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Research Article

Utilizing Coal Bottom Ash from Thermal Power Plants in Vietnam as Partial Replacement of Aggregates in Concrete Pavement

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In Vietnam, a large amount of coal bottom ash (CBA) is being discharged from thermal power plants and has been making serious environmental pollution. It is essential to utilize the CBA to reduce environmental pollution. So, this paper presents a series of experimental studies in the laboratory using CBA as a partial replacement of aggregates in concrete pavement for rural roads. In mixing concrete, the CBA is utilized to replace 15, 30, and 100% aggregates. The design of the composition must achieve the technical requirement of M-30 grade of concrete. A total 351 of specimens were tested on workability of fresh concrete, abrasion, compressive strength, and flexural tensile strength in order to achieve the technical requirement of concrete pavement for rural roads. Based on the experimental results, in order to achieve the required compressive strength, An Khanh CBA concrete uses more content of cement and water than control concrete; Cao Ngan CBA is only utilized to replace 15% aggregates, and Cao Ngan CBA concrete also uses more cement and water than control concrete. It also shown that the amount of water and cement content depend on types of CBA and the water amount and cement content of CBA concrete are larger than those of control concrete. The advantage of mixture CBA concrete is abrasion, and flexural tensile strength achieved the value as per the technical requirement.

1. Introduction

In recent years, Vietnam has been rapidly developing coal thermal power plants because of low investment cost and abundance of material resources. Currently, there are about 21 thermal power plants operating with a total capacity of 14,848 MW, consuming about 45 million tons of coal per year and discharging more than 16 million tons of coal ash (fly ash and CBA) per year. As expected, by 2025, there will be about 47 thermal power plants with a capacity of about 26,000 MW, these plants will consume about 63 million tons of coal per year, and the total amount of ash will exceed 30 million tons per year [1]. In fact, there is about 20–30% consumption of total coal ash, mainly fly ash, and CBA is not used in any form and is still stored in the ash dumps located in the plant. So, there is so much of CBA in the ash dumps and it leads to a series of environmental pollution problems such as air, water, and soil pollution and land appropriation for ash dumps. Therefore, it is necessary to conduct research on utilizing coal bottom ash for the protection of the environment and sustainable development.

The ash from coal thermal power plants consists of two components: fly ash is extracted from the boiler flue gases and CBA is collected from the bottom of the furnaces [2]. CBA is about $20 \div 30\%$ of the total coal ash and is used as sand in concretes, cement replacement, road base and subbase, embankment of backfill material, and structural or disposed of in landfills [3–5].

Numerous studies have been completed on chemical composition and physical properties of CBA. The chemical properties of CBA are mainly composed of silica, alumina, and iron oxide with percentage composition of 42.7–61.8%, 9.31–26.7%, and 5.8–25.03%, respectively [4, 6]. CBA can mostly be classified as ASTM Class F ash, and some CBA can be classified as ASTM Class C ash. The CBA is physically coarse, porous, granular, greyish, and incombustible materials [7]. The particle size ranges from fine gravel to fine sand [6], but the grain size occurred in a different range. The specific gravity of CBA is low, ranges from 1.39 to 2.41, and is affected by the carbon content.

CBA can be replaced as partial fine aggregates in concrete. In case of using CBA as partial replacement of fine aggregates, the workability of concrete is lower than the workability of control concrete [8, 9] and the change of workability is very different according to the type of CBA. The density reduced in concrete by replacing CBA for fine aggregates [10, 11].

When the CBA is replaced as partial fine aggregates in concrete, the mechanical properties of mixture concrete such as compressive strength, splitting tensile strength, and flexural strength are necessary to be studied. In [6, 7, 9, 11–14], these properties of concretes change due to the percentage of CBA replacing fine aggregate in concrete and the range of compressive strength is large. But the maximum strength of concrete was achieved with different CBA contents replacing fine aggregates. In [15], the results show that the compressive strength, the split tensile strength, and the flexural strength increased up to 20% replacement, and after that, these properties were decreased from 30% to 100% replacement. The results in [14] show that the use of CBA as partial replacement of 10% (15, 20, and 25%) fine aggregates increases the compressive strength of concrete.

Not only can CBA be used for normal concrete but also CBA can be applied to design the high-performance concrete. Experimental investigation was carried out to determine concrete properties using 25, 50, and 75% CBA replacing fine aggregate and it was found that the compressive strength at 28 days achieved more than 70 MPa, split tensile strength more than 5.56 MPa, and flexural strength also more than 6.64 MPa [16].

From a review of a literature, it was found that the properties of CBA concrete are very different due to the different chemical properties of CBA. A little study has been made on the investigation the partial replacement of coarse aggregates (gravel) and complete replacement of fine aggregates (sand) in concrete pavement. Particularly, abrasion of concrete pavement was not determined.

It is worth noting that the previous studies on the utilizing of CBA as aggregate for concrete mainly aimed at compressive strength, splitting tensile strength, and flexural strength. Other properties of mixture CBA concrete, such as workability of fresh concrete and water absorption, should be studied. In designing concrete pavement, the abrasion of concrete is very important for being used in rural roads. Moreover, the CBA properties mainly depend on the type of coal and combustion conditions [17]. The physical, mechanical, and chemical properties of CBA were affected by the type and origin of coal burned, boiler types, degree of pulverization, firing conditions in the furnace, and ash-handling practices [7]. In Vietnam, there are about 21 thermal power plants, in which 7 plants use circulating fluidized-bed combustion (CFB) with low-quality domestic coal, and 14 thermal power plants use pulverized combustion (PC) with better-quality domestic coal. So, the properties of CBA from these plants are very different.

In Vietnam, studies on reusing CBA in engineering construction are also still limited. There are no investigation and regulation for CBA in concrete pavement. Therefore, the present study aimed at the properties of CBA from An Khanh and Cao Ngan thermal power plant: determining the optimum content of CBA as a substitute for aggregates in concrete pavement for rural road; evaluating the properties of CBA concretes, including workability of fresh concrete, abrasion, compressive strength, and flexural tensile strength; the effect of particle grain distribution and chemical properties of CBA on the workability and compressive strength are then analyzed. This study will provide useful information on rural road construction.

2. Materials and Methods

2.1. Materials. The components of concrete include CBA, PCB40 cement, water, fine aggregates with size of 0.14–5.00 mm, and coarse aggregates with size of 5–20 mm. CBA was used as partial replacement or complete replacement of fine aggregates and partial replacement of coarse aggregates in concrete. CBA was collected from An Khanh and Cao Ngan thermal power plants at Thai Nguyen province (Figure 1). Two thermal power plants use circulating fluidized-bed combustion (CFB) with low-quality domestic coal.

2.2. Properties of Coal Bottom Ash. The An Khanh CBA and Cao Ngan CBA concrete were determined the chemical and mineral compositions and physical properties. The mineral composition was determined by the X-ray diffraction method and is shown in Table 1 and Figures 2 and 3. The chemical composition is also provided in Table 1, and physical properties are provided in Table 2.

The experimental results provided in Table 1 show that the percentage of SiO_2, Fe_2O_3, and Al_2O_3 of An Khanh CBA is greater than 70% which conforms to ASTM C618 as Class F ash type, and the percentage of SiO_2, Fe_2O_3, and Al_2O_3 of Cao Ngan CBA is lesser than 70% which conforms to ASTM C618 as Class C ash type. The shapes of CBA particle are porous and irregular (Figure 4). Similar results were observed in [12] also where almost all CBA particles were porous, glassy, grayish, and irregular shaped. These characteristics determined the different mix proportions when studying coal bottom ash as a partial replacement of aggregates in concrete.

The particle size of CBA was determined according to the Vietnamese Construction Standard TCVN 5772 : 2006-2. The ash samples were processed by (1) drying them in an oven at $105^{\circ} \pm 5^{\circ}C$ and then (2) using the dry sieve method to analyze the particle size. The samples were sieved, the residue on the sieve was weighed, and the percentage content of aggregate was calculated. The fine CBA (<5 mm) was determined the grading curve which is presented in Figure 5. The coarse CBA is also used in this study as a replacement to particle coarse aggregate. Some properties of An Khanh CBA and Cao Ngan CBA are presented in Table 2.

Figure 1: The ash dumps of An Khanh thermal power plant (a, b) and Cao Ngan thermal power plant (c, d).

Table 1: Chemical and mineral composition of An Khanh CBA, Cao Ngan CBA and Cement.

Composition	Properties	An Khanh CBA	Cao Ngan CBA	Cement PCB40
		Content (%)		
Chemical composition	SiO_2	60.12	37.5	20.32
	Fe_2O_3	24.93	11.93	3.30
	Al_2O_3	2.30	2.70	5.00
	SO_3	0.77	8.76	1.15
	CaO	1.30	19.67	62.5
	MgO	3.71	1.25	0.13
	K_2O	0.34	1.66	0.75
	Na_2O	0.30	0.05	0.26
	Loss of ignition	3.99	12.47	
	Alkaline index	0.08	0.52	
	Activity index, Al_2O_3/SiO_2	0.038	0.072	
	CaO + MgO	5.01	20.92	
Mineral composition	Mica	14–16	14–16	
	Pyrophyllite	5–7	—	
	Gypsum	—	14–16	
	Quartz	47–49	20–22	
	Calcite	1–3	13–15	
	Goethite	4–6	—	
	Hematite	4–6	5–7	
	Other	4% feldspat, amorphous substance	24% anhydride	
	C_3S			51.1
	C_2S			25.0
	C_3A			8.1
	C_4AF			10.0

2.3. Properties of Other Components (Cement, Water, and Coarse and Fine Aggregates) of Concrete. In this research, PCB40 cement from VICEM was used. The chemical composition and physicomechanical properties of the cement are shown in Tables 1 and 2. The specific gravity of the cement is 3.1, and the compressive strength of the cement at 28 days curing is 40 MPa.

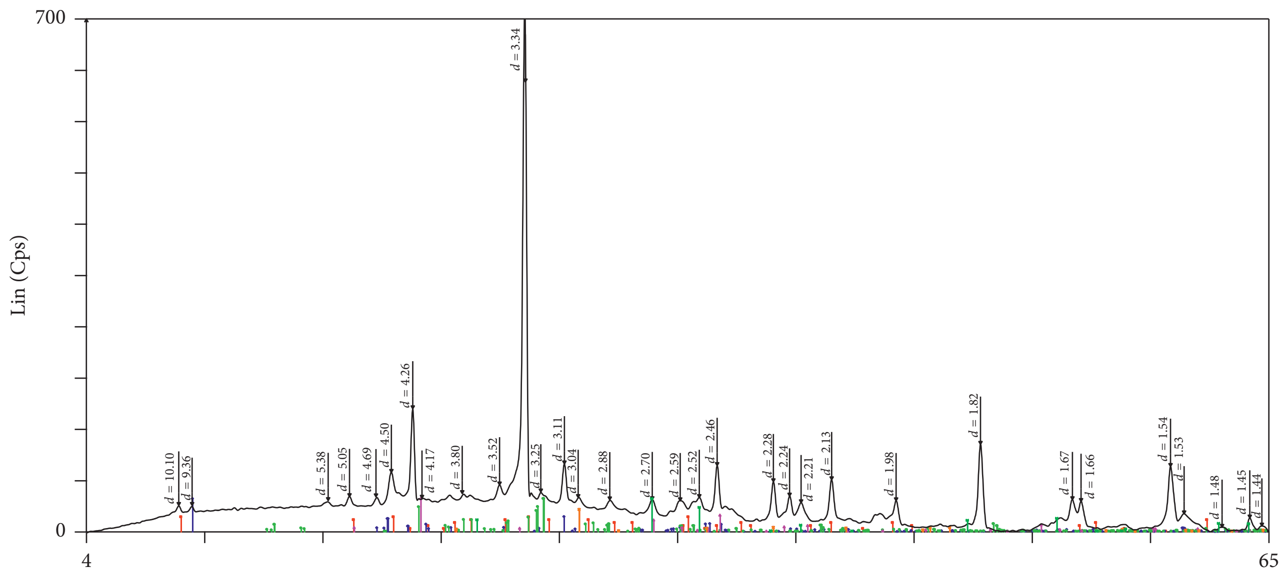


Figure 2: X-ray diffraction of An Khanh CBA.

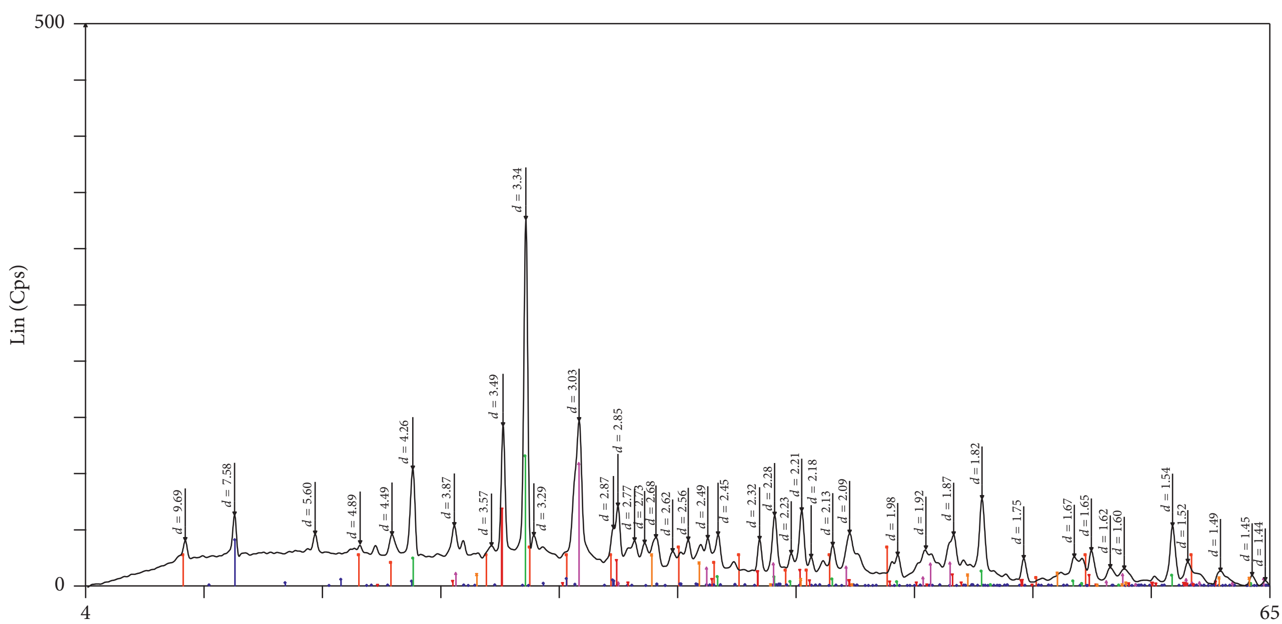
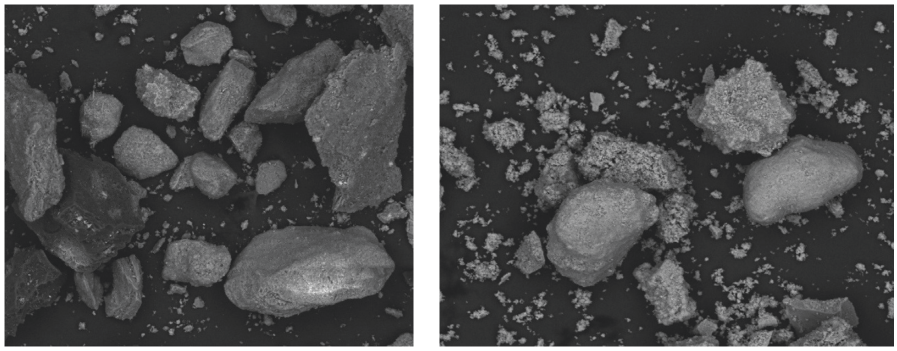


Figure 3: X-ray diffraction of Cao Ngan CBA.

Table 2: The physical properties of An Khanh CBA, Cao Ngan CBA, PCB 40 cement, and fine and coarse aggregates.

Physical properties	Value				
	An Khanh CBA	Cao Ngan CBA	Fine aggregates	Coarse aggregates	Cement
Specific gravity	2.48	2.52	2.66	2.66	3.10
Unit weight (kg/m^3)	1489	1365	1325	1370	1300
Fineness modulus	2.62	2.01	2.50		
Content of dust, mud in aggregates (%)	10.40	20.70			
Water content (%)	2.13	7.15			
Porosity (%)				51.10	
Compressive strength at 28 days curing (MPa)					40



(a) (b)

Figure 4: SEM micrograph of An Khanh CBA concrete (a) and Cao Ngan CBA concrete (b).

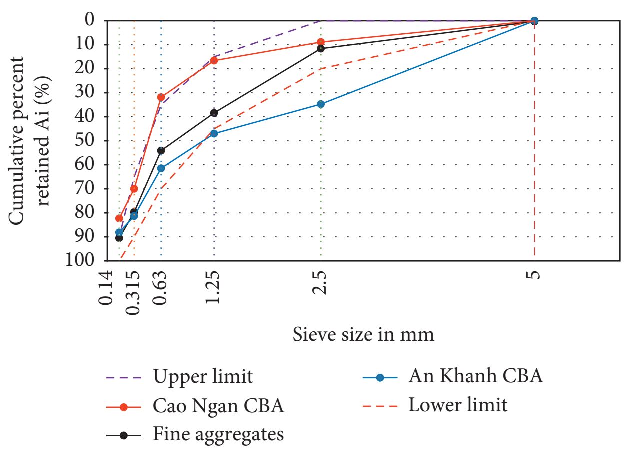


Figure 5: Particle size distribution curve of CBA and fine aggregates.

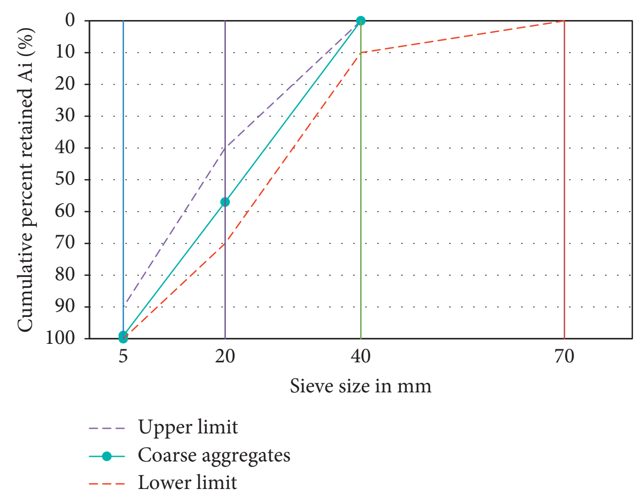


Figure 6: Particle size distribution curve of coarse aggregates.

Water used for concrete is fresh and meets the requirements of TCVN standards.

The grain size distribution curve of fine and coarse aggregates in the cement is shown in Figure 6, and some properties of these aggregates are shown in Table 2. Unit weight of fine and coarse aggregates is 1300 kg/m^3 and 1370 kg/m^3, respectively. Coarse aggregates have a nominal size of 20 mm and porosity of 51.1%.

3. Methods

3.1. Mix Proportions of Concrete. All mix proportions of concrete were designed to achieve the requirements of concrete pavement for rural roads with the compressive strength of 30 MPa, workability of 3–5 cm, abrasion <0.6 g/cm^3, and flexural tensile strength >4 MPa. Mix proportions of concrete were determined according to the Bolomey–Scramtaev method. Firstly, a mix proportion of the concrete M30 without CBA was prepared, and then five mix proportions of the concrete with An Khanh CBA and seven mix proportions of the concrete with Cao Ngan CBA were prepared. Fine aggregates in concrete were replaced 100% by An Khanh CBA and 15%, 30%, and 100% by Cao Ngan CBA. The mix proportions of the concrete are shown in Table 3.

3.2. Specimens and Testing

3.2.1. Slump Test. The mix proportions of the concrete were prepared according to TCVN 3105 : 1993 by hand mixing. After that, the workability of concrete specimens was determined by the slump cone test and was conducted in accordance with TCVN 3016 : 1993.

3.2.2. Compressive Strength Test. A total of 351 concrete specimens with dimensions of 150 × 150 × 150 mm after 3, 7, 14, and 28 days curing were prepared for the compressive strength test. The fresh concrete was casted and stored in the casting room at a temperature of 27 ± 2°C in accordance with TCVN 3015 : 1993.

After casting, tests were conducted to determine the compressive strength of concrete specimens according to TCVN 3118 : 1993. The specimens were compressed at a pressure of 6 ± 4 daN/cm^2 until they were destroyed. The compressive strength of concrete is calculated by load at the failure divided by area of specimens.

3.2.3. Flexural Tensile Strength Test. For each mix proportion of concrete M30, three specimens with dimensions

Table 3: Mix proportions of the concrete.

No.	Sample	Replacement ratio of fine aggregates	Fine CBA (<5 mm) (kg)	Coarse CBA (>5 mm) (kg)	Coarse aggregates (kg)	Fine aggregates (kg)	Cement (C) (kg)	Water (W) (l)	W/C
1	AK1	100	535	240	820	0	405	240	0.59
2	AK2	100	535	240	820	0	440	240	0.55
3	AK3	100	535	240	820	0	475	240	0.51
4	AK4	100	535	240	820	0	524	270	0.52
5	AK5	100	535	240	820	0	524	280	0.53
6	TC	100	0	0	1060	535	410	189	0.46
7	CN1	100	535	30	1030	0	414	272	0.66
8	CN2	100	535	30	1030	0	430	289	0.67
9	CN3	100	535	30	1030	0	468	281	0.60
10	CN4	100	535	30	1030	0	506	276	0.55
11	CN5	100	535	30	1030	0	520	252	0.48
12	CN6	30	160	30	1030	375	443	214	0.48
13	CN7	15	80	30	1030	454	443	214	0.48

Note: AK, concrete using An Khanh CBA; CB, concrete using Cao Ngan CBA; TC, concrete M30 without CBA.

of $150 \times 150 \times 600$ mm were casted for determining the flexural tensile strength at 28 days curing. The flexural tensile strength test on these specimens at 28 days curing was carried out according to TCVN 3119 : 1993 in accordance with ASTM C293 (center point loading). The specimen was placed on the loading points, and the loading system is located at the center of the specimen. After that, the load is applied at a pressure of 0.6 ± 0.4 daN/cm^2 until the sample was destroyed. The flexural tensile strength of concrete (R_{ku}, daN/cm^2) was calculated by the following equation:

$$R_{\mathrm{ku}} = \frac{PL}{ab^2}, \quad (1)$$

where P_{o} is the maximum load applied to the beam specimen, daN; L is the supported length, cm; a is the width of the beam specimen, cm; and b is the failure point depth.

3.2.4. Abrasion Test. For each mix proportion of concrete M30, three specimens with dimensions of $150 \times 150 \times 150$ mm were casted. The abrasion test on these specimens at 28 days curing was carried out according to TCVN 3114 : 1993. The abrasion test includes three steps: 1st, the specimen was weighed and abrasived by 20 g dry sand on the machine for 30 m abrasion line (with 30 rotations). The specimen was abrasived for five times with a total of 150 m abrasion line. 2nd, after one cycle, the sample was rotated 90° around the vertical axis and was also abrasived for 150 m abrasion line. 3st, the specimen was abrasived for four cycles with a total of 600 m abrasion line and then was weighed. The abrasion of concrete (M_{n}) was calculated by the following equation:

$$M_n = \frac{m_0 - m_4}{F}, \quad (2)$$

where m_0 is the weight of the specimen before testing and m_4 is the weight of the specimen after four cycles of abrasion.

3.2.5. Scanning Electron Microscope (SEM). For each mix proportion of concrete M30, the specimens at 3, 7, and 14 days were observed by the scanning electron microscope test. SEM provided the microstructural properties of mixture concretes.

4. Results and Discussions

4.1. Workability. The testing results on the workability of the concrete cubes with and without An Khanh CBA and Cao Ngan CBA are presented in Figure 7. It was observed that the workability ranges from 3 cm to 5 cm, whereas the ratio of N/X changes from 0.48 to 0.66, but the slump of concrete mix also increases insignificantly, only fluctuating in the range of nearly 3 cm (for Cao Ngan CBA concrete mix) and 5 cm for An Khanh CBA concrete mix. It was found that the CBA needs more water than the fine aggregates and the coal bottom ash was finer than the fine aggregates. Cao Ngan CBA was finer than the An Khanh CBA, its fineness modulus is 2.01, and content of dust and mud in aggregates is 20.7%. So, the Cao Ngan CBA needs more water than An Khanh CBA. It was also observed by the Aggarwal et al. [8] that the workability of concrete decreased with the increase in CBA due to the increase in water demand. CBA has a lot of fine, irregular-shaped, rough-textured, and porous particles, thereby increasing the internal particle friction [18]. These properties increase the water demand and reduce the workability. The finer CBA and the higher water absorption of CBA particles were the reasons for decrease of bottom ash concrete mixtures in the slump [11].

4.2. Compressive Strength. The summary test results for the values of compressive strength of the CBA concrete at 3, 7, 14, and 28 days curing are presented in Figures 8–11. It could be observed that the compressive strength of CBA concrete at 3, 7, and 14 days curing equals 25 ÷ 103%, 29 ÷ 112%, and 29 ÷ 109% of compressive strength of the concrete without CBA. The compressive strength of CBA concrete at 3, 7, and 14 days curing equals 28 ÷ 103%, 29 ÷ 112%, 28 ÷ 110%, and 29 ÷ 109% of control concrete without CBA at 28 days curing, respectively.

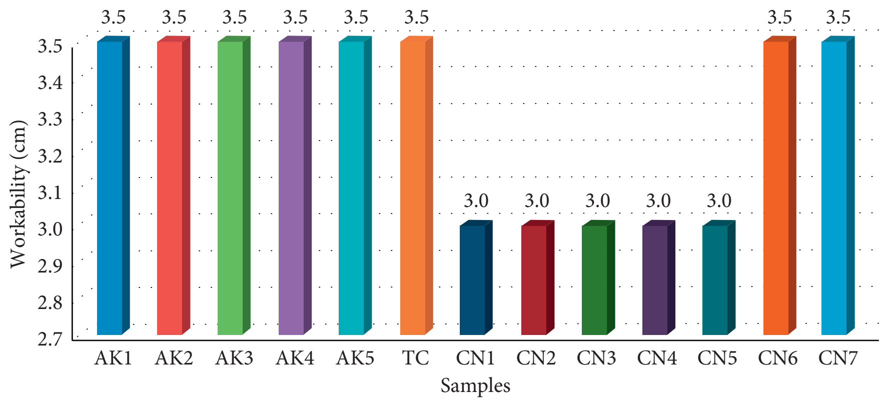


Figure 7: Workability of the concrete.

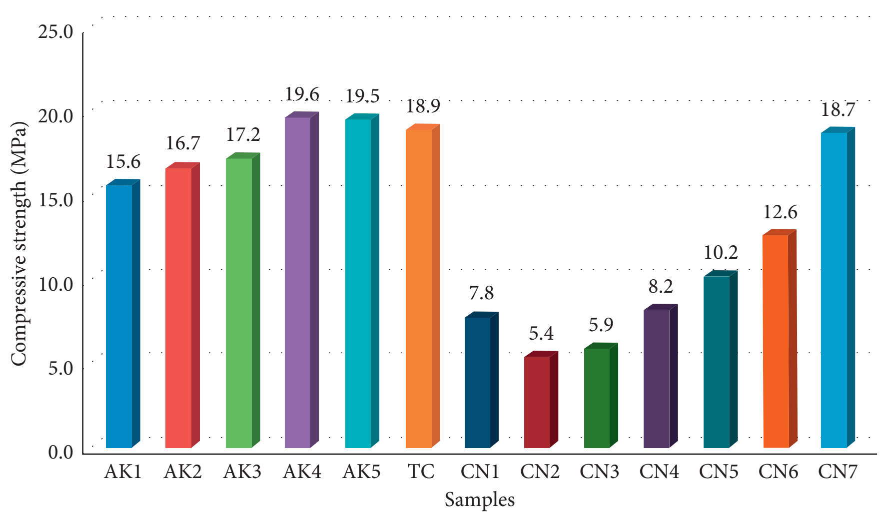


Figure 8: The compression strength of the coal bottom ash concrete at 3 days curing.

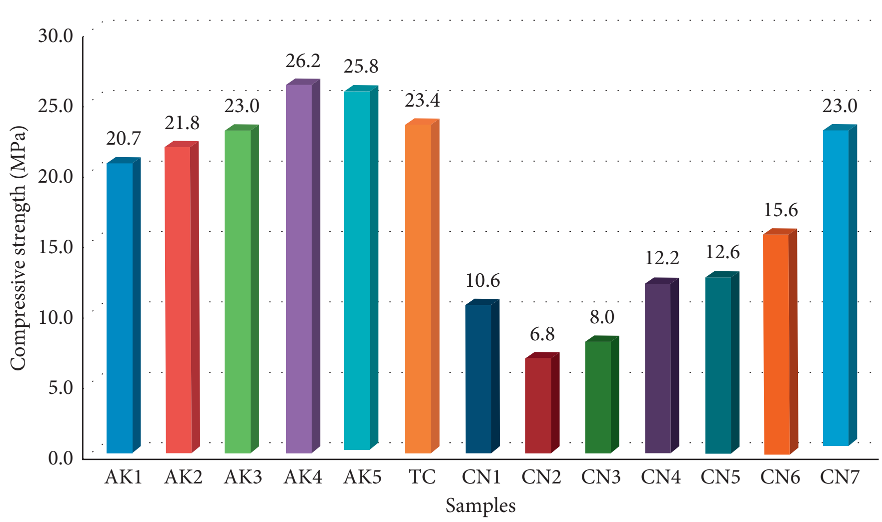


Figure 9: The compression strength of the coal bottom ash concrete at 7 days curing.

The compressive strength of concrete with 100% Cao Ngan CBA (CN1, CN2, CN3, CN4, and CN5) has low values at all curing days. It is observed that the compressive strength of these Cao Ngan CBA concretes is decreased from 40% to 71%, 56 to 70%, 44 to 71%, and 41 to 70% for 3, 7, 14, and 28 days, respectively, as compared with controlled

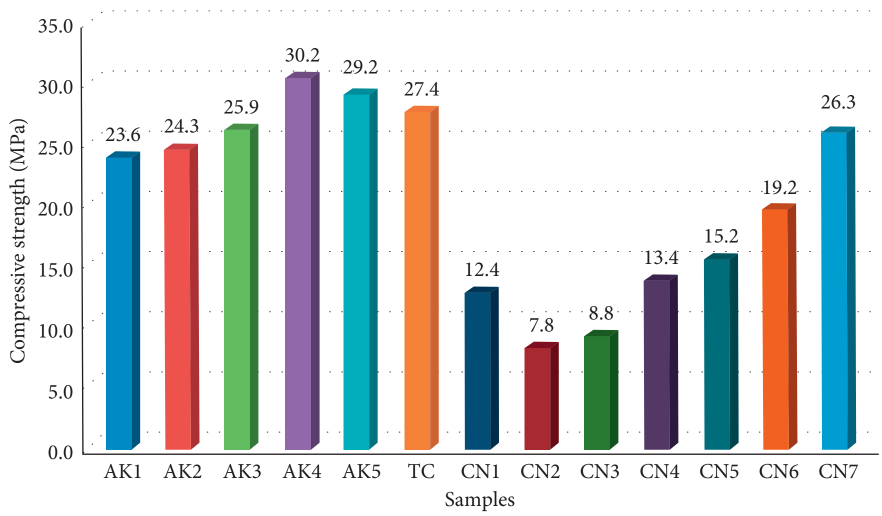


Figure 10: The compression strength of the coal bottom ash concrete at 14 days curing.

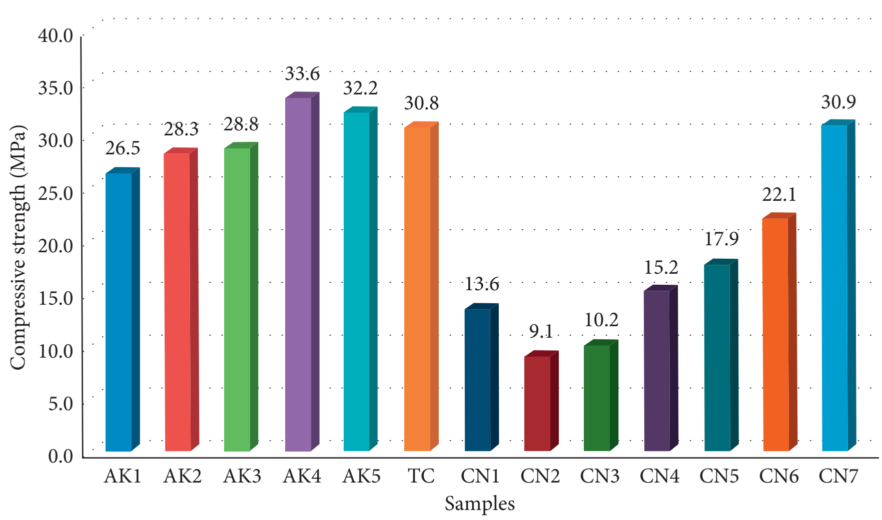


Figure 11: The compression strength of the coal bottom ash concrete at 28 days curing.

concrete. The compressive strength of concretes with 15% and 30% Cao Ngan CBA replacement of fine aggregate is decreased from 1% to 33%, 2 to 3%, 4 to 30%, and 0 to 28% for 3, 7, 14, and 28 days, respectively, as compared with controlled concrete. Whereas the compressive strength of concretes with 100% An Khanh CBA replacement of fine aggregate (AK1, AK2, and AK3) is only decreased from 9% to 17%, 2 to 11%, 5 to 14%, and 6 to 14% for 3, 7, 14, and 28 days, respectively, as compared with controlled concrete. This is due to the delay in hydration by using CBA as fine aggregates in concrete [9] and the bottom ash reacts slowly with liberation of calcium hydroxide when the cement is hydrated [8].

It was also found that An Khanh CBA concretes (AK4 and AK5) are increased from 3 to 12% as compared with control concrete. Therefore, it can be concluded that the An Khanh CBA has better quality than the Cao Ngan one. The concrete with 30 and 100% fine aggregates replaced by Cao Ngan CBA has low compressive strength and did not achieve 30 MPa. Concrete M30 can only be achieved when 15% of fine aggregates are replaced by Cao Ngan CBA. So, it is believed to be because of the quality of Cao Ngan CBA being lower with higher content of dust and mud, low percentage of $SiO_2 + Fe_2O_3 + Al_2O_3$, higher loss of ignition, and low fineness modulus as Class C ash type as compared with An Khanh CBA. It may be related to the chemical and mineral compositions of CBA. The An Khanh CBA has higher content of silica oxide and higher quarts than the Cao Ngan CBA. It was also reported in [12] that the compressive strength is decreased due to the physical nature of the ash particles. It was also found that the CBA with porous surface structure and high absorptivity nature of the material prevented the hydration of all cement particles.

The microstructural properties of An Khanh CBA concrete are presented in Figures 12(a), 12(c), and 12(e), and the microstructural properties of Cao Ngan CBA concrete are presented in Figures 12(b), 12(d), and 12(f). The C-S-H gel, CH crystals, and the pore structure can be

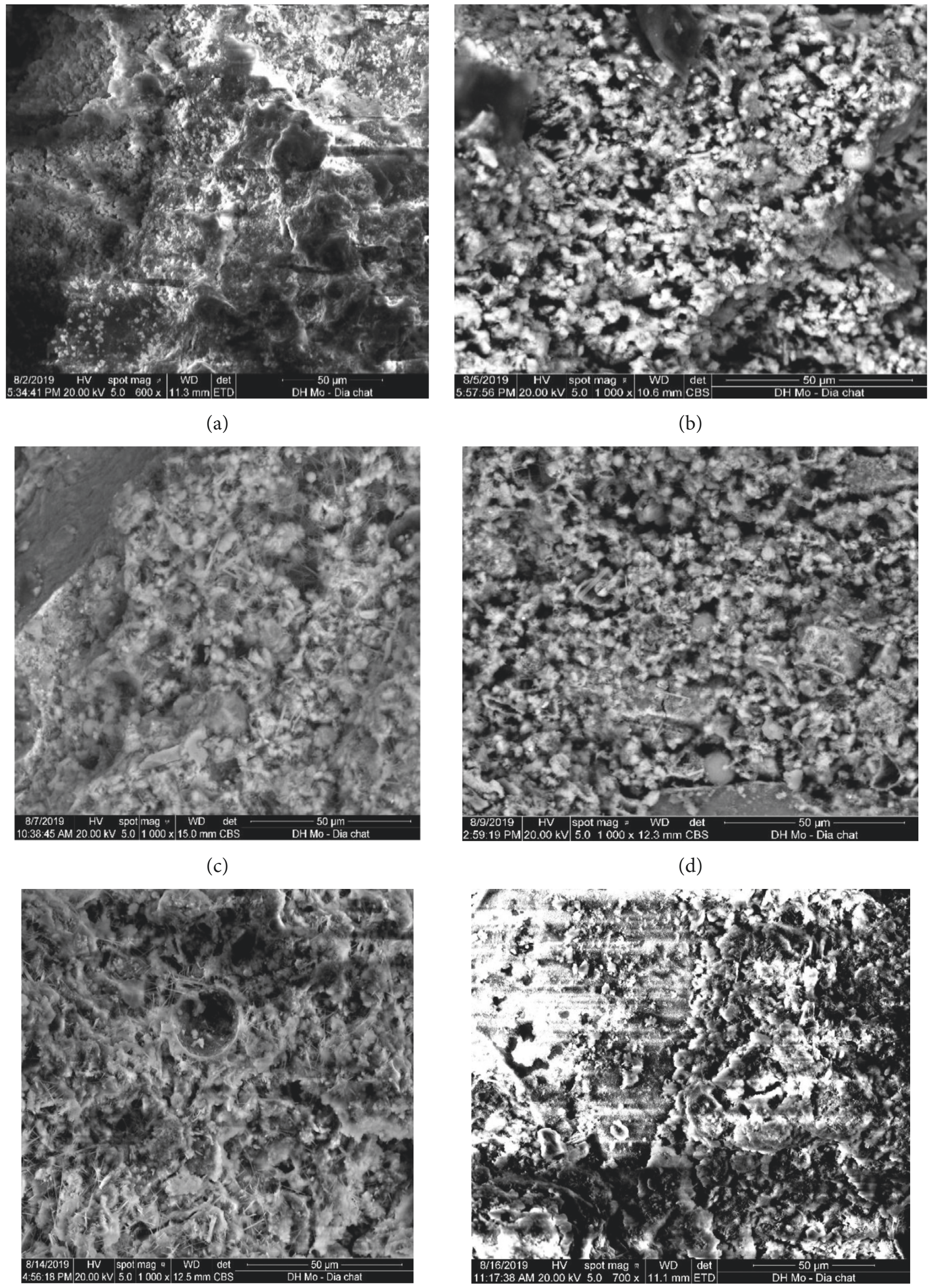


Figure 12: SEM micrograph of the hydrated bottom ash-calcium hydroxide mixture at 3, 7, and 14 days curing, respectively, for An Khanh CBA concrete (a, c, e) and Cao Ngan CBA concrete (b, d, f).

observed. It was found that the C-S-H gel has different microscopic shapes. These structures play a role in the development of concrete strength. It can also be found that there are different microstructural properties of concretes [19]. It make the develops strength of concrete. It is very different in shape of concrete.

The compressive strength of the CBA concretes and the control concrete at 3, 7, 14, and 28 days curing is provided in Figure 13. From Figure 13, it can be observed that the values of compressive strength develop rapidly at 3 to 7 days curing and develop slowly from 14 days to 28 days curing. The reason for increasing compressive strength is the hydration of cement. The density of the microstructure of concrete increases with days curing by reducing water and its porosity, thus improving the properties of concrete [19]. The compressive strength of CBA concrete at 3, 7, and 14 days curing equals $54 \div 61\%$, $70 \div 80\%$, and $85 \div 91\%$ of CBA concrete at 28 days curing, respectively.

Only AK4, AK5, and CN7 concrete specimens meet the requirement of compressive strength of the concrete M30.

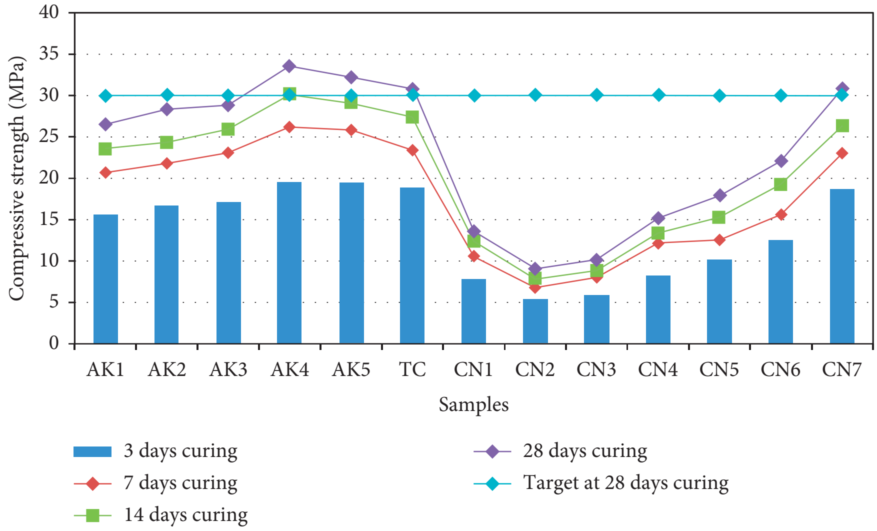


Figure 13: The compressive strength of the coal bottom ash concretes at 3, 7, 14, and 28 days curing.

It is believed that the Cao Ngan CBA is less suitable for reusing as replacement of aggregates in concretes. Similar results were also observed in [12] where washed bottom ash is more suitable for mortar rather than concreting sand.

4.3. Abrasion and Flexural Tensile Strength. For abrasion and flexural tensile strength tests, only AK4 and CN7 concrete specimens at 28 days curing were chosen. The flexural tensile strength of An Khanh CBA concrete and Cao Ngan CBA concrete is 4.233 MPa and 4.024 MPa, respectively. The flexural tensile strength of An Khanh CBA concrete and Cao Ngan CBA equals 13.2% and 13.0%, respectively, as compared with compressive strength of that concrete. The abrasion of An Khanh CBA concrete and Cao Ngan CBA is 0.30 MPa and 0.34 MPa, respectively. The flexural tensile strength and the abrasion of these concretes can meet the requirement of concrete pavement. Therefore, it can be concluded that AK4 and CN7 CBA concrete specimens meet the requirements of the concrete pavement for rural roads.

5. Conclusions

Based on the test results, the following conclusions can be drawn:

(i) Cao Ngan and An Khanh thermal power plants in Thai Nguyen province of Vietnam use the same CFP technology but CBA varies greatly in grain composition. Cao Ngan CBA is finer than An Khanh CBA. This property affected on the workability, compressive strength, and other mechanical properties of concrete.

(ii) The amount of water and cement content depend on the type of CBA, and the water amount and cement content of CBA concrete are larger than those of control concrete.

(iii) The workability of the CBA concretes decreases, so they need more cement and water to achieve the requirement on compressive strength.

(iv) An Khanh CBA is the suitable material to be used as a partial replacement of coarse aggregates and complete replacement of fine aggregates in concrete pavement for rural roads. Cao Ngan CBA is not suitable for complete replacement of fine aggregates. It can only be used as 15% of partial replacement of fine aggregates of the concrete for rural road construction.

(v) The advantage of mixture CBA concrete is abrasion, and flexural tensile strength achieved the value as per the technical requirement.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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