

Mortar Containing Coal Bottom Ash (CBA) Treated with Citric Acid as Partial Cement Replacement

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Abstract

The combustion process, a fundamental aspect of various industrial and energy production activities, plays a pivotal role in generating power and facilitating essential operations. While combustion is an integral part of our energy landscape, it inevitably produces a diverse range of byproducts that have far-reaching implications, for example boiler slag, coal bottom ash (CBA) and coal fly ash (FA). These byproducts have been in interest of researcher to be use as replacement materials in concrete. However, the presence of metallic elements in CBA imposes limitations on its industrial use. Extensive research has been conducted to address the issue of heavy metal amount in CBA. Past research has recommended using strong acid leaching treatment to eliminate metallic impurities from CBA. However, the employment of strong acids poses significant hazards to both human health and the environment. In this study, laboratory test indicate that acid leaching treatment has the potential to reduce metallic elements in CBA under optimum conditions, specifically at a solution temperature of 40°C with a 4% acid concentration during a 60-minute reaction period. The characteristics of CBA under optimum conditions were further determined by comparing the water consistency and setting time of untreated CBA with those of treated CBA. Additionally, mortar properties were evaluated by using 10%, 20%, and 30% cement replacement and comparing the compressive strength and water absorption results between mortar with untreated and treated CBA replacements.

1. Introduction

In recent years, considerable attention has been given to incorporating different types of waste materials as additives in cement and concrete production. Coal bottom ash (CBA) is a by-product material that has existed since humans realized that burning coal produces electricity, and it has been used in concrete production for almost a century. Bottom ash consists of ash particles formed in pulverized coal furnaces that are too large to be

carried by the fuel gases and remain unburned during the combustion phase. Bottom ash adheres to the furnace walls before falling to the bottom of the combustion chamber, where it is collected in a water-filled hopper. It is then removed using high-pressure water jets and transported via sluiceways to a decanting basin for dewatering, stockpiling, and potentially crushing. Additionally, bottom ash is coarse, with particle sizes ranging from coarse to fine, making it suitable as a replacement for aggregate, capable of acting as a binder, and meeting gradation requirements.

Currently, several papers focused on chemical, physical and mechanical properties of CBA only. Hence, it proved that the CBA is suitable for beneficial use in engineering and construction application such as CBA as a partial cement replacement. Unfortunately, only a few researchers studied on the treatment of CBA especially on removing unburned carbon from CBA. Several methods have been developed and commercialized to remove unburned carbon particles from coal ash, particularly fly ash (FA). These methods include low-temperature carbon combustion, mechanical/particle size classification, gravity separation, electrostatic separation, froth flotation, and combinations of these techniques. The treatment of CBA is very important since the unburned carbon content was very high. High content of carbon might affect the specific gravity of the CBA and the compressive strength of concrete may be affected as well.

The combustion process in power plants generates Coal Bottom Ash (CBA), comprising primarily of partially burned, mostly incombustible inorganic and organic matter. With the increasing prevalence of coal-burning power stations, substantial amounts of CBA, recognized as hazardous waste, have traditionally been disposed of on-site without any commercial purpose. However, rather than being dumped, significant potential exists for the utilization of CBA in various industries, such as its use as a fine aggregate replacement [1] and construction material [2]. Moreover, a comprehensive review conducted by Kim and Lee [3] demonstrated that CBA has conventionally found applications as soil replacement, gravel for embankment, structural fill, road construction material, and in the production of various cement products. Furthermore, the positive pozzolanic reaction observed between CBA, Ordinary Portland Cement (OPC), and water renders it viable as a cement replacement in concrete mixtures [4].

The primary challenges associated with Coal Bottom Ash (CBA) disposal likely stem from the existence of heavy metals in the residue. Previous research has experimentally confirmed the existence of heavy metal elements in CBA, including Copper (Cu), Nickel (Ni), Chromium (Cr), Zinc (Zn), Lead (Pb), Manganese (Mn), Ferum (Fe), and Arsenic (As). This classification has led to the categorization of CBA in Malaysia under Schedule Waste (SW 104) of the Environmental Quality Act [5], [6]. Toxic pollutants generated during the coal-burning process are predominantly released into the atmosphere, subsequently leaching into and contaminating soils, surface water, and groundwater [7]. These elements within the CBA possess a high potential to leach into the environment, accumulating therein. The presence of these elements in the ash poses environmental pollution risks and threatens public health, necessitating effective treatment to address this issue.

Therefore, it is imperative to verify an effective treatment method to reduce the leaching of heavy metals from CBA into the environment. Acid treatment appears to be a suitable approach to reduce heavy metal elements in CBA. The standard technique for analyzing the leaching action of heavy metal elements in bottom ash involves an extraction procedure in a strongly acidic medium. The elevated concentrations of hydrogen ions (H⁺) aim to solubilize these metal ions [8]. Previous research has experimentally demonstrated the use of strong acids such as sodium hydroxide (NaOH) [9], nitric acid [10], and ammonium hydroxide [11] in conventional acid treatments to reduce heavy metals in CBA. However, it is important to note that these agents are hazardous and may pose risks to the environment and human health.

2. Material and Method

The Tanjung Bin power plant relies on coal as its main source for generation of electricity energy. According to Muhardi [12], the power plant consumes around 18,000 tons of coal per day to produce electricity. The extensive use of coal leads to the production of considerable waste, and managing this waste poses a considerable disposal challenge due to the escalating demand for ash storage space [12]. Consequently, the need for expansive areas to handle coal waste increases, potentially giving rise to environmental issues in the future [13]. Since CBA contains heavy metal elements, a significant treatment process needs to be done in order to reduce the metallic content and as well increase the potential use of CBA in industries and decrease the environmental impact toward environment.

In this study, the raw CBA was dried in oven at 110°C for 12 hours to make sure the CBA was completely dried. Since the coal bottom ash that collected from combustion process of power plant has similar particle with fine aggregates, therefore, grinding process was done to produce finer particle of CBA which compatible to cement particle size. The collected CBA was prepared by grinding for 1 hour by using Los Angeles (L.A) abrasion machine and sieving with mean size of 75 µm. The prepared CBA were subsequently used in acid treatment, cement paste and mortar to determine the potential comparison between raw and treated CBA.

2.1 Acid Leaching Treatment

The presence of heavy metal elements in Coal Bottom Ash (CBA) necessitates a pre-treatment process before its utilization [8]. Several effective techniques are available for pre-treating CBA, including mechanical sieving, water-washing, leaching (involving demineralization and acidification) [14], [15], as well as thermal treatment (in the forms of gasification and pyrolysis) [16]. The process not only able to improve the physical and chemical properties, it could also able to improve the morphological properties despite its main aim to eliminate the heavy metal content.

Leaching, broadly defined, is the process of extracting a substance from a solid using a liquid extraction medium. In this process, the concentration and temperature of the citric acid solution were chosen as operating parameters because these factors influence the chelation reaction with metal impurities [17]. Adjusting the solution temperature optimizes solubility and mass transfer during the leaching process. Leaching can be classified into two categories: percolation and dispersed solid. Percolation involves continuous or batch contact between the solvent and solid, typically used for large quantities of solid material. In dispersed solid leaching, the solid is typically crushed into small pieces before being exposed to the solvent. Previous studies have confirmed that extraction and leaching treatments can reduce the heavy metal content in ash [18].

The CBA collected from Tanjung Bin, containing heavy metal compounds, served as the raw material. Following the treatment method outlined by Yahya [5] and Faizul [13], 40 g of CBA with a mean particle size of 75 μ m was weighed and placed into a 1000 mL citric acid solution in a beaker. During the leaching process, the concentration and temperature of the citric acid solution were chosen as operating parameters, and the stirring duration was set to 60 minutes. Equation (1) was utilized to calculate the mass of solute needed when using 1000 mL of distilled water with varying concentrations from 2% to 5%, where "m" represents the mass of solute, and "v" represents the volume of the solution.

$$\text{Concentration (\%)} = \frac{m}{v} \times 100 \quad (1)$$

Subsequently, the beaker was positioned on a hot plate, and a magnetic stirrer was employed to agitate the solution for a duration of 1 hour. The temperature of the solution varied within the range of 30°C to 60°C. Following the completion of the leaching process, a water rinsing treatment was executed using distilled water to eliminate any excess citric acid content from the ash. The treated CBA underwent drying in an oven set at 60°C for 60 minutes. Subsequently, the material was subjected to combustion at 800°C for 30 minutes in a furnace. The airflow rate during combustion was maintained at 2 ml/s until the conclusion of the combustion process.

2.2 Samples Preparation

The preparation of cement paste was conducted to assess the standard consistency and setting time of cement paste incorporating both raw and treated Coal Bottom Ash (CBA) as partial cement replacements. Additionally, a reference cement paste without any replacement was prepared for comparative analysis to achieve more robust results. The procedure outlined in ASTM C187-11 was followed for both the water consistency test and setting time test (Vicat test).

In addition, mortar cube samples were prepared in accordance with ASTM C109/C109M. The dimensions of the molds used for the compression and water absorption test were 50 mm x 50 mm x 50 mm. Compositions with 10%, 20%, and 30% replacements were employed to assess the compressive strength and water absorption of the mortar. All materials were thoroughly prepared and mixed to create mortar compositions containing CBA as a partial replacement for cement. Notably, designations B10, B20, and B30 represented mortars with raw CBA replacement, while C10, C20, and C30 represented mortars with treated CBA replacement. A control sample, A0, was also prepared, featuring mortar without any CBA replacement. All mortar samples were subjected to a curing period of 3, 7, and 28 days before undergoing water absorption and compressive strength tests.

2.3 Testing

In this study, the chemical properties of both raw and treated CBA were assessed through XRF analysis, wherein 40 pellet samples of each were prepared and compared. The evaluation of mechanical properties commenced with the determination of standard consistency, initial and final setting time of cement paste incorporating raw and treated CBA, following the standards outlined in ASTM C187-11. Subsequently, compressive strength and water absorption tests were conducted, utilizing the techniques specified in ASTM C109/C109M and ASTM C1403-15, respectively.

3. Results and Discussion

3.1 X-Ray Fluorescence

An X-ray Fluorescence test was conducted on treated Coal Bottom Ash (CBA) to compare the variations in heavy metal concentration between raw and treated CBA. The interaction between the solvent and acid concentration is a critical factor influencing the effectiveness of acid treatment. Fig. 1 to 6 illustrate the heavy metal concentration in CBA after treatment using a citric acid solution with controlled concentrations of 2%, 3%, 4%, and 5% at heating temperatures of 30°C, 40°C, 50°C, 60°C, and 70°C. The results indicate a consistent pattern of heavy metal extraction for all parameters. The concentrations of Pb and Ni exhibit fluctuating readings, with an increase observed with higher acid concentrations and solution temperatures. In contrast, Cu, Cr, and As show a slight decrease with higher acid concentrations and solution temperatures compared to raw CBA. Only Zn tends to decrease with increasing acid concentration and solution temperature.

Previous researchers have conducted leaching treatments at ambient temperature conditions [13]. However, the solution temperature does not demonstrate significant changes for all types of elements. The results exhibit a consistent trend, with a slight variation observed when the acid concentration was increased to 4% with higher solution temperatures. Under these conditions, all heavy metal concentrations after acid treatment surprisingly decreased, including elements such as Pb, Cu, and Ni. These elements showed a slight increase with higher heating temperatures. Yahya et al. [5] demonstrated that the application of higher temperatures led to an increased percentage concentration of heavy metals Pb, Cu, and Ni. However, the use of high temperatures may limit leaching performance due to the low boiling temperature and decomposition of citric acid in organic acid. The heat tends to cause the acid and distilled water to vaporize [19]. The solution temperature and the interaction between solvent and acid concentration are crucial factors in achieving favorable results after leaching treatment. Fig. 6 presents the percentage of heavy metals in raw and treated CBA after acid treatment using a citric acid solution under optimum conditions (solution temperature of 40°C and 4% acid concentration at 60 min reaction period).

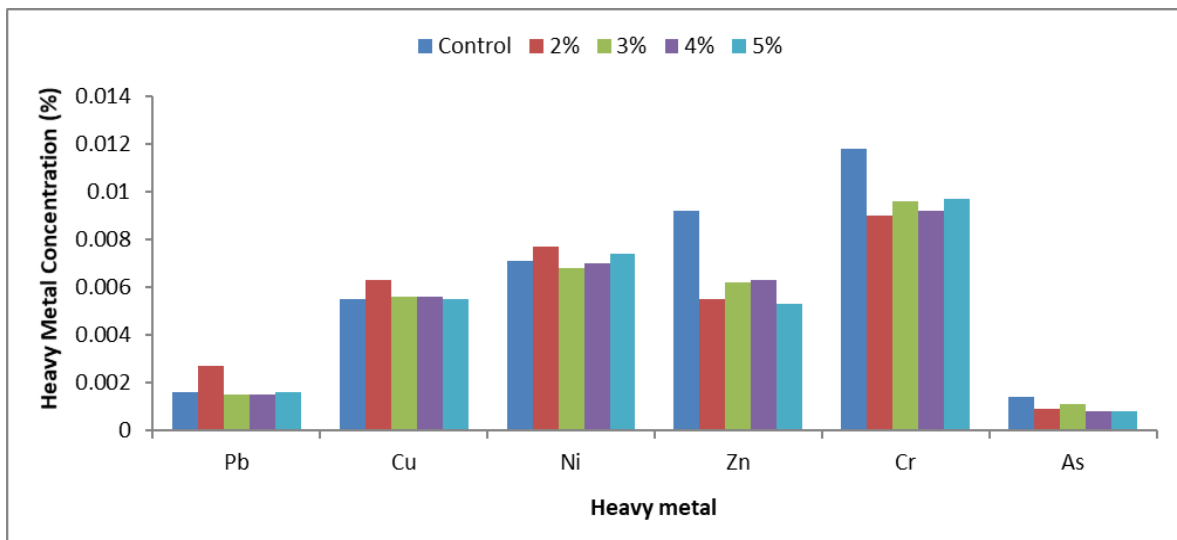


Fig. 1 Heavy metal concentration at 30°C heating temperature

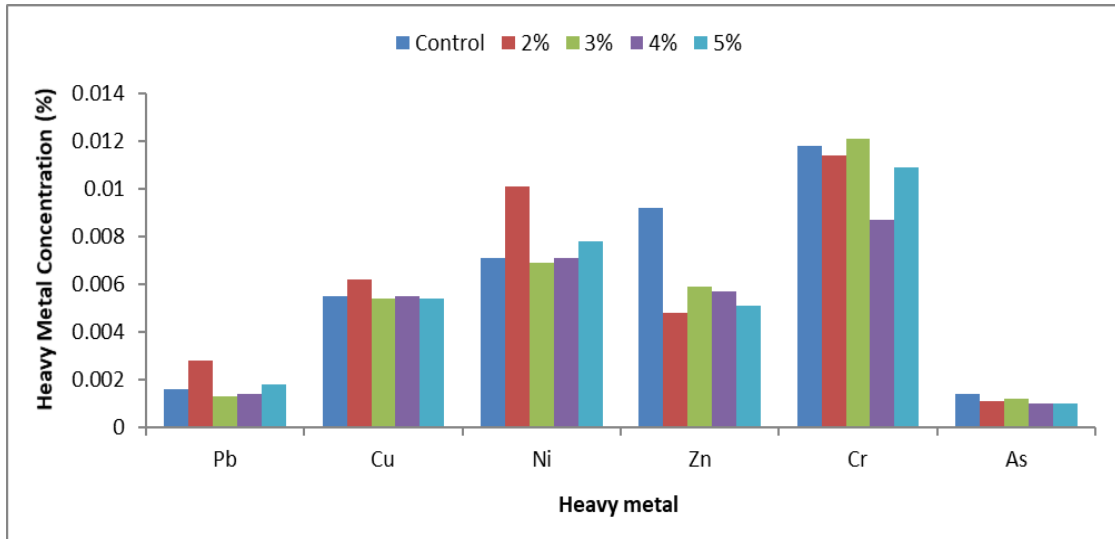


Fig. 2 Heavy metal concentration at 40°C heating temperature

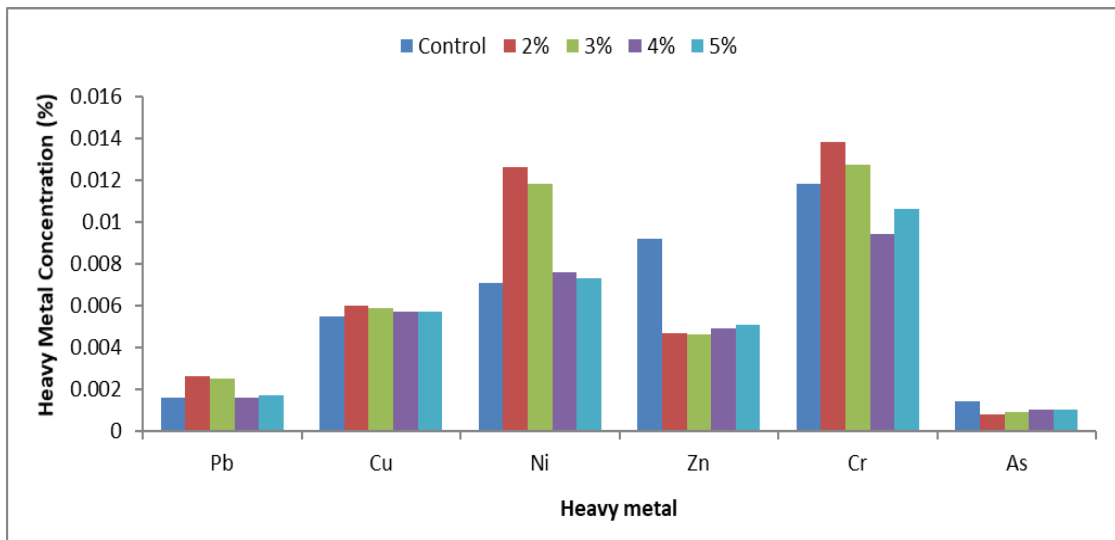


Fig. 3 Heavy metal concentration at 50°C heating temperature

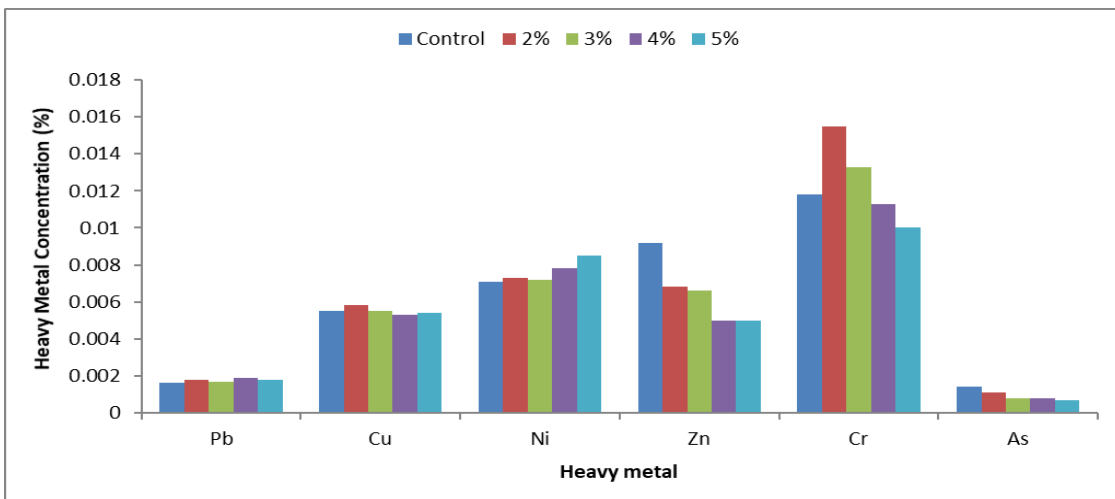


Fig. 4 Heavy metal concentration at 60°C heating temperature

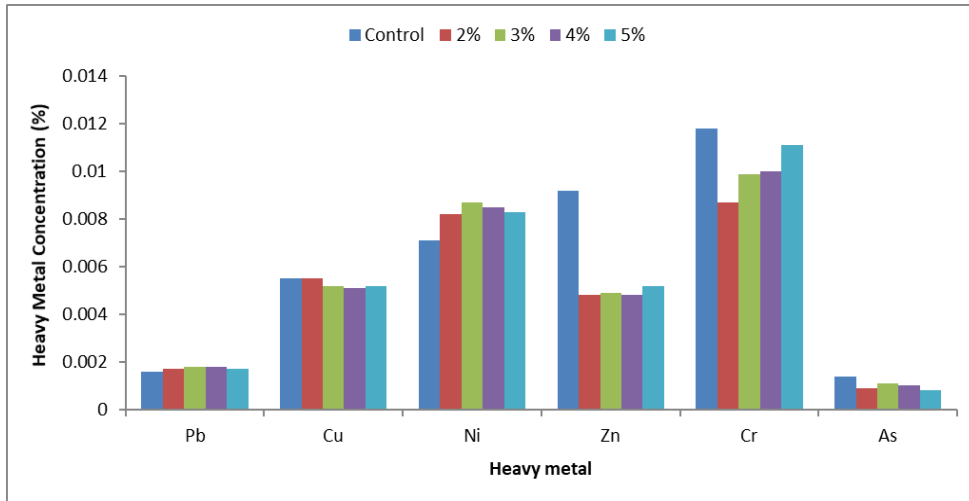


Fig. 5 Heavy metal concentration at 70°C heating temperature

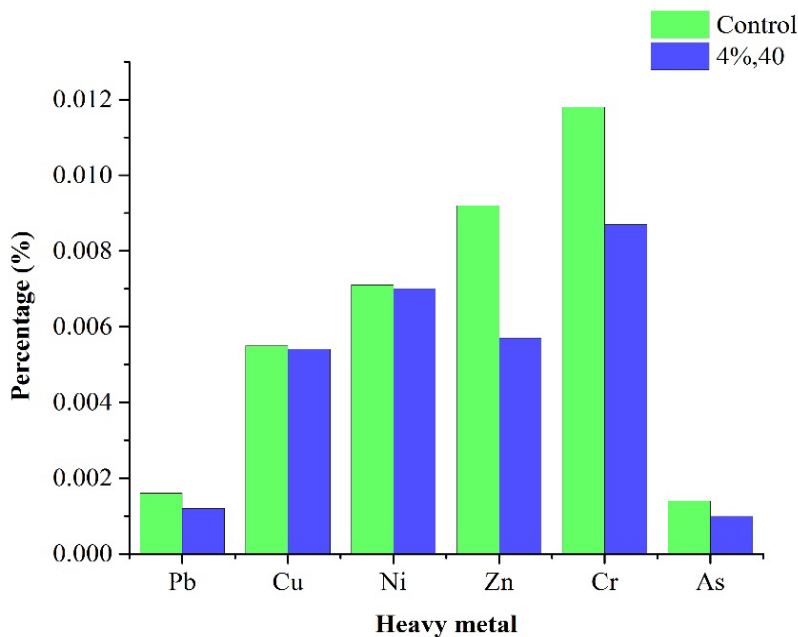


Fig. 6 Heavy metal concentration under optimum conditions

It was found that the heavy metal elements of Pb, Cu, Ni, Zn, Cr and As show an encourage result where all the element were successfully decrease compared to raw CBA. Heavy metal of Zn shows the higher minimization percentage of 61.4% followed by As, Cr and Pb with percentage of 40, 35.6 and 33%, respectively. Cu and Ni show the lower minimization percentage. Using high temperatures can enhance leaching performance. However, employing organic acids at high temperatures is constrained by their low boiling points and the decomposition of citric acid. The heat tends to vaporize both the acid and distilled water [19]. The treated CBA under optimum condition was used to analyze the mechanical properties of cement paste and mortar as partial cement replacement.

By referring to the result obtained from Fig. 6, the treated CBA was analysed by using X-ray fluorescence (XRF) to determine the chemical composition of optimum treated CBA. The XRF result shows that, the main chemical compound includes Silicate dioxide (SiO₂), Aluminium oxide (Al₂O₃) and Iron oxide (Fe₂O₃) and other compound such as Lead (Pb), Copper (Cu), Nickel (Ni), Zinc (Zn), Chromium (Cr), Arsenic (As), Manganese (Mn) and Ferrum (Fe) which in smaller compound were determined in OPC, raw CBA and treated CBA. The existence of Silicate dioxide (SiO₂), Aluminium oxide (Al₂O₃) and Iron oxide (Fe₂O₃) in raw CBA and treated CBA shows that, the coal bottom ash have a good potential as cement replacement. The comparison of chemical composition of OPC, raw CBA and treated CBA were presented in Table 1.

From the result, it shows that the major chemical contents in OPC was calcium oxide (CaO) with concentration value of 56.90%, while raw CBA and treated CBA was silicon dioxide (SiO₂) with concentration value of 40.1% and 45.51%. These finding were slightly similar with research that have been done by Naganathan [20], Sani et. al [21] and Muhardi et al. [12] where they studied the characteristic of CBA obtained from Tanjung Bin power plant, Pontian, Johor. According to Argiz et. al [22], coal bottom ash has significant potential to be used as a cement replacement. Its chemical composition, which includes CaO, SiO₂, Al₂O₃, and Fe₂O₃, aligns it with the family of common supplementary cementitious materials (SCMs) used in cement-based products.

In addition, the CBA collected from the thermal power plant can be classified as class C due to its total percentage of SiO₂ + Al₂O₃ + Fe₂O₃ was 61.18%. According to BS EN 450-1 2012 [23] when the total combination of these three composition was less than 70% but more than 50%, the ashes can be classified in class C ash. Research done by Ramzi et al. [24] also shows that, CBA which was collected from Tanjung Bin was class C ash. Class C ashes are produced from the combustion of lignite or sub-bituminous coal with a high calcium content. Bottom ash from Malaysia's power plant also includes minor amounts of potassium, magnesium, and sodium, as well as traces of barium, manganese, and zinc [25]. On the other hand, the bottom ash studied by Muhardi [12] was classified into Class F as the sum of SiO₂ + Al₂O₃ + Fe₂O₃ exceeds 70%. Class F ashes were a pozzolanic type which having more glass, alumina-silicate glass and quartz [26]. This can also be associated with the use of bituminous or anthracite coal, which results in low calcium content. In this research, the raw CBA and treated CBA can be classified in class C since the total percentage of SiO₂ + Al₂O₃ + Fe₂O₃ was 61.18% for raw CBA and 66.52 % for treated CBA. The increasing percentage of SiO₂ slightly affect the total percentage of bottom ash classification.

Table 1 Chemical composition of OPC, raw and treated CBA

No	Chemicals	Formula	Concentration (%)		
			OPC	Raw CBA	Treated CBA
1	Potassium Oxide	K ₂ O	0.29	1.18	1.05
2	Calcium Oxide	CaO	56.90	4.26	5.21
3	Titanium Oxide	TiO ₂	0.16	0.99	0.85
4	Iron Oxide	Fe ₂ O ₃	3.21	6.88	7.21
5	Sulphur Trioxide	SO ₃	3.89	0.81	0.50
6	Silicon dioxide	SiO ₂	15.4	40.1	45.51
7	Magnesium oxide	MgO	1.72	0.70	1.21
8	Aluminium oxide	Al ₂ O ₃	3.76	14.2	13.8
9	Phosphorus oxide	P ₂ O ₅	NA	0.34	0.40
10	Sodium oxide	Na ₂ O	NA	0.45	0.25
11	Barium oxide	BaO	NA	0.21	0.11
12	Strontium oxide	SrO	NA	0.16	0.13
13	Loss of Ignition	LOI			

Note:

NA- Not Available

3.2 Scanning Electron Microscopic (SEM)

In Fig. 7 and 8, SEM photomicrographs depict Tanjung Bin Coal Bottom Ash (CBA) with an average particle size of 75 µm, captured at magnifications of 500, 300, and 50. As illustrated in Fig. 7(a) and 8(a), most of raw CBA particles exhibit irregular, spherical, and angular shapes. The ash comprises a series of spherical vitreous particles of varying sizes, ranging from 20 µm to 100 µm in diameter. Three types of bottom ash particles are apparent, including a fraction of shattered bottom ash particles, spherical particles resembling fly ash, and agglomerates of bonded particles [12]. The presence of finer particles imparts a metallic luster, potentially indicative of metals present in coal bottom ash [27]. Fig. 7(b) reveals numerous finer particles observed on the surface of larger particles compared to treated CBA in Fig. 8(b). The reduced presence of finer particles in Fig. 8(b) was attributed to the process of acid leaching treatment.

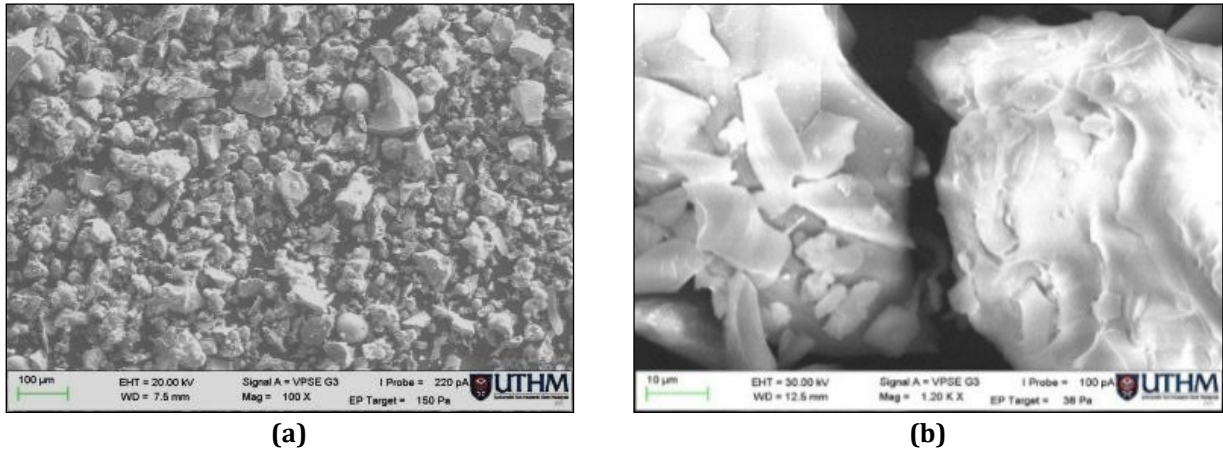


Fig. 7 Scanning electron microscopic result of raw CBA (a) 100 magnification; (b) 1200 magnification

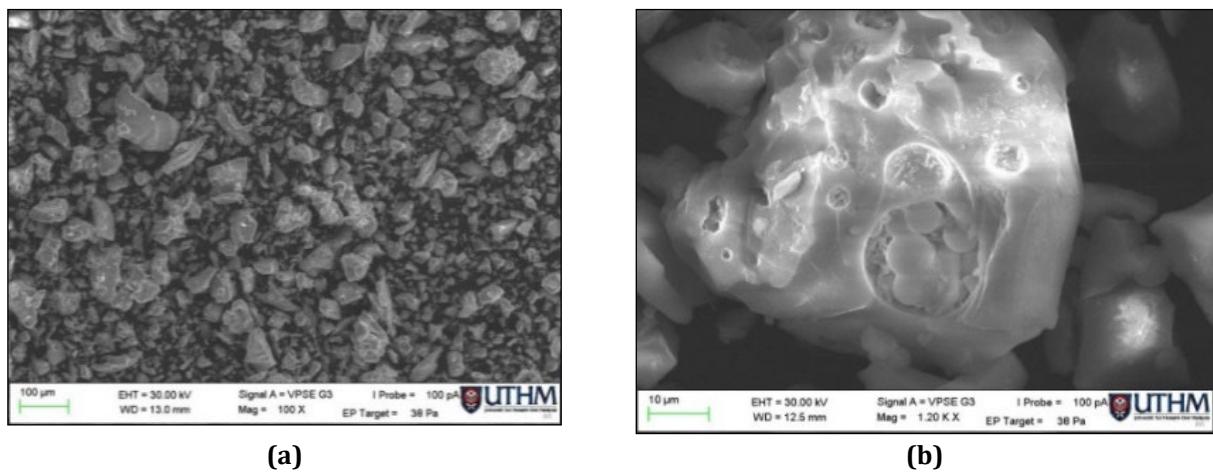


Fig. 8 Scanning electron microscopic result of treated CBA (a) 100 magnification; (b) 1200 magnification

3.3 Water Consistency and Setting Time

Table 2 presents the normal consistency and setting time data for Ordinary Portland Cement (OPC), raw Coal Bottom Ash (CBA), and treated CBA. The results reveal that the consistency of OPC was 26.8%, whereas the consistency for both raw and treated CBA increased with higher CBA replacement percentages. The substantial particle size and porous surface of CBA contribute to an elevated water demand [20], signifying that an increase in CBA replacement in OPC correlates with heightened water requirements [21]. Simultaneously, the incorporation of CBA into cement material leads to an extension of both the initial and final setting times compared to the reference mix which were 80 and 180 minutes, respectively. As for CBA, the setting times increased proportionally with the percentage of replacement. From Table 2, it can be seen that the initial setting times for raw CBA were recorded at 90, 120, and 180 minutes, and the final setting times were recorded at 235, 270, and 300 minutes for replacement percentages of 10%, 20%, and 30%, respectively. On the other hand, the results for treated CBA indicate that, at replacement percentages of 10%, 20%, and 30%, the initial setting times were 80, 120, and 160 minutes, respectively, while the final setting times were 220, 240, and 275 minutes, respectively. This shows that the use of CBA as a replacement for OPC marginally delays the setting time of the cement paste [21]. It can also be pointed out that the increment in CBA percentage also increases the setting time of the paste.

Table 2 Chemical composition of OPC, raw CBA and treated CBA that were determined from XRF

Samples	Water Consistency (%)	Initial Setting Time (min)	Final Setting Time (min)
A ₀	26.8	80	180
B ₁₀	30	90	235
B ₂₀	35.8	120	270
B ₃₀	41.9	180	300
C ₁₀	33	80	220
C ₂₀	37.5	120	240
C ₃₀	43.5	160	275

3.4 Water Absorption

The percentage of absorption was obtained by measuring the increase mass of mortar after a certain period. The percentage of absorption was recorded and calculated on 24 h soaked mortar sample after 3, 7 and 28 days cured as shown in Fig. 9. Fig. 9 shows almost the same trend of water absorption rate for all 7 mixes. Result shows that the percentage of absorption for B₁₀, B₂₀ and B₃₀ increase for all ages compared to A₀. But the percentages are much lower compared to C₁₀, C₂₀ and C₃₀. Mortar C₃₀ obtained the highest absorption of 12.96% at 3 days ages but, the percentage decreased as the curing period increased. The higher water demand on C₁₀, C₂₀ and C₃₀ was due to the porosity of treated CBA which are larger than raw CBA. As can be seen, 30% replacement shows an unexpected increase compared to 10 and 20% CBA replacement for raw and treated CBA. It shows that, by increasing the percentage of replacement, the water absorption also increases.

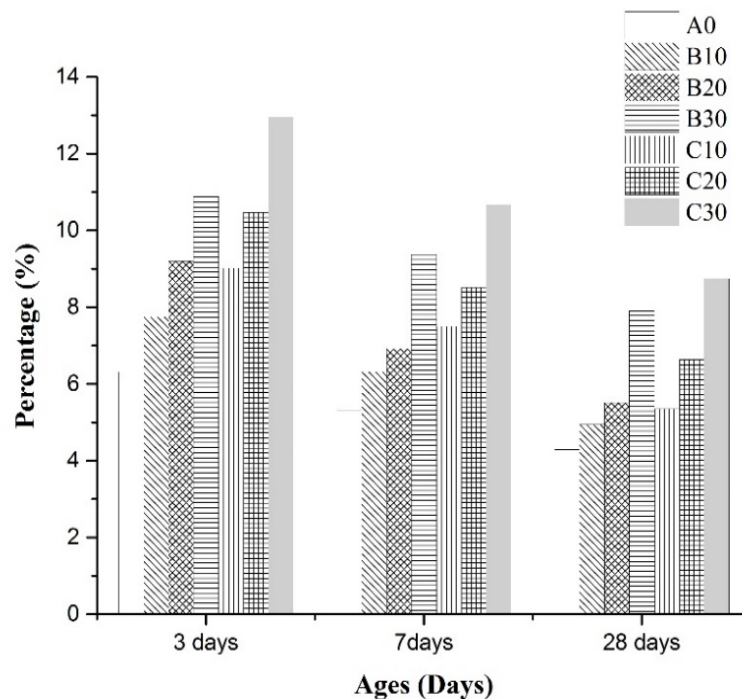


Fig. 9 Graphical data on the percentage of water absorption on mortar containing raw and treated CBA as partial cement replacement at curing period of 3, 7 and 28 days

3.5 Compressive Strength

This study was conducted to analyse the effects of raw and treated coal bottom ash on the properties of the mortar. The compressive strength was observed at curing ages of 3, 7 and 28 days as shown in Fig. 10.

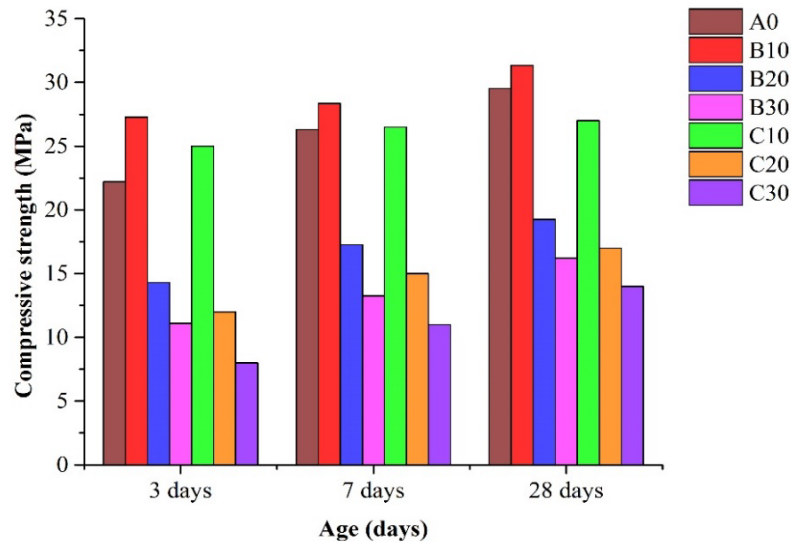


Fig. 10 Graphical data comparison on compressive strength between mortar without replacement and mortar containing raw and treated CBA as partial replacement of cement

Fig 10 shows that 10% replacement of raw and treated CBA helps to increase the compressive strength of mortar. The compressive strength of B₁₀ and C₁₀ increase gradually after 3, 7 and 28 days age for all samples. The compressive strength of C₁₀ is lower than B₁₀ but slightly higher than control mortar, A₀. The compressive strength of mortar containing raw and treated CBA respectively tends to decrease when the replacement percentage changed to 20 and 30%. Mortar B₂₀, B₃₀, C₂₀ and C₃₀ showed lower results at all ages (3, 7 and 28 days) compared to control sample. The mixture's poor performance is attributed to its high content of treated CBA, which, due to its relatively low reactivity, did not significantly enhance the strength at this very early stage. The compressive strength of C₁₀, C₂₀ and C₃₀ are slightly lower to B₁₀, B₂₀ and B₃₀ due to the high-water demand of treated CBA as shown in Table 1. The high water demands of CBA can negatively impact the compressive strength of mortar. However, the strength of concrete cannot be evaluated by water absorption alone as it depends on both surface and internal structures [22].

4. Conclusion

The experimental study shows that heavy metal constituents in CBA can be reduced by acid treatment with optimum condition. However, the treated CBA required higher water demand compared to raw CBA since the structure of treated CBA is more porous. By that, the compressive strength of treated CBA is lower compared to compressive strength of raw CBA since higher water demand can decrease the compressive strength of mortar. This property is then needs to be take into account in the design of concrete mix.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Noorwirdawati Ali; Abdul Aziz Abdul Samad **data collection:** Ahmad Asyari Yahya; **analysis and interpretation of results:** Ahmad Asyari Yahya; Noorwirdawati Ali; Nur Liyana Mohd Kamal **draft manuscript preparation:** Ahmad Asyari Yahya; Noorwirdawati Ali; Shahiron Shahidan; Siti Radziah Abdullah. All authors reviewed the results and approved the final version of the manuscript.

References

- [1] Cheriaf, M., Rocha, J. C. & Péra, J. (1999) Pozzolanic properties of pulverized coal combustion bottom ash. *Cement and Concrete Research*, 29(9), 1387–1391, [https://doi.org/10.1016/S0008-8846\(99\)00098-8](https://doi.org/10.1016/S0008-8846(99)00098-8)

- [2] Aggarwal, Y. & Siddique, R. (2014) Microstructure and properties of concrete using bottom ash and waste foundry sand as partial replacement of fine aggregates, *Construction and Building Material*, 54, 210-223, <https://doi.org/10.1016/j.conbuildmat.2013.12.051>
- [3] Kim, H. K. & Lee, H. K. (2015) Coal bottom ash in field of civil engineering: A review of advanced applications and environmental considerations, *Journal of Civil Engineering*, 19, 1802-1818, <https://doi.org/10.1007/s12205-015-0282-7>
- [4] Bajare, D., Bumanis, G. & Upeniece, L. (2013) Coal combustion bottom ash as microfiller with pozzolanic properties for traditional concrete, *Procedia Engineering*, 57, 149-158, <https://doi.org/10.1016/j.proeng.2013.04.022>
- [5] Yahya, A., Ali, N., Mohd Kamal, N. L., Shahidan, S., Beddu, S., Nuruddin, M. F. & Shafiq, N. (2017) Reducing heavy metal element from coal bottom ash by using citric acid leaching treatment, *MATEC Web of Conferences*, 103, 1-7, <https://doi.org/10.1051/MATECONF%2F201710301004>
- [6] Abubakar, A. U. & Baharudin, K. S. (2013) Tanjung Bin coal bottom ash: From waste to concrete material, *Advance Material Research*, 705, 163-168, <https://doi.org/10.4028/www.scientific.net%2FAMR.705.163>
- [7] Baba, A. & Kaya, A. (2004) Leaching characteristics of solid wastes from thermal power plants of western Turkey and comparison of toxicity methodologies, *Journal of Environmental Management*, 73(3), 199-207, <https://doi.org/10.1016/j.jenvman.2004.06.005>
- [8] Meawad, A., Bojinova, D. & Pelovski, Y. (2010) Study on elements leaching from bottom ash of enel maritsa East 3 Thermal Power Plant in Bulgaria, *Journal of the University of Chemical Technology and Metallurgy*, 45, 275-282
- [9] Rashidi, N. A. & Yusup, S. (2016) An overview on the potential of coal- based bottom ash as low-cost adsorbents, *ACS Sustainable Chemistry & Engineering*, 4(4), 1870-1884, <https://doi.org/10.1021/acssuschemeng.5b01437>
- [10] Amfo-Otu, R., Kyerewaa, S. G., Ofori, E. A. & Sadick, A. (2005) Comparative study of heavy metals in bottom ash from incinerators and open pit from healthcare facilities in Ghana, *Octa Journal of Environmental Research*, 3, 50-56
- [11] Quek, A., Xu, W., Guo, L. & Wu, D. (2016) Heavy metal removal from incineration bottom ash through washing with rainwater and seawater, *International Journal of Waste Resources*, 6, 1-9, <https://doi.org/10.4172/2252-5211.1000203>
- [12] Muhandi, A., Marto, A., Kassim, K. A., Makhtar, A. M., Wei, L. F. & Lim, Y. S. (2010) Engineering characteristics of Tanjung Bin coal ash, *Electronic Journal of Geotechnic Engineering*, 15, 1117-1129, <https://doi.org/10.1051/mateconf/201825001006>
- [13] Faizul, C.P., Abdullah, C., Fazlul, B. & Jamil, H.N. (2014) Extraction of silica from palm ash using organic acid leaching treatment, *Advanced Materials Research*, 795, 701-706, <https://doi.org/10.4028/www.scientific.net/AMR.795.701>
- [14] Balsamo, M., Di Natale, F., Erto, A. & Montagnaro, F. (2013) On the effect of the coal ash pre-treatment as a mean to improve their sorptive behaviour toward heavy metals in wastewaters, *Chemical Engineering Transaction*, 32, 325-330, <https://doi.org/10.3303/CET1332055>
- [15] Balsamo, M., Di Natale, F., Erto, A., Lancia, A., Montagnaro, F. & Santoro, L. (2013) Gasification of coal combustion ash for its reuse as adsorbent, *Fuel*, 106, 147-151, <https://doi.org/10.1016/j.fuel.2012.11.077>
- [16] Lam, C. H. K., Ip, A. W. M., Barford, J. P. & McKay, G. (2010) Use of incineration MSW ash: A review, *Sustainability*, 2, 1943-1968, <https://doi.org/10.3390/su2071943>
- [17] Faizul, C. P., Abdullah, C. & Fazlul, B. (2013) Extraction of silica from palm ash via citric acid leaching treatment, *Advanced Materials Research*, 795, 701-706
- [18] Sarode, D. B., Jadhav, R. N., Khatik, V. A., Ingle, S. T. & Attarde, S. B. (2010) Extraction and leaching of heavy metals from thermal power plant fly ash and its admixtures, *Polish Journal of Environmental Studies*, 19, 1325-1330
- [19] Gharabaghi, M., Irannajad, M. & Noaparast, M. (2010) A review of the beneficiation of calcareous phosphate ores using organic acid leaching, *Hydrometallurgy*, 103, 96-107, <https://doi.org/10.1016/j.hydromet.2010.03.002>
- [20] Naganathan, S., Mohamed, A. Y. O. & Mustapha, K. N. (2015) Performance of bricks made using fly ash and bottom ash, *Construction and Building Materials*, 96, 576-580, <https://doi.org/10.1016/j.conbuildmat.2015.08.068>
- [21] Sani, M. S. H. M., Muftah, F. & Muda, Z. (2010). The properties of special concrete using washed bottom ash (WBA) as partial sand replacement. *International Journal of Sustainable Construction Engineering and Technology*, 1(2), 65-76, <https://publisher.uthm.edu.my/ojs/index.php/IJSCET/article/view/64>
- [22] Argiz, C., Sanjuán, M. Á. & Menéndez, E. (2017) Coal bottom ash for Portland cement production, *Advances in Materials Science and Engineering*, 2017, <https://doi.org/10.1155/2017/6068286>
- [23] British Standards Institution (2012) *BS EN 450-1:2012: Fly ash for concrete. Definition, specifications and conformity criteria*, London: British Standards Institution, <https://doi.org/10.3403/30216589>

- [24] Ramzi, N. I. R., Shahidan, S., Maarof, M. Z. & Ali, N. (2016) Physical and chemical properties of coal bottom ash (CBA) from Tanjung Bin Power Plant, In *IOP Conference Series: Materials Science and Engineering*, 160, 012056, <https://doi.org/10.1088/1757-899X/160/1/012056>
- [25] Abubakar, A. U., & Baharudin, K. S. (2012) Properties of concrete using tanjung bin power plant coal bottom ash and fly ash, *International Journal of Sustainable Construction Engineering and Technology*, 3(2), 56-69, <https://penerbit.uthm.edu.my/ojs/index.php/IJSCET/article/view/518>
- [26] ASTM International (2019) *ASTM C618-19: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, West Conshohocken, <https://doi.org/10.1520/C0618-23>
- [27] Pollock, S. M., Goodarzi, F., & Riediger, C. L. (2000) Mineralogical and elemental variation of coal from Alberta, Canada: An example from the No. 2 seam, Genesee Mine. *International Journal of Coal Geology*, 43(1-4), 259-286, [https://doi.org/10.1016/S0166-5162\(99\)00063-4](https://doi.org/10.1016/S0166-5162(99)00063-4)