Feasibility of producing unfired four-hole hollow bricks from blended cement-fly ash-chippings under coupled-static forming pressure

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Abstract. Unfired four-hole hollow brick (UFHB) is a type of environmental-friendly brick with low energy consumption. However, the using of ordinary Portland cement (OPC) in UFHB is costly and indirectly affects the environment. This paper focuses on an exploratory study on the use of blended fly ash (FA)-OPC in the production of the UFHB and proposes the application of FA-OPC mixtures as a timely solution for the reduction of OPC in UFHB. The 80×80×180 mm UFHB samples were produced using different proportions of FA and OPC under a constant coupled-static forming pressure. The report exhibited experimental characterizations on physical and mechanical properties of both starting materials and UFHB products. In addition, a scanning electron microscope (SEM) analysis was used to evaluate the microstructure of the final UFHB. Test results show that the inclusion of FA in the UFHB mixtures provided positive effects on brick properties. As a result, 10% FA was found as an optimal content, which resulted in the highest brick’s strength, the lowest water absorption rate, and a denser microstructure. Furthermore, properties of all of the UFHB samples produced for this study satisfied the requirements of the National Vietnamese standard for non-bearing building brick.

1. Introduction
Vietnam is currently on the verge of large-scale urbanization hence facing huge demand for building houses and thus for the materials to build them. To cope up with this housing necessity, the country needs to use a million units of bricks per day. It is continually expanding on account of a rapid increase in demand for bricks in infrastructure and housing industry. To produce a traditional fired clay brick, a large number of natural sources and energy consumption are used. Therefore, the invention of unfired brick (UB) is necessary in order to limit the use of natural materials, as well as reduce the harmful effects on the environment. However, the production of UB spent a large amount of ordinary Portland cement (OPC) and it indirectly affects the environment as well [1, 2]. This underlines the need to find an eco-friendly substitute to OPC in order to develop an alternative green material. In recent decades, the application of fly ash (FA), a by-product of high-temperature combustion of coal in coal-fired power plants, has increased many folds [3, 4]. FA is not only a pozzolanic material (chemical effect) but also a
micro-filler (physical effect) that greatly contributes to enhancing the properties of the final products [5, 6]. So far, the utilization of FA in the production of UB and the study on characteristics of the UB have still been limited. Therefore, this study investigates the feasibility of producing a new type of UB, so-called unfired four-hole hollow bricks (UFHB), using a mixture of OPC, FA, and chippings. Especially, a coupled-static forming pressure was applied to form the UFHB samples. The effects various compositions of OPC and FA on engineering properties and microstructure of the UFHB samples were also studied.

2. Experimental works

2.1. Material properties

Locally grade 40-OPC and type F-FA were used as binder materials. Characteristics of both FA and OPC are shown in Table 1. It can be seen that the major mineralogical compositions of OPC were SiO$_2$ and CaO, whereas the major compositions of FA were SiO$_2$ and Al$_2$O$_3$, which may react with other products of cement’s hydration under Ca(OH)$_2$ environment to form C-S-H gel [7].

| Items                                | OPC   | FA    |
|--------------------------------------|-------|-------|
| Specific gravity                     | 3.15  | 2.29  |
| Mean particle size (µm)              | 19.1  | 21.5  |
| Specific surface area (m$^2$/g)      | 0.78  | 0.66  |
| Strength activity index at 28 days (SAI, %) | 100   | 86.5  |
| Chemical compositions (wt.%)         | SiO$_2$ | 20.04 | 64.01 |
|                                      | Al$_2$O$_3$ | 4.24  | 22.14 |
|                                      | Fe$_2$O$_3$  | 3.12  | 5.64  |
|                                      | CaO     | 62.43 | 2.75  |
|                                      | MgO     | 4.17  | 0.92  |
|                                      | SO$_3$  | 2.97  | 0.61  |
|                                      | K$_2$O  | 0.43  | 1.36  |
|                                      | Na$_2$O | 0.33  | 0.85  |

In addition, it can be clearly observed that the particle size of FA was almost similar to that of OPC (Table 1) and the FA had morphology form of spherical shape with different particle sizes (Figure 1). As usual, the smaller particle size results in a higher degree of reaction, indicating by a high SAI value of FA (86.5%) compared to OPC (Table 1).

Figure 1. SEM image of FA particles.

![Figure 1. SEM image of FA particles.](image1.png)

Figure 2. Gradation curve of chippings.

![Figure 2. Gradation curve of chippings.](image2.png)

Figure 3. The appearance of UFHB samples.

Chipping, in air-dry condition, with a maximum particle size of 5 mm, a density of 2550 kg/m$^3$, and water absorption rate of 3.1% was adopted as fine aggregate to produce the UFHB samples. The gradation curve of chippings is plotted in Figure 2. It is noted that the chipping with a particle size of 2.5 mm that accounted for more than 30% will form the resistance structure and contribute to enhancing the
samples’ strength. Furthermore, the appearance of the smaller particle size of below 0.63 mm will play as a filler and thus improve the physical properties of the brick.

2.2. Mix proportioning
In the present study, a total matrix of 6 UFHB mixtures was prepared. A fixed water-to-binder (w/b) ratio of 0.2 was used for all of the UFHB mixtures. The UFHB mixtures were proportioned to study the effects of different OPC and FA contents on the brick’s properties. The first three UFHB mixtures were prepared with various OPC contents of 8, 10, and 12%, while the rest three UFHB mixtures were prepared with the addition of FA to the mixtures at 10%, 15%, and 20%. The mix proportions for the preparation of the UFHB samples are shown in Table 2.

| Table 2. Ingredient proportions for making samples. |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Materials      | Brick mixtures | OPC            | FA             | Chipping       | Water          | Note: C represents the OPC content and F represents the FA content. |
| (kg/m³)        | C08F00         | C10F00         | C12F00         | C10F10         | C10F15         | C10F20         |
| OPC            | 195.4          | 242.9          | 289.8          | 229.7          | 223.6          | 217.8          |
| FA             | -              | -              | -              | 229.7          | 335.4          | 435.7          |
| Chipping       | 2247.2         | 2185.8         | 2125.1         | 1837.3         | 1676.9         | 1524.8         |
| Water          | 39.1           | 48.6           | 58.0           | 91.9           | 111.8          | 130.7          |

2.3. Samples preparation and test methods
All of the raw materials were prepared in accordance with Table 2. The dry materials were uniformly mixed using a laboratory mixer. The mixture was then filled up in a steel mold and was compacted under a coupled-static forming pressure of about 4.7 MPa to form the UFHB samples as presented in Figure 3. The brick samples were de-molded and placed in air for 24 h before fully immersed in water for 30 min and then covered by a thin plastic layer to keep the moisture until the testing time. The 28-day UFHB samples were subjected to the tests of compressive strength and water absorption following the guidelines of the National Vietnamese standard [8]. Furthermore, the broken specimens from the compression test were collected to evaluating the microstructure of the brick using SEM technique.

3. Results and discussion

3.1. Compressive strength
The 28-day compressive strength values of the UFHB samples with different OPC and FA contents are presented in Figure 4. The compressive strength increased proportionally OPC content. The brick’s strength of 4.24 MPa was obtained at 8% OPC and the compressive strength value increased by 4.0% and 9.4% with increasing OPC content to 10% and 12%, respectively. Moreover, it is expected that the inclusion of FA improved the compressive strength of the UFHB samples. The bricks with 10%, 15%, and 20% FA had compressive strength value of 36.7%, 17.7%, and 3.4% higher than the free-FA bricks. The fact that FA is a pozzolanic material with high SiO₂ content and high SAI (Table 1), which is the strength determinant in combination with CaO in OPC, forming hydrated lime (Ca(OH)₂) in the presence of water and resulting in the formation of calcium silicate hydrate (C-S-H) gel. This gel is responsible for the strength gain of the samples. Moreover, some small unreacted FA particles will play as a filler material to reduce the void between larger particles in structure. Hence, the presence of FA in the matrix increased the compressive strength of the UFHB. However, an excess amount of FA caused a reduction in brick’s strength. It may due to the presence of more unreacted FA particles, which resulted in a low degree of reaction and thus less formation of C-S-H gel in the matrix. The UFHB samples produced in this study satisfied for non-bearing wall construction as stipulated by TCVN 6477-2016 [8].
3.2. Water absorption

Figure 5 presents the water absorption (WA) levels of the UFHB samples. Obviously, the WA decreased with increasing OPC content. The inclusion of FA in brick mixtures was also attributable to the low WA rate of the bricks. However, the WA levels increased with FA content. This finding was supported by Bigas and Gallias [9]. It can be clearly perceived that more OPC content will generate more bonding agent (C-S-H gel) to create a denser structure and thus reduces the WA rate of the system. As the result, all of the UFHB samples produced in this study had the WA rates of below maximum limit of 12% as required by TCVN 6477-2016 [8]. Further, it is interesting to state that compressive strength was inversely proportional to the WA (Figure 6). It is attributed to the fact that the higher the compressive strength, the lower the porosity and WA of the brick was. The correlation between compressive strength and WA of the bricks was presented by the equation of \( y = 155.151 - 33.888x + 1.902x^2 \) with \( R^2 \) of 0.93. As the previous discussion, the inclusion of FA reduced the void within the brick structure and consequently reduced the WA rate of the bricks. However, more voids/pores were introduced with the presence of access amount of FA (Figure 7), which resulted in a high level of WA.

3.3. SEM observation

The SEM micrographs of the 28-day-old UFHB specimens are shown in Figure 7. This figure provided information on the degree of reaction within the system, indicated by the change in the material particle shape, the rearrangement of the system, and the presence of partial/unreacted particles.
There were three distinguishable phases that were detected from the micrographs, including aggregate particles (smooth grey areas), unreacted FA particles (round grey dots), and bonding gels between the particles (textured light grey areas). It can be clearly seen that increasing the OPC content from 8% to 10% and 12% resulted in an increased quantity of bonding gel as the result of cement hydration. This contributed to the higher strength of the UFHB samples as previously presented in Figure 4. On the other hand, the structure of the 10% FA brick was much denser than that of the others. Increasing the FA content to 15% and 20% caused a less dense structure with many unreacted particles and pores, leading to the lower strength and higher WA rate of the bricks. This observation was in good agreement with the results of the compressive strength and WA of the UFHB samples as aforementioned.

4. Conclusions
The present experimental works investigated the feasibility of producing UFHB using various proportions of OPC, FA, and chippings. Based on the obtained results, the following conclusions can be drawn:

1. The compressive strength of the UFHB samples increased proportionally with OPC content, whereas the reverse trend was observed for WA rates of the bricks.
2. The inclusion of FA in the brick mixtures provided a positive effect on the properties of the UFHB samples. All of the FA-bricks had higher strength values and lower WA levels as compared to the free FA-brick and the respective maximum strength value and the lowest WA rate of 6.03 MPa and 7.95% were achieved at the brick containing 10% FA.
3. SEM observation found that the UFHB samples with 10% FA content exhibited a denser structure relative to the other samples. This finding agreed with the compressive strength of the bricks.
4. The results of this study encourage the use of raw FA in the manufacture of unfired building bricks and particularly demonstrated great feasibility of producing UFHB with the utilization of FA, OPC, and chippings. The use of such materials is not only cost effective but also reduces the negative impact on the environment.
5. Further research may be conducted using other types of industrial solid waste materials in combination with OPC to produce UFHB in either laboratory scale or industrial scale.

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