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TECHNICAL PAPER

Engineering properties of mortar with untreated agricultural waste ashes as cement replacement materials

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Abstract
Rapid urbanization and industrialization result in increased demand for infrastructures and housing worldwide. Therefore, the consumption of construction materials continues to rise. Cement is a common component used in the manufacture of concrete and mortar. However, the cement manufacturing process severely influences the environment, which causes the release of large amounts of carbon dioxide into the atmosphere. In addition, the agriculture and plantation industries are primary economic pillars in many countries, particularly developing countries, including Indonesia, India, and China. However, it cannot be denied that this industry severely impacts the environment, as it generates biomass waste that cannot be efficiently managed. This study investigates and examines alternative materials for cement replacement in mortar production. This research evaluated the fresh and hardened properties of mortar on the laboratory scale. In addition to destructive tests, ultrasonic pulse velocity (UPV) and rebound hammer tests were also conducted. The fresh properties test consisted of a slump flow, while the hardened properties test included compressive strength, porosity, water absorption, and mass loss. It can be concluded that each waste has characteristics that make it a suitable replacement for cement in mortar production. The results indicate that 10% of agricultural waste can be substituted for cement to generate a mortar with comparable compressive strength to normal concrete, thereby reducing cement consumption by 10%. In terms of hardened properties, the increasing amount of waste results in a lower mass density hardened mortar compared to normal mortar, so the use of this waste has the potential to produce a lightweight material. Thus, employing sufficient amounts of agricultural waste as a cement substitute produces mortar with beneficial characteristics and reduces the use of cement to produce sustainable construction materials.

Keywords Bagasse ash · Corn cob ash · Rice husk ash · Cement replacement · Mechanical properties

Introduction

The agriculture and plantation industries are among the most vital socioeconomic support sectors in many countries, mainly tropical developing countries. The agriculture industry continues to grow with the support of more advanced and intelligent technology. Nonetheless, it cannot be denied that this industry also generates industrial waste that must be managed effectively. Insufficient regulation of the waste disposal process leads to an accumulation of hazardous waste in the environment. Several developing countries, such as China, India, the Philippines, Sri Lanka, Thailand, Cambodia, Vietnam, and others in Asia, have evaluated the potential of biomass waste from the agriculture industry [1, 2]. In addition, it was reported that such a technique of disposing of agricultural waste still regularly involves burning agricultural waste in an open field, particularly on small farms in rural areas [3, 4]. This is also a result of the lack of

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suitable disposal processes and waste management, as this traditional practice is still common among farmers. Even so, the results of burning agricultural waste by open field burning account for up to 34% of the total biomass burned yearly, with China and India accounting for the majority [5, 6]. This method of waste burning causes serious land and air pollution. This approach is also extensively employed to dispose of agricultural waste in Indonesia. Surprisingly, the results of this waste combustion are still underutilized.

Concrete is one of the most widely used construction materials for infrastructure and houses worldwide. Concrete is the most popular material among contractors since it is affordable and durable, and the constituent materials are readily available in many countries. In general, conventional concrete production requires cement (15%), water (22%), fine aggregate (23%), and coarse aggregate (40%) as raw ingredients [7, 8]. It is reported that the production of concrete and mortar will continue to increase significantly until 2050, particularly in developing countries such as China, Indonesia, India, Thailand, Vietnam, and other countries in Africa, the Middle East, and Asia [9, 10]. Therefore, cement production will increase in line with the high demand for concrete for construction materials. Due to the chemical conversion of limestone-based raw materials into cement clinker, it is necessary to consume around 110 kWh of electricity and emit approximately 800 kg of CO_2 to produce 1000 kg of cement [11–13]. Reportedly, the cement sector consumes up to 14% of global energy and emits up to 8% of global CO_2 emissions annually [14–16]. Additionally, the collection of raw materials, concrete mixing, transportation to the site, construction stage, curing stage, service stage, and demolition stage, concrete construction substantially influences the environment at every stage of its life cycle [17–19]. Nonetheless, cement production substantially negatively influences the environment and CO_2 emissions. Thus, it is essential to develop sufficient, sustainable, and environmentally acceptable technologies for renewable materials as cement replacements so that they can be employed to reduce CO_2 emissions from the cement industry.

Various advancements have been made to locate alternate cement replacements in its development. Several industrial waste materials have been commercialized and standardized, including fly ash, bottom ash, and granulated blast furnace slag [20–22]. In addition, various studies on the use of agribusiness waste as a substitute for cement in mortar production have been discovered, including rice husk ash [23–29], corn cob ash [30–32], palm oil fuel ash [33–44], sugarcane bagasse ash [45–48], coconut and walnut shell ash [49–52], and wood and leaf ash [29, 53–56]. Several studies have also been conducted on the application of agricultural waste ashes to actual structures, including pavements [57–59] and building components [60, 61]. However, the waste treatment procedure significantly impacts the quality of ashes that can be substituted for cement. Properly treated ashes can produce a more suitable chemical composition, producing higher pozzolanic content. In contrast to waste that has been appropriately processed, ashes produced from open-field burns cannot be generated with high and reliable quality. In addition, there is no facility in rural areas where waste may be treated and heated to the typical temperature range of 600–1200 °C for processing waste into pozzolanic material [62–64]. In order to employ agricultural and plantation wastes that are burned in open fields as a substitute for cement in the production of mortar, a more comprehensive and systematic study is required.

This study used agricultural waste in the form of rice husk ash, bagasse ash, and corn cob ash as a replacement for cement in mortar production. The waste utilized in this study results from open-field burning in rural agricultural regions in Indonesia. This research investigates the engineering properties of mortar from agricultural waste disposed of via open-field burning. Thus, this research is expected to utilize waste as a substitute for cement effectively. The Indonesian government has a considerable amount of work to perform to handle agricultural waste sustainably. Therefore, sufficient, appropriate, and straightforward innovations are required so that the community can readily utilize this waste, particularly in rural areas with a middle-to lower-income economy.

Significance and scope of the study

This study employs three different types of agricultural waste, including corn cob ash (CCA), rice husk ash (RHA), and sugarcane bagasse ash (BA). As stated in the introduction, several previous researchers have utilized agricultural waste as a substitute for cement in mortar production. However, various waste treatments in each study produce mortar or concrete with different characteristics. This research uses waste from open-field burning in Indonesia's rural agricultural regions. In addition, the farmers still insufficiently use the wastes, causing air and land pollution. Therefore, it is necessary to carry out an effective innovation to utilize these agricultural wastes in order to reduce the amount of biomass waste caused by open-field burning. In addition, limited information is known about the utilization of agricultural wastes produced by open-field burning in Indonesia. Innovative research and investigation are required to use these waste products as a substitute for mortar. Thus, this research utilizes agricultural wastes from open field burning in Indonesia as a cement substitute for mortar manufacture.

The properties of the constituent materials, including cement, agricultural wastes, and fine aggregate are examined. Figure 1 shows the experimental outline and scope of the investigation of this study. The microstructure level was investigated to examine the binder properties using a scanning electron microscope (SEM) and X-Ray diffraction

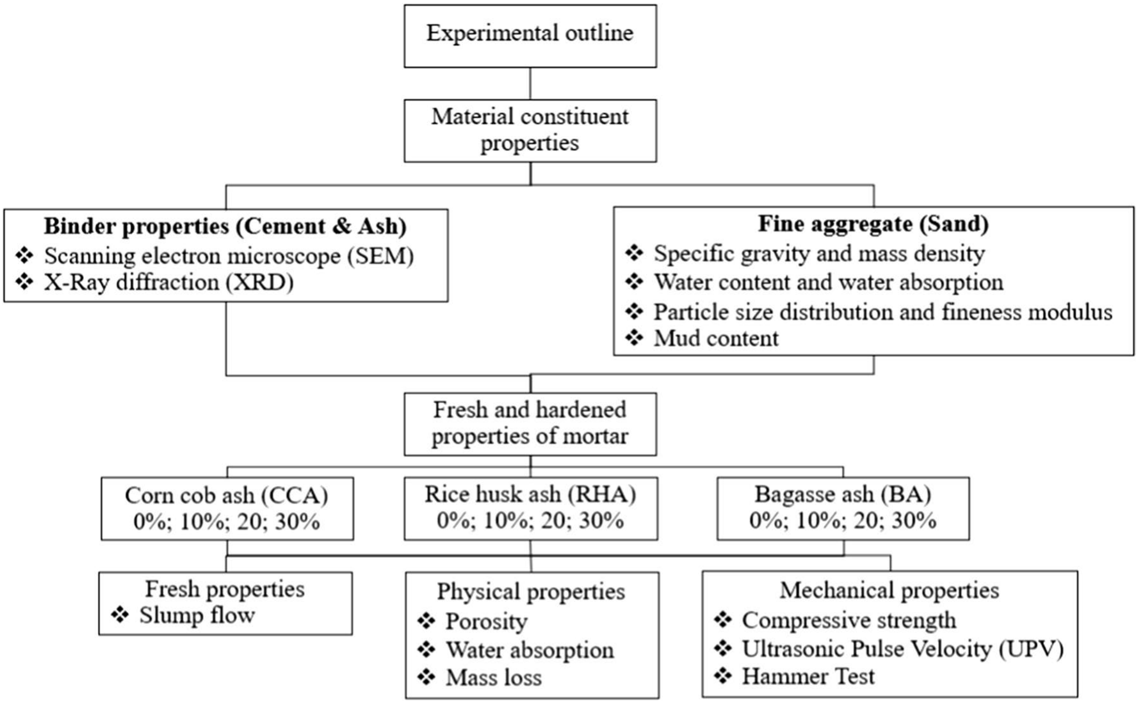


Fig. 1 Experimental outline and scope of the study

(XRD). The examination of physical and mechanical properties of fine aggregate, including specific gravity, mass density, water content, water absorption, particle size distribution, fineness modulus, and mud content, were investigated. Agricultural waste with variations of 0%, 10, 20, and 30% by weight of cement as cement replacement material is investigated for each type of waste used in mortar specimens. This study examined the engineering properties of mortar by assessing its fresh, physical, and mechanical properties. The fresh properties test consisted of a slump flow test to determine the workability and water consumption for producing mortar with varying amounts of waste. The investigation of physical properties, including porosity, water absorption, and mass loss. The porosity and water absorption investigation were conducted in specimens aged 28 days, while mass loss assessments were conducted on specimens aged 1–28 days. Variations in compressive strength at ages 3, 7, and 28 days were examined in the mechanical properties. In addition, ultrasonic pulse velocity (UPV) and hammer tests were conducted on the specimens at 28 days.

Experimental program

Materials

The materials used in this study consisted of binder (cement and agricultural waste), fine aggregate (river sand), and water. The cement used is categorized as Portland pozzolan cement (PPC) based on ASTM C595 [65] with a specific gravity of 3.10, while the agricultural waste used consists of rice husk ash (RHA), sugarcane bagasse ash (BA), and corn cob ash (CCA). This investigation used PPC cement because it is readily available and relatively inexpensive. The public widely utilizes PPC cement extensively, particularly in Indonesian industrial agriculture areas. Therefore, this study employs PPC-type cement as opposed to ordinary Portland cement (OPC) type, that market production is relatively limited. The chemical composition of the binders, namely PPC, RHA, BA, and CCA, can be seen in Table 1. This chemical composition

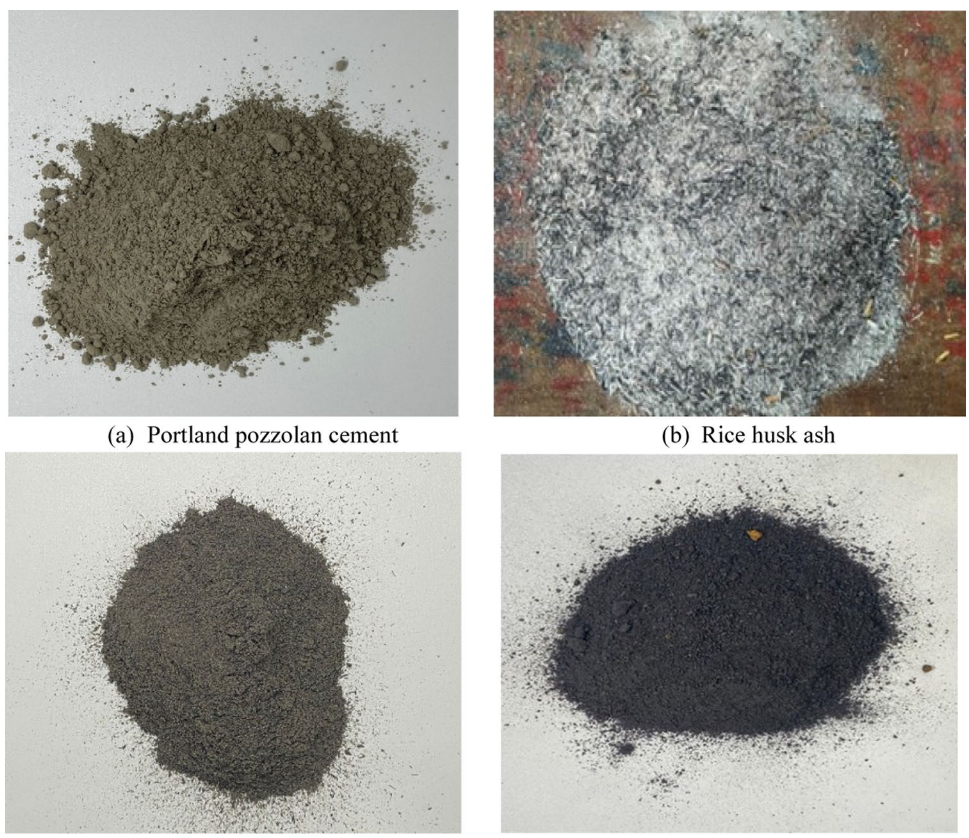
Table 1 Chemical compositions of binder

Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
PPC	32.59	7.51	2.05	47.83	1.61	2.90	3.62	1.80	0.09
RHA	20.58	19.28	7.78	48.70	2.03	0.99	0.44	0.19	0.01
BA	37.23	8.24	5.94	41.00	5.11	1.35	0.23	0.11	0.79
CCA	22.34	6.43	2.12	64.23	1.98	1.32	0.93	0.11	0.54

of binders reveals that the waste and cement contain higher amounts of CaO and SiO_2 than other substances.

Figure 2 shows the shape of the binders, including the cement substitute materials (PPC, RHA, BA, and CCA). All of the waste utilized originated from open-field burning in an Indonesian plantation region near Yogyakarta. Before being used as a substitute for cement, the waste products are filtered with a filter that passes No. 200. From Fig. 2, it can be seen that each waste produces a different color of ashes according to the type of waste and the duration of the combustion process. It should be noted that the burning and filtering processes significantly affect the texture of each waste. Therefore, different textures may result from different burning techniques. The characteristics of agricultural waste (RHA, BA, CCA) from open field burning based in several countries can also be found from the results of previous studies [45, 66–68]. Due to the influence of various waste resources, previous investigation demonstrates that the results of the properties of agricultural waste vary despite using the same investigation method of the same standard. This investigation focuses on the waste generated by burning open fields in rural agricultural areas of Yogyakarta, Indonesia. Because these wastes are primarily a result of open-field burning by farmers, neither temperature control nor duration of burning is carried out. The irregularity of the combustion process is one of the challenges that necessitate a comprehensive investigation into the practical application of agricultural ashes as one of the sustainable construction materials. Different chemical compositions evidence demonstrates this study (see Table 1), with CaO and SiO2 dominating the chemical composition of agricultural waste in this study.

The microstructural properties of the binder were also examined by carrying out the experiment using SEM and XRD. The results of the scanning electron microscope (SEM) investigation of mortar binder materials are shown in Fig. 3. This SEM examination reveals that each type of waste and cement has a particular microstructure. According to the SEM results, cement contains a single CaO molecule, whereas waste materials generally contain the alkali silica reaction products Al and SiO. In addition, XRD testing was conducted on cement and cement substitute waste materials. Figure 4 shows the XRD test results for binder materials used as mortar constituents. In the XRD test of cement material, the intensity of calcium (Ca), Silica (Si), and (O) has a very significant value. This demonstrates the nature of the behavior of cement, in which this element is the main component that contributes during the hydration process. Meanwhile, from testing on RHA, the Silica (Si), Oxygen (O), and Potassium (K) components dominate. In BA waste,



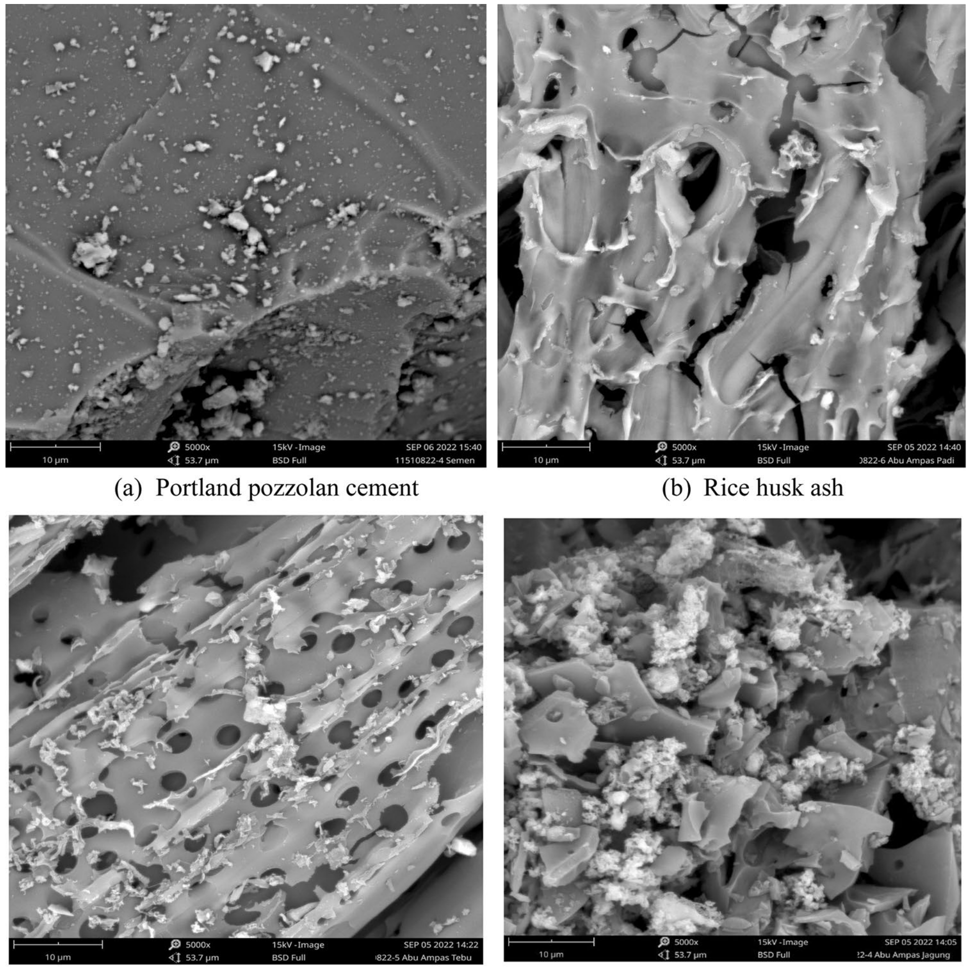
(a) Portland pozzolan cement

(b) Rice husk ash

(c) Sugarcane bagasse ash

(d) Corn cob ash

Fig. 2 Shape of binders (PPC, RHA, BA, and CCA)



(a) Portland pozzolan cement (b) Rice husk ash (c) Sugarcane bagasse ash (d) Corn cob ash

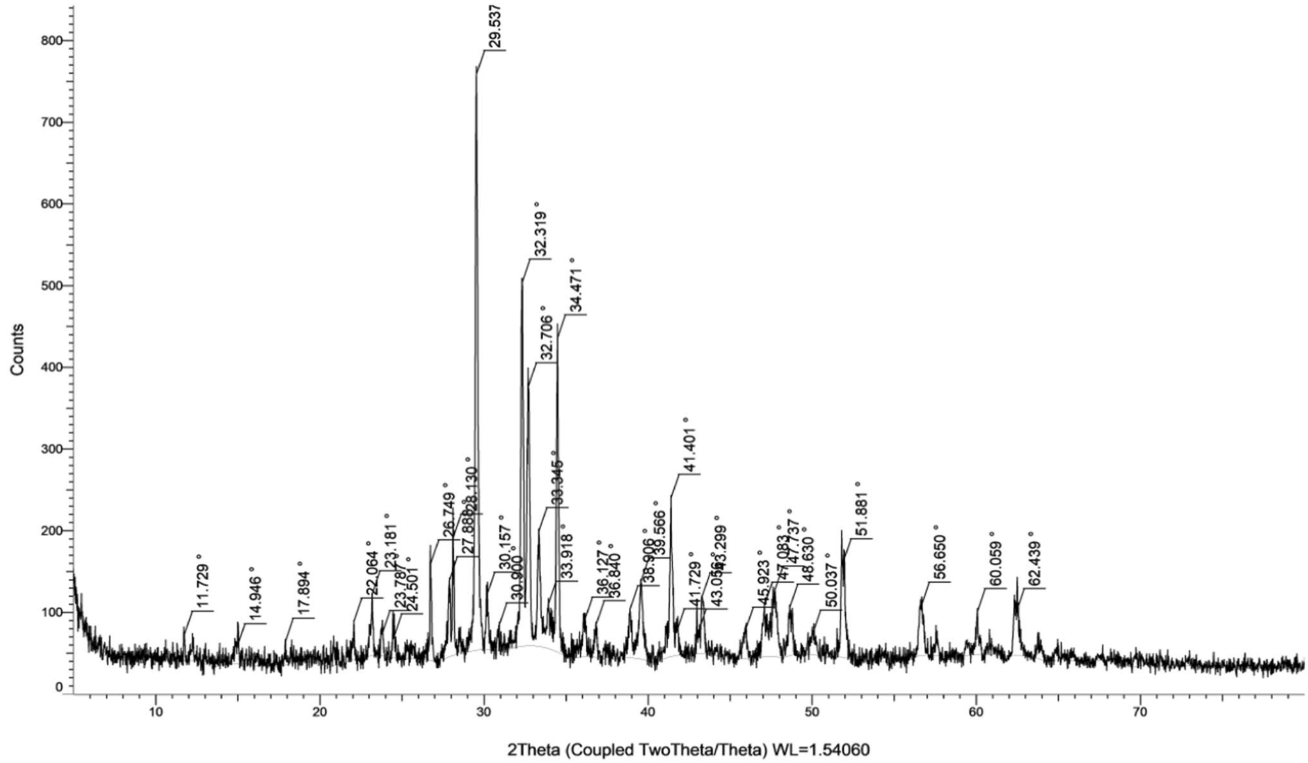
Fig. 3 Results of scanning electron microscope (SEM) for binder (PPC, RHA, BA, and CCA)

it can be seen that Oxygen (O), Silica (Si), Aluminum (Al), and potassium (K) are the dominant compounds, while CCA waste produces more Carbon (C), Oxygen (O), and Magnesium (Mg). Higher than other compounds. Apart from binders, mortar production also requires sand as a fine aggregate.

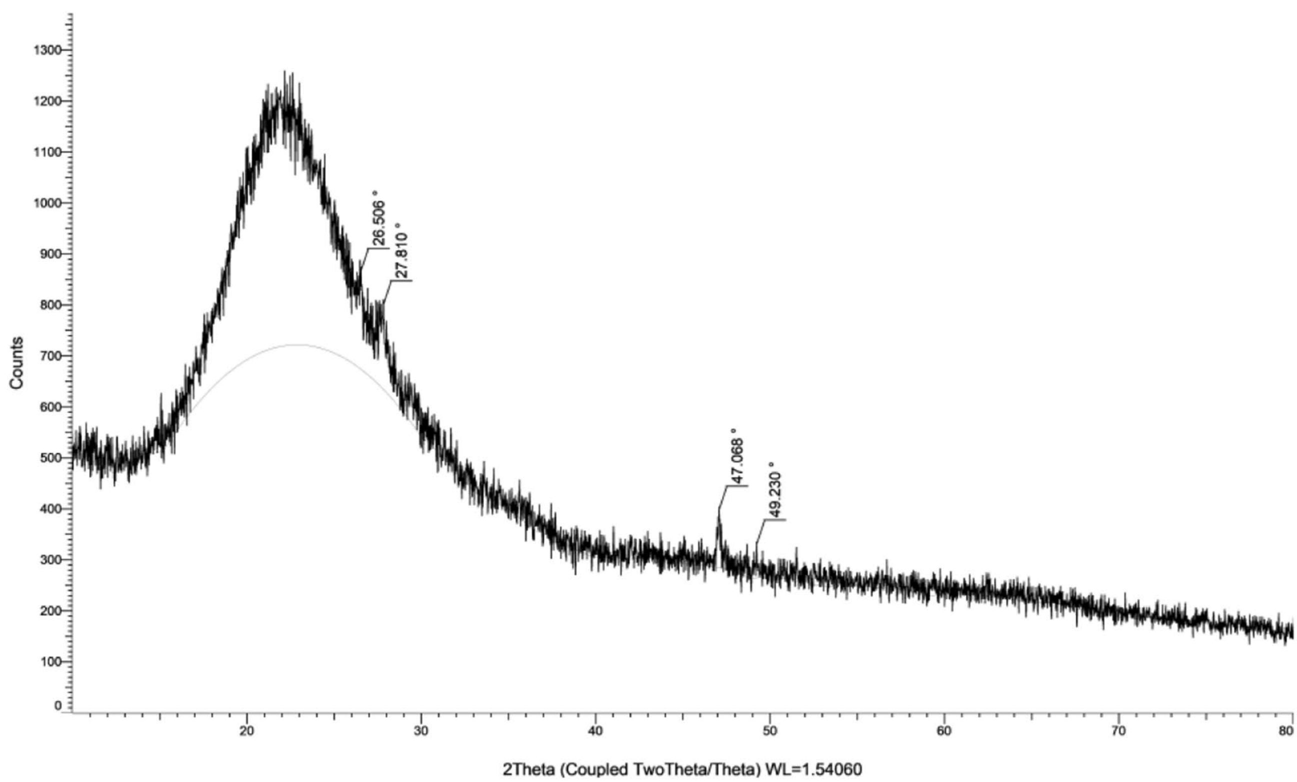
This study utilizes the sand river from Kulon Progo in Yogyakarta, Indonesia, as the fine aggregate. Before it is utilized for mortar manufacture, the physical and mechanical properties of the sand are evaluated. Table 2 displays the properties of the paste used. The properties examined for fine aggregate consist of specific gravity, water content, water absorption, mass density and fineness modulus, and particle size distribution. According to the investigation results into these properties, the used sand satisfies the specifications for building materials. In addition, the particle size distribution is inspected and compared to the particle size of each waste used for comparison. Figure 5 shows the results of the particle size distribution of fine aggregate and each waste used as a cement substitute material for making mortar. The use of sand as a mortar constituent material should be in saturated dry conditions. Testing the properties of sand as a mortar constituent refers to ASTM C33 [69], namely the standard specification for concrete aggregates. The test results showed that the specific gravity of the sand was 2.37, the water content was 1.34%, the water absorption was 2.10%, the mass density was 1.89 g/cm^3, and the fineness modulus was 2.43.

Mix proportions

This research focuses on examining the engineering properties of mortar by utilizing agricultural waste as a cement substitute material. The waste used is in the form of rice husk ash (RHA), sugarcane bagasse ash (BA), and corn cob ash (CCA). Each waste uses cement replacement variations of 10, 20, and 30% of the total weight of cement. Table 3 displays the mix proportions for each variation for manufacturing 3 cube-shaped specimens of $5.0 \times 5.0 \times 5.0$ cm^3. All waste is used as a substitute for cement in a dry condition. This study utilizes an amount of agricultural waste not more than 30% of the total binder weight. This is because it is anticipated that the use of large quantities of agricultural

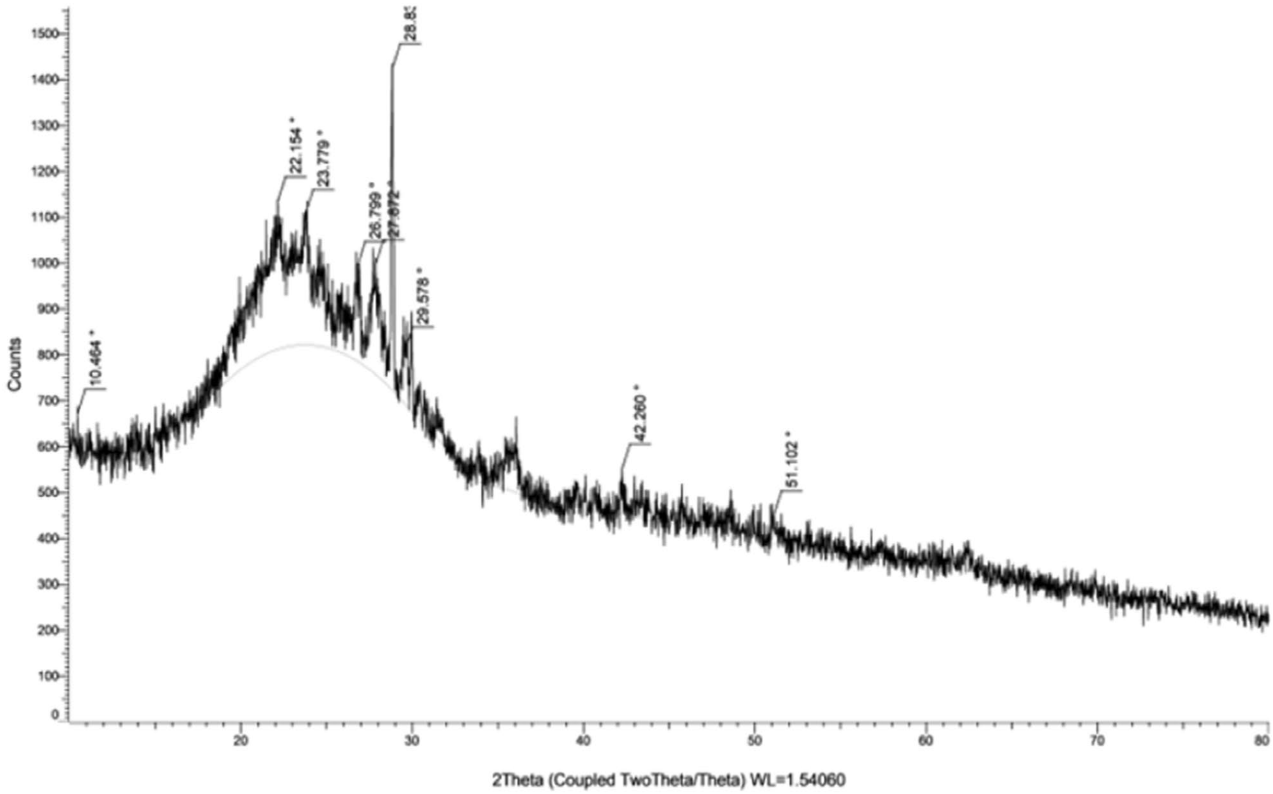


(a) Portland pozzolan cement

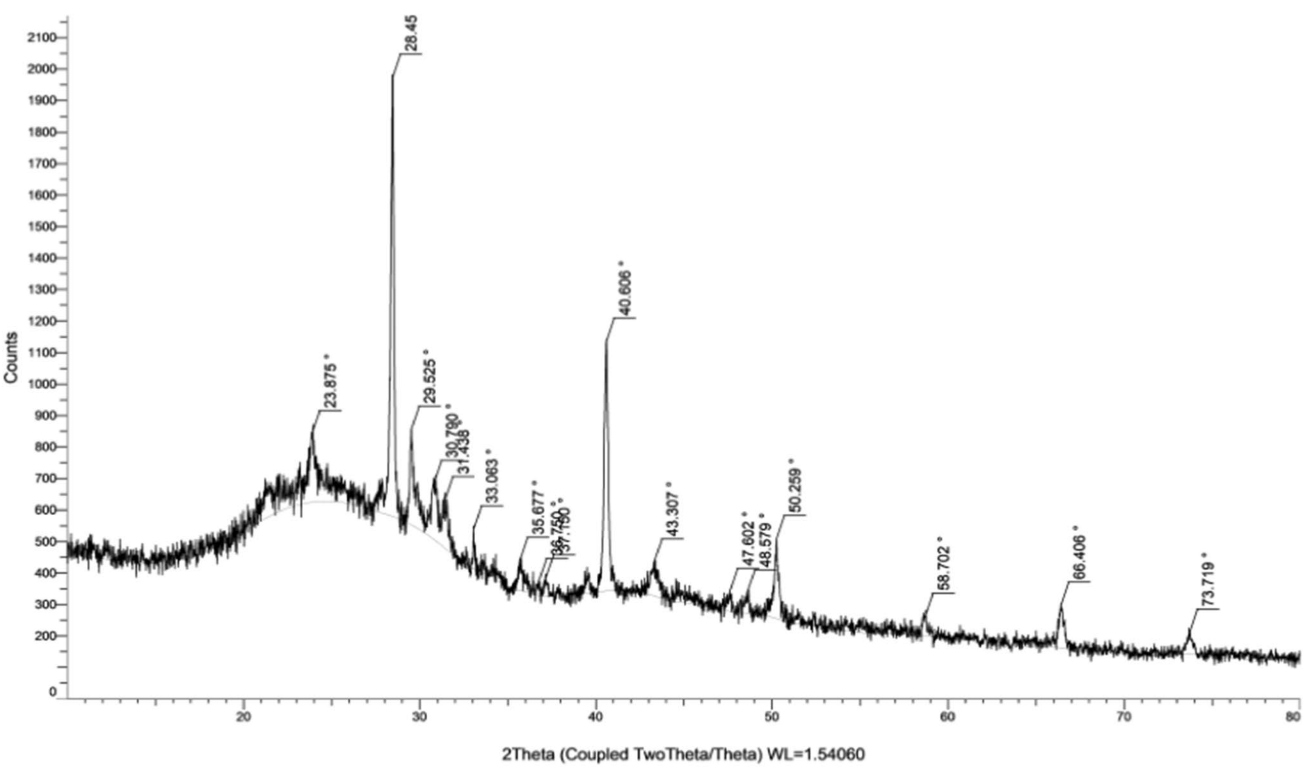


(b) Rice husk ash

Fig. 4 Results of X-Ray diffraction for binder (PPC, RHA, BA, and CCA)



(c) Sugarcane bagasse ash



(d) Corn cob ash

Fig. 4 (continued)

Table 2 Properties of fine aggregate (sand river)

Properties	Unit	Sand
Specific gravity	–	2.37
Water content	%	1.34
Water absorption	%	2.10
Mass density	g/cm^3	1.89
Fineness modulus	–	2.43

waste will reduce the quality of the mortar and cause a significant decrease in its performance. In addition, this study uses the same water to binder ratio for all variations, which is equal to 0.55. The selection of the water-to-binder ratio is based on the results of tests conducted on normal mortar (100 C), where a water-to-binder ratio of 0.55 demonstrates the most suitable fresh properties to produce mortar. In normal mortar specimen, various laboratory simulation is conducted to determine the required amount of water by controlling the slump flow in a fresh mortar. Once the water requirement for normal specimens has been determined, the water to binder ratio can be calculated. Because W/B is one of the significant component factors that influence the mechanical properties of mortar, this study uses water to binder ratio control for all test variations. In addition, a control water-to-binder ratio of 0.55 is utilized to investigate the workability of fresh mortar made with some agricultural waste as a cement substitute.

Experimental methods

This study evaluates the engineering properties of mortar made with agricultural waste as a cement replacement material (fresh and hardened properties). Before being used as a cement substitute, the waste products were the result of open field burning in rural areas of Yogyakarta, Indonesia, conducted by farmers. The workability of mortar is determined by examining its fresh properties. Flow table measurement was performed following ASTM C230 [70]. After conducting the flow table test, all fresh mortars are poured into the mold and removed 24 h later. Water curing was carried out

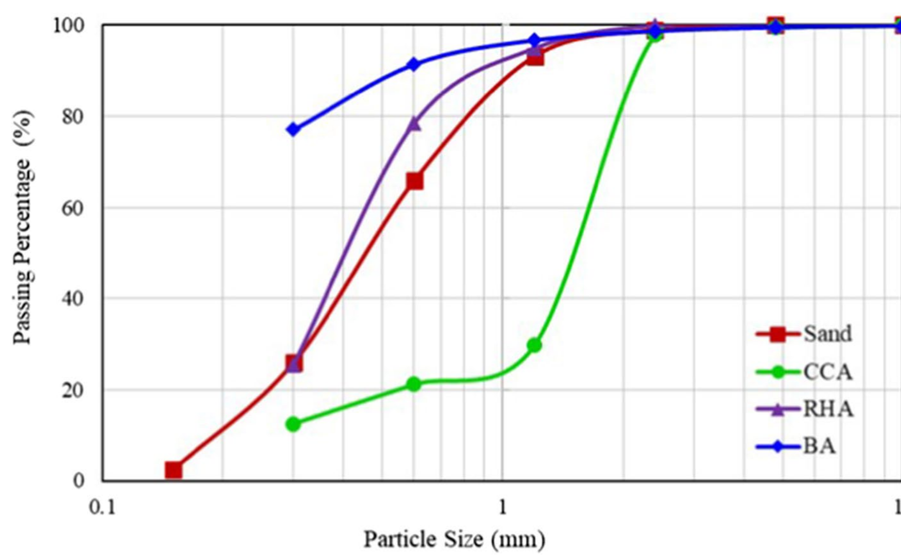


Fig. 5 Particle size distribution of sand and agricultural waste

Table 3 Mix proportions for three specimens in kg

Specimen ID	Cement	Water	Sand	RHA	BA	CCA
100C	0.2061	0.1134	0.6180	–	–	–
10RHA90C	0.1815	0.1134	0.6180	0.0206	–	–
20RHA80C	0.1649	0.1134	0.6180	0.0412	–	–
30RHA70C	0.1442	0.1134	0.6180	0.0618	–	–
10BA90C	0.1815	0.1134	0.6180	–	0.0206	–
20BA80C	0.1649	0.1134	0.6180	–	0.0412	–
30BA70C	0.1442	0.1134	0.6180	–	0.0618	–
10CCA90C	0.1815	0.1134	0.6180	–	–	0.0206
20CCA80C	0.1649	0.1134	0.6180	–	–	0.0412
30CCA70C	0.1442	0.1134	0.6180	–	–	0.0618

for 7 days, then all specimens were dried and cured at room temperature. The compressive strength test was conducted on mortar aged 3, 7, and 28 days. The test size of the specimens for compressive strength of $5.0 \times 5.0 \times 5.0$ cm^3 refers to ASTM C109 [71]. Figure 6 shows an example of fresh properties and compressive strength tests.

Mechanical properties of the hardened mortar were also inspected, including water absorption, mass density, mass loss, and porosity. The water absorption test is conducted per the ASTM C1403 standard [72], while the mass density and porosity test on hardened mortar is conducted per the ASTM D601 standard [73]. In addition, non-destructive testing was conducted to assess the quality of hardened mortar, and the relationship between destructive and non-destructive testing was evaluated. The non-destructive investigations consisted of ultrasonic pulse velocity (UPV) and hammer tests. Mortar that had been hardened for 28 days was subjected to UPV and hammer tests. The UPV test in this study refers to the ASTM C597 standard [74], while the hammer test refers to the ASTM C805 standard [75]. It should be noted that for testing, the hammer test and UPV use specimens of different sizes from the compressive strength test. This is done because it adjusts to the settings for each test and refers to each test standard.

Results and discussion

Fresh properties (flow table test)

Investigation of fresh properties is an important part of the mortar and concrete manufacturing process, particularly when special or new substances are employed. The purpose of investigating fresh properties is to determine the level of workability involved in fresh mortar. Therefore, this study also investigated the effect of the addition of agricultural waste on the properties of fresh mortar. It should be noted that in this investigation, the same water-to-binder ratio of 0.55 was used as the control for all variations. Figure 7 shows the results of the fresh properties test conducted by examining the flow table for each fresh mortar made with agricultural waste. In fresh mortar using 100% cement (without using waste materials as a substitute for cement) the results of the flow table test were 14.55 cm. This meets the requirements for fresh mortar according to ASTM C1437 [76]. This investigation reveals that the slump flow value decreases as the amount of waste used as a cement substitute increases, including fresh mortar with RHA, BA, and CCA waste.

The decrease in the slump flow in the mortar due to the addition of waste material indicates that the level of fresh properties of mortar decreases as the amount of waste used increases. As the amount of waste accumulates, the workability of fresh mortar decreases or becomes increasingly problematic to work. When using agricultural waste as a mortar constituent material, it is necessary to consider an appropriate amount of waste with a constant water to binder ratio. In addition, as the amount of waste increases, the processing of fresh mortar must be accelerated as the hardening process accelerates. Thus, it can be concluded that the decrease in slump flow in the mortar with waste material indicates that the water requirement has increased as the amount of waste used increases. From the results of this test, it can be seen that the mortar containing rice husk ash significantly reduced slump flow. This suggests that rice husk ash absorbs more water than bagasse and corn cob ash. This is supported by several studies that have reported that the waste material from agriculture is a porous material, so afterward it absorbs certain amounts of mixed water on its surface, resulting in a decrease in free water and lower slump [77–82].

(a) Fresh properties test (b) Compressive strength test

Fig. 6 Experimental process for flow table test and compressive strength

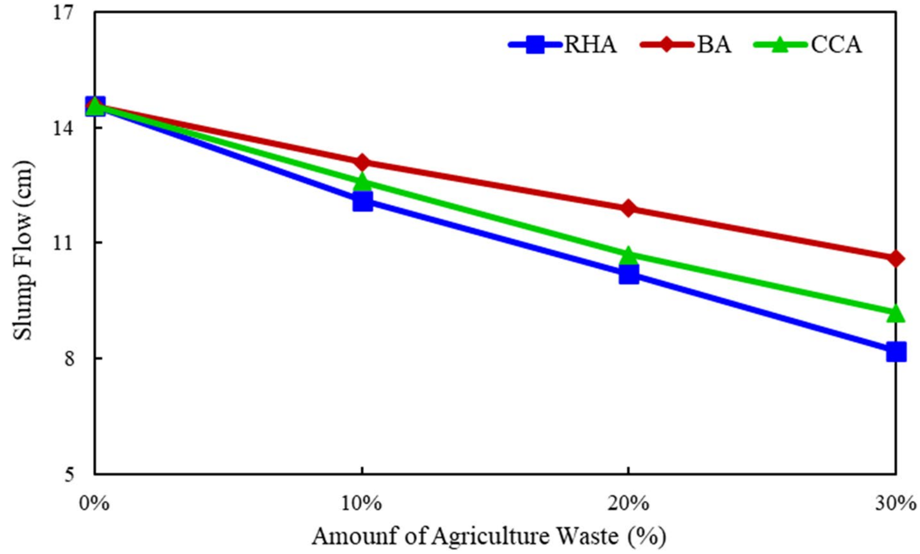
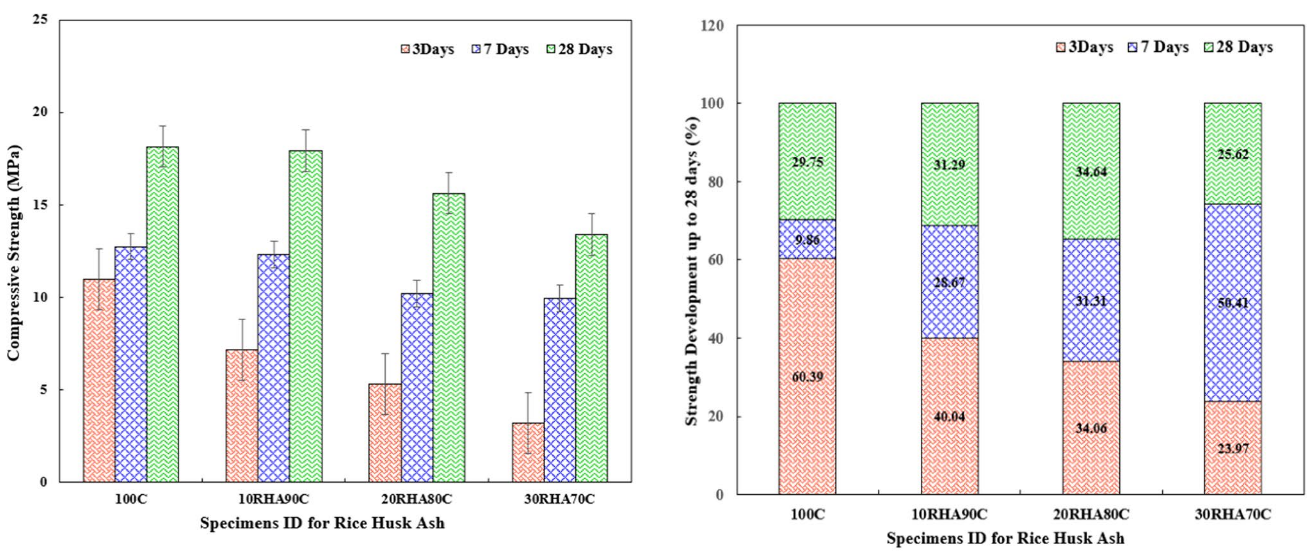


Fig. 7 Slump flow of mortar with agriculture waste as cement replacement

Compressive strength

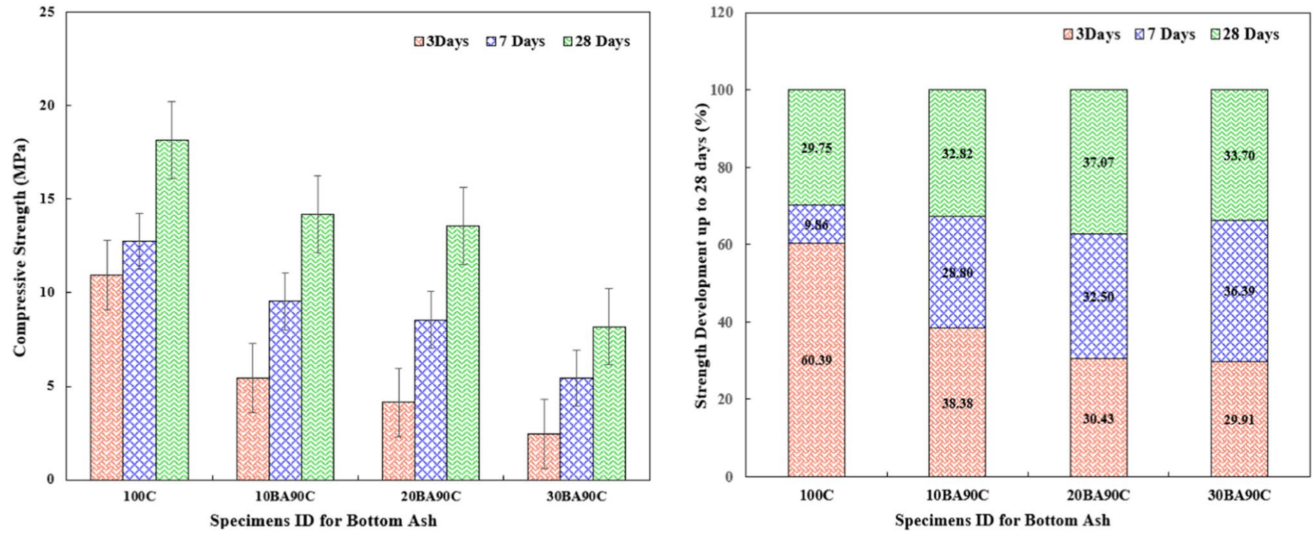
Compressive strength testing was carried out in each series with 3, 7 and 28 days of age variations. The compressive strength test results are the average of five specimens at each age and variation for each age category. The compressive strength test results and strength development along the ages can be seen in Fig. 8 for the utilization of rice husk ash waste, Fig. 9 for the utilization of bagasse ash waste, and Fig. 10 for the utilization of corn cob ash waste. The compressive strength test results on mortar containing rice husk ash and bagasse ash indicated that the compressive strength decreased as the amount of waste increased. Previous investigations involving mortar with rice husk ash [24, 66, 83] and bagasse ash [67, 84, 85] demonstrated comparable results.

Several possibilities cause a decrease in compressive strength, including the influence of the porous pozzolanic nature of agricultural waste, and the amount of cement used decreases, increasing the pores volume of the mortar and a decrease in its compressive strength. Agricultural waste (RHA, BA, and CCA) is a porous pozzolanic material, and using this waste increases the pore volume of mortar, as a consequence of an increase in the pore volume of mortar,



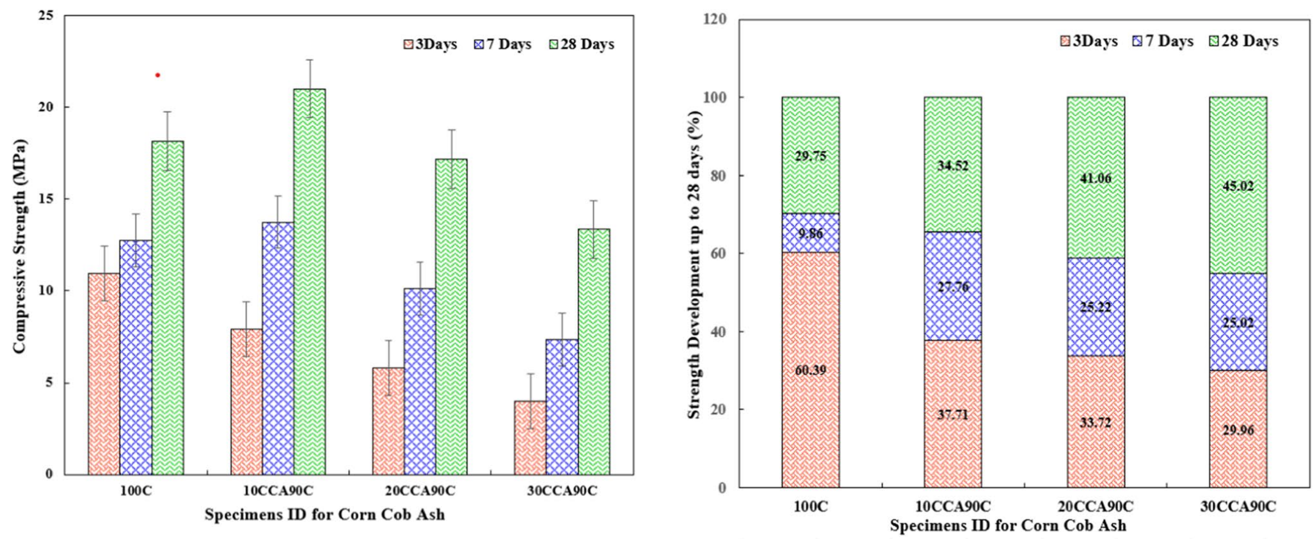
(a) Compressive strength with different age (b) Strength development along ages

Fig. 8 Compressive strength of mortar with rice husk ash as cement replacement



(a) Compressive strength with different age (b) Strength development along ages

Fig. 9 Compressive strength of mortar with bagasse ash as cement replacement



(a) Compressive strength with different age (b) Strength development along ages

Fig. 10 Compressive strength of mortar with corn cob ash as cement replacement

porosity and compressive strength decrease. Figure 3 from the SEM results proves agricultural waste material has more pores than cement. The compressive strength decreases significantly due to the deficient development of early strength of agricultural waste mortar at the early age of the concrete due to the low pozzolanic reaction [24, 86]. In addition, due to the effect of open-field burning on agricultural waste, the waste combustion process is not properly controlled, resulting in a lack of control over the quality of the waste for cement substitute material, which can contribute to a reduction in mortar quality. Additionally, using agricultural waste as a substitute for cement reduces the amount of cement in the mortar, which can reduce the compressive strength of mortar. Even though using these three wastes indicates that the values of fresh properties (slump flow) and compressive strength have decreased substantially, this is particularly the case for specimens incorporating 30% waste ashes as a cement substitute. However, the 10% waste ash specimens generated compressive strength and slump flow comparable to normal mortar.

The compressive strength test of mortar containing corn cob ash waste produced the highest compressive strength after 28 days when 10% CCA waste was used. This is possibly due to the fact that 10% waste as a substitute for cement is the optimal ratio to reach maximum compressive strength. Several previous researchers have also determined that the optimal compressive strength of corn cob ash is achieved by substituting 5–15% by the weight of cement [32, 49, 82]. In addition, Figs. 8, 9 and 10 show the strength development over time for the three wastes used as cement replacement for mortar manufacture. The results of this study indicate that at 3 days of age, the compressive strength of the mortar containing waste decreased significantly compared to normal mortar at an early age. This is due to the fact that the used waste is pozzolanic materials, which do not react instantaneously when mixed with water. Therefore, the compressive strength of the mortar at the early age of the mortar decreases as the amount of waste used increases. Meanwhile, in the mortar with the age of 7 days, it shows that the specimens using waste experienced an increase in the compressive strength of the mortar by 25–30%, while the increase in the compressive strength of the normal mortar at the age of 3–7 days tends to be lower. From the age of mortar 7–28 days, there was no significant difference between normal mortar and mortar using waste.

The relationship between the amount of agricultural waste and the compressive strength of concrete at the age of 3 and 28 days can be seen in Fig. 11. As the amount of agricultural waste increases, the compressive strength of the material decreases significantly at three days of age. When using the same cement substitute, mortar made from bagasse ash has a lower compressive strength than mortar made from corn cob ash. This shows that corn cob ash can produce a more optimal compressive strength compared to rice husk ash and bagasse ash. It should be noted that the waste material used in this study is burned waste resulting from open-field combustion. Therefore, the waste-burning process was not properly controlled. In addition, the use of waste reduces the required amount of cement. As a result of these two factors, the compressive strength of mortar decreases when waste is used as a substitute for cement.

In addition, when the mortar was 28 days old, it was observed that 10% corn cob ash increased the compressive strength of the mortar, while 10% rice husk ash produced a compressive strength that was almost the same as normal mortar, and only 10% bagasse ash produced a lower compressive strength than normal mortar. Through the results of this study, the authors would like to recommend that the use of 10% waste still fulfills the requirements for sustainable and environmentally friendly construction material in terms of compressive strength. Using 10% of this waste will be expected to decrease the cement required to produce a more sustainable and environmentally beneficial mortar. Several previous researchers have also recommended using agricultural waste as a substitute for cement in mortar and concrete, with an optimal percentage of 10%. The percentage used depends on the waste treatment, combustion, and burning process [31, 32, 49, 82, 87]. The use of less than 10% agricultural waste has a negligible effect on physical and mechanical properties while using waste that exceeds the optimum limit might reduce the compressive strength and durability of mortar. It is necessary to determine the optimal level of waste that can be used as a substitute for cement in mortar to reduce

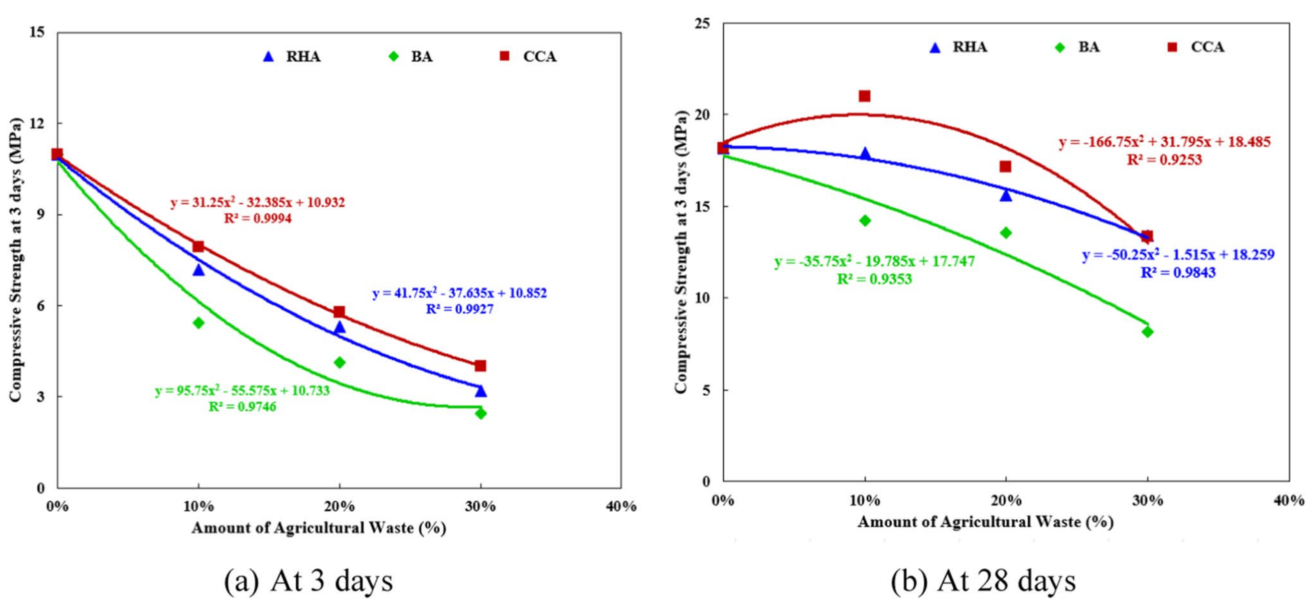


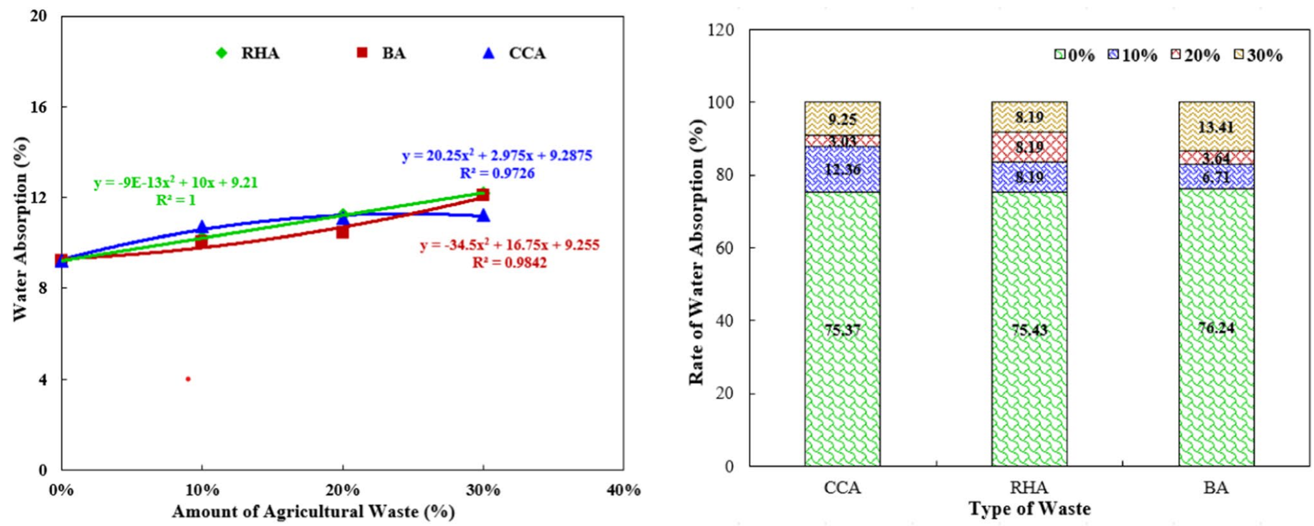
Fig. 11 Relationship between the amount of waste with compressive strength

the use of cement and consider the mechanical properties of the mortar.

Water absorption and porosity

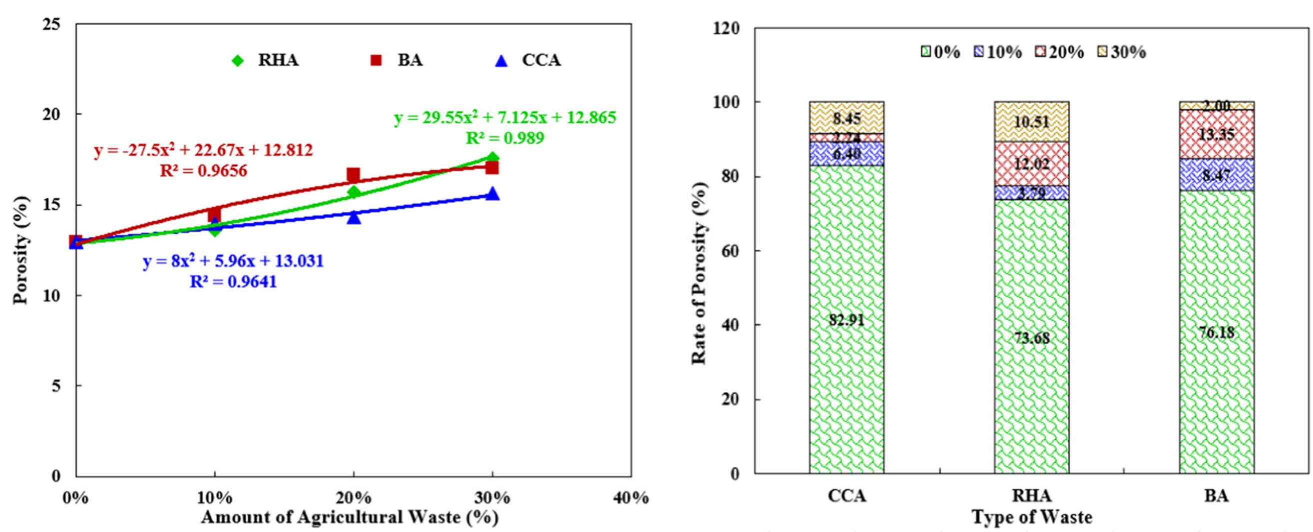
In addition to compressive strength tests, water absorption and porosity tests were performed on each variation of the target-hardened mortar after 28 days. The results of the water absorption and porosity investigations are the average of the results of five test objects for each series. Figure 12 shows the test results for water absorption, while Fig. 13 shows the test results for porosity. As shown in Fig. 12, as the amount of waste used increases, so does water absorption, although the increase is not statistically significant, from 9 to 12% of water absorption. This absorption occurs because the porosity value also increases as the amount of waste used increases, as shown in Fig. 13.

The results of the porosity test indicate that the porosity value increases as waste volume increases, this indicates that the pore volume in the mortar also increases as waste volume increases. This demonstrates that the three waste materials used are porous and produce more porosity than



(a) Water absorption (b) Rate of water absorption

Fig. 12 Relationship between the amount of agricultural waste and water absorption



(a) Porosity (b) Rate of porosity

Fig. 13 Relationship between the amount of agricultural waste with porosity cement mortar. In addition, the test results show that the porosity and water absorption values of the three used wastes were not significantly different, so it can be concluded that the three wastes have similar absorption and porosity patterns. The results of porosity and water absorption have a significant impact on the compressive strength of mortar, as porosity increases, so does water absorption. A high porosity indicates a high capillary volume in the mortar, which degrades the quality of the mortar. The results of porosity and water absorption in the study, which increased but not substantially, were also consistent with some of the results of previous studies, which indicated that the use of agricultural waste of up to 30% as a substitute for cement in the production of mortar or concrete was acceptable [24, 83, 88–92]. However, previous investigation indicates that the porosity and water absorption values decrease substantially when large amounts of waste (up to 60 percent) are utilized.

Mass loss and mass density

The mass loss test aims to determine the change in mass and the potential for mass loss because of using waste as a cement substitute material to manufacture mortar. Figure 14 shows the respective mass loss results for all three types of used waste. Figure 14 demonstrates that the trend curve has increased (a positive value), indicating that the mass of mortar has increased, whereas the trend curve has decreased (a negative value), indicating that the mass of mortar has decreased from its initial mass at the initial age. Rice husk ash, bagasse ash, and corn cob ash waste demonstrate that as concrete age reaches seven days, the mortar mass increases as more waste is applied. This is because the mortar is cured with water curing for the first week. As the amount of waste utilized increases, the mortar absorbs more water because of this curing. The results of the porosity and water absorption tests demonstrate this increase in mass, as a large quantity of waste results in a large amount of water absorption. This tends to apply to all waste types (rice husk ash, bagasse ash, and corn cob ash), with the variant of 30% waste resulting in a higher mass increase throughout the curing process. It should be noted that the addition of mass during the curing process does not exceed 8%. After the curing process, all test objects were placed in a dry place with controlled room temperature and relative humidity.

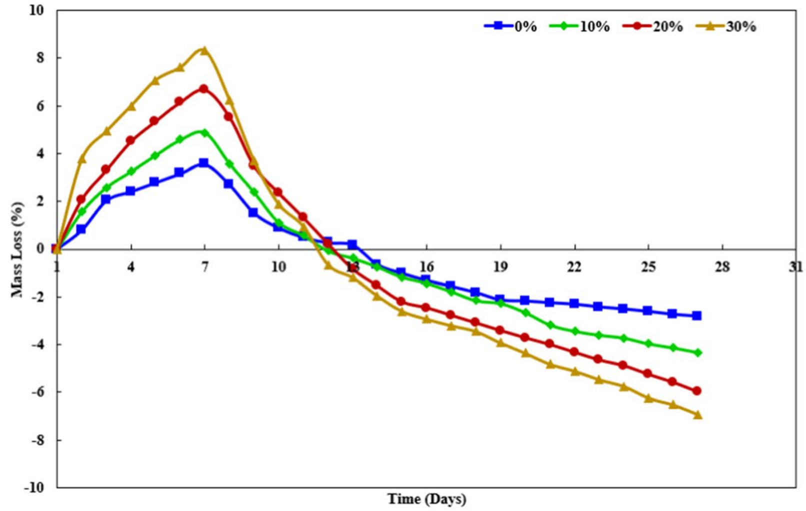
The results of the mass loss investigation revealed that the mass of all specimens decreased after being exposed to air curing at room temperature. This indicates that a drying and evaporation process is occurring with mortar the air curing. In addition, investigations at the age of 28 days mortar revealed that the highest mass loss was always observed in the hardened mortar with waste containing 30% of RHA, BA, and CCA. As the amount of waste produced increases, the resulting mass loss also increases. However, the mass loss in mortar containing 30% waste does not exceed 6% for BA and CCA and 8% for RHA. This shows that RHA has higher possibility of mass loss than BA and CCA mortar. This mass loss can also indicate shrinkage, with RHA mortar shrinking more than BA and CCA mortars. The significant mass loss in the mortar with an amount of waste of 30% occurs due to the influence of the waste used as a cement substitute. With a high amount of waste, it causes the ability to absorb water to be higher. In addition, it also causes the ability to evaporate water in the mortar to be higher and faster.

Figure 15 shows the results of the mass density measurement for each mortar variation at 28 days of age. Based on the results of this experiment, it is obvious that all waste has the same effect on mass density, as more waste is added, the mass density decreases. It can be concluded that waste used as a cement substitute can produce a lightweight harder mortar. This is a significant advantage as an alternative construction material that is more eco-friendly and can produce lightweight materials. The investigation results show that hardened mortar using CCA produces a lower mass density than BA and RHA mortar. However, the difference in mass density between the three types of waste in the hardened mortar is not very significant. It can be concluded that apart from being a sustainable material capable of reducing the use of cement, this agricultural waste material can also produce a lightweight structure that can produce hardened mortar lighter than normal mortar. Some previous studies also demonstrate that an increase in the amount of agricultural waste causes decreases in the mass density of mortar or concrete [49, 93–95].

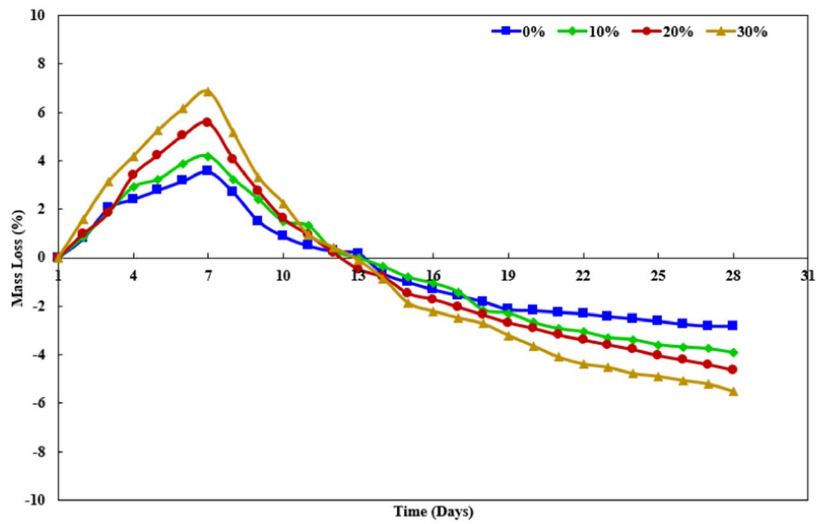
Hammer test and ultrasonic pulse velocity (UPV)

In general, the non-destructive test on hardened mortar investigates the hardened properties, such as compressive strength and porosity of the hardened mortar. In this study, UPV and rebound hammer tests were carried out to evaluate the compressive strength of the mortar. Figure 16 shows the results of the non-destructive test on the specimens that of 28 days old. The results shown are the average of 5 test objects for each variation. The results of the UPV test show that the velocity rate has decreased as the amount of waste used increases, both RHA, CCA, and BA waste mortar. The same trend was also generated through the rebound hammer test, where the rebound number decreased in specimens with a higher amount of agricultural waste. This demonstrates that as the velocity rate value on the UPV test results decreases, so does the compressive strength of the mortar, as well as the results of the rebound hammer test, where the decreased rebound number indicates a decrease in the strength of the hardened mortar.

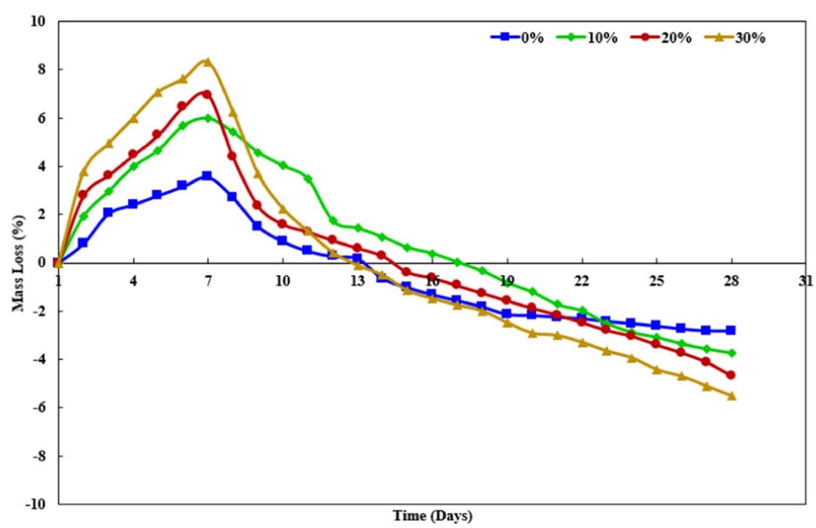
Fig. 14 Mass loss of mortar for 28 days



(a) Rice husk ash as cement replacement



(b) Bagasse ash as cement replacement



(c) Corn cob ash as cement replacement

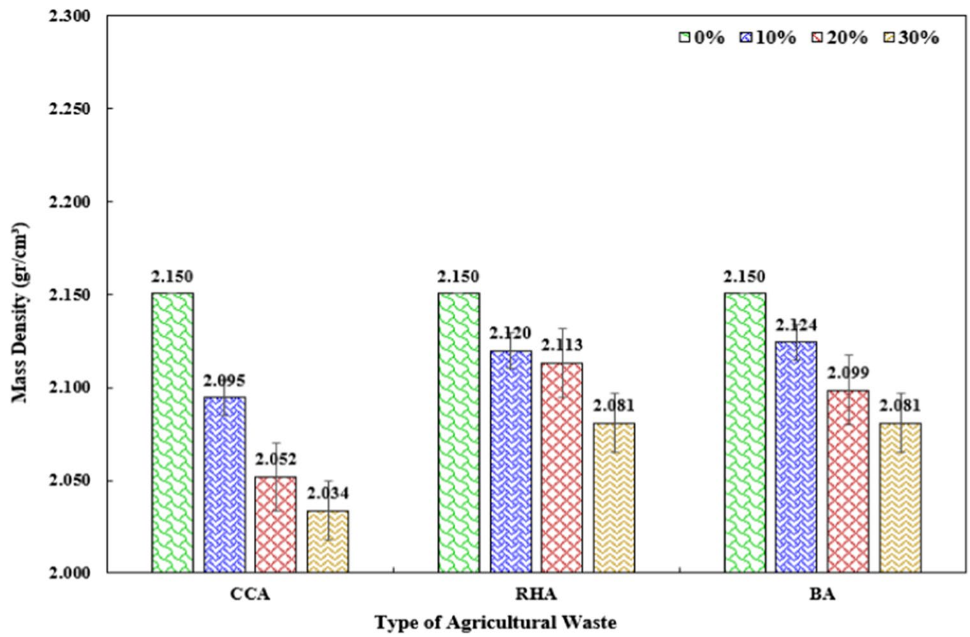


Fig. 15 Mass density

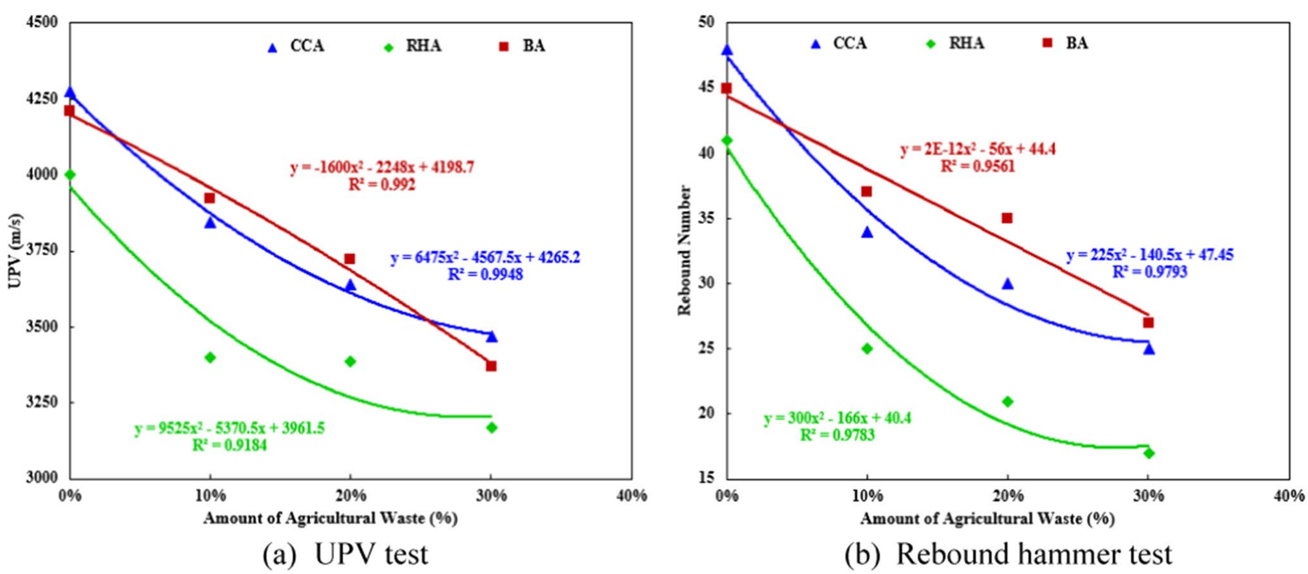


Fig. 16 The results of UPV and rebound hammer test

In addition, this study observes a correlation between the non-destructive test results and the concrete compressive strength test results, as shown in Fig. 17. The results indicate that the correlation coefficient between compressive strength and UPV test results is 0.829, indicating that compressive strength will also increase as the velocity rate increases. In addition, the correlation coefficient between the results of the rebound hammer test and the compressive strength of the mortar is 0.8229. It can be concluded that there is a strong correlation between the results of the non-destructive test and the compressive strength test. The regression analysis used to calculate the correlation between compressive strength and the non-destructive test applies to all three wastes. Previous studies demonstrated a similar correlation between UPV values and compressive strength [96–99] and rebound hammer test values and compressive strength [100–103]. According to the results of previous studies, it also shows an increase in the velocity rate, and the rebound number indicates an increase in compressive strength.

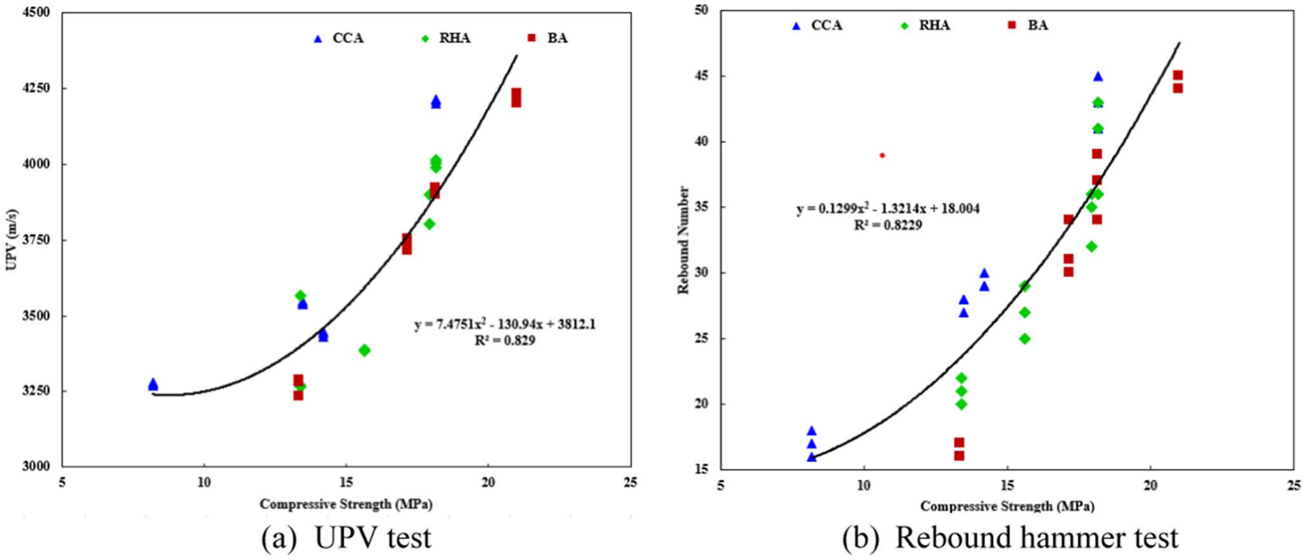


Fig. 17 Correlation between compressive strength and non-destructive test

Conclusions

This study investigated the engineering properties of mortar containing untreated agricultural waste ashes (RHA, BA, CCA) as cement replacements. This study determines the various characteristics of agricultural waste used in the production of mortar in order to produce sustainable construction materials. Various destructive and non-destructive inspections were conducted on both fresh and hardened properties. This research determined the optimal composition of the amount of agricultural waste that can be utilized by taking into account the quality of the mortar produced. Based on the experimental results that have been discussed above, some conclusions can be drawn as follows.

1. Mortar containing agricultural waste has inferior fresh properties compared to conventional fresh mortar. This is due to the waste ability to absorb large amounts of water. As the amount of waste increases, fresh mortar's workability decreases.
2. The compressive strength test results indicate that as the amount of agricultural waste used increases, the resulting compressive strength decreases substantially, particularly at the early age of mortar. In addition, the authors suggest substituting 10% of waste for cement. This is due to the proven fact that 10% waste can reduce cement consumption and produce mortar with comparable compressive strength to normal mortar.
3. The results of the hardened properties for water absorption porosity, mass loss, and mass density show the same pattern. The water absorption and porosity increase in correlation to the amount of waste used, although the results are insignificant compared to normal mortar. In addition, the increasing amount of waste results in a lower mass density hardened mortar than normal mortar. So that the use of this waste has the potential to produce a lightweight material.
4. The correlation between the results of non-destructive tests, such as UPV and rebound hammer tests, and the compressive strength tests for all types of waste variations are strong correlations, which is 0.829 correlation between UPV and compressive strength, and 0.8229 correlation coefficient between the results of the rebound hammer and the compressive strength.

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Author contributions HP: conceptualization, data curation, formal analysis, funding acquisition, methodology, supervision, writing review & editing. FM: data curation, investigation, project administration, supervision, writing original draft. SAP: data curation, investigation, writing original draft. RAL: data curation, investigation, writing original draft. DEW: data curation, supervision, writing review & editing.

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Declarations

Conflicts of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate The authors declare their consent to participate in this work.

Consent to publish The authors have participated in the preparation or submission of this paper for publication in Innovative Infrastructure Solutions.

Informed consent All the authors are aware of this paper. For this type of study formal consent is not required.

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