

INFLUENCE OF SODA LIME GLASS PARTICLES ON CERAMIC TILE PROPERTIES USING BOTTOM ASH AND KAOLIN

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Received: September 04, 2025; Revised: October 07, 2025; Accepted: October 20, 2025

Abstract

This research investigated the influence of fine soda lime glass (FSLG) and coarse soda lime glass (CSLG) particles on the physical properties and microstructure of ceramic tiles produced using bottom ash (BA) from a municipal solid waste (MSW) power plant, and kaolin. A triaxial mixture design comprising 20 formulations was constructed to study the effects of FSLG and CSLG particles, with the mixtures divided into four groups based on varying BA contents of 0, 10, 20, and 30%. Specimens were uniaxially pressed at 10 MPa and fired at 950°C. The results showed that ceramic tiles containing 50, 60, and 70% FSLG without BA could meet the ISO 13006 standard in terms of both modulus of rupture and water absorption. Moreover, replacing 10% of kaolin with BA in the FSLG mixture was found to be the optimal content for achieving the ISO 13006 standard due to the fine particle size and the high fluxing oxide of FSLG and BA. Optical microscopy revealed that FSLG mixtures formed a continuous glassy phase and had a lower porosity than CSLG mixtures. It was consistent with the porosity analysis using the thresholding method in ImageJ software, which showed that the porosity of CSLG and FSLG images ranged from 2.72-6.96% and 1.64-4.00%, respectively. It can be concluded that producing ceramic tiles by reusing FSLG and BA is feasible to reduce the burden of waste disposal on entrepreneurs and to promote sustainable resource utilization.

Keywords: Bottom ash; Ceramic tiles; Coarse soda lime glass; Fine soda lime glass; Glass particle size; Waste glass

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DOI: <https://doi.org/10.55766/sujst11360>

Suranaree J. Sci. Technol. 33(2):030383(1-10)

Introduction

The growing global population and evolving consumption patterns have significantly increased organic and inorganic waste. This issue is particularly evident with inorganic waste such as glass packaging, which has a short lifespan, leading to the accumulation of large volumes of waste glass. However, the remanufacturing of waste glass is limited by complex sorting requirements related to particle sizes, color variations, and contaminants (da Costa *et al.*, 2020). While the EU reports a waste glass recycling rate above 70%, many regions, lacking glass manufacturing infrastructure struggle with collection and recycling. As a result, the global waste glass recycling rate remains below 30%. This low rate contributes to approximately 200 million tons of waste glass ending up in landfills annually, which exacerbates land scarcity (Huang *et al.*, 2024). For this reason, several studies have already investigated alternative solutions to utilize waste glass, and many investigations have revealed solutions which are technically feasible in the ceramics field. Replacing fine and coarse aggregates with waste glass particles in ceramics has recently attracted attention in the construction industry (Subhani *et al.*, 2024). In particular, finely powdered waste products, e.g., scrap soda lime glass, can serve as an alternative flux to feldspar. This glass flux provides a viscous liquid phase at lower sintering temperatures, resulting in substantial energy savings (Bernardo *et al.*, 2008).

Similarly, while waste-to-energy (WTE) technology offers a promising solution for converting municipal solid waste (MSW) into electricity, it generates a significant amount of bottom ash as a byproduct. In Thailand, a WTE plant in Nonthaburi province, with an installed capacity of 8 MW, processes about 300–400 tons of MSW per day. This facility converts refuse-derived fuel (RDF) into electricity, supplying about 60 million units per year to the Electricity Generating Authority of Thailand (EGAT). However, the incineration process results in a substantial amount of ash, with bottom ash comprising approximately 80% of the total ash volume, thereby posing a significant disposal challenge (Wong *et al.*, 2020). Nevertheless, bottom ash contains valuable oxides such as silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3) and calcium oxide (CaO), making it a potential raw material for other industries. Although the majority of bottom ash is disposed of in landfills, many studies have explored its potential as a raw material for various products such as aggregates, backfill materials, concrete, and ceramics (Zhang *et al.*, 2020).

As a local material sourced from Lampang province, Thailand, kaolin has been widely used as a raw material for various ceramic products. Its main constituents are SiO_2 and Al_2O_3 . It also contains a minor amount of potassium oxide (K_2O), which serves as a fluxing agent. This clay is characterized by its ability to vitrify gradually without deformation at temperatures around $1,200^\circ\text{C}$ (Mulinta and Thiansem, 2019). In a previous study, Jaya *et al.* reported that a suitable firing temperature for kaolin-based ceramics was approximately $1,200^\circ\text{C}$, enabling vitrification and the attainment of high mechanical strength (Jaya *et al.*, 2016). However, this high-temperature firing process poses a significant challenge in ceramic production. Therefore, there was a need to investigate alternative materials that could act as efficient fluxing agents to lower the firing temperature of kaolin-based ceramics. As reported, waste glass and bottom ash have been identified as effective fluxing agents. Bernardo *et al.* investigated the reuse of waste glass as a substitute for feldspar in porcelain stoneware. The glass-ceramic stoneware was found to sinter at $1,000^\circ\text{C}$ and exhibited a bending strength of 90 MPa, which was similar to that of conventional porcelain stoneware (Bernardo *et al.*, 2008). Moreover, the incorporation of fine waste glass could lower the firing temperature by 100°C due to the fluxing properties of Na_2O , K_2O , and CaO (Piyarat *et al.*, 2022). Rambaldi *et al.* reported that vitrified bottom ash, when substituted at 5–10%, acted as a strong fluxing agent and promoted the sintering of porcelain stoneware (Rambaldi *et al.*, 2010).

Therefore, the novelty of this study lies in the comparative investigation of fine and coarse soda lime glass particles and bottom ash in kaolin-based ceramics, systematically optimized using a triaxial mixture design. This approach exploits the synergistic fluxing effects of waste glass and bottom ash for efficient waste valorization at a reduced firing temperature of 950°C . The physical properties compare with the ISO 13006 standard for ceramic tiles, as verified by optical microscopy and porosity analysis.

Materials

The chemical compositions of the raw materials used in this study were determined by X-ray fluorescence (XRF) analysis, as presented in Table 1. Soda lime glass (SLG) was obtained from a recycling factory situated in Ayutthaya province,

Thailand. Bottom ash (BA) was sourced from an MSW to waste-to-energy plant located in Nonthaburi province, Thailand. Kaolin (K) acquired from Lampang province, Thailand, was utilized to enhance plasticity and facilitate the forming of ceramic bodies. SLG, BA, and K were all identified as SiO₂-rich materials, suggesting their potential for application in ceramic production. Moreover, SLG was employed as good fluxing oxides, e.g., Na₂O, K₂O, and CaO, which helped lower the sintering temperature of ceramic tiles.

Table 1. Oxide composition of raw materials

Oxides	SLG (%)	BA (%)	K (%)
SiO ₂	71.08	65.96	72.13
Al ₂ O ₃	1.69	9.33	17.43
Fe ₂ O ₃	0.12	8.22	0.67
K ₂ O	0.18	1.59	3.06
CaO	10.11	7.08	0.09
MgO	2.48	1.43	0.09
TiO ₂	0.06	0.77	0.03
Na ₂ O	14.11	1.52	0.26
SO ₃	0.12	0.88	-

Methods

The dried materials were then ground using a ball mill at 100 rpm under dry conditions. After grinding, the raw materials were sieved. The SLG was divided into two particle size groups. The fine SLG (particles smaller than 50 mesh, equivalent to less than 297 µm) primarily acted as a fluxing agent (Maingam *et al.*, 2021). The coarse SLG (particles ranging from 50 to 10 mesh, equivalent to 297 to 2,000 µm) was the residual fraction retained on the 297 µm sieve. It was subsequently utilized as a coarse comparative material, as determined from preliminary experiments. The other powdered materials were sieved through a 297 µm mesh using a sieve shaker. A triaxial mixture design was employed to develop the formulations. A total of 20 compositions were prepared, consisting of 10 formulas based on coarse soda lime glass (CSLG), as shown in Table 2, and 10 formulas based on fine soda lime glass (FSLG), as shown in Table 3. These mixtures were divided into four groups (A, B, C, and D) based on varying BA contents of 0, 10, 20, and 30%, respectively, with kaolin constituting the remainder of the compositions. The blended powders were subsequently shaped into specimens with dimensions of 50×100×7 mm using a uniaxial press at 75 bars. The pressed specimens were fired in an electric kiln. The firing schedule involved a heating rate of 100°C/h to a maximum temperature of 950°C, which was held

for 1 h. The firing temperature was determined according to (Wangrakdiskul *et al.*, 2020), and was indicated to achieve suitable densification and physical strength using waste materials in ceramic tiles. The properties of the specimens were tested, including fluxing agent properties, modulus of rupture (ISO 10545-4), water absorption (ISO 10545-3), bulk density (ISO 10545-3), shrinkage, and weight loss. The results for modulus of rupture and water absorption were compared with the ISO 13006:2012 standard for ceramic tiles. Moreover, XRF analysis was employed to determine the chemical composition of the dry powdered materials using a wavelength-dispersive XRF (WDXRF) spectrometer (Model: S8 TIGER, Bruker, Germany). The microstructures were also analyzed using an Olympus DSX1000 optical microscope with a polarization mode. Images were captured using an Olympus DSX10-XLOB Plan FL 10x/0.30 WD 30 lens. The acquired images were processed using the DSX software. Porosity analysis was then performed using ImageJ software, which applied a thresholding method to segment the pores.

Table 2. Mixture formulas based on CSLG

No.	CSLG (µm)	CSLG (%)	BA (%)	K (%)
AC1	297-2000	40	0	60
AC2	297-2000	50	0	50
AC3	297-2000	60	0	40
AC4	297-2000	70	0	30
BC1	297-2000	40	10	50
BC2	297-2000	50	10	40
BC3	297-2000	60	10	30
CC1	297-2000	40	20	40
CC2	297-2000	50	20	30
DC1	297-2000	40	30	30

Table 3. Mixture formulas based on FSLG

No.	FSLG (µm)	FSLG (%)	BA (%)	K (%)
AF1	<297	40	0	60
AF2	<297	50	0	50
AF3	<297	60	0	40
AF4	<297	70	0	30
BF1	<297	40	10	50
BF2	<297	50	10	40
BF3	<297	60	10	30
CF1	<297	40	20	40
CF2	<297	50	20	30
DF1	<297	40	30	30

Results and Discussion

The physical properties of all formulations were investigated in two groups. The results are presented as mean values and standard deviation (SD) based

on testing 15 specimens, except for the fluxing agent value, which was a calculated parameter and therefore not associated with a SD. All tested properties showed a relative SD (RSD) of less than 10%.

Fluxing Agent

The calculation was performed on the basis of the combined contents of Na_2O , K_2O , and CaO , as identified from the oxide composition determined by XRF analysis. It is not significantly affected by the particle size of CSLG and FSLG, as their average values were identical. Instead, it varies depending on the mixture formulation, as shown in Figure 1. For example, within group A, the fluxing agent value generally increases from formula AF1 to AF4, with AF4 having the highest value at 18.52%. A similar trend is observed in groups B, C, and D, where the highest values were 17.04%, 15.56%, and 14.08%, respectively. This increase is attributed to the higher content of SLG, which contains fluxing compounds that enhance the melting behavior of the material, thereby improving physical strength and reducing porosity in the specimens. A similar conclusion was reported by (Boulaiche *et al.*, 2022).

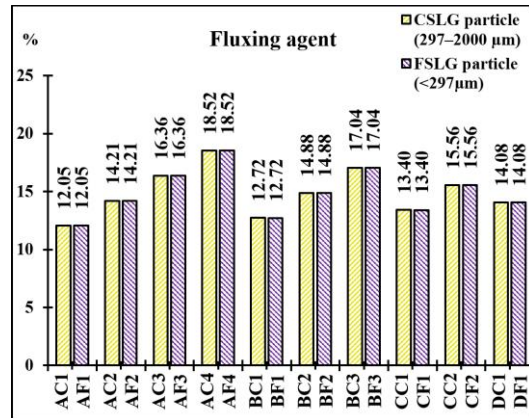


Figure 1. Fluxing agent (%)

Modulus of Rupture (MOR)

MOR increases with a higher amount of SLG due to its elevated fluxing agent content, as shown in Figure 2, which promotes strength and densification. A similar effect was reported by (Natrah *et al.*, 2019). Therefore, the highest MOR values of formulas AF4, BF3, CF2, and DF1 correspond to the highest SLG content within each group. Conversely, replacing kaolin with BA at ratios of 10, 20, and 30% in groups B, C, and D,

respectively, leads to a decrease in MOR, as it reduces both the total fluxing agent content and the liquid-phase sintering. Notably, replacing more than 20% of BA in groups C and D leads to a decrease in the MOR. This finding corresponds with the results of (Lin *et al.*, 2022). This reduction in MOR can be attributed to the irregular shape of BA, which promotes a porous structure originating from gas-forming ash during firing (Arshad *et al.*, 2022). Moreover, the use of FSLG consistently results in a higher MOR than CSLG due to improved melting behavior associated with finer particle sizes, which leads to stronger ceramic bodies. Specifically, FSLG enhances vitrification by sintering kinetics, which facilitates mass transport via viscous flow as a direct result of the increased surface area (Fernandes *et al.*, 2023).

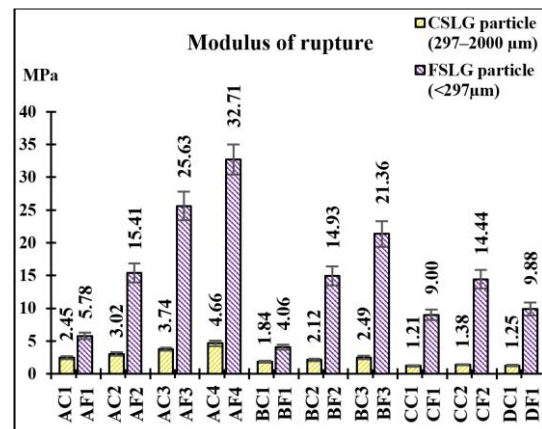


Figure 2. Modulus of rupture (MPa)

Water Absorption

Increasing the proportion of SLG results in higher MOR and lower water absorption, as illustrated in Figure 3. In group A, this effect is due to the fluxing action of SLG, which enhances vitrification and reduces porosity. Similarly, increasing the proportion of BA in groups B, C, and D causes a slight decrease in water absorption due to its fluxing action. However, BA undergoes the decomposition of organic matter during firing. As organic components burn off and release carbon dioxide (CO_2), additional pores are formed in the ceramic body. A similar result was reported by (Pitak *et al.*, 2022). Furthermore, formulas containing FSLG exhibit lower water absorption compared to CSLG, as the finer particles melt more effectively, which reduces overall porosity. Therefore, the formulas AF4, BF3, CF2, and DF1 have the lowest water absorption of each group.

However, the water absorption of all formulas remained below 20% according to the ISO 13006 standard of ceramic tiles.

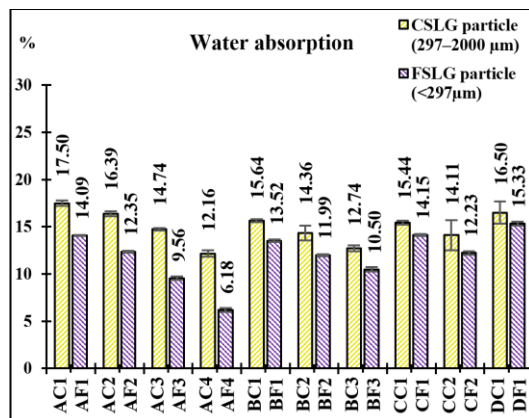


Figure 3. Water absorption (%)

Shrinkage

As presented in Figure 4, shrinkage is significantly influenced by raw materials used and particle sizes. Increasing the amount of SLG leads to higher shrinkage due to its high content of fluxing agents, which promote effective melting and enhance MOR. Conversely, increasing BA content in groups B, C, and D reduces shrinkage due to the decomposition of organic matter, which lowers the effective fluxing agent content and inhibits complete melting. Furthermore, formulations containing FSLG consistently exhibit greater shrinkage because they melt more efficiently, pulling other components together and reducing water absorption. For example, the highest shrinkage of formulas AF4, BF3, CF2, and DF1 has

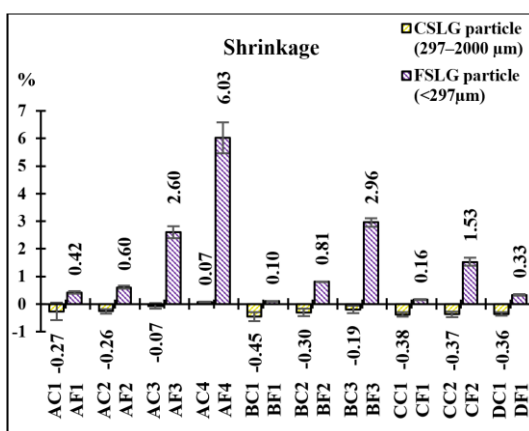


Figure 4. Shrinkage (%)

the highest FSLG content of each group. In contrast, CSLG tends to melt incompletely, resulting in slight expansion and higher water absorption of formulas AC1, BC1, CC1, and DC1, which is a similar result to that reported by (Maingam *et al.*, 2021). Nevertheless, the shrinkage rate is below 8%, indicating that all formulations can be effectively controlled in terms of dimensions, thereby reducing the risk of cracking in ceramic bodies (Phonphuak *et al.*, 2016).

Weight Loss

In group A, increasing the proportion of SLG reduces weight loss due to its inherent thermal stability and high melting point. Conversely, group B, containing BA, causes greater weight loss because BA has a lower melting point and a higher content of volatile organic matter, as shown in Figure 5. The high carbonaceous content of BA in groups B, C, and D also contributes significantly to weight loss after firing, as also reported similarly by (Rocca *et al.*, 2013). Furthermore, weight loss values of CSLG and FSLG mixtures are within the range of 1.23-2.32% and 1.14-2.08%, respectively. Consequently, formulations containing FSLG resulted in slightly lower weight loss than CSLG, owing to the influence of particle size on firing reactions. Therefore, FSLG content can be attributed to its higher thermal stability, which facilitates the preservation of structural integrity during sintering, thereby minimizing mass loss (Conte *et al.*, 2020).

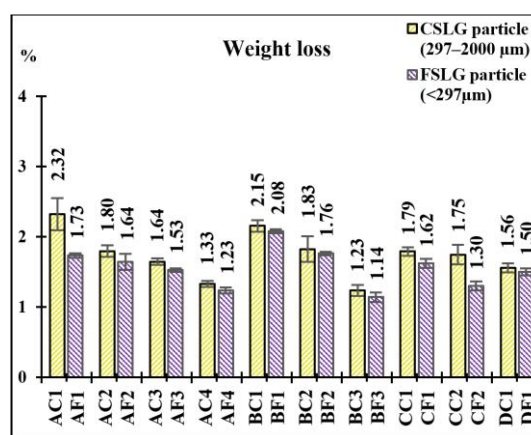


Figure 5. Weight loss (%)

Bulk Density

Figure 6 illustrates that the formulations exhibit bulk density values ranging from 2.22 to 2.36 g/cm³. A slight decrease in bulk density is observed with increasing contents of SLG, which is attributed to the low specific gravity of this material

(Hisham *et al.*, 2021). In group A, the higher bulk density is due to the kaolin content, with a similar result to (Funsueb *et al.*, 2023). Groups B, C, and D, containing higher proportions of BA, exhibit slightly higher bulk density. This is consistent with the findings of (Cheeseman *et al.*, 2003). This finding is consistent with the higher specific gravity of kaolin and BA compared to SLG. In addition, formulas containing CSLG exhibit slightly higher bulk density as compared to FSLG composition due to more mass per unit volume upon firing, which is consistent with (Malek *et al.*, 2020).

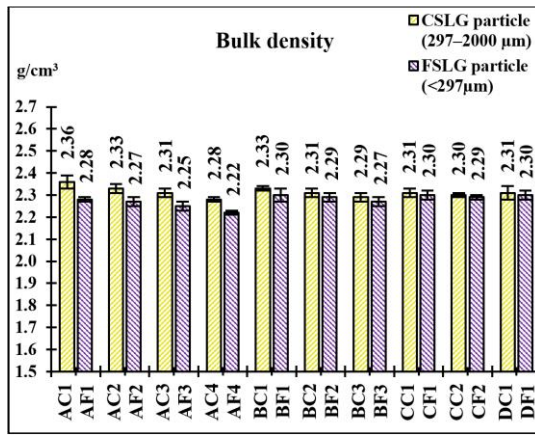


Figure 6. Bulk density (g/cm³)

Comparison of MOR and Water Absorption with ISO 13006 Standard for Ceramic Tiles

As presented in Table 4, formulas AF2, AF3, and AF4, containing 50, 60, and 70% FSLG without BA, attained the MOR requirements for classes BIII, BII_a, and BI_b, respectively. These formulas also met the water absorption (WA) requirements for classes BIII, BII_b, and BII_b, respectively. Moreover, replacing 10% of kaolin with BA in formula BF3 resulted in compliance with MOR class BII_b and water absorption class BIII. However,

when comparing formulas AF3 and BF3, both of which contain 60% FSLG, the inclusion of BA in formula BF3 led to a decrease in MOR and an increase in water absorption. The colors and textures of ceramic tiles can pass the ISO 13006 standard, as shown in Figure 7(a-d).

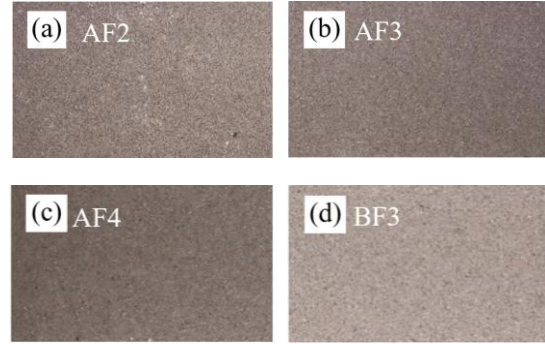


Figure 7. The colors and textures of ceramic tiles comply with the ISO 13006 standard: (a) formula AF2, (b) formula AF3, (c) formula AF4, and (d) formula BF3

Optical Microscope (OM) Analysis

Microstructural analysis was performed using optical microscopy to characterize the surface morphology of samples. All observations were performed at 150× magnification with a 400 µm scale bar. Specimens with the highest and lowest MOR values in groups A, B, C, and D were selected for characterization. Accordingly, the selected CSLG formulas included AC1, AC4, BC1, BC3, CC1, CC2, and DC1, as shown in Figure 8(a-g), respectively. Meanwhile, the FSLG formulas were AF1, AF4, BF1, BF3, CF1, CF2, and DF1, as shown in Figure 9(a-g), respectively. Figure 8 illustrates the CSLG formulas with the lowest MOR in each group, namely, AC1, BC1, CC1, and, DC1, which exhibited a distribution of small and large pores. These pores resulted from the coarse powder of SLG

Table 4. Comparison of MOR and water absorption (WA) with the ISO 13006 standard

No.	Compositions (%)			ISO 13006 specifications							
				Class BI _b		Class BII _a		Class BII _b		Class BIII	
	FSLG	BA	K	MOR	WA	MOR	WA	MOR	WA	MOR	WA
				>30 MPa	0.5% <E≤ 3%	>22 MPa	3% <E≤ 6%	>18 MPa	6% <E≤ 10%	>15 MPa	10% <E≤ 20%
AF2	50	0	50	-	-	-	-	-	-	15.41	12.35
AF3	60	0	40	-	-	25.63	-	-	9.56	-	-
AF4	70	0	30	32.71	-	-	-	-	6.18	-	-
BF3	60	10	30	-	-	-	-	21.36	-	-	10.50

and the higher BA content in groups B, C, and D, leading to a significant reduction in the MOR of the samples. This corresponds with the results of (Lin *et al.*, 2021). Figure 9 shows that the FSLG formulas with the highest MOR in each group, including AF4, BF3, CF2, and DF1, showed a dense structure and a continuous glassy phase, resulting from the fine powder and high fluxing oxide content in FSLG. This phase effectively filled interstitial spaces, acting as a strong fused bond that

significantly enhanced the MOR and reduced the water absorption of the ceramic bodies. This is consistent with the findings of (Wangrakkdiskul *et al.*, 2020).

Porosity Analysis of Ceramic Tiles with ImageJ Software

Porosity was defined as the ratio of the pore area to the total area of the OM images at 150 $\times$ magnification, according to Figures 8 and 9.

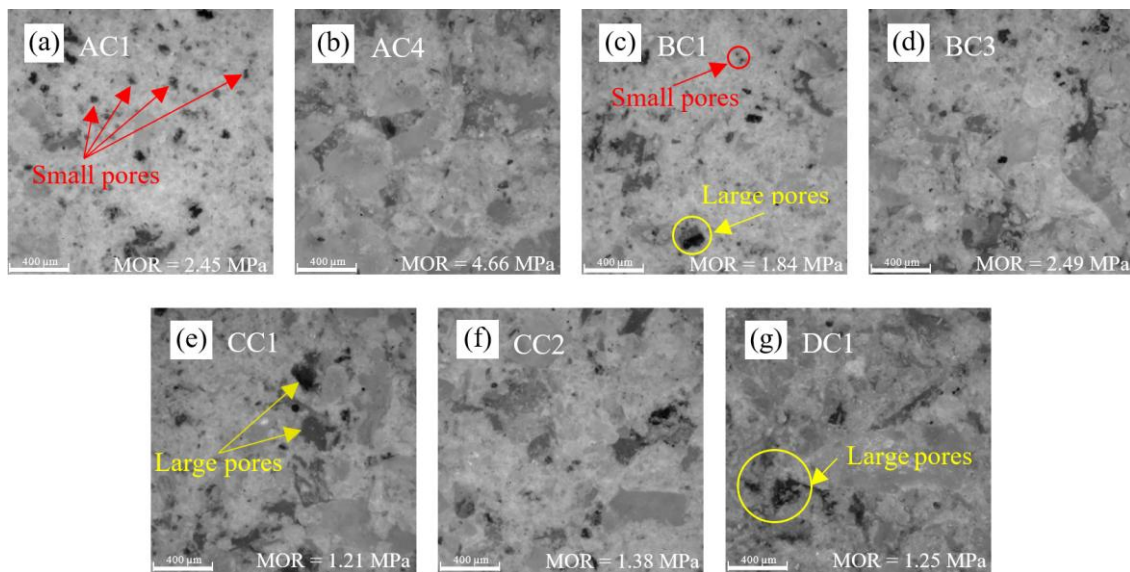


Figure 8. The OM images of the microstructure surfaces (150 $\times$), including CSLG formulas: (a) AC1, (b) AC4, (c) BC1, (d) BC3, (e) CC1, (f) CC2, and (g) DC1

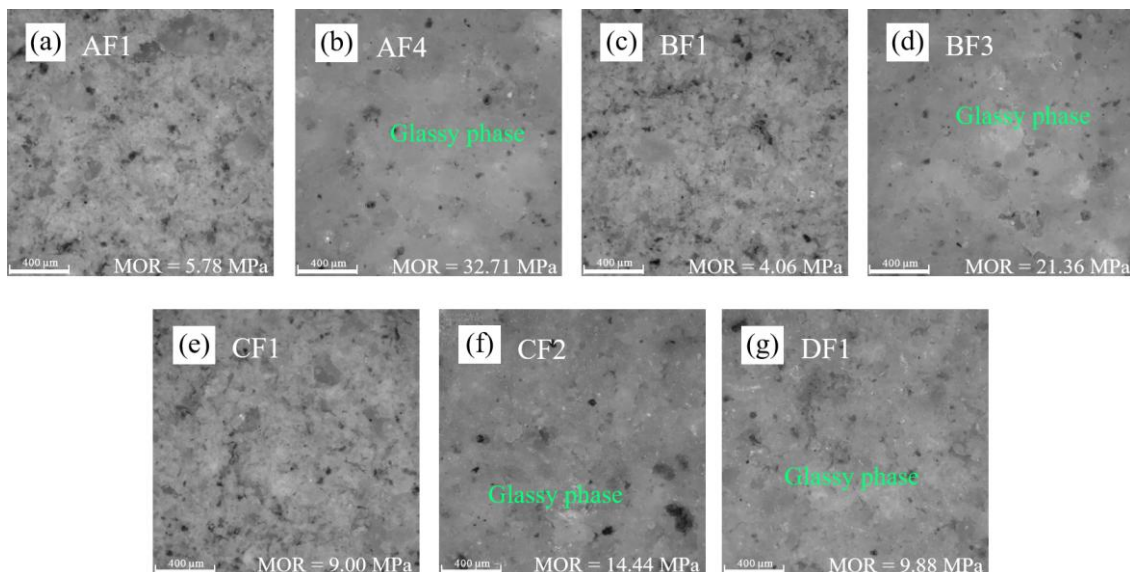


Figure 9. The OM images of the microstructure surfaces (150 $\times$), including FSLG formulas: (a) AF1, (b) AF4, (c) BF1, (d) BF3, (e) CF1, (f) CF2, and (g) DF1

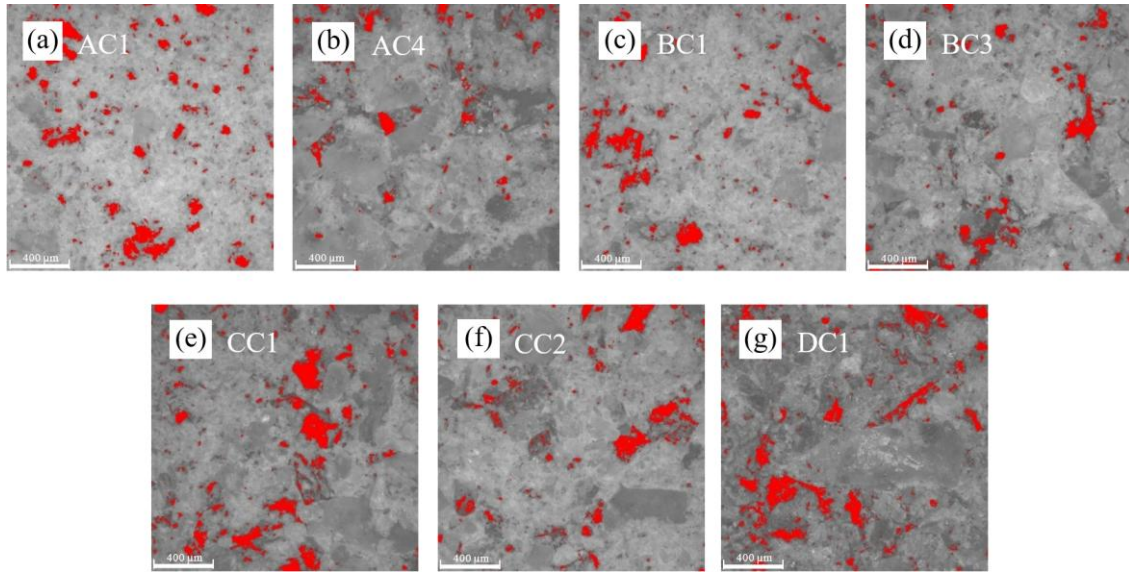


Figure 10. The segmentation results from ImageJ show red areas represent pores, including CSLG formulas: (a) AC1, (b) AC4, (c) BC1, (d) BC3, (e) CC1, (f) CC2, and (g) DC1

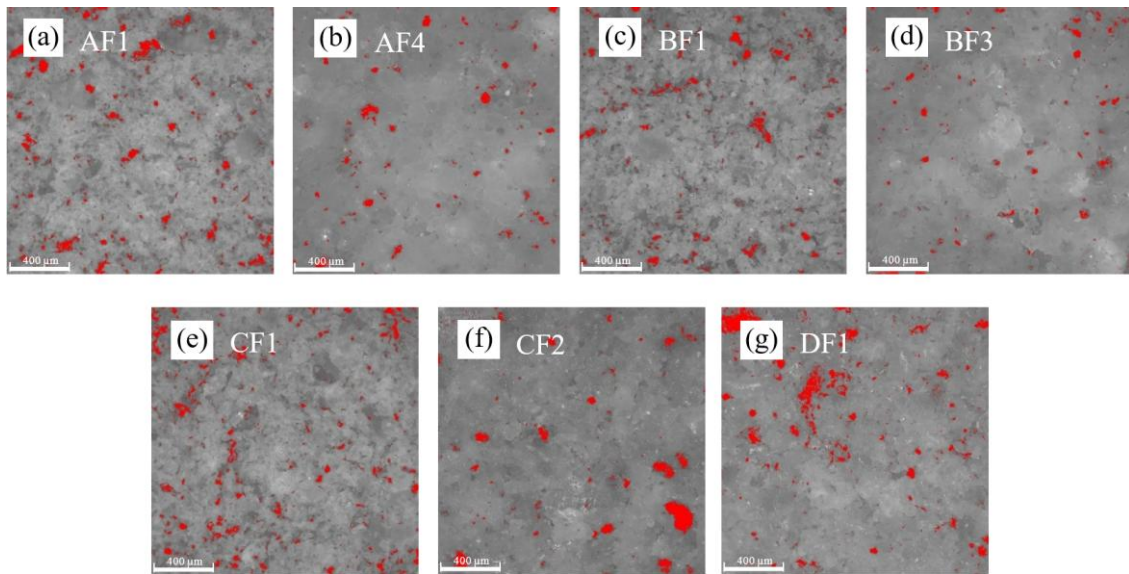


Figure 11. The segmentation results from ImageJ show red areas represent pores, including FSLG formulas: (a) AF1, (b) AF4, (c) BF1, (d) BF3, (e) CF1, (f) CF2, and (g) DF1

The porosity percentage for each image was calculated using ImageJ software, which applied a thresholding method for pore segmentation. The segmented images were then analyzed with red areas representing the pores. A range of suitable threshold values was determined (Shi *et al.*, 2023). The segmentation images of CSLG formulas were AC1, AC4, BC1, BC3, CC1, CC2, and DC1, as shown in Figure 10(a-g), respectively. Meanwhile, the segmentation images of FSLG formulas were

AF1, AF4, BF1, BF3, CF1, CF2, and DF1, as shown in Figure 11(a-g), respectively. In addition, the porosity of CSLG and FSLG images from ImageJ analysis ranged from 2.72-6.96% and 1.64-4.00%, as presented in Tables 5 and 6, respectively. From Table 5, formulas AC1, BC1, CC1, and DC1 containing CSLG showed higher porosity in each group, with the densest and most widespread red areas found in formula DC1. These observations confirmed that image samples with a higher

concentration of red areas correspond to higher porosity, whereas fewer red areas indicated lower porosity. In contrast, Table 6 showed that formulas AF4, BF3, CF2, and DF1 containing FSLG contributed to pore refinement, reducing pore size and distribution, as evidenced by fewer and smaller red areas of each group, when compared with those containing CSLG.

Table 5. %Porosity analysis of CSLG formulas using ImageJ analysis

CSLG formula no.	Porosity (%)
AC1	6.14
AC4	2.72
BC1	4.30
BC3	3.54
CC1	6.39
CC2	4.12
DC1	6.96

Table 6. %Porosity analysis of FSLG formulas using ImageJ analysis

FSLG formula no.	Porosity (%)
AF1	3.16
AF4	2.06
BF1	2.06
BF3	1.64
CF1	2.85
CF2	2.50
DF1	4.00

Conclusions

This study successfully investigated the feasibility of producing ceramic tiles by utilizing FSLG and BA as alternative kaolin-based ceramics at a low firing temperature of 950°C. The compositions were systematically optimized using a triaxial mixture design into groups A, B, C, and D based on varying bottom ash contents. Group A compositions containing 50-70% FSLG without BA can attain the minimum MOR and water absorption requirements of the ISO 13006 standard, confirming that FSLG is superior to CSLG as a flux. The finer particle size of FSLG enhances vitrification, resulting in higher MOR and shrinkage, while reducing water absorption, weight loss, and bulk density. Group B compositions, in which 10% of kaolin is replaced by BA, can also pass the ISO 13006 standard. However, groups C and D containing more than 20% BA require further development and investigation to meet the requirements of the ISO 13006 standard. The incorporation of additional flux materials is

recommended for future studies. Optical microscope analysis verifies that FSLG-based compositions develop a continuous glassy phase and exhibit lower porosity as compared to CSLG-based compositions. In conclusion, this research confirms that FSLG and BA are effective fluxing agents for improving the strength of ceramic tiles, offering a sustainable and cost-efficient strategy for reusing industrial byproducts and mitigating the burdens of waste disposal.

Acknowledgements

The authors wish to thank Pitchaya Niamsang and Ketsopon Piriyaawattachai for their technical assistance. We are also grateful for the provision of all necessary resources by the Production and Robotics Engineering Department, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand.

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