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Using Recycled Coal Ash from Thermal Power Plants and Rice Husk Ash as Alternative Aggregates for the Manufacturing of Terrazzo Tiles

Nguyen Thi Minh Trang[1], Nguyen Thi Thanh Huong[1], and Ngo Anh Dao Ho[2*]

[1]*Department of Urban Infrastructure Engineering, University of Architecture Ho Chi Minh City, Ho Chi Minh City, Vietnam*
[2]*Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam*

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*** Corresponding author:**
E-mail:
hongoanhdao@tdtu.edu.vn

ABSTRACT

This study investigated the technical specifications of Terrazzo tiles manufactured using coal ash from thermal power plants and rice husk ash (RHA) to partially replace sand and cement as primary aggregates. Sample bricks with different mixed ratios of fly ash, bottom ash (slag), and RHA were produced with a hydrostatic-press machine with a standard mode of 400×400×30 mm. Our results showed that the brick density, flexural strength, and water absorption were significantly affected by the variation of fly ash and RHA content. The optimum ratio by weight of aggregate ingredients was found to be fly ash of 10%wt., RHA of 30%wt., and slag of 5%wt., accompanied by crushed stone at 55%wt. This produced brick products comparable to Terrazzo tiles, type 2, Mac 4.0. This classification satisfies the Vietnamese national standard for exterior bricks, and also is competitive with commercial quality in the local market. The reuse and recycling of waste from thermal power plants and RHA for manufacturing new construction material was thus demonstrated successfully in this study. This helps to emphasize the trend of net zero emissions, and further encourages the concept of reutilization towards sustainable development.

1. INTRODUCTION

According to statistics and estimation from The Vietnam Union of Science and Technology Associations (VUSTA), from 2025 to 2035, the quantity of waste slag generated from all coal thermal power plants in Vietnam is about 12.00-14.48 million tons of fly ash and 2.12-2.56 million tons of bottom ash (Truong, 2019). Based on the Law on Environmental Protection 2020 (Vietnam), ash and slag are encouraged to be recycled and reused as secondary building materials to reduce environmental impacts (VNA, 2020). Specifically, the ash and slag generated from the Formosa Thermal Power Plant (FTPP) in Dong Nai Province, Vietnam, have been certified as recyclable wastes due to the satisfaction of their compositions to the national standards of backfill materials and additives of cement (i.e., TCVN 12249:2018, TCVN 6882:2016) (MOC, 2017). It was reported that the heavy metal content in ash and slag was low (e.g., Hg concentration in fly ash of 0.0005 mg/L is lower than the maximum level regulated by the national standard of hazardous waste of 0.2 mg/L) (Nguyen et al., 2020). Ash and slag from thermal power plants have been investigated for different reuse purposes in the construction material industry, such as additives for cement manufacturing (Abdullah et al., 2011; Le et al., 2019), additives for concrete production (Oner et al., 2005; Teixeira et al., 2019), adobe brick (Dharek et al., 2020; Trang et al., 2021), landfill cover layer (Brännvall and Kumpiene, 2016; Shaikh et al., 2021), backfill material (Li et al., 2020; Behera et al., 2021), and reinforced construction foundations (Mohajerani et al., 2017; Pant et al., 2019; Ashfaq and Moghal, 2022). Thus, further investigation of the combination of ash and other waste materials should be carried out to explore more recycling potentials.

On the other hand, rice cultivation and production also release agricultural wastes, especially

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rice husk (RH) and rice husk ash (RHA). According to the General Statistics Office of Vietnam, the total rice output in 2022 reached 42.66 million tons (GSOV, 2022). A study reported that for each ton of rice produced, there are about 200 kg of RH and 40 kg of RHA generated, which leads to considerable environmental issues (Ling and Teo, 2011). Many studies have shown the prospect of RHA application in building material manufacturing (Peng and Yang, 2016; Hossain and Islam, 2022). However, most studies focus on using RHA burned under controlled temperature and crushed to optimal size. Although the RHA obtained under these conditions can help to improve the mechanical properties and the durability of concrete (de Sensale, 2006; Giaccio et al., 2007), the crushing process leads to high cost of input material since the maximum alternative amount of RHA for cement is just about 10% (w.t.) (Talsania et al., 2015). The investigation of the raw RHA without burning or crushing to apply in construction materials production is still limited. Thus, study on the application of raw RHA as aggregates for adobe brick manufacturing is a promising approach.

Generally, adobe brick is produced through the shaping process without temperature treatment, from which its structural bonding is different from the common one. The strength of adobe brick depends on the pressure or vibration and adhesive components applied during the manufacturing. Also, the durability will be increased over time through the petrified reaction of different aggregates (Trang et al., 2021). In Vietnam, the commercial pavement brick is Terrazzo tiles - one common adobe brick type, which is produced from traditional materials through vibration or static pressing procedures. Compared with other pavement bricks, Terrazzo tiles have many advantages, including having good bearing capacity and no water retention. In terms of composition, Terrazzo tiles are concrete with a low water ratio in which mixed aggregates are pressed tightly in steel molds to form products with particular shapes. Thus, the aggregate ingredients with appropriate proportions and a proper static pressure control for brick shaping play an important role in the brick quality. Previous studies have investigated the feasibility of using industrial wastes (e.g., incineration bottom ash (Huynh et al., 2021), exhausted lime, and glazing sludge (Andreola et al., 2016), and polishing sludge (Al-Zboon et al., 2010)) as alternative raw materials in the production of building bricks and Terrazzo tiles (ceramic tiles) for pavement. Most studies successfully demonstrated that these waste materials can be used to produce Terrazzo tiles of which the transverse strength, water absorption, and tile measurements comply with national standards. However, the effects of aggregate ingredients were not examined in details. In addition, the manufacturing of Terrazzo tiles using coal ash and RHA as the main aggregates has not been studied much in Vietnam. Thus, this study is expected to expand the database for recyclable materials in the field of construction engineering and also tackle environmental issues due to the waste generation.

The objectives of this study include: (1) to determine the aggregates proportion between coal ash and RHA to produce Terrazzo tiles following the abrasion resistance, surface water absorption, and flexural strength guidelines of the Vietnamese Standard TCVN 7744:2013 on Terrazzo tiles (MOC, 2016); and (2) to evaluate the roles of coal ash and RHA to replace sand and cement in aggregate ingredients. Results obtained in this study will promote the development of advanced technology for adobe brick manufacturing using waste materials. The novelty of this study is the combination of 2 waste materials to partially replace the use of cement, which has yet to be conducted in Vietnam. This study shows significance in both environmental and economic aspects, which helps to strengthen the inevitable trend of recycling and reuse in waste treatment.

2. METHODOLOGY

2.1 Preparation of aggregates and additives

2.1.1 Aggregates

Coal ash (fly ash and bottom slag) collected from the Formosa Thermal Power Plant (FTPP) in Dong Nai Province, Vietnam, and rice husk ash (RHA) from Cai Be Rice Milling Factory in Tien Giang Province, Vietnam, were used as the main aggregates. In addition, crushed stone obtained from the Bien Hoa Stone Mine in Dong Nai Province, Vietnam, replaced the use of sand during the brick-making experiments to ensure that the strength of the bricks satisfies the national standard TCVN 7744:2013 (MOC, 2016).

(1) Coal ash: Table 1 shows the compositions and properties of fly ash and bottom slag obtained from FTPP that satisfy the national standard (i.e., TCVN 10302:2014) to serve as the alternative aggregates for the manufacturing of building materials. Also, the extracted concentrations of heavy metals are below the hazardous waste thresholds of the national standard (i.e., QCVN 07:2009) and

meet the requirements to reuse as backfill material (i.e., TCVN 12249:2018).

(2) RHA: The RHA used in this study was directly collected from the raw ash generated at the rice milling factory without the grinding process. Raw RHA with a black color and density of 2.316 g/cm^3 was then separated through a standard sieve of 0.180 mm to obtain fine RHA before mixing with other aggregates. The chemical compositions of fine RHA are presented in Table 2. It shows that the SiO_2 content occurring in RHA is very high (i.e., 91.4%) which is relatively equivalent to SiO_2 content in silica fume (i.e., >90%) - a mineral additive with high pozzolan activity commonly used in mixing concrete and mortar. This result also satisfies the TCVN 8827:2011 national standards on mineral admixture in which the SiO_2 in RHA is regulated above 85% to serve as admixtures for concrete and mortar. Thus, RHA can fill micro-holes in the brick structural matrix, improving its the durability and decreasing the amount of water used to make bricks.

Table 1. Physical-mechanical properties and chemical compositions of FTPP coal ash

Parameters		Type of coal ash		National standard TCVN 10302:2014 (*)	National standard QCVN 07:2009 (**)	National standard TCVN 12249:2018 (***)
		Fly ash	Bottom slag			
Physical-mechanical properties						
Bulk density, (g/cm^3)		0.635	0.812			
Specific gravity, (g/cm^3)		2.264	2.557	-	-	-
Residue on 0.045μm sieve, (%wt.)		19.7	37.1	<25	-	-
Humidity (%)		0.4	1.2	<3	-	-
Chemical compositions						
Content of metal oxides (% w.t.)	SiO_2	52.8	64.2	>70.0	-	-
	Al_2O_3	21.7	19.6		-	-
	Fe_2O_3	6.4	7.2		-	-
	SO_3	2.8	0.6	<3.0	-	-
	K_2O	0.4	0.8	<1.5	-	-
	Na_2O	0.7	0.1		-	-
	MgO	1.0	0.6	-	-	-
	CaO	1.9	2.1	-	-	-
	P_2O_5	1.6	1.8	-	-	-
	LOI- Loss on Ignition	10.7	3.0	<12	-	-
Heavy metal extracted concentration (mg/L)	Arsenic (As)	0.08	0.05	-	2	0.1
	Cadmium (Cd)	<0.001	<0.001	-	0.5	0.1
	Lead (Pb)	<0.001	<0.001	-	15	0.5
	Zinc (Zn)	0.002	0.002	-	250	3.0
	Nickel (Ni)	0.002	0.002	-	70	0.5
	Chromium (Cr)	0.1	0.03	-	5	0.1
	Flouride (F)	1.0	1.0	-	180	10.0

(*) TCVN 10302:2014 - Vietnam national standard for activity admixture - Fly ash for concrete, mortar, and cement.
(**) QCVN 07:2009 - Vietnam National Technical Regulation on Hazardous Waste Thresholds.
(***) TCVN 12249:2018 - Coal ash of thermal power plant using as backfill material - general requirement (Vietnam).

(3) Crushed stone: Crushed stone with an average size of <5.0 mm was used to replace sand as common material to reduce the brick manufacturing cost. The physical-mechanical properties of crushed stone are presented in Table S1 of the Supplementary Material.

2.1.2 Adhesives

(1) Cement: The adhesive partially used in this study was PCB40 cement obtained from Portland Vicem Ha Tien Cement Company with the physical-mechanical properties and chemical composition shown in Table S2 of the Supplementary Material.

Table 2. Chemical compositions of fine RHA

Chemical compositions	Content of metal oxides (%wt.)									
	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	Na_2O	MgO	CaO	P_2O_5	Loss on ignition
This study	91.4	1.4	0.6	0.4	0.8	0.1	0.5	1.0	0.3	3.5
Vietnamese National Standards (TCVN 8827:2011) (*)	> 85	-	-	-	-	-	-	-	-	< 3.0

(*) TCVN 8827:2011 - Vietnamese National Standard for Highly Activity Pozzolanic Admixtures for Concrete and Mortar - Silica Fume and Rice Husk Ash (RHA)

(2) Geopolymer: Due to high SiO_2 and Al_2O_3 content in coal ash (i.e., Si:Al ratio of 2.4-3.1>2.0) and RHA (i.e., Si:Al ratio of 65.3>5.0), the mixing of these waste materials with an alkaline solution of liquid glass (sodium silicate Na_2SiO_3) can produce a geopolymer as poly (sialate-siloxo) and poly (sialate-multisilixo) (Trang et al., 2021). This geopolymer was used as an adhesive to improve the adhesion of different aggregates and reduce the PCB40 cement applied. As compared to traditional cement, this geopolymer is less harmful to the environment. The quality of the geopolymer depends on the ratio of Si/Al in the chemical composition, which is usually over 2.0 for fly ash. For this, the liquid glass (analytical grade Na_2SiO_3 solution) was obtained from a local vendor in Vietchem Chemical and Equipment Import Export Joint Stock Company, Hanoi, Vietnam. The chemical composition of the liquid glass was 13.4% Na_2O, 23.9% SiO_2, and 62.7% H_2O, with a density of 2.61 g/cm^3 and water solubility of 22.2 g/100 mL.

2.1.3 Additives

(1) Polypropylene fiber (PP fiber): The PP fiber is widely used as an additives in the building material field, such as adobe brick manufacturing and geopolymer concrete, to enhance the tensile strength and shrinkage of the product, which reduces the breakage of bricks and also increases the crack resistance of geopolymer concrete (Zhang et al., 2009). In addition, the PP fibers have low density and form good adhesion with the aggregate mixture of brick and concrete. In this study, the PP fiber with a length per diameter (l/d, mm) of 12/0.03 obtained from Zhongshan Kecheng Chemical Fiber Co. Limit in Guangdong, China, was used. Technical specifications of these PP fibers are shown in Table S3 of the Supplementary data.

(2) Pigment: The iron oxide pigment obtained from a local vendor (Ha Noi, Vietnam) was used to add color surface for Terrazzo tiles. This additive helps bricks to increase resistance to adverse environmental conditions. Technical specifications of this iron oxide pigment are shown in Table S4 of the Supplementary data.

2.2 Hydrostatic-press machine

The hydrostatic-press method was applied for the experimental bricks making in this study. The Terrazzo T-120 pressing machine from Huu Thang Construction Materials Manufacturing Co., Ltd. In Tien Giang Province, Vietnam, was used during the experiments. The technical specifications of the Terrazzo T-120 machine are shown in Table S5 of the Supplementary data.

2.3 Experimental procedure for brick making

A standard Terrazzo tile has 2 layers that are pressed and mounded together (Figure 1). The first surface layer is comprised of all aggregates (fly ash, bottom slag, RHA, and crushed stone), adhesives (cement, liquid glass), additives, and granite grains (100-gram grains in each experiment). Similar material components were added to the second bottom layer, except for granite grains and low water amounts. Water and liquid glass were mixed with the aggregate mixture to ensure the appropriate humidity, avoid the hardening reaction of aggregates, and facilitate the hydrostatic pressing process.

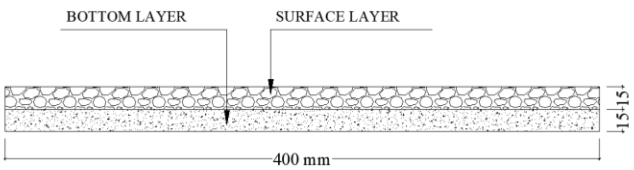

Figure 1. Structural cross-section of terrazzo tiles

According to the national standard TCVN 7744:2013 of Terrazzo tiles manufacturing (MOC, 2016), the traditional aggregate proportion is crushed stone above 60%wt., cement of 10-15%wt. The brick-making experiments E1-E5 were then designed using

20 brick samples (i.e., M1-M20) with different aggregate ingredients, as shown in Table 3. Depending on the objective of each experiment, the aggregate proportions were different. In addition, a commercial brick sample produced by Huu Thang Construction Materials Manufacturing Co., Ltd. was used as a control sample (i.e., M0 with conventional aggregates as cement, sand, and crushed stone of 15%, 25%, and 60%).

Table 3. Design of experimental Terrazzo tiles making with different aggregate ingredients

Experiment No.	Objectives	Sample No.	Aggregate ingredients						
			Fly ash (%wt.)	RHA (%wt.)	Bottom slag (%wt.)	Cement (%wt.)	Crushed stone (%wt.)	PP fiber (%/1 m^3 aggregates)	Water and liquid glass (10 mL/L)
-	Control sample	M0	Conventional aggregates as cement, sand, and crushed stone of 15%, 25%, and 60%						
E1	Determine the effects of fly ash	M1	40	Not used	Not used	0	60	Not used	Depending on each sample, a flexible amount was added to the mixing trough. The residual water (if any) was removed from the brick mold during the compression.
		M2	35			5			
		M3	30			10			
		M4	25			15			
		M5	20			20			
E2	Determine the effects of RHA	M6	Not used	40	Not used	0	60	Not used	
		M7		35		5			
		M8		30		10			
		M9		25		15			
		M10		20		20			
E3	Determine the effects of both fly ash and RHA	M11	Optimum value obtained from E1	Optimum value obtained from E2	Not used	Not used	60	Not used	
		M12							
		M13							
E4	Determine the effects of fly ash, RHA, and bottom slag	M14	Optimum value obtained from E3	Optimum value obtained from E3	5	Not used	55	Not used	
		M15			10		50		
		M16			15		45		
		M17			20		40		
E5	Determine the effects of PP fibers	M18	Optimum value obtained from E4	Optimum value obtained from E4	Optimum value obtained from E4	Optimum value obtained from E4	Optimum value obtained from E4	0.25	
		M19						0.5	
		M20						1.0	

All experiments were carried out in duplicate mode. In each experiment, all aggregate ingredients were prepared and mixed properly to obtain a homogeneous mixture, which was then added by layer into a square brick mold (400×400×30 mm) for the hydrostatic pressing step. A compressed pressure of 14 MPa was applied to achieve optimal density and compressive strength. After the pressing step, the bricks were picked up automatically from the mold by pulleys and dried at room temperature for 48 h to avoid rapid water loss. To promote the hydration process, the bricks were hydrated by soaking them in water for 24 h and storing them in at a cool temperature for 24 h.

Then, the bricks were transferred to the surface polishing and grinding process to obtain the aesthetics finish, as shown in Figure 2. After 28 days of the curing process, the brick samples were prepared for the quality testing according to TCVN 7744:2013 standards.

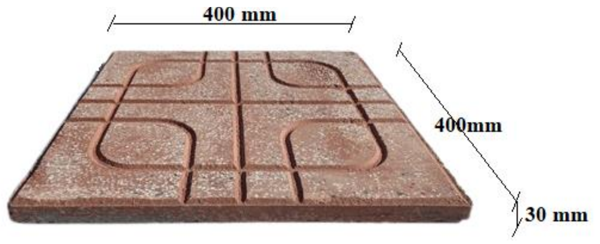

Figure 2. Typical Terrazzo tile product

2.4 Analytical methods and calculations

2.4.1 Analysis of aggregate compositions

The properties and compositions of aggregates such as coal ash and RHA were carried out using analytical grade reagents and standard methods

(APHA, 2012) in laboratory conditions. In particular, the laboratory of the Department of Civil Engineering, Ho Chi Minh City University of Architecture, Vietnam, was utilized in this study. The physical-mechanical properties and chemical compositions of fly ash and bottom slag (Table 1) were determined using the mass balance method, X-ray diffraction (XRD, model GBC Emma 3kW, Australia), and X-ray fluorescence (XRF, model 1.0 YY6312 Defan, Zhejiang Nuofan Motor Co., Ltd.) analysis. The heavy metal concentration was extracted and analyzed using an inductively coupled plasma (ICP) spectrometer (ICP-MS Model Ultramass 700, Varian - Australia).

2.4.2 Verification of brick strength

The flexural strength X (MPa) for each brick sample is determined based on the following calculation:

$$X = \frac{3.P.l}{2.b.h^2} \quad (1)$$

In which P is the destructive load of the brick sample (N); l is the distance between the two roller bearings of the testing machine (mm); b is the width of the brick sample, (mm); and h is the height of the brick sample (mm).

In this study, the electronic digital flexural strength testing machine (i.e., SKZ-10000, Hunan Zhenhua Analysis Instrument Co., Ltd., China) was employed, with l of 350 mm, corresponding to the brick dimension of 400×400 mm to facilitate the direct measurement of flexural strength of brick samples.

2.4.3 Surface water absorption $H_{m.a}$ (%) for each brick sample:

$$H_{m.a} = \frac{m_{a.c} - m_{k.s}}{m_{k.s}} \times 100\% \quad (2)$$

In which: $m_{k.s}$ is the dried weight of the brick sample (gram); $m_{a.c}$ is the total weight of the brick sample saturated by water absorbed for at least 4 days, (gram).

3. RESULTS AND DISCUSSION

3.1 Results of visual inspection of brick samples

All Terrazzo brick samples (i.e., M1-M20 with a thickness of 30 mm) obtained from experiments had a thickness difference of 0.52 mm to 1.78 mm. This difference satisfied the allowable value of ≤ ±2 mm, according to TCVN 7744:2013 standards (MOC, 2016). In terms of the specific density, the results of M1-M20 varied in a range from 1.650 to 1.929 g/cm^3. This was lower than that of commercial Terrazzo tiles (M0), which normally range from 2.292 to 2.500 g/cm^3 when produced from the factory. This can be explained by the fact that the density of waste material in the experimental aggregate ingredients, which include fly ash of 2.264 g/cm^3, bottom slag of 2.557 g/cm^3, and RHA of 2.316 g/cm^3, is much lower than traditional aggregates with cement of 3.1 g/cm^3). Also, the spherical shape of fly ash, accompanied by hollow and porous particles of RHA, is different from the angular grain shape of cement and sand, which may cause the difference in internal friction between aggregate particles and affect the density of the aggregate mixture (Abdullah et al., 2011).

As for the external defects, 3 brick samples (i.e., M17, M19, and M20) were broken after pressing and could not be shaped from the mold. The others (i.e., M15, M16) were also cracked and broken partially after hydration and storage steps (Figure 3). This issue is due to the effects of aggregate ingredients: fly ash, RHA, and bottom slag. These ingredients contributed to brick samples gaining over 50-60%wt. On the other hand, Terrazzo brick samples with crushed stone was below 50 %wt., which increased their bending property and decreased their hardness. This preliminary result indicates that although poly (sialate-siloxo) and poly (sialate-multisilixo) geopolymers produced from the mixture of coal ash, RHA, and liquid glass could replace cement, the content of these alternative materials in aggregate ingredients should be limited to 50%wt. to ensure the shape and hardness of the brick samples during the pressing, hydration, and curing processes. Furthermore, the addition of a large amount of PP fiber (i.e., 0.5-1.0%/1 m^3 aggregates) to the aggregate mixture with coal ash and RHA content of 45%wt. may cause the "broken phenomenon" in M19 and M20 samples. This confirmed that the adhesion and connection of coal ash, RHA, PP fiber, and liquid glass strongly affected the shape of the brick samples, which could enhance the flexural strength but reduce the hardness of the bricks.

3.2 Technical features of control sample

The testing results of the control sample M0 showed that the flexural strength was X^{7}_{ave}= 3.86 MPa (after 7 days of curing) and X^{28}_{ave}= 4.53 MPa (after 28 days of curing). The results verified that the control sample with conventional aggregate is an exterior Terrazzo tile, type 2 (X^{28}_{ave} ≥4.0 MPa) according to national standard TCVN 7744:2013 (MOC, 2016).

The M0 sample has a bulk density of 2.390 g/cm^3 and an average surface water absorption by mass of 4.73%. These technical specifications of the M0 control sample were then used for comparison with experimental brick samples obtained from experiments E1-E5 in this study.

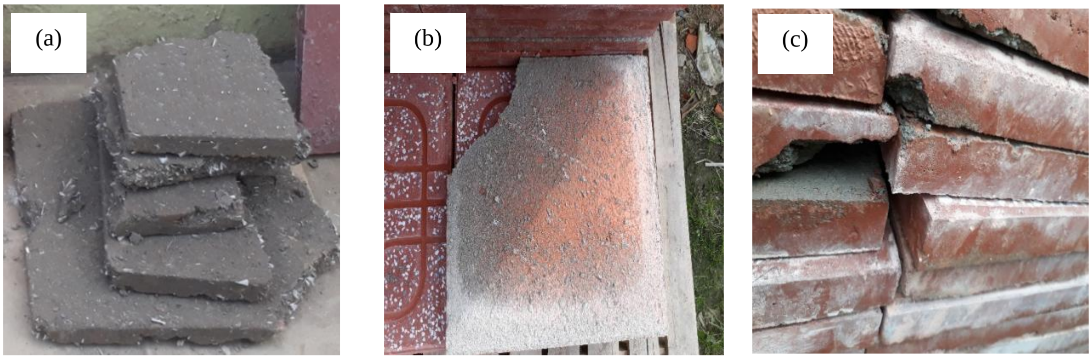

Figure 3. External defects of brick samples (a) M19, M20, (b) M16, M17, and (c) M15

3.3 Effects of aggregate ingredients on the flexural strength

3.3.1 Fly ash

Table 4 and Figure 4 present the effects of fly ash on the flexural strength, which were investigated in experiment E1 with 5 brick samples (i.e., M1-M5).

Results showed that the replacement of sand and cement by fly ash (i.e., 30-40%) in aggregate ingredients (M1, M2, M3 samples) caused a significant change in flexural strength (X_{ave}^{28}decreased from 3.82 to 3.57 MPa), corresponding to exterior Terrazzo tile type 3 (X_{ave}^{28} ≥3.5 MPa) and was lower quality as compared to M0 control samples (i.e., type 2). The lesser the fly ash, the lower the flexural strength. This was contrary to cement content. Specifically, when decreasing the fly ash and increasing the cement content, the X_{ave}^{28} decreased accordingly. The result showed that brick sample M4 and M5 did not meet the standard of exterior Terrazzo tile, type 3.

This can be explained by the fact that when the cement content in aggregate ingredients was increased, the pozzolan reaction occurred rapidly, causing more C-S-H products to be formed during the hydration of cement. In contrast, for fly ash, the C-S-H products are created slowly in the early days since the formation rate of poly (sialate-siloxo) geopolymer is faster than the pozzolan reaction rate (Phuong and Hien, 2021). Thus, the maximum cement content in aggregates should be 10%wt.

On the other hand, the improvement of flexural strength along with the increase of fly ash may be due to the spherical particle shape of fine fly ash, which helped to retain water and avoid the clumping of cement particles, leading to the increase of plasticity of the aggregate mixture and reducing water demand (CESTI-DOST, 2019). Accordingly, the minimum fly ash content to serve as aggregates for making of Terrazzo tile, type 3, with brick strength grade M 3.5, was determined to be 30%.

3.3.2 RHA

In experiment E2, the fly ash was replaced by RHA for making brick samples M6-M10. The flexural strength results of these samples are presented in Table 5 and Figure 5.

Table 4. Effects of fly ash content on the flexural strength of Terrazzo brick samples

Sample No.	Aggregate ingredients			Flexural strength X_{ave}^{7} (MPa)	Flexural strength X_{ave}^{28} (MPa)	Bulk density (g/cm^3)	Brick strength grade[a] (MPa)	Brick type[a]
	Fly ash (%wt.)	Cement (%wt.)	Crushed stone (%wt.)					
M1	40	0	60	3.27	3.82	1.650	M 3.5	Exterior Terrazzo tile, type 3
M2	35	5	60	2.98	3.63	1.691	M 3.5	
M3	30	10	60	2.89	3.57	1.733	M 3.5	
M4	25	15	60	2.71	3.46	1.775	-	-
M5	20	20	60	2.56	3.36	1.817	-	-

[a]Brick strength grade and brick type were determined based on the flexural strength after 28 days of curing, according to national standard TCVN 7744:2013.

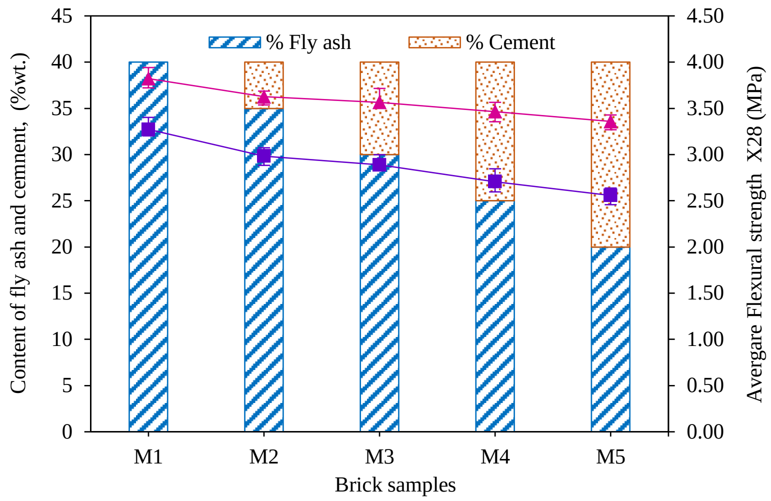

Figure 4. Change of flexural strength of brick samples with different fly ash and cement contents

Table 5. Effects of RHA content on flexural strength of Terrazzo brick samples

Sample No.	Aggregate ingredients			Flexural strength X^{7}_{ave} (MPa)	Flexural strength X^{28}_{ave} (MPa)	Bulk density (g/cm^3)	Brick strength grade[(a)] (MPa)	Brick type[(a)]
	Fly ash (%wt.)	Cement (%wt.)	Crushed stone (%wt.)					
M6	40	0	60	3.49	4.17	1.670	M 4.0	Exterior Terrazzo tile, type 2
M7	35	5	60	3.53	4.12	1.710	M 4.0	
M8	30	10	60	3.28	4.05	1.749	M 4.0	
M9	25	15	60	3.11	3.99	1.788	M 3.5	Exterior Terrazzo tile, type 3
M10	20	20	60	3.00	3.92	1.827	M 3.5	

[(a)] Brick strength grade and brick type were determined based on the flexural strength after 28 days of curing, according to national standard TCVN 7744:2013

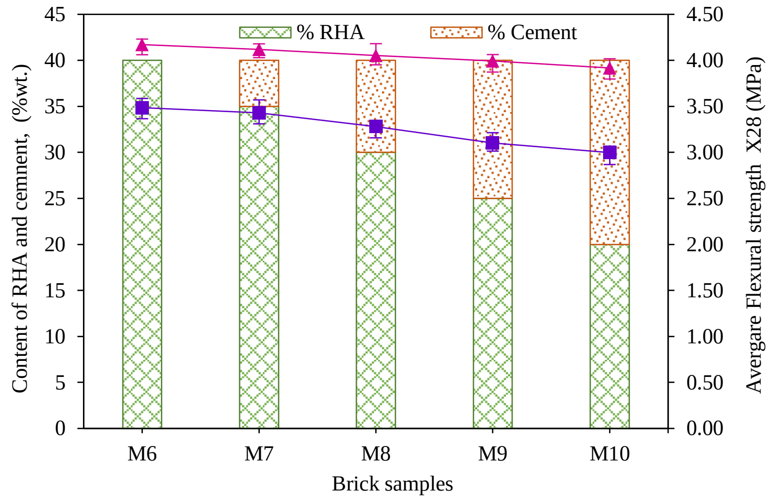

Figure 5. Change of flexural strength of brick samples with different RHA contents

The study found that although the brick samples M6, M7, and M8 could satisfy the exterior Terrazzo tile, type 2, their flexural strength was lower than that of M0. However, the bulk density and flexural strength of brick samples made from RHA in brick samples M6-M10 (Figure 7) were better than those made from FTPP fly ash in brick samples M1-M5 in Table 4 and Figure 4 under the same experimental conditions. This indicates the feasibility of both fly ash and RHA to replace sand and cement for brick making, and RHA was shown to be more effective than fly ash.

This is due to the higher specific density of RHA with 2.316 g/cm^3) as compared to fly ash with 2.264 g/cm^3). Furthermore, RHA particles with a hollow and porous structure can show a higher ability to absorb water than round-ball-shaped fly ash. Moreover, the SiO_2 content in RHA of about 92% is higher than that found in FTPP fly ash with 52.8%), which helped to produce better technical specifications in RHA-brick samples, as compared to fly ash-products.

In summary, with the aims to produce the exterior Terrazzo tile with the brick strength grade of M 3.5-M 4.0, the fly ash and RHA can be used as aggregates with the content of 30-40%wt., accompanied by the appropriate cement of <10%wt. and crushed stone of at least 60%wt.

3.3.3 Mixture of fly ash and RHA

Based on the results of experiment E1 and E2, the brick samples M1 and M6 were used as reference samples to adjust the mixing ratio of fly ash and RHA in the aggregate ingredients of brick samples M11-M13 in experiment E3. The flexural strength results of M11-M13 are presented in Table 6 and Figure 6 below.

Results showed that when the fly ash and RHA with a total content of 40%wt. were used to replace cement in aggregates of brick samples M11-M13, the flexural strength X_{tb}^{28} of the brick samples was proportional to the RHA content, but inversely proportional to the fly ash content. Sample M13 with the ratio of fly ash and RHA of 10:30%wt. was chosen as the optimum mixing ratio to produce Terrazzo tile, type 2 (M 4.0). The aggregate ratio of M13 was then used as a reference sample for further experiments.

Table 6. Effects of fly ash and RHA mixture on flexural strength of Terrazzo brick samples

Sample No.	Aggregate ingredients			Flexural strength X_{ave}^{7} (MPa)	Flexural strength X_{ave}^{28} (MPa)	Bulk density (g/cm^3)	Brick strength grade[a] (MPa)	Brick type[a]
	Fly ash (%wt.)	Cement (%wt.)	Crushed stone (%wt.)					
M1 (reference sample)	40	0	60	3.27	3.82	1.650	M 3.5	Exterior Terrazzo tile, type 3
M11	30	10	60	3.29	3.93	1.655	M 3.5	
M12	20	20	60	3.31	3.96	1.660	M 3.5	
M13	10	30	60	3.38	4.02	1.665	M 4.0	Exterior Terrazzo tile, type 2
M6 (reference sample)	0	40	60	3.49	4.17	1.670	M 4.0	

[a] Brick strength grade and brick type were determined based on the flexural strength after 28 days of curing, according to national standard TCVN 7744:2013

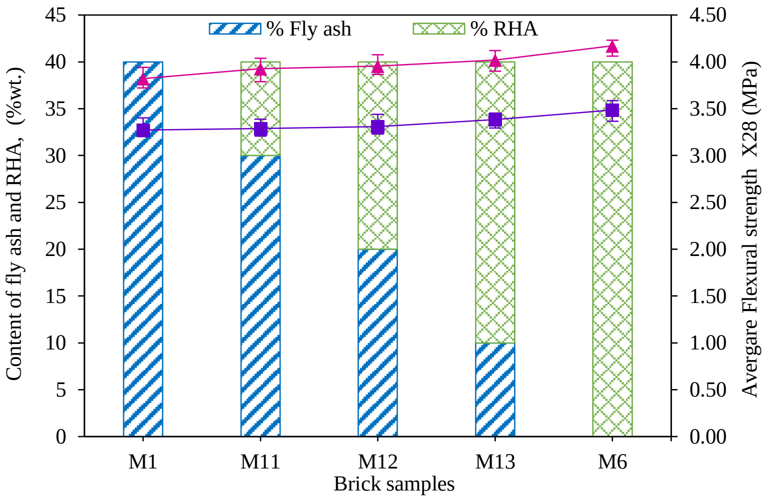

Figure 6. Change of flexural strength of brick samples with different fly ash and RHA contents without cement

3.3.4 Bottom ash (slag)

In order to investigate the feasibility of bottom ash (slag) for Terrazzo tile making, the experiment E4 was designed to partially replace the crushed stone content with slag (i.e., 5-20%wt.) in samples M14-M17. The analysis of brick samples quality is presented in Table 7 and Figure 7.

Unfortunately, the brick samples M15, M16, and M17 were broken after the hydraulic pressing and hydration process. This is due to the decrease of crushed stone (i.e., <55%wt.) and the replacement of slag (i.e., >5%wt.) in the experimental aggregates. Thus, it is believed that the maximum content of slag in aggregates should be 5% to avoid external defects during the brick shaping. The results obtained in this experiment E4 also confirmed that the high content of SiO_2 in the slag of 64.2%, as compared to that in fly ash of 52.8% in Table 1, may help to form the geopolymer adhesives poly (sialate-silixo), which enhances the flexural strength of brick samples. However, unburned coal components in FTPP bottom slag without pre-treatment by the ash separation method may cause some changes in the volume of the hydrated product during the solidification (CESTI-DOST, 2019).

Table 7. Effects of bottom ash (slag) on the flexural strength of Terrazzo brick samples.

Sample No.	Aggregate ingredients			Flexural strength X^{7}_{ave} (MPa)	Flexural strength X^{28}_{ave} (MPa)	Bulk density (g/cm^3)	Brick strength grade[(a)] (MPa)	Brick type[(a)]
	Fly ash (%wt.)	Cement (%wt.)	Crushed stone (%wt.)					
M13 (reference sample)	10	30	0	60	3.38	4.02	1.650	Exterior Terrazzo tile, type 2
M14	10	30	5	55	3.52	4.26	1.731	
M15	10	30	10	50	Not analyzed	Not analyzed	1.797	External defects
M16	10	30	15	45	Not analyzed	Not analyzed	1.863	
M17	10	30	20	40	Not analyzed	Not analyzed	1.929	

[(a)] Brick strength grade and brick type were determined based on the flexural strength after 28 days of curing, according to national standard TCVN 7744:2013.

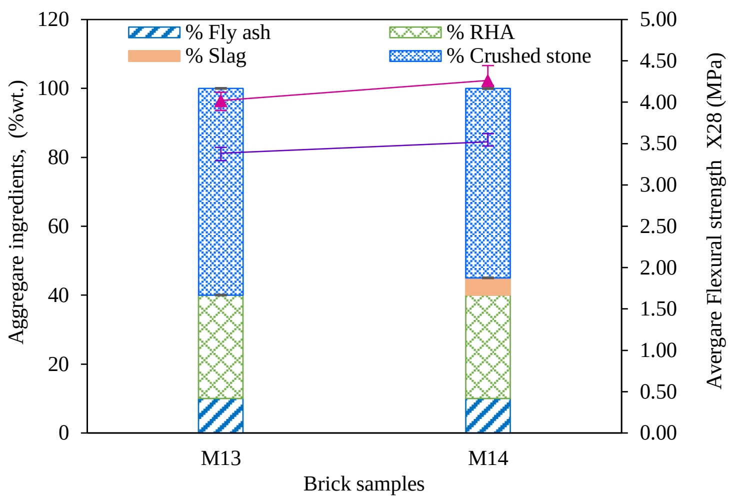

Figure 7. Effects of bottom ash (slag) on the change of flexural strength of brick samples

3.3.5 Polypropylene fiber (PP fiber)

The study showed that the addition of PP fiber to aggregate ingredients could help to improve the flexural strength of adobe bricks (Trang et al., 2021). In experiment E5, brick samples M18-M20 were prepared with the PP fiber of 0.25-1.00% to determine its effects on the Terrazzo tile quality.

Results confirmed that a small amount of PP fiber (i.e., 0.25%/1 m^3 aggregates) in sample M18 helped to increase slightly the flexural strength (i.e., 4.28 MPa), as compared to sample M14 without PP fiber (i.e., 4.26 MPa). However, when the PP fiber amount was increased (i.e., 0.5 and 1%/1 m^3 aggregates) in the samples M19 and M20, external defects were observed visually in brick samples, as described in section 3.1. This can be explained by the fact that the addition of PP fiber leads to the increase of water content in aggregate material, which causes a pliable state and difficulty in freezing brick samples. In summary, the PP fiber did not significantly improve the Terrazzo tile strength; in contrast, the excess amount of PP fiber used in aggregate ingredients can destroy the shaping and freezing of products. Therefore, this study suggests that PP fiber should not be used as an aggregate for the manufacturing of Terrazzo tile.

Table 8. Effects of PP fiber on flexural strength of Terrazzo brick samples

Sample No.	Aggregate ingredients			Flexural strength X^{7}_{ave} (MPa)	Flexural strength X^{28}_{ave} (MPa)	Bulk density (g/cm^3)	Brick strength grade[(a)] (MPa)	Brick type[(a)]
	Fly ash (%wt.)	Cement (%wt.)	Crushed stone (%wt.)					
M14	10	30	5	55	0	3.52	4.26	Exterior Terrazzo tile, type 2
M18	10	30	5	55	0.25	3.53	4.28	
M19	10	30	5	55	0.5	Not analyzed	Not analyzed	External defects
M20	10	30	5	55	1	Not analyzed	Not analyzed	

[(a)] Brick strength grade and brick type were determined based on the flexural strength after 28 days of curing, according to national standard TCVN 7744:2013

3.4 Evaluating the water absorption of brick samples

The water absorption of adobe brick is an important factor affecting the absorption and adhesion of bricks and mortar during construction. It also indirectly reflects the permeability of bricks. Therefore, it is related to the chemical corrosion resistance of bricks (CESTI-DOST, 2019). Therefore, the water absorption requirement of Terrazzo tiles must not exceed 6% according to the Vietnam national standard TCVN 7447-2013 (MOC, 2016).

According to the results of experiment E1-E5, brick samples M1, M6, M13, M14, and M18 were chosen to determine the surface water absorption. The results are presented in Figure 8.

Results indicated that the surface water absorption of experimental Terrazzo samples varied in a range of 4.90-6.22%, which is higher than that of control sample M0 (i.e., 4.73%, section 3.2). Most brick samples satisfied the requirement of water absorption (i.e., <6%) of the national standard, except the sample M18 (i.e., 6.22%) due to the addition of PP fiber. The PP fiber may reduce the condensed structure of brick samples and form more mini-pores, which increases the surface water absorption.

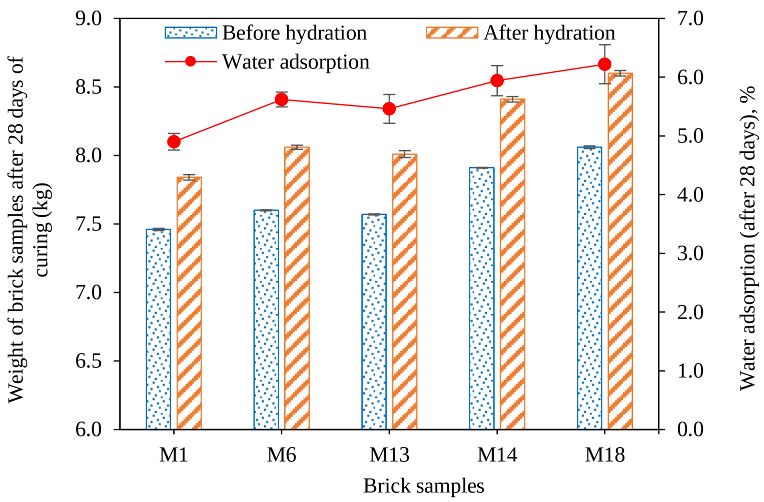

Figure 8. Changes of water absorption with different aggregate ingredients of brick samples

3.5 Evaluation of economic efficiency

In order to evaluate the economic efficiency obtained in this study, the manufacturing costs of samples M1, M6, M13, and M14 were analyzed and compared with the market price of the control sample

M0. The cost analysis is based on the actual price applied during the experiment.

Table 9 indicates that the manufacturing cost of each brick sample obtained in this study was comparable and competitive with the commercial product. Specifically, the cost of a brick sample was about 0.375-0.391 USD/ 01 sample, while the market price of a brick product from Huu Thang Construction Materials Manufacturing Co., Ltd. (Tien Giang Province, Vietnam) is currently 0.388 USD/01 brick piece. This finding raises the feasibility, applicability, and price competitiveness of brick samples produced in this study, which also confirms the economic benefits of recycling of waste from thermal power plants and rice milling factories.

Table 9. Cost analysis for Terrazzo tile manufacturing

Sample o.	Cost unit (USD/01 brick piece)						References
	Material	Labour	Electricity	Water	Depreciation of machinery and equipment	Total price	
M0	0.207	0.086	0.051	0.0031	0.029	0.388	Market price
M1	0.212	0.086	0.051	0.0015	0.029	0.391	This study
M6	0.194			0.0025		0.375	
M13	0.198			0.0019		0.379	
M14	0.211			0.0021		0.391	

4. CONCLUSION

This study was successful in demonstrating the feasibility of using coal ash from thermal power plants and rice husk ash to partially replace sand and cement for the manufacturing of Terrazzo tiles. The study also confirmed that the flexural strength, surface water absorption, and shaping and freezing of brick products were affected significantly by the mixing ratio of fly ash and RHA as alternative aggregates. Specifically, the brick samples prepared with RHA showed better flexural strength but higher bulk density and waster absorption, as compared to samples using fly ash. To achieve the quality of Terrazzo tiles (i.e., type 2, Mac 4.0, or type 3, Mac 3.5, according to national standard TCVN 7747:2013), the aggregate ingredients included the followings: (1) Fly ash content should not exceed 40%wt. and the optimum value was 10%wt.; (2) RHA should not be higher than 40%wt. and the optimum value was 30%wt.; and the highest content of bottom ash (slag) was 5%wt. In contrast, the addition of PP fiber as aggregates did not improve the quality of brick samples but destroyed the shaping and freezing of products. Thus, PP fiber was not encouraged to serve as an additive of aggregates for Terrazzo tiles manufacturing.

The consideration of economic aspects also showed the equivalence and competitiveness between the experimental brick samples obtained in this study and commercial products being distributed in the local market. This result confirmed again the feasibility of reuse and recycling of coal ash and RHA to eliminate the environmental pollution effects and then create a new and eco-friendly construction material, which adapts to the trend toward the sustainable development.

Recommendations

The coal ash and RHA employed in this study were raw materials obtained from the local factory without any step for pretreatment of unburned coal components. Thus, the quality of brick products may be affected (i.e., the brick strength grade of Mac 4.0 and type 2). Therefore, it is recommended that an activation process of raw coal ash before using it as aggregates for brick making should be investigated to enhance the flexural strength and achieve a higher brick strength grade (i.e., X_{ave}^{28} >5.0 MPs). Furthermore, the microstructural and morphological characterization of brick products using SEM, XRD, and XRF techniques is suggested to be carried out in future studies to obtain a deeper understanding of brick characteristics and demonstrate their practical applications in brick making. Moreover, advanced analysis to measure the adhesion force among different types of waste should be carried out to provide a better understanding of the effects of adhesion on the brick shaping, flexural strength, and surface water absorption.

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SUPPLEMENTARY DATA

Table S1. Physical-mechanical properties of crushed stone

Table S2. Physical-mechanical properties and chemical composition of PCB40 cement

Table S3. Technical specifications of PP fibers

Table S4. Technical specifications of iron oxide pigment

Table S5. Technical specifications of Terrazzo T-120 hydrostatic-press machine

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