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Utilizing coal combustion bottom ash as a sustainable alternative to natural aggregate in eco-friendly building bricks

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ABSTRACT

As a substitute for fried clay and stone powder-cement bricks, this study developed novel green bricks based on coal-combustion bottom ash (CCBA) obtained from a thermal power plant in Vietnam. By using varied replacement amounts of stone powder at 0, 10, 20, 30, and 40% in weight, ten brick compositions with water-to-binder (w/b) ratios of 0.35 and 0.40 were developed. Testing was done on the bricks' characteristics, such as compressive strength, ultrasonic pulse velocity, water absorption, water permeability, electrical resistance, and thermal conductivity. The findings showed that increasing CCBA content or w/b ratio has a negative impact on the characteristics of unburnt bricks. However, all the brick samples made for this investigation performed exceptionally well when compared to the requirements of the national Vietnamese standard. The brick samples produced in this study are recommended to apply in real practice.

1. INTRODUCTION

As well as concrete, bricks are popularly used in the construction industry with about 1.391 billion units over the world, produced annually (Zhang, 2013). Most of them are fired-clay and cement-based bricks. Fired-clay bricks are manufactured from clay under high burning temperatures, causing the dwindling of natural resources and environmental problems. Which is also considered a non-renewable material and needs to be replaced by green materials. Cement-based bricks are referred to as unburnt bricks because they are formed by the hydrated reaction of cementitious materials. In Vietnam, most of them are produced from cement and stone powder, leading to declining natural resources and also environmental pollution. The stone powder is obtained from the stone grinding process. This process releases abundant dust into the air and causes noise pollution. Thus, it is necessary to find an alternative material instead of stone powder.

On the other hand, numerous CCBA is released from thermal power plants each year and it is typically dumped in ponds or landfills. In India, the released CCBA was calculated at around 30 million tons, annually (Singh & Siddique, 2014). In Vietnam, it is projected that 29 million tons of fly ash and CCBA will be liberated; in which, the amount of CCBA is around 5.8 million tons (Ngo et al., 2018). The massive amount of these ashes harms the environment through their toxicity. To overcome this problem, CCBA should be captured in construction materials like bricks or concrete. However, only approximately 5.28% of CCBA was reprocessed over the world (Kurama & Kaya, 2008). Therefore, turning such industrial waste into construction materials is an important task for Vietnamese researchers. This is also mentioned in the decision of the Vietnamese Government to encourage the recycling of these ashes and the production of waste-based materials instead of conventional ones.

The manufacturing of building bricks incorporating CCBA received much attention from researchers. The production of unfired bricks from cement, CCBA, and lateritic soil was studied by Vinai et al. (2013). Within this range, CCBA content accounts for 52.5 to 75% in volume. Test results indicated that the compressive strength (CS) and density of bricks were respective from 4.0 – 27 MPa and 1.2 – 1.6 g/cm^3. Similar way, Lawane et al. (2019) used 66.9 – 84% CCBA to produce unburnt bricks. These bricks have characteristics such as CS of 4.0 – 5.2 MPa, water absorption (WA) of 20.6 – 28.7%, and thermal conductivity (TC) of 0.31 – 0.48 W/mK. Although the insulation capacity of these bricks is really low; however, their WA value is high compared to the limitation by the Vietnamese standard (TCVN 6477:2016). To restrict the permeability and chemical attack of bricks, the Vietnamese standard requires WA and the water permeability of bricks below 14% and 16 L/m^{2}h, respectively.

Furthermore, the utilization of both fly ash and CCBA were also used to manufacture unburnt bricks (Ngo et al., 2020). Under alkaline activation, geopolymer bricks produced from fly ash and CCBA had a CS of 1.5 – 15.6 MPa and WA of 5.8 – 38.4% (Freidin, 2017). Naganathan et al. (2015) investigated the use of fly ash and cement as binders, while CCBA was used as fine aggregate in unburnt brick mixtures. The obtained results showed that their bricks had a good performance with CS of 7.13 – 17.36 MPa, and ultrasonic pulse velocity (UPV) of 2.2 – 2.96 km/s; however, WA was high with a value of 12.6 – 29.2%. The CCBA was also used in producing fired-clay bricks (Sutcu et al., 2019) and foam lightweight bricks (Pahroraji et al., 2020).

Commonly, the CS requirement for building bricks is around 3.5 – 7.5 MPa in practice. Most of the bricks produced in previous studies showed a suitable strength or even better, but the WA value violated the stipulation of the Vietnamese standard (TCVN 6477:2016). To save natural resources and treat the solid waste from thermal power plants, the objective of this study is to recycle CCBA as a part of fine aggregate in producing unburnt building bricks. The effect of CCBA content and water/binder (*w/b*) ratio on the properties of bricks including CS, UPV, WA, electrical resistance (ER), TC, and water permeability (WP) were also investigated.

2. MATERIALS AND METHODS

2.1. Materials

Stone powder and CCBA with respective densities of 2.69 T/m^3 and 1.99 T/m^3 were used as fine aggregates in brick mixtures. The stone powder was a by-product of the stone grinding process, which was acquired from a local stone factory in Vietnam. While CCBA was obtained from the Nghi Son coal power plant in Vietnam. Table 1 shows the sieve analysis of both the stone powder and CCBA. Both stone powder and CCBA had a maximum particle size of 5 mm; however, the mean particle size of CCBA was smaller than that of stone powder. The scanning electron microscopy (SEM) image of CCBA with a magnification of 1500 times is presented in Fig. 1. The porous structure of CCBA can be observed. This image also explained the lower density of CCBA in comparison with that of stone powder.

Table 1. Sieve analysis of stone powder and CCBA

Sieve size (mm)	Passing (%)	
	Stone powder	CCBA
5.0	99.8	99.6
2.5	74.8	49.3
1.25	68.6	42.6
0.63	58.3	31.3
0.315	48.7	22.2
0.14	40.9	15.3
Fineness modulus	2.09	3.39

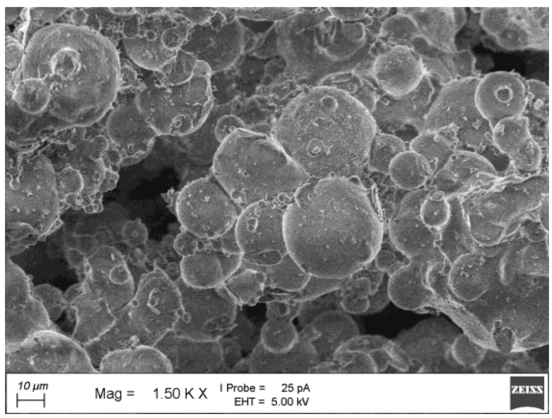

Figure 1. The porous structure of CCBA

The cement used is also provided by a local company in Vietnam, which is classified as type PCB40. The main components of cement include calcium oxide (61.0%), silicon oxide (21.2%), aluminum oxide (5.5%), and iron oxide (4.9%). The specific gravity and loss on ignition of cement are 3.12 and 0.4%, respectively.

2.2. Mixture proportions

Ten brick mixtures were designed with *w/b* ratios of 0.35 and 0.40, denoted as W35 and W40 groups, respectively. For each *w/b* ratio, the stone powder was replaced by CCBA with 0, 10, 20, 30, and 40% (by volume), referred to as B00, B10, B20, B30, and B40, respectively. Two free-CCBA mixtures (W35B00 and W40B00) were the control mixtures. All solid raw materials in dried condition were used, and their contents are tabulated in Table 2. The purpose of this design is to investigate the influence of the *w/b* ratio and CCBA content on the properties of green building bricks. It is noticed that all brick samples were immediately de-molded after casting. Hence, the w/b ratios were selected to ensure that the shape of the brick was consistent after demolding. After several trials, the w/b values of 0.35 and 0.4 and the water content of 160 kg/m^3 were selected for the control mixtures.

Table 2. Mixture proportions of bricks

Mixtures	*w/b*	Ingredients (kg/m^3)			
		Cement	Stone powder	CCBA	Water
W35B00	0.35	457	1865	0	160
W35B10		446	1639	182	156
W35B20		436	1423	356	153
W35B30		426	1217	521	149
W35B40		417	1020	680	146
W40B00	0.40	400	1915	0	160
W40B10		390	1681	187	156
W40B20		381	1459	365	152
W40B30		372	1247	534	149
W40B40		364	1044	696	145

2.3. Samples preparation and test methods

Ten batches of bricks were fabricated based on mix proportions in Table 2. Brick samples (see Fig. 2) were formed in a steel mold with a dimension of 160 × 85 × 40 mm and under a forming pressure of 0.5 MPa. Based on the mixture proportions as shown in Table 2 and with this size, the weight of each brick sample is in the range of 1.22 – 1.36 kg, satisfying the requirement of not exceeding 20 kg according to TCVN 6477:2016. After forming, they were immediately de-molded and stored in natural conditions at the laboratory until the testing days. Each batch consisted of twenty-one samples, of which twelve samples were used for UPV, TC, and CS tests, while nine others were used for WA, WP, and ER tests. Each test was conducted on three samples, and the average value of three measurements was used as the reported value herein. For the first testing branch, the UPV test was done first, followed by the TC test, and then the CS test. A total of twelve samples were used for the first branch test (at 3, 7, 14, and 28 days). It is noticed that TC was only tested at 28 days. For the second testing branch, the WA, WP, and ER of the brick samples were independently tested. These tests were conducted at only 28 days; therefore, nine samples were used for the second branch test.

CS, WA, and WP were tested in accordance with the Vietnamese standard for cement brick (TCVN 6477:2016). In which, the WP test was described by Ngo (2020). UPV and ER were tested complying with American Society of Testing Materials (ASTM) C597 (2022) and American Association of State Highway and Transportation Officials (AASTHO) T277 (2015), respectively. An ISOMET 2114 was used to measure the TC value of brick samples. It is noticed that the CS value presented herein is modified with a coefficient of 0.7 to reflect the effect of the brick's dimension as stipulated by TCVN 6477:2016.

Figure 2. Brick samples

3. RESULTS AND DISCUSSION

3.1. Compressive strength

The CS development of both W35 and W40 brick samples are presented in Figs. 3 and 4, respectively. As the basic knowledge, the CS of brick samples increased with curing time. At 28 days, the CS of free-CCBA brick samples were 61.3 and 38.5 MPa, respectively. For W35 samples, the CS of bricks reduced to 52.7, 43.5, 32.8, and 28.9 MPa corresponding to CCBA content of 10, 20, 30, and 40%. Similar to W35 samples, the CS of W40 brick samples also decreased to 35.9, 31.4, 30.0, and 28.1 MPa, when the replacement levels of stone powder by CCBA were 10, 20, 30, and 40%, respectively. Therefore, the CS of bricks decreased with the addition of CCBA, which is due to the porous structure of CCBA as aforementioned (Fig. 1). Most prior studies indicated that the addition of CCBA to a concrete mixture resulted in CS reduction (Bai et al., 2005; Kou & Poon, 2009).

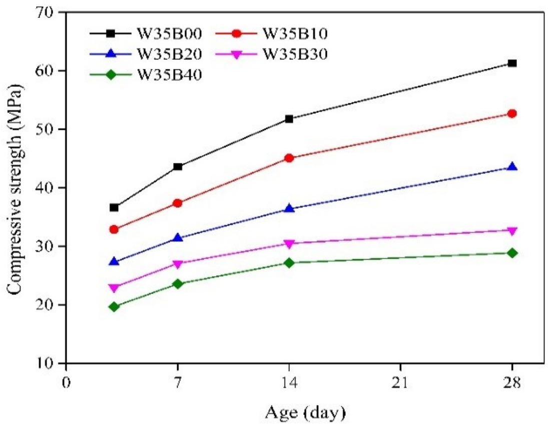

Figure 3. CS of W35 brick samples

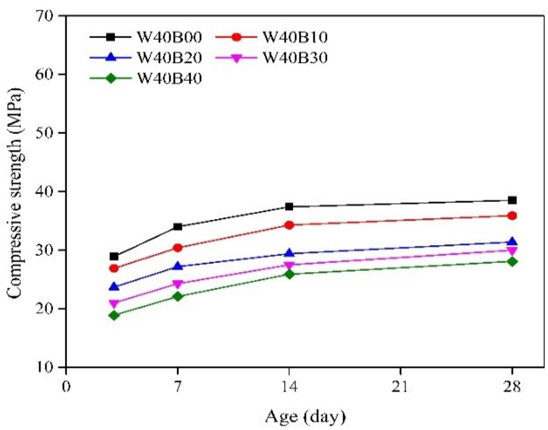

Figure 4. CS of W40 brick samples

On the other hand, the CS of W35 brick samples is greater than that of corresponding W40 brick samples. In other words, the CS of bricks increased if the *w/b* ratio declined. However, the CS of CCBA bricks investigated in this study was in the range of 28.1 to 52.7 MPa, which is considered a very good quality in comparison to the required CS of bricks used in reality. The CS of popular bricks used in real applications is only from 3.5 to 7.5 MPa. This study indicated that it is possible to continuously increase CCBA content for the production of green bricks. This will be further considered in future studies.

3.2. Ultrasonic pulse velocity

The quality of brick is related to density, voids, and micro-cracks inside the structure of the brick sample. Therefore, the higher the UPV value, the higher the quality of the brick is. The UPV test is commonly used to evaluate the quality of concrete because it is a non-destructive test. In this study, the UPV test was also utilized to assess the relative quality of CCBA bricks. All UPV values of bricks are plotted in Figs. 5 and 6 corresponding to brick samples with *w/b* ratios of 0.35 and 0.40. As well as CS, the UPV value of bricks increased with the brick's age and it reduced with increasing CCBA content. As mentioned above, UPV value is associated with density; thus, the reduction in UPV value of CCBA bricks is mainly attributable to the porous structure of CCBA. The higher the CCBA content, the higher the porosity of brick samples, consequently resulting in lower UPV values.

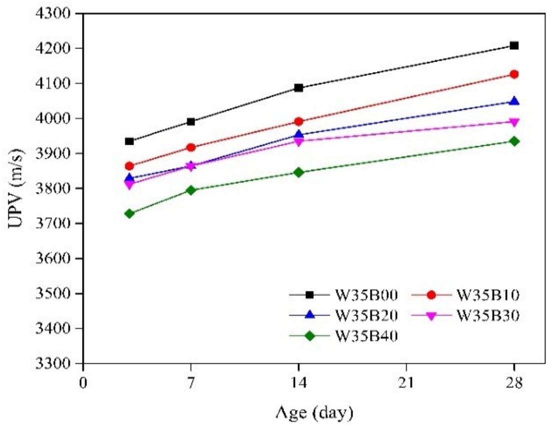

Figure 5. UPV of W35 brick samples

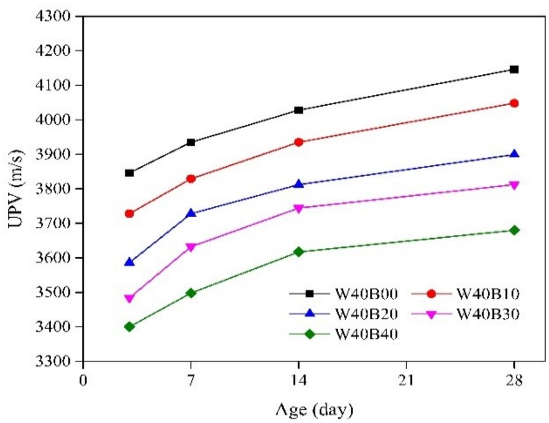

Figure 6. UPV of W40 brick samples

The UPV value of the W35 brick samples was higher than that of the corresponding W40 brick samples. When the replacement level of stone powder by CCBA increased from 0% to 40%, the UPV values of W35 and W40 brick samples reduced from 4208 to 3935 m/s and from 4146 to 3680 m/s, respectively. This range is much higher than the reported UPV values of bricks from a previous study (Naganathan et al., 2015). It is also noticed that the CS of bricks in this study is much greater than that of bricks in Naganathan et al.'s study. That is because the UPV value and CS value had a close correlation with each other (Carcaño & Moreno, 2008). Based on UPV value, all CCBA brick samples in this study are classified as good quality.

3.3. Water absorption

The effect of both the *w/b* ratio and CCBA content on the WA of brick samples is shown in Fig. 7. The WA values of brick samples increased with increasing *w/b* ratio or CCBA content. The WA of bricks is related to the density of the brick structure, hence closely associated with CS values. Brick samples with high density resulted in high strength, thus leading to low WA. Therefore, W35 brick samples showed lower WA values than corresponding W40 brick samples. The low WA values of the CCBA brick sample are associated with the porous structure of CCBA. However, the WA values of all brick samples in this study were felt in the range of 4.57 – 7.25%, these values are much lower than the limited value stipulated by TCVN 6477:2016.

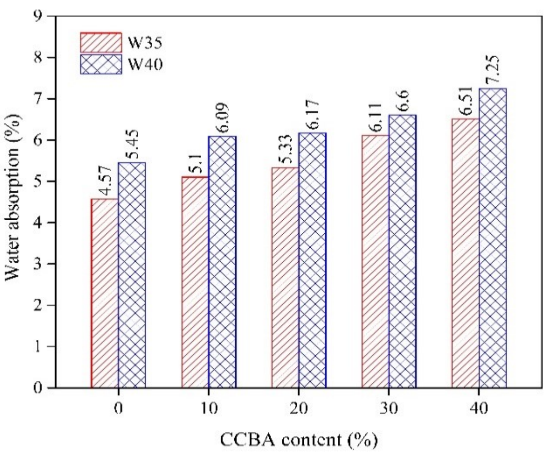

Figure 7. WA of brick samples

For W35 brick samples, as replacement of stone powder by CCBA at 10, 20, 30, and 40%, the WA of bricks increased by 11.6, 16.6, 33.7, and 42.5%, respectively. A similar trend was observed in W40 brick samples, the WA of bricks increased by 11.8, 13.3, 21.2, and 33.1% corresponding to CCBA replacement levels of 10, 20, 30, and 40%. The increase rate of WA is significant when the replacement level is high. Therefore, if the CCBA replacement level was above 40%, the WA of CCBA bricks should be doubly checked before application in real practice.

3.4. Water permeability

The 28-day WP values of both W35 and W40 brick samples are plotted in Fig. 8. The WP values of W35 brick samples increased from 0.77 to 1.47 $L/m^2.h$ when CCBA content changed from 0% to 40%. These corresponding values ranged from 0.92 to 2.72 $L/m^2.h$ for W40 brick samples. It means that the higher the replacement level of stone powder by CCBA, the greater the WP of bricks was. Similar to WA, the increase in WP of brick samples is the involvement of CCBA's porous structure. However, all CCBA bricks investigated in this study had much lower WP values compared to the restriction value specified by the Vietnamese standard (TCVN 6477:2016).

Both WA and WP of bricks increased with the presence of CCBA and increasing *w/b* ratio. The WP of the W40 brick samples is higher than that of the corresponding W35 brick samples. The internal structure of the brick sample with a low *w/b* ratio is denser than that of the brick sample with a high *w/b* ratio. That is due to the highly hydrated reaction of cement to form C-S-H gels, which is known as basic knowledge of construction material. The denser structure of bricks shows a high ability against the movement of water particles, leading to a reduction in WP values.

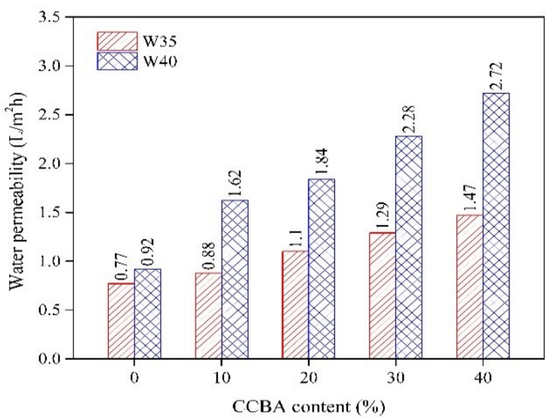

Figure 8. WP of brick samples

3.5. Electrical resistance

The reduction in ER values of the brick samples is shown in Fig. 9 as increasing *w/b* ratio or CCBA content in the mixtures. The ER values of control samples (W35B00 and W40B00) were 54.6 and 44.6 kΩ.cm, corresponding to *w/b* ratios of 0.35 and 0.40. When the replacement level of stone powder by CCBA at 10, 20, 30, and 40%, the ER values of bricks reduced to 49.5, 40.1, 38.0, 33.5, and 40.5, 35.5, 32.8, and 30.7 corresponding to *w/b* ratios of 0.35 and 0.40, respectively. The presence of CCBA is a cause for the reduction in ER values. As mentioned above, the porous structure of CCBA (shown in Fig. 1) is the main reason for negatively affecting to properties of bricks. As proved by Morris et al. (2002), concrete with an ER value of above 20 kΩ.cm was classified as having excellent resistance to chemical attack. All brick samples in this study showed an excellent ability against chemical attacks. This finding is also related to other properties of bricks such as CS, UPV, WA, and WP as the above discussion.

Similar to CS and UPV, the ER value of the brick sample declined with increasing *w/b* ratio. As an increment in the *w/b* ratio from 0.35 to 0.40, the reduction in ER values was 22.4, 22.2, 13.0, 15.9, and 9.1% corresponding to CCBA replacement levels at 0, 10, 20, 30, and 40%. The ER value of bricks is also related to the internal structure density of the brick. The lower the w/b ratio, the higher the internal structure density, resulting in a higher ER value.

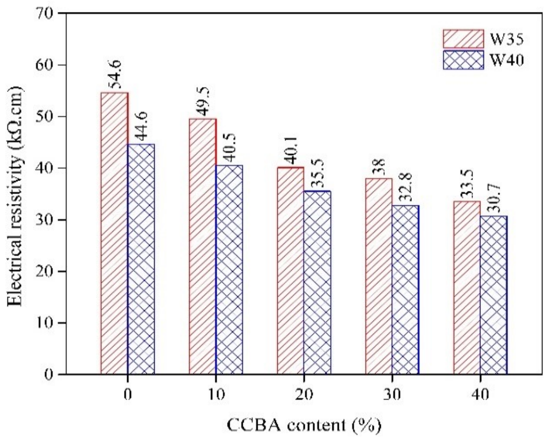

Figure 9. ER of brick samples

3.6. Thermal conductivity

The heat isolation of the brick sample was examined through the TC test. The measured TC values of all brick samples at 28 days of age are plotted in Fig. 10. A similar trend to CS, UPV, and ER, the TC value of brick samples decreased when the replacement level of stone powder by CCBA increased or increased *w/b* ratio. The TC value is dependent on density (Uysal et al., 2004) and moisture content (Kim et al., 2003). As aforementioned, a denser internal structure of a brick sample with a low *w/b* ratio resulted in higher CS, UPV, ER, and also in higher TC. The decrease in TC value of brick samples containing CCBA is attributed to their high WA and high porosity, as mentioned above. The TC value of brick samples in this study ranged from 1.56 to 2.20 W/mK, which is much higher than those values of brick samples studied by Lawane et al. (2019). It is noticeable that the TC and CS had a close relationship based on the internal density of the brick structure. The CS of bricks investigated by Lawane et al. (2019) was much lower than that of bricks in this study; therefore, their TC is also much lower, too.

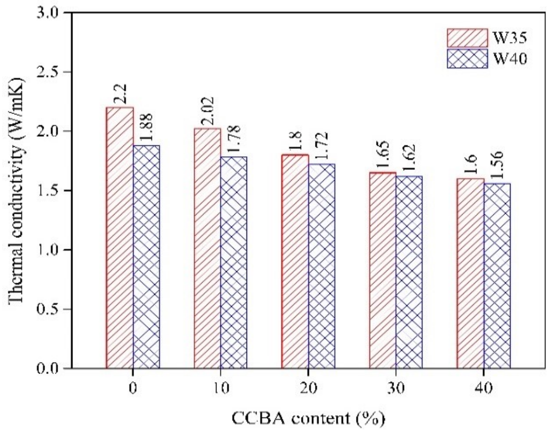

Figure 10. TC of brick samples

4. CONCLUSION

In this study, CCBA was used to replace stone powder at different levels of 10, 20, 30, and 40% within the production of unburnt green building bricks. The main findings based on the experimental program above can be listed as follows:

(i) The inclusion of CCBA or increasing *w/b* ratio in brick mixtures negatively affected on properties of unburnt bricks, except for TC. However, all bricks produced in this study show a really good performance with characteristics such as CS of 28.1 – 61.3 MPa, UPV of 3680 – 4146 m/s, WA of 4.57 – 7.25%, WP of 0.77 – 2.72 L/m^{2}h, ER of 30.7 – 54.6 kΩ.cm, and TC of 1.56 – 2.20 W/mK.

(ii) Even using up to 40% CCBA replacement for stone powder, all CCBA bricks in this study showed good quality in comparison to the specifications of Vietnamese standards for cement-based bricks.

(iii) In further study, the CCBA replacement level should be increased; however, the WA and WP of bricks should be further studied before use. Because the WA and WP of brick rapidly increased with increasing CCBA content.

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