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PRESERVATION OF NATURAL RESOURCES BY UTILIZING COMBUSTION ASH IN CONCRETE AND DETERMINATION OF ITS ENGINEERING PROPERTIES

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Abstract

Due to the large amount of combustion ash being thrown into landfills, which can lead to environmental pollution, new alternatives to construction materials can be developed by utilising this combustion ash as a part of the main raw materials, while at the same time helping to preserve natural resources in the concrete manufacturing industry. Generally, using new waste materials will eventually affect the engineering properties of concrete. Therefore, the main objective of this study is to analyse the engineering properties of concrete containing combustion ash as a partial replacement for ordinary Portland cement (OPC). CA can be classified as combustion bottom ash (CBA) and combustion fly ash (CFA). CA is tested for its chemical compositions using X-Ray Fluorescence (XRF), and its four main compositions, which are silica, alumina, iron, and calcium, are examined and discussed extensively. Other testing for the property of CA includes Scanning Electron Microscopic (SEM) and specific gravity testing for coarse aggregate. To produce sustainable concrete from waste, several tests have been conducted to determine the engineering properties of the concrete, such as compressive strength, flexural strength, and splitting tensile strength. Results show that CA, which consists mainly of silica dioxide, contributed to the strength of concrete. SEM images show that CBA has a porous structure with an angular and rough texture, whereas CFA has more rounded particles, which influence the overall compressive strength. Furthermore, it was discovered that as the proportion of CBA utilised increased, the compressive strength, flexural strength, and splitting tensile strength of the concrete improved. Based on the results of the testing, CBA is suggested for use as a supplementary cementitious material in concrete.

***Keywords**: Concrete; Cement; Combustion ash; Compression strength; Supplementary cementitious materials; X-Ray Fluorescence (XRF)*

Introduction

The depletion of natural resources is concerning nowadays, as many industries exploit them to gain financial profits. Many forests were cut, and extensive blasting of the mountain and marine ecosystems was disturbed in the name of development. Actions should be taken to protect

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the environment from future damage. Many waste materials were not treated and were dumped directly at the landfill. Other than common solid waste from domestic use, ash from the incineration process and from combustion activity was also dumped at the landfill. Not only that, agricultural waste can also be found in abundance, for example, rice husk, coconut fibre, sawdust, and palm oil fruit bunches [1]. Even though in some countries, enforcement has been made that requires the ash to be treated before disposal, more proactive solutions can be suggested for a more sustainable environment. The increased output of combustion ash, which normally comes from coal-fired power plants, resulting in product waste generated as coal-fired power plants now account for approximately 38% of total global electricity generation. Combustion bottom ash (CBA) and combustion fly ash (CFA) were the most common coal ash waste products being produced. Since bottom ash is typically heavier, it is more difficult to transport by flue gas than fly ash. The composition of CBA and CFA varies greatly depending on the source and components of the coal being burned. CFA mainly consists of silicon dioxide and calcium oxide, which are the main ingredients of many existing coal-bearing rocks [2]. Numerous studies have appeared interested in investigating the possible application of CBA and CFA as one of the raw materials for construction materials. For instance, CBA and CFA were widely used for blended cement, aggregate, brick manufacturing, concrete, and mortar [3]. These ashes consist of pozzolan materials, which are beneficial for altering the properties of construction materials, thus increasing the motivation to investigate their full potential [4]. Many of these studies are initiated as an alternative solution to reduce the depletion of natural sources for the protection and preservation of the environment. Sometimes, an adequate modification process is required to ensure proper adhesion and bonding between particles, but at the same time, it should cause no harm to the environment [5].

Many years ago, concerns regarding the carbon dioxide emissions due to cement production increased, and this issue is discussed involving many relevant parties. Global cement production has risen drastically and becoming the third largest source of carbon dioxide emissions globally. To reduce these problems, other sources of supplementary cementitious materials (SCM) were introduced as one of the main raw materials, especially for cement [6]. Other than that, the application of ash in cement or concrete is designed to save energy and reduce the overall cost of materials by incorporating waste materials. Therefore, this study is initiated to find out the effects of utilising combustion ash in concrete. Its bonding properties will be discussed, especially in terms of strength and comparison with standard concrete.

Materials and methodology

Collection of combustion ash and preparation of the main raw materials

This study utilised combustion ash produced from the coal burning process at a thermal powerplant. Both types of ashes, i.e., combustion bottom ash (CBA) and fly ash (CFA), were collected from the plant and kept in proper containers. It was then oven-dried in the furnace at 110±5°C. Next, to produce fine ash that is below 63μm in size, the sample went through the grinding and sieving process. Figure 1 shows the process of sieving and grinding the dried CBA to ensure the coarser materials were cleared away. The other main substances used in this research are cement, aggregate, sand, and water. The type of cement used for this study is ordinary Portland cement (OPC). It is crucial to identify the basic characteristics of the main materials so that their effect on the later properties of concrete can be well discussed. Testing that was involved to determine the properties of these ashes and OPC was specific gravity, water absorption, surface morphology, and chemical composition using X-Ray Fluorescence (XRF).

Fig. 1. Grinding and sieving of CBA.

Methods for testing of raw materials

Scanning Electron Microscopy (SEM) was used to examine the surface morphological characteristics of CBA. SEM produces a range of signals on the surface of solid specimens by using a focused stream of high-energy electrons and provides a two-dimensional picture that illustrates spatial changes in qualities such as chemical characterization and material orientation. SEM can also be used for very small particles in the size of nano which are also called nanoparticles [7]. Specifically, this study utilised the SEM model JEOL JSM-6460LA with ×100 magnification, which is a high-resolution scanning electron microscope. It uses a high energy beam at an acceleration voltage of 10kV. Next, X-ray fluorescence (XRF) was used to identify the elemental composition of CBA. XRF a non-destructive expository approach that can be used to determine the fundamental chemical composition of materials. XRF analyzers determined the chemistry of a test by recognising the fluorescence (or auxiliary) X-ray released by the test when it was activated by a primary X-ray source. In this study, the XRF PANalytical MiniPal 4 Machine is used to test CBA with a size of less than 63μm. XRF results were expected to have silica, alumina, press oxide, and calcium oxide. Meanwhile, other traces such as magnesium, kalium, barium, potassium, sodium, and titanium oxides are all expected to appear in small amounts in both ashes. From XRF results, an indirect classification of CBA can be made based on the standard method ASTM C618 [8]. Other than XRF and SEM, the specific gravity of coarse aggregates was applied to evaluate the material's strength or quality.

Mix design for concrete and experimental set-up

To contribute to natural resource preservation and conservation, part of the OPC used in this study was replaced with CBA and CFA as a partial replacement to produce new blended cement. Six different OPC replacements were selected for this study, which is 5, 10, 15, 20, 25, and 30%. Samples containing 0% combustion ash act as control samples. All these mixtures had a constant water to cement ratio of 0.6. Mix proportions for each component of concrete were tabulated in Table 1. The focus of this study was to investigate the engineering properties and behaviour of concrete samples containing these ashes. Therefore, the testing for concrete containing CBA and CFA includes compressive strength, which was tested using a compression test machine following the standard method of MS EN 12390-3:2012 [9]. Other than that, flexural strength testing and splitting tensile strength testing were also conducted based on ASTM C78/C78M 22 [10] and ASTM C496 [11], respectively. Figures 2a and b show an experimental set-up for flexural and splitting tensile tests. For compressive strength, water absorption, and density testing, the size of the specimens was 100×100×100mm, whereas for flexural testing, the size of the specimens was 100×100×500mm. Lastly, splitting tensile testing using specimens with dimensions of 300×150mm.

Table 1. Mix proportion for each mixture.

Mixing proportions (%)	OPC (kg/m³)	Combustion ash (kg/m³)	Sand X (kg/m³)	Aggregate (kg/m³)	Water (kg)
0 (control)	463.2	0	526.3	1600	4.2
5	440.0	23.2	526.3	1600	4.2
10	416.9	46.3	526.3	1600	4.2
15	393.7	69.5	526.3	1600	4.2
20	370.6	92.6	526.3	1600	4.2
25	347.4	115.8	526.3	1600	4.2
30	324.2	139.0	526.3	1600	4.2

(a) Flexural testing (b) Splitting tensile

Fig. 2. Experimental set-up for a) flexural testing and b) splitting tensile.

Results and discussion

General properties of main raw materials

Figure 3 shows the surface morphology of CBA and CFA captured using SEM and OPC from another source. It can be seen clearly that CBA has a rougher surface and is more angular in shape when compared with OPC. This image is in accordance with the finding from [12]. It shows that CBA has a larger size than CFA. On the other hand, the SEM image for CFA shows that it has more rounded shapes compared with CBA. OPC has a needle-shape image, which indicates the existence of an ettringite component [13].

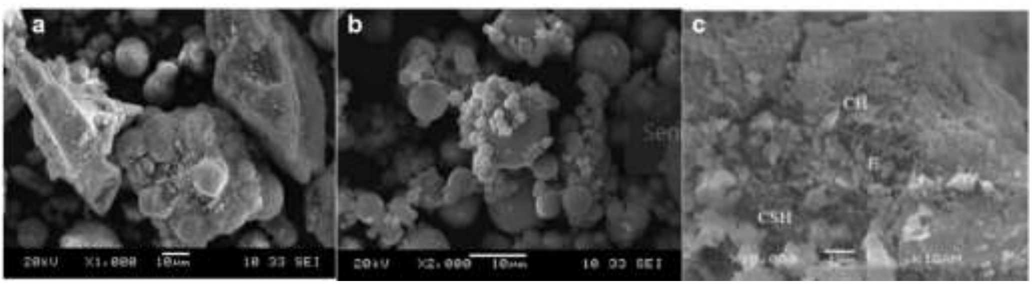


Fig. 3. Morphology images of (a) CBA, (b) CFA and (c) OPC [13]

Table 2 shows the results for XRF for CBA, CFA, and OPC. It summarises the major components of these materials, which were silica oxides, aluminium oxides, iron oxides, and calcium oxides. It can be observed that for all samples, CBA contains the highest SiO_2 (43%), followed by CFA (40%), and OPC (18%). SiO_2 is produced when heating is involved; hence, it can be easily found in the combustion ash. Also, for calcium content, OPC dominates the majority, as it contains 62% of the calcium content in the total chemical composition and thus contributes to the strength of the concrete. CBA and CFA have the same amount of CaO (12%). On the other hand, CFA has the highest amount of Al_2O_3, with 31%, which is 29% higher than CBA. OPC only contains 10% of Al_2O_3. Other minerals also existed in these ashes, such as magnesium, natrium, and kalium, but their elemental compositions are not further discussed in this paper.

Table 2. Chemical compositions of CBA, CFA and OPC measured using XRF

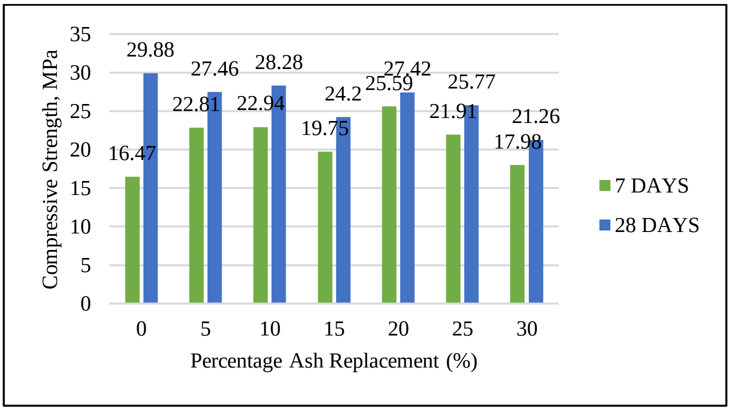
Element	CBA (%)	CFA (%)	OPC (%)
SiO_2	43	40	22
Al_2O_3	24	31	10
Fe_2O_3	15	10	1
CaO	12	12	62

Based on the element composition, the CFA can be classified. However, the classification is only subject to CFA. To the author's knowledge, there is no classification guideline available for CBA. Class C ash can simply be identified if the total percentage of the three main elements, namely silica, iron, and aluminium, is between 50% and 70%. Class C is also known as calcareous fly ash and is usually produced by the burning of lignite or sub-bituminous materials. For CFA, if the sum of these three principal constituents is 70% or more and reactive calcium oxide is less than 10%, the CFA can be considered siliceous fly ash or class F fly ash. Such a type of CFA is produced by the burning of anthracite or bituminous coal and possesses pozzolanic properties. For that matter, FA, which consists of 81% of those three principal constituents, falls into Class F ash [14]. For the specific gravity (SG) of coarse aggregate, the result shows that the SG obtained is 2.43.

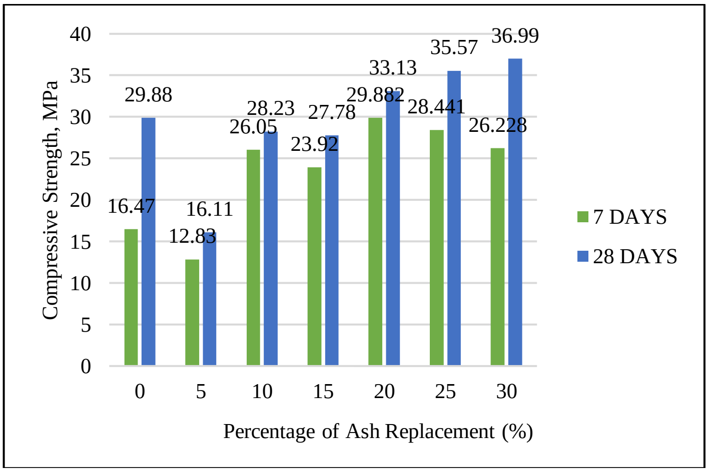
Engineering properties of concrete

Compressive strength

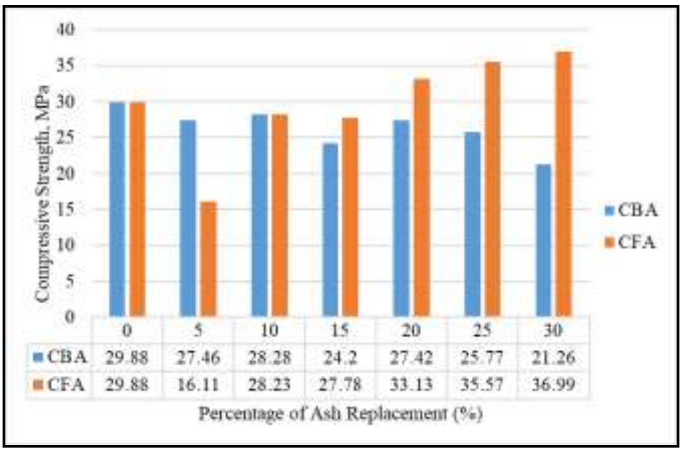
Figure 4 shows results for the compressive strength of concrete measured at 7 days and 28 days. Testing at 7 days is necessary to ensure that the early strength of hardened concrete is achieved. The compressive strength grows significantly in the first five days but slowly decreases from the fifth to the seventh day [15]. Generally, 65-70% of the strength development is completed in 7 days. Meanwhile, compressive strength after 28 curing days is called the characteristic strength of concrete and is used to categorise the grade of concrete. This study uses 25MPa as the target strength. It can be seen from Figure 4a that all concrete specimens incorporating CBA have achieved early strength. The early strength of concrete that consists of a mixture of OPC and CBA is usually decreasing, which means that the approach of cement or concrete content CBA is restricted to some degree and its technological use is also subject to some regulations. Even though at 7 days the strength of CBA sanples achieved 60% of target strength, the trend for the percentage ash replacement is difficult to monitor because it fluctuated within samples.



(a) Compressive strength of concrete containing CBA after 7 and 28 days of curing period.



(b) Compressive strength of concrete containing CFA after 7 and 28 days of curing period



	0	5	10	15	20	25	30
CBA	29.88	27.46	28.28	24.2	27.42	25.77	21.26
CFA	29.88	16.11	28.23	27.78	33.13	35.57	36.99

(c) Comparison of compressive strength for concrete after 28 days of curing period
for both types of combustion ash

Fig. 4. Overall data for compressive strength of all concrete specimens containing CBA and CFA

However, generally, at 28 days, the compressive strength reduces linearly with the increment of CBA in specimens. The highest strength obtained is 28.28MPa for concrete containing 10% CBA, while the lowest compressive strength obtained is for specimens incorporating 30% CBA, with a strength of 21.26MPa.

For specimens containing CFA, the results of compressive strength at 7 days and 28 days are depicted in Figure 4b. Other than control specimens, the compressive strength for CFA samples shows a positive linear trend. When CFA was added to the mixture, the compressive strength increased. The highest compressive strength for CFA specimens is for specimens containing 30% CFA, with a strength of 36.99 MPa. Concrete with a strength less than 25MPa does not reach the required target strength, but this might be due to some human error while handling the specimens. Further investigations need to be done to validate the results for 5% CFA in specimens.

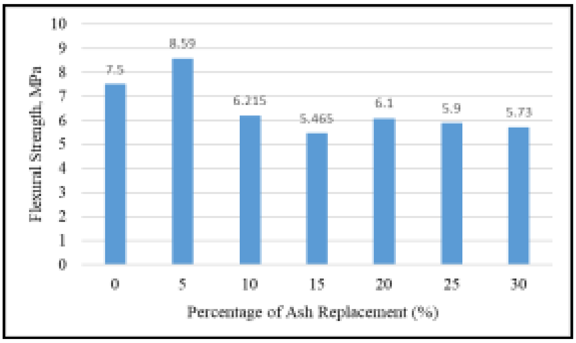
For a better comparison of compressive strength results, Figure 4c is depicted to show the difference in strength performance of concrete containing CBA or CFA at 28 days. For CFA, the results show that almost all specimens have exceeded the targeted strength, with the lowest value of 28.23MPa except for specimen 5%. The percentage difference between CFA specimens and CBA specimens at 5% replacement is almost 74%. This is in relation to the different chemical compositions of these ashes. The pozzolanic components in the ash increased the hydration process of the concrete [16]. Overall, almost all percentages of CFA replacement in concrete give comparable concrete quality with control, and the strength keeps increasing until 30% replacement. It can be concluded that, during the hydration process, when fly ash is introduced to OPC, calcium hydroxide bonds with the ashes to create calcium silicate hydrate (C-S-H). It modifies the matrix's pore size and porosity, improving water absorption resistance while enhancing strength and durability.

However, the relatively large size of the particles led to a lesser hydration and hydration percentage than normal fly ash. The early strength of concrete, along with cement, consists of fly ash, and the strength production is also decreasing, which means that the use of cement or concrete-content fly ash is restricted to some degree and its technological use is also subject to some regulations.

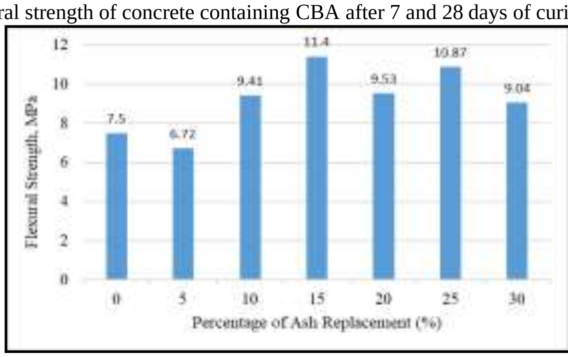
Flexural strength

Flexural testing was done to measure the concrete's ability to endure bending failure. The outcome of the flexural test on the concrete is demonstrated as a modulus rupture, which is signified as (MR) in MPa. For this study, the flexural test measures the force required to bend a beam under three-point loading conditions. It was tested after a 28-day curing period. Based on Fig. 5(a) below, the highest flexural strength was obtained from 5% CBA ash replacements in concrete, with a value of strength 8.59MPa. The lowest flexural strength is 5.73MPa and it was achieved for concrete containing the highest percentage of CBA replacement, which is 30%. Overall, almost all specimens have lower flexural strength compared with control specimens, which consist of 0% CBA. The percentage reduction in flexural strength between the lowest percentage and the control specimen is 23.6%. On the other hand, the percentage increment of flexural strength between the highest value and the control sample is 14.5%.

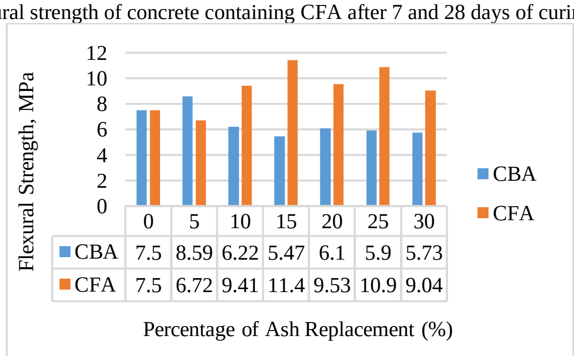
Concrete containing CFA shows a positive linear trend for flexural strength compared with the control sample (Fig. 5b). The highest is for specimens with 15% CFA, and the flexural strength achieved was 11.4 MPa, in contradiction with CBA specimens at 5% replacement, where CFA shows a much lower flexural strength of 6.72%. Overall, the range of flexural strength for all specimens' concrete containing CFA is less than 12 MPa.



(a) Flexural strength of concrete containing CBA after 7 and 28 days of curing period.



(b) Flexural strength of concrete containing CFA after 7 and 28 days of curing period.



(b) Comparison of flexural strength for concrete after 28 days of curing period for both types of combustion ash.

Fig. 5. Overall data for flexural strength of all concrete specimens containing CBA and CFA

In addition, the overall performance of both types of concrete is depicted in Figure 5c. From this figure, one can conclude that the average performance of CFA is greater than that of CBA, which has the same trend for compressive strength results. Generally, flexural strength is lower compared with compressive strength for most cases of concrete [17].

Splitting tensile strength

Figure 6 shows the overall performance of concrete in terms of its splitting tensile values. Splitting the tensile values indicates the tensile strength of the concrete. It is estimated that the tensile strength of concrete is typically 10% of its compressive strength. Splitting tensile strength is critical for the design of concrete structural elements subjected to transverse shear, shrinkage, torsion, and thermal stresses [17].

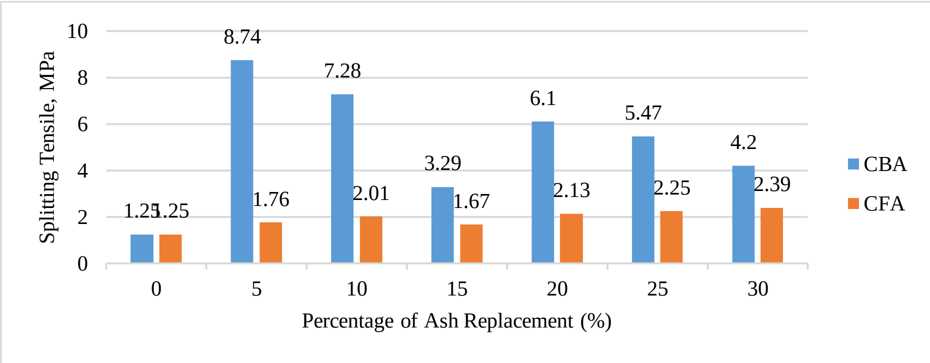


Fig. 6. Overall data for splitting tensile strength of all concrete specimens containing CBA and CFA

In figure 6, the highest splitting tensile strength for CBA specimens is obtained for the specimen with a value of 8.74MPa. For the highest CBA replacement in concrete, the splitting tensile strength achieved is only 4.2MPa. For 15% CBA replacement, the strength is 3.29MPa which makes it the lowest value. However, this value may be inaccurate due to its sudden drop from 10% CBA and may require extensive examination or repetitive experimental work to be done. Overall, CBA specimens show a negative linear trend. The higher the amount of CBA being replaced in the mixture, the lower the values of splitting tensile strength. However, that is not the case for CFA samples. It shows that the more CFA added to the specimens, the greater the value of the splitting tensile. Figure 6 also indicates that CFA contributes to the increasing trend in tensile strength. The highest value is for specimens containing 30% CFA. Nevertheless, even though CFA contributes to positive trends, the maximum splitting tensile values obtained did not reach strength in all CBA specimens. During splitting tensile, all concrete substrates were bonded well together, thus giving the appropriate results. It shows that specimens could sustain high loading because of the additional calcium from the ashes.

Conclusions

The compressive strength of the concrete is relatively higher compared with the flexural and splitting tensile strengths of all concrete samples. From the results of compressive strength and flexural strength, CFA performs better than CBA in concrete, which is due to the chemical composition of the ash. For CBA, compressive strength and flexural strength are reduced when the percentage replacement is increased. On the other hand, the greater the amount of CFA added to the mixture, the greater the compressive strength. The splitting tensile strength of the concrete samples for CBA samples shows an inconsistent trend and requires further experimental investigations. The utilisation of combustion ash as a partial cement replacement shows promising potential in concrete, as shown in its engineering properties. It is hoped that this effort to preserve nature can be further investigated so that the aim to create a more sustainable environment does not end in vain.

Acknowledgments

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