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Research Article

Flowability and compressive strength of ternary blended cement mortar of coal bottom ash and ground cockle shell ash

Nabilla Mohamad [a], Rahimah Embong [a], Nor Hazurina Othman [b], Khairunisa Muthusamy [a,*], Mohd Faizal Md Jaafar [a]

[a] *Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300 Kuantan, Pahang, Malaysia*
[b] *Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia*

ABSTRACT

Flourishing cement industry to meet the demand of construction industry has negative impact to the global environment owing to the carbon emission during calcination of cement. At the same time, the disposal of coal bottom ash and cockle shell from coal power plant and cockle trade which pollutes the environment also need to be resolved. In view of circular economy, the present research aims to produce ternary blended cement consisting of coal bottom ash (CBA) and cockle shell ash (CSA) for sustainable mortar production. The research was conducted to determine the effect of CBA as partial cement replacement on flowability and compressive strength of CSA blended cement mortar. Seven mortar mixes consisting of CBA as supplementary cementitious material ranging from 0% to 60% by weight of cement were prepared. All specimens were water cured up to 56 days. The flowability test was conducted to assess the properties of the fresh state, while hardened properties were evaluated through compressive strength test at 1, 3, 7, 28, and 56 days. The results showed flowability decreased by 5% to 31% with increasing CBA content compared to the control mix. The use finer sized CBA forms a slightly stickier mortar mix with lower flowability. A combination 10% to 20% CBA is the best percentage to use for formation of CSA mortar with enhanced strength. However, a maximum strength of 23 MPa was achieved at 56 days with an optimal CBA replacement of 10%. This research demonstrates the potential by transforming industrial waste for low-carbon cement production to save the use of landfills for waste disposal and optimize consumption of non-renewable resources.

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1. Introduction

The most popular material used in building and infrastructure construction is concrete, a mixture made mostly of aggregates, water, and binder (Shanks et al. 2019). The advantageous attributes of the concrete in terms of flexibility, robustness, sustainability, and low-cost has led it to be used globally (Singh et al. 2020). Concrete is used in all types of building construction. The increase in the use of concrete as main building material due to expanding population demand also results in a flourishing cement manufacturing trade. Production of cement is increasing by 2.5% per year and it is anticipated to be between 3.7 and 4.4 Gt by 2050 (Akashi et al. 2011). About 60% of global CO_2 emissions is from cement industry (Scrivener et al. 2018). On overall, concrete industry is accountable for roughly 10% of worldwide industrial CO2 emissions, which contribute to climate change (Amin et al. 2019; Adesina 2020). Realizing that cement is increasingly used owing to its role as a

* *Corresponding author*. Tel.: +60-9-431-5014 ; E-mail address: khairunisa@umpsa.edu.my (K. Muthusamy)
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sole binder in the famously utilized concrete worldwide, unearthing new alternate material would decrease the reliance on cement and benefits the environment. Thus, investigating alternatives that use materials with a lower carbon footprint and can replace Portland cement in this regard is crucial to promote cleaner industry. Inclusion of by-product from industrial activity as a filler or pozzolanic material in concrete has thus been the subject of extensive research in recent years. A variety of waste have been investigated its use as an alternative binder in concrete such as fly ash, slag, palm oil fuel ash, rice husk ash, oyster shell ash, cockle shell ash and many more. However, as the cement consumption continue to rise, more alternative materials need to be discovered to produce low carbon cement and also to reduce reliance on the consumption of natural resource. In view of circular economy, recycling the waste from any industries for product development would benefits the environment and decrease use of landfill space for disposal purpose.

The increasing for energy from various industries has resulted in larger quantity of coal used in coal power plants. Fly ash and coal bottom ash (CBA) are by-products generated at plant which disposed as environmental polluting waste. From the whole coal ash, approximately 10 to 20% of is comprised of CBA (Argiz et al. 2017). CBA is among the largest form of industrial wastes generated by coal-fired thermal power plants (Baite et al. 2016). Due to rapid development, the quantity of solid wastes generated from coal-fired power plants every year continues to increase (Ramzi Hannan et al. 2020). This, in turn, produces a large volume of CBA which is disposed of as wastes. The dumping of this waste poses negative effect to the environment (Muthusamy et al. 2018). Dumping of this waste contaminates the soil and reduces the quality of air as well as water (Singh et al. 2022) which affect the living things. The existence SiO_2 and Al_2O_3 in CBA has enabled it to possess pozzolanic activity (Basirun, et al. 2017; Menéndez et al. 2021) which makes it suitable candidate for cement replacement. The beneficial effect of CBA when used at the right proportion which results in concrete strength increment owing to pozzolanic reaction that creates denser internal structure makes more exploration were carried out to reveal its potential. Investigation has been conducted on the use of CBA as partial cement replacement in concrete (Argiz et al. 2017), high strength concrete (Khongpermgoson et al. 2020) and geopolymer concrete (Ping et al. 2022). Nevertheless, the application of CBA in construction material production needs to be increased to reduce waste dumping at landfill.

In the Southeast Asian region, cockles (Anadara granosa), which live primarily on intertidal mudflats, are an essential protein source. It is one type of sea molluscan widely consumed in various delicacies in Southeast Asian countries. Worldwide mollusk production (16 million tons) accounts for approximately 22% of global aquaculture growth (Food & Agriculture Organization 2016). A cockle is an edible, marine bivalve mollusk. Bivalve shellfish are very common in marine species (Eziefula et al. 2018). According to Shellfish Association of Great Britain (2012), cockles are a low-calorie food. A total of 100 g of cockles contains only 53 kcal compared to 180 kcal in 100 g of salmon (Shellfish Association of Great Britain 2012). Blood cockles are a common source of protein for Southeast Asian coastal communities, such as Malaysia, Singapore, Thailand and Indonesia (Mirsadeghi et al. 2011). Consumer demand for shellfish and other seafood has led to a considerable expansion in their aquaculture in fresh, brackish, and marine areas, with a total production of 73.8 million metric tons and an estimated value of USD 160 billion in 2014 (Food & Agriculture Organization 2016). This included 16.1 million metric ton of mollusks composed of 104 species valued at USD 19 billion (Food & Agriculture Organization 2016). In addition, according to Food & Agriculture Organisation (2017), the world production of cockles in 2017 was 535k tons which slightly decreased from the year 2016 with 561k tons. Meanwhile, the Department of Fisheries Malaysia (2011) reported that 57,544 tons of cockles had been harvested in the past decade along the Peninsular Malaysia's west coast. . The cockle's shell has a very high content of calcium. It is generally composed of calcium carbonate of prismatic layers (Lertwattanaruk et al. 2012; Mohamed et al. 2012). The calcium carbonate, $CaCO_3$, accounts for higher than 90% of the weight in the cockle shell (Jatto et al. 2010; Martínez-García et al. 2017; Mo et al. 2016; Mohamed et al. 2012; Olivia et al. 2015, 2017; Safi et al. 2015). It is almost equal to limestone (Othman et al. 2018; Soltanzadeh et al. 2018).

In order to alleviate this waste from being dumped, researchers have explored the potential use of CBA combined with OPC producing binary blended cement-based concrete (Argiz et al. 2017; Muthusamy et al. 2024) and high strength concrete (Khongpermgoson et al. 2020) However, research on the integration of CBA as partial cement replacement with other types of cement replacement material in ternary blended cement remain to be investigated. The effect of CBA as partial cement replacement combined with cockle shell ash on the flowability, compressive strength and microstructure of cement-based composite remains unanswered. Thus, the present research investigated the effect of integrating CBA as partial cement replacement on the flowability, compressive strength and microstructure. CBA used in this research were collected from power plant. Then it was ground before it is blended as cement replacement CBA ranging from 0% to 60% in mortar mixes. A total of seven mortar mixture were subjected to flowability test and compressive strength test. The use of cockle shell and CBA as partial cement replacements would contribute towards formation of sustainable concrete and helps in reducing waste disposal issues.

2. Methodology

2.1. Materials

Ordinary Portland cement (OPC), fine aggregate, coal bottom ash (CBA), cockle shell ash (CSA) and water were used in this research work. Local river sand passing sieve 1.18 mm were used as fine aggregate. CBA which was obtained from one of the coal power plant were ground to be fine powder. Cockle shells were collected from the dumping area in a fishing village in Peninsula Malaysia were washed thoroughly using flowing water to remove the mud and dirt before it is dried. Then, the shells were calcined at 650°C using furnace and ground utilizing grinding machine until it trans-formed into fine powder using the processing steps reported by Mohamad et al (2024). In this research, the particle size of CBA and CSA is similar to that of OPC particles with an average size of 45 μm, which is targeted to improve performance in cementitious applications. Both ground CBA and CSA were subjected to wet sieve test to ensure the ashes passes the limit of wet sieve result stated ASTM C618 (2019). Fig. 1 illustrates the CBA and CSA used in this research. The oxide content of the binders is tabulated in Table 1.

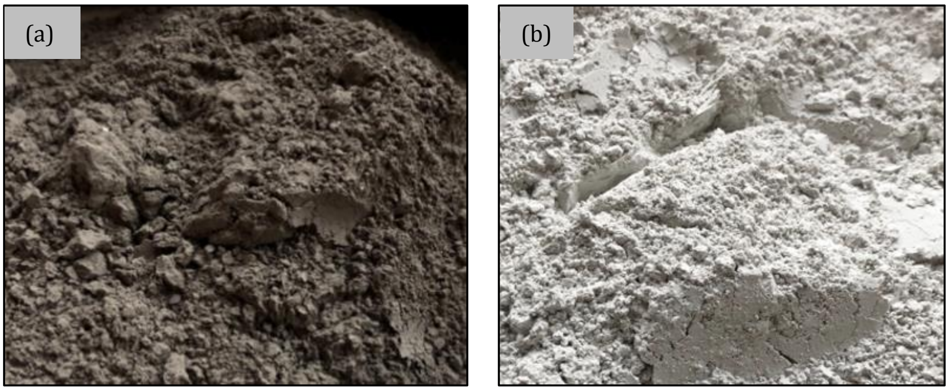

Fig. 1. Binder used: (a) Coal bottom ash; (b) Cockle shell ash.

Table 1. Oxide composition of binders.

Oxide	OPC	CSA	CBA
SiO_2	18.84	0.39	60.14
Al_2O_3	5.39	0.18	19.30
Fe_2O_3	3.79	2.54	13.56
MgO	0.03	0.01	0.04
Na_2O	0.10	0.94	–
K_2O	0.30	0.02	1.19
SO_3	3.06	0.13	0.42
CaO	62.21	93.50	3.56
LOI	3.94	3.97	2.30

2.2. Mix proportion and specimen preparation

Seven mixes of blended cement were used to produce mortar. Mix produced using 10% cockle shell ash (CSA) and 90% identified as CA10, were utilized as control specimen (CA10). A control mix with 100% OPC was not included in this research work, as the focus was to evaluate the effect of a combination of 10% cockle shell ash and various levels of coal bottom ash (CBA) replacement on mortar performance. The contribution of 10% CSA as cement replacement towards strength increment of mortar as compared to other replacement has been reported by Mohamad (2023). Other six mixes were prepared by integrating 10% CSA with CBA ranging from 0% to 60%. Details of the mixes used is shown in Table 2. Preparation of mortar mixture were done using clean apparatus. All ingredient were accurately weighed and mixed homogenously before filled in the oiled mould. Proper compactions were done, and the specimen were left overnight. The next day, the hardened mixes were removed from the mould, labelled and immersed in water for curing until the testing days.

2.3. Testing

The flowability test was carried out using flow table in accordance to ASTM C1437-07 (2007). Earlier, flow table would be ensured to be in damp condition and clean before placing a flow mold in the middle. The mold was then filled in three layers with the mixture. Each layer was compressed with 20 tamping rod strokes. After compacting the top layer, a sawing motion was used to move the stuffing rod to strike the mortar surface. Following that, the mold was removed 60 seconds after the compaction activity was performed and the table was dropped 25 times. Finally, the diameter of the mortar spread was measured along the four-boundary line on the tabletop. The compressive strength test was done in accordance with ASTM C109 (2016). During the testing, the mortar specimen was placed in the testing machine below the center of the upper bearing block. Then, the load rate at a relative rate of movement between the upper and lower platens was applied to specimen faces that were in contact with the true plane surfaces of the mold. The internal structure of hardened mortar mixes was observed through Field emission scanning electron microscopy (FESEM) testing using equipment shown in Fig. 2 which was conducted at Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), UMPSA. The sample was dried and ground to a powdered form. It was then placed on the aluminum stubs using adhesive carbon tape and followed by platinum coating to increase conductivity to prevent charging problems. The stub was then placed into the vacuum chamber of the instrument. The surface morphology obtained by using magnification ranging from 500x to 25,000x times.

Table 2. Mix proportion (kg/m³).

Mix	Cement	Sand	Cockle shell ash	Coal bottom ash	Water content
CA10	180	600	20	–	0.70
CABA10	160	600	20	20	0.70
CABA20	140	600	20	40	0.70
CABA30	120	600	20	60	0.70
CABA40	100	600	20	80	0.70
CABA50	80	600	20	100	0.70
CABA60	60	600	20	120	0.70

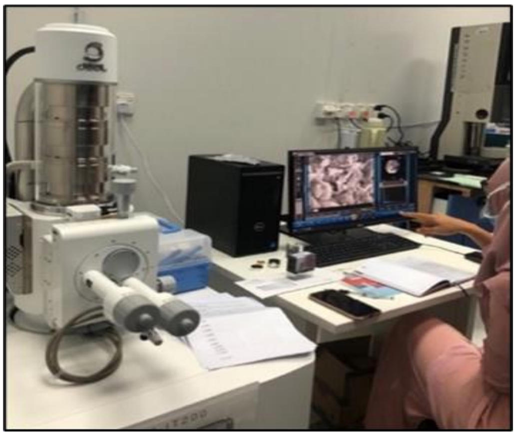

Fig. 2. FESEM testing apparatus.

3. Results and Discussion

3.1. Flowability

The flowability of mortar mixes consisting blend of 10% CSA and varying percentage of CBA is shown in Fig. 3. The control mixture (10% CSA and 0% CBA) revealed an optimal flowability value of about 105%. The introduction of CSA appears to provide good workability characteristics. However, it clearly shows that the flowability values of CSA mortar incorporating different level of CBA replacement labeled as CABA10, CABA20, CABA30, CABA40, CABA50 and CABA60 was found to be 104%, 101%, 93%, 86%, 82% and 73%, respectively. A decrease in flowability is evident when the replacement of CBA in CSA mortar is increased from 10% to 60%. CSA mortar with higher amount of CBA (60% CBA) demonstrate the lowest flowability value of 73%. This reduction can be attributed to CBA's characteristic properties like porous nature of CBA itself that increases water absorption. It can be observed that integration of CBA forms a stickier mixture which reduce the flow dispersion. The rate of flowability reduction ranged from 5% to 31% when compared to the control mix. Flowability value declines as larger percentage of this industrial ash is used. It can be suggested that higher content of CBA, may require an adjustment of water content or the addition of a superplasticizer. The flow spread of CSA mortar with 10% CBA and 60% CBA is illustrated in Fig. 4. The use of the smaller size of CBA with a BET surface area of 22800 cm²/g as compared to OPC of 5700 cm²/g resulted in a lower flowability value. The use of finer ash requires a larger amount of water to cover its surface reduced the flowability. The effect of using smaller sized particle towards increased water requirement to coat the bigger surface area has been pointed out by Neville and Brooks (2010).

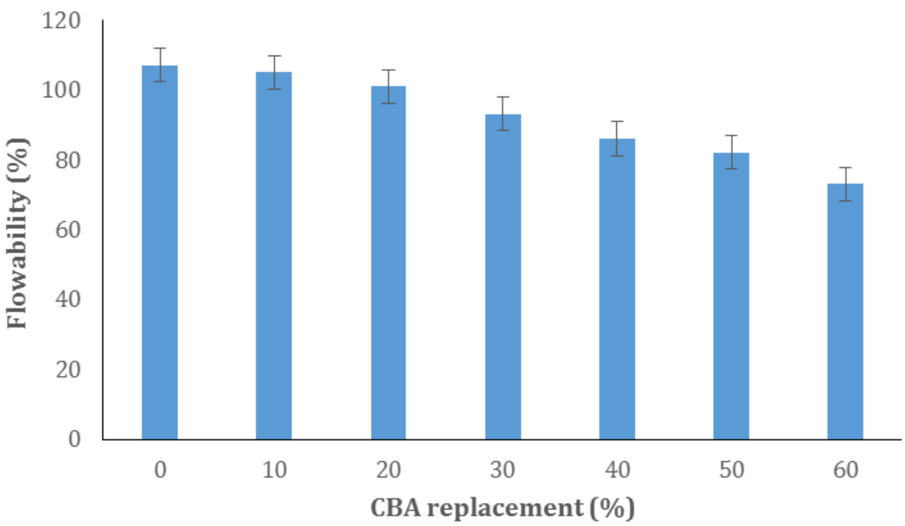

Fig. 3. Flowability test results.

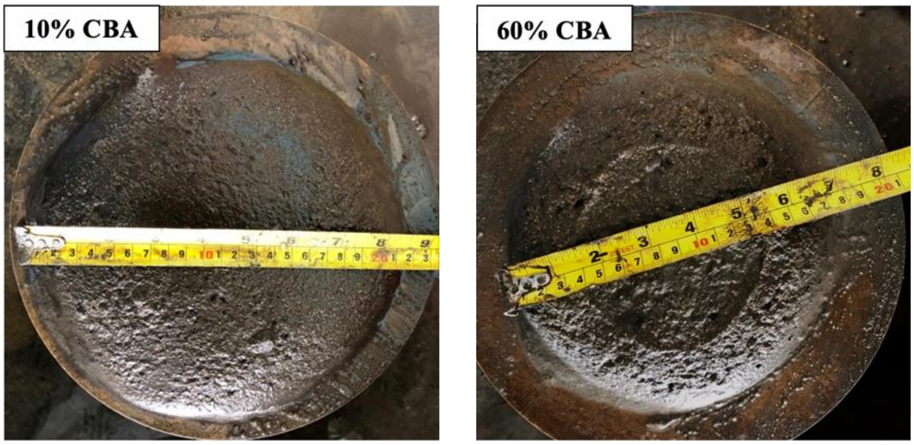

Fig. 4. Effect of CBA content on spread of mortar mixture.

3.2. Compressive strength

The compressive strength of mixes with ternary blended cement cockle shell ash (CSA) and coal bottom ash (CBA) is illustrated in Fig. 5. At day 1, the strength of 10% CSA mortar ranged from 12.40 MPa (0% CBA) to 1.24 MPa (60% CBA replacement). At 3 days, the strength increased to 16.52 MPa to 2.27, followed by 16.75 MPa to 3.23 MPa at 7 days of curing. It is evidently shows that higher proportion of CBA (20% to 60%) reflected significantly lesser compressive strength compared to the control mix and combination with 10% CBA. This happens because of the slow pozzolanic reaction experienced by CBA. Since CBA contains pozzolanic activity, it requires calcium hydroxide (CH) from cement hydration, which is lacking in the early stages of curing leading to a slower formation of C-S-H gel for strength development. By 28 days, the obtained strength was significantly developed between 20.34 MPa to 7.43 MPa. The increase in strength observed for the mixture containing 10%CBA surpassing that of the control mix. It can be attributed to the optimal pozzolanic reaction that appears at this level of replacement. Previous studies also found that the strength of mortar with pozzolanic materials increases over time with optimal performance noted at specific replacement levels (Sakthivel and Suthaviji 2024; Kang et al. 2024; Pinheiro et al. 2024). On the other hand, the finer particle size of CBA (22800 cm^2/g BET surface area) compared to OPC (5700 cm^2/g) helps fill voids in the mortar, reducing porosity and increasing strength. Therefore, prolonged the age of curing has provided the filler action and pozzolanic reaction simultaneously (Chen et al. 2022; Al Biajawi et al. 2024). The maximum strength was reached at 56 days, ranging from 23.12 MPa for control mix to 10.57 MPa for 60% CBA replacement. The maximum strength was reached at 56 days of curing, ranging from 23.12 MPa for control mixture to 10.57 MPa for the 60% CBA replacement. The results show that as the age increases, the strength of all mixes continues to improve due to prolonged hydration and pozzolanic activity. In this stage, the CSA mortar samples with 10% CBA consistently present excellent compressive strength as compared to control mix. It was also found that mortar samples containing 0%, 10% and 20% exceeded the threshold of 20 MPa as shown in Fig. 5, however, a series of CSA mortar mixes significant strength reduction beyond 30% CBA. Therefore, the mix with 10% CBA confirmed the optimal replacement level in the production of 10% CSA mortar but limited the CBA replacement to 20% for acceptable strength development.

Overall, the results show positive strength development with prolonged curing time, indicating increased C-S-H gel formation. This is due to chemical reactions of the binders benefitting from the continuous presence of water for all mixes. The strength of mixes consisting of CBA remains slightly lower because of late pozzolanic reaction which is commonly observed in other types of mortar blended with pozzolanic ash. However, mix with 10% CBA exhibits the highest strength value amongst all mixes after cured for 28 days owing to pozzolanic reaction. Presence of moisture at all time with the blend of right amount of CBA has enabled better hydration process and pozzolanic reaction contributing to formation of binding gel which is crucial for strength of cement-based material. The augmentation of cement-based composites mechanical properties is achievable via enhanced pozzolanic effect and filler role of the pozzolanic material (Isaia et al. 2003). Nevertheless, the overuse of CBA poses adverse effect to the strength achievement due to extreme reduction in cement use that lowers the hydration process with lesser CSH gel and calcium hydroxide formed. As a result, the ample supply of silicon dioxide from CBA unable to form secondary C-S-H gel owing to the limited availability of CBA. The strength declination of cement-based composite resulting from high usage of pozzolanic ash has been reported by Masazza (1993). As a comparison, the denser internal structure of mix with 10% CBA with lesser voids in contrast to mix with 60% CBA content with high number of voids is shown in Fig. 6. The image shows that CABA10 sample containing 10% CSA and 10% CBA shows a denser microstructure, and the voids are smaller and more compact. In contrast, CABA60 sample that incorporating 60% CBA showed a more porous microstructure, looser compaction and larger gaps in the voids. It is proven that CABA10 provides a better particle packing, it improves the filling effect and boost the strength enhancement. Evidently, this finding corroborated with the previous studies (Singh et al. 2021; Alosta et al. 2024).

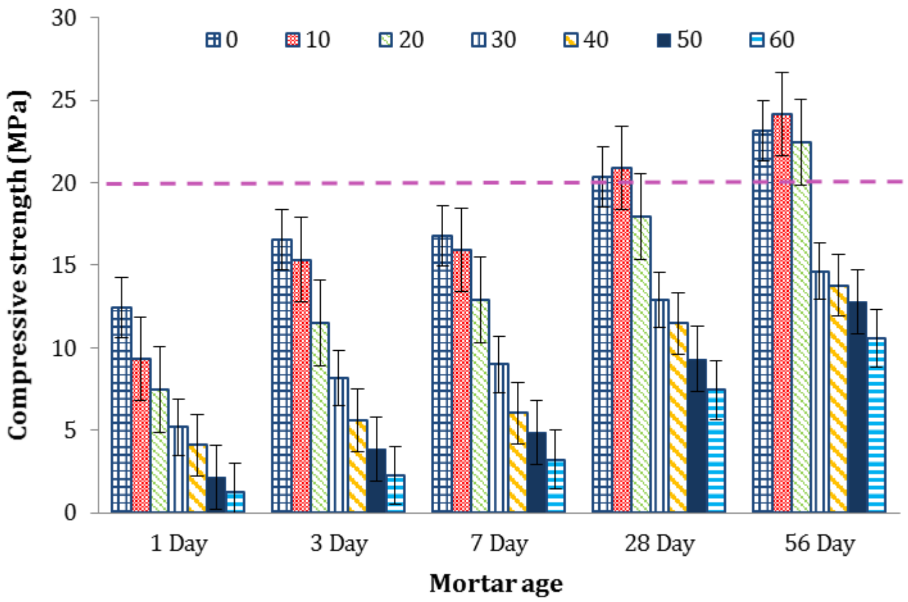

Fig. 5. Compressive strength result of mortar mixes.

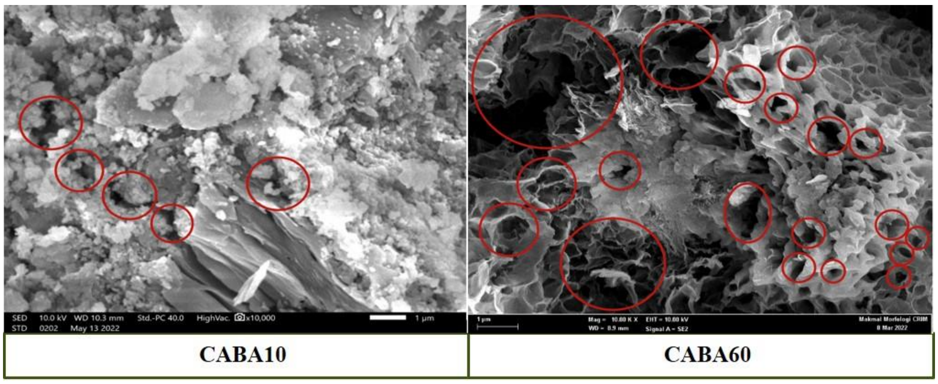

Fig. 6. Morphology of mortar with 10% and 60% CBA with high number of voids.

4. Conclusions

The introduction of coal bottom ash (CBA) in the cockle shell ash (CSA) mortar mixes have significant effect on both fresh and hardened properties. It was observed that flowability continued to decrease with increasing CBA content from 0% to 60%, where the reduction in flowability values ranged from 5% to 31% of that of the control mix. This decrease in workability does not appear to have a large effect on strength development. The results show that the ideal CBA replacement is around 10% to 20% to balance the need between flowability and strength requirements. However, blending 10% CBA contributes towards strength increment through pozzolanic reaction that forms compact microstructure of the cement-based material. Microstructural images also revealed that 10% CBA produce a more compact (denser) and filling effect that directly correlates with strength performance. Excessive use of CBA needs to be avoided as it results in weaker mortar. Ternary blended cement formed of CSA and CBA supports the idea of reducing waste disposal to the environment and optimization on the use of natural resources for cement production. Approach of producing low carbon construction material support implementation of sustainable construction for achieving SDG 11 (Sustainable Cities and Communities).

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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