Engineering properties of unfired building bricks produced using URHA-FA cement blends

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Abstract:

The production of cement and traditional fired clay bricks consumes intensive energy and inversely affects the environment. In addition, a huge quantity of solid waste materials such as rice husk ash and fly ash (FA) are generated from both industrial and agricultural activities. This study investigates the use of unground rice husk ash (URHA) and FA for manufacturing unfired building bricks. FA was used as a cement substitute (15%, 30%, and 50%), whereas URHA was used as a chippings replacement (5%, 10%, and 15%) in the brick mixtures. Test results indicate that all of the brick samples had consistent dimensions and were free of visible defects. Generally, increasing the URHA or FA replacement levels reduced the strength, bulk density, and material cost. However, it increased the water absorption capacity of the brick samples. Moreover, bricks with 10% URHA and 50% FA registered the lowest cost. Properties of all of the brick samples met the Grade M15 requirements of the TCVN 6477-2011 standard of high-quality unfired building bricks.

Keywords: ***compressive strength, cost analysis, fly ash, unfired building brick, unground rice husk ash.***

Classification number: ***2.3***

Introduction

Due to the rapid development of the construction industry in Vietnam, building bricks are consumed profusely annually. Most of them are conventional fired clay bricks or concrete bricks. Conventional fired bricks are produced from clay at high temperature, while concrete bricks are produced from ordinary Portland cement. To produce the conventional fired clay bricks, a significant energy and intensive amount of natural clay is used, leading to a negative effect on the environment due to the generation of carbon dioxide (CO_2) and the depletion of agricultural land. On the other hand, the production of cement also consumes intensive energy and releases a significant quantity of CO_2 into the air, causing greenhouse effect and contributing to climate change. Furthermore, the mass of industrial wastes is rapidly increasing and has an inverse effect on the environment. Therefore, instead of considering them as waste materials, turning such wastes into green construction materials has received much attention from researchers.

Vietnam is predominantly an agricultural country and falls within the top rice export nations in the world. In consequence, a large amount of rice husk was generated as a by-product of rice production. A part of the rice husk was used to produce animal food and fertilizer, while the rest was utilized as fuel in rural households and small businesses because of its cheap price. Rice husk ash is obtained from burning rice husk. It is worth noting that the properties of rice husk ash strongly depend on the burning conditions. When rice husk is burned at temperatures ranging between 600 and 800^{o}C, rice husk ash consists of around 91-95% reactive silica (SiO_2) [1, 2]. Hence, it can be used for manufacturing unfired building bricks. Moreover, fly ash (FA), a by-product of coal power plants, is widely employed as a supplementary cementitious material in order to reduce the amount of cement produced. The use of FA and rice husk

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ash in unfired building bricks is a visible solution to the environmental problem as well as economical effectiveness.

FA is extensively used for producing unfired building bricks. However, the properties of unfired building bricks are significantly dependent on FA content and its quality as well as forming pressure. The use of FA as the main binder in unfired building bricks was examined in some previous studies [3-7]. Under forming pressure of 10-26 MPa, unfired building bricks exhibited a compressive strength of higher than 13 MPa and water absorption of lower than 20% [3-5]. Cicek and Tanriverdi (2007) [6] investigated the use of 50-80% FA in the total amount of brick and under forming pressures varying between 0.5 and 30 MPa. Test results showed that unfired building bricks had a compressive strength of lower than 10 MPa and water absorption higher than 33%. Using 60-90% FA and forming by vibration table, unfired building bricks showed low properties with a compressive strength lower than 8 MPa and water absorption between 29-37% [7]. It was found that using the vibration table to form the sample was not as effective as using high forming pressure. Shakir, et al. (2013) studied the use of a combination of cement and FA as binder materials in unfired building bricks [8]. The compressive strength and water absorption of bricks ranged between 6.2-26.3 MPa and 12.9-19.1%, respectively. In order to increase the pozzolanic reaction of FA, the alkali-activators were added into the brick mixtures [9-11]. Kumar, et al. (2013) studied the use of 60-100% FA and 0-40% red mud in unfired building bricks [9]. These bricks exhibited good performance with a compressive strength higher than 16 MPa and water absorption lower than 7%. The combination of FA and bottom ash were investigated by Freidin (2017) [10] and Arioz, et al. (2010) [11]. Under forming pressures of 4 MPa and 30 MPa, unfired building bricks showed compressive strength up to 20 MPa and 60 MPa, respectively.

Recently, rice husk ash has been used for producing unfired building bricks [12-16]. Unfired building bricks were made from FA, rice husk ash, and sand using geopolymerization technology [12-14]. Other unfired building bricks were made from cement, FA, and rice husk ash based on the cementing reaction [15-16]. It was noted that rice husk ash was used in the following two kinds: ground rice husk ash and unground rice husk ash (URHA). In these studies, URHA was considered as fine aggregate to replace 10-40% amount of sand and ground rice husk ash was used as a supplementary cementitious material. All of the brick samples were formed under the high pressure of 35 MPa. Experimental results revealed that all unfired building bricks show a good performance with properties satisfying the requirements of TCVN 6477-2011 [17].

Compared with TCVN 6477-2011 [17], the unfired building bricks from previous studies had a water absorption much higher than 14%, over the requirements of the Vietnamese standard. All the previous studies selected FA with high quality and the loss on ignition lower than 6% as required by ASTM C618 [18]. URHA was applied to replace a part of sand, and unfired building bricks were manufactured under high forming pressure. The primary objective of this study is to investigate the use of low quality raw FA, with a high loss on ignition and URHA, in the production of unfired building bricks. Raw FA and URHA were used to replace part of the cement and chippings, respectively. The FA used herein has a 15.8% loss on ignition that is much higher than the requirement of ASTM C618 [18]. Unfired building bricks were produced under low forming pressure of around 5 MPa. The effects of FA and URHA content on the properties of the unfired building bricks such as compressive strength, water absorption, and bulk density were also investigated in accordance with TCVN 6477-2011 [17]. Moreover, cost analysis was conducted to find out the optimal brick mixture.

Materials and experimental programs

Materials

Unfired building bricks were prepared from cement, FA, chippings, and URHA, where cement and FA were used as binder materials, with properties as shown in Table 1, while chippings and URHA were used as fine aggregates. In this study, ordinary Portland cement Nghi Son PC40, with a specific gravity of 3.12, was used. FA, a raw material sourced from the Nghi Son coal power plant that was classified as class-F based on ASTM C618 [18], with a specific gravity of 2.16 and a 15.8% loss on ignition was used as a cement substitute. Chippings was a byproduct from the stone crushing process with a maximum size of 5 mm, density of 2.65 T/m^3, fineness modulus of 3.54, and moisture content of 0.5%. URHA, with a density of 2.10 T/m^3, fineness modulus of 2.58, and water absorption of 30%, was taken from the steam boiler at Nghi Son industrial zone. Gradation curves of chippings and URHA are presented in Fig. 1. Fig. 2 shows the images of chippings, URHA, and scanning electron micrograph (SEM) of URHA.

Table 1. Properties of cement and FA.

Items		Cement	FA
Physical properties	Specific gravity	3.12	2.16
	Loss on ignition (%)	1.9	15.8
Chemical composition (wt.%)	SiO_2	22.4	48.4
	Al_2O_3	5.3	20.4
	Fe_2O_3	4.0	4.8
	CaO	55.9	2.8
	MgO	2.8	1.4
	Others	4.5	4.3

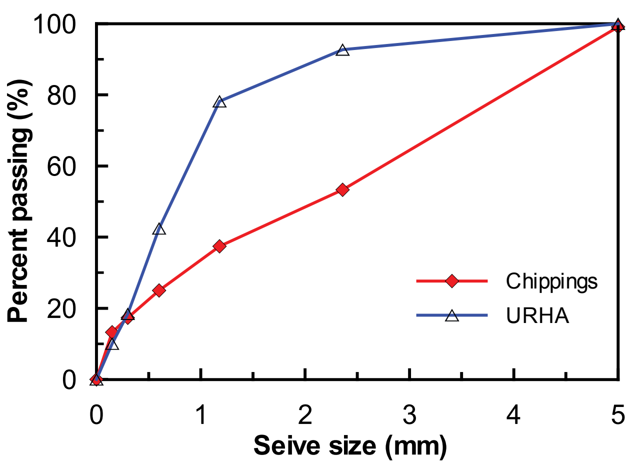


Fig. 1. Gradation curves of chippings and URHA.

Brick mixtures

The brick mixtures were divided into two groups as shown in Tables 2 and 3. Table 2 shows the first group that was designed to investigate the effect of URHA content on the properties of the unfired building bricks. In this group, URHA was used to replace 5%, 10% and 15% of chippings. Table 3 shows the second group that was designed to investigate the effect of FA content on properties of the unfired building bricks. A constant amount of 10% URHA was used for all mixtures in this group. FA was used to replace 15%, 30%, and 50% of the cement. The nomenclature of the mixtures is described as follows: M5 and M6 denote the water-to-binder ratios of 0.5 and 0.6, respectively; the numbers after them (0, 5, 10, and 15) are the percentages of URHA replacement for chippings; the numbers in front of FA (15, 30, and 50) indicate the percentages of FA replacement for cement.

Fig. 2. (A) Chippings, (B) URHA, (C) SEM image of URHA.

Table 2. First group mixture proportions.

Mixture	Ingredient proportions (kg/m³)			
	Cement	*Chippings*	*URHA*	*Water*
M5-0	440	1693	0	220
M5-5	436	1595	84	218
M5-10	433	1499	167	216
M5-15	429	1404	248	215
M6-0	367	1756	0	220
M6-5	364	1653	87	218
M6-10	360	1553	173	216
M6-15	357	1454	257	214

Table 3. Second group mixture proportions.

Mixture	Ingredient proportions (kg/m³)				
	Cement	*FA*	*Chippings*	*URHA*	*Water*
M5-10-15FA	364	64	1485	165	214
M5-10-30FA	297	127	1472	164	212
M5-10-50FA	210	210	1454	162	210
M6-10-15FA	304	54	1541	171	215
M6-10-30FA	248	106	1530	170	213
M6-10-50FA	176	176	1514	168	211

Samples preparation and test programs

Unfired building bricks were prepared in a steel mold, with dimensions of 220×105×65 mm, applying forming pressure of around 5 MPa that is much lower than the forming pressures used in most of the previous studies (10-35 MPa) [3-6, 11-16]. The purpose of this study is to assess the use of low forming pressure and industrial and agricultural by-products for producing unfired building bricks.

The dimensions and visible defects, compressive strength, water absorption, and bulk density of the unfired building brick samples were tested in accordance with TCVN 6477-2011 [17]. The compressive strength values were measured at the 3, 7, 14 and 28-day ages, with the presented values were the average values of the three samples. Other brick properties were measured at the 28-day ages.

Test results and discussion

Dimensions and visible defects

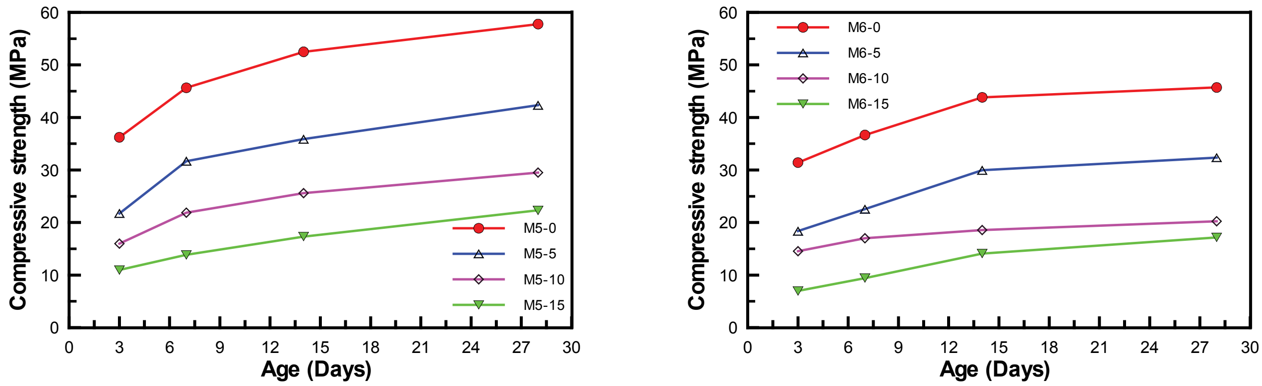
The measured dimensions of the unfired building bricks are shown in Table 4. All the bricks possessed a slight difference in dimensions compared with the standard size (220×105×65 mm). This is due to the deformation of the steel mold under repeated forming pressure during the production of bricks. The detected error is lower than the allowable error stipulated by TCVN 6477-2011 [17]. Table 5 shows the visible defects of the brick samples. No visible defects were observed on the surface, edge, and corner of the samples, indicating that all the unfired building bricks had consistent shape, and satisfied the TCVN 6477-2011 requirements [17].

Table 4. Dimensions of brick samples.

Dimension	Measured dimension (mm)	Allowable error (mm)
Width	105 ± 1	± 2
Length	220 ± 1	± 2
Height	65 ± 1	± 3

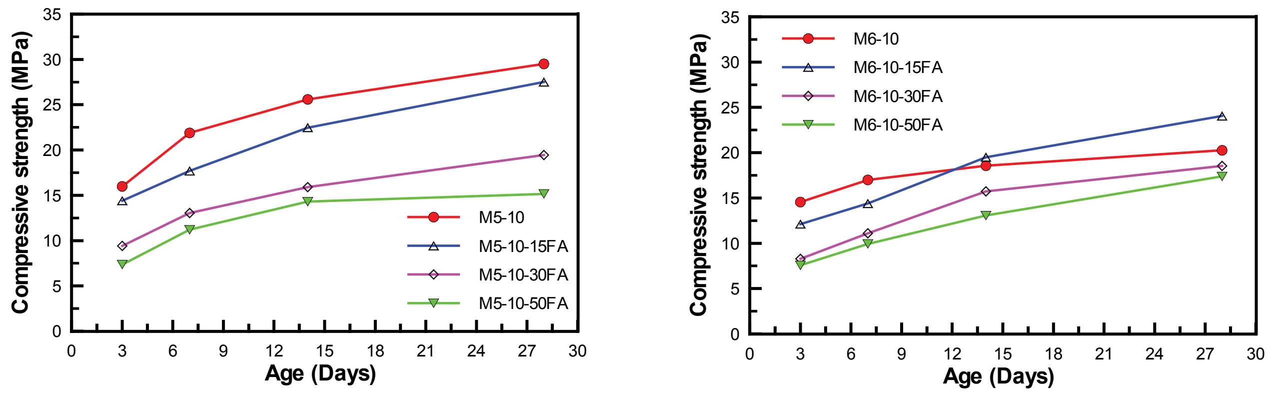
Table 5. Visible defects of brick samples.

Type of visible defects	Allowable level	Visible defects of brick samples
The curvature of the surface of brick (mm), no more than	3	No
The number of edges and corner cracks with the depth of 5±10 mm and the length of 10±15 mm, no more than	4	No
The number of cracks through the thickness pulling to a width that not exceeding 20 mm, no more than	1	No



(A) (B)

Fig. 3. Compressive strength development of the unfired building brick samples with various URHA contents.



(A) (B)

Fig. 4. Compressive strength development of the unfired building brick samples with various FA contents.

Compressive strength

The effect of URHA content on compressive strength development of brick samples is shown in Fig. 3. The compressive strength of bricks significantly reduced as the URHA content increased. For brick mixtures with water-to-binder ratios of 0.5 and 0.6, the compressive strength of the 28-day-old brick samples with 5%, 10%, and 15% URHA were, respectively, about 26.7%, 48.9%, and 61.4% and about 29.2%, 55.7%, and 62.4% lower than that of the control samples without URHA. It could be observed from Fig. 2C that URHA was made of highly porous particles that caused an inverse effect on the compressive strength of brick samples. Increasing URHA replacement levels resulted in the loss of structural compactness and, in turn, led to a lower compressive strength. However, all the brick samples incorporating URHA possessed the 28-day compressive strength that was higher than 17 MPa. Thus, these brick samples could be classified as the high-quality unfired building bricks (Grade M15) in accordance with TCVN 6477-2011 [17].

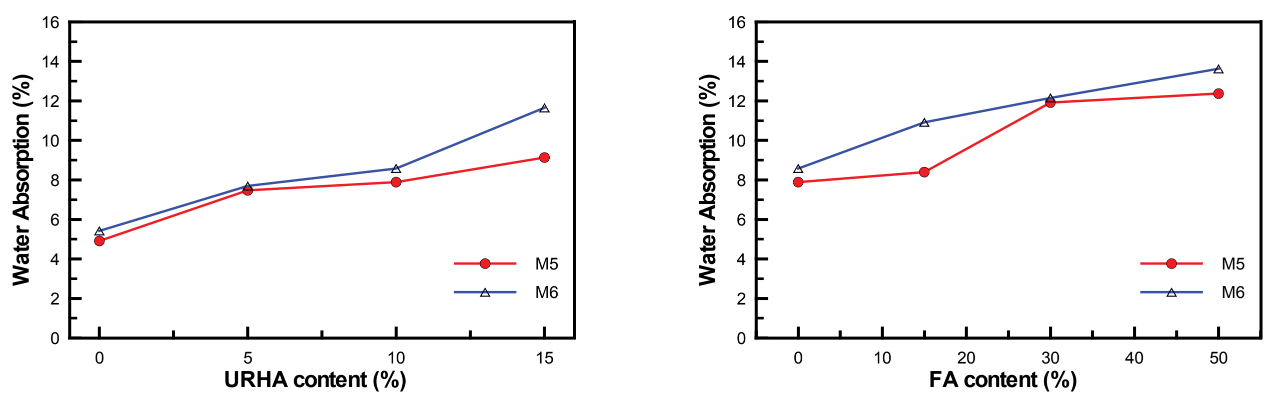
Figure 4 shows the compressive strength development of the unfired building brick samples with varied FA content. After 28 days of age, the unfired building brick samples of the M5 group with 15%, 30%, and 50% FA replacement levels had compressive strength values of 27.5, 19.4, and 15.2 MPa, respectively. These values were 6.8%, 34.1%, and 48.6% lower than the compressive strength values of the FA-free samples (M5-10), respectively. The compressive strength of the M5 mixtures decreased as the FA replacement levels increased. However, for the M6 mixtures, the brick sample with 15% FA showed the highest compressive strength at the 28-day ages (Fig. 4B). Previous studies [19-21] have proved that the use of FA at optimal dosage enhanced the compressive strength of concrete because of the pozzolanic reaction. The optimal dosage of FA was varied, depending on its properties and mixture proportion. If FA was added over and above the optimal dosage, all of it did not participate in a chemical reaction; it acted as the fine aggregate rather than a cementitious material. In this case, the amount of FA in the M6-10-15FA mixture may be close to the optimal FA content, resulting in a higher compressive strength than control mixture M6-10. It is also worth noting that the FA used in this research was of low quality with a high loss on ignition. Thus, the compressive strength of all the brick samples reduced when FA content increased, except the M6-10-15FA mixture as mentioned above. However, similar to the first mixture group, the lowest compressive strength value among M6 brick samples was 15.2 MPa that satisfied the Grade M15 of the TCVN 6477-2011 [17].

As can be seen from to Figs. 3 and 4, the compressive strengths of mixtures with a water-to-binder ratio of 0.5 were higher than those of corresponding mixtures with a water-to-binder ratio of 0.6. This is due to the fact that the amount of binder in M5 mixtures is higher than that of M6 mixtures (Tables 2 and 3), resulting in more hydration products. Consequently, the compactness and strength capacity of bricks were enhanced because hydration products were the main carriers of strength in unfired building bricks. Therefore, the compressive strength increased since water-to-binder ratio reduced.

Water absorption

Water absorption is an important property of unfired building bricks, which significantly affects the progress and quality of construction. Bricks with high water absorption capacity will absorb a higher amount of water from mortar, affecting the bond between bricks and mortar. Therefore, the TCVN 6477-2011 [17] has limited the maximum level of water absorption of 14%. Fig. 5A shows the relationship between water absorption and URHA content. The water absorption of bricks increased with URHA content. For M5 mixtures, the unfired building bricks with the URHA replacement levels of 5%, 10%, and 15% had the water absorption levels of 52.2%, 60.7%, and 86.1%, respectively, higher than that of the control mixtures without URHA. A similar trend was observed among the M6 group bricks with 5%, 10%, and 15% URHA content that had water absorption values of 41.9%, 58.4%, and 115%, respectively, higher than that of the bricks without URHA content. This phenomenon is because of the high porosity of the URHA as mentioned above. However, all the brick samples produced in this study had water absorption values lower than 14% in accordance with TCVN 6477-2011 requirements [17].

Figure 5B shows the relationship between water absorption and FA content. As the amount of FA increased, the water absorption of bricks increased. The water absorption level of brick samples containing 50% FA was about 60% greater than that of the control mixture without FA. This finding is associated with the low quality of FA with a high loss on ignition. It is worth noting that the loss on ignition of FA is due to the loss of carbon and sulfur at high burning temperatures. The presence of unburned carbon increased the water absorption of FA [22-24], leading to an increase in the water absorption of FA bricks. However, all the FA brick samples had water absorption capacity of below 14% that satisfied the TCVN 6477-2011 requirements [17].



(A) (B)

Fig. 5. Effect of (A) URHA and (B) FA contents on water absorption of the unfired building brick samples.

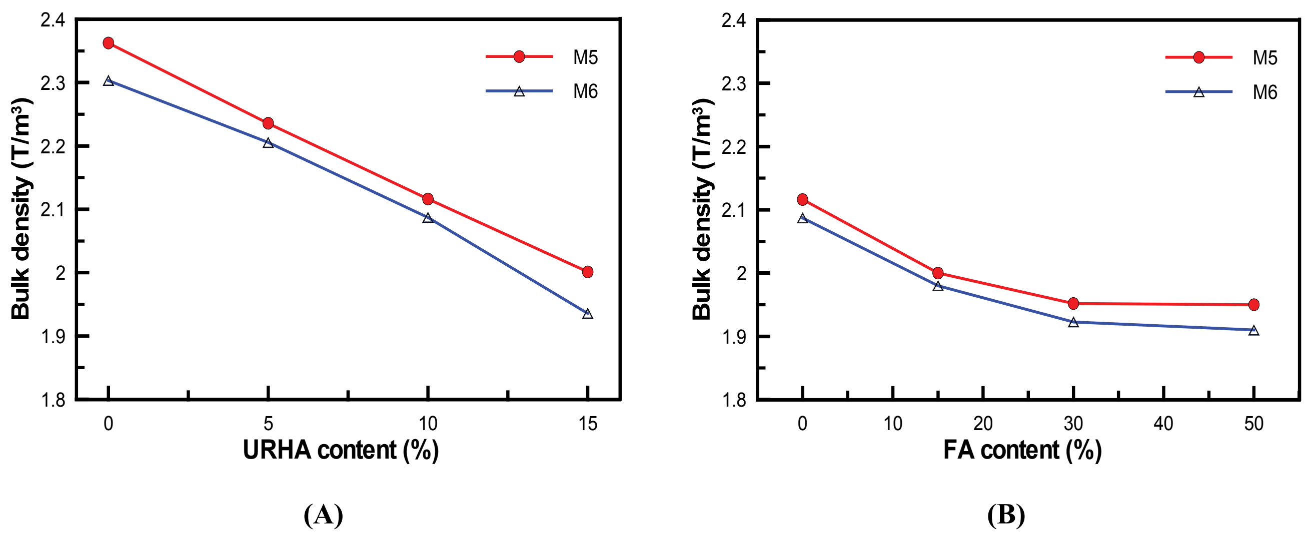


Fig. 6. Effect of (A) URHA and (B) FA contents on bulk density of the unfired building brick samples.

The water absorption of M5 mixtures was lower than that of the corresponding M6 mixtures. The lower water absorption values were mainly related to the amount of binder as mentioned previously. The water absorption of bricks has been negatively associated with its compactness and mechanical strength. In other words, brick samples with high strength and good compactness will register a low water absorption.

Bulk density

The bulk density is defined as the mass of brick divided by its volume. It is used as an indicator to classify a solid building brick. If the bulk density of bricks is high, the total mass of the building laying on the foundation is also high. Consequently, the required structure of the foundation needs to be strong enough to suffer the intensive load. Therefore, the use of light weight bricks is a good option to reduce the foundation cost. However, the bulk density is often inversely correlated with water absorption capacity. Fig. 6A shows the plot of the average bulk density of brick samples at the 28-day age against URHA content. The bulk density reduced by increasing the URHA content. The average bulk density of brick samples with 5%, 10% and 15% URHA content was around 4.8%, 9.9%, and 15.6%, respectively, lower than that of the no URHA bricks. This is mainly attributable to the lower specific density of the URHA in comparison with chippings.

Figure 6B shows the plot of the average bulk density of brick samples at the 28-day ages against FA content. Similarly, replacing cement with FA led to a reduction in bulk density of the brick samples. The average bulk density of brick samples with 15%, 30%, and 50% FA was around 5.3%, 7.8%, and 8.2%, respectively, lower than that of the FA-free bricks. This is mainly due to the lower specific density of FA compared with cement. The lowest bulk density of 1.91 T/m^3 was obtained from the M6-10-50FA mixture.

Cost analysis

The cost of bricks is a very important factor that shows the applicability of bricks in the market. Thus, the cost analysis was conducted to assess the economic efficiency of all brick mixtures. Table 6 shows the cost analysis for a brick. At the same water-to-binder ratio, the cost of each brick reduced with the use of more URHA and FA in the brick mixture. It is noted that the cost analysis was calculated based on the unit price of construction materials announced by the Department of Construction in Thanh Hoa in the first quarter of 2017. The price of water and URHA was taken as selling price in the current market. The unit price of cement, FA, chippings, water, and URHA was 1,227 VND/kg, 200 VND/kg, 1,238,000 VND/m^3, 13,860 VND/m^3, and 50,000 VND/ton, respectively. The labor cost was not included in this calculation. The result showed that the M6-10-50FA mixture had the lowest price of 500 VND, while the actual price of a Grade M15 unfired building brick available in the market was higher than 1,200 VND.

Table 6. Cost analysis for a brick.

Mixture	Material cost for a brick (VND)	Mixture	Material cost for a brick (VND)
M5-0	934	M6-0	803
M5-5	927	M6-5	797
M5-10	919	M6-10	790
M5-15	912	M6-15	784
M5-10-15FA	812	M6-10-15FA	702
M5-10-30FA	706	M6-10-30FA	614
M5-10-50FA	568	M6-10-50FA	500

Analysis for optimal mixture

As presented above, all the brick samples had compressive strength and water absorption levels that satisfied the TCVN 6477-2011 standard [17], in which the strength of bricks met the Grade M15 requirement and water absorption of bricks was below 14%. Therefore, the optimal mixture is a mixture that has the lowest bulk density and cost. Based on bulk density test and cost analysis, the M6-10-50FA brick mixture was found to be the optimal one. It had great potential to be manufactured on a large scale. This mixture provided a compressive strength value of 15.2 MPa, water absorption of 13.6%, bulk density of 1.91 T/m^3, and material cost of about 500 VND per sample.

Conclusions

In the present study, raw FA and URHA were used to produce unfired building bricks. The following conclusions may be drawn based on the above experimental results:

(1) All the brick samples made from URHA and FA had good properties that satisfied the TCVN 6477-2011 requirements. All the samples showed consistent shape without any visible defects.

(2) Using more URHA resulted in a reduction in compressive strength, bulk density, and brick cost. However, an adverse trend was observed with water absorption of brick samples.

(3) Increasing the FA content led to a reduction in compressive strength, bulk density, and brick cost, but an increase in the water absorption capacity of the brick samples, except mixture M6-10-15FA.

(4) With the compressive strength value meeting the Grade M15 requirement, a water absorption of lower than 14% and the lowest bulk density and material cost, the M6-10-50FA brick mixture was considered as the optimal mixture.

(5) The test results of this study encourage the use of raw FA and URHA in the manufacture of unfired building bricks. The recycling of such wastes is not only cost effective, but also reduces the negative impact on the environment due to the disposal of waste materials.

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