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Properties of unfired solid bricks produced primarily from thermal power plant fly ash and bottom ash

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ABSTRACT

In this study, a large amount of fly ash (FA) and bottom ash (BA) from the Nghi Son coal-fired thermal power plant in Thanh Hoa, Vietnam is used in producing unfired solid bricks. FA was utilized to substitute up to 85% (by weight) of the cement amount, while BA was used as a fine aggregate. Test results showed that all bricks produced in this study had a unit weight of 1.51 – 1.68 T/m^3 and were classified as Grade M3.5 to M15. As FA replacement level increased, the unit weight, compressive strength, and thermal conductivity of bricks reduced, meanwhile water absorption and water permeability increased. The quality and amount of FA used had a strong effect on the brick's properties. When the amount of FA used was too much, a part of them did not participate in the chemical reaction but played a role as a fine aggregate.

1. INTRODUCTION

Currently, most countries worldwide are concerned about the large amount of FA and BA produced by coal-fired power plants. The annual amount of these ashes was approximately 185.5 million tons in India, Malaysia, and Thailand (Chindaprasirt et al., 2008; Rafieizonoor et al., 2016; Singh & Siddique, 2016). In Vietnam, the total amount of these released ashes was around 29 million tons (Ngo et al., 2018), of which the amount of FA was about 16.4 million tons (Ngo et al., 2020). As stated in a previous study (Kurama & Kaya, 2008), the FA was reused in construction materials at a rate of 47% compared to just 5.3% for BA. There were still large amounts of FA and BA stored in storage yards, which led to numerous environmental issues. It is observed that FA is frequently utilized in brick or concrete mixtures as a binder material, meanwhile, BA with properties similar to river sand has been used as fine aggregate (Muthusamy et al., 2020). With the low rate of recycling, the recycling of both FA and BA in producing construction materials has continued to receive attention from researchers worldwide.

Previous studies have examined the use of FA in producing unfired bricks (Kumar, 2002; Cicek & Tanriverdi, 2007; Zhang et al., 2012; Shakir et al., 2013). The use of FA and limestone powder has been investigated by Turgut (2010), in which the amount of FA was up to 30% of brick weight. Test results indicated that the unit weight (UW) and thermal conductivity (TC) of this brick were around 1.8 T/m^3 and 0.91 – 1.02 W/mK, while compressive strength (CS) and water absorption (WA) were in the range of 6 – 15 MPa and 14 – 19%, respectively. The use of FA up to 40% was conducted by Shakir et al. (2013) with similar results. The UW, WA, and CS of unfired bricks were approximately 1.65 T/m^3, 16.5%, and 14 MPa when FA was utilized to 100% (Zhang et al., 2012). It is noticed that the quality of raw materials, forming, and curing methods in these studies (Turgut, 2010; Zhang et al., 2012; Shakir et al., 2013) were various, so the properties of corresponding bricks were also different. The FA was also used in the manufacturing of lightweight bricks with UW of around 1.2 T/m^3, CS of below 10 MPa, WA of 28.9 – 40.5%, and TC of around 0.35 W/mK (Kumar, 2002; Cicek & Tanriverdi, 2007).

The utilization of FA and BA in making unfired solid bricks remains limited (Naganathan et al., 2012; Naganathan et al., 2015; Freidin, 2017). Freidin (2017) used an alkaline activation method to produce geopolymer bricks, however, the maximum WA of this brick was around 38.4%. It has been observed that using alkaline activators could result in higher production costs. Thus, to manufacture unfired bricks, a small amount of cement has been used incorporating both FA and BA (Naganathan et al., 2012; Naganathan et al., 2015). Even though the CS of this brick was quite good, the WA was still high (around 29%). It is concluded that most coal-fired ash bricks produced from previous studies had a comparable CS with traditional fired-clay bricks, but their WA value was over 14% or even extremely high. It is worth noting that the resistance to chemical attacks is correlated with WA and WP. For this reason, these values cannot be more than 14% and 16 L/m^{2}h, respectively, according to the Vietnamese standard (TCVN 6477-2016). As previously noted, the majority of bricks produced in earlier studies had WA values greater than 14%, while the WP test was not conducted.

In Vietnam, cement-based brick is commonly used, meanwhile, the use of FA and BA in producing unfired bricks has been still limited. The use of coal-fired thermal power plant ashes in the production of unfired building bricks has been studied in the previous study (Luu & Le, 2021). However, several important properties of raw materials used in this study were missing such as the scanning electron microscopy observation (SEM) of both fly ash and bottom ash, and the size distribution of bottom ash. Consequently, the explanation for the test results has been not convincing. The FA replacement level in the previous study (Luu & Le, 2021) was up to 70% and the water permeability test and the microstructure of bricks have been still missing. In this study, ternary solid materials of FA, BA, and cement were used to produce unfired solid bricks; in which, FA was used to replace up to 85% of cement by weight and BA played a role as fine aggregate. Characteristics of unfired solid bricks including UW, CS, WA, WP, TC, and their microstructure were examined. Furthermore, an investigation was conducted into the influence of FA content on the properties of bricks.

2. EXPERIMENTAL PROGRAM

2.1. Materials properties

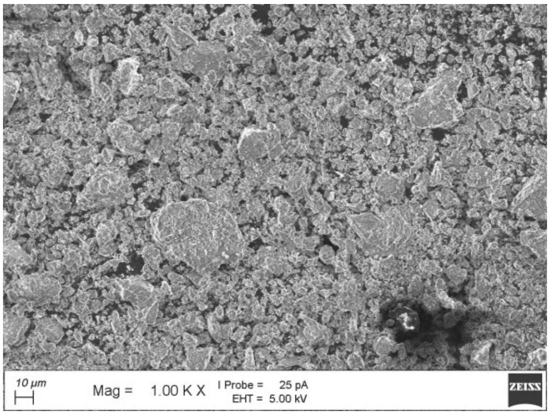
The materials used in this study include cement, FA, and BA, their densities are 3.12, 2.16, and 1.99, respectively. Cement is type PCB40, which was sourced from Nghi Son company. FA and BA, industrial by-products, were supplied by the Nghi Son coal-fired power plant. While cement and FA were utilized as binder materials, BA was used as fine aggregate, respectively. It is noticed that both FA and BA are raw materials without any pretreatments. The main chemical compositions of these materials are presented in Table 1. The SEM micrographs of these materials are shown in Figures 1a, b, and c, respectively. FA particles were seen as spherical shapes with varying sizes (Figure 1b), in contrast to the irregular shapes of cement particles (Figure 1a). Compared to FA used in earlier studies (Kumar, 2002; Cicek & Tanriverdi, 2007; Turgut, 2010; Zhang et al., 2012; Shakir et al., 2013; Naganathan et al., 2015; Freidin, 2017; Muthusamy et al., 2020), it is noted that the FA used in this study had a loss on ignition (LOI) of 15.9%, which is extremely high. As shown in Figure 1b, the unburnt impurities could be the irregularly shaped particles, this was the cause of the high LOI of FA as presented in Table 1.

Table 1. Main chemical compositions of materials

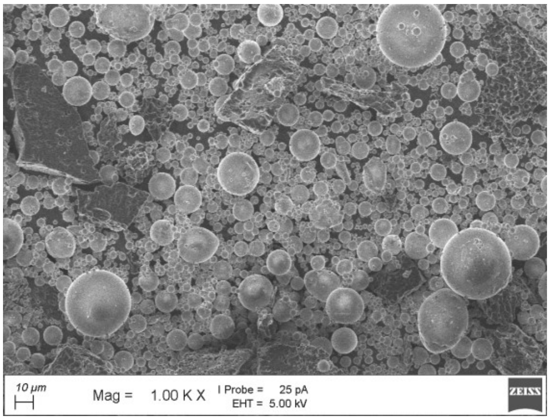
Composition (%)	Cement	FA	BA
SiO_2	21.2	51.5	52.2
Al_2O_3	5.5	20.2	20.0
Fe_2O_3	4.9	7.1	7.2
CaO	61.0	2.0	2.4
MgO	3.0	1.2	1.2
Loss on ignition	0.41	15.9	15.0

Table 2. Sieve analysis of BA

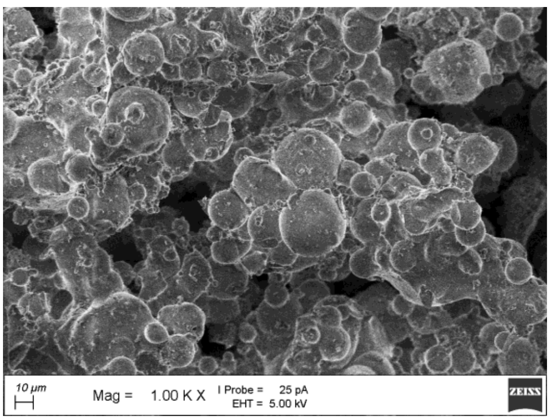
Sieve size (mm)	Retained (wt. %)	Accumulated retained (wt. %)
2.5	4.5	4.5
1.25	3.8	8.3
0.63	23.7	32.0
0.315	39.6	71.5
0.14	9.0	80.6
Fineness modulus	1.97	



(a) Cement



(b) FA



(c) BA

Figure 1. SEM images of raw materials

As observed in Figure 1c, the structure of BA is porous and consists of a large matrix of different-sized spherical particles. Therefore, its density was 1.99, which is the lowest among the three solid materials. The high porosity of BA also contributes to its WA of 23.08%. Table 2 displays the sieve analysis of BA, which has a fineness modulus of 1.97 and a maximum size of 5 mm. These values resemble those of sand found naturally in rivers. For this reason, BA was utilized as a fine aggregate in producing unfired solid bricks.

2.2. Mixture proportions

Table 3 shows the proportions of all brick mixtures in the present study. First, the control mixture without FA (denoted as M35-FA00) was designed with a water-to-binder (W/B) ratio of 0.35 and water content of 129 kg/m^3, these values were determined based on several batch trials so that the workability of the mixture was just enough to fabricate the sample. It means that after demolding, the brick samples were stable without any damage. The amount of cement and BA was calculated for one cubic meter. After that, the cement was replaced by FA at replacement levels of 30, 50, 70, and 85% by weight (denoted as M35-FA30, M35-FA50, M35-FA70, and M35-FA85). It is noticed that the density of FA is less than that of cement. Hence, when replacing cement with FA, the total volume of the mixtures containing FA was higher than one cubic meter. The amount of all ingredients in FA brick mixtures was recalculated for exactly 1 m^3 and are given in Table 3.

Table 3. Mixture proportions (Unit: kg/m^3)

Mix ID.	Cement	FA	BA	Water
M35-FA00	368	0	1500	129
M35-FA30	253	109	1476	127
M35-FA50	179	179	1461	125
M35-FA70	106	248	1447	124
M35-FA85	53	299	1436	123

2.3. Samples preparation and test programs

All tests were performed using the 160 × 80 × 40 mm brick samples that are depicted in Figure 2. With this dimension, the mass of each brick sample was around 1.04 – 1.09 kg, satisfying the requirement stipulated by TCVN 6477:2016. Immediately casting, the brick samples were de-molded and stored in the natural condition. The basic properties of unfired bricks such as UW, CS, WA, and WP were conducted based on the guidance of (TCVN 6477:2016). The Controls compression machine was used for the CS test. The TC of bricks was directly measured using a device named ISOMET-2014. While compression test was performed at 3, 7, 14, and 28 days, others were tested at 28 days. The microstructure of bricks was analyzed based on broken pieces from compression tests at 28 days using a ZEISS scanning electron microscopy. The broken pieces were dried for 24 hours at a temperature of 60 – 70ºC. The SEM images were captured at an acceleration voltage of 5 kV at a magnification of 1000 times. The test results presented herein are the average value of at least three measurements. To consider the effect of brick dimension, all compressive strength presented in the study has been multiplied with a coefficient of 0.73 as stipulated by TCVN 6477:2016.

Figure 2: Brick sample preparation

3. RESULTS AND DISCUSSION

3.1. Unit weight

The dry UW of all brick samples is displayed in Figure 3 corresponding to FA content from 0% to 85%. As FA content increased, the UW of bricks reduced from 1.68 T/m^3 to 1.51 T/m^3. This is because cement has a density of 3.12 T/m^3, whereas FA has a density of 2.16 T/m^3. It means that the reduction of UW is related to the lower density of FA.

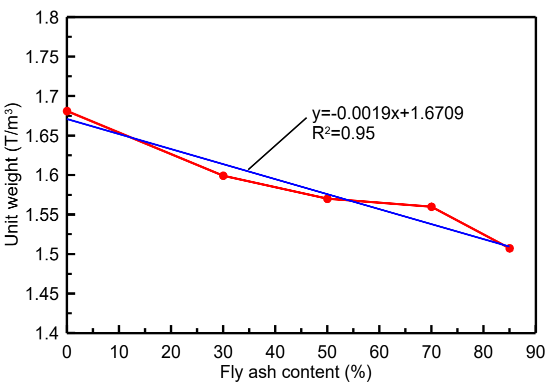


Figure 3. Unit weight of the brick samples

The correlation between UW and FA content is expressed by a linear relationship $y = -0.0019x + 1.6709$ as shown in Figure 3 with a high coefficient of determination ($R^2 = 0.95$). Additionally, the UW of the bricks produced in the present study is lighter than cement bricks in practice (2.0 – 2.2 T/m^3) and comparable to those of the bricks from previous studies (Naganathan et al., 2012; Luu & Le, 2021). In actual use, the low UW of bricks contributes to reducing the size of the building foundation due to reducing the dead load acting on the structures.

3.2. Compressive strength

The strength development of all brick samples with curing time and FA contents is shown in Figure 4. As observed in Figure 4, the CS declined with increasing FA replacement level and rose with curing time. The 28-day compressive strength of bricks reduced from 16.1 MPa to 4.8 MPa corresponding to FA content increase from 0% to 85%. The reduction rates were 7.7%, 19.4%, 46.7%, and 70.3% with the FA replacement level of 30%, 50%, 70%, and 85%. As the FA content rose, the loss of CS was noticeable. The CS development with curing time is related to the hydration and pozzolanic reactions of cement and FA, which continuously happen with time. The loss of CS is associated with the reactive ability and quality of FA. As mentioned above, the FA used in this study has a high LOI, which limited the participation of FA in the chemical reaction of FA. As discovered by Fraay et al. (1989), the pozzolanic reaction only extensively happens after several weeks. Therefore, only a part of FA participated in the pozzolanic reaction as a binder material, while others function as filling material as fine aggregate. This causes the amount of binder in the brick mixture to decrease, which lowers the CS of the brick. Based on TCVN 6477:2016, the classification of brick based on CS is shown in Table 4. In which, M35-FA85 with a CS of 4.8 MPa is classified as Grade M3.5, while B35-FA70 with a CS of 8.6 MPa is classified as Grade 7.5. Others with CS of higher than 12.5 MPa are classified as Grade M12.5 or M15. It indicates that it is possible to produce unfired building bricks using the ashes from coal-fired power plants as the primary ingredient.

The CS of bricks produced in this study is higher than that of bricks manufactured by Luu & Le (2021), and slightly lower than that of bricks created by Nagarathan et al. (2015). The previous study conducted by Luu & Le (2021) used a water-to-binder ratio of 0.38, which is higher than the W/B ratio of 0.35 used in this study. Just like concrete, the compressive strength of cement-based bricks increases when the W/B ratio decreases. On the other hand, Nagarathan et al. (2015) indicated that the CS of bricks increased with increasing FA content. It is noticed that the FA was not used to replace cement in Nagarathan's study but simultaneously increased both cement and FA contents in comparison with BA content. Another reason is that the LOI of FA used in Nagarathan's study is significantly lower than that of FA used in this study. In conclusion, the increased CS of brick in the previous study (Nagarathan et al., 2015) is associated with the quality of FA and increasing both the amount of FA and cement.

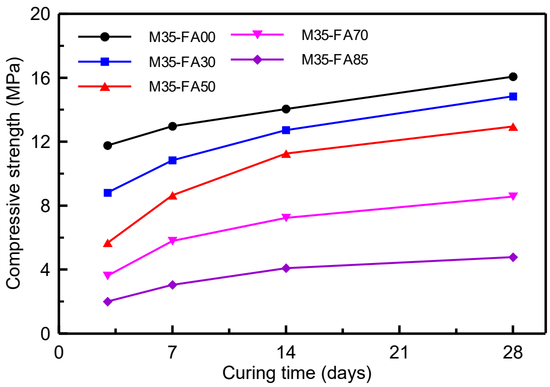


Figure 4. Compressive strength of the brick samples

Table 4. Brick classification based on TCVN 6477:2016

Mix ID.	28-days compressive strength (MPa)	Grade (MPa)
M35-FA85	4.8	M3.5
M35-FA70	8.6	M7.5
M35-FA50	13.0	M12.5
M35-FA30	14.8	M12.5
M35-FA00	16.1	M15

3.3. Water absorption

The WA has a strong effect on the construction process; therefore, the value of WA is restricted to lower than 12% or 14% depending on the grade of brick samples (TCVN 6477:2016). Figure 5 presents the WA values of all brick samples incorporating FA replacement level. As observed in Figure 5, the brick WA increased as FA content rose, this trend is adverse toward UW and CS. For brick samples with FA replacement levels of 0%, 30%, 50%, 70%, and 85%, the corresponding WA values were 11.7%, 14.25%, 14.86%, 15.07%, and 16.10%. The high WA of the bricks is the cause of the original BA's high porosity (Figure 1c) and high WA (23.08%). Another reason is due to the unreacted FA. Even the voids between BA particles were filled by FA when increasing the FA replacement level, the WA of bricks still increased due to the low pozzolanic reaction of FA in a normal condition and the low quality of FA with a high LOI of 15.9% as shown in Table 1. In other words, a part of FA did not join the pozzolanic reaction, which played a role as fine aggregate.

In this investigation, the brick samples had lower WA values than the findings from earlier studies (Muthusamy et al., 2020; Turgut, 2010; Shakir et al., 2013; Zhang et al., 2012; Cicek & Tanriverdi, 2007; Kumar, 2002; Freidin, 2017; Naganathan et al., 2015). As compared to the specifications stipulated by (TCVN 6477:2016), only the sample without FA has a WA of lower than 12%, satisfying the requirement. Other samples containing FA have a WA of slightly higher than 14%. It is noticed that the bricks produced in this study have a lower WA than the bricks produced in the previous study (Luu & Le, 2021). This finding is due to the use of a lower W/B ratio. The relationship between WA and FA content is described by a linear equation as shown in Figure 5.

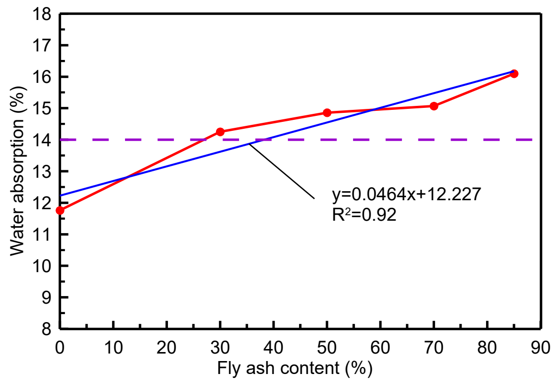


Figure 5. Water absorption of the brick samples

3.4. Water permeability

The WP is an important characteristic of bricks, which indirectly reflects the ability of bricks to chemical attack; however, this test was not conducted in previous studies (Turgut, 2010; Shakir et al., 2013; Zhang et al., 2012; Cicek & Tanriverdi, 2007; Kumar, 2002; Freidin, 2017; Naganathan et al., 2015; Naganathan et al., 2012; Luu & Le, 2021). Figure 6 illustrates the WP of bricks versus the FA contents. As well as WA, the WP of bricks rose as the FA replacement level increased. The WP values increased from 3.68 to 11.69 L/m^{2}h as the FA replacement level changed from 0% to 85%. WP and FA content were found to be correlated using the linear equation $y = 0.0976x + 2.7159$ ($R^2 = 0.93$) as shown in Figure 6. As previously mentioned, voids resulting from unreacted FA particles are also the cause of the high value of WA and WP. The microstructure observation in the following section will clarify this finding. However, all bricks produced in this study have a WP of lower than 16 L/m^{2}h, satisfying the requirement stipulated by (TCVN 6477:2016).

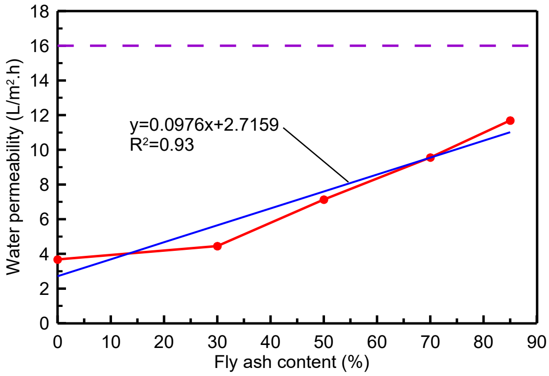


Figure 6. Water permeability of the brick samples

3.5. Thermal conductivity

The TC test is used to assess the heat isolation of bricks. Figure 7 shows the TC of bricks corresponding to different FA replacement levels. The TC value decreased as FA content increased. According to earlier studies (Kim et al., 2003; Uysal et al., 2004), the density and moisture content are the keys, which have a strong effect on the TC value. Due to the low UW and high WA, brick samples with high FA content had a lower TC value than that of the control sample without FA. A linear line with the formula y = -0.0037x + 0.742 (R^2 = 0.96) was used to describe the relation between TC and FA content.

As a result, the TC value of bricks produced in this study was from 0.29 to 0.69 W/mK, which is similar to that of bricks from the study conducted by Luu & Le (2021) and higher than that of bricks from the study conducted by (Cicek & Tanriverdi, 2007). However, these TC values are lower than the values recorded in Turgut's study (2010). As aforementioned, the UW and WA are the primary effects on the TC of bricks. Also in Turgut's study, the UW of bricks was approximately 1.8 T/m^3, which is higher than that of bricks produced in this study, resulting in higher TC. On the other hand, the UW of bricks produced by Cicek & Tanriverdi (2007) was significantly lower than those bricks herein, so the TC of the former is lower than that of the latter.

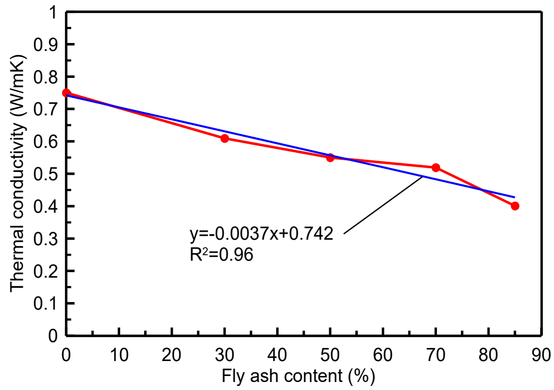
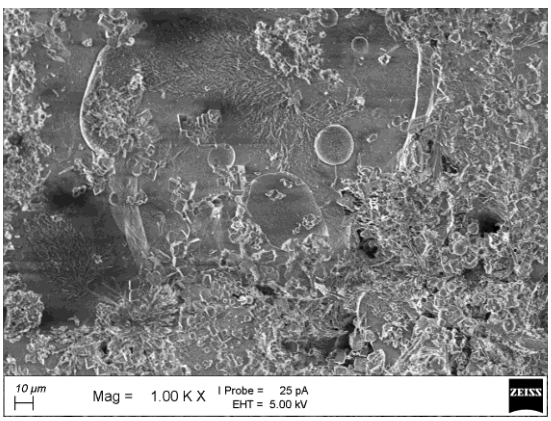


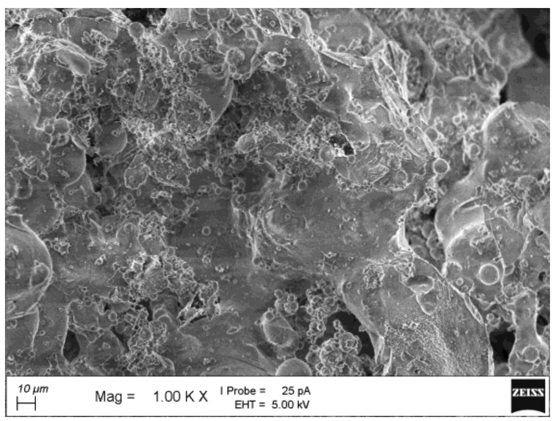
Figure 7. Thermal conductivity of the brick samples

3.6. SEM observation

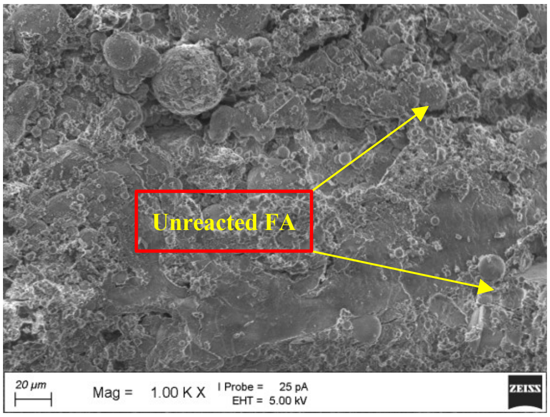
SEM micrographs of all brick samples are shown in Figure 8, which were used to examine the brick microstructure. Numerous unreacted FA particles and voids were found in the brick samples with a high FA content as shown in Figs. 8c, d, and e, which led to a less dense and non-homogenous brick structure. These findings have an adverse influence on the quality of bricks that was associated with the experimental results, as presented above.



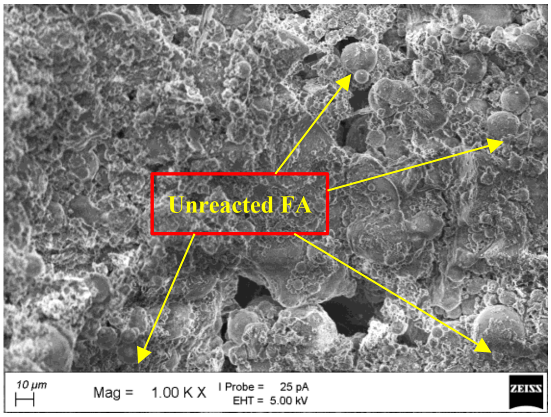
(a) M35-FA00



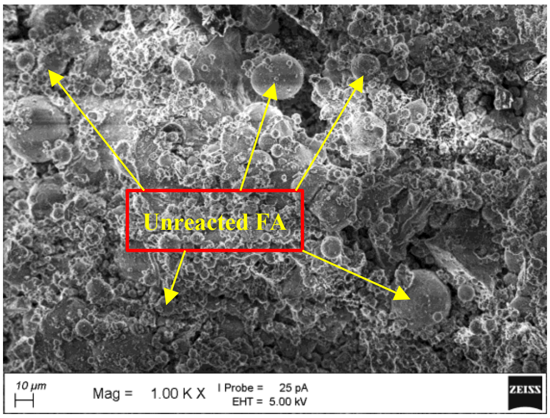
(b) M35-FA30



(c) M35-FA50



(d) M35-FA70



(e) M35-FA85

Figure 8. SEM micrographs of the brick samples

4. CONCLUSION

To recycle solid industrial wastes, coal-fired power plant ashes were utilized as primary ingredients to produce unfired bricks. Based on the experimental program, some main conclusions were drawn as follows:

(i) All bricks produced in this study have a UW of 1.51 – 1.68 T/m^3 and are classified from Grade M3.5 to M15 based on the Vietnamese Standard.

(ii) As the FA content increased, UW, CS, and TC of bricks declined, while WA and WP increased. Most FA bricks have WA of slightly higher than 14%, meanwhile the WP of lower than 16 L/m^{2}h.

(iii) The reduction in the quality of bricks containing FA is attributed to the low quality of FA with a high LOI and a part of FA did not join in the pozzolanic reaction, which was demonstrated by SEM observation.

(iv) Further studies on the use of both FA and BA in the production of unfired brick are needed to control the brick WA of below 12% or 14% as required by TCVN 6477:2016.

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