

CALCIUM CARBIDE RESIDUE AND GLASS AS CEMENT REPLACEMENT IN CEMENTITIOUS TILES WITH BOTTOM ASH ADDITIVE

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Abstract

This study investigates the utilization of industrial waste materials, namely calcium carbide residue (CCR) and green glass cullet (GGC) as partial replacements for ordinary Portland cement (OPC) in cementitious tiles with bottom ash (BA) as an additive. OPC was partially replaced by CCR and GGC, either individually or in combination at total replacement levels of 5, 10, and 15 wt%. The influence of adding BA at 5 and 10 wt% was also examined. Specimens were cured for 7 and 28 days. At 28 days, the results showed that mixture B2 containing 5 wt% CCR as an OPC replacement exhibited a modulus of rupture (MOR) of 12.49 MPa, a breaking strength of 421.11 N, and water absorption of 15.13%. Meanwhile, mixture E1 comprising 5 wt% CCR as an OPC replacement and 5 wt% BA as an additive had an MOR of 12.81 MPa, a breaking strength of 452.87 N, and water absorption of 15.06%. Both mixtures maintained identical proportions of OPC, river sand, and laterite soil to the control mixture. The MOR and water absorption values of mixtures B2 and E1 met the ISO 13006 class BIII requirements, qualifying them as floor tiles based on the breaking strength criterion. Optical microscopy revealed that CaO-rich CCR and aluminosilicate-rich BA enhanced hydration and microstructural bonding, leading to pozzolanic reactions and calcium aluminosilicate hydrate (C-A-S-H), which contributed to strength development. This research demonstrates a sustainable approach for producing eco-friendly cementitious tiles by valorizing industrial by-products while reducing cement consumption and landfill waste.

Keywords: Calcium Carbide Residue; Glass Waste; Bottom Ash; Ordinary Portland Cement; Physical Properties; Cementitious Tiles

Introduction

Ordinary Portland cement (OPC) is the most widely used cementitious material in concrete. However, its production is an energy-intensive and highly polluting process, responsible for approximately 5-8% of global anthropogenic carbon dioxide (CO₂)

emissions (Li, 2024). One effective approach to reducing dependence on OPC, as evaluated and validated by numerous researchers, is the utilization of waste materials, which can be either organic or inorganic for partial or full replacement. The

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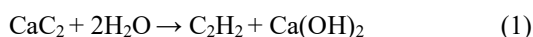
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incorporation of waste materials and industrial by-products possessing cementitious and pozzolanic properties can substantially decrease cement consumption in the construction industry and consequently lower the CO₂ emissions resulting from cement production (Akinyemi *et al.*, 2021).

Calcium carbide residue (CCR) is an industrial by-product produced from the hydrolysis of solid calcium carbide (CaC₂) during the large-scale production of gaseous acetylene (C₂H₂), a gas widely used in welding and metal cutting. The generation of CCR results from the hydrolysis reaction of CaC₂ in water. This reaction generates calcium hydroxide (Ca(OH)₂), which is the major constituent of CCR in slurry form with a large volume fraction (Mahmmod & Abbas, 2025), as shown in Equation (1):



Based on Equation (1), the hydrolysis of 64 g of CaC₂ produces 26 g of C₂H₂ and 74 g of CCR in the form of Ca(OH)₂. Globally, the average annual production of CCR is estimated to be approximately 5.6×10^7 tons (Lv *et al.*, 2023). In Thailand, the annual demand for CaC₂ for acetylene gas production is about 18,500 tons, generating approximately 21,500 tons of CCR, and the demand is continuously increasing each year. CCR is an unutilized waste material that is commonly disposed of in open areas and landfills due to the lack of effective large-scale reuse methods. The disposal practice poses a significant environmental threat because of the high alkalinity (pH > 12) of CCR (Horpibulsuk *et al.*, 2015). To mitigate this environmental pollution, efforts have been made to explore the potential utilization of CCR in more beneficial ways, particularly within the construction industry. CCR releases excess Ca(OH)₂, which subsequently reacts with silica (SiO₂) and alumina (Al₂O₃) derived from CCR or supplementary pozzolanic sources to form additional phases similar to those generated during the hydration reaction of CCR, namely calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H). These phases are primarily responsible for promoting the long-term behavior and characteristics of cementitious composites (Mahmmod & Abbas, 2025). Research findings by Wang *et al.* reported that replacing 10-20 wt% of cement with CCR in concrete provided satisfactory results after 28 days (Wang *et al.*, 2013). The potential of the main component of CCR, Ca(OH)₂, is that it can react with siliceous materials via pozzolanic reactions. Mokuolu *et al.* indicated that when CCR was combined with certain pozzolanas such as fly ash, rice husk ash, or silica fume, which

contained high amounts of SiO₂ and Al₂O₃, the pozzolanic reactions produced products similar to those resulting from cement hydration (Mokuolu *et al.*, 2018).

The problem of waste disposal is exacerbated by the global volume of municipal solid waste (MSW). Approximately 2 billion tons of MSW are generated annually, and this volume is projected to increase by 70% by 2050. Waste glass constitutes about 5-10% of the total MSW, depending on the region. Moreover, this proportion is expected to rise, as global solid waste generation is anticipated to reach 3.8 billion tons by 2050 (Bhat *et al.*, 2024). Glass cullet typically contains higher levels of color impurities. These collection, sorting, and market constraints reduce the value and usability of green and amber cullet, leading to significant volumes of glass being diverted to low-value applications or landfill instead of being reintroduced into closed-loop production. However, green glass cullet has recently attracted considerable attention due to its high SiO₂ and calcium oxide (CaO) contents. When finely ground, waste glass powder exhibits pozzolanic reactivity, enabling it to partially replace OPC in concrete. Karamberi and Moutsatsou examined the pozzolanic activity and compressive strength of different glass cullets, reporting that green cullet demonstrated better results than flint glass cullet, while amber cullet showed the worst behavior (Karamberi & Moutsatsou, 2005). Maingam *et al.* studied the effect of using green glass powder as a partial cement substitute, finding that replacing 20 wt% of cement with green glass powder enhanced the MOR of non-fired ceramic tiles due to the pozzolanic reaction (Maingam *et al.*, 2021).

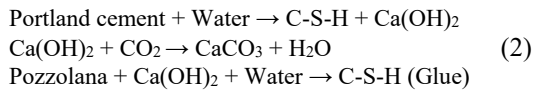
Meanwhile, MSW is commonly incinerated to reduce its overall mass and volume while simultaneously generating energy in the form of heat that can be utilized for electricity production. However, incineration plants generate combustion residues in the form of ashes, consisting of approximately 80% bottom ash (BA) and 20% fly ash (Tang *et al.*, 2016). Consequently, the disposal and recycling of BA has become a growing environmental concern worldwide. At present, the majority of BA is disposed of through landfilling, whereas a smaller portion is reused as a raw material in the production of aggregates, backfill materials, and concrete. BA contains valuable oxides such as SiO₂, Fe₂O₃, CaO, and Al₂O₃. Given that BA was largely composed of non-crystalline material, it had high potential for use as a pozzolan (Rahim *et al.*, 2023). Previous studies had confirmed the potential of BA as a substitute building material, demonstrating that modified BA could be used as a pozzolan when its particles were

ground to retain less than 5 wt% on a No. 325 sieve (Abdulmatin *et al.*, 2018).

Previous studies have mainly examined CCR, glass, and ash as OPC replacements in standalone or binary concrete systems. However, the synergistic potential of multi-component waste-derived binders and additives remains insufficiently understood, particularly in tile applications. This study addresses this gap by investigating a hybrid waste-based binder-additive system using CCR and GGC as partial OPC replacements and BA as a supplementary additive. This approach is expected to produce sustainable cementitious tiles that meet relevant standards, while improving resource efficiency through large-scale industrial waste recycling and reducing greenhouse gas (GHG) emissions.

Chemical Properties of Materials

The primary conventional material used for building infrastructure is a mixture of cement, fine aggregate, coarse aggregate, and water, commonly referred to as concrete. A major step in concrete production involves determining the chemical properties of these components. When the ingredients and water are combined, specific chemical reactions occur, and these processes ultimately determine the concrete's final strength (Dubey *et al.*, 2024), as shown in Equation (2):



In Equation (2), the reaction between Portland cement and water forms C-S-H and Ca(OH)_2 . The formation of C-S-H is primarily responsible for the early strength of concrete. Calcium hydroxide reacts with atmospheric CO_2 to form calcium carbonate (CaCO_3) and water, a process that can influence the long-term durability of concrete. Moreover, when pozzolanic materials with high silica content react with lime and water, additional C-S-H is generated. This secondary hydration product serves as the main binding phase within the cementitious matrix, further enhancing the strength of concrete.

Materials

The chemical compositions of the raw materials were characterized using X-ray fluorescence (XRF) analysis, as presented in Table 1.

Table 1. Oxide composition of raw materials

Oxide	CCR (%)	GGC (%)	BA (%)	OPC (%)	RS (%)	LS (%)
SiO ₂	6.49	69.91	45.81	18.13	78.05	71.00
Al ₂ O ₃	2.55	1.91	10.61	4.60	10.96	21.79
Fe ₂ O ₃	3.25	0.43	14.96	3.36	1.14	4.45
K ₂ O	3.17	0.36	1.52	0.77	6.35	1.16
CaO	70.78	10.81	14.12	66.63	1.35	0.24
MgO	0.47	1.24	1.68	1.11	0.44	0.43
TiO ₂	-	0.08	1.50	0.24	0.23	0.64
P ₂ O ₅	-	-	1.08	0.08	-	0.09
Na ₂ O	-	14.64	0.62	0.22	0.95	0.09
SO ₃	4.92	0.07	2.84	4.65	0.03	0.03

All raw materials were collected as bulk samples from single sources within the same collection period to ensure material consistency and sampling representativeness. Calcium carbide residue (CCR), a by-product from acetylene gas production, was acquired from Nakhon Pathom Province, Thailand. CCR mainly consists of CaO, which is similar to the compound produced during the cement hydration process. It also contains about 12.29% pozzolanic oxides, including SiO₂, Al₂O₃, and Fe₂O₃. This naturally high level of pozzolanic components leads to cementation through the pozzolanic reaction. Green glass cullet (GGC) was sourced from a glass recycling plant in Ayutthaya Province, Thailand. GGC is rich in amorphous SiO₂, which promotes pozzolanic reactions with Ca(OH)_2 released from cement hydration. Bottom ash (BA) from municipal solid waste incineration (MSWI) was collected from a waste-to-energy plant in Nonthaburi Province, Thailand. BA also contains substantial amounts of SiO₂, CaO, Al₂O₃, and Fe₂O₃, which are typically found in pozzolanic and cementitious materials. The constituent materials used in this study were consistent with those reported by (Wangrakdiskul & Neamlut, 2018). Ordinary Portland cement (OPC) type I, conforming to ASTM C150, served as the primary binder cementitious for the constituent materials. Additionally, the naturally occurring local materials, river sand (RS) and laterite soil (LS), were sourced from Kanchanaburi Province, Thailand. RS was employed as a fine aggregate to improve the volumetric stability of the mixture, thereby reducing the susceptibility to drying shrinkage and crack formation within the matrix. LS was utilized together with OPC as a stabilizing agent to serve as the base material.

In accordance with the chemical requirements specified in ASTM International (2015) class N, the waste-derived materials used in this study, namely GGC and BA, can be classified as natural pozzolanic materials, as presented in Table 2. Both GGC and BA present combined SiO₂ + Al₂O₃ +

Fe₂O₃ contents exceeding 70%. Furthermore, the maximum allowable sulfur trioxide (SO₃) content for class N is 4%, while GGC and BA contain 0.07% and 2.84%, respectively, meeting the minimum requirement for class N. Consequently, they are categorized as viable natural pozzolans, confirming their high potential for acceptable functionality as a partial cement replacement.

Table 2. Chemical requirements of waste materials under the requirements of ASTM C 618 class N

Chemical properties	Class N type pozzolan	GGC	BA
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ , min (%)	70.0	72.25	71.38
SO ₃ , max (%)	4.0	0.07	2.84

Table 3. Mixture formulations

Mixtures no.	Compositions (wt%)					
	CCR	GGC	BA	OPC	RS	LS
A1	0	0	0	22.5	15	62.5
B1	0	5	0	17.5	15	62.5
B2	5	0	0	17.5	15	62.5
B3	2.5	2.5	0	17.5	15	62.5
C1	0	10	0	12.5	15	62.5
C2	10	0	0	12.5	15	62.5
C3	5	5	0	12.5	15	62.5
D1	0	15	0	7.5	15	62.5
D2	15	0	0	7.5	15	62.5
D3	7.5	7.5	0	7.5	15	62.5
E1	5	0	5	17.5	15	62.5
E2	5	0	10	17.5	15	62.5

Methods

The experimental mixtures were systematically divided into five groups (A, B, C, D, and E), as summarized in Table 3. Group A, the control mixture, adopted proportions from the optimized formulation of non-fired tiles developed by (Wangrakdiskul & Neamlut, 2018), comprising 22.5 wt% OPC type I, 15 wt% RS, and 62.5 wt% LS. In this experiment, the subsequent mixtures were formulated to investigate the influence of partial OPC replacement with supplementary cementitious materials (SCMs). The experimental design involved incorporating CCR and GGC as partial OPC replacements, with the mixtures initially categorized into groups B, C, and D, corresponding to total replacement levels of 5, 10, and 15 wt%, respectively, as determined based on the preliminary modulus of rupture trials. Each group included sub-formulations in which CCR and GGC were used either individually or in combination to determine the optimal blending

ratio. The optimum mixtures from groups B, C, and D were then identified. Finally, mixture B2 as the optimum mixture was used as the base composition for group E, in which BA was further added at proportions of 5 and 10 wt% to promote the utilization of industrial waste without reducing the primary cementitious binder content.

All raw materials were oven-dried at 200°C for 2 hours at a heating rate of 100°C/hour, ground in a ball mill at a rotational speed of 100 rpm, and sieved through a No. 50 sieve (297 µm) using a sieve shaker to achieve a uniform particle size distribution. The resulting powders were stored in sealed containers at room temperature to prevent moisture uptake prior to mixture preparation. The homogenized mixtures were obtained by adding 10 wt% water, which was uniformly sprayed to attain a suitable consistency for the pressing process. Each mixture was uniaxially pressed at 10 MPa to form 15 specimens measuring 50 × 100 × 7 mm per mixture. After forming, the specimens were lightly sprayed with water and covered with a plastic sheet to cure at room temperature for 7 and 28 days. The curing procedure followed the methodology reported by (Piyarat *et al.*, 2021). Following the curing period, all specimens were oven-dried at 200°C for 2 hours and then allowed to cool to room temperature. Previous studies have shown that drying at temperatures up to 200°C enhances the compressive strength of CCR by promoting reactions with free lime, leading to the formation of additional C-S-H and calcium aluminate hydrate (C-A-H) phases, whereas higher temperatures cause a reduction in strength (Kelechi *et al.*, 2022a). In addition, microcracking has been reported at 250°C in mixtures containing 0 and 5 wt% CCR (Rahmawati *et al.*, 2020). Therefore, the drying temperature in this study was limited to 200°C to improve CCR reactivity and strength relative to conventional curing, while avoiding thermal damage. After drying, the physical properties of the specimens were tested, including modulus of rupture (ISO 10545-4), breaking strength (ISO 10545-4), water absorption (ISO 10545-3), drying shrinkage, weight loss, and bulk density (ISO 10545-3). The results of modulus of rupture, breaking strength, and water absorption were compared with the ISO 13006:2012 standard for ceramic tiles.

Modulus of Rupture (MOR): MOR represents the maximum stress that a specimen can withstand before failure under bending. It was determined using a three-point bending test. The span between the support rods (*l*₂) was 80 mm, in accordance with the ISO 10545-4 standard. MOR value was calculated using Equation (3):

$$MOR = \frac{3Fl_2}{2bh^2} \quad (3)$$

Where;

MOR = modulus of rupture (MPa)

F = the breaking load (N)

l_2 = the span between the support rods (mm)

b = the width of specimen (mm)

h = the minimum thickness of specimen (mm)

Breaking Strength (BS): BS refers to the maximum load or force sustained by a specimen just before breaking. This property was used for the classification of wall or floor tiles. BS was calculated using the following Equation (4):

$$BS = \frac{Fl_2}{b} \quad (4)$$

Where;

BS = breaking strength (N)

F = the breaking load (N)

l_2 = the span between the support rods (mm)

b = the width of specimen (mm)

Water Absorption (WA): WA is a measure of water penetration into the open pores of a specimen. It was determined by comparing the dry and wet masses of the specimen. Each specimen was immersed in boiling water for 2 hours and then allowed to remain immersed in water to cool naturally for 4 hours. The excess moisture on the surface was removed with chamois leather before measuring the wet mass. WA was calculated using Equation (5):

$$WA = \frac{W_w - W_d}{W_d} \times 100 \quad (5)$$

Where;

WA = water absorption (%)

W_d = the mass of the dry specimen (g)

W_w = the mass of the wet specimen (g)

Drying Shrinkage (DS): DS represents the percentage reduction in specimen length after drying. It was calculated by comparing the specimen's length before and after the drying process using Equation (6):

$$DS = \frac{L_0 - L}{L_0} \times 100 \quad (6)$$

Where;

DS = drying shrinkage (%)

L_0 = the length of specimen before drying (mm)

L = the length of specimen after drying (mm)

Weight Loss (WL): WL is defined as the percentage of mass loss determined by comparing the weight of a specimen before and after the drying process. WL was calculated with Equation (7):

$$WL = \frac{W_1 - W_2}{W_1} \times 100 \quad (7)$$

Where;

WL = weight loss (%)

W_1 = the weight of specimen before drying (g)

W_2 = the weight of specimen after drying (g)

Bulk Density (BD): BD is expressed as the ratio of the dry mass of a specimen to its exterior volume, including pores based on Archimedes' method with a standard densimeter (Alfa Mirage, EW-300SG). BD was calculated using Equation (8):

$$BD = \frac{m}{v} \quad (8)$$

Where;

BD = bulk density (g/cm³)

m = the dry mass of specimen (g)

v = the exterior volume (cm³)

Furthermore, the chemical compositions of the powdered raw materials were determined using X-ray fluorescence (XRF) analysis with the wavelength-dispersive X-ray fluorescence (WDXRF) spectrometer S8 TIGER produced by Bruker AXS, Germany. The microstructure of the cementitious tiles was observed using optical microscopy (OM; Olympus, DSX1000) under polarized light. Images were captured using an Olympus DSX10-XLOB Plan FL 10×/0.30 WD 30 objective lens and subsequently processed using the dedicated DSX software.

Results and Discussion

The average and standard deviation (SD) values of physical properties were investigated from 15 specimens in each mixture, as presented in Figures 1-6. To assess the repeatability and reliability of the results, the relative standard deviation (RSD) was subsequently calculated. The RSD values for all tested properties were below 10%, which is considered acceptable for this type of experiment (Xu *et al.*, 2024).

Modulus of Rupture

Across all mixture groups, the MOR results consistently showed higher strength at 28 days than at 7 days, reflecting progressive hydration kinetics

and sustained pozzolanic reactions, as illustrated in Figure 1. Compared with the control mixture, the MOR values exhibited a progressively decreasing trend from group B to group D as the OPC replacement level increased from 5 to 15 wt%, regardless of whether CCR and GGC were used individually or in combination. This trend indicates a dilution effect associated with higher OPC replacement levels. In group B, mixture B2 containing 5 wt% CCR as a partial replacement for OPC exhibited an MOR of 12.49 MPa at 28 days of curing, demonstrating enhanced late-age strength due to increased calcium availability from CCR. This high MOR was ascribed to the high pozzolanic reactivity of CCR during curing (Bilondi *et al.*, 2018) and the formation of C-S-H from OPC and CCR hydration, consistent with the findings of (Latifi *et al.*, 2018). In contrast, mixtures containing GGC showed lower MOR values than those containing CCR alone due to limited calcium availability and slower pozzolanic reactivity. However, the combination of GGC and CCR partially compensated for this limitation by supplying additional calcium, resulting in a higher MOR relative to GGC individually. Based on the promising results of mixture B2, further development was carried out by incorporating BA as an additional component at 5 and 10 wt% in group E mixtures. Mixture E1 containing 5 wt% CCR as a partial OPC replacement and 5 wt% BA as an additive had the highest MOR of 12.81 MPa at 28 days. This finding was attributed to the optimized synergistic ratio of calcium-rich CCR and aluminosilicate-rich BA, which accelerated pozzolanic reaction kinetics. The supplementary calcium and silica provided by CCR and BA increased the Ca/Si ratio, while the reactive aluminosilicates from BA promoted secondary hydration reactions, leading to the formation of C-A-S-H, in agreement with (Abdulmatin *et al.*, 2018). According to the ISO 13006 class BIII specification, the control mixture had an MOR of 13.34 MPa at a thickness of 6.91 mm. Therefore, it did not meet the MOR requirement for specimens thinner than 7.5 mm, which must exceed 15 MPa. Conversely, for specimens with a thickness greater than 7.5 mm, the minimum MOR requirement is 12 MPa. Both mixtures B2 and E1 satisfied this requirement with MOR values of 12.49 and 12.81 MPa, respectively, as shown in Table 4. The increased thickness observed in mixtures containing CCR and BA was an experimental outcome resulting from the lower specific gravity and higher porosity of these waste materials compared with OPC. Under a constant compaction pressure, the greater bulking tendency of the CCR and BA led to a final specimen thickness exceeding 7.5 mm.

Table 4. Comparison of thickness and MOR with the ISO 13006 standard of cementitious tiles at 28 days

No.	Thickness (mm)	MOR (MPa)	ISO 13006 specifications class BIII	
			Thickness $\geq$ 7.5 mm	Thickness $\leq$ 7.5 mm
			MOR (> 12 MPa)	MOR (> 15 MPa)
A1	6.91	13.34	×	×
B2	7.54	12.49	✓	×
E1	7.62	12.81	✓	×

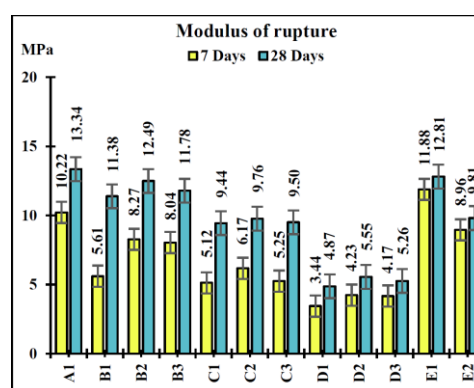


Figure 1. Modulus of rupture (MPa)

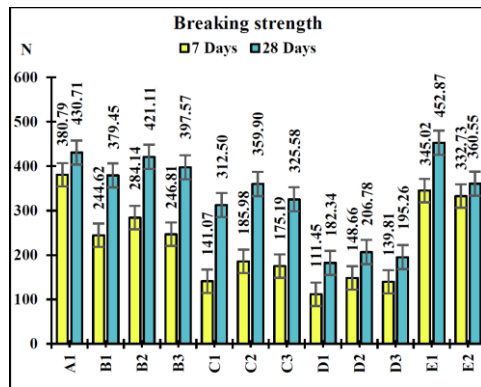
Breaking Strength

The breaking strength results indicated that the effects of raw materials and curing periods followed a consistent trend with the MOR results, as shown in Figure 2. Based on the ISO 13006 standard, the breaking strength must be less than 400 N for wall tiles and must exceed 400 N for floor tiles. Mixtures B2 and E1 had previously passed the MOR requirement at 28 days of curing, exhibiting breaking strength values of 421.11 N and 452.87 N, respectively.

These results confirmed that mixtures B2 and E1 complied with the ISO 13006 specifications for floor tiles, as summarized in Table 5, thereby qualifying both mixtures as suitable cementitious tiles. The improvement in breaking strength, particularly in mixtures B2 and E1, can be developed due to the calcium hydroxide ($\text{Ca}(\text{OH})_2$) released from the CCR during cement hydration and the pozzolanic reactions between the reactive silica and alumina of BA (Horpibulsuk *et al.*, 2015). These reactions promote the formation of C-S-H gel for enhancing matrix bonding and physical strength in concrete applications (Kelechi *et al.*, 2022b).

Table 5. Comparison of breaking strength with the ISO 13006 standard of cementitious tiles at 28 days

No.	Breaking strength (N)	ISO 13006 specifications class BIII	
		Wall tiles	Floor tiles
		Breaking strength (< 400 N)	Breaking strength (> 400 N)
B2	421.11	×	✓
E1	452.87	×	✓

**Figure 2. Breaking strength (N)**

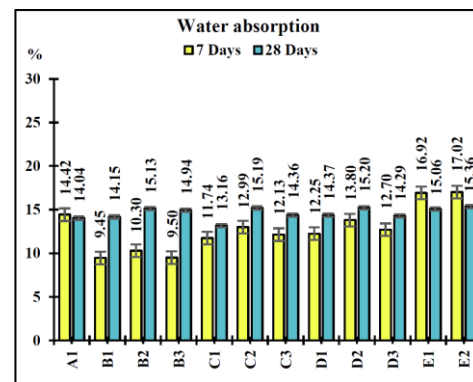
Water Absorption

The water absorption results of specimens cured for 7 and 28 days are presented in Figure 3. For group B, the water absorption at 7 days was lower than that of the control mixture. However, it slightly increased after 28 days of curing compared to the control mixture, and a similar trend was found in groups C and D. The increase in water absorption was related to the higher replacement ratios of CCR and GGC, suggesting that the substitution of OPC with these waste materials led to an increase in porosity and the inherent water absorption capacity of CCR (Kelechi *et al.*, 2022a). Additionally, the mixtures incorporating 5 wt% CCR replacing OPC and an additional BA of mixtures E1 and E2, yielded water absorption values slightly higher than mixture B2 due to the irregular particle shapes of BA. However, the high degree of fineness of CCR and BA increased the surface area of the cementitious matrix, thereby reducing water absorption to a level comparable to that of mixture B2 at 28 days (Abdulmatin *et al.*, 2018). According to the ISO 13006 class BIII specification, the acceptable water absorption range is 10-20%. Mixtures B2 and E1 previously met the MOR and the breaking strength requirements at 28 days of curing, achieving water absorption values of

15.13% and 15.06%, respectively, thus complying with the ISO 13006 standard in terms of water absorption, as presented in Table 6.

Table 6. Comparison of water absorption with the ISO 13006 standard of cementitious tiles at 28 days

No.	Water absorption (%)	ISO 13006 specifications class BIII
		Water absorption (10% < E < 20%)
B2	15.13	✓
E1	15.06	✓

**Figure 3. Water absorption (%)**

Drying Shrinkage

Across all mixtures at 7 and 28 days of curing, the drying shrinkage of all specimens remained below 1%, indicating minimal dimensional change during the drying process (Piyarat *et al.*, 2021), as shown in Figure 4. The results revealed that the drying shrinkage slightly decreased with increasing CCR replacement. This effect was caused by the high CaO content in CCR, which hydrates and effectively reduces the available water content in the mixture. This finding also suggests that the specimens are suitable for cold-weather applications and exhibit a lower tendency for cracking in the concrete (Ogork & Ibrahim, 2017). At 28 days of curing, mixtures in groups B, C, and D, incorporating CCR and GGC either individually or in combination as a partial replacement, showed a slight increase in drying shrinkage compared with 7 days. This can be associated with the continued hydration process and ongoing strength enhancement. In contrast, mixtures in group E containing CCR as a partial OPC replacement and BA as an additive showed marginally higher drying shrinkage, likely associated with increased water demand and the formation of a refined pore structure, as supported by optical microscopy observations.

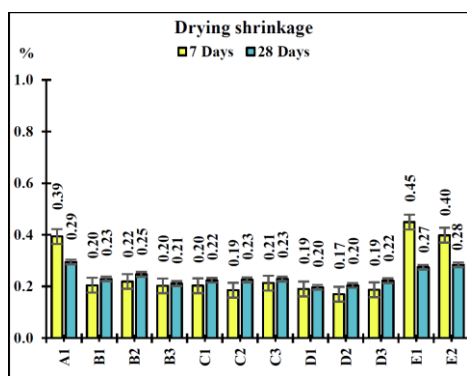


Figure 4. Drying shrinkage (%)

Weight Loss

Figure 5 presented the weight loss of specimens at curing periods of 7 and 28 days. The results indicated that the weight loss values increased slightly with longer curing duration. This behavior can be explained by the greater water and retention within the matrix pores during extended curing. Consequently, when the specimens were oven-dried to terminate curing, a larger amount of moisture evaporated, resulting in higher weight loss. Mixtures containing higher proportions of CCR as a partial OPC replacement exhibited lower weight loss than the control mixture. This reduction can be attributed to the high CaO content in CCR, which provides an excess of $\text{Ca}(\text{OH})_2$ within the cement matrix (Kelechi *et al.*, 2022a). Moreover, the use of GGC as a partial OPC replacement led to slightly lower weight loss compared with the control mixture, which is attributed to its low water absorption capacity and the dense, impermeable structure of the glass particles (Wang *et al.*, 2014). Conversely, the addition of BA in group E resulted in a marginally higher weight loss, likely due to its porous structure and rough surface texture, which promoted greater water evaporation during drying (Kuo & Gao, 2018).

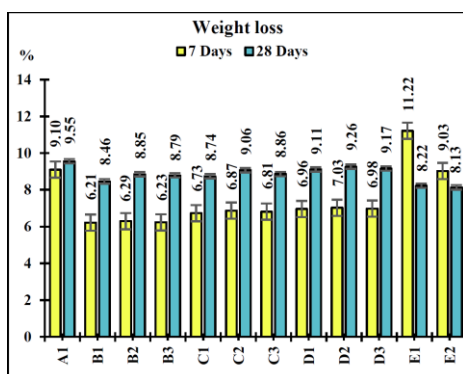
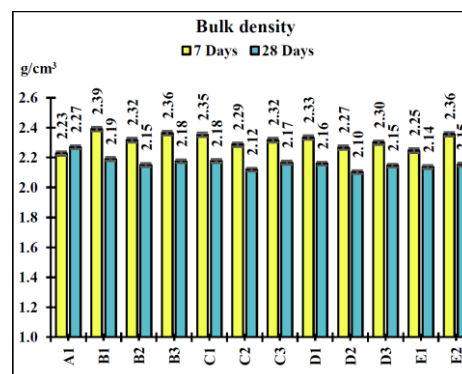


Figure 5. Weight loss (%)

Bulk Density

The bulk density values for all mixtures ranged from 2.10 to 2.39 g/cm^3 at 7 and 28 days of curing, as shown in Figure 6. The partial replacement of OPC with either CCR or GGC slightly increased the bulk density at the early curing stage. At 28 days, the control mixture composed of OPC, RS, and LS exhibited the highest bulk density compared with mixtures containing CCR and/or GGC. A gradual decrease in bulk density was found when increasing CCR as partial substitution of OPC. Mixture D2 containing 15 wt% CCR replacement showed the lowest bulk density due to the lower specific gravity of CCR as compared with OPC (Mahmmud & Abbas, 2025). Conversely, the incorporation of GGC resulted in higher bulk density values than CCR due to its higher specific gravity (Al-Zubaidi *et al.*, 2018). Furthermore, the addition of BA in group E provided a comparable effect to mixture B2, indicating that BA had an insignificant influence on the bulk density of the tile bodies.

Figure 6. Bulk density (g/cm^3)

Comparison of Modulus of Rupture (MOR) and Water Absorption (WA) of Cementitious Tiles with the ISO 13006 Standard Class BIII

As presented in Table 7, at 28 days of curing, mixture B2 contained 5 wt% CCR as an OPC replacement, whereas mixture E1 was fabricated by replacing OPC with 5 wt% CCR and adding 5 wt% BA. Both mixtures maintained identical proportions of OPC, RS, and LS. According to the ISO 13006 class BIII specifications of tiles, the MOR must exceed 12 MPa with a thickness greater than 7.5 mm, while the water absorption (WA) should range from 10% to 20%. Mixtures B2 and E1 satisfied these criteria under the ISO 13006 standard class BIII and can therefore be classified as floor tile products based on the breaking strength requirement. The surface appearances of the

samples are illustrated in Figures 7(a) and 7(b). Both cementitious tiles demonstrated a uniform light brown color and smooth surfaces, indicating homogeneous particle bonding and densification. The utilization of industrial by-products from CCR and BA contributed to the enhancement of the strength of cementitious tiles.

Table 7. Comparison of MOR and WA with the ISO 13006 standard class BIII of cementitious tiles at 28 days

No.	Mixture formulations (wt%)					ISO 13006 specifications class BIII	
	BA	CCR	OPC	RS	LS	MOR (> 12 MPa)	WA (10% < E ≤ 20%)
B2	0	5	17.5	15	62.5	12.49	15.13
E1	5	5	17.5	15	62.5	12.81	15.06

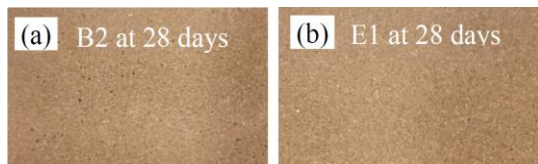


Figure 7. The surface appearances of the cementitious tiles at 28 days: (a) mixture B2 and (b) mixture E1

Optical Microscopy

Optical microscopy analysis was conducted to support the correlation between the surface morphology and MOR value of the samples with the highest MOR values among the five groups, namely A1, B2, C2, D2, and E1 at 7 and 28 days of curing, as shown in Figure 8 (a-e) and Figure 9 (a-e), respectively. Owing to its simple specimen preparation and effectiveness for comparative surface analysis, optical microscopy was considered suitable for this study. The samples were observed using a magnification of 300× with a 200 μm scale bar. Focusing on all samples, a highly dense arrangement into continuous matrix bodies was evident at 28 days as compared with 7 days, indicating improved interparticle bonding due to the ongoing hydration process during long-term curing. At 28 days of curing, mixture A1 without CCR replacement showed a compact and well-developed matrix, reflecting effective cement hydration. Similarly, mixture B2 incorporating 5 wt% CCR as a partial OPC replacement also displayed a dense microstructure at 28 days. This suggests that the elevated CaO content in CCR provides cementitious potential and enables reactions with

pozzolanic materials rich in silica and alumina, as reported by (Ogork & Ibrahim, 2017). In contrast, the micrographs of mixtures C2 and D2 containing 10 and 15 wt% CCR as a replacement for OPC, respectively, revealed a noticeable reduction in matrix compactness with the presence of micropores and voids, despite the occurrence of carbonate precipitation (Bawab *et al.*, 2024). A considerable quantity of unreacted particles could also be responsible for the reduction in MOR values at higher CCR replacement levels (Akinyemi *et al.*, 2021). Additionally, mixture E1 containing 5 wt% CCR as a partial OPC and 5 wt% BA as a supplementary additive, developed a denser microstructure compared to mixture B2. The synergistic effect between CCR and BA promotes the consumption of calcium, silica, and alumina ions, leading to the formation of C-A-S-H gel (Latifi *et al.*, 2018), as evidenced by the gel-like C-A-S-H morphology observed in Figure 10 at a magnification of 2000× with a 30 μm scale bar. The pozzolanic activity of BA further supported these reactions by effectively filling pore spaces and improving particle bonding through the formation of C-S-H and C-A-H phases. These hydration products densify the pore structure and reduce Ca(OH)₂ content (Kelechi *et al.*, 2022b), thereby contributing to an increased MOR value for cementitious tiles, similar to the findings reported by (Rafieizonooz *et al.*, 2016).

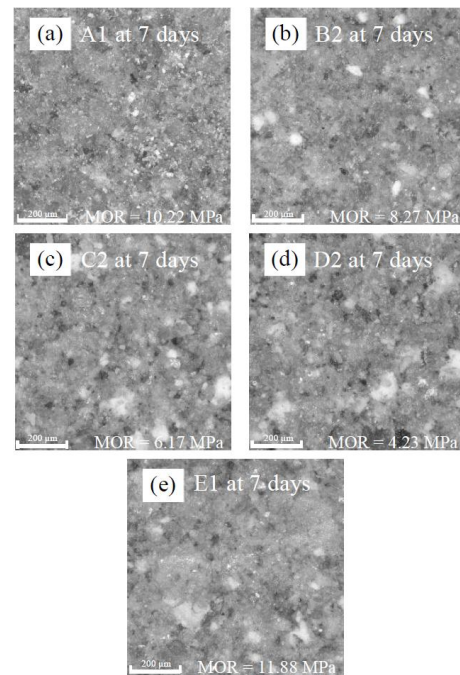


Figure 8. Optical microscopy images (300×) of cementitious tiles at 7 days: (a) A1, (b) B2, (c) C2, (d) D2, and (e) E1.

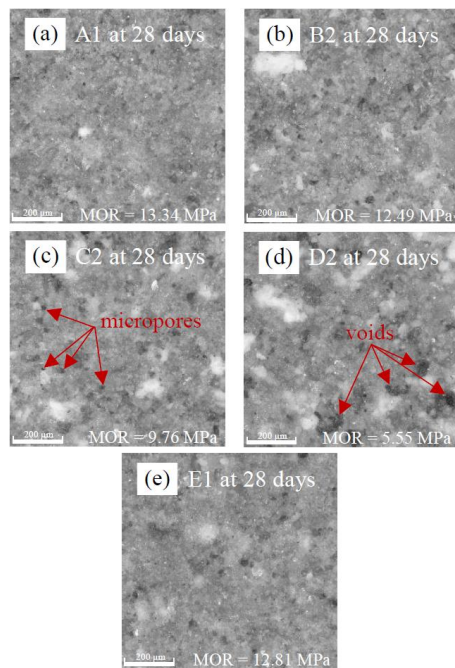


Figure 9. Optical microscopy images (300 $\times$) of cementitious tiles at 28 days: (a) A1, (b) B2, (c) C2, (d) D2, and (e) E1.

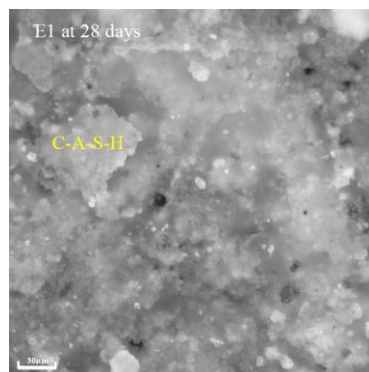


Figure 10. Optical microscopy images (2000 $\times$) of mixture E1 at 28 days

Conclusions

This study demonstrated the feasibility of producing sustainable cementitious tiles by partially replacing ordinary Portland cement (OPC) with calcium carbide residue (CCR) and green glass cullet (GGC), while incorporating bottom ash (BA) as an additive. Although GGC is classified as a natural pozzolanic material under ASTM C618 class N, mixtures containing only GGC exhibited lower MOR values than those containing CCR.

Notably, the combination of GGC and CCR improved the MOR relative to the use of GGC alone. The optimum mixture was E1, which incorporated 5 wt% CCR as a partial replacement for OPC together with 5 wt% BA as a supplementary additive. This mixture fulfilled the ISO 13006 class BIII requirements for floor tile products, including the criteria for MOR, water absorption, and breaking strength. These results confirm that CCR and BA enhance the pozzolanic reactivity of calcium, silica, and alumina components, promoting the C-A-S-H, which contributes to the strength of cementitious tiles. Furthermore, utilizing CCR as binder components provides significant environmental benefits, including an approximate 22.2% reduction in OPC consumption compared with the control mixture, while also minimizing the volume of waste requiring landfill disposal.

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Author Contributions

Conceptualization: N.P., P.M.; Methodology: N.P., P.M.; Investigation: N.P., P.M.; Data Curation: N.P., P.M.; Writing - Original Draft: N.P., P.M.; Writing - Review & Editing: N.P., P.M.; Supervision: N.P., P.M. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

Ethical approval was not required for this study because it did not involve human participants, animals, identifiable personal data, or materials requiring institutional ethical review.

Declaration of Generative AI Use

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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