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Investigating the Reaction of Coal Bottom Ash (CBA) as Partial Cement Replacement in Mortar

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Abstract: Malaysia generates approximately 8.5 million tonnes of coal ash as waste per year, which includes bottom ash and fly ash. Increasing amounts of coal bottom ash (CBA) from coal power plants becomes raising concerns as a huge amount of waste is currently landfilled. The wide production of Portland cement has a great environmental concern in terms of carbon dioxide (CO_2) emissions. This study investigates the effect of varying ratios of alkali-activated coal bottom ash (CBA) as a partial replacement for cement mortar. CBA mixtures have been activated with the calcium chloride $CaCl_2$ solution. Mix proportion used for this study was 1:3: 0.5. Four sample were used in this study. CBA were used as a partial cement replacement (CBA/OPC) at varying ratios of 0%, 20%, 40%, and 60% mixed with 0%, 2%, 4% and 6% alkali activator content which is Calcium Chloride ($CaCl_2$) as a core binder. The effects of these substitutions on the workability were investigated using the Flow Table Test according to ASTM D 792. The result found that the increase CBA, the increase of flow in mortar. Physical properties CBA were analyse using Particle size analyser (PSA) according to ASTM C 1467 standard. Identical result found from the (PSA) has confirmed that CBA can be utilized as supplementary cementitious material when the specific gravity for both CBA and OPC were shown 2.67, respectively. Other than that, the particles diameter of CBA D10, D30, and D60 are more finess than OPC.

Keywords: Mortar, Coal Bottom Ash, Flow Table Test, Hydration Heat Measurement

1. Introduction

According to [1] coal bottom ash (CBA) is produced by coal power plants and consists of coarse and glassy particles that congregate at the bottom of the furnace. It is composed of agglomerated ash particles that are too large to be carried in the flue gases and fall through open grates to an ash hopper at the furnace's bottom [2]. The use of BA as a pozzolanic material may necessitate some treatment for increased effectiveness. Nowadays, waste materials has gained a high attention among researchers as a

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replacement to cement and aggregates in mortar or concrete CBA has a high tendency to act as a pozzolanic material, which improves the concrete durability [3] Previously, it was thought that the use of CBA reduces the permeability of water through mortar [4] The sense of recycled a waste material for conventional products aiming not only for sustainable purposes and reduce environmental impacts as more solid waste produces day by day. Its potential benefits include lower density and higher hydraulic conductivity than natural soils, as well as greater strength compared to artificial lightweight aggregates [5]. Besides, it also available locally, low cost and easy to handle as it technically equivalent to the original materials. Innovation in this kind of works are the great concerns to maintain sustainability. Recycling and recovery of waste considered as a promising solution to meet the deficit between production and consumption and protecting the environment [6].

The wide production of Portland cement has a great environmental concern in terms of carbon dioxide (CO_2) emissions [7]. [8] stated that cement production could represent nearly 10% of total global warming CO_2 emissions in the near future due to a world-wide increase in the demand for ordinary Portland cement (OPC). Furthermore, the limestone harvesting in this country increases to meet the demand of cement industry [3] In order to deal with the growing concern of CO2 production caused by cement manufacturing industries, many studies were carried out to find more environmentally friendly supplementary cementitious materials. It is desired to design and develop a sustainable binder to reduce the demand for cement in the construction industry [9].

[10] [11][12] stated that CBA particles are angular, irregular, and porous, with a rough surface texture. BA particles have dark, angular shapes with porous textures. Declared by [13] the grinding process is an important stage for CBA in the production of mortar. Mentioned by [14] after grinding, CBA has pozzolanic properties and has a high potential for use as a cement replacement material in concrete production. The grinding operation were carried out to reduce porosity and improve the pozzolanic properties of BA [3]. BA low specific gravity is explained by its low iron oxide content. The presence of BA particles was porous or vesicular textures. BA particle porosity influences apparent specific gravity [15]. Reveals that the specific gravity are varies from 1.67 to 2.41 while the surface are varies in 3635.70 cm^2/g to 3960.00 cm^2/g from the previous study by [16] [12] [17][16][17][18][19].

Chemical additives are powdered materials that are added to the cement mixture to extend the hydration time of the cement matrix [20]. Alkali activation was used to improve the natural pozzolanic properties of various materials [21]. Furthermore, as the BA content increases, it may cause a reduction of workability and increase the porosity. When the replacement level of the bottom ashes higher, the flow of the mortars was reduced. Besides that, flowability is affected by various factors: for example, raw material type, water-to-cement ratios, and superplasticizer usage [10]. According to [10]The limit diameter of mortar for proper casting is 20.5cm to 21cm. A range flow limit of control and BA mortars were prepared in between 100 and 110.

Highlighted by [22] when cement is exposed to water, heat is produced. The cement hydration reactions are exothermic [4][23] The amount of heat released is determined by the properties of the cement, the ambient temperature, and the thermal properties of the system [21]. The main constituents of Portland cement are calcium. The amount of calcium in the mix will definitely influence overall heat development. A high cement content in concrete may be beneficial for achieving a higher initial strength. However, the increased heat as a result of chemical reactions can cause concrete durability issues such as cracking and shrinkage [23].

Therefore, the aim of this study is to examine the physical properties of mortar with activated alkali CBA and to investigate the effect of fresh and hardened mortar consisting activated alkali CBA as partial cement replacement.

2. Materials and Methods

The materials and methods section, otherwise known as methodology, describes all the necessary information that is required to obtain the results of the study.

2.1 Materials

In this study, original CBA obtained from Manjung Power Station, Perak, Malaysia also known as Sultan Azlan Shah Coal-fired Power Plant were used. Activate using calcium chloride ($CaCl_2$) alkali activator. CBA collected were dried in an oven at a temperature of 110±5˚C for 24 hours. Original CBA was then placed in Los Angeles (LA) machines for 8 hours per day for 6kg. This process was continued for two days to convert 100% CBA to achieve the desired particles size. The particles are then collected for further experiment. Next, a sieving process were done to isolate the particles. CBA passing 63 microns consider fine particles in this study. Figure 1 shows the different particles size of CBA.

a) Original CBA

b) CBA retained 63micron

c) CBA passing 63micron

Figure 1: Different Particle size CBA

In this study, $CaCl_2$ was chosen as additive alkali for CBA. Cementitious mixtures were made by combining various proportions of activated CBA and Ordinary Portland Cement (OPC) type I 42.5 R with a water/total solids weight ratio of 0.5. The investigated CBA/(CBA + OPC) ratios were 0%,20%,40% and 60% w/t ratio respectively, whereas the activator additions used (expressed as activator/CBA ratio) were 0%, 2%, 4% and 6% wt ratio. Figure 2 shown the type of alkali used for this study[21].

Figure 2: Calcium Chloride, $CaCl_2$

2.2 Design mixes

In this study, mix designs for Flow Table Test (FTT) and Hydration Heat Measurement (HHM) were different in terms of quantities of materials to produce mortar. Cement, alkali-activated CBA, sand, and water are properly mixed in dry conditions. The proportion of mortar used was one part of cement (5, 1), three-part of CEN standard sand (5, 3), and one-half part of water (5, 0.5) (water/cement ratio 0, 50) 1:3:0.5 as shown in table 3.2. There are four samples with different percentages of CaCl2 and CBA used in this study. CBA was varied from 0%, 20%, 40% and 60% by weight of cement. While, CaCl2 was varied from 0%, 2%, 4%, and 6% by weight of CBA, respectively for each specimen. Water is then added gradually and mixed using a shovel. The water-cement ratio was fixed to 0.50. There should be no clay and other impurities in the water. Cement mortar was then operated by hand-mixed.

i. Flow table test
For FTT, four different mix designs were prepared. The first one is a control mix for the comparison of the others. The mix designs were prepared with a fixed initial w/c ratio, 0.5. The control mix was prepared with 2350-g sand, sand, 450-g cement, and 225-g water. Table 1 lists the mix design proportions chosen in this study.

Table 1: Mix Design Ratio of CBA Mortar Specimens for FTT

Mixes Codes	Cement (g)	CBA (g)	$CaCl_2$ (g)
Control	450	-	-
20% CBA, 2% $CaCl_2$	360	90	1.8
40% CBA, 4% $CaCl_2$	270	180	7.2
60% CBA, 6% $CaCl_2$	180	270	16.2

ii. Hydration heat measurements
For HHM, 4 different mix designs were prepared. The first one is a control mix for the comparison of the others. The mix designs were prepared with a fixed initial w/c ratio, 0.5. The control mix was prepared with 8190-g sand, 2730-g cement, and 1365-g water. Table 2 lists the mix design proportions chosen in this study.

Table 2: Mix Design Ratio of CBA Mortar Specimens for HHM

Mixes Codes	Cement (g)	CBA (g)	$CaCl_2$ (g)
Control	450	-	-
20% CBA, 2% $CaCl_2$	360	90	1.8
40% CBA, 4% $CaCl_2$	270	180	7.2
60% CBA, 6% $CaCl_2$	180	270	16.2

2.3 Testing Method

i. Physical size analysis
This experiment were done to examine the particle size properties between CBA and cement sample. For CBA, diluted a spoon of CBA into 250ml beaker which contains with 50ml distilled water as shown in Figure. Make sure the water free from any impurities. Next, prepared a two beaker of 100ml water. Then, set the information in software before run the experiment. After that, put the sample into CILAS. When the beaker at software turns red, put water in 100ml

beaker into the CILAS until it turns blue. Wait for a few minutes. If the beaker at software turns red, put water again until it turns blue. Repeat the procedure until it achieved the result. Result of the experiment was obtained from the software. The same procedure were repeated for cement sample.

Figure 3: CBA sample diluted with distilled

Figure 4: put sample into PSA CILAS

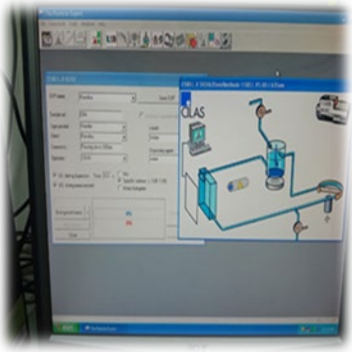

Figure 5: CILAS software

ii. Flow table test

This laboratory test was conducted according to [10]. The fresh mortars were tested following ASTM C1437 requirements to determine the flow level of the mortars for different percentages CBA and $CaCl_2$. During this experiment, 0.50 water cement ratio were fixed for all sample. The flow of four sample mortar with different percentages CBA and $CaCl_2$ were investigated. The test was started with control sample. Ensure the flow table and flow mould apparatus meet the requirements of ASTM C230. Mixed all the materials by hand mixed using shovel. The flow mould was positioned in the centre of the freshly cleaned and wiped flow table. The mortar was layered into the mould about 25 mm thick and tamped 20 times. Next, the rest of the mould was filled with mortar and tamped 20 times more. Then, cut off the excess mortar. As a result, the mortar was evenly distributed throughout the mould. The top of the mould was plane and cleaned the surface of the flow table, especially if there was water on the flow table. After that, lift the mould away from mortar one minutes after the completion of mixing operation. Then, immediately drop the table through a height of 12.5mm for 25 times in 15 seconds. Lastly, measured at least three diameters of mortar. Repeat the same procedure for 20% CBA 2% $CaCl_2$, 40% CBA 4% $CaCl_2$ and 60% CBA 6% $CaCl_2$. The flow table are shown in Figure 6.Repeat the same procedure for 20% CBA 2% $CaCl_2$, 40% CBA 4% $CaCl_2$ and 60% CBA 6% $CaCl_2$. The flow table are shown in Figure 6.

Figure 6: Flow Table

iii. Hydration heat measurement

The hydration heat measurement designed for this research was based on the method used by previous researchers such as [24]and [23]. Plywood with size 300 mm x 300 mm x 450 mm cube was used as the exterior mould. In this study, polystyrene 76 mm thick acted as the insulator. The cylindrical mould with a diameter of 150 mm and a 300 mm height was used to fill the mortar mixed, as shown in Figure 8. A thermocouple (Type K) was inserted into the centre of each box. In this study, the thermocouple serves as a temperature sensor instrument that measures the degree of hotness or coolness from the mortar in the mould and converts it into a readable unit. Then, thermocouples are connected to the data logger system, whereas these electronic devices play a big role in monitoring and recording environmental parameters automatically over time, as shown in Figure 7. Temperature recording of mortar continued for 72 hours for each composition.

Figure 7: Thermocouple Connected to Data Logger System

Figure 8: Mortar filled in an insulated cylinder

3. Results and Discussion

3.1 Physical size analyser

Specific surface area was evaluated through particle size analyser (PSA). Specific gravity for the sample can be calculated manually by using the density per factor result. According to PSA result, the density per factor for both CBA and OPC was 2.66g/cm^3/1.00. The density of water are 0.997g/cm^3. The specific gravity can be calculated manually according to ASTM D792 standard by using the equation 4.1 below. It was found that the specific density was 2.67. The details of physical properties provided in Table 3 below.

Table 3: Physical properties OPC and CBA

Sample	Specific Gravity	Range of Particle Size (Micron)			Specific Surface Area (cm^2/g)
		D10	D30	D60	
CBA	2.67	1.36	5.95	13.73	6927.01
OPC	2.67	1.68	7.23	15.67	6227.21

3.2 Flow table test

Table 4: Flow table test result

Mixes Name	w/c	Diameter (cm)	Terms of Flow
Control	0.5	20.5	105
20% CBA, 2% $CaCl_2$	0.5	21	110
40% CBA, 4% $CaCl_2$	0.5	22	120
60% CBA, 6% $CaCl_2$	0.5	23	130

The effect of CBA as partial cement replacement in mortar mixtures on flow values is tabulated in Table 4. Flow values are given in between Figure 4.4 with water to cement ratios for each mix. Flow values of control mixes for mortars were 105 mm. The flow values were found between 105 - 130 mm. The consistency was found to be increased because the presence of CBA in the paste absorbed more water than the normal OPC paste. According to the Figure 4.5, only flows in control and 20% CBA, 2% $CaCl_2$ are in the flow range limit. The consistency for both was resulted wet. While, 40% CBA, 4% $CaCl_2$ and 60% CBA, 6% $CaCl_2$ sloppy.

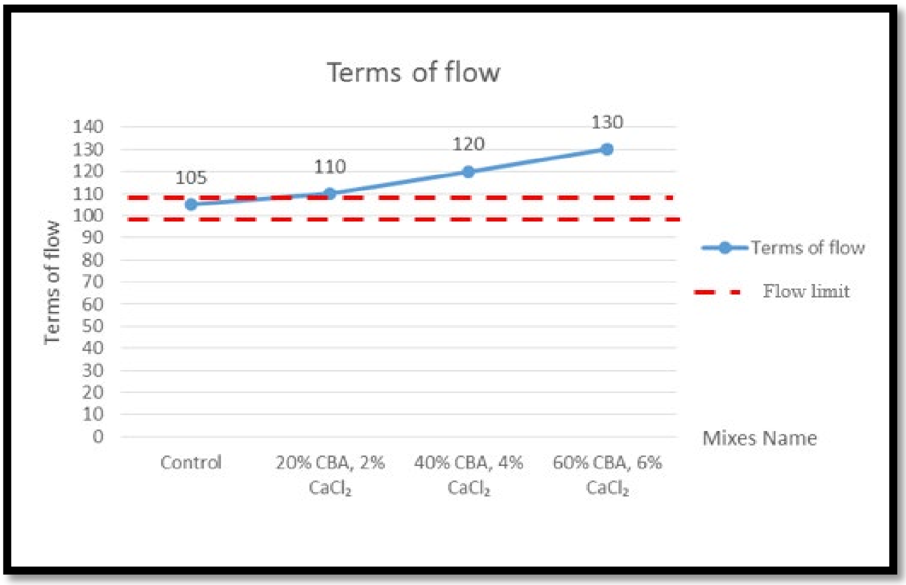

Figure 9 Terms of flow for each flow

Basically, the fine pozzolanic material increases the workability of the cement mortar. As shown in Figure 9 the increases additional $CaCl_2$ and CBA contents in mortar, the increases the flows. The fluidity of paste depends on the thickness of the water film. The amount of the filling water is related to the packing density of the system. Suppose the specific surface of pozzolanic material is extensive, although the filling water can be reduced. In that case, the total amount of water increases due to the significant demand for water in the surface layer.

3.3 Hydration Heat measurement

Recorded data was measured in centre depth cylinder mortar. Meanwhile, temperature development were due to heat liberation at the centre mortar depth during the hydration process of all specimens shown in Figure 10. Other than that, the peak temperature for each sample was summarized in Table 5.

Table 5: Summary of peak temperature

Mix Design	Initial Temperature (˚C)	Peak Temperature (˚C)	Time since mixing to peak temperature (hr)
Control	27	39	18
20% CBA, 2% $CaCl_2$	28	42	17
40% CBA, 4% $CaCl_2$	28	36	15
60% CBA, 6% $CaCl_2$	28	33	16

It has been observed that during the initial reading, the temperature rise for the 20%, 40%, and 60% CBA as partial cement replacement mortars is almost similar, which is 28˚C except for 0% CBA, which is 27˚C. However, these four specimens seem to have reached the maximum temperature simultaneously. Despite the development of thermal temperature behavior approximately being the same, mortar made of 80% OPC with 20% CBA and 2% $CaCl_2$ was recorded at the highest peak temperature of 42°C at 13 hours after casting. The specimen made with 60% OPC with 40% CBA and 4% $CaCl_2$ mortar peaks at 36°C after 11 hours. The specimen made with 40% OPC with 60% CBA and 6% $CaCl_2$ mortar peaks at 33°C after 12 hours, while the control mortar made with 100% OPC recorded a peak temperature of 39°C after 14 hours of casting. High contents of CBA and low $CaCl_2$ in mortar contribute to higher causing the mortar to increase the hydration temperature. The fineness of replacement materials particulates also has been a major factor in boosting the reactivity between all materials and increasing the hydration acceleration of CBA mortars. The lowest peak temperature was achieved by a specimen made of 40% OPC with 60% CBA and 6% $CaCl_{2.}$

After peak temperature reading was recorded, the heat produced was then observed to be decreasing gradually over time to a point where similar temperature reading was achieved for all four specimens. The final temperature recorded at the end of the test for all samples was in the range of 27-41°C. The mortar temperature made of 80% OPC with 20% CBA and 2% $CaCl_2$ started to drop down from 41˚C-27°C at 17 hr. 60% OPC with 40% CBA and 4% $CaCl_2$ started to drop down from 35˚C-27°C at 15 hr. 40% OPC with 60% CBA and 6% $CaCl_2$ started to drop down from 32˚C-27°C at 16 hr. At the same time, the temperature of the control mortar started to drop down from 38˚C-27°C at 18 hr.

The use of a mixture of CBA and CaCl2 in the mortar was observed to be effective in reducing the heat of hydration produced during the curing period and hardening paste. The hydration temperature of mortar depends on the amount of $Ca(OH)_2$ produced in the hydration process of cement and the reactivity of materials used [23]. Huge amount contains in CBA with huge amount of $CaCl_2$, produces high amount of $Ca(OH)_2$ in the hydration products. The observation made below suggest that the partial replacement of OPC by CBA bring a significant effect in reducing the heat of hydration produced during curing by added more amount CBA along with $CaCl_2$.

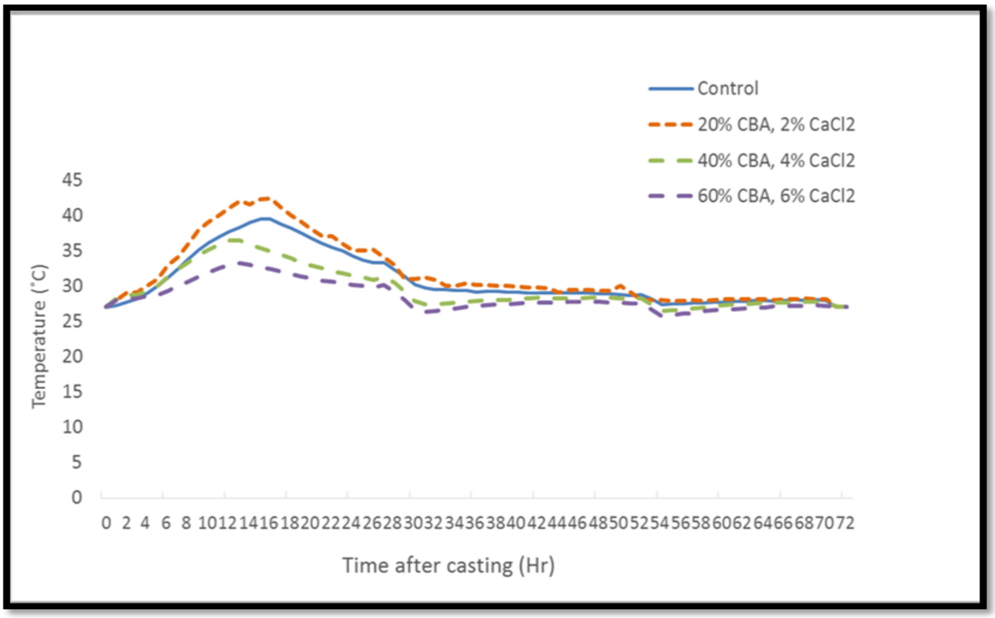

Figure 10 The development of hydration temperature

4. Conclusion

CBA with passing sieve 63micron found similar specific gravity to Portland cement which is 2.67. Specific gravity for CBA were accepted as it not more than cement. Moreover, the specific surface area for CBA found higher than OPC which is 6927.01cm²/g while OPC was 6227.21cm²/g. Range of particle size for CBA found finess than OPC when diameter particles for D10, D30 and D60 was 1.36, 5.95 and 13.73 respectively compared to original OPC diameter which is 1.68, 7.23 and 15.6. Result found from Particle size analyser (PSA) has confirmed that CBA can be utilized as supplementary cementitious material.

The mixture designs on mortar paste during pre-casting were prepared with 0%, 20%, 40% and 60% replacement ratios CBA as partial cement replacement by weight of cement and 0%, 2%, 4% and 6% CaCl2 were used by weight of CBA. The flow on mortar seems to be increased with the used of huge amount CBA and CaCl2 into mortar. The suitable flow range limit for mortar was 105 to 110. A sample of control and 20%CBA,2%CaCl2 are in flow range limit which is 105 and 110 respectively and resulted wet. Meanwhile, 40%CBA,4%CaCl2 and 60%CBA,6%CaCl2 was 120 and 130 respectively and resulted sloppy. The possible reason of this result was causes by the high porosity of the CBA. In this study, the workability of mortar were proved by 20%CBA, 2%CaCl2 as the flow was in the range limit comply with ASTM C1437 standard as partial cement replacement.

For hydration heat measurement, the results showed the specimens with huge amount of CBA and CaCl2 contains in mortar mixes during the hydration process can helped in reducing the temperature of hydration. It was verified by 40%CBA,4%CaCl2 and 60%CBA,6%CaCl2 sample when the peak temperature decreased along with CBA and alkali contains in mortar increased. However, mortar with 20%CBA,2%CaCl2 reached higher peak temperature than control. It might happened because of human error during the material preparation. For example, the amount of CaCl2 contains might be added too much during the activation process with 20% CBA.

Nevertheless, this project has successfully achieved the objectives of the outset with the combination of CBA and CaCl2. This combination has a potential to replace partial cement in mortar mixes.

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