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An assessment of terrazzo tile properties: Effect of waste incineration bottom ash content

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KEYWORDS

Terrazzo tiles
Waste incineration bottom ash
Flexural strength
Water absorption
Surface abrasion

ABSTRACT

The increasing scarcity of natural aggregates and the rising cost of raw materials in the construction industry are driving the demand for sustainable alternatives. At the same time, municipal solid waste incineration generates significant volumes of bottom ash, which is typically landfilled, posing environmental and economic challenges. This study explores the technical and economic feasibility of using waste incineration bottom ash (WIBA), blended with coal thermal fly ash (FA), as a partial or full substitute for crushed sand in the production of terrazzo tiles—a high-value, architectural cementitious product requiring strong mechanical performance and a polished surface finish. Five mix designs were developed, with WIBA-FA blends at a fixed WIBA:FA ratio of 75:25 by mass were used to replace 0% (control), 70%, 80%, 90%, and 100% crushed sand in the mixtures. The tiles were fabricated using a semi-dry pressing method and cured for 28 days before testing. Experimental evaluation included flexural and compressive strengths, full and surface water absorption, surface abrasion resistance, and material cost analysis. Results showed that the mix (X5) with 70 % WIBA inclusion achieved a 30.1 % reduction in cost while meeting all technical requirements, with compressive and flexural strengths of 28.6 MPa and 3.8 MPa, respectively. Moreover, a multivariate overall performance score was developed to identify the optimal formulation by integrating normalized strength, durability, and cost metrics. The experimental outcomes demonstrate the viability of using WIBA–FA blends in high-finish terrazzo tiles and contribute a quantitative framework for material optimization under sustainability and performance constraints.

1. Introduction

The construction industry is a major consumer of natural resources and a significant contributor to global CO_2 emissions [1], accounting for approximately 38 % of global energy-related emissions, primarily due to cement production and raw material extraction. As environmental concerns rise and urbanization accelerates, there is increasing demand for sustainable construction materials that reduce both resource consumption and ecological impact [2]. One promising direction is the incorporation of industrial waste and by-products into building materials, thereby supporting circular economy strategies and reducing landfill pressure [3].

Waste incineration bottom ash (WIBA), a by-product of municipal solid waste incineration, is produced in large quantities worldwide, with limited beneficial reuse and high environmental disposal costs [4]. In detail, the global municipal solid waste generation is rising rapidly, estimated to reach 2.2 billion tons per year by 2025, and around 15-25 wt.% of incinerated waste remains as ash, of which WIBA constitutes the major fraction [5], [6]. In Vietnam, although large-scale incineration is still developing, studies show that bottom ash is a dominant residue in incinerated waste, and emissions of hazardous metals in bottom ash have been documented at several Northern incinerators [7]. Typically classified as non-hazardous after proper processing, WIBA possesses granular characteristics and a broad particle size distribution, making it a potential alternative to fine aggregates in non-structural applications [8]. Recent studies have highlighted WIBA as a promising alternative to natural aggregates, supporting circular economy strategies in construction. Zou et al. [9] identified that while WIBA is non-hazardous and abundant, its reuse is limited by weak regulatory standards and decentralized management. Godyń et al. [10] reported that fine WIBA fractions (< 0.063 mm) pose higher leaching risks for Zn and Cu. Sliem et al. [11] addressed this using CO_2-assisted mechanochemical treatment, achieving up to 99 % heavy metal removal. On mechanical performance, Yuan et al. [12] found that replacing 10–20% cement with WIBA increased 3D concrete structuration rate from 2.9 to 7.3 Pa/min. Liu et al. [13] achieved 28-day compressive and flexural strengths of 53.5 MPa and 8.3 MPa, respectively, in sprayed mortars with 6% FA and 12% silica fume. Yan et al. [14] showed that 5% WIBA boosted the strength to 130.4 MPa at 28 days. Besides, geopolymer studies by Li et al. [15] and Zhang et al. [16] further improved strength to 43 MPa and 23.4 MPa, respectively,

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with Cr immobilization up to 86.4 %.

In tile and ceramic applications, WIBA and fly ash (FA) have also shown strong potential. Yuan et al. [12] reported that ceramic tiles with 30 % industrial waste FA reduced climate impact by 8 %, acidification by 10 %, ecotoxicity by 22.5 %, and cost by 11.3 %. Yuan et al. [17] found that 3–15 % high-CaO FA increased tile strength from 15.9 to 24.4 MPa, with water absorption under 6 % and compliant leaching results. Du et al. [18] developed WIBA-FA geopolymers with paraffin, achieving a latent heat of 53.5 J/g and reducing indoor temperature fluctuation by 1–1.5 °C. Overall, WIBA-FA blends offer cost-effective, durable solutions for architectural materials like terrazzo and ceramic tiles. However, the physical performance of WIBA-incorporated composites can vary significantly depending on ash treatment, source variability, and mix design. Previous studies have shown partial success in using bottom ash in concrete blocks, paving stones, and lightweight panels, but its application in polished terrazzo tiles remains underexplored.

Among various finishing materials, terrazzo tiles are widely used in residential, commercial, and institutional flooring due to their durability, aesthetic finish, and low maintenance. Traditionally composed of Portland cement, marble chips or crushed stone, and natural aggregates, terrazzo tiles rely heavily on non-renewable resources, particularly sand. With growing environmental restrictions on sand mining and the depletion of high-quality natural aggregate sources, the substitution of conventional aggregates with recycled or industrial waste materials has emerged as a viable alternative [19]. The technical feasibility of such substitutions must, however, be rigorously evaluated to ensure performance parity with traditional materials. In addition to WIBA, FA (a pozzolanic by-product of coal combustion) has long been used in concrete to improve workability, reduce permeability, and enhance long-term strength. When combined with WIBA, FA may help refine the pore structure and compensate for potential mechanical deficiencies due to ash porosity. However, the synergistic effect of WIBA and FA in tile composites has not been comprehensively investigated, especially in relation to strength, durability, abrasion resistance, and economic viability.

This study addresses the research gap by quantitatively evaluating the mechanical, durability, and economic performance of terrazzo tiles incorporating a blended fine aggregate composed of WIBA and FA. Five mix designs (namely X1–X5) were developed: X1 served as the control mix with 0 % WIBA, while X2 to X5 replaced 100 %, 90 %, 80 %, and 70 % of crushed sand with a fixed WIBA:FA blend ratio of 75:25 % by mass. All mixtures were produced using a semi-dry pressing method with approximately 10 % moisture content and tested at 28 days of curing. The experimental program included flexural and compressive strength testing (five specimens per mix), full and surface water absorption to assess porosity, and surface abrasion resistance measured by mass loss. Additionally, a detailed material cost analysis was performed using real market prices, and a multivariate overall performance score (OPS) was introduced to integrate and normalize technical and economic indicators for optimal mix identification. The novelty of this work lies in applying WIBA to architectural-grade cementitious products with stringent surface finish requirements, employing Vietnamese national standards (TCVN) for evaluation, and proposing a practical performance framework that supports sustainable and cost-effective terrazzo tile production.

2. Experimental details

2.1. Materials and mixture proportions

The primary binder used in this study was PCB40 cement, conforming to TCVN 6260:2009, with a specific gravity of 2.86 g/cm^3. Type-F FA, complying with TCVN 10302:2014 and possessing a density of 2.17 g/cm^3, was also incorporated as a supplementary cementitious material. The fine aggregates included river sand, crushed sand, and WIBA collected from a municipal solid waste incineration facility. WIBA, as shown in Figure 1, was a granular, heterogeneous material composed of vitrified particles, unburnt residues, and mineral fragments. The physical properties of the aggregates are summarized in Table 1. Crushed sand had the highest density at 2.77 g/cm^3, followed by river sand at 2.63 g/cm^3 and WIBA at 2.27 g/cm^3. Water absorption was significantly higher in WIBA (7.53 %) compared to river sand (0.41 %) and crushed sand (0.37 %), reflecting its highly porous structure. All aggregates met the target particle size range of 0.14–10 mm, ensuring compatibility in grading and workability. These material characteristics played a crucial role in determining the mix designs and final performance of the terrazzo tiles, particularly influencing strength, absorption, and cost efficiency.

Figure 1. Waste incineration bottom ash used in this study.

In addition to physical characterization, the environmental safety of the WIBA was evaluated by analyzing the concentration of primary heavy metals. As shown in Table 2, WIBA samples exhibited extremely low leachable concentrations of Cu (<0.01 mg/L), Cr(VI) (<0.003 mg/L), Pb (<0.0007 mg/L), Ni (<0.001 mg/L), and Zn (<0.015 mg/L). The only quantified element was Cd at 0.0003 mg/L.

All measured values were significantly lower than the permissible limits specified in QCVN 04:2009/BTNMT for industrial waste discharge, such as Cr(VI) (≤5 mg/L), Cd (≤0.5 mg/L), and Pb (≤15 mg/L). These results confirm that the WIBA used in this study meets environmental safety thresholds and can be considered non-hazardous with respect to heavy metal leaching. Therefore, its application as a partial replacement for fine aggregates in terrazzo tile production poses minimal environmental risk and aligns with current regulatory frameworks for recycled materials in construction.

The mix designs used in this study are summarized in Table 3. Mix X1 served as the control, representing a conventional industrial terrazzo tile formulation comprising cement, crushed sand, and river sand, with no WIBA or FA. In contrast, mixes X2 to X5 involved partial substitution of crushed sand with a WIBA-FA blend at different replacement levels. Specifically, WIBA replaced crushed sand at 100 %, 90 %, 80 %, and 70 % in mixes X2 through X5, respectively. Within the substituted portion, a constant ratio of 75 % WIBA and 25 % FA was applied across all modified mixes.

To maintain comparable workability for compaction, the water content for each mix was adjusted to achieve a target moisture level of approximately 10 % relative humidity, suitable for semi-dry pressing. Additionally, a constant admixture dosage of 1 % by cement weight was added to each mix to improve strength development and compaction. Cement content slightly increased from 338 kg/m^3 in X2 to 351 kg/m^3 in X5 to compensate for strength loss due to increased WIBA. The trend also shows that as the WIBA content decreased across X2 to X5, crushed sand content increased proportionally to restore packing density and improve mechanical performance. This staged substitution strategy enabled systematic assessment of WIBA's effect on both technical and economic parameters.

2.2. Sample preparation and test methods

The terrazzo tile specimens were fabricated using a semi-dry pressing technique consistent with industrial production practices. For each mix, the dry constituents, including cement, fine aggregates (river sand, crushed sand, and WIBA), and FA, were first weighed according to the proportions listed in Table 3 and thoroughly mixed for 3 minutes using a horizontal pan mixer to ensure uniform distribution of particles. Water mixed with the chemical admixture was then added gradually, and mixing continued for an additional 2 minutes until the mixture exhibited a damp, cohesive consistency with a target moisture content of approximately 10 % by total mass. This moisture level was determined experimentally to optimize compactability and reduce the risk of segregation or bleeding, while remaining suitable for uniaxial hydraulic pressing.

The fresh mixtures were cast into steel molds with internal dimensions of 300 × 300 × 50 mm. The compaction was carried out using a hydraulic press applying a consistent pressure of approximately 18 MPa for 5 seconds to simulate industrial tile pressing conditions. Demolding was performed immediately after pressing, and all tiles were labeled and stored in an open-air environment for one day. After curing, the tile surfaces were ground and polished using a three-stage process (coarse–medium–fine) with silicon carbide abrasives to achieve the final terrazzo appearance and expose the internal aggregate structure, as shown in Figure 2. Surface finishing was carried out uniformly across all samples to minimize the effect of surface texture variability on test results.

Figure 2. Finished terrazzo tile samples.

All terrazzo tile samples were tested at 28 days of curing to evaluate their mechanical and durability properties using standardized methods outlined in TCVN. A total of five replicate specimens were tested for each property to ensure statistical reliability. The test program for all terrazzo tile specimens includes flexural strength, compressive strength, full water absorption, surface water absorption, and surface abrasion as summarized in Table 4. These tests comprehensively captured key performance indicators relevant to both structural integrity and in-service durability of terrazzo tiles, enabling comparative evaluation of each mix design's suitability for flooring applications.

Table 1. Physical properties of fine aggregates.

Properties	River sand	WIBA	Crushed sand
Density (g/cm^3)	2.63	2.27	2.77
Water absorption (%)	0.41	7.53	0.37
Particle size (mm)	0.14 – 5.0	0.14 – 10	0.14 – 10

Table 2. Concentration of primary heavy metals in WIBA.

Concentration (mg/L)	Cu	Cr (VI)	Cd	Pb	Ni	Zn
WIBA	< 0.01	< 0.003	0.0003	< 0.0007	< 0.001	< 0.015
QCVN 04:2009/BTNMT	-	≤ 5	≤ 0,5	≤ 15	≤ 70	≤ 250

Table 3. Material proportions of terrazzo tile samples.

Mix ID.	Material quantity (kg/m^3)					
	Cement	WIBA	Crushed sand	River sand	FA	Admixture
X1	436	0	1526	763	0	6.5
X2	338	1557	0	0	519	5.1
X3	342	1418	210	0	473	5.1
X4	346	1276	425	0	425	5.2
X5	351	1131	646	0	377	5.3

Table 4. Test methods used to evaluate the terrazzo tile's properties.

Test name	No. of test specimens	Age of tested specimens	Reference standards
Flexural strength	5	28	TCVN 6355-3:2009
Compressive strength	5	28	TCVN 6476:1999
Water absorption	5	28	TCVN 6355-4:2009
Surface water absorption	5	28	TCVN 7744:2013
Surface abrasion	5	28	TCVN 6065:1995

3. Results and discussion

3.1. Flexural strength

The flexural strength results of the terrazzo tiles incorporating varying contents of WIBA are illustrated in Figure 3. The reference mix X1, which does not contain WIBA, exhibited the highest flexural strength of 4.1 MPa, exceeding the minimum target requirement of 3.5 MPa (type III as per TCVN 7744:2013). In contrast, the strength significantly dropped to 3.1 MPa in mix X2, where 100 % of crushed sand was replaced by WIBA and 25 % FA was added. This represents a 24.4 % reduction in strength compared to the reference, likely due to the porous, angular nature and lower bonding ability of the WIBA particles, which weakened the internal matrix [13]. However, as the replacement rate of WIBA decreased progressively from X3 to X5 (e.g., increasing crushed sand and reducing WIBA), the flexural strength improved steadily: 3.6 MPa (X3), 3.7 MPa (X4), and 3.8 MPa (X5). These results represent improvements of 16.1 %, 19.4 %, and 22.6 %, respectively, over X2. The recovery in strength is attributed to the partial reintroduction of crushed sand, which enhances particle packing, reduces porosity, and strengthens the interfacial transition zone (ITZ) between the binder and aggregate.

Notably, mixes X4 and X5 not only surpassed the 3.5 MPa flexural strength threshold but also closely approached the strength of the control mix, suggesting a viable balance between mechanical performance and sustainable material use. These findings align with literature reports, such as those by Liu et al. [13], who also observed strength recovery when WIBA was partially substituted and supplemented with pozzolanic materials like FA to enhance binding properties. Overall, the results demonstrate that while full replacement of crushed sand with WIBA significantly reduces flexural strength, optimized partial substitution strategies can achieve both strength compliance and material circularity.

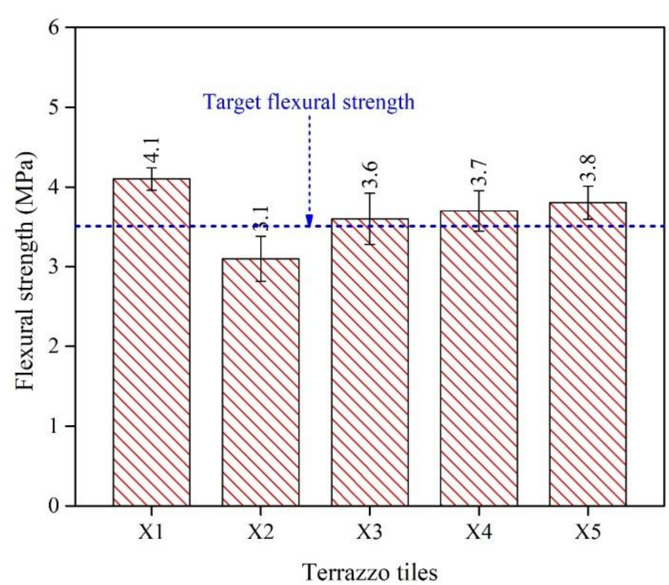

Figure 3. Flexural strength of terrazzo tiles.

3.2. Compressive strength

The compressive strength results of the terrazzo tiles are shown in Figure 4, revealing similar performance trends to flexural strength, yet with clearer improvements across the partial replacement mixes. The control mix (X1) achieved the highest compressive strength of 35.4 MPa, which is significantly above the minimum target threshold of 20 MPa (TCVN 6476:1999). In contrast, mix X2, which replaced 100 % of crushed sand with WIBA and added 25 % fly ash, showed the lowest value of 23.8 MPa, a 32.8 % decrease from X1. This reduction is primarily attributed to the porous and angular nature of WIBA, which impairs particle packing density and increases internal voids, negatively impacting the load-bearing capacity of the matrix.

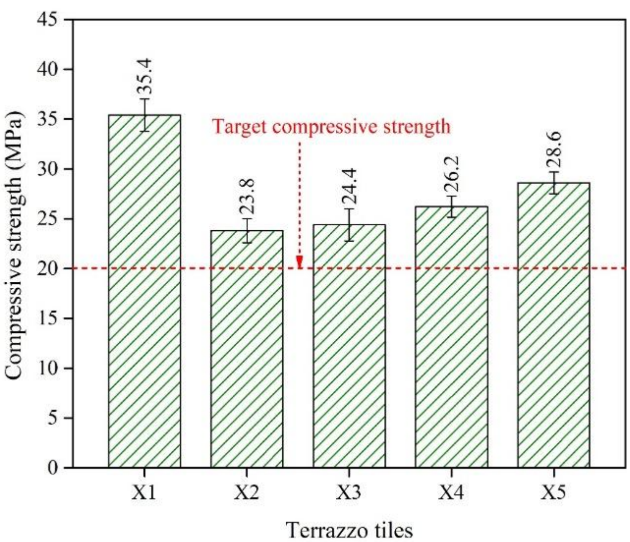

Figure 4. Compressive strength of terrazzo tiles.

Progressive reintroduction of crushed sand in mixes X3 through X5 led to incremental improvements in compressive strength: 24.4 MPa (X3), 26.2 MPa (X4), and 28.6 MPa (X5). These represent increases of 2.5 %, 10.1 %, and 20.2 %, respectively, over X2. The strength gain is linked to improved granular skeleton structure due to the denser and harder crushed sand particles [20], which enhances stress distribution and interfacial bonding. Additionally, the synergistic effect of FA and WIBA may have contributed to secondary pozzolanic reactions [21], which marginally refined the pore structure and improved strength, particularly in X4 and X5. It is noteworthy that all mixes exceeded the target strength, affirming the technical viability of WIBA-based terrazzo tiles under modified mix designs. These findings are consistent with prior studies (e.g., Yan et al. [14]) that advocate partial substitution strategies to achieve sustainability goals without compromising strength. Among all variants, mix X5 stands out, balancing strength (28.6 MPa) and material replacement, making it a strong candidate for practical, eco-efficient applications.

3.3. Water absorption

The water absorption results of the terrazzo tile mixtures, as depicted in Figure 5, show a clear trend in response to the replacement of crushed sand with WIBA. The control mix X1 exhibited the lowest absorption value of 7.2 %, attributed to the use of well-graded crushed and river sand, which provided better particle packing and lower porosity in the hardened matrix. In contrast, the full replacement mix X2 recorded the highest absorption at 9.1 %, indicating a 26.4 % increase compared to X1. This increase is primarily due to the high porosity and irregular shape of WIBA particles, which contribute to a more open internal structure, facilitating higher water uptake.

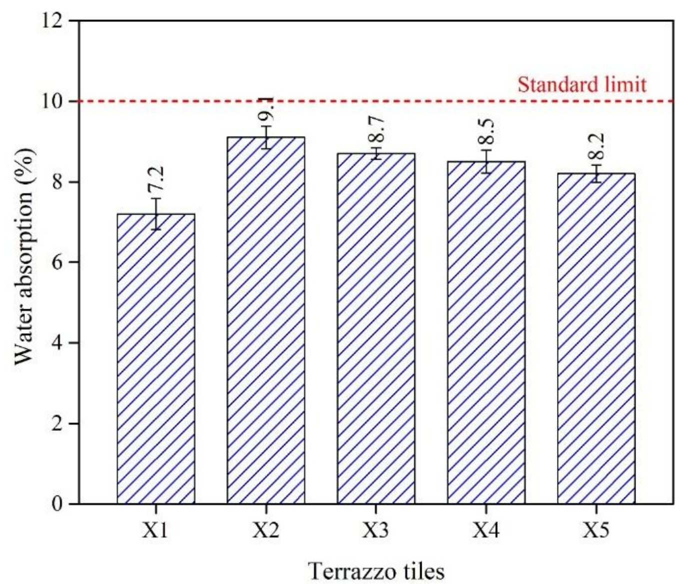

Figure 5. Water absorption of terrazzo tiles.

As the replacement rate of WIBA decreased from X3 to X5, a gradual improvement in water absorption was observed: 8.7 % (X3), 8.5 % (X4), and 8.2 % (X5). These values reflect reductions of 4.4 %, 6.6 %, and 9.9 %, respectively, compared to X2, and suggest that increasing crushed sand content enhances compaction and reduces the capillary pores responsible for water penetration. While none of the mixes matched the low absorption of the control, it is significant that all values remained below the standard limit of 10 % (TCVN 6476:1999), indicating acceptable durability for most indoor and semi-exposed applications. These findings are consistent with studies by Yan et al. [14], which reported that the substitution of natural aggregates with waste materials typically increases water absorption due to microstructural irregularities, but can be mitigated through hybrid aggregate blending and optimized binder content. Thus, mixes X4 and X5 offer a favorable compromise between sustainability and water resistance, with values nearing those of conventional materials while incorporating a substantial proportion of recycled content.

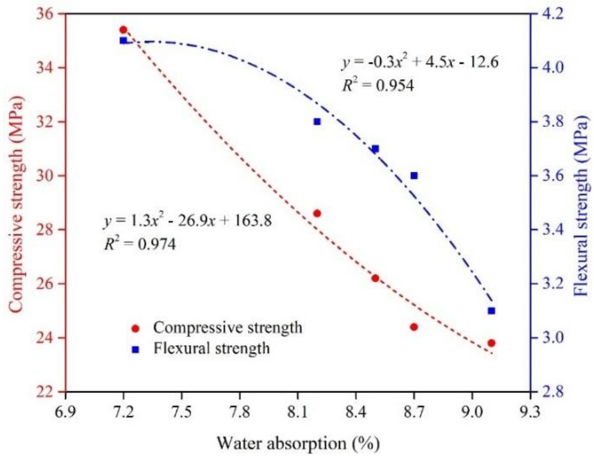

Figure 6. Correlation between water absorption and the strength of terrazzo tiles.

Figure 6 demonstrates the inverse correlation between water absorption and both compressive and flexural strengths of the terrazzo tiles. As water absorption increases, the mechanical performance of the tiles declines, confirming the strong negative relationship between porosity and strength. The compressive strength (red dots) follows a downward quadratic trend defined by the equation $y = 1.3x^2 - 26.9x + 163.8$ ($R^2 = 0.974$) while the flexural strength (blue squares) fits a separate quadratic model: $y = -0.3x^2 + 4.5x - 12.6$ ($R^2 = 0.954$). Both equations demonstrate high coefficients of determination ($R^2 > 0.95$), indicating that water absorption is a strong predictor of strength degradation. This inverse trend is attributed to the increased pore connectivity and capillary porosity associated with higher water absorption [22], which weakens the internal matrix of the composite. Mix X2, with the highest absorption (9.1 %), correspondingly exhibits the lowest strengths (23.8 MPa compressive, 3.1 MPa flexural), while mix X1 shows the lowest absorption (7.2 %) and the highest strengths (35.4 MPa and 4.1 MPa, respectively). This confirms that the durability and mechanical integrity of terrazzo tiles are highly dependent on microstructural densification, which is negatively influenced by excessive WIBA content. These findings are supported by prior research (e.g., Yan et al. [14]), which observed similar strength–absorption relationships in concrete containing high-porosity recycled aggregates. Importantly, this analysis underscores the need for optimal WIBA dosage, where sustainable material substitution does not lead to excessive porosity and water ingress. Mixes X4 and X5, with moderate absorption and satisfactory strengths, exemplify this balance.

3.4. Surface water absorption

Figure 7 shows the surface water absorption performance of the terrazzo tile mixtures, reflecting their capacity to resist moisture ingress at the exposed surface layer, a critical parameter for durability in service environments. The control mix X1, with conventional fine aggregates, registered the lowest surface absorption at 4.2 %, due to its dense microstructure and minimal open surface pores. In contrast, mix X2, containing 100 % WIBA as aggregate replacement, showed the highest value of 4.7 %, representing an 11.9 % increase over X1. This rise is consistent with WIBA's high porosity and irregular particle geometry, which contribute to elevated near-surface permeability. As crushed sand content increased from mixes X3 to X5, surface absorption values showed a gradual decline: 4.6 % (X3), 4.5 % (X4), and 4.4 % (X5). Compared to X2, these values represent reductions of approximately 2.1 %, 4.3 %, and 6.4 %, respectively. The improvement reflects the role of crushed sand in enhancing surface compactness, thereby reducing the capillary action at the tile surface. While none of the mixes achieved values significantly below 4 %, they all remained within acceptable ranges for standard building applications (TCVN 7744:2013), especially in non-submerged conditions. These results reinforce the trend seen in total water absorption data (Figure 5) and align with prior research [23], which reported that composite materials with high-waste content tend to exhibit elevated unless properly compensated by finer, denser aggregates or additives. The consistency across all surface absorption values also confirms the uniformity in compaction and curing processes applied throughout the experiment. In practical terms, mix X5 strikes a favorable balance, achieving the lowest surface absorption among WIBA-based mixes while maintaining strong mechanical performance.

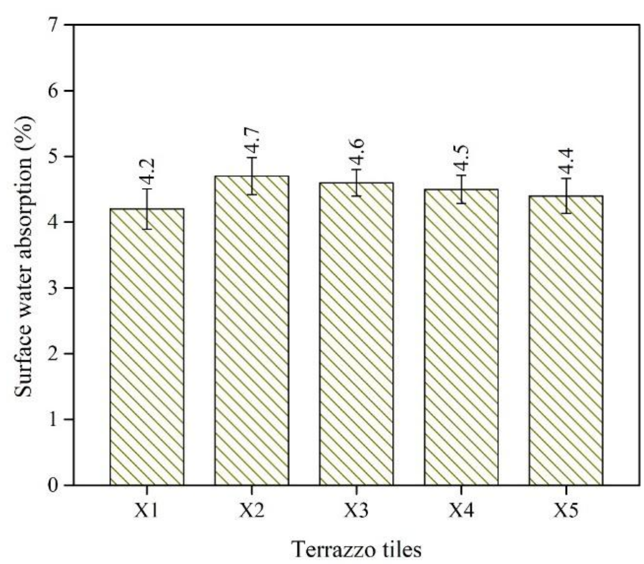

Figure 7. Surface water absorption of terrazzo tiles.

3.5. Surface abrasion

Surface abrasion resistance is a crucial performance indicator for terrazzo tiles, especially in high-traffic or flooring applications. As shown in Figure 8, all terrazzo tile mixes demonstrated excellent resistance to surface wear, with abrasion values ranging narrowly between 0.25 and 0.26 g/cm², significantly below the standard limit of

0.5 g/cm^2 (TCVN 6476:1999). The fluctuation can be attributed to the surface materials, composed of white cement, yellow pigment, and white stone. Since the same composition was used for all samples, the minor variations in abrasion resistance are likely due to experimental error. As a result, all terrazzo tiles can safely be recommended for use in pedestrian or light-load floorings without concern for accelerated surface wear.

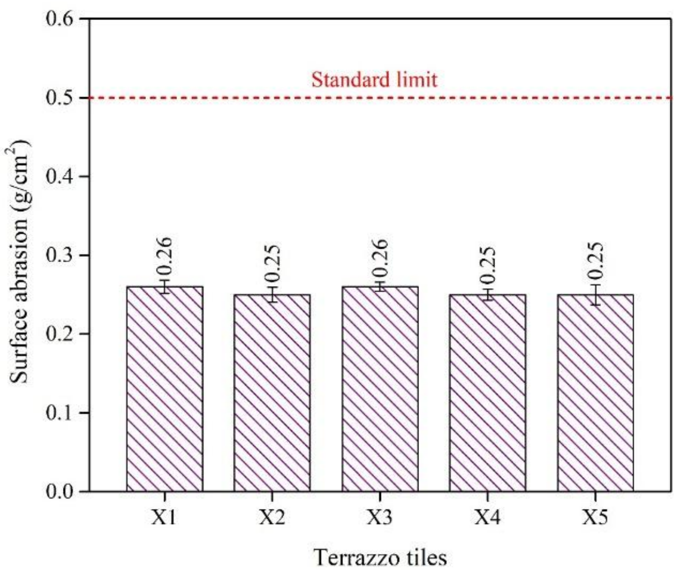

Figure 8. Surface abrasion of terrazzo tiles.

3.6. Analysis of material cost

Table 5 summarizes the calculated material costs for terrazzo tile production per cubic meter, incorporating actual market prices (converted per kg) for each component. The control mix X1, composed entirely of conventional cement, river sand, and crushed sand, incurs the highest production cost of 1,556,000 VND/m^3, serving as the baseline for comparison. In contrast, the mix with full replacement of crushed sand by WIBA and FA (X2) shows a significant cost reduction to 945,000 VND/m^3, representing a 39.2 % decrease relative to X1. As the WIBA content is gradually reduced from X3 to X5, production costs increase incrementally but remain substantially lower than the reference. Specifically, X3 costs 989,000 VND/m^3 (-36.4 %), X4 costs 1,037,000 VND/m^3 (-33.4 %), and X5 costs 1,088,000 VND/m^3 (-30.1 %). These trends clearly demonstrate that WIBA is the most cost-effective component, priced at just 70 VND/kg, compared to 292–308 VND/kg for natural aggregates and 1,500 VND/kg for cement. The high unit price of admixtures (34,000 VND/kg) has a limited impact due to their low dosage (≈1 % of cement content).

From a cost-performance perspective, mix X2 offers the greatest savings but falls short in mechanical properties (as seen in Sections 3.1 and 3.2). Meanwhile, mixes X4 and X5 present a strategic balance between mechanical integrity and economic feasibility. For instance, X5 achieves a 30.1 % cost reduction while still exceeding both strength and durability standards. These findings are consistent with circular economy principles in construction, as they highlight that incorporating waste-derived materials not only supports sustainability but also lowers production costs, a critical factor for commercial viability and large-scale adoption.

3.7. OPS Analysis and Evaluation

To quantitatively evaluate and rank the performance of each terrazzo tile formulation, a multivariate assessment framework was developed based on the OPS. This metric integrates both technical and economic indicators into a single score, allowing for objective comparison of different mix designs. Six key criteria were considered: flexural strength, compressive strength, water absorption, surface water absorption, surface abrasion resistance, and material cost. Each parameter was normalized using min–max scaling, which transforms raw data into a common scale between 0 and 1. Parameters were categorized based on performance direction: properties where higher values are desirable (e.g., flexural and compressive strength) were normalized using the following equation:

$$Normalized\ score = \frac{x - x_{min}}{x_{max} - x_{min}}$$

For properties where lower values are desirable (e.g., water absorption, surface water absorption, abrasion, and cost), the inverse formulation was applied:

$$Normalized\ score = \frac{x_{max} - x}{x_{max} - x_{min}}$$

Each normalized indicator was equally weighted, and the final OPS for each mix was computed as the arithmetic mean of its six normalized scores. The results are presented in Table 6, which includes both raw performance values and their normalized equivalents. Among all formulations, Mix X1 (reference) achieved the highest OPS score (0.667), driven by superior mechanical strength and low absorption values, although it had the highest cost. Mix X5 followed closely with an OPS of 0.659, balancing strong mechanical performance and a 30.1 % cost reduction compared to X1. Mixes X4 and X3 showed intermediate performance, while Mix X2, despite being the most economical, ranked lowest (OPS = 0.333) due to significantly lower strength and higher porosity. These findings confirm that incorporating WIBA-FA blends up to 30 % replacement (Mix X5) can deliver a high-performance terrazzo tile that is both technically viable and economically advantageous. The OPS method proved effective in capturing trade-offs between strength, durability, and cost, offering a practical decision-making tool for sustainable material design.

Table 5. Calculation of the material cost for terrazzo tile production.

Mix ID.	Unit price for 1 kg of each material (VND/kg)						Total (VND × 1000/m³)	Cost change (%)
	Cement	WIBA	Crushed sand	River sand	FA	Admixture		
	1500	70	292	308	300	34000		
	Material cost (VND × 1000/m³)							
X1	654	-	446	235	-	221	1556	0
X2	507	109	-	-	156	173	945	-39.2
X3	513	99	61	-	142	173	989	-36.4
X4	519	89	124	-	128	177	1037	-33.4
X5	527	79	189	-	113	180	1088	-30.1

Table 6. Min–max normalized scores, and OPS for terrazzo tile mix designs.

Mix	CS (Norm.)	FS (Norm.)	Water Absorption (Norm.)	Surface Water Absorption (Norm.)	Surface Abrasion (Norm.)	Cost (Norm.)	OPS (Norm.)
X1	1.000	1.000	1.000	1.000	0.000	0.000	0.667
X2	0.000	0.000	0.000	0.000	1.000	1.000	0.333
X3	0.052	0.500	0.211	0.200	0.000	0.928	0.315
X4	0.207	0.600	0.316	0.400	1.000	0.849	0.562
X5	0.414	0.700	0.474	0.600	1.000	0.766	0.659

4. Conclusions

This study investigated the feasibility of using blended WIBA-FA as a partial replacement for crushed sand in terrazzo tile production. Five mixes were tested for mechanical strength, durability, and cost performance. Based on the test results, the key conclusions are as follows:

- Flexural strength ranged from 3.1 MPa to 4.1 MPa, while compressive strength ranged from 23.8 MPa to 35.4 MPa. Mix X5 achieved 3.8 MPa (flexural) and 28.6 MPa (compressive), exceeding standard requirements and approaching the control mix performance.

- Water absorption values varied between 7.2 % and 9.1 %, and surface water absorption ranged from 4.2 % to 4.7 %. Mix X5 recorded 8.2 % and 4.4 %, respectively, staying within acceptable durability limits. A strong correlation (R^2 > 95 %) was found between mechanical strength and water absorption, confirming the inverse relationship between porosity and strength.

- Surface abrasion results were consistently low (0.25–0.26 g/cm²) for all mixes, indicating good wear resistance regardless of WIBA content.

- Material cost analysis showed that mix X5 reduced production cost by 30.1 % compared to the control mix. Mix X2 achieved the highest cost savings (39.2 %) but had the lowest strength and performance.

- A multi-criteria OPS analysis based on normalized performance indicators ranked mix X5 as the optimal blend. It achieved an OPS score of 0.659, closely following the control mix (0.667) but with significantly better cost-efficiency.

In conclusion, mix X5 is recommended as the most balanced and sustainable terrazzo tile formulation, meeting all technical standards while offering substantial material cost savings. Limitations of this study include the absence of long-term durability and field testing. Future research should investigate freeze-thaw resistance, life cycle assessment, and scaling to production environments.

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