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Evaluation of the Performance of Concrete Containing Coal Bottom Ash through the Nondestructive Tests and Microstructure Analysis

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ABSTRACT: Coal bottom ash is one of the waste materials generated by coal thermal power plants. In the world, there is a huge amount of coal bottom ash released to the environment every year. The availability of such coal bottom ash with insufficient treatment method leads to many serious environmental troubles. Therefore, turning this waste ash into useful construction material is concerned by many researchers so far. The performance of concrete incorporating coal bottom ash as a natural sand substitution was evaluated in this study through the compressive strength and other nondestructive tests of ultrasonic pulse velocity, water absorption, porosity, electrical surface resistivity, and thermal conductivity. Moreover, the scanning electron microscope was also used to characterize the microstructure of the hardened concrete. In this study, coal bottom ash sourced from Vietnam was used to replace the natural sand in the normal-strength concrete at different replacement levels of 0, 30, 50, 70, and 100% by weight. The results show that using coal bottom ash to replace natural sand was found to have a significant influence on the properties and performance of concretes. The compressive strength, ultrasonic pulse velocity, electrical surface resistivity, thermal conductivity, water absorption, and porosity values of concretes were measured in the ranges of 14.2 – 27.7 MPa, 4336 – 4823 m/s, 6.41 – 12.25 kΩ cm, 1.202 – 1.739 W/mK, 2.47 – 5.72%, and 3.72 – 8.34% after 28 days of curing, respectively. In real practice, therefore, an optimal coal bottom ash replacement level will be suggested with the consideration of specific requirements for the quality of concrete used in particular applications. The results of this study further demonstrate the good performance of concrete incorporating coal bottom ash and the optimal replacement level of natural sand by coal bottom ash was 30%.

Keywords: Coal bottom ash, Compressive strength, Concrete, Microstructure, Nondestructive test.

Abbreviations: CBA, coal bottom ash;UPV, ultrasonic pulse velocity; ESR, electrical surface resistivity; TC, thermal conductivity; WA, water absorption; CS, compressive strength; SP, superplasticizer; FM, fineness modulus; D_{max}, the maximum diameter of coarse aggregate; SEM, scanning electron microscope; w/c, water-to-cement ratio; NS, natural river sand; ASTM, American society for testing of materials; CTP, coal thermal power plant.

I. INTRODUCTION

Concrete has been soonly recognized as a major construction material that widely used in many activities of the construction industry for a long time. Natural sand (NS) is one of the primary components, which occupies a large proportion of concrete. Therefore, the consumption of a large number of concrete equivalents to a large demand for NS, leading to the depletion of this natural aggregate type as announcing by the local Government in Vietnam.

Besides, the coal thermal power plant (CTP) has recently been developed in Vietnam. Currently, a total of 21 CTPs is responsible for releasing about 16 million tons of coal ash every year. As the estimation of the Local Government, the amount of coal ash will exceed 30 million tons by 2025, in which, coal bottom ash (CBA) registers for about 20-30% [1]. It is important to note that the generation of such a large quantity of CBA will cause serious pollution to the environment if there are no sufficient treatment methods. CBA is naturally porous in structure and granular in shape with the particle size of similar to NS [2, 3]. Therefore, it is considered to be recycled as fine aggregate in the production of concrete.

So far, the use of CBA as fine aggregate in concrete has been studied by many researchers. Bai *et al.,* [4] studied the strength and drying shrinkage of concrete containing furnace bottom ash (FBA) as fine aggregate. In their study, the NS was replaced by FBA at different levels of 0, 30, 50, 70, and 100%. They found that the compressive strength (CS) and drying shrinkage of concrete decreased with increasing FBA content. They also suggested that the optimal replacement level of NS by FBA was 30%. A study on properties of concrete containing CBA as fine aggregate has been conducted by Singh and Siddique [5]. They used CBA to replace 0, 30, 50, 75, and 100% river sand in concrete. Their results show that the CS and ultrasonic pulse velocity (UPV) of concrete were not affected when CBA was used to replace river sand. The initial water absorption (WA) and abrasion resistance of CBA-concrete increased, while permeable pore space and later WA reduced significantly as compared to the control concrete. Andrade *et al.* [6] investigated the effect of CBA as fine aggregate on fresh properties of concrete.

The authors reported that fresh concrete containing CBA was susceptible to water loss by bleeding. In addition, increasing CBA content resulted in a reduction in plastic shrinkage and the delay in setting time of fresh concrete. An investigation on CS, drying shrinkage, and chemical resistance of concrete incorporating CBA as a substitution for NS at levels of 20, 30, 40, 50, 75, 100% was carried out by Singh and Siddique [7]. The results found that CBA-concrete showed an enhancement in dimensional stability, chloride ion penetration resistance, and acid resistance as compared to conventional concrete. Ibrahim *et al.*, measured the splitting tensile strength of self-compacting concrete containing CBA as a replacement for fine aggregate at different levels of 0%, 10%, 20%, and 30% with various w/c ratio of 0.35, 0.40, and 0.45. They reported that slump flow, L-box ratio, and sieve segregation resistance of fresh CBA-concrete mixture were decreased, while T_{500} slump and flow time increased with CBA content. Moreover, the inclusion of CBA caused the reduction of split tensile strength and density of concrete [8].

It can be seen that most of the previous studies regarding the use of CBA as fine aggregate in concrete were mainly focused on mechanical strength and the properties of concrete containing CBA were different from study to study as the variation of CBA's properties from different sources. Therefore, to fill the gap in the literature, this paper is aimed at turning CBA sourced from a local CTP in Vietnam asa fine aggregate to partially and fully replace NS in the production of normal-strength concrete. Thus, the performance of CBA-concrete was evaluated using the nondestructive tests and microstructure analysis in order to evaluate the potential recycling of CBA in real practice.

II. MATERIALS AND METHODS

A. Materials properties

This study used Nghi Son cement of type-PC40 with a density of 3.12 as binder material for making concrete. NS (density of 2.62, WA of 1.08, and Fineness Modulus (FM) of 2.83) and stone (density of 2.69, WA of 0.18, and D_{max} of 12.5 mm) were used as fine and coarse aggregate, respectively. Besides, CBA (density of 1.99, WA of 23.2, and FM of 1.97) was also used as an NS substitution. The gradation curves of both NS and CBA are plotted in Fig. 1.

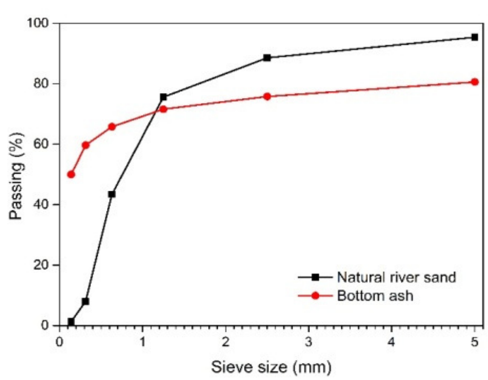


Fig. 1. Gradation curves of naturalriver sand and CBA.

The CBA used in this investigation was sourced from a coal thermal power plant in Northern Vietnam. The scanning electron microscope (SEM) image of the CBA particles is shown in Fig. 2. As can be seen, the structure and shape of CBA particles were porous and mostly irregular, respectively. It explains the very high WA rate of CBA as compared to NS. Besides, some spherical particles like fly ash were also observed in Fig. 2.

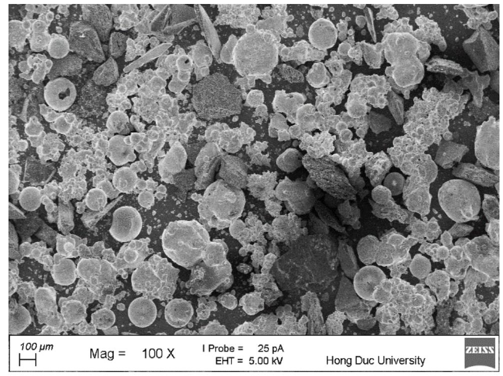


Fig. 2. SEM image of CBA particles.

B. Mixture proportions

The control concrete mixture (denoted as CBA00) was designed using cement, NS, coarse aggregate, water, and superplasticizer (SP) with quantities of 461.5, 963.6, 751.1, 175.4, and 4.6 kg/m^3, respectively. To investigate the effect of CBA on the performance of concrete, a series of mixtures were then designed by replacing 30, 50, 70, and 100% (by weight) of NS from the control mixture by CBA with a fixed water-to-cement (w/c) ratio of 0.39. These mixtures were named as CBA30, CBA50, CBA70, and CBA100, respectively. In which, "CBA" indicates coal bottom ash and the number after "CBA", e.g. 30, 50, 70, and 100, indicates the percentage of coal bottom ash was used to replace natural sand in the concrete mix.

C. Samples preparation

According to the designed mixtures, all of the ingredients were prepared prior to mix, and a laboratory mixer was used for mixing. Cement was firstly mixed with about 2/3 of water and a part of SP for about 2 minutes to obtain a viscous paste. NS, together with CBA was then added and the mixer was allowed to run for an additional 2 minutes. Coarse aggregate was finally added to the mixture, followed by the rest of the water and SP. Mixing continued for a further 2 minutes to achieve a uniform mixture. Right after mixing, cylindrical concrete samples of 100 mm in diameter and 200 mm height were prepared and cured in saturated lime-water until the date of testing.

D. Test methods

The performance of concretes was evaluated through the tests of CS, UPV, electrical surface resistivity (ESR), thermal conductivity (TC), WA, and porosity. The CS test was conducted at 3, 7, 14, and 28 days following ASTM C39, while the other tests were performed at 28 days. In which, the UPV values were measured according to ASTM C597, the ESR and TC tests were performed following the guidelines of Hwang and Tran [9], and the WA and porosity measurements were performed according to ASTM C642. The average value of the three measures was reported as the final result of each test. Moreover, an SEM of ZEISS at 5 kV and 25 pA chamber pressure was also used to characterize the microstructure of concretes after 28 days of curing.

III. RESULTS AND DISCUSSION

A. Compressive strength

The growth in CS of concretes is presented in Fig. 3. As expected, the CS of all concrete samples increased with the curing time continuously. Especially, the increment rate of concrete samples containing 30% CBA was more significant than the others. On the other hand, the replacement of NS by CBA caused a reduction in CS of the concretes. The CS values of the 28-day-old concrete samples with 0, 30, 50, 70, and 100% CBA replacement levels were 27.7, 27.6, 22.4, 19.7 and 14.2 MPa, respectively. Thus, the substitution of NS by 30, 50, 70, and 100% CBA reduced approximately 0.5, 24, 41, and 95% CS values of concretes. In addition, the CS of concrete was found to be reduced remarkably at the CBA replacement levels of ≥50%. The inclusion of CBA with a highly porous structure (Fig. 2) introduced more voids/ pores within the concrete and attributed to the reduced concrete's strength. A similar finding was previously reported by Kumar and Bishnoi [10]. Fig. 3 further indicated that the CBA replacement level of 30% was sufficient since the concrete's strength was reduced in significantly as compared to the CS of the non-CBA concrete.

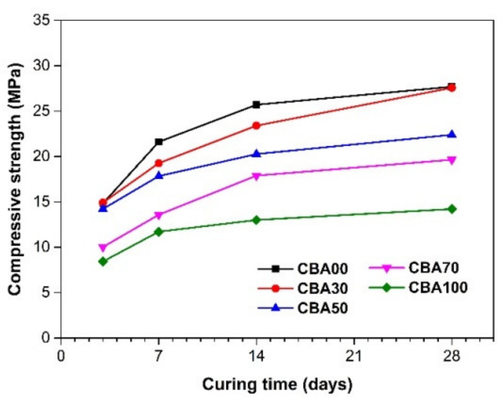


Fig. 3. Compressive strength of concretes.

B. Ultrasonic pulse velocity

In this study, a nondestructive test of UPV was used to check the quality of concrete samples. Usually, higher UPV value indicates good quality and continuity of concrete, while lower UPV values may indicate concrete with many cracks or voids [11]. The results of the UPV test are shown in Fig. 4.

It can be seen that the UPV values of concrete samples ranged from 4336 m/s to 4823 m/s. Moreover, Fig. 4 shows that concrete containing CBA had lower UPV value than that of the control sample. In fact, the CBA30, CBA50, CBA70, and CBA100 concrete samples registered UPV values of about 1, 6, 9, and 11% lower than the UPV value of the CBA00 sample. As mentioned above, the lower velocity may cause by the presence of cracks or voids in the system, which was attributable to the inclusion of porous CBA particles in the concrete. Although the replacement of NS by CBA reduced the UPV of concretes, all of the concrete samples achieved the UPV values of above 4100 m/s. Therefore, all of the concrete samples WA and ASTM prepared for this study could be classified as good quality concretes as suggested by Carcaño and Moreno [12].

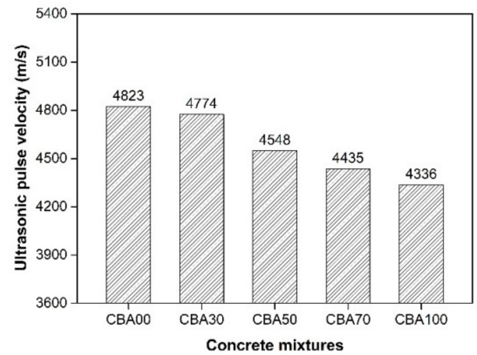


Fig. 4. UPV values of concretes.

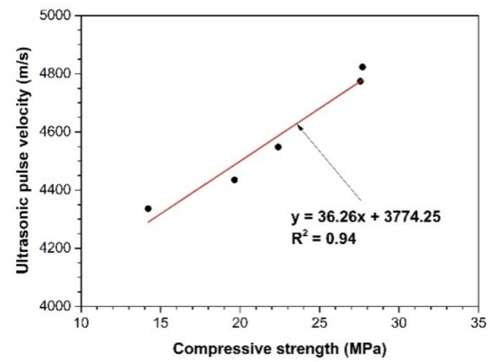


Fig. 5. Relationship between UPV and compressive strength of concretes.

On the other hand, the UPV was found to have a close relationship with the CS of the concretes. The correlation between UPV and CS of the 28-day concrete samples was expressed by a linear equation of $y = 36.26x + 3374.25$ with $R^2 = 0.94$ (Fig. 5). One again, Fig. 5 confirms that higher UPV values were associated with higher CS values. Thus, the results of the UPV test well supported the CS of concretes.

C. Electrical surface resistivity

The nondestructive ESR measurement can be used for the quality control and durability assessment of concrete. It is reported that concrete ESR played a crucial role in controlling the corrosion rates, as higher ESR value indicated lower corrosion potential and better resistance to chemical attack [13, 14]. The ESR values of 28-day-old concrete samples are shown in Fig. 6. The replacement of NS by CBA increased the ESR values of concretes. The control concrete sample had an ESR value of 6.41 kΩ.cm. Whereas, the ESR values of concretes with 30, 50, 70 and 100% CBA were about 12, 41, 69, and 91%, respectively, higher than that of the control concrete. The result of ESR measurement of this study was somehow different from previous studies, as the inclusion of porous CBA particles increased the ESR of concretes [15]. This difference can be explained by the saturation degree of the sample. Another possible reason for the increase of ESR values was the involvement of some very fine and active CBA particles in the pozzolanic reaction, generating additional C-S-H gel [7].

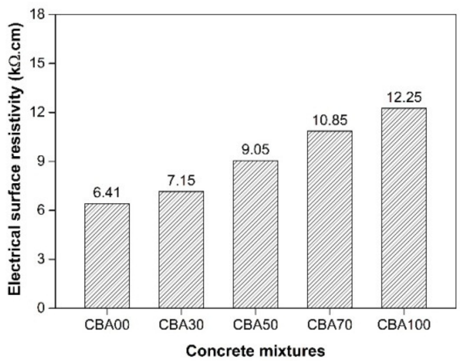


Fig. 6. ESR values of concretes.

Furthermore, the increase in ESR values indicates that CBA-concretes had better resistance to the chemical attack and lower corrosion potential in comparison with the control concrete.

D. Water absorption and porosity

The measurement and calculation of WA and porosity of all concrete samples were conducted at 28 days, with the results as presented in Fig. 7. The WA rate and porosity level of the CBA00 sample were 2.47% and 3.72%, respectively. By using CBA to replace NS at the replacement levels of 30, 50, 70, and 100%, the WA of concretes increased to 3.01, 3.53, 4.72 and 7.52%, while the porosity of concretes jumped to 4.62, 5.28, 6.17, and 8.34, respectively. It can be said that both WA and porosity increased proportionally with CBA content in the concrete. As aforementioned, the presence of porous CBA particles (Fig. 2) in the concrete attributed to increasing void volume within the concrete structure, leading to an increase in porosity and WA of the hardened concrete. Although it is reported that higher porosity and WA rate negatively affected the concrete's properties, as well as durability performance [16], all of the concrete samples prepared for this study had a relatively low rate of both WA and porosity.

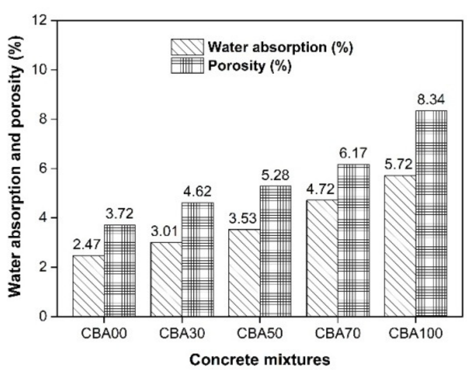


Fig. 7. WA and porosity of concretes.

On the other hand, the porosity of concretes was closely associated with their CS and UPV. These relations are presented in Fig. 8. In which, the relationship between porosity and CS could be expressed by the linear equation of y = 39.96 – 3.14x with R^2 = 0.93, whereas the relationship between porosity and UPV could be expressed by the linear equation of y = 5211.7 – 111.73x with R^2 = 0.83. Fig. 8 further explained for the lower values of both CS and UPV, as displayed in Fig. 3 and 4, when more CBA was used to replace NS in the concrete mix.

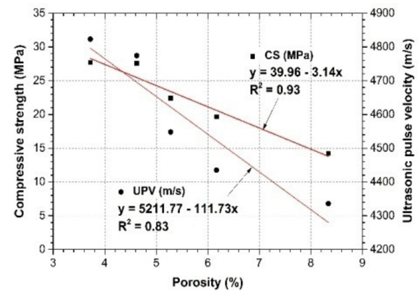


Fig. 8. The relationship between porosity and CS and UPV of concretes.

E. Thermal conductivity

The TC values and the relationship between TC and porosity of all concrete samples are exhibited in Fig. 9 and 10, respectively.

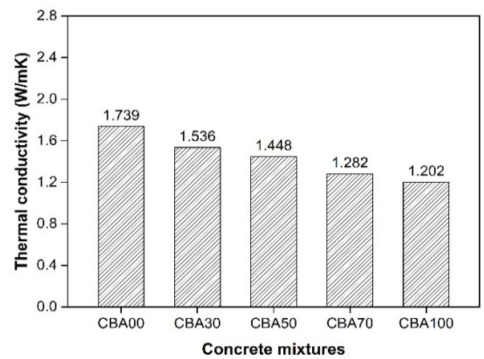


Fig. 9. TC values of concretes.

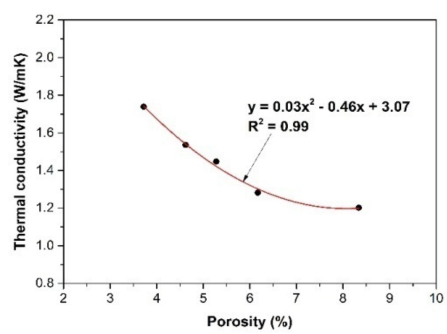


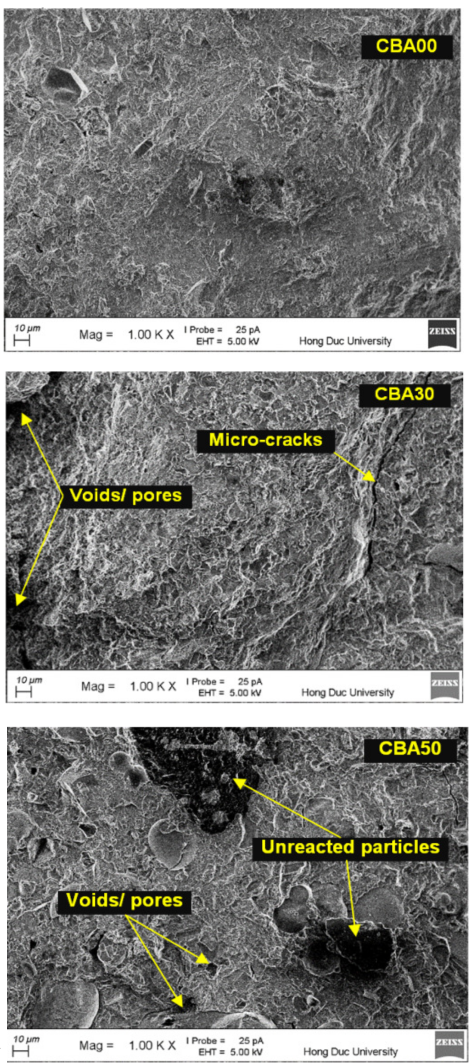
Fig. 10. The relationship between TC and porosity of concretes.

The TC values of concretes felt within the range of 1.202 – 1.739 W/mK. As expected, the use of CBA to replace the NS in concrete resulted in a reduction in concrete's TC. In fact, the TC values of concretes reduced approximately 13, 20, 36, and 45% when CBA was used to replace 30, 50, 70, and 100% NS in concrete, respectively. Therefore, the higher the CBA content in the concrete mix, the lower the TC values of the concrete were. This behavior is due to the increased porosity of concretes with the presence of more porous CBA particles (Fig. 2) as mentioned above, resulting in the reduction of TC of concretes [17]. Furthermore, the equation of $y = 0.03x^2 – 0.46x +$ 3.07 (R^2 = 0.99) was used to express the correlation between TC and porosity of concretes. Thus, the replacement of NS by CBA is beneficial in terms of reducing TC of the concretes.

F. SEM observation

The surface morphologies of all concrete samples used in this study are displayed in Fig. 11. It is interesting to found that the use of CBA as NS substitution introduced more voids/pores and re-arranged the pore structure within the concrete. This phenomina is mainly attributable to the porous structure of CBA as can be seen in Fig. 2. The number of voids and pores was more significant when the replacement level of above 50%. At these levels, moreover, more unreacted or partially reacted CBA particles together with micro-cracks were also detected in the SEM micrographs of the concretes. Thus, the looser and non-homogeneous concrete's structure was observed, which negatively affected the quality of the concretes.

Fig. 11 further explained for the increased porosity and WA, as well as the declined CS and TC of the CBA-concrete as compared to those of the non-CBA concrete as above mentioned sections.



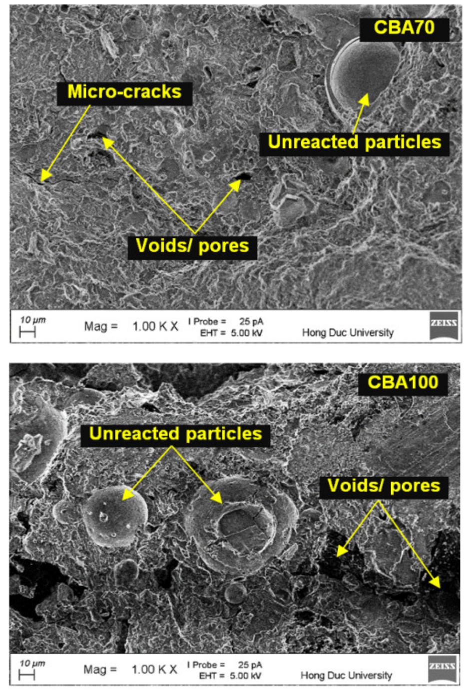


Fig. 11. Surface morphologies of concretes.

IV. CONCLUSION

The present study evaluated the performance of concrete containing CBA using the nondestructive tests and microstructure analysis. Based on the experimental results, the following conclusions may be drawn: (1) The CS, UPV, ESR, TC, WA, and porosity values of concretes were measured in the ranges of 14.2 – 27.7 MPa, 4336 – 4823 m/s, 6.41 – 12.25 kΩ.cm, 1.202 – 1.739 W/mK, 2.47 – 5.72%, and 3.72 – 8.34% after 28 days of curing, respectively; (2) Utilizing of CBA to replace NS in concrete was found to have a negative effect on the CS, UPV, WA, and porosity of concrete. Adversely, this replacement was beneficial in terms of ESR and TC of concretes. These effects were more significant at higher replacement levels (≥ 50%); (3) The inclusion of CBA with porous structure resulted in an increase in the number of voids and pores in the concrete structure as observed by SEM. This caused the looser microstructure and negatively influenced the quality and performance of the hardened concrete, e.g., increasing the porosity and WA capacity, reducing CS and UPV, etc; (4) The results of this study further demonstrate a high potential of recycling of CBA as fine aggregate in the concrete mix. The fact that concrete incorporating CBA exhibited good performance and the optimal replacement level of natural sand by CBA was found at 30%.

V. FUTURE SCOPE

The large size of concrete specimens could be prepared and double-checked for the industrial-scale applications.

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Conflict of Interest. The authors declare that there is no conflict of interest regarding the publication of this paper.

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