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ARTICLE

Influence of setting time and compressive strength for coal bottom ash as partial cement replacement in mortar

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ABSTRACT

Environmental degradation from forestry practices to extract limestone from mountains, as well as subsequent calcination in cement factories and dumping of coal bottom ash (CBA) waste from thermal power plants, are among the wastes from industry. However, it is essential for the construction industry to look for sustainable solutions to mitigate the negative impact on the environment. In order to promote an environmentally friendly and sustainable ecosystem, the use of recycled CBA waste as a partial substitute for cement in the manufacturing process has significant potential to mitigate the environmental damage caused by the two distinct sectors of cement and waste management. A series of six mortar preparations were prepared, each containing varying percentages of CBA as a partial substitute for cement. The percentages used ranged from 0% to 50% by weight of cement. The time tests were performed on freshly prepared pastes. All samples were cured with water until the respective test time was reached. The experiment included the evaluation of the compressive strength of hardened mortar cubes at three different time intervals: 7, 14 and 28 days. The findings of the study demonstrate that the incorporation of CBA as a partial substitute for cement affects both the setting time and the compressive strength of the mortar. It has been shown that the use of up to 20% CBA as a cement replacement effectively increases the compressive strength of the mortar. Conclusively, the successful use of CBA as a partial substitute for cement in the manufacture of mortar has the potential to reduce the amount of cement consumed, eliminate the need for landfill space for waste disposal, and contribute to the production of a more sustainable environment, thereby promoting a better lifestyle for the surrounding population.

1. Introduction

Concrete has become a widely used building material throughout civilization and is a crucial component of today's construction projects (Al Biajawi and Embong, 2023; Embong, et al., 2021a; Townsend and Anshassi, 2023). The importance of this element is reflected in its extensive use in the field of infrastructure development, as it serves as a fundamental component in the construction sector (Hammond et al., 2008; Mansour and Al Biajawi, 2022). Concrete is widely considered an effective construction material for a variety of structures, including but not limited to bridges, highways, dams, and buildings, because of its exceptional durability and strength (Al-Rifaie et al., 2018; Muthusamy et al., 2021). Concrete is a widely used structural component in the construction sector due to its flexibility, efficiency and affordability (Al Biajawi et al., 2023a; Asmara, 2023). Concrete continues to be a key component in the design, construction, and maintenance of various structures, and thus plays an important role in the advancement of construction. However, it is important to note that

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an essential component of concrete is OPC (Biernacki et al., 2017; Kusbiantoro et al., 2018). The emission of carbon dioxide (CO_2) resulting from widespread cement production has led to significant ecological impacts, including global warming, amplification of environmental impacts, and subsequent changes in ecology. On the contrary, the cement sector has been identified as a major contributor to greenhouse gas emissions (Kusbiantoro et al., 2017; Tayebani et al., 2023). The cement industry is responsible for about 5% of global CO_2 emissions. The depletion of key resources used as the main ingredient of concrete in Malaysia is progressing at an alarming rate (Hossain et al., 2017;Tanash et al., 2022). The overuse of natural resources has led to the degradation of the ecosystem. Therefore, reducing the use of such resources as building materials by incorporating industrial by-products in the production of concrete is a positive measure towards environmentally friendly growth (Al Biajawi et al., 2023b; Hossain et al., 2021).

In contrast, it is worth noting that coal-fired power plants are responsible for a significant portion, 95%, of total greenhouse gas emissions (Ruether et al., 2004). These emissions are also caused by several waste materials, including fly ash (FA) and (CBA), both of which are recognized to have toxic properties that can adversely affect soil due to their significant leaching potential (Embong et al., 2021b). Previous studies (Ghazali et al., 2021; Kusbiantoro et al., 2019) have shown that it is possible to produce sustainable and environmentally friendly concrete by incorporating industrial byproducts, such as (FA) and (CBA), among others. Nevertheless, it is worth noting that power generation in Malaysia results in significant annual production of BA and FA, amounting to approximately 1.7 and 6.8 million tonnes (Rafieizonooz et al., 2016), correspondingly. Based on the available statistics by (Tenaga, 2014) indicate that by 2024, approximately 83% of the electrical energy generated in Malaysia will come from fossil fuels, with coal accounting for 58% and gas for 25%. From the data, the use of coal as a fossil fuel for electricity generation is expected to increase significantly, from 43% in 2014 to 58% in 2024, indicating that the production of coal ash (FA) and (CBA) is expected to increase as a direct result of the increased use of coal. It is anticipated that the increased use of coal will lead to a corresponding increase in the production of coal ash, exacerbating environmental problems. The American Coal Ash Association (Adams, 2020) has outlined that coal ash (CBA) production will be about 7.9 million tonnes in 2020, with a usage rate in the construction sector of only 3.8%, indicating rather low usage. The use of CBA as a substitute for cement not only mitigates greenhouse gas emissions, but also promotes ecology in construction and improves land utilization. Therefore, the aim of the present study is to investigate the effects of CBA as a partial replacement for cement on the setting time and compressive strength of the mortar mix.

2. Material and methods

The experimental study consists of three stages that involve provision of material used, and preparation of mortar specimens' mixture and, finally with testing of mortar samples. The following subsection will explain in detail. Furthermore, All the testing and mixture design in accordance with specific standard for each test.

2.1 Material preparation and properties

All the materials used in this study are readily accessible within the immediate area. The study used Ordinary Portland cement sourced from a local manufacturer. The cement grade in question is classified as 52.5 N and it meets the requirements outlined in the MS EN 197-1: 2014 standard. The density, specific gravity, and Blaine surface area values for cement were recorded as 3.15, 399.8 m^2/kg, correspondingly. In contrast, the corresponding values for CBA were measured as 2350 kg/m^3, 2.37, and 0.494. The mortar mixture was prepared using river sand as a fine aggregate. The upper limit for the particle size of fine aggregate is 1.18 mm. The absorption rate of fine aggregate was observed at 3%. The original CBA originated from a thermal power plant in Tanjung Bin, Johor, Malaysia. The original CBA was found to have mainly a coarser and porous structure resembling volcanic material, as shown in the Figure 1. The scanning electron micrograph (SEM) of CBA, shown in Figure 2, reveals the presence of irregular, sharp, spherical, and porous particles, as well as a mixture of textures. The CBA was dried in an oven at a controlled temperature of 110 ± 5 ºC for 24 hours. It was then sieved through a 300-micron sieve. The material was then subjected to 7000 cycles in the Los Angeles machine, following the criteria recommended in ASTM C618 (American Society for Testing and Materials, 2019). These procedures were performed to ensure that the CBA had the desired properties of a suitable pozzolanic material.

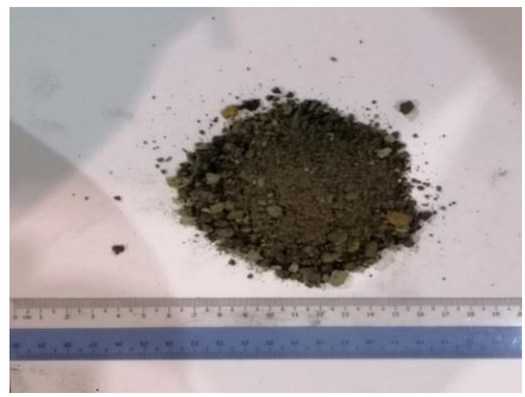

Figure 1. Original coal bottom ash

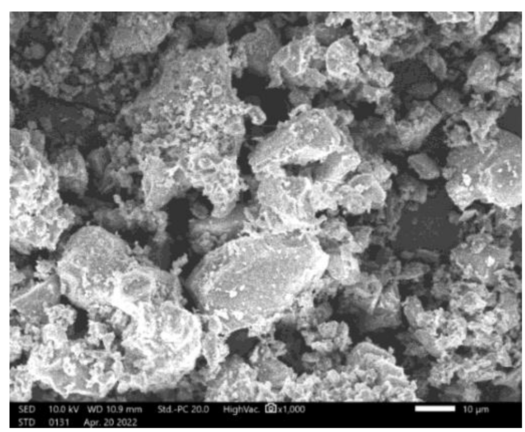

Figure 2. SEM morphology of CBA

2.2 Sample preparation and mixing details

The ingredient compositions of the mortar mixtures used and examined in this study are listed in the table. A series of six mortar combinations were prepared, each consisting of cement, sand and water in the ratio 1:2.10:0.50 with a water to binder ratio of 0.58. Mortar mixes with different proportions of CBA were prepared, with the CBA content ranging from 10% to 50%, and a corresponding amount of Portland cement was substituted. In the standard mixes, only Portland cement was used as a binder. Consequently, the mortar mixes were classified as CBA 0, CBA 10, CBA 20, CBA 30, CBA 40 and CBA 50 with respect to the mortar specimens. Before preparing the sample, the required raw components were carefully measured. The samples were prepared using a compact mixer in which the components were combined. To ensure consistency and standardization of the mortar samples, the materials were mixed in a series of steps. The fine and coarse aggregates were added to the drum mixer and stirred for three minutes. Then, the mixing materials (OPC) and (CBA) were poured according to the specified mixing patterns and mixed for another three minutes. After adding water, the mixture was thoroughly mixed for another three minutes. The freshly mixed concrete was to be poured into moulds and left undisturbed for 24 hours. For each test, three samples were prepared for each mixture design. After a period of 24 hours, the samples were removed from the moulds and immediately immersed in water to allow them to cure until the time of testing. In the laboratory, the temperature ranged from 25 to 30 °C, and the humidity ranged from 70 to 80 %.

Table 1 Mix design proportion of mortar mixes (g)

Mix ID	Cement	Sand	CBA	Water
CBA0	1700	3600	0	850
CBA10	1530	3600	170	850
CBA 20	1360	3600	340	850
CBA 30	1190	3600	510	850
CBA 40	1020	3600	680	850
CBA 50	850	3600	850	850

2.3 Testing involves

A compressive strength test was performed to evaluate the compressive strength of standard mortar as well as the compressive strength of mortar with CBA as an alternative to cement. Mortar cubes measuring 50 mm x 50 mm x 50 mm were used for compressive strength measurements. A calibrated compressive load was applied using a hydraulic- mechanical movement device. The compressive strength was evaluated according to ASTM C109/C109 standards (Standard, 2013). This test was performed on specimens with curing ages of 7, 14 and 28 days. To obtain a suitable result in each test, average of three mortar cube samples representing each mortar mix type were used. The setting time test was carried out according to the ASTM C191 (ASTM, 2008) standard.

3. Result and Discussion

3.1 Setting time

Figure 3 illustrates the effects of including CBA as a partial replacement for cement on the initial and final setting times of hardened cement paste. The incorporation of different proportions of CBA 10%, 20%, 30%, 40% and 50% as partial replacement for cement has effects on the setting time of hardened cement paste. The results regarding setting time showed a positive correlation between the proportion of CBA replacement and the time required for setting of the hardened cement paste mixture. The standard consistency for conventional samples is 29%, with initial and final setting times of 95 and 230 Mins, correspondingly. The study assessed the typical consistency of CBA at various levels of substitution and observed values ranging from 33% to 39%. The inclusion of CBA in the paste resulted in an improvement in consistency, as it exhibited a higher water absorption capacity compared to the conventional cement paste. The substitution of cement with CBA leads to a decrease in the quantity of tri-calcium-silicate (C_3S) present in the cement paste, thereby leading to an extended duration for the setting time process in the cement paste. The setting timeframes of all CBA pastes must adhere to the prescribed criteria outlined in ASTM C150 (C150, 2017), which stipulates that the first setting time should be no less than 45 minutes and no more than 375 minutes for the final setting time. The incorporation of CBA as a substitute for cement, ranging from 10% to 50% by weight, led to an increment in the levels of C_3A and C_3S in the paste. Consequently, the setting times of the CBA pastes exhibited a modest increase when compared to the conventional samples (CM) of cement paste. The results of the current study are consistent with the results of previous research studies (Abdulmatin et al., 2018; Argiz et al., 2017).

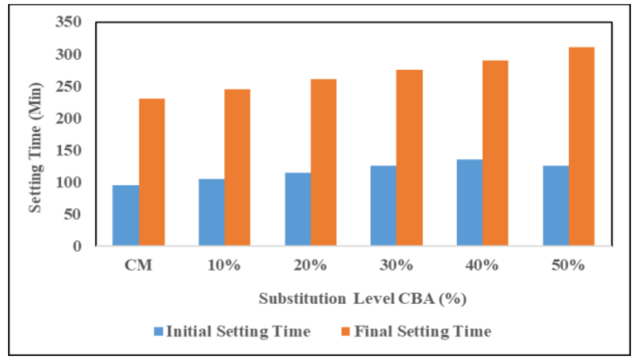

Figure 3. Setting of cement paste for control sample and CBA with various replacement ratio

3.2 Compressive strength

Figure 4 illustrates the impact of different amounts of CBA as a partial substitute for cement on the compressive strength of mortar. Overall, it can be seen that the strength of all samples improves as the curing age progresses. Extended immersion duration in water enhances the cement hydration process, leading to the formation of a greater amount of binding gel. Consequently, this results in an increased capacity of mortar to withstand applied loads. The process of hydration involves the chemical interaction between water and cement, resulting in the formation of a bonding agent. The results of the study demonstrated a steady reduction in compressive strength as the amount of CBA added to the mixture increased. The findings indicate that the variation in compressive strength across different mixtures is contingent upon the amount of CBA included within the mixture. The study findings indicate that the optimal ratio of CBA for enhancing compressive strength in mortar mixtures is up to 20% as a partial substitute for cement. Additionally, the compressive strength of the specimens without CBA exhibited compressive values of 28 MPa, 33 MPa, and 37 MPa after 7, 14, and 28 days of curing, respectively. During the first 7-day curing period, it was observed that the compressive strength of the concrete increased by up to 20% when including CBA. This improvement may be attributed to the pozzolanic impact of the fine ash particles contained in the waste material that was added to the concrete mixture. Furthermore, a second reason contributing to the observed rise in compressive strength is the progressive hydration of cement. Previous studies have also shown the advantageous impact of the pozzolanic reaction induced by CBA on the compaction of the internal structure of concrete. A comparable trend is also seen in the context of high strength when using CBA as a partial substitute for cement. The use of CBA at varying proportions of 30%, 40%, and 50% results in a decrease in the strength of concrete. The workability of concrete mix is hindered by the reduced compaction process due to the increased water absorption characteristic of CBA particles, which is attributed to their porous nature in comparison to dense river sand particles. According to (Canpolat et al., 2004). it has been shown that concrete with a higher proportion of CBA tends to possess increased porosity and hence has reduced strength. The incorporation of an appropriate quantity of CBA, up to 20% as a partial substitute for cement, results in an enhancement in the compressive strength of mortar. Moreover, the inclusion of 30%, 40%, and 50% of CBA leads to a decrease in strength. Previous research (Embong, 2019;

Mangi et al., 2019; Oruji et al., 2017) has shown the beneficial impact on the strength of mortar mix when a certain proportion of CBA is used as a substitute for cement. The substitution of conventional cement has two benefits: first, a reduction in greenhouse gases from carbon dioxide (CO_2) and second, the potential to reduce construction costs. Therefore, it can be considered a financially efficient and environmentally friendly strategy (Aydin, 2016; Khan and Ganesh, 2016).

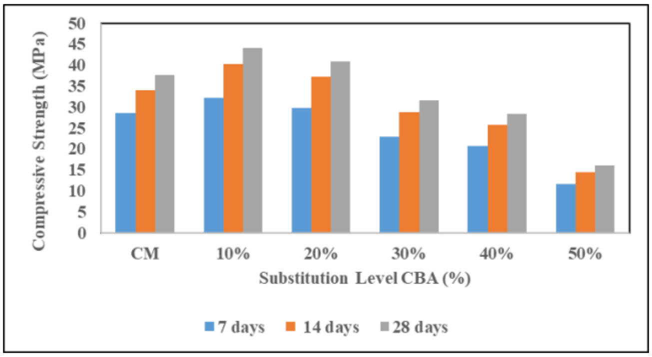

Figure 4. Compressive strength for control sample and CBA with various replacement ratio

4. Conclusion

The current study demonstrates that the incorporation of CBA as a substitute material in mortar, up to a maximum of 20%, has promising potential for utilization in concrete manufacturing. Based on the results, it can be inferred that the use of CBA as a partial substitute for cement has an impact on the setting time of cement. The inclusion of 20% of CBA in mortar results in an improvement in its compressive strength. Nevertheless, the overuse of this waste material leads to a decrease in strength. Additional investigation is required to examine the impact of incorporating CBA into concrete on its durability characteristics. Success in utilizing this coal ash in construction material production would reduce quantity of waste thrown and save the usage of land for waste dumping. The successful use of CBA in the production of building materials would result in a reduction in the amount of waste disposed of and preserve land resources that would otherwise be used for waste disposal. The use of cost-benefit analysis (CBA) in the context of building material manufacturing has shown to be a beneficial approach for recycling waste materials, as opposed to disposing of them in landfills, which may lead to environmental contamination and create an unpleasant living environment for local inhabitants.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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