure. These fine, evenly distributed air voids contribute to reduced unit weight and enhanced flowability of the CLSM matrix.

Coal fly ash was incorporated as a

supplementary cementitious material to partially replace cement. The fly ash exhibits high fineness, with more than 70% of particles passing the 45 μm sieve. Its specific gravity ranges from 2.1 to 2.6 g/cm^3 , and the loss on ignition (LOI) remains below 6%. The pozzolanic activity index reaches at least 75% at 28 days, confirming effective reaction with $\text{Ca}(\text{OH})_2$ to form secondary C–S–H gel and enhance long-term strength and durability. The chemical compositions of cement, fly ash, and IBA are summarized in Table 1.

The particle size distributions of natural sand, IBA, and fly ash were analyzed to assess grading compatibility and packing characteristics (Fig. 2). Natural sand exhibits a typical fine aggregate gradation, with the majority of particles retained on the 1.18 mm and 2.36 mm sieves. IBA shows a broader distribution, with a substantial fraction passing the 0.300 mm sieve. Fly ash is the finest constituent, with more than 70% passing the 0.075 mm sieve. This fine fraction contributes to filling interparticle voids between sand and IBA, improving packing density and partially reducing matrix porosity.

Clean tap water conforming to TCVN 4506:2012 [30] was used for both mixing and curing. The water had a pH ranging from 6.0 to 8.0, with total dissolved solids below 2000 mg/L. Chloride and sulfate contents were maintained below 500 mg/L and 300 mg/L, respectively, to prevent adverse effects on cement hydration and setting behavior.

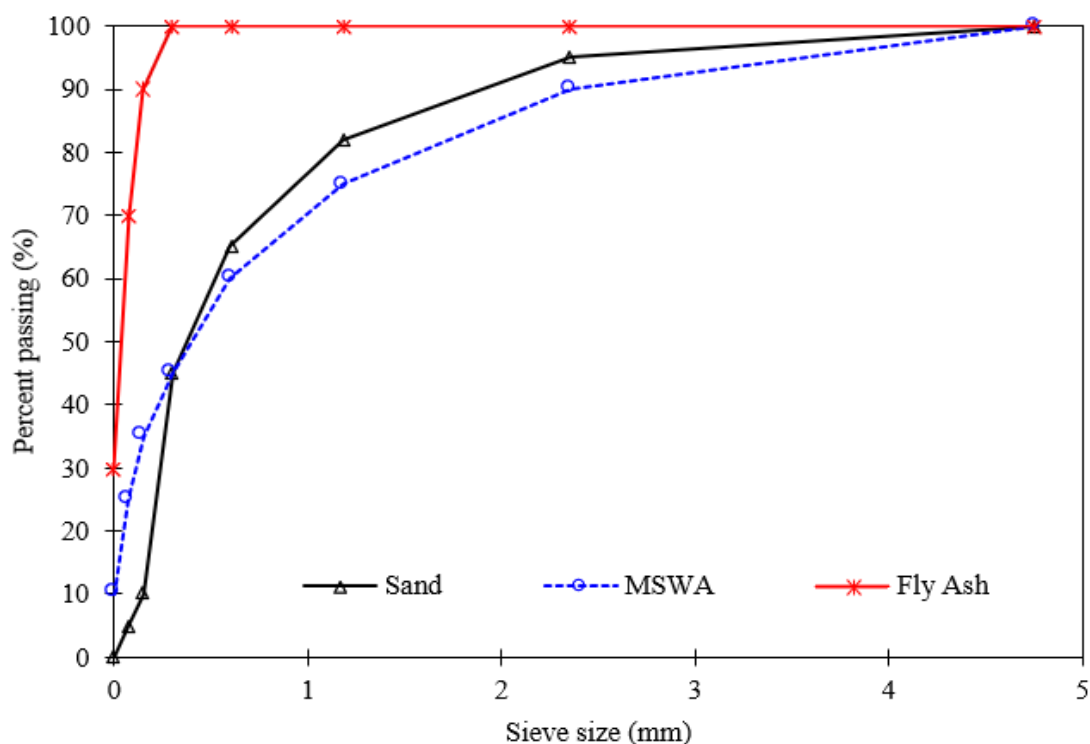


Fig. 2. Particle size distribution

Table 2. Mixture proportions of CLSM

Mix ID.	IBA/Sand (wt.%)	Fly ash/Cement (wt.%)	Foam (vol.%)	Cement (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)	Fly ash (kg/m ³)	IBA (kg/m ³)
M1	0	0	0	260.0	1053.0	520	0.0	0.0
M2	0	10	10	234.0	1053.0	520	26.0	0.0
M3	0	20	20	208.0	1053.0	520	52.0	0.0
M4	10	0	0	260.0	947.7	520	0.0	105.3
M5	10	10	10	234.0	947.7	520	26.0	105.3
M6	10	20	20	208.0	947.7	520	52.0	105.3
M7	20	0	0	260.0	842.4	520	0.0	210.6
M8	20	10	10	234.0	842.4	520	26.0	210.6
M9	20	20	20	208.0	842.4	520	52.0	210.6
M10	30	0	0	260.0	737.1	520	0.0	315.9
M11	30	10	10	234.0	737.1	520	26.0	315.9
M12	30	20	20	208.0	737.1	520	52.0	315.9
M13	40	0	0	260.0	631.8	520	0.0	421.2
M14	40	10	10	234.0	631.8	520	26.0	421.2
M15	40	20	20	208.0	631.8	520	52.0	421.2

2.2. Mix design

Fifteen CLSM mixtures were systematically designed to evaluate the combined effects of IBA, fly ash, and pre-formed foam. IBA replaced natural sand at 0%, 10%, 20%, 30%, and 40% by weight,

while fly ash replaced cement at levels of 0%, 10%, and 20%. Foam was incorporated at 0%, 10%, and 20% of the total mixture volume. This factorial combination resulted in three mixtures for each IBA replacement level, enabling direct comparison of

additive effects. It should be noted, however, that fly ash and foam were increased together within each mixture series; therefore, their individual effects were interpreted in combination rather than as fully independent variables. Cement and aggregate contents were proportionally adjusted, while the water content was kept constant at 520 kg/m³ to isolate the influence of waste materials and foam on rheological behavior and strength development. The resulting mixture proportions are presented in Table 2, providing a controlled framework for evaluating fresh, hardened, and durability-related properties across a wide range of sustainable CLSM compositions. Because fly ash and foam were introduced together at matching levels (0, 10, and 20%), the present design is most suitable for evaluating their combined modification effect rather than fully isolating their independent contributions.

2.3. Test methods

Cylindrical molds with a diameter of 60 mm and a height of 120 mm were prepared for specimen casting. The molds were fabricated from rigid PVC to ensure dimensional stability during curing and testing. To facilitate demolding without inducing surface damage or cracking, each mold was modified with a longitudinal slit along its side. Prior to casting, the internal mold surfaces were coated with a thin layer of release oil to minimize adhesion between the hardened CLSM matrix and the mold walls.

All mixing operations were conducted under controlled laboratory conditions, with ambient temperatures maintained between 20°C and 25°C to ensure consistent hydration behavior. A 30 L planetary-type mechanical mixer was used to achieve uniform dispersion of all constituents. Initially, cement, natural sand, IBA, and fly ash were weighed using an electronic balance with a precision of ± 0.1 g and dry-mixed for 2 minutes at a rotational speed of 60 rpm to promote homogeneous particle distribution and limit agglomeration (Fig. 1c). Subsequently,

approximately 70% of the total mixing water was gradually added, and mixing continued for an additional 3 minutes at the same speed to fully wet the solid particles and form a cohesive base matrix. In the final stage, pre-formed foam corresponding to 10–20% of the total mixture volume was introduced together with the remaining 30% of the mixing water (Fig. 1d). To minimize bubble collapse, the mixing speed was reduced to 30 rpm, and mixing was continued for 4–5 minutes until uniform foam dispersion was achieved. The total mixing time ranged from 8 to 10 minutes per batch. After mixing, the fresh mixture was allowed to rest for approximately 1 minute for visual inspection of segregation, followed by a brief 1-minute remixing cycle prior to casting.

Immediately after fresh-state evaluation, the CLSM mixtures were cast into the prepared molds. Owing to the self-compacting nature of the material, no mechanical vibration or external compaction was applied. For each mixture, two replicate specimens were prepared to account for experimental variability. Three curing regimes were employed to evaluate performance under different exposure conditions. For standard curing, specimens were kept in the molds at room temperature ($20 \pm 2^\circ\text{C}$) for the first 24 hours to limit early moisture loss, then demolded and submerged in a water-curing tank maintained at $20 \pm 2^\circ\text{C}$ for curing periods of up to 28 days (Fig. 1e). To simulate natural weathering, a subset of specimens was cured in rainwater collected from the Cần Giỏi area, characterized by a slightly acidic pH of 5.5–6.5 and low total dissolved solids (10–50 mg/L), at temperatures between 25°C and 30°C. For marine exposure, another subset was immersed in seawater from the Cần Giỏi coastal region, with total dissolved solids of 35,000–40,000 mg/L and a pH range of 7.5–8.5, while maintaining curing temperatures between 25°C and 30°C.

A comprehensive testing program was implemented to evaluate the fresh-state, hardened, and durability performance of the CLSM mixtures

in accordance with relevant ASTM standards. All tests were conducted under controlled laboratory

conditions to ensure consistency and repeatability across mixture groups.

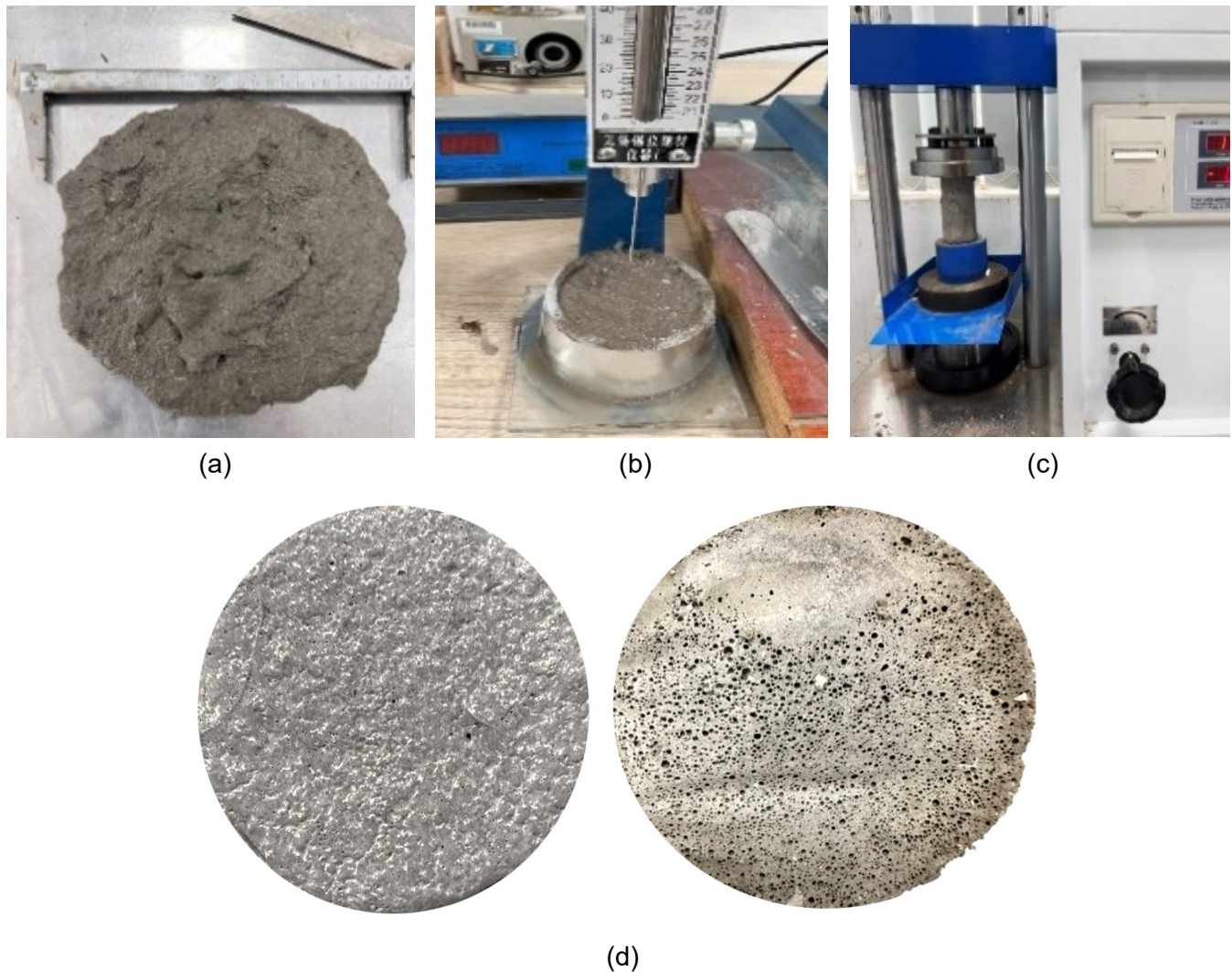


Fig. 3. (a) Flowability test; (b) setting time test; (c) UCS test; and (d) surface of sample without and with 20% pre-formed foam

Fresh-state properties were evaluated immediately after mixing. Flowability was measured using the flow consistency (spread) test in accordance with ASTM D6103/D6103M-17 [31] (Fig. 3a). The flow spread was recorded as the average of two perpendicular diameters of the spread. The measured values were then compared with commonly cited workability ranges for CLSM, noting that a flow spread of approximately 200–300 mm is typically associated with self-compacting placement. Bleeding characteristics were evaluated in accordance with ASTM C232/C232M-26 [32] to quantify mixture stability and susceptibility to segregation. Setting behavior was

determined using the Vicat needle method following ASTM C191-21 [33] (Fig. 3b), allowing the determination of both initial and final setting times and providing insight into the retarding effects induced by IBA, fly ash, and pre-formed foam incorporation.

Hardened mechanical performance was characterized through UCS testing. Cylindrical specimens with dimensions of 60 mm in diameter and 120 mm in height were tested at curing ages of 3 and 28 days in accordance with ASTM D4832/D4832M-23 [34], as shown in Fig. 3c. These testing ages were selected to capture early-age strength development as well as the stabilized

mechanical performance relevant to CLSM applications. In addition, porosity-related characteristics were evaluated through water absorption tests conducted in accordance with ASTM C642-21 [35], providing an indirect assessment of the internal pore structure and permeability potential of the hardened matrix.

Durability performance was investigated by exposing cured specimens to aggressive environments representative of tropical coastal conditions. Two exposure regimes were employed: simulated acid rain and seawater immersion. After 28 days of exposure, material degradation was quantified through mass loss and compressive-strength reduction using a laboratory evaluation procedure adapted from common durability-assessment practices, rather than as a direct application of ASTM C666-97 [36]. Visual inspection of specimen surfaces, including the comparison between mixtures without foam and those incorporating 20% pre-formed foam, is presented in Fig. 3d, highlighting the influence of internal pore structure on surface integrity after curing and exposure. The results obtained from fresh-state tests, mechanical characterization, and durability assessment were subsequently used as input parameters for the normalized multi-criteria assessment, enabling an integrated evaluation of performance trade-offs among workability, strength, durability, and environmental efficiency.

3. Results and discussion

3.1. Bleeding

The bleeding behavior of the developed self-compacting CLSM mixtures exhibited pronounced variability, with measured values ranging from 2.10% to 6.90%, indicating a strong sensitivity to the interaction between aggregate characteristics and mixture modification strategies. As illustrated in Fig. 4, the incorporation of IBA in mixtures without foam and fly ash led to a systematic increase in bleeding. While the control mixture M1 showed a moderate bleeding rate of 3.20%, increasing the IBA content progressively intensified

water separation, with mixture M10 (30% IBA) reaching 6.50%.

It was found that the bleeding response in the IBA–foam system is time-dependent and reflects competing mechanisms. At the early stage, the porous/absorptive IBA can temporarily reduce free water, and the pre-formed foam network may initially retain part of the mixing water within bubble films, resulting in low visible bleeding immediately after casting. With time (≈ 2 h), partial foam drainage/coalescence and collapse can release the water previously held by foam films and reduce the early-age bubble skeleton, which locally decreases cohesion. The released liquid can then migrate upward through preferential void pathways associated with IBA morphology and the foam-derived pore system, leading to delayed bleeding (water separation). This interpretation is consistent with previous IBA studies reporting that water separation and workability are strongly governed by ash grading/angularity and water demand, and that loss of cohesion can trigger segregation/bleeding [37].

The combined introduction of fly ash and pre-formed foam exerted a non-linear influence on bleeding stability, with the effect strongly dependent on additive dosage. At lower additive contents (10%), bleeding instability was amplified rather than mitigated. For example, mixture M2 (10% fly ash and foam without IBA) exhibited a bleeding rate of 5.80%, substantially higher than the control, while mixture M8 (20% IBA with 10% additives) recorded the maximum bleeding value of 6.90%. This behavior suggests that, at low additive dosages, the combined effects of insufficient paste densification and limited foam-network stability were not enough to suppress water migration, so segregation tendencies remained pronounced.

In contrast, increasing the additive dosage to 20% resulted in a marked improvement in bleeding resistance. Mixture M3 showed a substantial reduction in bleeding to 2.50%, while mixture M15 (40% IBA with 20% additives) achieved a bleeding

rate of 4.70%, which is lower than its non-foam counterpart M13 (5.50%). This enhanced stability at higher additive contents is attributed to a combined mechanism: fly ash improves paste cohesiveness and particle packing and, with ongoing pozzolanic reaction, contributes to a denser binder matrix at later stages [38]. In parallel, the pre-formed foam introduces a stable bubble network that limits continuous drainage paths and reduces upward water migration [39]. Together, these effects restrain free-water separation and increase mixture cohesion even at high IBA

replacement levels. The observed stabilization at higher fly ash and foam dosages is consistent with previous findings reported by Ding et al. [10], who demonstrated that fly ash incorporation significantly reduced bleeding in lightweight aggregate systems by counteracting segregation tendencies induced by porous waste aggregates. Overall, the results indicate that while IBA inherently increases bleeding susceptibility, an appropriate combination and dosage of fly ash and foam can restore fresh-state stability, even at relatively high levels of waste utilization.

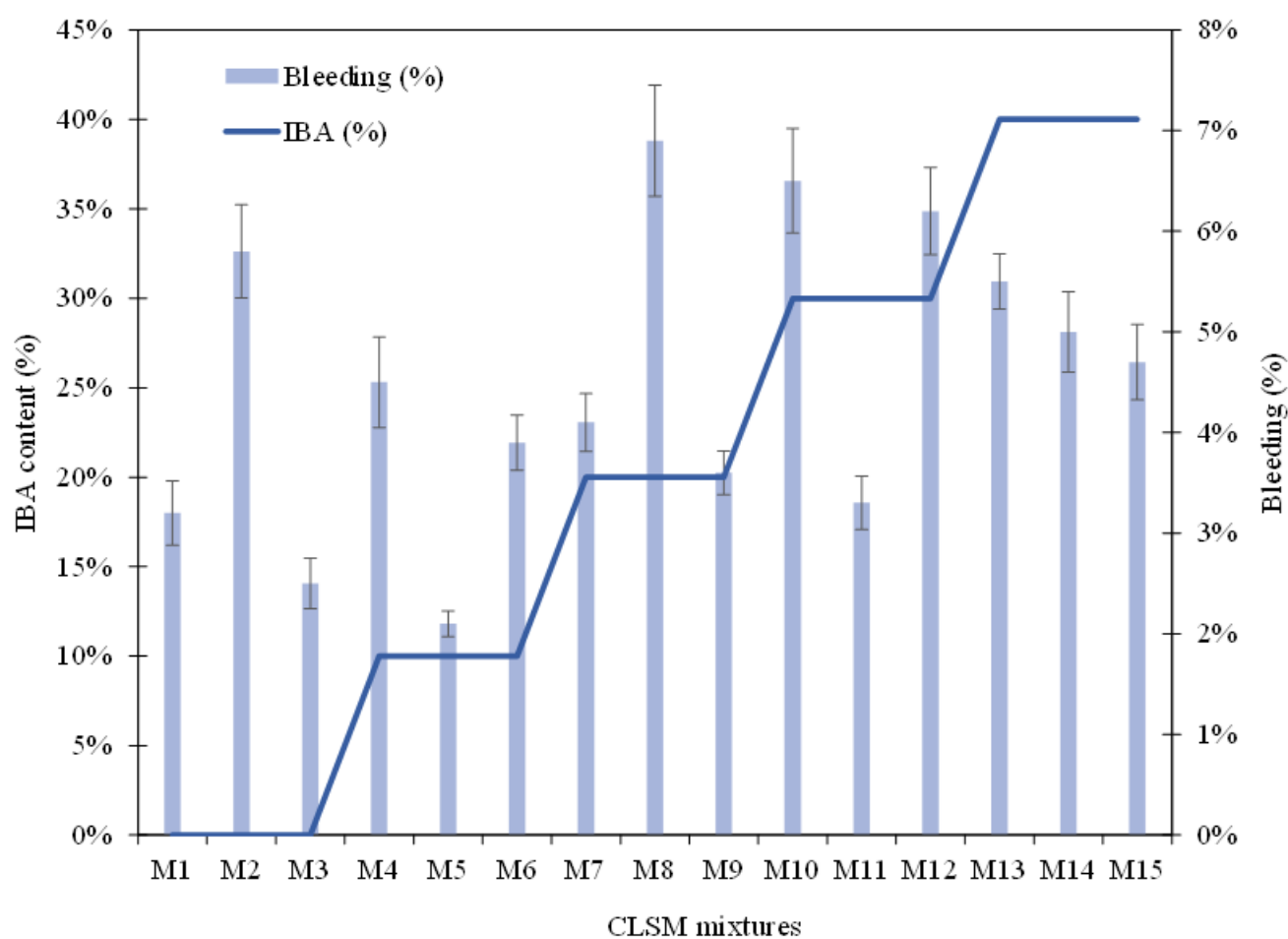


Fig. 4. Variation in bleeding of CLSM mixtures

3.2. Flowability

The flowability results, which ranged from 130 mm to 270 mm, reveal a pronounced interaction between aggregate replacement and mixture modification through fly ash and pre-formed foam, as illustrated in Fig. 5. The flowability test was conducted as a screening step to identify

unsuitable mixtures (i.e., those with inadequate workability) and to select practical CLSM mixtures that achieve an appropriate balance between flow and stability. Although a self-compacting CLSM flow spread of approximately 200–300 mm is commonly reported, several trial mixtures in this study exhibited lower spreads (≈ 130 – 170 mm) and

therefore are not classified as self-compacting. These low-flow mixtures were retained only for comparative assessment and are not recommended for practical application; the recommended mixtures are those meeting the target flow range while maintaining low bleeding and segregation. In mixtures without foam and fly ash, flowability exhibited a nearly linear decline with increasing IBA content. Relative to the control mixture M1 (170 mm), each 10% increment in IBA replacement reduced the flowability by approximately 5.9%, ultimately reaching 130 mm in mixture M13 with 40% IBA. This progressive loss

of workability is primarily governed by the physical characteristics of the bottom ash. Unlike naturally rounded river sand, IBA particles are angular, irregular, and highly porous, which substantially increases interparticle friction and water demand within the fresh matrix. Consequently, the yield stress of the mixture rises, leading to a marked reduction in flowability despite the constant water content. This behavior is consistent with the findings of Alnezami et al. [5], who reported that the incorporation of bottom ash significantly increases water demand due to its porous structure and irregular morphology.

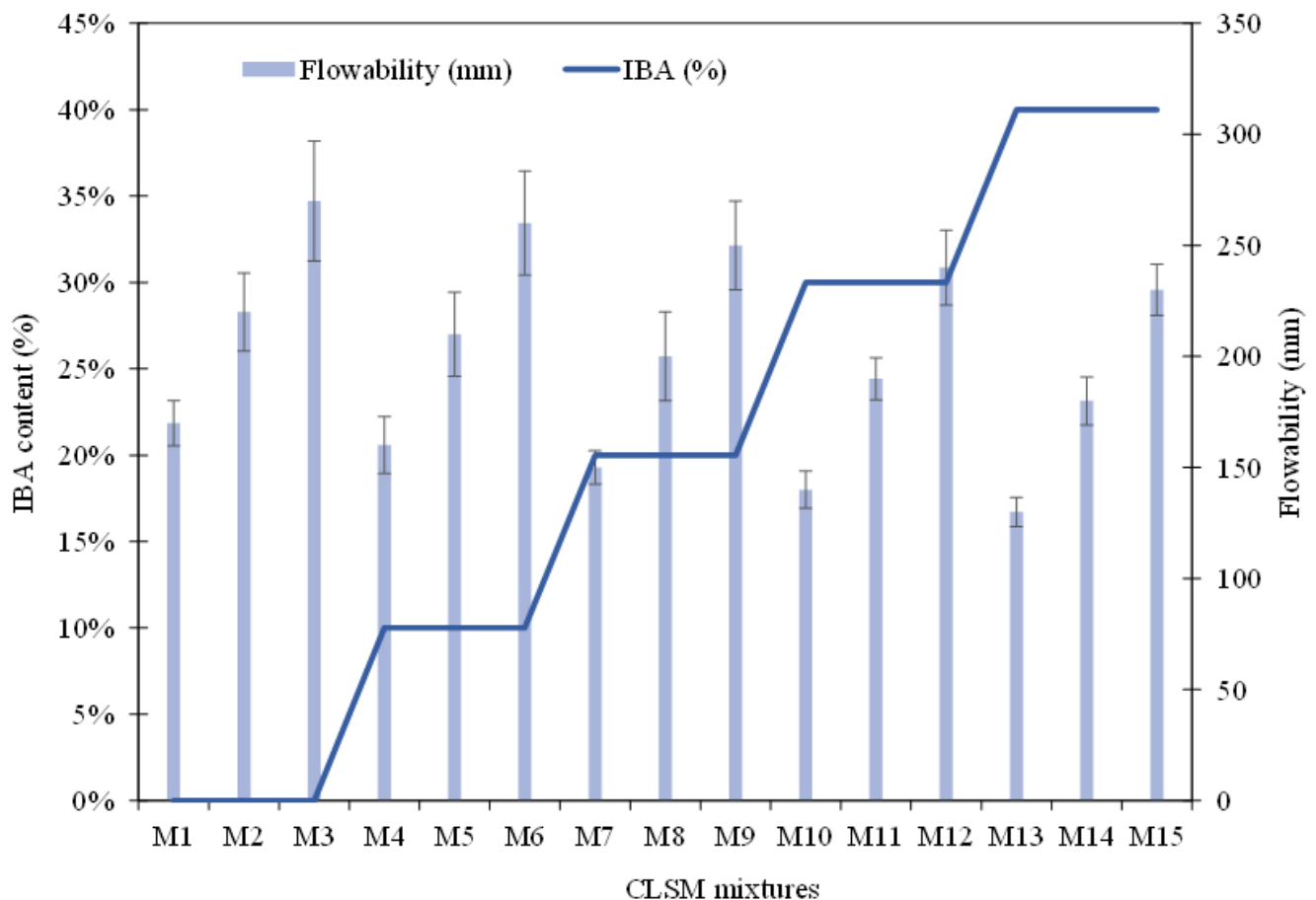


Fig. 5. Variation in flowability of CLSM mixtures

In contrast, the combined incorporation of fly ash and pre-formed foam became the dominant modifying factor affecting fresh workability within the tested mixture system, partially offsetting the workability reduction caused by IBA. The addition of 20% fly ash and foam consistently increased flowability by more than 50% across all IBA

replacement levels. For instance, mixture M3 achieved the highest recorded flowability of 270 mm, representing a 58.8% increase relative to the control. More importantly, even in the high-waste group, mixture M15 (40% IBA with 20% additives) attained a flowability of 230 mm, corresponding to a 76.9% improvement compared with its non-foam

counterpart M13 and exceeding the flowability of the natural sand control mixture by 35.3%. These results indicate that the rheological benefits associated with fly ash and foam can, under the tested conditions, outweigh the adverse effects of angular waste aggregates when appropriately dosed. The enhanced flowability observed in additive-rich mixtures can be attributed to a combined lubrication mechanism. The spherical morphology of fly ash particles provides a well-established “ball-bearing” effect that reduces interparticle friction and improves particle mobility within the paste. Concurrently, the uniformly distributed air bubbles generated by the pre-formed foam act as deformable inclusions, further facilitating flow by reducing internal resistance and

promoting a more homogeneous stress distribution during deformation. This synergistic action allows the mixture to maintain self-compacting characteristics even at high IBA contents, consistent with observations reported by Bodur et al. [40]. Overall, the flowability results indicate that while IBA incorporation alone significantly compromises workability, the combined use of fly ash and pre-formed foam provides an effective strategy to restore and even enhance flowability. This finding is particularly relevant for CLSM applications, where high flowability is essential for self-leveling and complete filling of confined spaces, and highlights the importance of mixture optimization when pursuing high-volume waste utilization.

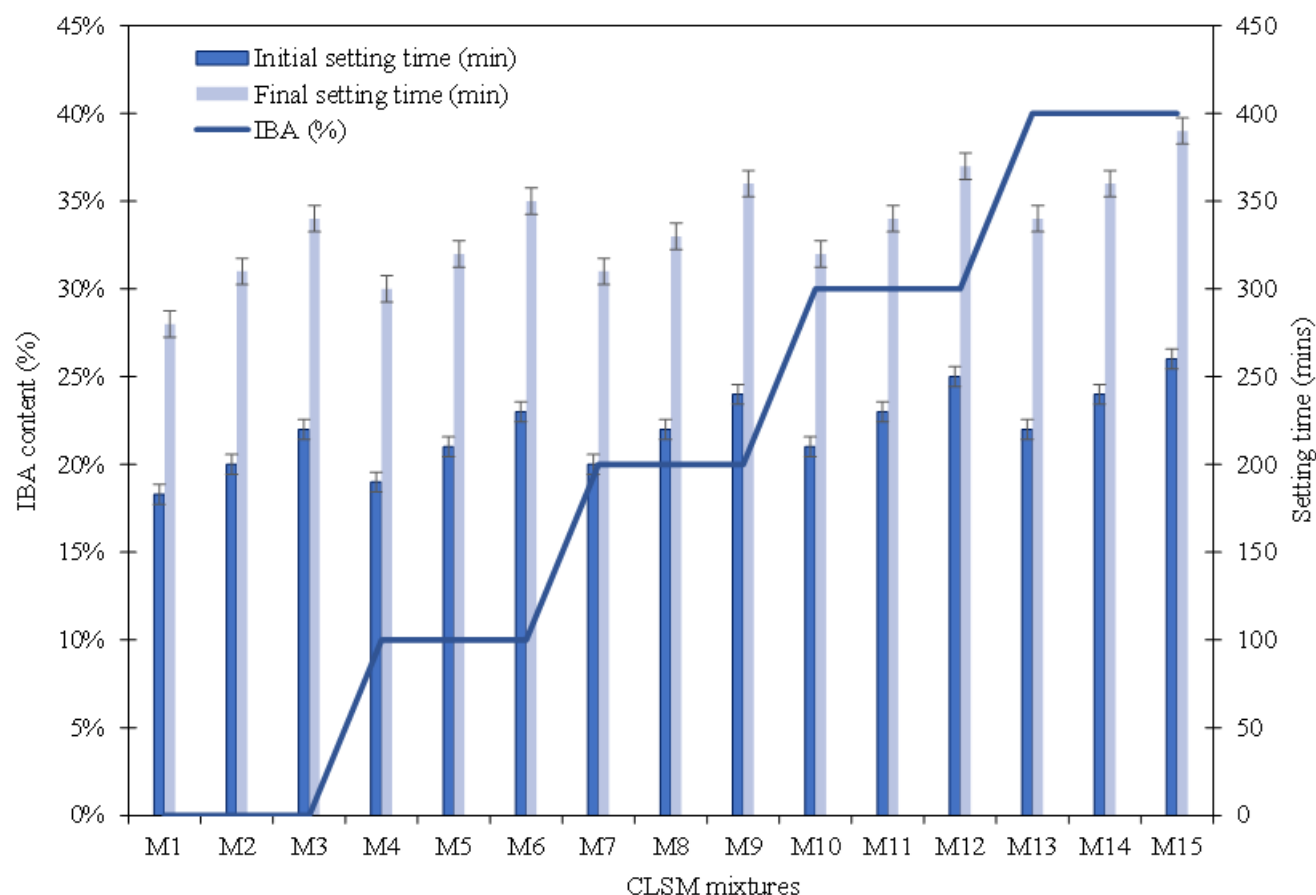


Fig. 6. Initial and final setting times of CLSM mixtures

3.3. Setting times

The setting time results (Fig. 6) show that IBA, fly ash, and pre-formed foam influence hydration through different mechanisms, and the overall delay reflects their combined effects.

Because fly ash and foam were varied together in the present mixture matrix, the following discussion distinguishes their likely contributions based on controlled comparisons where possible, while recognizing that some effects remain coupled.

Initial setting times ranged from 183 to 260 min and final setting times from 280 to 390 min, indicating that changes in water availability, binder reactivity, and pore/phase continuity govern stiffness development.

To isolate the role of IBA, mixtures without fly ash and foam were compared at increasing IBA replacement. As natural sand was progressively replaced by IBA, both initial and final setting times increased systematically. For example, the control mixture M1 exhibited an initial setting time of 183 min, whereas M13 with 40% IBA increased to 220 min (+20.2%). Final setting similarly increased from 280 min (M1) to 340 min (M13) (+21.4%). This retardation is primarily attributed to the porous and absorptive nature of IBA, which reduces early free-water availability and delays the formation of a continuous hydration product network. In addition, dissolution of ionic species from bottom ash into the pore solution may interfere with early hydration reactions, further slowing setting, as reported by Liu et al. [41].

At a fixed aggregate condition (no IBA), introducing fly ash and foam (M3) increased the initial setting time to 220 min, confirming that binder replacement and foam also contribute substantially to the delay. The fly ash component can prolong early setting mainly through cement dilution and slower early-age pozzolanic kinetics compared with cement hydration. Meanwhile, the foam introduces a discontinuous air-void system that reduces solid-phase connectivity and slows the percolation of hydration products required for rigidity development; surfactant films around bubbles may also hinder water–cement contact at early ages. Similar foam/air-void induced retardation has been reported for lightweight cementitious systems by Zhang et al. [7].

When high IBA content was combined with fly ash and foam, the longest setting times were observed. Mixture M15 (40% IBA + 20% fly ash + foam) reached 260 min initial and 390 min final setting time, corresponding to increases of 42.1%

and 39.3%, respectively, compared with M1. Although fly ash contributes to early retardation, it should not be viewed only as a negative factor: under adequate curing and appropriate mixture design, fly ash can improve later-age performance through filler and pozzolanic effects that refine pore structure and densify the matrix. Therefore, fly ash in this study is interpreted as an early-age retarder with potential later-age benefits, while foam mainly governs setting delay through increased air-void discontinuity.

All mixtures satisfied the minimum initial setting time requirement (45 min) in TCVN 6017:2015; however, the final setting time of M15 slightly exceeded the recommended upper limit (375 min). This indicates that while retardation can be beneficial for providing sufficient working time during placement, excessive combined dosages of IBA, fly ash, and foam may result in overly prolonged hardening and should be carefully calibrated for practical applications.

3.4. Water absorption

Fig. 7 illustrates the evolution of water absorption as a function of mixture composition, highlighting the dominant role of internal porosity introduced by both IBA and pre-formed foam. Across all mixtures, measured absorption values ranged from 3.54% to 5.91%, reflecting substantial variation in pore structure despite the relatively narrow range of binder and water contents. In mixtures without foam and fly ash, water absorption increased steadily with increasing IBA replacement. The control mixture M1 exhibited the lowest absorption value of 3.54%, whereas mixture M13, incorporating 40% IBA, reached 5.28%, corresponding to an increase of approximately 49.2%. This trend is primarily associated with the intrinsic characteristics of the bottom ash. Compared with dense river sand, IBA particles possess a highly porous internal structure and rough surface texture, which not only increases their own water uptake but also promotes the formation of a more open interfacial transition zone

within the hardened matrix. As a result, the overall permeable pore volume increases with higher IBA content. Similar observations have been reported by Yan et al. [23], who attributed elevated absorption in bottom-ash-based mortars to the combined effects of particle porosity and reduced matrix densification.

The influence of pre-formed foam on water absorption is even more pronounced and acts as the controlling factor in highly modified mixtures. Regardless of IBA content, mixtures incorporating 20% foam consistently exhibited the highest absorption values within their respective groups. For example, mixture M3 (20% foam without IBA)

recorded an absorption of 5.44%, representing a 53.7% increase compared with the control mixture. When high IBA content and foam were combined, the effect became cumulative: mixture M15 reached the maximum absorption of 5.91%, corresponding to a 66.9% increase relative to M1. This behavior reflects the development of a dual-porosity system, in which the micro-pores inherent to IBA coexist with the macro-scale voids introduced by pre-formed foam. Such a pore hierarchy significantly increases the volume of interconnected voids available for water ingress, as previously observed in foam-modified lightweight cementitious systems by Le et al. [24].

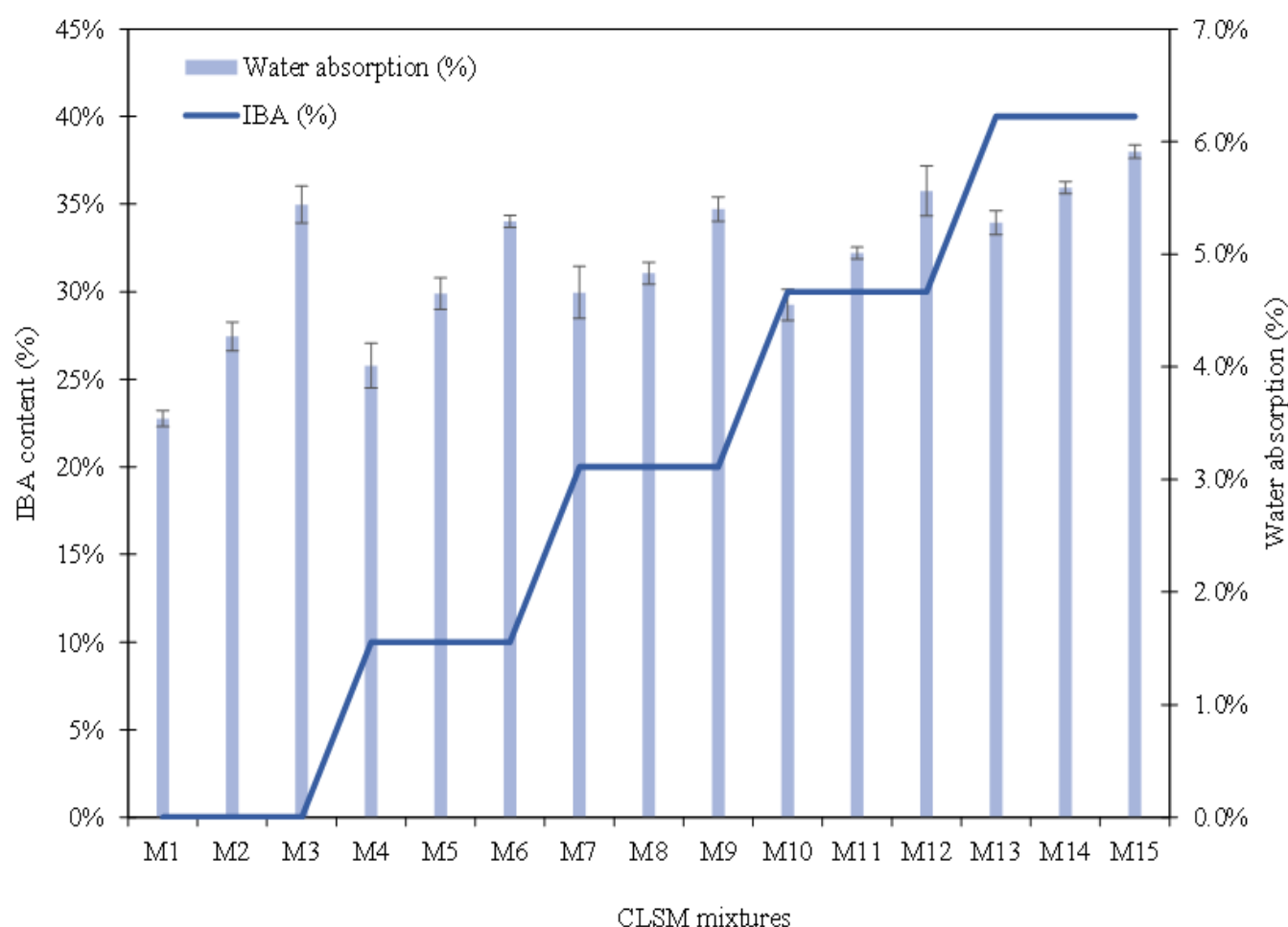


Fig. 7. Water absorption of hardened CLSM samples at 28 days

Despite this general increase, the presence of fly ash appears to partially moderate the rise in water absorption. Although fly ash does not fully offset the porosity introduced by IBA and foam, comparisons among mixtures with similar foam

contents suggest a slight dampening effect. This can be attributed to the filler action and pozzolanic reactivity of fly ash, which contribute to pore refinement by filling interstitial voids and forming secondary C–S–H gel that locally densifies the

paste. Consequently, the increase in absorption is less severe than would be expected from the simple superposition of porous aggregate and air-void effects. From an application perspective, it is important to note that all measured absorption values remained below 6%. While higher than those of conventional dense mortars, these values remain within a range that may be acceptable for

many CLSM and lightweight backfilling applications, provided that the target use does not require low-permeability performance. Therefore, although increased absorption is an inherent trade-off of high-volume waste and foam incorporation, it does not preclude the practical use of the developed CLSM mixtures for non-structural and geotechnical applications.

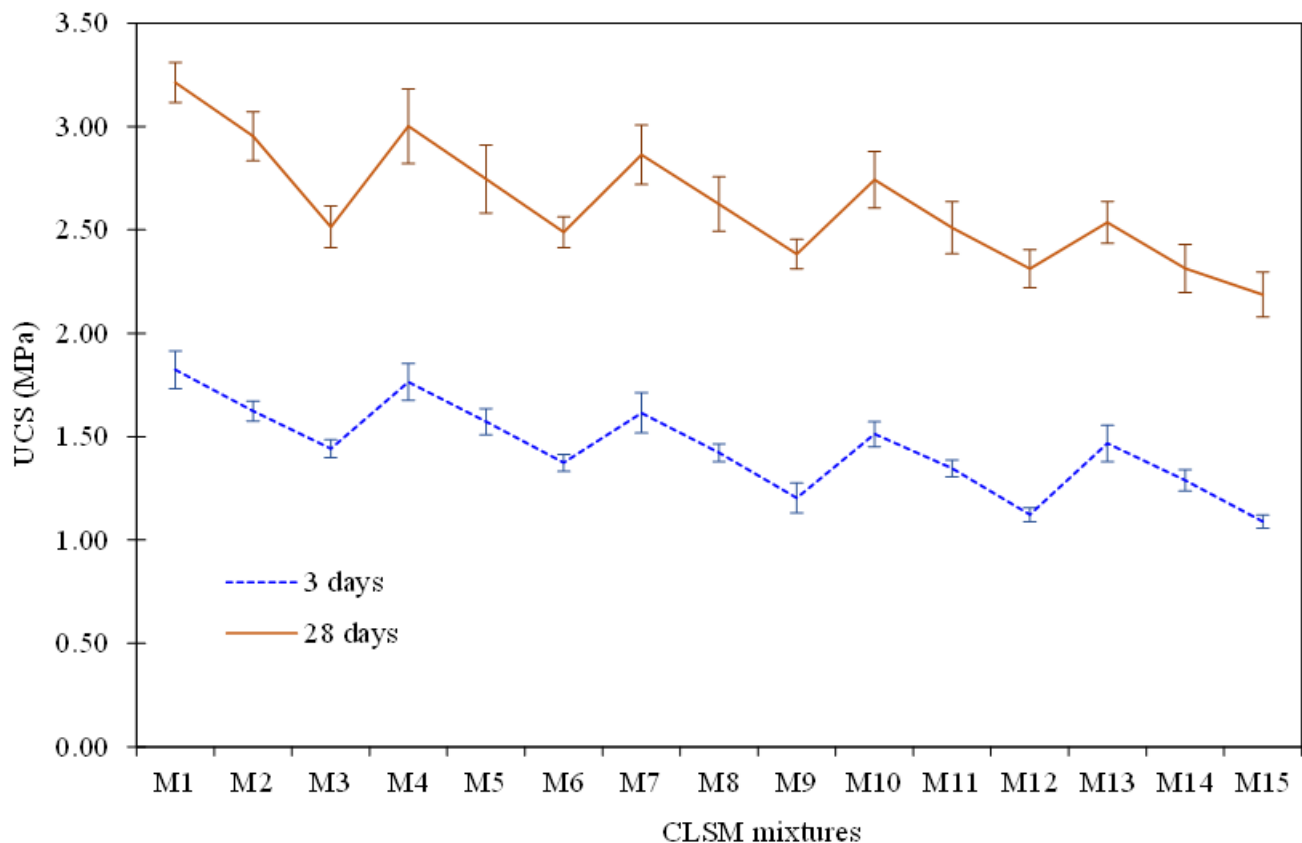


Fig. 8. Development of UCS at 3 and 28 days for all CLSM mixtures

3.5. Unconfined compressive strength (UCS)

The development of UCS reflects the combined influence of mixture porosity, aggregate quality, and hydration kinetics, as shown in Fig. 8. At an early curing age of 3 days, UCS values ranged from 1.089 MPa to 1.823 MPa, indicating a relatively slow strength development characteristic of CLSM systems incorporating high volumes of waste materials and pre-formed foam. The control mixture M1 exhibited the highest early-age strength (1.823 MPa), whereas mixture M15, containing the highest combined levels of IBA and additives, showed the lowest value of 1.089 MPa, corresponding to a reduction of approximately

40.3%. This early-age strength loss can be attributed mainly to two concurrent factors: the absorption of mixing water by porous IBA particles, which delays effective cement hydration, and the reduction of the effective load-bearing cross-sectional area caused by air voids introduced through foam incorporation. A similar monotonic decline in early-age compressive strength with increasing IBA content has been reported by Avudaippan et al. [4], who associated this behavior with the lower density and higher porosity of MSWI-derived aggregates.

By 28 days, all mixtures exhibited a clear increase in UCS, with values ranging from 2.187

MPa to 3.213 MPa, confirming ongoing hydration and matrix densification over time. Nevertheless, the negative influence of IBA on mechanical performance remained evident. Replacing natural sand with 40% IBA reduced the 28-day UCS from 3.213 MPa in the control mixture to 2.536 MPa in M13, representing a decrease of approximately 21.1%. This reduction reflects the inherently lower crushing strength and higher deformability of IBA particles compared with dense siliceous sand, which limits their ability to effectively transfer compressive stresses within the hardened matrix. In addition, the angular and irregular morphology of the ash particles can promote localized stress concentrations at the aggregate–paste interface, facilitating microcrack initiation under compressive loading, as also observed by Zhang et al. [8].

The influence of foam and fly ash on 28-day UCS followed a similar downward trend, largely governed by the air-entrainment mechanism of the foam. When 20% fly ash and foam were incorporated without IBA (mixture M3), the UCS decreased to 2.514 MPa, corresponding to a 21.8% reduction relative to the control mixture. Although fly ash is generally associated with long-term strength enhancement through pozzolanic reactions [42], the high foam content in this mix generated a level of porosity that dominated the mechanical response at 28 days, outweighing the potential densification benefits of secondary C–S–H formation. The combined influence of porous aggregates and pre-formed foam was most pronounced in mixture M15, which exhibited the lowest 28-day UCS of 2.187 MPa.

Despite the strength reductions, all mixtures still achieved 28-day UCS values well above 1.0 MPa, which is commonly considered a minimum level for CLSM and non-structural fill applications. Even the weakest mixture (M15) exceeded this threshold, indicating adequate load-bearing capacity for typical uses such as trench backfilling, utility bedding, and void filling. It should also be emphasized that CLSM is often intentionally

designed as a controlled low-strength material to ensure serviceability while maintaining excavatability for future maintenance. Accordingly, the UCS decreases associated with higher IBA and foam contents should be interpreted relative to the target strength class and practical performance objectives, rather than as a universal drawback. The results indicate that an appropriate balance between waste utilization and mechanical performance can be achieved without compromising the functional requirements of CLSM systems.

3.6. Durability

The durability of the CLSM mixtures was assessed under simulated acid rain and seawater exposure to represent aggressive tropical coastal conditions in the Can Gio region. As shown in Fig. 9, durability is controlled by competing mechanisms: (i) increased porosity and permeability caused by IBA and foam, which accelerates ingress of aggressive ions and leaching; and (ii) the potential mitigation from fly ash through reduced portlandite content and later-age matrix refinement. The measured trends indicate that, within the exposure duration and mixture design used in this study, transport-controlled effects dominate [21].

Under acid rain exposure, degradation was mainly associated with surface softening and leaching of alkaline hydration products, resulting in compressive strength reductions of 4.77–10.51%. The control mixture M1 showed the best resistance, with only 4.77% strength loss and 1.80% mass loss. Increasing IBA content reduced acid resistance; for example, M13 (40% IBA without foam) exhibited a 7.91% strength reduction (≈ 1.65 times that of M1). The most severe loss occurred in M15 (40% IBA + 20% fly ash + foam), with 10.51% strength loss and 3.39% mass loss. This behavior is attributed to acid attack on alkaline hydration products (notably $\text{Ca}(\text{OH})_2$ and decalcification of C–S–H), while the more connected pore network generated by porous IBA

particles and foam facilitates deeper penetration beyond the surface zone and accelerates matrix weakening.

Under seawater exposure, deterioration was more pronounced, with strength losses of 8.34–16.61%, confirming that marine conditions are more severe for these CLSM systems. Even M1 showed 8.34% strength loss. Consistent with acid rain results, higher-porosity mixtures experienced greater degradation: M13 lost 13.10% strength, and M15 exhibited the largest loss of 16.61% with

3.61% mass loss. The damage is likely driven by combined chemical and physical actions, including magnesium and sulfate interactions with hydration products (leading to destabilization of the binder gel) and salt crystallization within capillary pores that generate internal pressures and microcracking during moisture fluctuations. The porous and angular IBA particles may further intensify this process by retaining saline solution and promoting repeated crystallization/ingress within the internal pore structure [43].

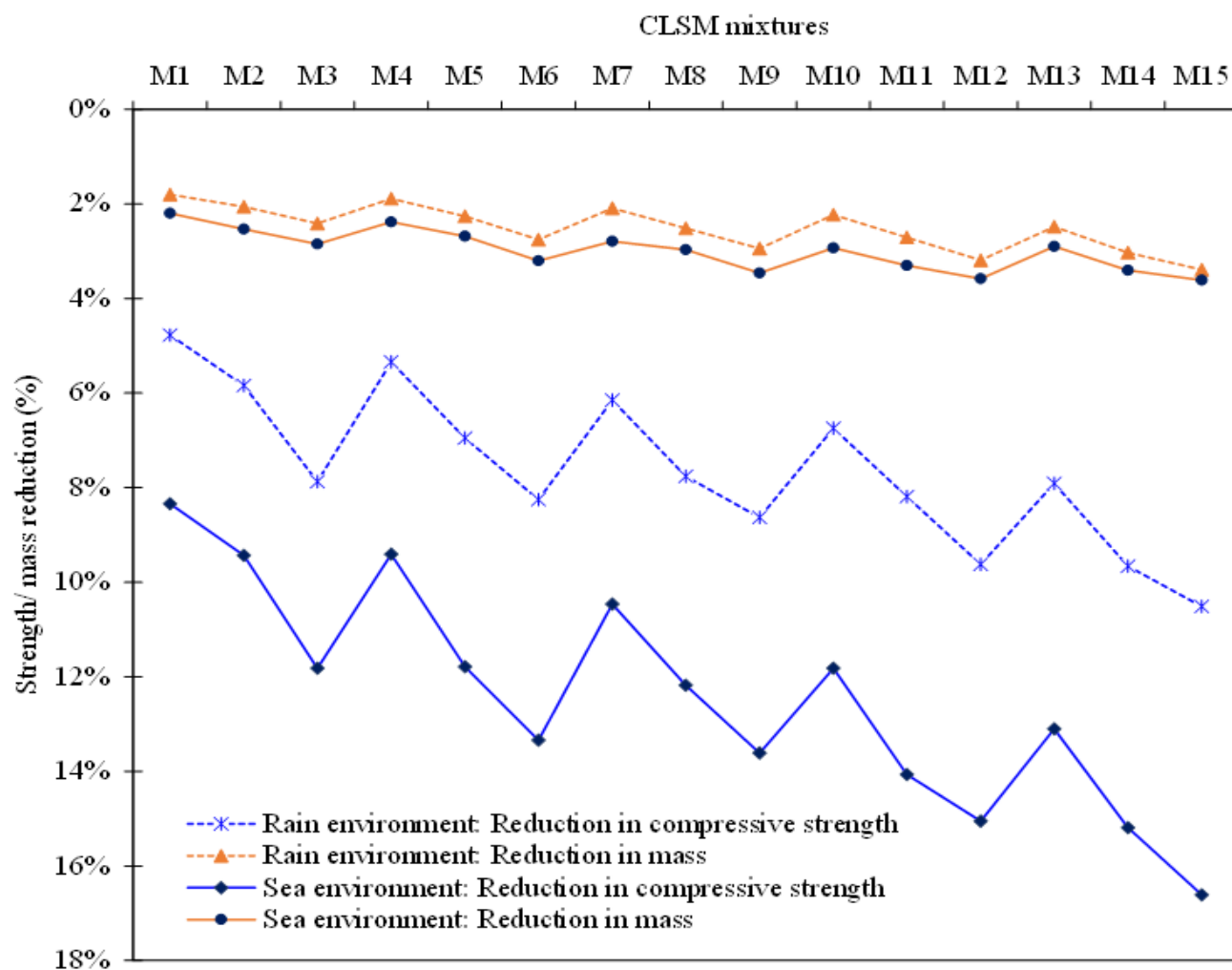


Fig. 9. Durability test results of CLSM mixtures

Importantly, the role of fly ash should be interpreted in this competitive framework. Fly ash can improve durability in marine environments by reducing portlandite, lowering the amount of readily leachable phases, and refining pore structure through filler and pozzolanic reactions at later ages. However, in the present IBA–fly ash–foam

mixtures, the increase in void content and connectivity associated with foam and high IBA replacement increases permeability and accelerates ion transport, which can outweigh fly ash's refinement benefits over the exposure period considered. This explains why the fly ash-containing, high-porosity mixture (M15) still

exhibited the greatest strength loss under seawater exposure.

A direct comparison confirms that seawater exposure was substantially more aggressive than acid rain for the tested mixes. Nevertheless, even the most vulnerable mixture (M15) retained more than 83% of its original compressive strength after seawater exposure and about 89% after acid rain exposure, indicating that the overall integrity of the

CLSM remained largely intact. From a practical perspective, these results suggest that mixtures incorporating moderate levels of IBA and foam can be suitable for non-structural backfilling applications in aggressive environments, provided that mixture selection prioritizes a balance between workability, stability, and durability and avoids excessively high connected porosity.

3.7. Correlation analysis

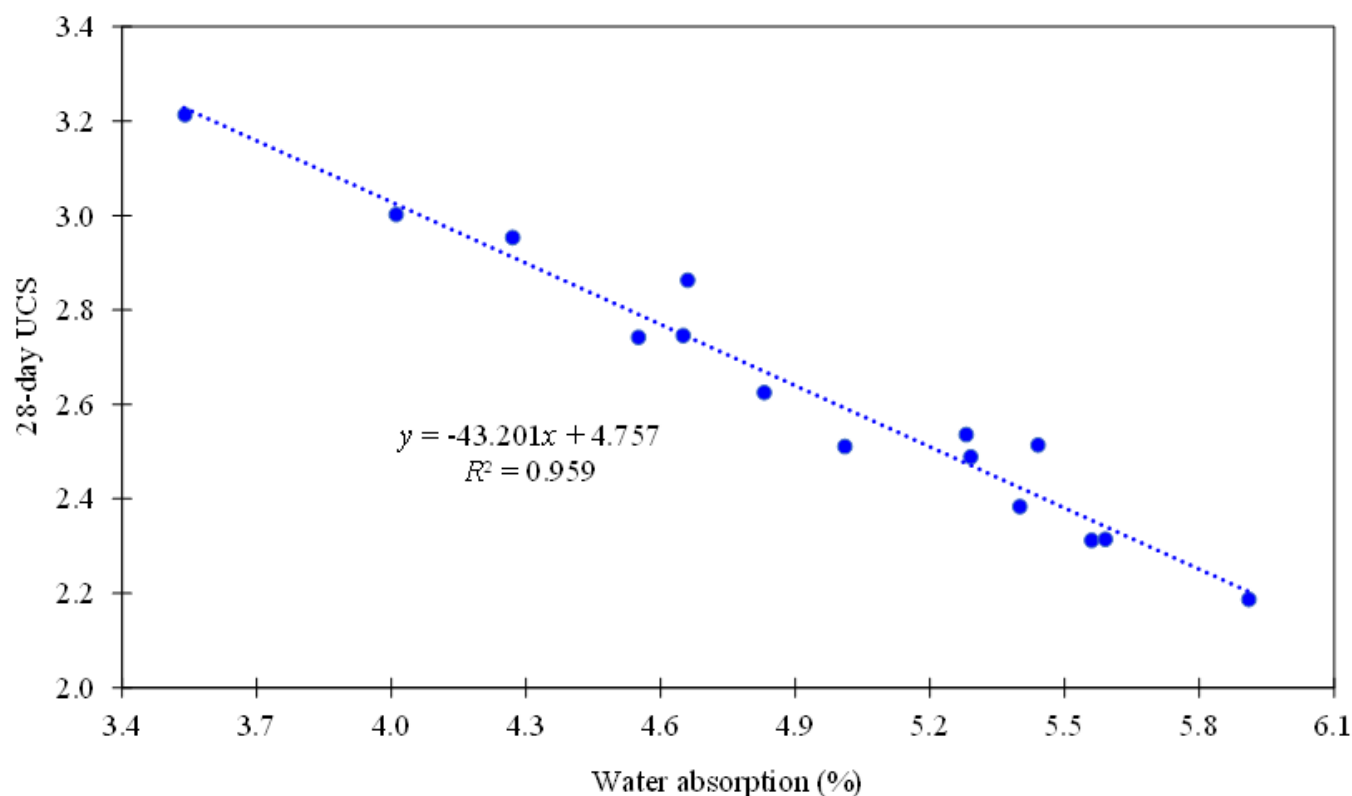


Fig. 10. Correlation between water absorption and 28-day compressive strength

The relationship between water absorption and 28-day UCS provides a quantitative link between mixture porosity and mechanical performance. As shown in Fig. 10, a strong negative linear correlation is observed across all mixtures (M1–M15), indicating that increased water absorption, as a proxy for porosity, directly compromises compressive strength. Linear regression analysis yielded the relationship $y = -43.201x + 4.757$, where y represents the 28-day UCS (MPa) and x denotes water absorption expressed as a dimensionless fraction (e.g., 0.04 for 4%). The coefficient of determination ($R^2 = 0.959$) indicates an exceptionally strong

correlation, with approximately 96% of the variation in compressive strength explained by changes in water absorption. This result indicates that water absorption, as an indirect indicator of accessible pore volume, is strongly associated with the mechanical response of the developed CLSM mixtures, regardless of whether porosity originates from porous IBA particles or air voids introduced by foam. The intermediate mixtures generally follow the same linear trend, suggesting a progressive reduction in compressive strength as water absorption increases. This finding reinforces the importance of limiting excessive water absorption when designing CLSM mixtures, particularly in

applications where a minimum strength threshold must be maintained.

The interdependence between bleeding and flowability was further examined by comparing mixtures without foam (0% foam group) and those incorporating 20% foam group, as illustrated in Fig. 11. In both cases, the relationship between bleeding percentage and flowability follows a shallow non-linear (quadratic) trend rather than a simple linear dependency. The coefficients of determination were $R^2 = 0.755$ for the 0% pre-formed foam group and $R^2 = 0.737$ for the 20% pre-formed foam group, indicating a moderate but meaningful correlation. For mixtures without pre-formed foam, increasing bleeding from approximately 3% to 6% was generally accompanied by a reduction in flowability from about 170 mm to 130–140 mm. This behavior reflects the progressive loss of matrix cohesion as free water migrates upward, leaving behind a stiffer granular skeleton dominated by angular IBA

particles. At higher bleeding levels, the reduced continuity of the paste phase limits deformation under self-weight, resulting in lower flow despite the presence of excess water. In contrast, mixtures containing 20% pre-formed foam consistently exhibited substantially higher flowability over the same bleeding range, with flowability remaining between approximately 230 mm and 270 mm. Although a slight reduction in flowability was still observed as bleeding increased, the magnitude of this reduction was clearly smaller than that of the mixtures without foam. This suggests that the presence of pre-formed foam modified the fresh-state response sufficiently to preserve high workability even when some water separation was still present. Overall, the correlation analysis indicates that bleeding influences flowability, but does not solely control it; the combined effects of foam and fly ash also play an important role in determining the fresh-state performance of the tested CLSM mixtures.

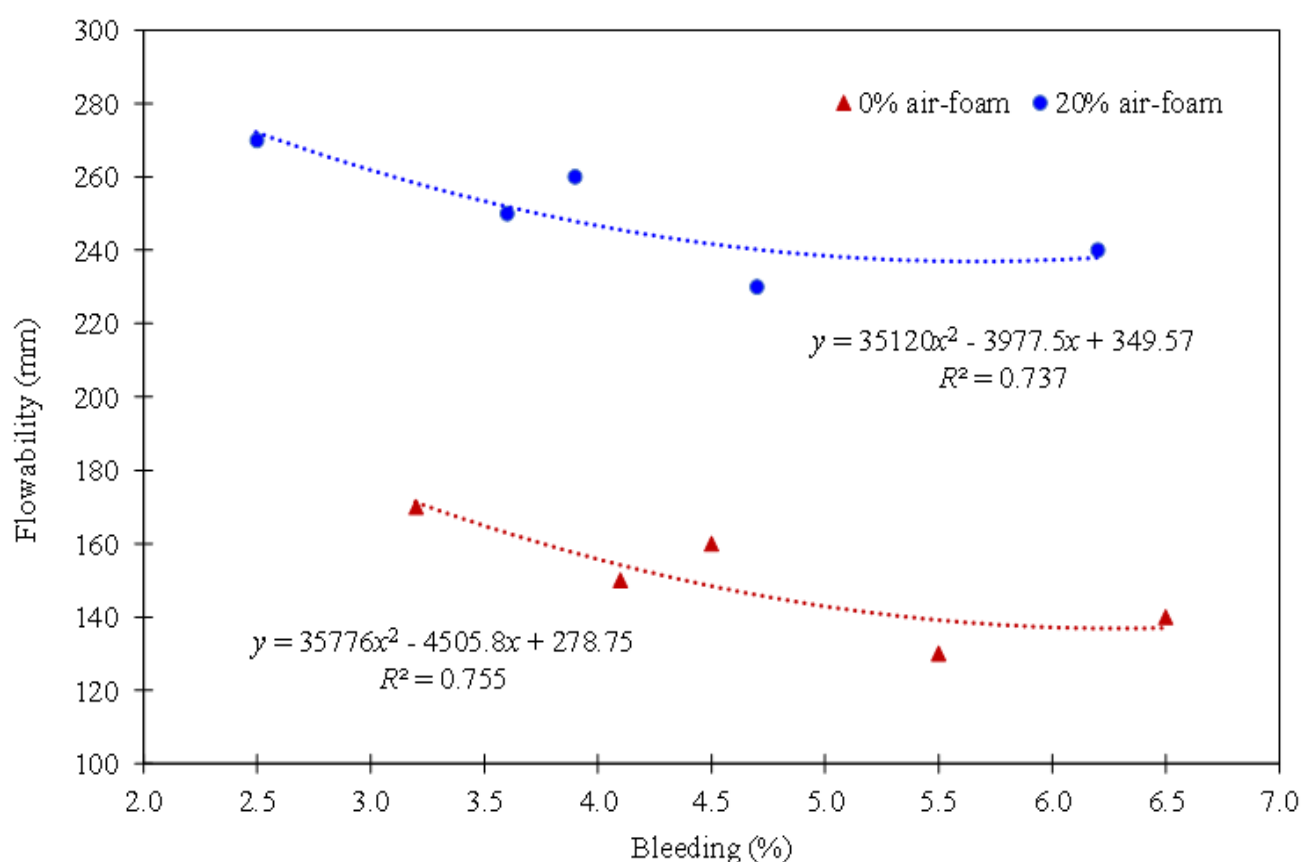


Fig. 11. The relationship between bleeding percentage and flowability for mixtures without foam and with 20% pre-formed foam

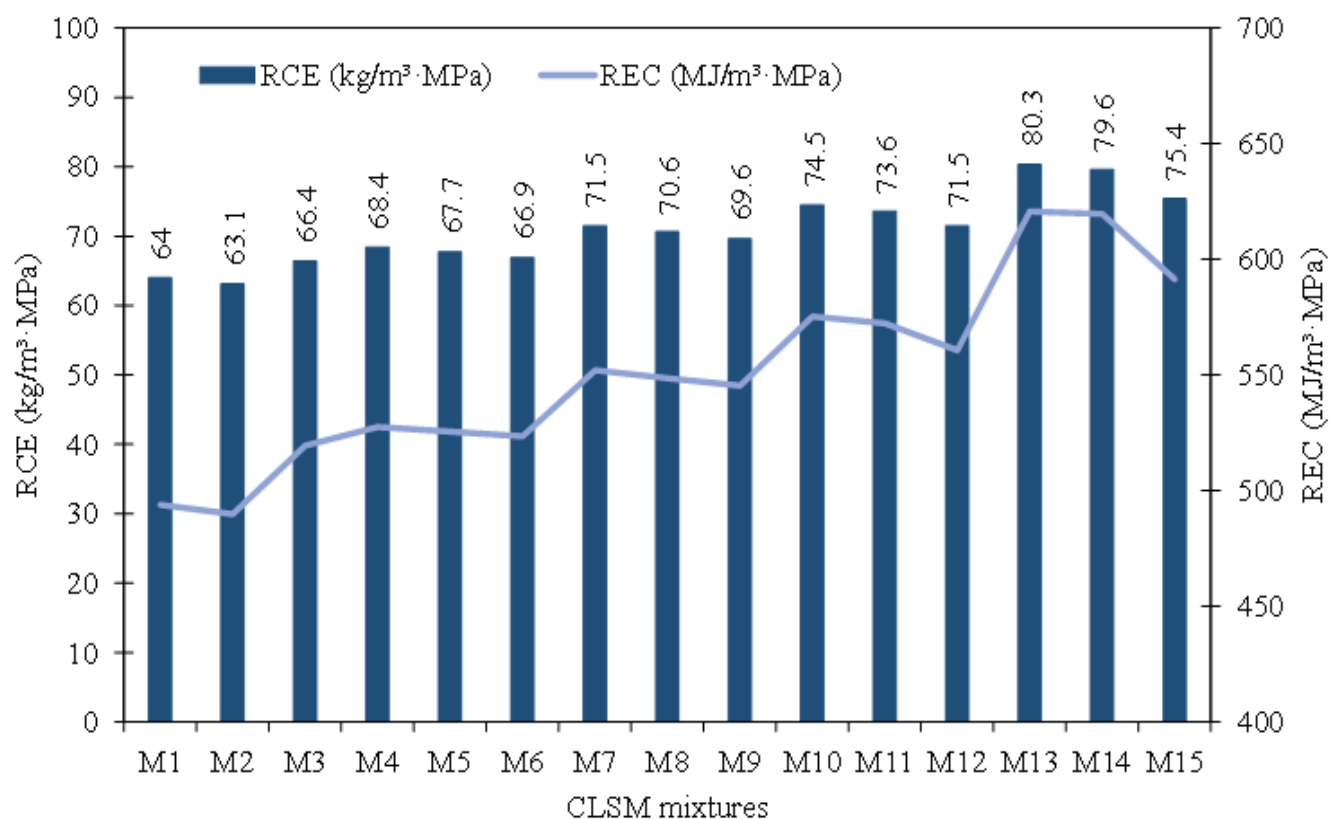


Fig. 12. Eco-mechanical indicators (RCE and REC) of CLSM mixtures

Table 3. Normalized MCA scores, integrating mechanical performance, durability, and sustainability indicators (RCE and REC)

Mix ID.	Norm. bleeding	Norm. flowability	Norm. final setting time	Norm. water absorption	Norm. UCS 28d	Norm. mass reduction	Norm. UCS reduction	Norm. RCE	Norm. REC	Final score
M1	0.77	0.29	1.00	1.00	1.00	1.00	1.00	0.95	0.97	0.89
M2	0.23	0.64	0.73	0.69	0.75	0.81	0.87	1.00	1.00	0.75
M3	0.92	1.00	0.45	0.20	0.32	0.46	0.58	0.81	0.77	0.61
M4	0.50	0.21	0.82	0.80	0.79	0.90	0.87	0.69	0.71	0.70
M5	1.00	0.57	0.64	0.53	0.54	0.62	0.58	0.73	0.73	0.66
M6	0.63	0.93	0.36	0.26	0.29	0.39	0.40	0.78	0.74	0.53
M7	0.58	0.14	0.73	0.53	0.66	0.76	0.74	0.51	0.52	0.58
M8	0.00	0.50	0.55	0.46	0.43	0.48	0.54	0.56	0.55	0.45
M9	0.69	0.86	0.27	0.22	0.19	0.33	0.36	0.62	0.58	0.46
M10	0.08	0.07	0.64	0.57	0.54	0.66	0.58	0.34	0.35	0.43
M11	0.75	0.43	0.45	0.38	0.32	0.40	0.31	0.39	0.37	0.42
M12	0.15	0.79	0.18	0.15	0.12	0.16	0.19	0.51	0.46	0.30
M13	0.29	0.00	0.45	0.27	0.34	0.45	0.42	0.00	0.00	0.25
M14	0.40	0.36	0.27	0.14	0.12	0.15	0.17	0.04	0.01	0.18
M15	0.46	0.71	0.00	0.00	0.00	0.00	0.00	0.28	0.22	0.19

3.8. Eco-mechanical efficiency (RCE and REC)

The eco-mechanical performance of the CLSM mixtures was evaluated using the strength-normalized indicators RCE ($\text{kg/m}^3\cdot\text{MPa}$) and REC ($\text{MJ/m}^3\cdot\text{MPa}$), which express embodied carbon emissions and energy consumption per unit of compressive strength. As illustrated in Fig. 12, RCE values ranged from approximately 63 to 80 $\text{kg/m}^3\cdot\text{MPa}$, while REC values ranged from approximately 490 to 620 $\text{MJ/m}^3\cdot\text{MPa}$. M2 exhibited the lowest RCE and REC values, and M1 also lay near the lower end of both ranges. This agrees with their high normalized environmental scores in Table 3, where a higher score denotes a lower RCE or REC. Increasing IBA replacement generally increased both strength-normalized indicators. Within the IBA-containing series, the combined addition of fly ash and foam generally reduced RCE and REC relative to the corresponding mixture without these additions, as seen for M6 versus M4 and M12 versus M10. However, M3, M6, and M12 did not have the lowest values across all fifteen mixtures. M13 exhibited the highest RCE and REC values. These results show that reducing cement content does not necessarily minimize environmental burdens per unit of strength, because the accompanying strength reduction also affects the ratios. The indicators therefore describe the balance between estimated embodied impacts and measured mechanical capacity within the simplified assessment framework adopted here.

3.9. Multi-criteria assessment

The overall performance of the developed CLSM mixtures was evaluated using an MCA framework that integrates fresh-state properties (bleeding and flowability), setting behavior, hardened performance (water absorption and 28-day UCS), durability under acid rain and seawater exposure, and strength-normalized sustainability indicators (RCE and REC). Under the adopted equal-weight scheme, all nine criteria contributed proportionally to the final composite score,

enabling an objective comparison among mixtures with markedly different compositions. It should be noted that this ranking is therefore conditional on the adopted equal-weight assumption; different application-specific priorities could shift the relative preference among mixtures. As summarized in Table 3, mixtures with conventional or low levels of waste incorporation generally achieved higher composite scores. The control mixture M1 attained the highest overall score (0.89), reflecting its favorable setting behavior, low water absorption, high compressive strength, and superior durability, combined with relatively low RCE and REC values. Similarly, mixture M2 (0% IBA, 10% fly ash, 10% foam) achieved a high score of 0.75, benefiting from enhanced flowability and reduced environmental impact while maintaining acceptable mechanical and durability performance. Mixture M4 (10% IBA without foam) also performed strongly, with a score of 0.70, indicating that limited IBA replacement can be introduced without compromising overall performance. Among mixtures emphasizing sustainability, mixture M5 (10% IBA, 10% fly ash, and 10% foam) emerged as the most balanced option, achieving the highest score (0.66) within the waste-valorized group. This mixture effectively balanced fresh workability, mechanical capacity, durability, and environmental efficiency, demonstrating that moderate levels of waste incorporation can deliver robust overall performance. Accordingly, M5 should be interpreted as the most balanced option within the selected weighting framework, rather than as a universally optimal mixture for all CLSM applications. Mixtures M6 and M7 followed with scores of 0.53 and 0.58, respectively, suggesting that further increases in waste content remain feasible but introduce increasing trade-offs, particularly in strength and durability.

In contrast, mixtures with the highest waste and foam contents (M9, M12, M13, M14, and M15) exhibited substantially lower MCA scores, ranging

from 0.18 to 0.46. These lower scores are primarily attributed to reduced compressive strength, elevated water absorption, prolonged setting times, and increased susceptibility to environmental degradation. In addition, strength normalization amplified the penalties associated with lower UCS values, leading to higher relative RCE and REC contributions despite reduced absolute environmental burdens. Overall, the MCA results clearly indicate that while low-waste mixtures naturally achieve the highest composite scores, certain waste-optimized mixtures—particularly M5—provide a compelling balance between sustainability and engineering performance. This finding underscores the importance of integrated performance-based evaluation when designing CLSM systems for high-volume waste utilization, as single-criterion optimization would fail to capture the complex trade-offs inherent in such materials. The identified ranking should therefore be interpreted as a decision-support outcome specific to the adopted equal-weight scenario. In practice, alternative weighting strategies emphasizing excavatability, durability, or environmental efficiency could lead to different mixture preferences.

4. Conclusion

This study experimentally evaluated the feasibility of producing foam-based eco-lightweight CLSM incorporating high volumes of IBA, fly ash, and pre-formed foam. Based on the experimental results and integrated multi-criteria evaluation, the following conclusions can be drawn:

Increasing IBA replacement from 0% to 40% reduced flowability from 170 mm to 130 mm (−23.5%) and increased water absorption by up to 49.2%, reflecting the unfavorable influence of the porous and angular characteristics of IBA on fresh and hardened behavior. Nevertheless, the incorporation of fly ash and foam effectively compensated for this workability loss, with 20% additives increasing flowability to a maximum of 270 mm (+58.8% relative to the control).

Both IBA and foam acted as hydration retarders. Initial and final setting times increased from 183–280 min for the control mixture to 260–390 min for the mixture with 40% IBA and 20% additives, corresponding to delays of approximately 42% and 39%, respectively. While all mixtures satisfied the minimum initial setting time requirement, excessive additive dosages may require calibration to avoid overly prolonged hardening.

Water absorption increased progressively with both IBA and foam incorporation, reaching a maximum of 5.91% in the most porous mixture. Despite this increase, all mixtures maintained absorption levels below 6%, which are considered acceptable for CLSM and lightweight backfilling applications.

UCS decreased with increasing porosity. The 28-day UCS declined from 3.213 MPa for the control mixture to 2.187 MPa for the mixture with the highest combined waste and foam content (−31.9%). Importantly, all mixtures exceeded the typical minimum requirement of 1.0 MPa for CLSM applications, confirming their suitability for non-structural and geotechnical uses.

Durability assessment revealed strength losses of 4.77–10.51% under acid rain exposure and 8.34–16.61% under seawater immersion, indicating that seawater exposure was consistently more severe than acid-rain exposure for the mixtures tested. Even under the most severe exposure, all mixtures retained more than 83% of their original strength, demonstrating acceptable durability for confined or protected applications such as coastal and municipal backfilling.

Eco-mechanical indicators (RCE and REC) showed limited variation across mixtures (63–80 kg/m³·MPa and 490–620 MJ/m³·MPa), with M2 exhibiting the lowest values and M1 remaining near the lower end of both ranges. Increasing IBA replacement generally increased these strength-normalized indicators, whereas the combined addition of fly ash and foam generally reduced

them within the IBA-containing series. Environmental efficiency therefore depends on the balance between embodied impacts and compressive strength.

The normalized multi-criteria assessment identified mixture M5 (10% IBA, 10% fly ash, and 10% foam) as the most balanced sustainable option, achieving an MCA score of 0.66 while maintaining adequate flowability (~210 mm), moderate bleeding (~4.0%), acceptable porosity (~5.0%), a 28-day UCS exceeding 2.5 MPa, and strength retention of 85–88% under aggressive environments.

Overall, the results indicate that the combined incorporation of IBA, fly ash, and pre-formed foam can produce lightweight CLSM with a favorable balance between engineering performance and strength-normalized sustainability indicators for non-structural, coastal, and municipal backfilling applications. However, the recommended mixture ranking remains dependent on the adopted MCA weighting scheme and should be further validated through long-term durability, microstructural, and field-scale studies.

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Declaration of Generative AI

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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