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The Utilization of Coal Bottom Ash as a Natural Sand Replacement in Mortar Containing Fly Ash

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Abstract

The substantial generation of waste ashes from coal thermal power plants (CTP), particularly fly ash (FA) and bottom ash (BA), poses significant environmental challenges; meanwhile, the exhaustion of natural river sand for the construction industry is more serious. The study aims to explore the use of BA as a sand replacement and FA as a partial cement substitute in mortar production, focusing on sustainability. In this research, FA and cement served as binder materials, with FA comprising 15% of the total binder mass. BA was incorporated as a fine aggregate, replacing sand at varying levels of 0%, 25%, 50%, 75%, and 100% by weight. The study assessed the effects of BA substitution on the mortar's compressive strength (CS), ultrasonic pulse velocity (UPV), water absorption (WA), thermal conductivity (TC), and resistance to sulfate attack. Additionally, scanning electron microscopy (SEM) was utilized to analyze the mortar's microstructure. Results indicate that substituting sand with BA negatively impacted all tested properties. As BA content increased, CS, UPV, and TC of mortar samples decreased, while WA and sulfate expansion increased markedly. At 56 days, the mortar samples exhibited CS values ranging from 20.6 to 57.0 MPa, UPV values from 3395 to 4203 m/s, WA values from 5.58% to 18.70%, and TC values from 0.89 to 1.73 W/m·K. Furthermore, the control mortar demonstrated a length change of 0.0218% due to sulfate attack, whereas the length changes for specimens with 25%, 50%, 75%, and 100% BA replacement were approximately 68.8%, 96.3%, 155.0%, and 162.4% higher, respectively.

Keywords

mortar, fly ash, bottom ash, SEM observation, natural sand

1 Introduction

As Vietnam experiences economic development and urbanization, the construction of coal thermal power plants (CTPs) has increased due to their low investment costs and abundant resources. According to government information as of 2023, the country operates 31 CTPs, which emit over 18.07 million tons of coal ash annually, with emissions projected to rise each year. By 2025, the number of CTPs is expected to increase to 47, with a total capacity of approximately 26000 MW, resulting in annual coal ash production exceeding 30 million tons [1]. Coal ash collected from flue gas is known as FA, while the coarser fraction accumulated at the bottom of the boiler is referred to as BA. FA consists of finer particles than cement and has been extensively studied for its pozzolanic properties, making it a valuable material in the construction industry. In contrast, BA is a coarser material that exhibits lower pozzolanic activity. Characterized by its porous, vitreous, granular, and non-combustible nature, BA is primarily used as landfill material. However, hazardous components in coal BA pose a risk of leaching into groundwater or surface water, potentially affecting living organisms. By the end of 2023, approximately 83 million tons of FA had been utilized, representing only 66.2% of total emissions. Consequently, a substantial amount of coal ash from CTPs remains unused. According to Kurama and Kaya [2], 47% of FA is repurposed in the production of construction materials, whereas only about 5.28% of BA is reused. As a result, the government is actively promoting research and application of BA in construction materials.

Currently, the demand for natural sand for concrete and construction mortar in Vietnam is substantial, expected

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to reach 170-190 million m^3 per year by 2025 and 200-220 million m^3 per year by 2030 as estimated by the government. Vietnam's total sand resources are approximately 2.3 billion m^3, primarily used for plastering and leveling applications. However, the current rate of sand extraction exceeds the annual natural replenishment rate, leading to a depletion of natural sand resources that is expected to be insufficient to meet future construction demands. BA, composed mainly of silica, alumina, and iron oxide, along with smaller quantities of calcium and magnesium sulfate, exhibits a particle shape and size distribution comparable to that of natural sand [3–5]. These characteristics render BA a viable alternative for sand replacement, thereby enhancing sustainability in the construction industry.

There have been a substantial number of studies on unfired brick and concrete production incorporating coal ash as a fine and coarse aggregate replacement [5–11]. Ngo et al. [5] produced unfired bricks from FA and BA with a NaOH solution above 10M, achieving a strength of over 5 MPa and WA below 14%, meeting the Vietnamese specification for cement bricks. Naganathan et al. [6, 7] created self-compacting unfired bricks from a mix of FA, BA, and cement, showing superior quality compared to traditional fired clay bricks, with a density of 1.5-1.69 t/m^3, CS ranging from 5.5 to 17.36 MPa, UPV of 2.3-2.96 km/s, and WA of 2.04%-29.2%. In several other studies, BA was used as a substitute for sand in concrete production [2, 4, 8–11]. Kurama and Kaya [2] and Ramzi et al. [8] concluded that incorporating BA and FA in concrete can lead to the production of strong and durable materials. Singh and Siddique [4] found that using BA can yield both beneficial and detrimental effects, such as enhancing CS and tensile strength over time, while potentially reducing chloride resistance and increasing WA. Additionally, UPV measurements indicated that high-quality concrete can be achieved by using BA as a sand substitute [6]. Kim and Lee [9] utilized BA of different particle sizes as both fine and coarse aggregates in high-strength concrete, achieving compressive strengths ranging from 60 to 80 MPa. They noted that while the strength properties of the concrete incorporating coal BA as a fine aggregate remained largely unchanged, there was a marked decrease in its modulus of elasticity. Siddique et al. [10] studied self-compacting concrete (SCC) with BA substituting fine aggregate at 0%, 10%, 20%, and 30%, and FA replacing cement at 15-35%. They found that 20% BA replacement resulted in a 15-20% strength reduction, with optimal FA content between 25-35%, achieving SCC strengths of 40-50 MPa. Reducing the water/cement ratio and FA content increased CS and tensile strength, while higher BA content decreased strength. All SCC samples showed a gradual increase in strength over time. Rafieizonooz et al. [11] investigated concrete with BA replacement ratios of 0%, 20%, 50%, 75%, and 100%, along with 20% FA substituting cement. Their findings indicated that workability decreased as the BA content increased. However, at 28 days, there were no significant differences in strength among the concrete samples. By 91 and 180 days, all samples exhibited a marked increase in CS, with the sample containing 75% BA demonstrating superior flexural and tensile strength compared to the one without BA. Notably, the drying shrinkage of samples with 50%, 75%, and 100% BA was lower than that of the sample without any BA.

The recycling of BA as fine aggregate replacement in producing mortar has been conducted by several researchers [12–15]. Ghosh et al. [12] demonstrated that using FA and BA in masonry mortars enhances the TC of buildings. Mortar mixes with FA and BA replacing sand at various proportions met specifications, even at replacement rates of up to 100%. These mortars exhibited lower bulk density, and higher porosity, and reduced TC by up to 82% compared to conventional mortars. Baite et al. [13] studied the use of BA from the Tefereyre (Niger) power plant as a fine aggregate in cement mortar. The results indicated that the addition of BA increased porosity, which led to higher WA and permeability. However, over time, mortar densification reduced both porosity and permeability, as confirmed by SEM and ultrasonic measurements. Additionally, BA lowered the specific weight and thermal conductivity of the material. Ramadoss and Sundararajan [14] examined the potential of using lignite BA as a substitute for fine aggregate in masonry mortar. Their study determined that a 20% replacement ratio provided the best results in terms of mechanical strength and durability. Similarly, Hashemi et. al. [15] investigated the use of BA as a fine aggregate replacement in mortar mixtures, exploring various water-cement ratios and silica sand replacement levels. The study found that BA contains a reactive pozzolanic fraction, which improves compressive strength when it replaces up to 40% of the fine aggregate. However, higher BA replacement levels led to a decrease in strength due to its porous nature, which absorbs water and increases pore volume. Additionally, a superplasticizer enhanced the mechanical properties of BA-based mortar when the water-cement ratio was above 0.3, but had limited impact in water-deficient mixtures.

As aforementioned, the explosion of BA and FA from CTPs and the exhaustion of natural river sand are urgent issues for the Vietnamese government, especially since the recycling of BA is still really low. Many researchers have conducted studies on the use of BA or FA in the production of concrete, mortar, and unfired brick. However, the use of both BA and FA in producing mortar is still limited. Additionally, the characteristics of FA and BA can vary significantly based on the combustion technology and type of coal used at different CTPs [16, 17], which in turn affects the mortar's technical properties. The objective of this study is to investigate the utilization of raw materials, BA and FA, from a local CTP in Vietnam in producing mortar. The raw BA was sieved to obtain fine particles in the size range of 0.14-1.25 mm and then used to replace sand at substitution levels of 0%, 25%, 50%, 75%, and 100% by mass in the mortar mix. FA, which replaced 15% of the cement by binder mass, was also incorporated into the mix. An experimental program was conducted to evaluate the utilization of BA and FA on various technical properties of the mortar samples, including CS, UPV, WA, TC, and resistance to sulfate attack.

2 Materials and experimental program

2.1 Material

In this study, FA and BA were sourced from the Nghi Son CTP in Thanh Hoa province, with specific gravities of 2.16 and 1.99 t/m^3, respectively. The cement used was Portland cement PCB40, which has a specific gravity of 3.12 t/m^3 and an average particle diameter of about 20.8 µm. The average particle diameter of FA is about 10.4 µm. Cement and FA serve as binders (abbreviated as B) to reduce cement consumption, utilize industrial waste, and protect the environment. The chemical compositions of cement, FA, and BA are presented in Table 1. The X-ray diffraction (XRD) patterns of cement, FA, and BA are presented in Fig. 1. The particle size distribution of cement and FA is shown in Fig. 2. Cement primarily consists of SiO_2 and CaO, with a total content reaching up to 77.75% by mass. In contrast, FA contains only a small amount of CaO, while the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeds 70%, classifying it as type F fly ash according to ASTM C618 [18]. In this study, BA exhibits a chemical composition similar to FA, with a low CaO content. The main components of BA are SiO_2, Al_2O_3, and Fe_2O_3, accounting for 54.32%, 20.56%, and 7.26%, respectively. The primary component of river sand is SiO_2, constituting more than 90%. In addition, natural river sand contains other minor components, including Fe_2O_3, Al_2O_3, $CaCO_3$, and others [19]. The XRD patterns of cement, FA, and BA (Fig. 1) align with the findings from the chemical composition analysis (Table 1), revealing that both FA and BA are primarily composed of stable crystals of quartz (SiO_2) and mullite (Al_2O_3). The loss on ignition (LOI) values for cement, FA, and BA are 0.45%, 6.9%, and 12.68% respectively. Figs. 3(a) and 3(b) illustrate the SEM microstructural images of cement and FA at a magnification of 1000x, respectively. The images indicate that cement is primarily composed of irregularly shaped particles, while FA exhibits a regular shape, consisting of discrete spherical particles of varying sizes and containing various impurities.

Table 1 Main chemical compositions of cement, FA, and BA (%)

Composition	Cement	FA	BA
SiO_2	22.30	55.73	54.32
Al_2O_3	6.68	21.67	20.56
Fe_2O_3	4.73	6.58	7.26
CaO	55.45	1.06	2.13
MgO	2.40	2.17	1.26
SO_3	1.28	0.01	-
Na_2O	0.56	0.22	-
LOI*	0.45	6.90	12.68

* Loss on ignition

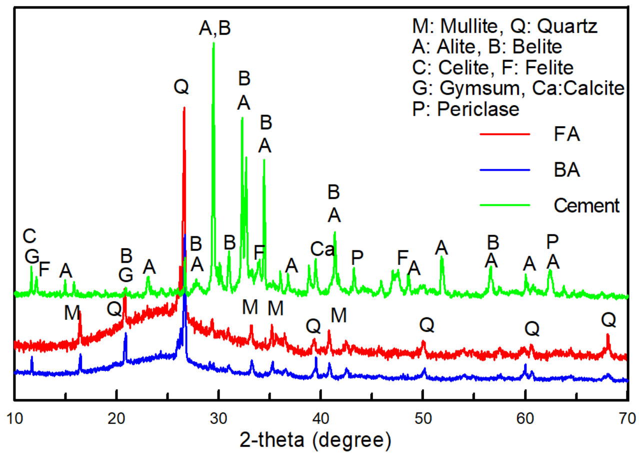


Fig. 1 XRD patterns of cement, FA and BA

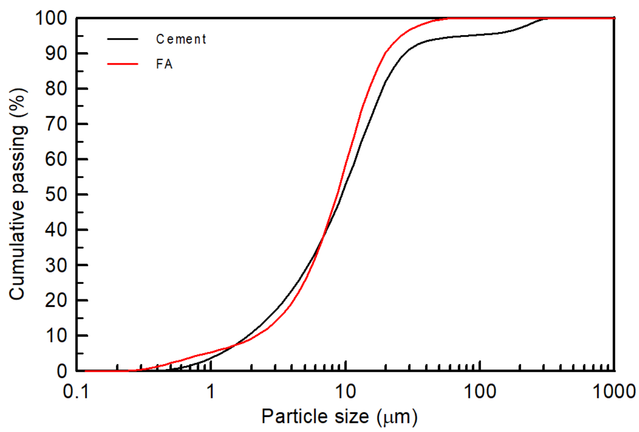
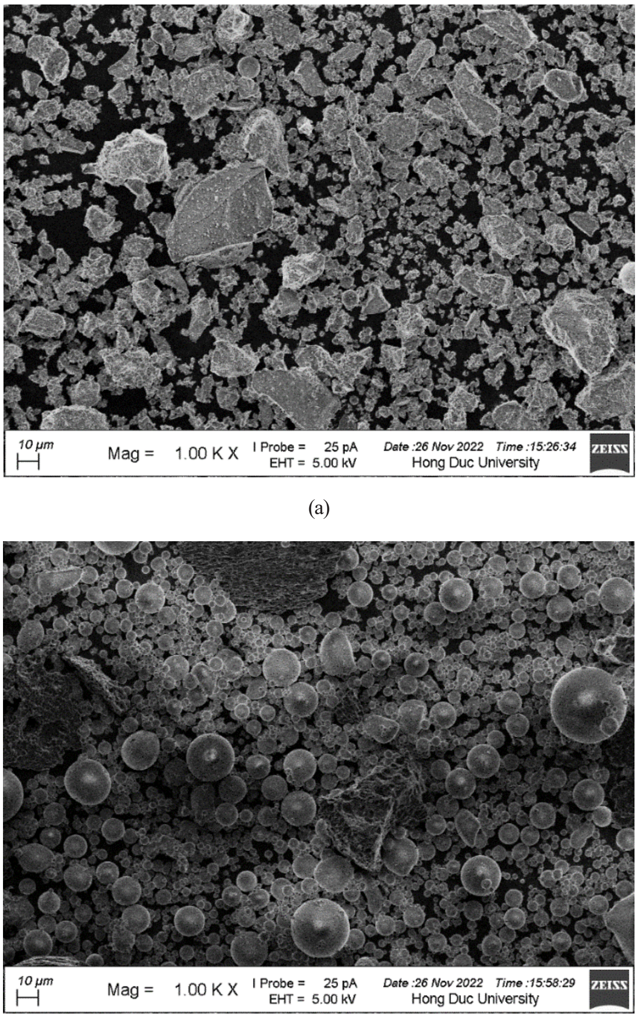


Fig. 2 The particle size distribution of cement and FA



(a)

(b)

Fig. 3 SEM images of (a) cement and (b) FA

Both natural sand and BA were sieved to remove particles larger than 1.25 mm and smaller than 0.14 mm. The sieve analysis and fineness modulus of natural sand and BA are given in Table 2, indicating that both materials possess similar particle sizes and compositions. These materials were used as fine aggregates (abbreviated as A) with the same fineness modulus of 1.21. Physical properties of the natural sand and BA are summarized in Table 3. It can be seen that the WA capacity of BA is much greater than that of the natural sand. The high WA of BA is attributed to its porous and hollow structure, as observed in the microstructural image of BA at 2000x magnification shown in Fig. 4. As a result, despite having similar particle size distributions, the density of BA is considerably lower than that of natural sand (1.99 t/m^3 compared to 2.62 t/m^3), which significantly influences the properties of the construction mortar. The superplasticizer (SP) type F with the main composition of Naphthalene Formaldehyde Sulfonate and a specific gravity of 1.15 was used to control the mortar workability with a flow diameter of around 175 ± 5 mm.

Table 2 The sieve analysis and modulus of natural sand and BA

Sieve size (mm)		1.25	0.63	0.315	0.14	FM*
Cumulative percent retained (%)	Sand	0	5.1	16.0	100	1.21
	BA	0	6.6	14.7	100	1.21

* Fineness modulus

Table 3 Physical properties of natural sand and BA

Material	Specific gravity (t/m^3)	Dry bulk density (t/m^3)	Moisture content (%)	Water absorption (%)
Natural sand	2.62	1.45	0.53	0.42
BA	1.99	1.04	0.44	23

2.2 Mix design and proportions

The mortar samples in this study were designed using the absolute volume method with the detailed composition presented in Table 4. FA was incorporated to replace 15% of the cement by binder mass. The samples were designed with an aggregate-to-binder ratio (A/B) of 2.8. The aggregates in the mortar samples consisted of sand and BA, with the replacement ratios of BA for sand set at 0%, 25%,

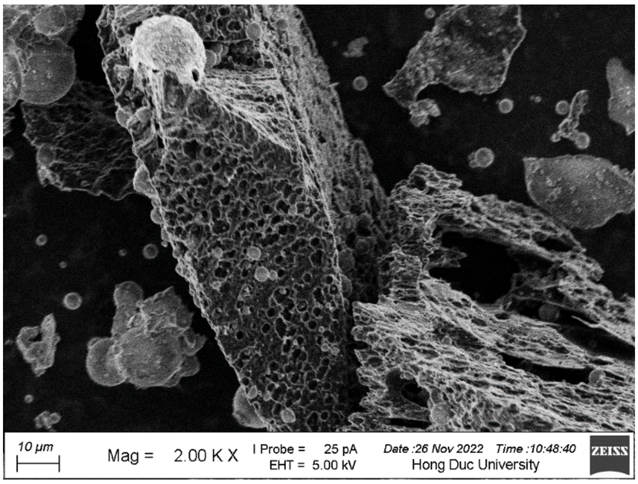


Fig. 4 SEM image of coal bottom ash

Table 4 Mix proportions

Mixture	Ingredient proportions (kg/m^3)					
	Cement	FA	Sand	BA	Water	SP
BA00	461	81.3	1517	0	225	12.6
BA25	425	75.1	1051	350	239	15.9
BA50	376	66.4	620	620	288	16.8
BA75	336	59.3	277	831	328	17.5
BA100	297	52.5	0	979	375	17.8

50%, 75%, and 100% by mass. The mortar samples are labeled as BA*x*, where "BA" represents bottom ash and "*x*" indicates the percentage by mass of BA replacing sand in the mix. All samples incorporated a superplasticizer (SP) with a density of 1.15 to reduce water content and enhance the workability of the mortar. The BA00 mortar mixture was initially designed with a water-to-binder (W/B) ratio of 0.4 and an SP/B ratio of 2.33% to achieve the desired flowability range of 175 ± 5 mm, as specified in TCVN 4314:2022 [20] (see Table 4). Due to BA's considerably higher WA capacity than natural sand, it was necessary to adjust the water and superplasticizer content in mortar mixtures containing BA to maintain the required flowability. As shown in Table 4, ratios of superplasticizer to binder for the BA25, BA50, BA75, and BA100 mortar mixtures were set at 3.18%, 3.79%, 4.43%, and 5.09%, respectively. It is noticed that extra water was also added in previous research to maintain the similar workability of all mortars [13]. In another study, the fine aggregate with high WA was saturated in water before use [21]. The objective of designing this test mortar mix is to evaluate the CS, physical properties, and chemical durability of the mortar samples containing 15% FA by binder mass, with varying levels of BA incorporated as a replacement for sand.

2.3 Sample preparation and test method

Based on the compositions presented in Table 4, all materials including cement, FA, sand, and BA were accurately prepared and weighed before mixing in the laboratory. Fig. 5 displays the sieved and dry materials prepared before the mixing process. The dry mixture, consisting of sieved aggregates (natural sand and BA) and binders (cement and FA), was first added to the mixing pan and thoroughly mixed for two minutes. Subsequently, the water mixed with SP in the proportions as indicated in Table 4, was added to the mixture until a homogeneous consistency was achieved. A flow test was conducted in accordance with ASTM 1437 [22] to ensure all samples achieved a flow within 175 ± 5 mm by adjusting the amounts of water and SP. Once the desired flow was reached, the mortar mixture was poured into the steel molds. Steel molds measuring 5 × 5 × 5 cm were used for samples intended for CS and WA testing, respectively. For measuring UPV and TC, cylindrical molds measuring 100 × 200 mm were employed, while steel molds sized 25 mm × 25 mm × 285 mm were used for assessing the resistance of sulfate attack. The mortar samples were removed from the molds one day after casting (as seen in Fig. 6) and were soaked and cured at room temperature until the experiments were conducted. The CS of the mortar samples was determined according to the ASTM C109 standard [23], using a specialized control compressor at the ages of 3, 7, 14, 28, and 56 days. WA and TC tests were performed at 28 and 56 days, with WA measured following ASTM C642 [24] and TC assessed using an ISOMET-2114 measuring device. The UPV of the mortar samples was measured at 14, 28, and 56 days according to ASTM 597 [25], using a MATEST C369 device. Sulfate attack resistance tests were performed following ASTM C490 [26] at 1, 3, 7, 14, 28 and 56 days. It is noteworthy that the initial length for the sulfate attack resistance test was recorded from the day the samples were removed from the molds, while the age of the specimen for other tests was calculated from the casting date. The experimental results presented herein represent average values obtained from three measurements. Additionally, the surface microstructure images of the mortar specimens at 28 days were captured using an EVO 18 scanning electron microscope at 1000x magnification.

3 Results and discussion

3.1 Compressive strength

The CS of the mortar samples, assessed at 3, 7, 14, 28, and 56 days, is illustrated in Fig. 7. The results reveal a clear trend that CS increases with curing time while decreasing with higher BA content. At 28 days, the CS values for mortar samples with 0%, 25%, 50%, 75%, and 100%

Fig. 5 Dry material for mixing

Fig. 6 Sample preparation

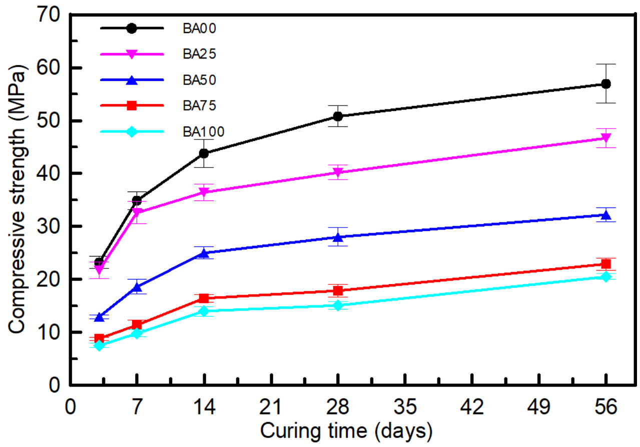


Fig. 7 Effect of BA content on compressive strength of the mortars

BA were measured at 50.8, 40.2, 28.0, 17.9, and 15.1 MPa, respectively. At 56 days, the CS for these same levels of BA content recorded values of 57.0, 46.7, 32.2, 22.9, and 20.6 MPa, respectively. The development of CS with curing time can be attributed to the continuous hydration and pozzolanic reactions of the cement and FA over time. Notably, this finding aligns with previous research on unfired bricks and concrete [3, 4, 6, 9, 10]. It is noticed that FA exhibits a finer particle size and demonstrates pozzolanic activity [17, 27]. The pozzolanic reaction of FA progresses slowly in the early stages, but it intensifies significantly in the later stages [16]. Grinding BA particles also exhibit pozzolanic reactivity due to the presence of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), which is similar to the behavior of FA. These compounds interact with calcium hydroxide ($Ca(OH)_2$), resulting in the formation of additional calcium silicate hydrate (C-S-H). Singh and Siddique [4] and Cheriaf et al. [28] observed that the consumption of portlandite through the pozzolanic action of BA was particularly significant between 28 and 90 days. However, in this study, the sieved bottom ash particles are generally coarse, which plays a role as fine aggregate, and their pozzolanic reactivity is restricted.

As BA content increases, particularly beyond 50%, there is a notable decline in CS. Specifically, the 28-day CS of the mortar samples with 25%, 50%, 75%, and 100% BA decreased by 20.9%, 44.9%, 64.8%, and 70.3%, respectively, compared to the BA-free mortar sample. The decrease in CS can be attributed to two primary factors. First, an increase in BA content results in an increase in the porosity of mortar. As shown in Fig. 4, BA was observed with high porosity like a honeycomb, leading to significantly lower specific gravity compared to natural river sand. In addition, the WA of BA was also significantly higher than that of natural river sand. This means that BA has a higher porosity than natural sand. Therefore, when replacing sand with BA, the porosity of the mortar increased. Secondly, the porous nature of BA particles leads to significant WA during mixing. Consequently, to maintain the flowability of the mortar, the water content must be increased as the BA content rises, resulting in a higher W/B ratio. As the sample dries, excess water evaporates, creating voids within the mortar structure. This increased water content at higher BA levels contributes to a reduction in the density of the mortar and, ultimately, its CS.

Fig. 7 illustrates that the 28-day CS of mortar samples containing BA ranges from 15.1 to 40.2 MPa, which exceeds the specified range of 7.5 to 30 MPa for normal mortar samples according to TCVN 4314:2022 [20]. This suggests that BA can be effectively used in mortar production, provided that its strength meets the standards outlined in TCVN 4314:2022 [20].

3.2 Ultrasonic pulse velocity

The UPV passing through the mortar samples serves as an indirect indicator of CS and overall mortar quality. Fig. 8 displays the UPV values of mortar samples at 14, 28, and 56 days of curing age with varying levels of BA replacing sand. These values exhibited a gradual increase over time, consistent with the findings of previous studies [29, 30]. Notably, UPV values significantly decreased as the content of BA increased. At 28 days, the UPV values for mortar samples containing 0%, 25%, 50%, 75%, and 100% BA were 3996, 3941, 3476, 3230, and 3200 m/s, respectively. At 56 days, the corresponding UPV values were 4203, 4058, 3774, 3462, and 3395 m/s. The UPV values at 28 days for BA-containing samples

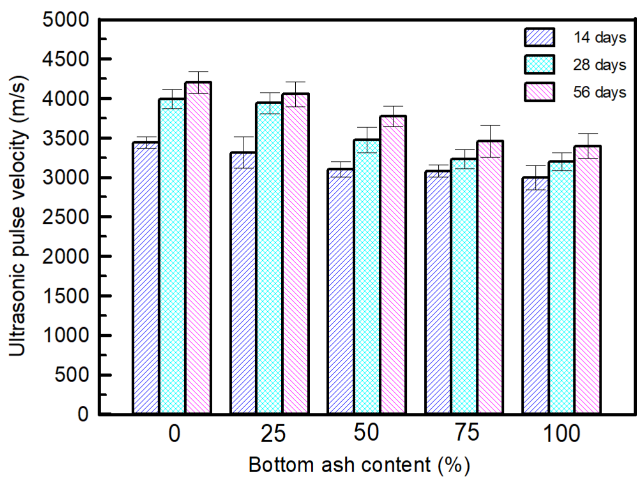


Fig. 8 Effect of BA content on ultrasonic pulse velocity of the mortars

were approximately 1.4%, 13.0%, 19.2%, and 19.9% lower than that of the BA-free mortar sample. According to Lafhai et al. [31], mortar porosity is the key factor influencing the UPV value, with an increase in porosity, being negatively correlated with UPV. As stated in the previous section, the naturally high porosity of BA resulted in a high porosity of mortar, leading to a reduction in UPV values. Furthermore, prior studies [29, 32, 33] reveal a positive correlation between higher UPV and greater CS. The observed reduction in CS with a higher BA replacement level, as illustrated in Fig. 7, aligns with the decline in UPV values as shown in Fig. 8, reinforcing the relationship between these two properties [29, 32, 33].

As stated in a previous study, Khatib et al. [34] have classified the quality of the mortar based on UPV value. Based on that, the BA00 and BA25 samples were categorized as type II, based on 28-day UPV values ranging from 3500 to 4000 m/s, which reflects good to very good quality. In contrast, the BA50, BA75, and BA100 samples were categorized as type III, with 28-day UPV values between 3000 and 3500 m/s, which signifies satisfactory quality. In summary, the BA mortar samples assessed in this study demonstrated notable quality, suggesting that the level of BA replacement can be adjusted to meet the diverse needs of various applications.

3.3 Water absorption

WA is also one of the parameters that reflect the chemical corrosion resistance of mortar samples. The higher the WA, the greater the possibility of the sample being eroded by chemical corrosive agents. The WA of mortar samples at 28 days and 56 days of curing age are shown in Fig. 9. It was observed that WA increases with higher BA content

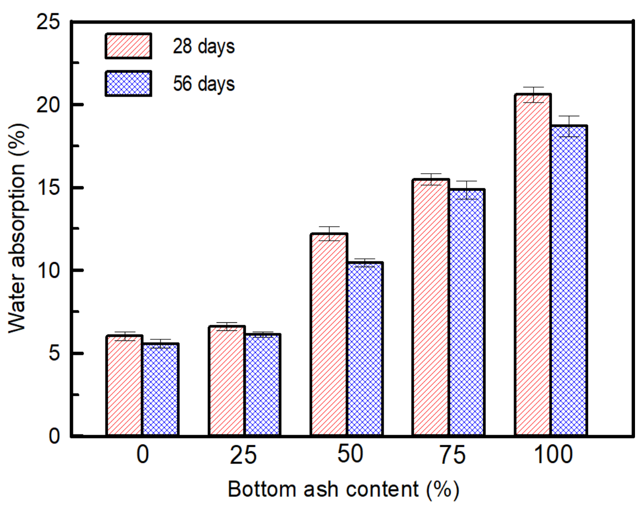


Fig. 9 Effect of BA content on water absorption of the mortars

and decreases with extended curing time. At 28 days, WA values were 6.04%, 6.62%, 12.2%, 15.5%, and 20.6% for BA contents of 0%, 25%, 50%, 75%, and 100%, respectively. At 56 days, WA values decreased to 5.58%, 6.13%, 10.45%, 14.85%, and 18.70% compared to those at 28 days. When 25% of the sand was replaced with BA, the WA increased slightly. However, significant increases in WA were noted when BA content reached 50% or more. The higher WA capacity of BA compared to natural sand contributes to the increased absorptivity of the BA mortars relative to the control mixture (BA00). This trend was also observed in the microstructural morphology, as analyzed using scanning electron microscopy, which is presented in the final section. The reduction in WA at 56 days can be attributed to the forming of hydration products over the curing period, filling voids and compacting the mortar's structure, which decreases porosity [35].

In comparison to the findings of Ngo et al. [36], the WA of the BA00 and BA25 mortar samples in this study aligns with the concrete samples containing the same BA content. However, for BA contents of 50% or more, the WA of the mortar samples was significantly higher than that of the concrete samples in the previous study. This discrepancy arises from the fixed W/B ratio of 0.45 in the prior study, whereas this study employed W/B ratios ranging from 0.4 to 1.1 due to the increased water and superplasticizer needed to achieve a flow of approximately 175 mm. As the water content increased, the CS decreased, and the internal structure of the mortar developed many voids due to the evaporation of excess water, leading to high WA.

Typically, the porosity of a mortar sample correlates with its other technical properties. Therefore, as the BA content increases, the porosity of the mortar samples also increases, resulting in a decrease in CS and an increase in WA. However, when replacing natural sand with up to 25% BA, the CS of the samples reaches 40.2 MPa, and the WA is 6.6%. This mortar sample demonstrates relatively good quality compared to the technical requirements specified in TCVN 4314:2022 [20].

3.4 Resistance to sulfate attack

Resistance to sulfate attack is an essential durability characteristic of mortars. The variations in length of the mortar specimens with different levels of BA replacement measured at 1, 3, 7, 14, 28, and 56 days, when immersed in a 5% Na_2SO_4 solution, are illustrated in Fig. 10. This figure reveals that the rate of expansion of the mortar samples (change in length) increases over curing age and significantly rises with higher

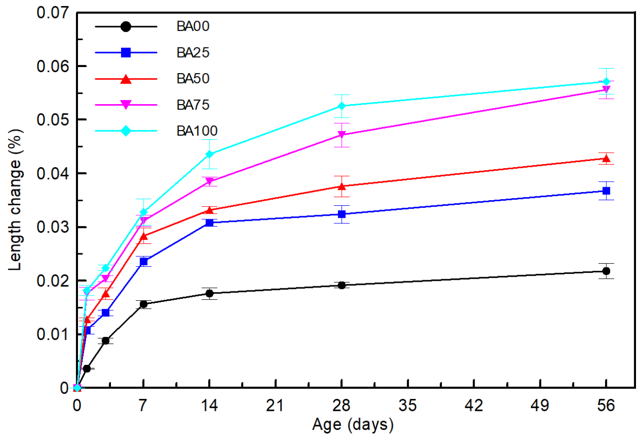


Fig. 10 Effect of BA content on length change of the mortars in a sulfate solution

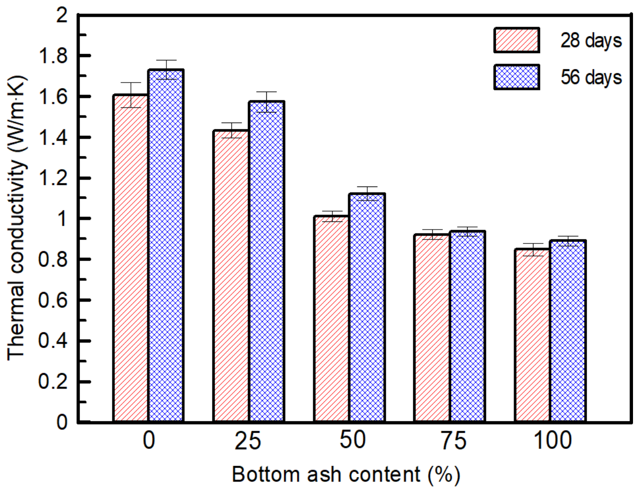


Fig. 11 Effect of BA content on thermal conductivity of the mortars

BA content. At 28 days, the length changes for mortar specimens with 0%, 25%, 50%, 75%, and 100% BA replacement were recorded at 0.0192%, 0.0324%, 0.0376%, 0.0472%, and 0.0526%, respectively. By 56 days, these length changes increased to 0.0218%, 0.0368%, 0.0428%, 0.0556%, and 0.0572% for the corresponding BA replacement levels.

As sulfate salts penetrate the mortar, complex chemical reactions occur, forming compounds such as ettringite and gypsum, which are known to induce expansion and adversely affect durability. As shown in Fig. 10, the sulfate attack resistance of mortar decreased with increasing BA replacement level. This phenomenon is due to the naturally high porosity of BA as aforementioned, leading to high porosity of mortar and high WA, creating favorable conditions for the reactions that produce ettringite and gypsum. It is noticed that with coarse particle sizes, BA plays a role as fine aggregate rather than binder materials. At 56 days, the length changes for mortar specimens with 25%, 50%, 75%, and 100% BA replacement were approximately 68.8%, 96.3%, 155.0%, and 162.4% greater, respectively, compared to the control specimen. This signifies a substantial reduction in resistance to chemical corrosion as BA content increases. Therefore, these mortar samples should be used cautiously in environments with minimal or no corrosive agents. Further research is warranted to explore potential solutions to mitigate this limitation.

3.5 Thermal conductivity

The thermal conductivity (TC) values of the mortar samples were measured to assess their heat insulation properties at 28 and 56 days, as illustrated in Fig. 11. At 28 days, TC values ranged from 0.85 to 1.61 W/m·K, while at 56 days, they ranged from 0.89 to 1.73 W/m·K. A notable decline in TC values was observed with increasing BA replacement levels for sand. Specifically, when BA replaced 25%, 50%, 75%, and 100% of the sand, the TC of the mortar samples decreased by approximately 10.8%, 37.0%, 42.6%, and 47.2%, respectively, compared to the BA-free mortar sample at 28 days. The results in Fig. 11 indicate a slight decrease in TC with 25% BA replacement, but significant reductions were evident at higher BA levels. This trend can be attributed to the increased porosity of the mortar samples resulting from the larger voids in BA particles, as confirmed by scanning electron microscopy (SEM) observations (see Fig. 12). This increase in porosity is linked to a corresponding reduction in TC values, supporting the findings by Kim et al. [37]. Interestingly, at 56 days, the TC values of the mortar samples showed a slight increase compared to those at 28 days (see Fig. 11). This phenomenon can be attributed to moisture content, which plays a critical role in influencing TC [37]. As curing time increased, the reduction in WA, as depicted in Fig. 9, contributed to the observed decrease in TC values.

Low TC is critical for modern green buildings. In urban areas, high population density and widespread concrete use contribute to temperature increases of approximately 2-3 °C compared to rural regions. Consequently, finding building materials with low heat absorption is essential. Despite the BA mortar samples demonstrating lower CS and reduced resistance to sulfate attack relative to control samples, they maintain relatively low TC values. This characteristic makes them a promising choice for sustainable construction practices.

3.6 SEM observation

In this study, SEM was employed to examine the changes in the microstructural morphology of the mortar samples. The SEM micrographs of all produced mortar specimens

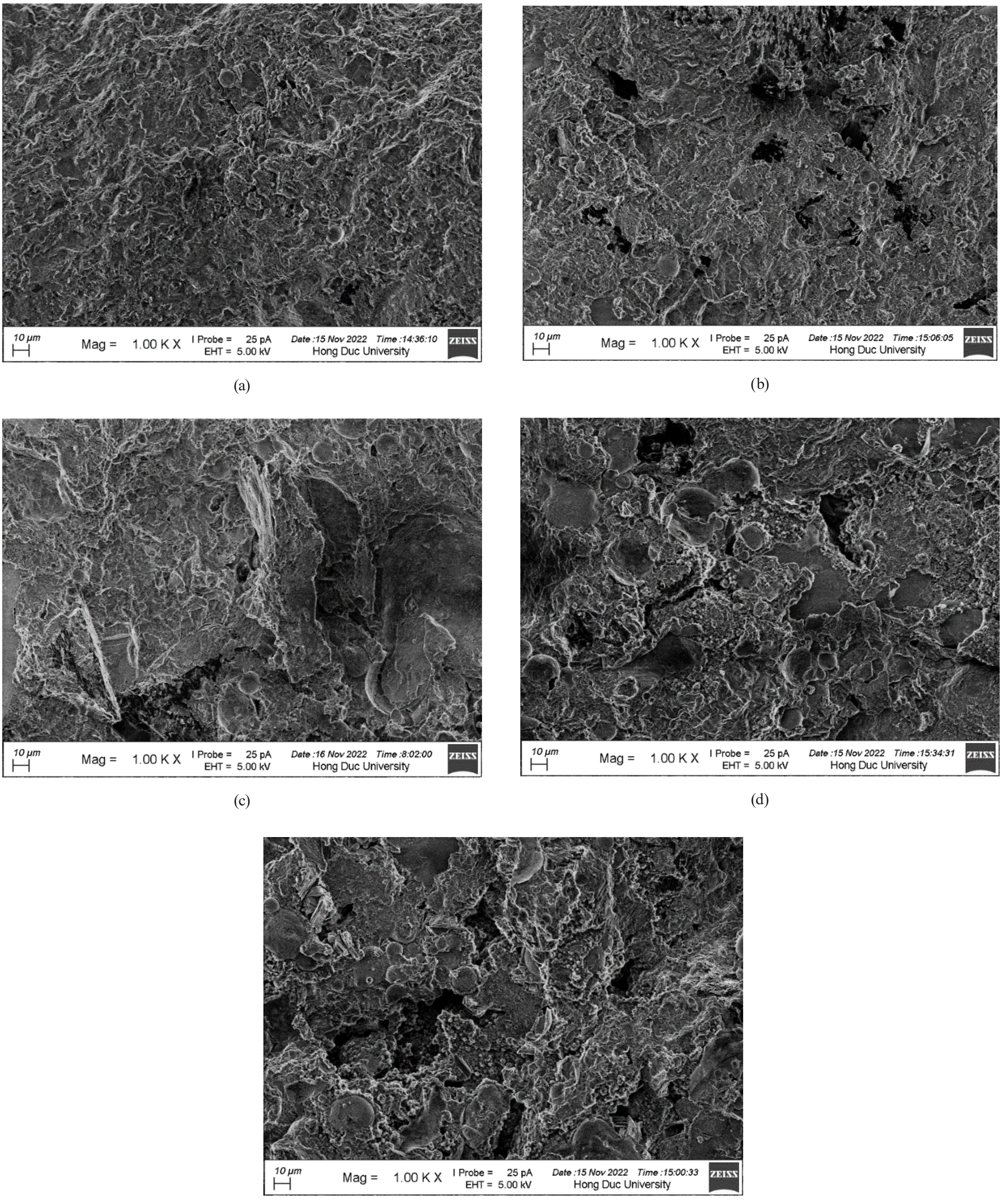


Fig. 12 SEM images of mortar, (a) BA00, (b) BA25, (c) BA50, (d) BA75, (e) BA100

are presented in Fig. 12. As can be seen from Fig. 12, the substitution of sand with BA negatively impacted the microstructure of the mortar samples. Notably, the BA particles shown in Figs. 12(b) and 12(c) appear black, while those in Figs. 12(d) and 12(e) exhibit a nearly spherical shape, resembling FA particles but significantly larger. The increased porosity in mortar samples containing 75% and 100% BA is evident in Figs. 12(d) and 12(e).

This increased porosity offers substantial evidence to elucidate the degradation characteristics of BA mortar, including CS, TC, UPV, and resistance to sulfate attack, as well as the elevated WA discussed in previous sections.

4 Conclusions

This study aimed to investigate the use of BA as a sand replacement and FA as a partial substitute for cement in mortar. The raw materials, FA and BA, were sourced from Nghi Son 1 Thermal Power Plant, a local electricity provider in Thanh Hoa Province. In this research, FA and cement served as binders, with FA comprising 15% of the total binder mass. The impact of FA and BA replacement on the engineering properties of the mortar samples was evaluated, focusing on CS, UPV, WA, TC, and resistance to sulfate attack. Additionally, the SEM technique was employed to assess the microstructure of the mortar samples. The study led to several key conclusions, summarized as follows:

1. The CS values of the mortar samples increased with curing time. The CS values of the 28-day mortar samples with the BA replacement levels of 0, 25, 50, 75, and 100% were 50.8, 40.2, 28.0, 17.9, and 15.1 MPa, respectively. Although BA negatively impacts the CS of the mortar, the CS of the mortar samples containing BA still exceeds the typical range of 7.5 to 30 MPa specified in Vietnamese Standard.
2. The WA values of the mortar samples decreased with curing time and increased with BA content. Conversely, the TC values increased with curing time but decreased with BA content.
3. The inclusion of BA content had a detrimental effect on both the UPV and the resistance of the mortar specimens to sulfate attack. The UPV values of the mortar samples demonstrated an increase with curing time; however, they showed a decline as the BA content increased. Furthermore, all mortar mixtures were classified as satisfactory to very good quality, with 28-day UPV values ranging from 3200 to 3996 m/s. At 56 days, the control mortar specimen experienced a length change of 0.0218% due to sulfate attack. In contrast, the length changes observed in mortar specimens with BA replacement of 25%, 50%, 75%, and 100% were approximately 68.8%, 96.3%, 155.0%, and 162.4% higher, respectively, compared to the control specimen.
4. SEM observations revealed a higher concentration of BA particles within the mortar matrix. This presence contributed to an increase in void volume in the mortar system, leading to elevated WA and a reduction in CS, UPV, TC, and resistance to sulfate attack in the hardened mortar samples.
5. In scenarios where resources, particularly sand, are limited, BA may serve as a partial or complete substitute for natural sand. Mortar samples containing BA should be applied in environments with a low risk of sulfate erosion. The proportion of BA should be determined according to the load-bearing requirements of the construction components to ensure compliance with the specified technical standards. For structures with lower strength demands, such as walls, wall plastering, and flooring, a higher BA ratio can be used as a sand replacement. In contrast, for structures requiring higher strength, such as foundations or mortar for load-bearing structures, a lower BA ratio should be selected.

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