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Material Characterization and Optimum Usage of Coal Bottom Ash (CBA) as Sand Replacement in Concrete

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Abstract: Recently, the deficiency of natural sand is considered one of the most important thoughtful issues in the construction industry as it is one of the raw materials of concrete. The use of industrial waste by-products as an alternative material in concrete production is one solution to natural sand depletion. Therefore, the aim of this study is to investigate the properties of the concrete containing Coal Bottom Ash (CBA) produced by coal-based power plants as sand replacement material. Initially, physical, chemical, microstructural properties like specific gravity, density, sieve analysis, X-ray fluorescence and scanning electron microscopic were investigated. Then, the optimum replacement of sand with CBA was determined based on the workability, compressive and splitting tensile test. The results displayed that the physical properties of CBA are similar to sand. Moreover, CBA was classified chemically as Class-F ash. It was found that the optimum replacement dosage of CBA with sand is 10% in which achieved the targeted/designed strength. In general, CBA has good potential to be utilized as a sand replacement material.

Keywords: Coal bottom ash, sand replacement material, workability, compressive strength, splitting tensile, and pozzolanic

1. Introduction

Nowadays, the abundant of natural aggregates as main materials in concrete was affected by the aggressive construction development [1]. Aggregates including fine aggregates were occupying more than 70% of volume in concrete mixture and it was considered as main constituent material in concrete production [2]. The higher demand for construction development has increased the utilization of fine aggregates which commonly obtained by mining from the rivers beds. The raise of sand mining activity not only changes the aquifer of the rivers beds but also affects the environmental issues [3]. In such a situation the construction industry is looking for alternative sand replacement materials since the river sand has been depleted continuously. Accordingly, industrial waste by-products such as coal bottom ash (CBA) from thermal coal-power plants becomes popular and has been utilized as fine aggregate replacement in concrete. However, the ability and character of CBA as sand replacement material should be studied before it used as replacement material in concrete.

Coal bottom ash (CBA) is well known as a waste by-product and non-combustible material produced from the combustion of the furnace in the electrical power plant. Literally, there are four electrical power plants in Malaysia

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which are Sultan Salahuddin Abdul Aziz in Kapar Selangor, Tanjung Bin Power Plant in Pontian Johor, Sultan Azlan Shah in Manjung Perak and lastly in Negeri Sembilan which is at Jimah Power Plant that use a coal as a main material to produce electricity [4]. Each of coal fired power plants produced large quantities of coal waste products [5]. In fact, there are 80% of product after coal burning process is fly ash which has been industrialized in cement production and the other 20% is bottom ash. The bottom ash were collected at the bottom of the furnace during the burning process. According to Vikas [6], the physical character of CBA is the glassy, porous, uneven shape, greyish in colour, and coarser compared to fly ash.

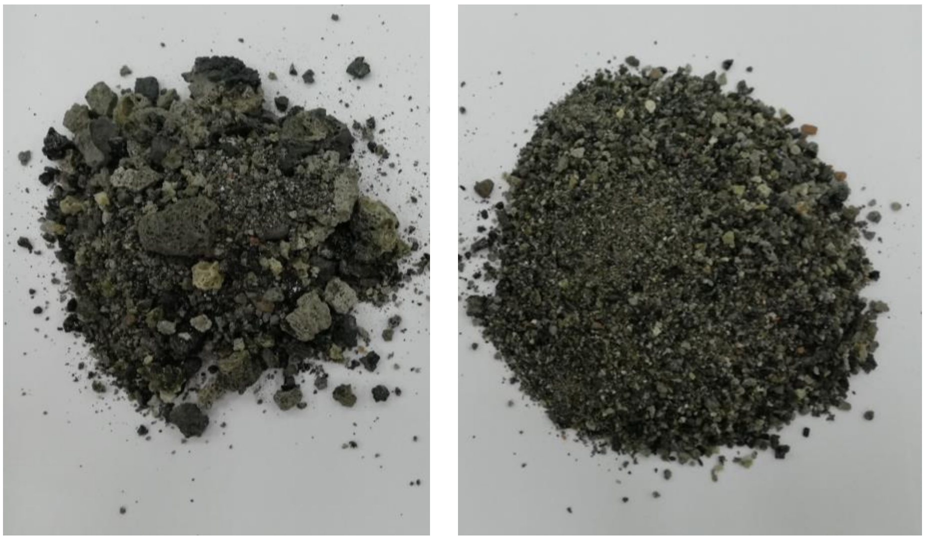
Kiran and Sanjith [7] mentioned that CBA could replace the fine aggregates due to its character was coarse and less pozzolanic compared to fly ash. It is also mentioned by Abhishek and Gobind [8] which the particle size of CBA also looks similar to the natural sand appearance. A study by Abdulhameed et al. [9] showed that CBA has the potential to be a replacement of sand in concrete in which the results displayed that the compressive strength of concrete containing 5 to 20% of CBA was higher than control concrete. Meanwhile, a study conducted by Bakoshi [10] indicated that the CBA concrete has the ability to produce a better strength of concrete in long term period. Moreover, the tensile and compressive strength increases gradually as the percentage of CBA replacement, and curing day increase. Singh [11] investigated the furnace bottom ash towards its workability, permeability, compression strength, chloride penetration, and carbonation test and found that the workability of concrete was increased while the compressive strength decreased. The bottom ash concrete was achieved higher values than the normal concrete in terms of carbonation, sorptivity and air permeability. Besides that, bottom ash also has been utilized as sand replacement in the auto-claved and geo-polymer mortar as per conducted by Sathonsaowaphak et al. [12] and Kim and Lee [13]. The replacement percentage and particle size distribution of bottom ash is the causes of the concrete strength improvement [14].

Conclusively, there are many applications of CBA that meet the requirement in many sectors of civil engineering as it can replace the fine aggregates [15-17] such as in building blocks and bricks, road construction, sound insulated walls, pavement, and highway development. However, the amount of CBA that can be a replacement for sand to produce a better performance of concrete need further investigated in order to achieve the target strength. Hence, this paper aimed to find the optimum percentage and influences of CBA as sand replacement materials against concrete properties.

2. Experimental Program

2.1 Materials

CBA was collected from Coal-Fired Power Plant, Pontian, Johor, Malaysia. CBA was dried in an electronic furnace at a specified temperature of 110°C at a heating rate of 20 C°/min for 24 hours and allowed to call to 20 C°. The dried CBA sieved into sieve passing 5mm and then used as sand replacement. Fig. 1 shows the raw and sieved CBA. Other than that, Type-I of ordinary Portland cement (OPC) was used which comply with MS EN 197-1:2014 [18]. Passing 10 mm and 5 mm in size of uncrushed coarse aggregate and uncrushed river sand (fine aggregates), respectively were used. The conditions for all the materials used were in accordance with BS EN 1200:2013 [19] which is stored in air and watertight containers to avoid atmospheric humidity contact. Lastly, tap water was used during casting.



(a) (b)

Fig. 1 - (a) Raw CBA, and (b) Sieved CBA

2.2 Mixture Design of Concrete

The concrete mixture proportion was designed and calculated based on the DOE method (Concrete Mix Design of British Standard) for grade G35 with a target strength of 35 MPa at 28 days. All the water-cement ratio of mixes was fixed at 0.55. Six different series of CBA as partial replacement of sand; 0% CBA was acting as a control specimen, 10%, 20%, 30%, 40% and 50% of CBA to replace sand by volume. The six different concrete mixture proportions were tabulated in Table 1.

Table 1 - Details of Concrete Mix proportions (kg/m^3)

Optimum Content of Coal Bottom Ash						
Series	**Replacement Level (%)**	**Cement (kg/m^3)**	**Water (kg/m^3)**	**CBA (kg/m^3)**	**Sand (kg/m^3)**	**Coarse Aggregate (kg/m^3)**
M1	0	13.52	7.44	0	31.89	28.23
M2	10	13.52	7.44	3.19	28.70	28.23
M3	20	13.52	7.44	6.38	25.51	28.23
M4	30	13.52	7.44	9.57	22.32	28.23
M5	40	13.52	7.44	12.76	19.13	28.23
M6	50	13.52	7.44	15.95	15.94	28.23
Total	-	81.12	44.64	47.85	143.49	169.38

2.3 Experimental Tests and Specimens Preparations

The experimental work was investigated the materials characterization and properties of concrete containing CBA as sand replacement material. CBA and sand were classified in terms of physical, chemical and microstructure properties. The physical tests consist of sieve analysis, specific gravity, and density were conducted according to BS 410: 2000, ASTM D2320-98 and BS EN 12390-7 respectively [20], [22]. Meanwhile the chemical properties was determined using an X-ray fluorescence test in accordance with BS ISO 29581-2:2010 [23]. Furthermore, a scanning electron microscope (SEM) was conducted as per ASTM E2809-13 [24] on sieved CBA and sand to examine the microstructure properties of the materials.

On the other hand, two major tests which are compressive and splitting tensile tests were conducted to determine the optimum content of CBA as sand replacement in concrete. The cubes with the dimension of 100 mm were used for compression tests as per BS EN 12390-3:2009 [25], while the cylinders with a size of 200 mm (height) x 100 mm (diameter) were used for the splitting tensile tests according to BS 1881: 117: 1983 [26]. Three specimens of each series at the age of 7, 28 and 56 days for each test were cast by a total of 54 cubes of compression test and 54 cylinders of splitting tensile test. Furthermore, the fresh properties of concrete were performed using slump test to obtain the workability of concrete in accordance with BS EN 12350-2 [27].

3. Results and Discussion

3.1Physical Characterization of CBA and Sand

In the plot of Fig. 2, the CBA and sand have similar particle sizes distribution and fall within the lower and upper limit of fine aggregate as per BS 882: 1992 [28]. The size ranges were from 150 µm to 5 mm and it would be defined as fine aggregates. From previous studies, the distribution of CBA from Tanjung Bin Power Plant was classified from fine gravel to fine sand as its particles consist of low silt-clay percentages [29 & 30]. Therefore, the CBA that was used in this study is acceptable to be used by partially replacing the fine aggregates with different proportions in concrete.

On the other hand, the results of the density and specific gravity displayed that the density of CBA was lower than sand which is 789.14 kg/m^3 and 1250.54 kg/m^3 respectively. According to study by Aggrawal [31], CBA has a benefit in light-weight concrete since it has a lower density compared to sand. Next, the specific gravity value also presents that value of CBA was lower than sand which is 2.34 (CBA) and 2.86 (sand) due to higher carbon content in CBA that contribute to lower value. Based on the research of Andrade [32], different power plant station has a different value of specific gravity which is in between 1.39 to 2.66.

3.2 Chemical Properties of CBA and Sand

Based on the X-ray fluorescence (XRF) test, it can be seen from Table 2, the major amount of chemical composites found in CBA were Silicates (SiO_2), Aluminates (Al_2O_3) and Iron oxide (Fe_2O_3). It was classified as a Class F due to its total concentration percentage of SiO_2 + $Al2O_3$ + $Fe2O_3$ compounds surpass more than 70% which is 74.17%. This percentage was higher than sand due to CBA particles is more glassy and contains ferrous and non-ferrous metals. ASTM C618 [33] was explained that Class F was referred to the pozzolanic type and it can be recognized as Bituminous Coal which produces less calcium content. Besides that, both of silica content inside CBA and sand was high which is 53.80% and 52.0% respectively. Silicon oxide is necessary for concrete mixing as it is one of the important compounds. As reported by Ghassan et al. [34], CBA that has a high content of silica will have a high cementitious property which is called a pozzolanic. In conclusion, the chemical composition of CBA was indicated its benefits to be used as a pozzolanic material in concrete due to the high percentage of silica content. Therefore, the presence of CBA as a replacement material of sand may result in enhancing the concrete strength.

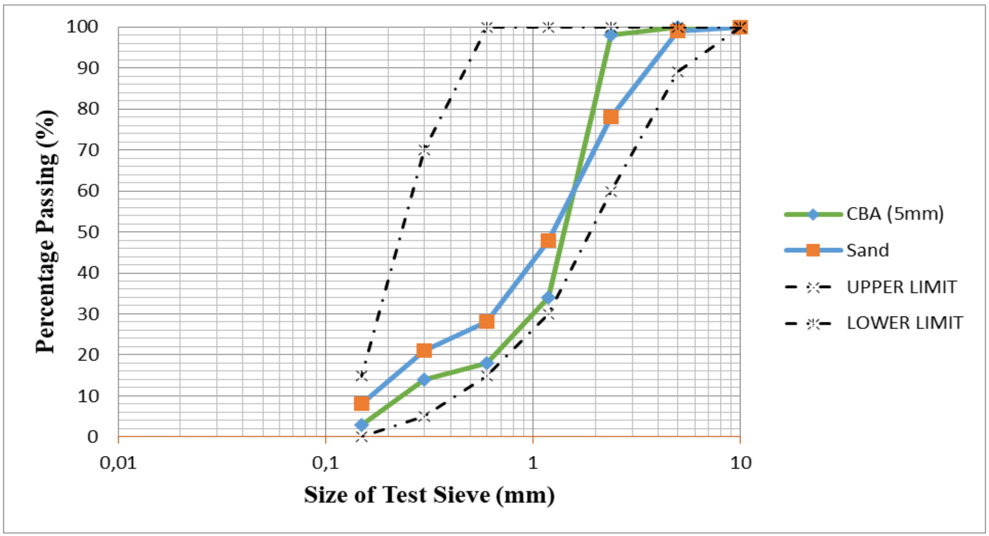


Fig. 2 - Grading analysis of CBA and sand

Table 2 - Chemical composition of CBA and sand

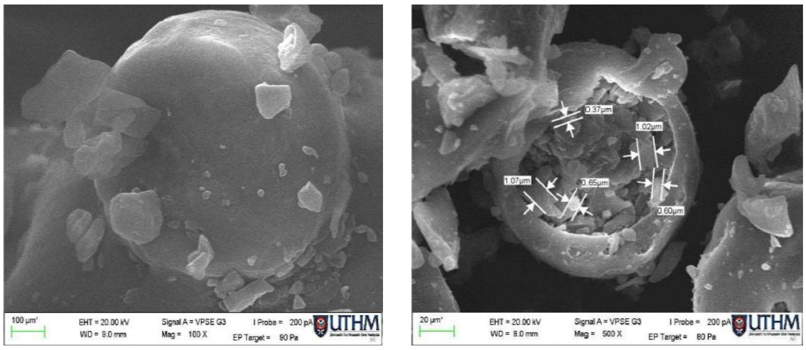
Chemical Composition	Coal Bottom Ash	Sand
Bottom Ash	8.00	8.00
Added (Wax)	2.00	2.00
SiO_2	53.80	52.00
Al_2O_3	15.10	6.62
F_e2O_3	5.27	0.37
C	0.10	-
CaO	1.32	0.46
K_2O	1.00	0.42
TiO_2	0.91	0.54
MgO	0.53	-
Na_2O	0.23	-

3.3 Microstructure Properties of CBA and Sand

Scanning Electron Microscope (SEM) was used to assess the microstructure images of CBA and sand in this study. It was observed that CBA has round, angular form, porous and irregular shape particles as highlighted in Fig. 3(a). In addition, the appearance of CBA could have an influence on the crystallite (C_3S) and anamartinez (C_2S) [35]. It can be concluded that CBA seems to be denser than sand in some areas, while in other areas, it is highly porous with the smallest size which is 0.37µm as shown in Fig. 3(b). Meanwhile, Fig. 4 shows the microstructure images of sand which have fine surface, compact and disjointedness texture.

3.4 Fresh Properties of Concrete

In this study, slump test was conducted to perform the workability and consistency of fresh concrete. Six different batches of concrete containing CBA as sand replacement material were tested and the results are shown in Fig. 5. Based on the figure, it is clearly showing the decrement in slump height from control up to 50% replacement of sand with CBA which is from 65 mm to 40 mm. It can be seen the workability of control concrete mixtures was higher than concrete containing CBA mixtures. Obviously, the increment of the CBA amount was lead to the decrement of concrete workability. For instance, the slump height of 50% CBA replacement was lowered than 10% CBA replacement which is 58 mm and 40 mm, respectively. This is due to the particle fineness of CBA which increases the surface area; therefore, more water was absorbed by the concrete mix [36]. Besides that, Abhishek et al. [37] also found in his study that the workability of concrete decreases with the addition of CBA as a sand replacement due to the high porosity of the CBA surface, hence required more water than sand. A study by Amrak [38] reported that about 25 to 50% of the water content of CBA concrete must be higher than control concrete in order to achieve better workability. Nevertheless, the height of slump for these six types of the mixture still acceptable and within the range, as specified in mixture design.



(a) (b)

Fig. 3 (a) - SEM of CBA (100µm), and (b) – SEM of CBA (20µm)

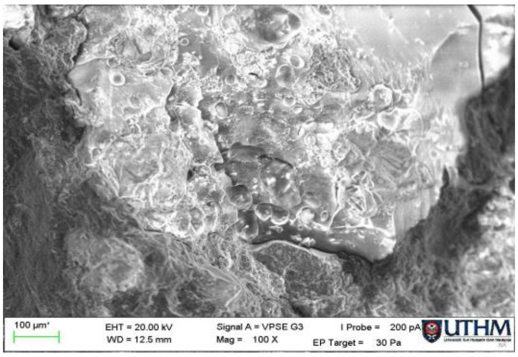


Fig. 4 - SEM of sand

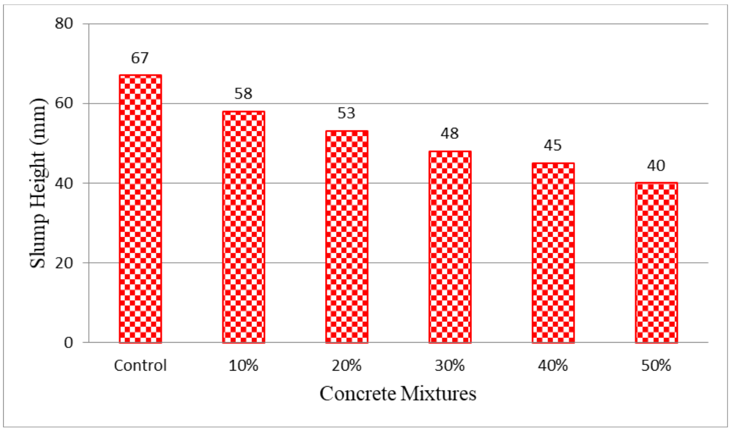


Fig. 5 - Comparison of slump height test of CBA concrete

3.5 Hardened Properties of Concrete

3.5.1 Compressive strength test

The result of compressive strength test was presented in Fig. 6. The results were evaluated in order to obtain the optimum strength of CBA content as sand replacement in concrete. Referring to Fig. 7, the highest strength of CBA replacement was achieved by 10% of replacement which is 58.3MPa at 56 days. The strength is 15% slightly higher than the control specimen. It can be observed that the compressive strength of CBA concrete was reduced as the level of CBA replacement increases. For instance, 10% of CBA replacement gained about 58.3 MPa of strength while 50% replacement only achieved 38.2 MPa at 56 days of curing. This observation is similar to Bakoshi et al. [39] as he explained that excessive usage of CBA in concrete mixtures was contributed to the porous structure of concrete, therefore the compressive strength of concrete will be reduced. Furthermore, CBA concrete gains strength slowly at the initial stage and faster gaining at later ages which is beyond 28 days due to the pozzolanic reaction of CBA is not initiated at an early age. It could be seen from Fig. 7, the strength of concrete at 7 and 28 days is lower than the strength at 56 days of curing. At the curing age of 56days, the compressive strength of concrete mixtures containing 10% of CBA surpassed that of control concrete although the strength of 10% CBA replacement was lower than control mixtures at 28 days which is 37.1MPa and 39.7MPa respectively. CBA presence could affect the hydration process and low pozzolanic reaction to compose a C-S-H gel of concrete at the early days of curing [40]. Hence, as a conclusion, 10% of CBA was found to be optimum replacement level in replacing the sand in concrete as the strength is the most sufficient and the targeted strength was achieved.

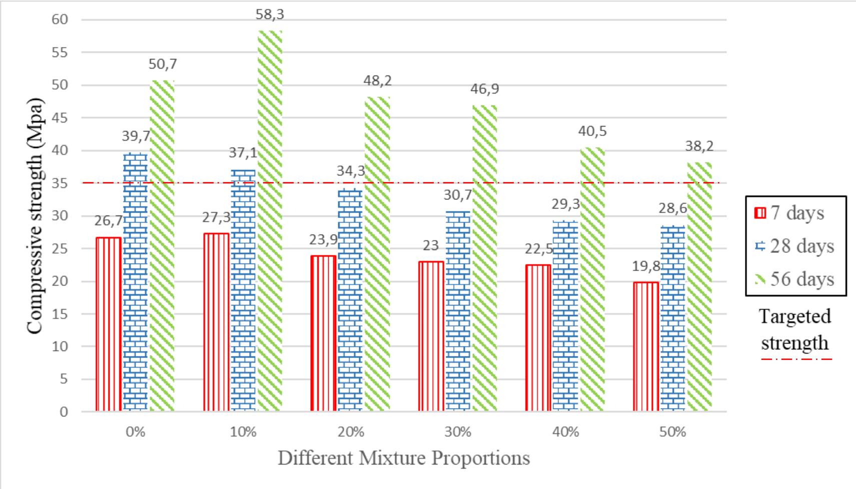


Fig. 6 - Compressive strength of different replacement percentage of CBA

3.5.2 Splitting tensile strength test

The variation results of splitting tensile with different curing days and replacement percentage of CBA were illustrated in Fig. 7. It was examined that the splitting tensile strength of 10% replacement of CBA at 56 days was the highest strength compared to other mixtures. The concrete containing CBA showed a reduction of splitting tensile strength with the additional percentage of CBA. For example, 50% of CBA replacement acquired about 1.78 MPa while 10% of CBA replacement gained about 2.3MPa at 7days. It could be a porous, angular and irregular shape of CBA particles was contributed to the strength reduction of splitting tensile strength [41]. However, the spilling tensile strength shows an increment with the increase of curing ages. According to Wan Ibrahim et al. [42], the C-S-H gel in concrete started to develop at longer curing periods. It can be concluded that 10% of CBA is suitable to be a replacement of sand in concrete as its strength was 10% higher than control mixtures.

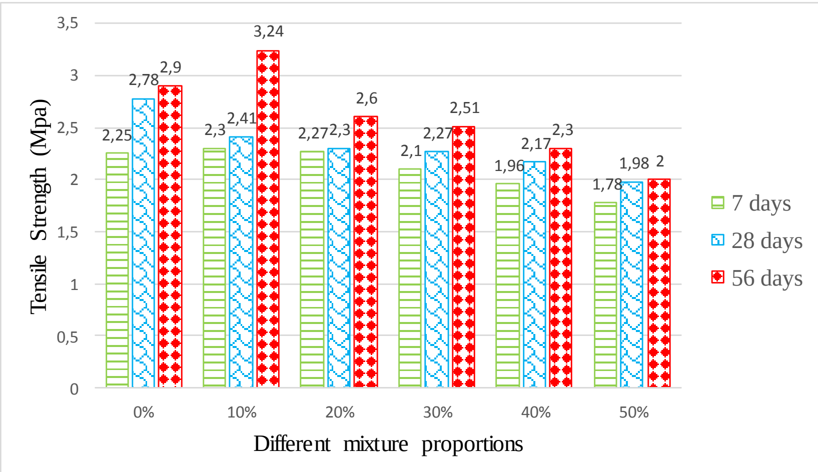


Fig. 7 - Splitting tensile strength of different replacement percentage of CBA

4. Conclusions

The material characterization of CBA and the optimum usage of CBA as partial replacement of sand in concrete have been analysed and discussed in this study. On the basis of the findings, the following conclusions are drawn:

- CBA particles have a porous structure, uneven shape, angular and coarse texture compared to sand which is more fineness. CBA and sand have similar particle sizes distribution as the distribution size was passing the ranges and limits. Overall, CBA that collected from the Tanjung Bin Power plant is acceptable to be used as sand replacement material in concrete.
- CBA has a lower density and specific gravity value compared to the sand due to a high porosity on its surface and light-weight character that contributes to less compaction.
- CBA can be classified as a Class F due to its total concentration percentage of SiO_2, Al_2O_3 and Fe_2O_3 account for about 74.17%. It can be used as a pozzolanic material to enhance the concrete strength due to its containment of the high amount of silica compounds.
- The workability of CBA concrete was decreased when CBA percentage in concrete increase due to its porous surface, which absorbed more water during the mixing of the concrete.
- The strength for all mixes was increased with the increase of curing age due to the pozzolanic reaction that could not perform at the early age of curing. However, the compressive strength of concrete was decreased when the percentage of CBA increases. The highest strength of 58.3 MPa for the concrete was achieved by 10% of sand replacement with CBA, and the lowest strength of 38.2 MPa was gained by 50% of sand replacement with CBA at 56 days. Therefore, 10% of CBA as a partial replacement of sand was found to be the optimum amount as it was achieved the targeted/designed strength.
- Similar to compressive strength, the splitting tensile strength was reduced with the increase of CBA percentage in the concrete. The highest tensile strength was obtained with 10% of sand replacement with CBA.
- Overall, 10% of sand replacement with CBA was determined as the optimal amount to replace the sand in concrete as it had an improvement in strength compared to the control concrete. Hence, it is recommended to further investigate on the flexural and elasticity strength of concrete containing CBA as sand replacement material.

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