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PROPERTIES EVALUATION OF TERRAZZO TILES PRODUCED FOR EXTERNAL USE USING A FINE AGGREGATE FROM A DOMESTIC WASTE INCINERATION PLANT

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Abstract

The increasing amount of incineration ash raised significant environmental concerns, particularly regarding waste disposal and pollution. To address these issues and promote sustainable development, this study explored the production of terrazzo tiles using a fine aggregate of waste incineration bottom ash (WIBA) and a ternary binder of cement, fly ash, and hydrated lime. The findings revealed that the substitution of cement with hydrated lime at an optimal level (i.e., 1% by weight) enhanced the flexural and compressive strengths while reducing the surface water absorption of the terrazzo tiles. The surface abrasion resistance remained relatively unchanged due to the consistent use of the same surface material across samples. Observation of scanning electron microscope images further confirmed the obtained engineering properties of the terrazzo tiles. As a result, the terrazzo tiles met the Vietnamese National standard requirements for external use, further indicating their suitability for various applications in construction. This study found that the terrazzo tiles produced using a mixture of 13% cement, 1% hydrated lime, 10% fly ash, and 76% WIBA earned the lowest surface water absorption of 2.56% and the highest flexural and compressive strengths of 3.86 and 21.37 MPa, respectively. Whereas, the surface abrasion of the sample was recorded at 0.241 g/cm^2, making it an optimal choice for practical use in construction.

Keywords: flexural strength; surface abrasion; surface water absorption; terrazzo tile; waste incineration bottom ash.

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1. Introduction

The use of terrazzo tiles has evolved significantly, and they are now recognized as valuable materials due to their durability, versatility, and low maintenance requirements. So far, these tiles are commonly used in high-traffic areas such as airports, hospitals, and schools. Besides, terrazzo tiles are increasingly used in external applications like sidewalks, pedestrian areas, walkways, terraces, commercial centers, and swimming pools [1]. Terrazzo tile is a kind of concrete brick, normally composed of cement, water, and aggregates. According to the purpose of use, the TCVN 7744:2013 [2] divided the terrazzo tiles into external-used and interior-used classes. It can be observed that the terrazzo tiles for external use are different from interior tiles due to the limited mechanical properties for exclusive pedestrian circulation [3].

Currently, sustainable development has become an increasingly important consideration in construction, leading to a growing interest in incorporating by-product materials into building products

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such as brick. May et al. [4] investigated the impact of using incineration bottom ash on the mechanical and durability properties of concrete bricks, demonstrating that 28-day compressive and flexural strengths were greater than 20 MPa and 3.5 MPa, respectively, after entirely replacing crushed sand with incineration bottom ash. However, the water absorption and surface abrasion of concrete brick exhibited the reverse trend with mechanical strength due to the porous structure of incineration bottom ash particles. Alam et al. [5] studied the cost-effectiveness of using incineration bottom ash to produce concrete brick, highlighting the remarkable reduction in material cost (above 50%). Thus, the incineration bottom ash would be used as aggregates in this study due to the abovementioned adequate strength and saving cost.

Apart from using incineration bottom ash, previous studies also explored the effect of coal thermal fly ash and bottom ash on the performance of concrete bricks. Naganathan et al. [6] reported experimental results on the strength and durability of brick made of bottom ash and fly ash, finding a compressive strength of 17 MPa and an ultrasonic pulse velocity of about 2.96 km/s. Moreover, the brick showed good fire resistance, with compressive strength increasing by up to 30% after heating, indicating the feasibility of replacing normal brick and contributing to sustainable development. Çiçek and Çinçin [7] used fly ash and lime to make brick, revealing the average compressive and flexural strength values of 7.5 and 0.5 MPa, respectively. They concluded that using fly ash in brick reduced the environmental problems and replaced aerated cellular concrete due to the low cost of raw material. Kumar and Hooda [8] studied the differences between fly ash brick and normal clay brick, showing the enhancement of a ringing sound, structure, average absorbed moisture content, and crushing strength. Nevertheless, the efflorescence of fly ash brick was lower than 10%, proving a higher performance of fly ash brick.

Previous studies have demonstrated the feasibility of using either waste incineration bottom ash (WIBA) as fine aggregate or coal thermal fly ash as a cementitious material in brick-making technology [5–7, 9]. Although these materials have been re-used in many applications, their remaining amounts in Vietnam are still large. Therefore, this study combined these materials into a sustainable mixture for producing terrazzo tiles. In the present study, WIBA was used to fully replace natural aggregate, and the effect of ternary binder compositions, including cement, fly ash, and hydrated lime, on the engineering properties (i.e., flexural and compressive strengths, surface water absorption, and surface abrasion) of the terrazzo tiles was evaluated. In addition, a scanning electron microscope (SEM) was performed to confirm the engineering properties of the terrazzo tiles. Furthermore, based on the findings of the study, the optimal mixture was proposed for production, and the potential applications of the terrazzo tiles were also suggested for sustainable construction.

2. Materials and experimental methods

2.1. Materials

This study used a ternary mixture of blended Portland cement, type-F fly ash, and hydrated lime as a binder for making terrazzo tiles. The densities of cement, fly ash, and lime are 2.86, 2.17, and 2.15 g/cm^3; the major chemical compositions of these binders are shown in Table 1.

The fine aggregate used in terrazzo tile mixtures was WIBA, as shown in Fig. 1, which was obtained from a local domestic waste incineration plant. To control the quality and properties variation of WIBA, this study followed the sampling principles and techniques suggested by the national technical regulation on hazardous waste thresholds (QCVN 07:2009/BTNMT [10]) to collect the samples for testing and finding that WIBA had a particle size of 0.14-10 mm, a density of 2.44 g/cm^3, and a water absorption rate of 6.8%.

Table 1. Chemical compositions of binder materials

Composition (wt.%)	Cement	Fly ash	Lime
SiO_2	20.5	62.0	0.7
Al_2O_3	4.3	20.8	-
Fe_2O_3	4.9	9.1	0.2
CaO	63.5	2.3	95.4
MgO	1.4	-	2.8
SO_3	2.9	0.5	-
K_2O	0.5	2.8	0.1
Na_2O	1.2	0.5	0.4
Others	0.8	2.0	0.4

Figure 1. WIBA used in this investigation

2.2. *Mixture proportions*

Based on preliminary trials in the laboratory, following the practical-based approach, the quantity of each raw material used for the preparation of terrazzo tile samples was proportioned, as shown in Table 2. It is a fact that about 14-18% of cement content was used for mass production in most terrazzo tile factories. This study fully used WIBA as fine aggregate in the mixtures with adding 10% fly ash to modify the grain size distribution of WIBA and promote the pozzolanic effect of fly ash for better quality and durability of the final products. Hence, for the control sample (L0 mix), cement, fly ash, and WIBA were fixed at 14%, 10%, and 76%, respectively. In addition, to enhance the chemical reaction in the cement-fly ash system, lime was then introduced into the mixtures. In detail, a portion of cement was then replaced by lime at levels of 1% (L1 mix), 2% (L2 mix), 3% (L3 mix), and 4% (L4 mix), while other ingredients were kept constant. It is important to note that various water content was added to adjust the moisture of each terrazzo tile mixture to approximately 10%, and WIBA was used in saturated surface dry form.

Table 2. Material proportions (% by weight) for the preparation of terrazzo tiles

Mixtures	L0	L1	L2	L3	L4
Cement	14	13	12	11	10
Lime	0	1	2	3	4
Fly ash	10	10	10	10	10
WIBA	76	76	76	76	76

2.3. *Sample preparation*

The procedures for making the terrazzo tile samples were described as follows: Raw materials with their proportions, as shown in Table 2, were first prepared. All of these materials were then mixed in a mechanical mixer (Fig. 2(a)) to obtain a uniform mixture with proper moisture content. Hence, the mixture was poured into a steel mold with dimensions of 300×300×50 mm, and a static forming pressure of about 180 kG/cm^2 was applied to form the terrazzo tile sample (see Fig. 2(b)). The sample was removed from the mold immediately after compression and stored in open air for 1 day. After that, it was subjected to the grinding equipment (Fig. 2(c)) to obtain the final sample with a smooth surface, as shown in Fig. 2(d).

(a) Mixing process

(b) Forming process

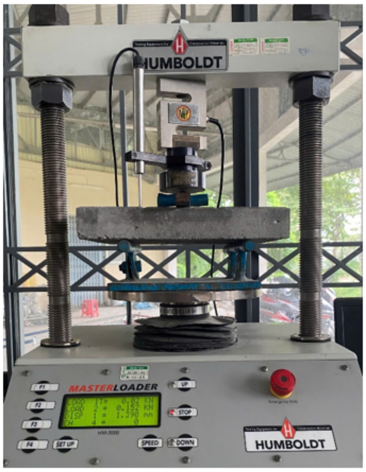
(c) Grinding process

(d) Terrazzo tile sample

Figure 2. Terrazzo tile's production processes

2.4. Test methods

To evaluate the properties as well as the potential applications, all of the terrazzo tile samples were subjected to the test series of flexural strength, compressive strength, surface water absorption, and surface abrasion based on the procedures as described in the respective national standards of TCVN 6355-3:2009 [11], TCVN 6476:1999 [12], TCVN 7744:2013 [2], and TCVN 6065:1995 [13]. The tests were performed on 28-day-old samples (see Fig. 3) with an average value of 5 repeated tests reported as the final result. Besides, SEM analysis was conducted following similar procedures previously described by Huynh et al. [14].



(a) Flexural strength

(b) Compressive strength

(c) Surface water absorption

(d) Surface abrasion

Figure 3. Test methods used to determine the terrazzo tile's properties

3. Results and discussion

3.1. Flexural strength

Flexural strength is one of the most important characteristics of terrazzo tiles since it directly impacts the service life and performance, especially in load-bearing areas, of the tiles. In this study, the flexural strength values of terrazzo tile samples are demonstrated in Fig. 4. As a result, the L0 sample had a flexural strength value of 3.63 MPa. The inclusion of hydrated lime at levels of 1% and 2% increased the tile's flexural strength by approximately 6.3% and 1.1% in comparison with that of the control sample, respectively. Replacing 3% and 4% of cement with hydrated lime caused the loss in flexural strength of the terrazzo tiles, with respective 6.9% and 11.0% strength reduction. The reduction in flexural strength after adding lime was related to less cement content, as previously reported by Meddah et al. [15] and Wang et al. [16]. This phenomenon will also be discussed lately in section 3.2.

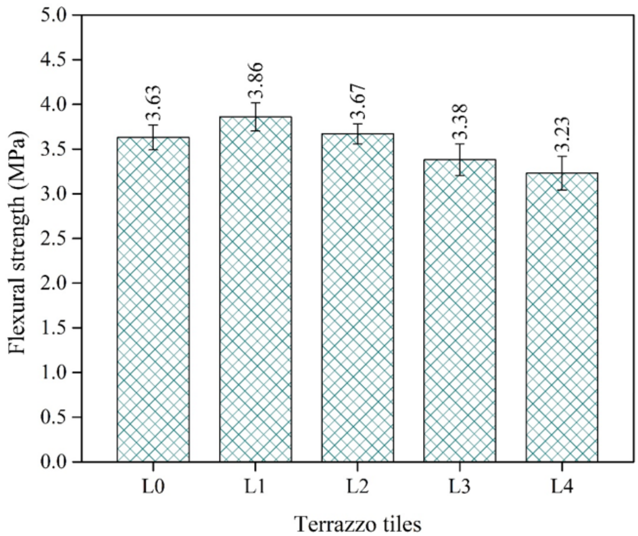


Figure 4. Flexural strength of terrazzo tiles

3.2. *Compressive strength*

The analysis of compressive strength for terrazzo tiles demonstrated significant variations in response to different lime contents (Fig. 5). Specifically, samples containing 1% and 2% lime exhibited slight increases in compressive strength by 2.3% and 0.4%, respectively, compared to the control sample (L0) with a compressive strength of 20.88 MPa. However, the addition of 3% and 4% lime resulted in a notable reduction in compressive strength by approximately 4.8% and 11.3%, respectively. This trend could be explained by the dual role of lime in the cement matrix. A previous study [17] stated that finely dispersed lime particles acted as nucleation sites for the formation of calcium silicate hydrate (C-S-H gel), thereby enhancing the cement hydration process and contributing to increasing compressive strength. Moreover, Wang et al. [16] identified an optimal lime content that maximizes compressive strength through a filler effect. However, when lime content exceeded this optimal proportion, the excess lime led to a dilution effect on the cement, which negatively impacted the mechanical strength [15, 16, 18]. This strength reduction could also be attributed to a decrease in the hydraulically active clinker fraction with higher lime content, as noted by Sezer [18]. Moreover, the chemical composition of lime played a crucial role in this phenomenon. The reactive silica and alumina content in lime are significantly lower than in cement (see Table 1). This lower reactivity contributes to a weakened cementitious reaction, leading to reduced compressive strength [15].

The relationship between compressive strength and flexural strength was established, as shown in Fig. 6. The quadratic correlation was witnessed at 28 days, which aligned with the discussed trend above. It is recognized that the mechanical strength is related to the cement hydration and filler effect of lime. Beyond the optimal level, the higher the lime content, the lower the mechanical strength of the terrazzo tiles. Thus, the increase in compressive strength is closely associated with the rise in flexural strength. This relationship was displayed by the equation $y = -6.5x^2 + 50.7x - 76.8$, which could be used to determine either compressive strength or flexural strength at 28 days when one of the two factors was known.

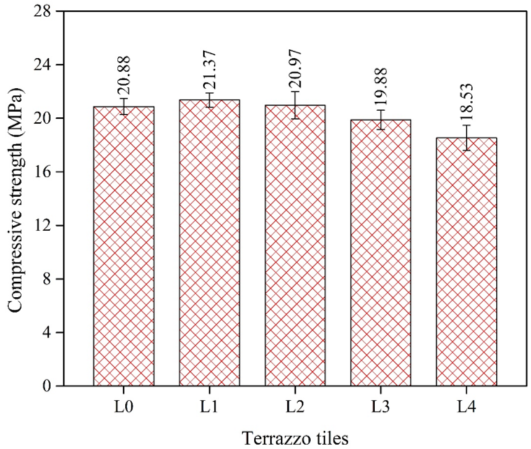


Figure 5. Compressive strength of terrazzo tiles

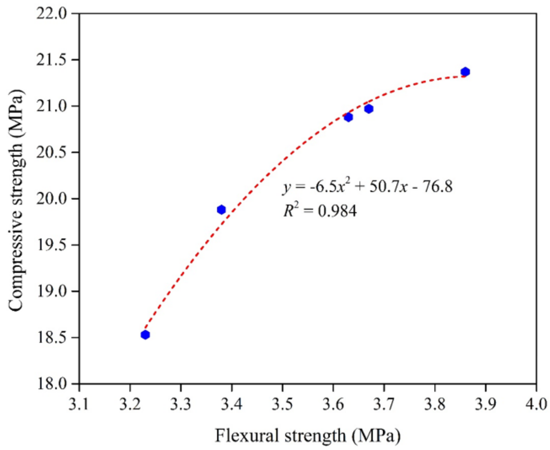


Figure 6. Correlation between compressive and flexural strengths of terrazzo tiles

3.3. Surface water absorption

Fig. 7 illustrates the surface water absorption of terrazzo tiles, revealing a slight increase compared to the control sample (L0). Specifically, the surface water absorption of the terrazzo tiles ranged from 2.56% to 2.89%, with a noticeable trend observed as the lime content increased from 1% to 4%. The L0 sample exhibited a surface water absorption rate of 2.66%, while the L1 and L2 samples demonstrated marginally lower values of 2.56% and 2.65%, respectively. However, as the lime content was further increased to 3% and 4%, a rise in surface water absorption was noted, with values of 2.78% and 2.89%, corresponding to increases of 0.12% and 0.23%. The relatively consistent surface water absorption values across all samples can be partly explained by the uniform surface layer thickness of approximately 3-5 mm. The differences in surface water absorption were attributed to variations in the porosity of the tile structures. In particular, the lime in the L1 sample exhibited a filler effect, which effectively reduced surface water absorption by improving the density of the matrix. Conversely, the addition of lime beyond the optimal content led to a dilution effect, resulting in a more porous structure and, consequently higher surface water absorption [19]. Despite these variations, all terrazzo tile specimens maintained a surface water absorption rate of less than 3%, well within the limits set by TCVN 7744:2013 [2], with a maximum allowable level of 6%.

3.4. Surface abrasion

Fig. 8 shows the value of surface abrasion of terrazzo tiles. Overall, there was a fluctuation of the surface abrasion value regardless of the lime content. The surface abrasion values of all samples were around 0.234 g/cm^2. This fluctuation could be attributed to the surface materials, a mixture of white cement, color powder in yellow, and white stone. In detail, the same material composition was used to cast the surface layer of all samples in this investigation. Thus, the slight differences in the abrasion resistance value could be considered an experimental error. However, all samples in this investigation exhibited lower surface abrasion values than the requirement of TCVN 7744:2013 [2], indicating the feasibility of terrazzo production.

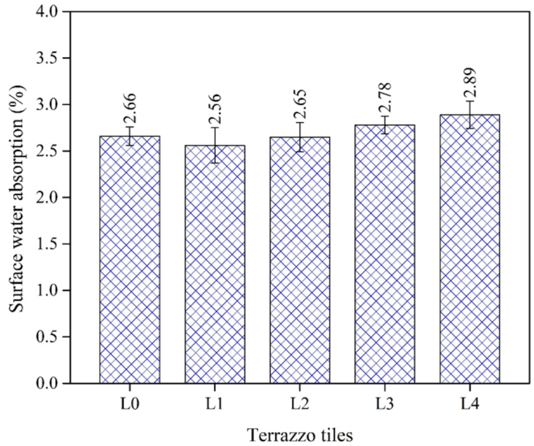


Figure 7. Surface water absorption of terrazzo tiles

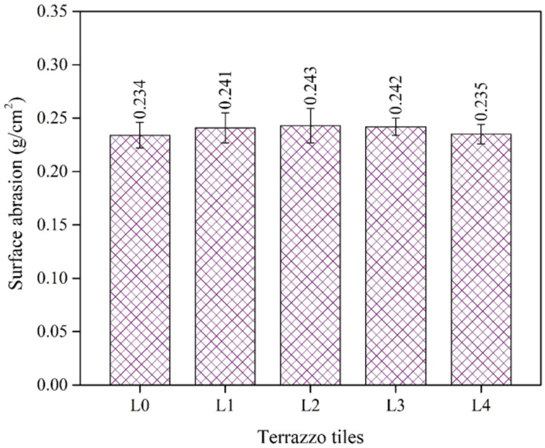
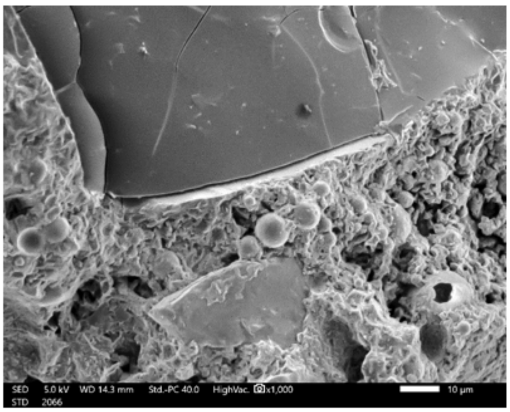


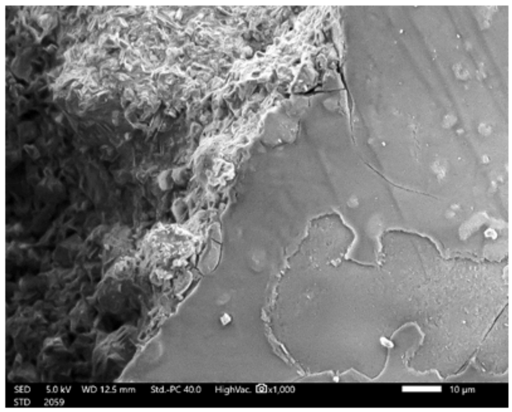
Figure 8. Surface abrasion of terrazzo tiles

3.5. Microstructure analysis

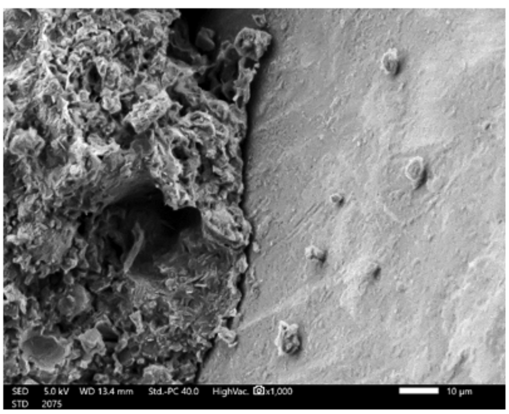
The changes in the microstructures of the terrazzo tiles were examined using their SEM morphologies, as shown in Fig. 9. The SEM images could be used to explain and confirm the changes in the engineering properties of the terrazzo tiles. Generally, the results revealed that the microstruc-



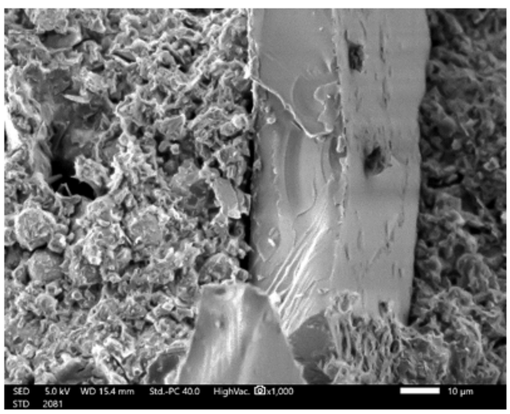
(a) L0



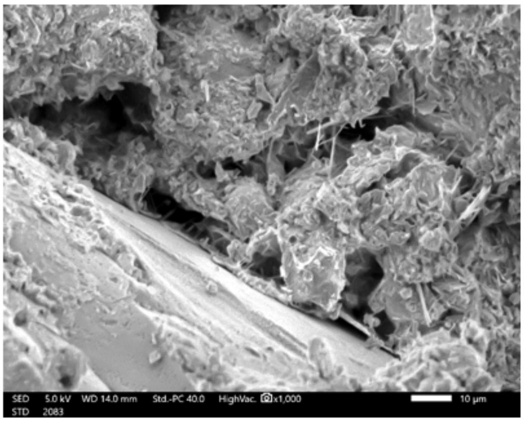
(b) L1



(c) L2



(d) L3



(e) L4

Figure 9. SEM morphologies of terrazzo tiles

tures of the terrazzo tiles were relatively uniform with the presence of hydration products and some un-hydrated components (i.e., fly ash particles). A closer observation confirmed that the microstructure of the L1 specimen was denser with a better bond between the binder matrix and aggregate as compared to that of the other specimens. Indeed, homogeneity in the terrazzo tile's microstructures was reduced in the order of L1, L2, L3, and L4 specimens, as shown in Figures 9(b-e), respectively. These observations provided good evidences to explain the changes in the mechanical strengths, surface water absorption, and surface abrasion of the terrazzo tiles, as already discussed in previous sections.

3.6. Application potential of terrazzo tiles

The summarized results of flexural strength and surface abrasion are detailed in Table 3. As a result, only L0, L1, and L2 mixtures registered flexural strength values higher than the requirement of the TCVN 7744:2013 [2]. In addition, the abrasion resistance of all terrazzo tiles was significantly lower than the limitation of the National standard. Due to the adequate flexural strength, compressive strength, surface water absorption, and abrasion resistance, all terrazzo tiles prepared in this investigation can be used for many applications. Indeed, terrazzo tiles are versatile and can be used for finishing materials such as wall surfaces, countertops, and flooring finish materials where human traffic is predicted to be heavy [20, 21]. For outdoor use, terrazzo tiles with 5 cm thickness are often used for light traffic areas. Furthermore, terrazzo tiles are also applied for texturized or surface texture, swimming pools, stairs, tactiles, and pavement applications [22, 23].

Table 3. Properties of terrazzo tiles in comparison with national standard requirements

Properties	Flexural strength (MPa)	Surface abrasion (g/cm^2)
L0	3.63	0.234
L1	3.86	0.241
L2	3.67	0.243
L3	3.38	0.242
L4	3.23	0.235
Standard requirements for type-3 [2]	≥ 3.5	≤ 0.5

4. Conclusion

Based on the experimental results, the following conclusions may be drawn:

- The flexural and compressive strengths of terrazzo tiles fluctuated by lime content. The flexural strength ranged from 3.23 to 3.86 MPa, while the compressive strength ranged from 18.53 to 21.37 MPa. The L1 sample exhibited maximum flexural and compressive strength values of 3.86 and 21.37 MPa, respectively.

- Replacing up to 4% of lime with cement resulted in a maximum surface water absorption of 2.89% and the surface abrasion of all terrazzo tiles was recorded in the ranges of 0.234-0.243 g/cm^3, which was still significantly below the allowable level recommended by the Vietnamese National standard for externally used terrazzo tiles.

- The terrazzo tile produced using a composition of 13% cement, 1% hydrated lime, 10% fly ash, and 76% WIBA exhibited the best performance, making it an optimal choice for practical use in construction.

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