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Engineering Properties and Production Costs of Paving Blocks Incorporating Different Types of Agricultural Wastes

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Abstract

Open-field burning is still widely utilized as a traditional waste disposal method in agriculture, particularly in developing countries. In some locations in Yogyakarta, Indonesia, the ashes formed by the open field burning of agricultural waste have not been utilized to their full potential. This research aims to utilize waste ashes from three different agricultural industries, including sugarcane bagasse ash (SBA), rice husk ash (RHA), and corn cob ash (CCA), as replacements of cement in the paving blocks production. The purpose of utilizing agricultural waste ashes was to reduce soil pollution caused by waste in plantation areas around Yogyakarta, as well as initiatives to reduce the use of cement for non-structural constructions. The laboratory scale experiments examined the engineering properties of paving blocks, including slump flow, splitting tensile strength, compressive strength, flexural strength, mass loss, water absorption, porosity, mass density, and initial suction rate (IRS). Besides, an analysis of the production cost was also conducted. This research found that the maximum amount of waste that can be used is 20% of the total binder for a composition ratio of 1:9 (binder: sand). Based on the mechanical properties, it was found that a 10% composition of agricultural waste ashes is the optimum amount recommended for use with comparable properties to normal paving blocks. However, by using agricultural waste ashes between 15% to 20% decrease the mechanical properties of paving block. In addition, by utilizing 10% of waste ashes in total binder, it is possible to reduce production costs by 2.25% to 2.43%.

1. Introduction

The paving block is extensively used in many construction infrastructures like sidewalks, parking lots, bus stops, industrial plants, garages, and other construction sites. In its development, paving blocks made of different materials have been used for thousands of years. The Romans were the first to construct roads using stone blocks, followed by various countries. In the 1940s, road construction in Holland began using cement concrete paving blocks, causing a significant revolution in the global development of paving blocks, where cement-based materials continue to be used in various countries [1]. Conventional paving blocks are typically characterized as composite construction materials composed of water, aggregates and cement [2]. Cement-based paving blocks are most widely used for non-structural infrastructure purposes, especially in urban areas. Alongside the increasing trend of infrastructure development, the production of paving blocks is also increasing. The increase in paving block production required by market demand will inevitably lead to a rise in demand for primary source materials. This is also one of the factors that causes cement production to increase continuously, thereby making it extensively utilized material in infrastructure construction [3].

The increase in cement utilization in large amounts as a construction material is predicted to continue to increase over a long period. Several researchers estimate that a substantial increase in the production of concrete or mortar is directly proportional to the increase in cement production until 2050, particularly in developing countries in Asia, America, and Africa [4-7]. However, it was estimated that approximately 8% of global CO_2 emissions are produced annually by the cement industry, primarily due to its use of around 14% of global energy [8-11]. The relatively high energy consumption in cement production results from the chemical conversion of limestone-based raw materials into cement clinker, which requires approximately 110 kWh of electricity and emits between 800 kg to 900 kg of CO_2 per ton of cement production [12-15]. According to reports, CO_2 emissions are the primary cause of global warming, making it one of the primary concerns of the Sustainable Development Goals (SDGs) program [16, 17]. Obviously, this is also a concern for the cement and concrete manufacturing industry, which annually generates a significant amount of CO_2 emissions. In addition, the SDGs program aims for all industries, including construction and cement industries, to be able to produce cement-based products with net zero emissions by 2050 [18]. To reach the cement production goal of zero net emissions by 2030, it will be necessary to reduce CO_2 emissions from cement production by at least 3% annually by 2030 [19-21]. Therefore, various innovative and advanced methods are required for concrete and cement production that is sustainable and environmentally friendly.

To reduce the cement utilizations in civil construction, it is important to explore some alternative replacement materials, particularly for non-structural types of infrastructure that do not sustain heavy loads and were not considered significant hazards to infrastructure users. Paving block is a cement-based material typically used for low-loading infrastructure, where the predominant working forces are compressive and frictional forces. In recent years, the production of paving blocks has continued to increase in sync with market demand, resulting in an increase in cement consumption by the paving block industry. Alternatively, paving blocks are frequently used for infrastructure components that are non-structural or intended to enhance the aesthetic appeal of an infrastructure. Under these circumstances, it is possible to use alternative materials to replace cement in producing paving blocks promoting sustainable and eco-friendly paver. Several studies have also been found regarding paving blocks using various materials as a substitute for cement or aggregate, including using plastic waste [22-28], glass waste [29-33], industrial waste, such as steel slag [34-38], fly ash [39-43], bottom ash [44-48], and organic-based waste ash, such as rice husk ash [49-53], sugarcane bagasse ash [54-57], cob corn ash [58,59], and palm oil ash [60-62]. It can be concluded that using various materials as cement substitutes produces different characteristics, including mechanical and physical properties of paving blocks. The most significant difference was in the engineering properties of paving blocks, such as compressive strength, flexural strength, tensile strength, and friction effect. In addition, it is also necessary to pay attention to the durability of paving blocks, particularly on infrastructure exposed to sulphate or chloride environments.

It is well known that agricultural waste, such as rice, palm oil, sugar cane, corn, coconut, etc., has the potential to be used as a partial replacement for cement in construction materials. The agricultural sector is expanding significantly in many tropical and southeast and south Asian countries such as Indonesia, Philippines, Sri Lanka, Thailand, Malaysia, Cambodia and Vietnam [63,64]. However, the agricultural industry cannot prevent the production of industrial waste, which must be managed following applicable regulations. The accumulation of hazardous refuse in the environment may result from insufficient regulation of the disposal procedure. Various investigation results demonstrate that there are still many improperly managed industrial waste disposal processes, particularly in developing countries that lack adequate waste disposal regulations and policies [65-67]. It was also reported that open-field burning is a common method for disposing of agricultural wastes, particularly in rural agricultural communities and small islands [68,69]. Open-field burning is a traditional practice that is prevalent among farmers. The majority of open field burning for the disposal of agricultural waste occurs in China and India, where it accounts for 34% of the total biomass burned annually [70,71]. Furthermore, waste from open burning in the form of agricultural waste ash is not optimally utilized, resulting in land contamination. This research aims to utilize waste from open field burning as partial substitute for cement in paving block production

Utilization of agricultural waste, which is frequently used as a substitute for cement, is a material that has been appropriately processed, where the waste is detreated and heated in the range of approximately 600 °C to 1200 °C, thereby transforming waste as a source pozzolanic materials [72-74]. However, there are no facilities for converting agricultural by-product into high-quality pozzolanic material, so waste from open field burning is still limited information and questionable, particularly in the plantation/agricultural industry in rural areas. Previous research involving agricultural waste ash to produce mortar demonstrates that this waste has a promising potential for use in various types of non-structural infrastructure [75,76]. However, limited information is available regarding the use of agricultural waste ashes derived from open field burning as a partial replacement for cement in paving block production. In this study, various types of agricultural waste ash obtained through open burning were utilized as partial cement substitutes for manufacturing paving blocks consists of RHA, SBA, and CCA. All these wastes used originally from open field burning disposal methods in rural Yogyakarta, Indonesia. This research is intended to develop a paving block industry that is more sustainable and environmentally friendly, capable of producing excellent engineering properties, and takes production costs into account. This research is expected to reduce the proportions of agricultural waste and cement utilized in non-structural constructions.

2. Significance and Scope of the Study

This research incorporates RHA, SBA, and CCA as a cement replacement pozzolanic material for paving block manufacture. Several investigations on using agricultural by-product ash as alternative binder are well-known. However, there is still limited information regarding the utilization of agricultural waste ashes in producing paving blocks. In addition, the primary innovation of this study is the investigation of agricultural waste ashes was generated through open burning practices in rural areas of Yogyakarta, Indonesia. No prior study has been conducted on using agricultural waste as a substitute for cement to produce paving blocks. Recently, farmers have not adequately utilized agricultural waste ashes, resulting in an accumulation of waste that causes water and land pollution. Therefore, an investigation is required to identify innovative approaches for repurposing agricultural wastes, which are intended to reduce biomass accumulation resulting from open-field combustion. In addition to evaluating the engineering properties and sustainability these agricultural waste ashes, this study also investigates the economic value of producing paving blocks from agricultural waste ashes. This study is expected to identify price competition in the local market for both the manufacture and distribution of paving blocks. An overview of the experimental design and the scope of this research is illustrated in Fig. 1.

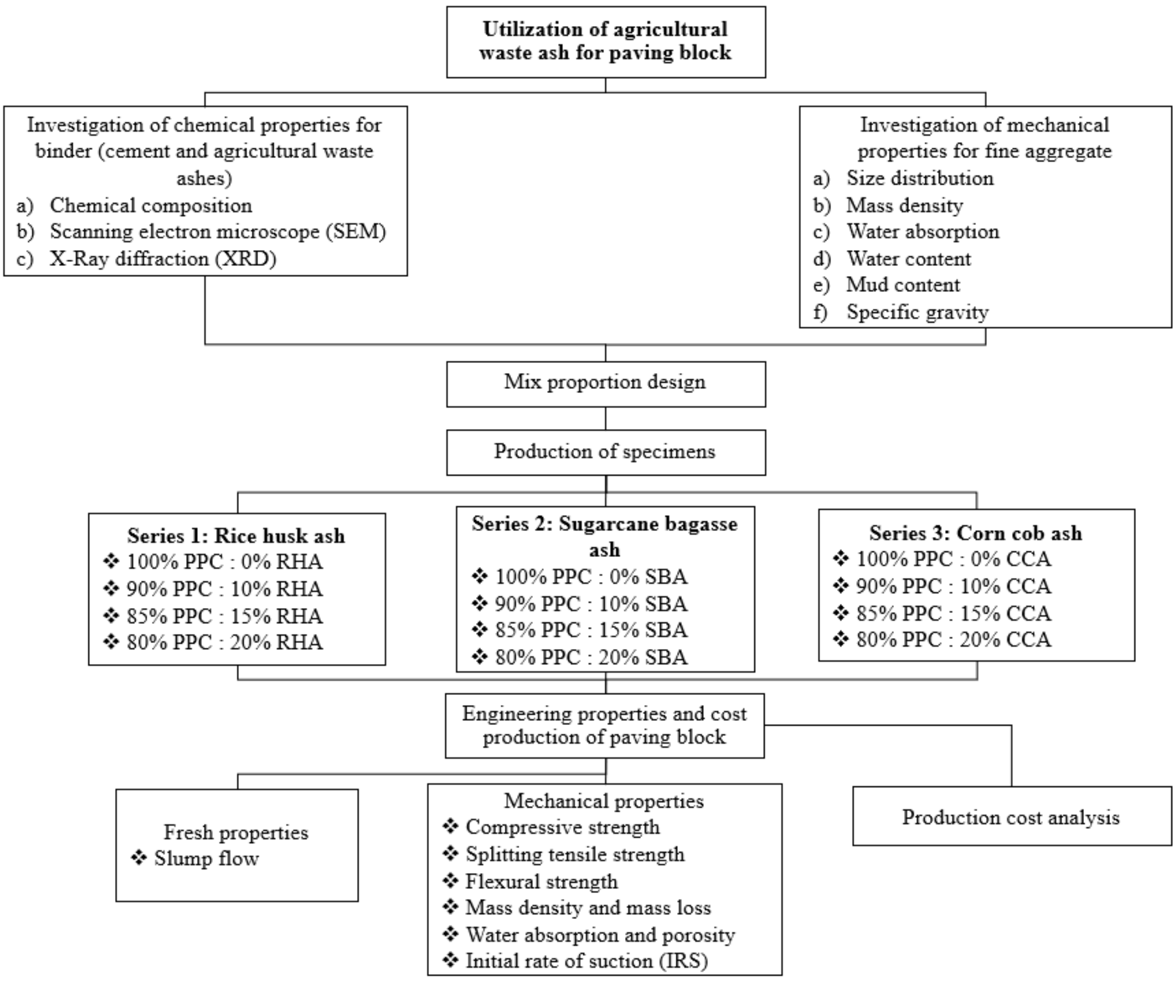


Fig. 1 *Experimental outline and scope of the study*

The main objective of this research is to investigate the engineering properties and production costs of paving blocks made with three different types of agricultural waste-derived ash for cement substitution. The initial stage of the research began with investigating the constituent materials properties, including examining microstructure of the binders and the mechanical properties of fine aggregate. The microstructure inspection was conducted because the used waste resulted from open field burning, which did not control the burning temperature, the burning duration, or the possibility of particle mixing. Therefore, microstructure inspection for binders (cement and agricultural waste ashes) needs to be carried out. Meanwhile, mechanical properties of fine aggregate testing were conducted to determine the quality of sand utilized to produce the paving blocks. The fine aggregate used in this study is sand, usually used to produce paving blocks in the area where this research was conducted. This study was intended to prepare the mix proportion is to quantify the amount of each component substituent material and the amount of water required during the mixing process. The test specimens were made with each variation, namely 0%, 10%, 15%, and 20% agricultural by-product ash as a substitute for Portland pozzolan cement (PPC). The experimental investigation involved conducting a slump flow test to evaluate the fresh properties of the mixture, while hardened properties included compressive strength, splitting tensile strength, flexural strength, mass density, mass loss, water absorption, porosity, and initial suction rate (IRS). By using agricultural waste ash, it is expected that this research will enable the produce of paving blocks that can compete in the local market. In addition, it is also expected that the results of this study will be able to reduce biomass waste and cement used for paving blocks to help contribute to sustainable, durable, and environmentally friendly paving blocks.

3. Experimental Program

3.1 Materials

This study utilized water, river sand, cement, and agricultural waste ashes as materials for paving block manufacture. Portland pozzolan cement (PPC), conforming to ASTM C595 [77] was utilized in this study, with a specific gravity of 3.10. It should be noted that PPC type is used because it is readily available on the market and relatively inexpensive, particularly in agricultural industrial areas. In addition, the use of Ordinary Portland Cement (OPC) has become highly uncommon recently, and production is limited. The pozzolanic material used as a cement substitute consisted of three distinct types of agricultural by-product ash: RHA, SBA, and CCA. These three types of waste were collected from small-scale farms in rural areas in Yogyakarta, Indonesia. All three types of waste used were collected in ash form after being burned by farmers without considering the duration or temperature of the burning process. The resulting ash waste is filtered through filter No. 200 and dried until no water contains. Fig. 2 shows the shape of each binder used in this research. Before use, each type of binder must be analyzed for its chemical composition, microstructure, and X-ray diffraction (XRD) properties. The chemical composition results for each binder used (PPC, RHA, SBA, and CCA) are listed in Table 1. The chemical composition results indicate that cement produces more CaO than other substances, while agricultural waste particles produce more SiO_2 than other substances.

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	37.80	7.94	2.84	45.53	1.61	2.67	1.10	0.80	0.01
RHA	48.71	8.90	1.95	29.64	0.85	1.91	7.35	0.64	0.02
SBA	48.27	13.74	1.35	25.79	0.65	0.38	1.53	2.35	0.94
CCA	48.53	10.21	1.87	10.93	1.87	0.68	24.15	0.97	0.79

(a) PPC

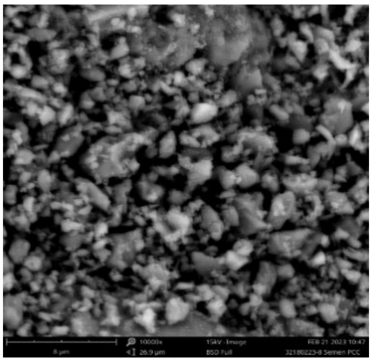
(b) RHA

(c) SBA

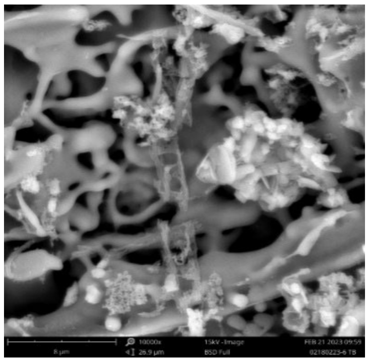
(d) CCA

Fig. 2 *Naked eye appearance of binders*

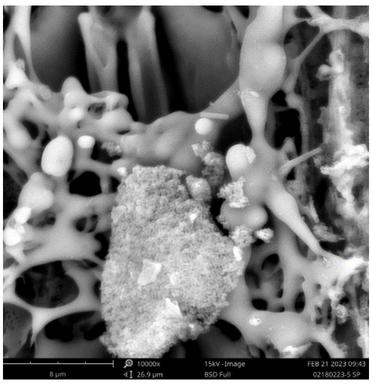
The microstructural characteristics of the binder materials were investigated through Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses. SEM observations of the different binder types namely Portland pozzolan cement (PPC), rice husk ash (RHA), sugarcane bagasse ash (SBA), and corn cob ash (CCA) are presented in Fig. 3. The SEM images indicate that each binder exhibits a unique microstructural morphology. The cement sample showed a higher concentration of isolated calcium oxide (CaO) particles, whereas the waste-derived binders were predominantly composed of alkali-silica-related compounds, specifically aluminum (Al) and silicon oxides (SiO). Complementary to this, XRD tests were carried out on both the cement and alternative binder materials. Fig. 4 illustrates the diffraction patterns of the various binders used in the paving block mixtures. In the case of cement, peaks corresponding to calcium (Ca), silicon (Si), and oxygen (O) were notably intense, affirming their central role in the cement hydration mechanism. Conversely, the RHA sample was found to contain high levels of silicon (Si), oxygen (O), and potassium (K). The SBA specimen demonstrated a dominant presence of oxygen (O), silicon (Si), aluminum (Al), and potassium (K), while the CCA sample exhibited comparatively higher intensities of carbon (C), oxygen (O), and magnesium (Mg).



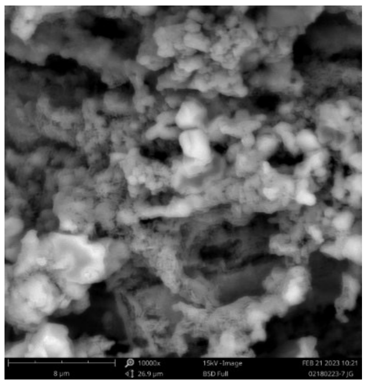
(a) PPC



(b) RHA

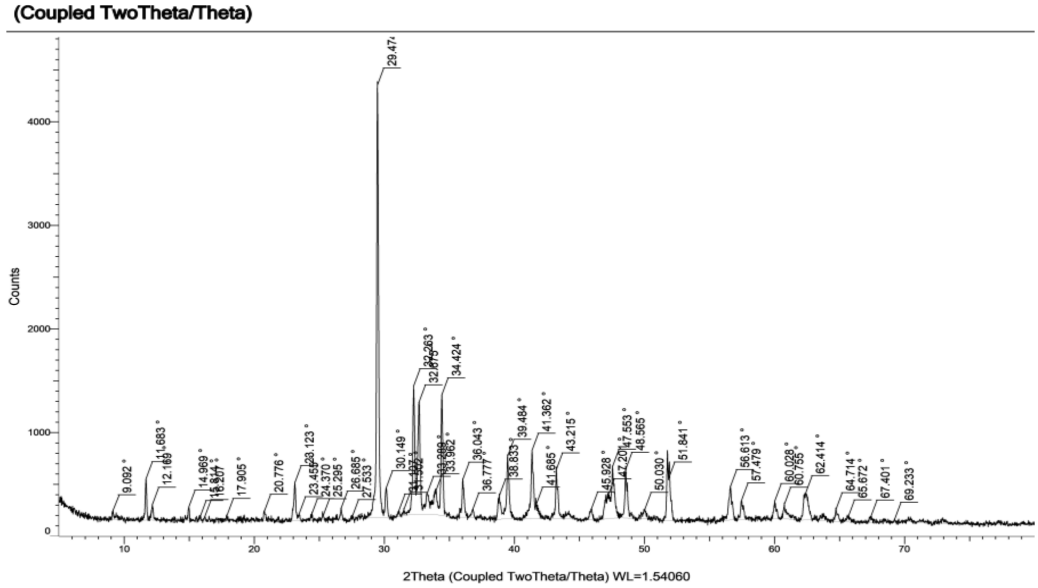


(c) SBA

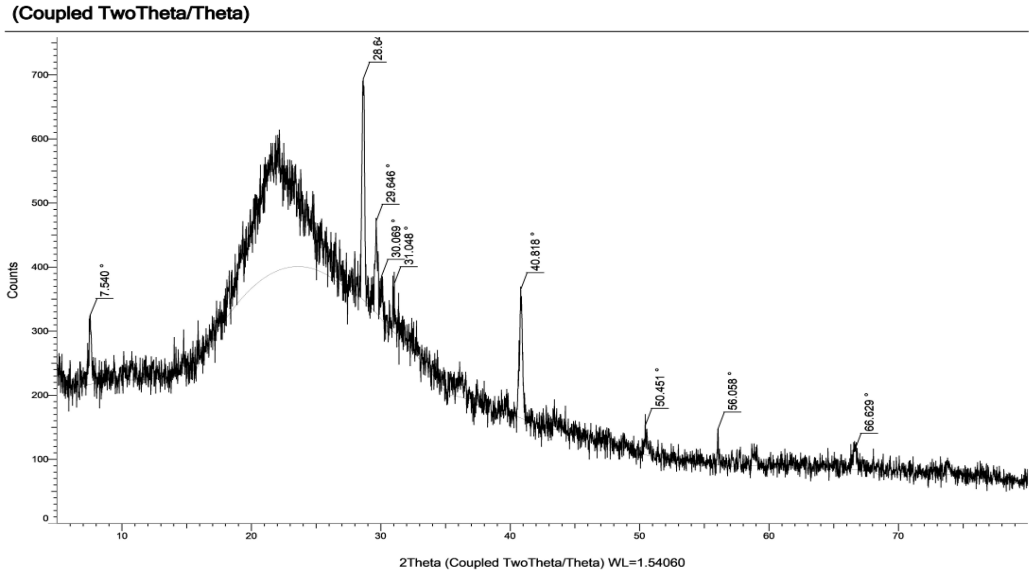


(d) CCA

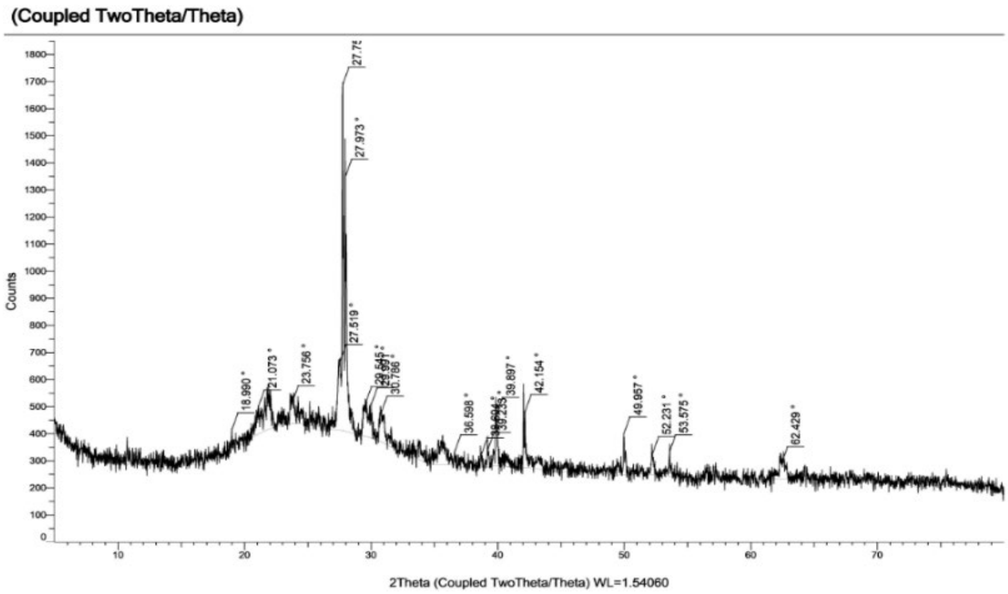
Fig. 3 *Results of scanning electron microscopes (SEM) binder constituent for paving block*



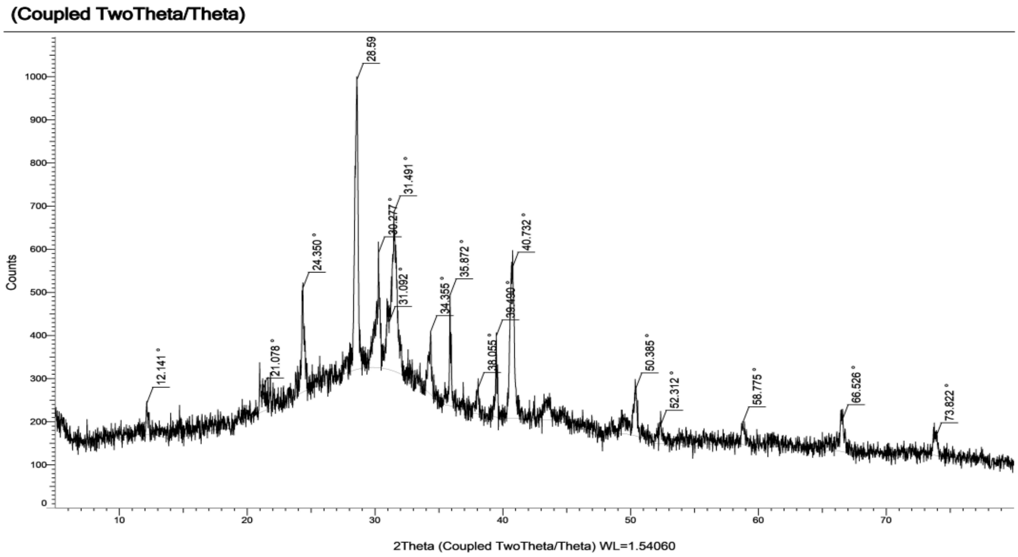
(a) PPC



(b) RHA



(c) SBA



(d) CCA

Fig. 4 *Results of X-ray diffraction (XRD) binder constituent for paving block*

Locally sourced river sand from Kulon Progo, Yogyakarta, Indonesia was utilized in this study as the fine aggregate for paving block production. To assess the suitability of the sand utilized in the production of paving blocks, its physical and mechanical characteristics were examined. The mechanical properties of the fine aggregate are summarized in Table 2. The parameters evaluated include specific gravity, moisture content, water absorption, bulk density, fineness modulus, and particle size distribution. Fig. 5 shows the results of the particle size distribution inspection. Based on the river sand properties results, it can be concluded that the sand meets the requirements for use in the production of paving blocks. It should be noted that sand must be used to make paving blocks in saturated dried conditions. The testing mechanism of the mechanical properties of fine aggregate for paving blocks refers to the applicable standard of ASTM C33 [78].

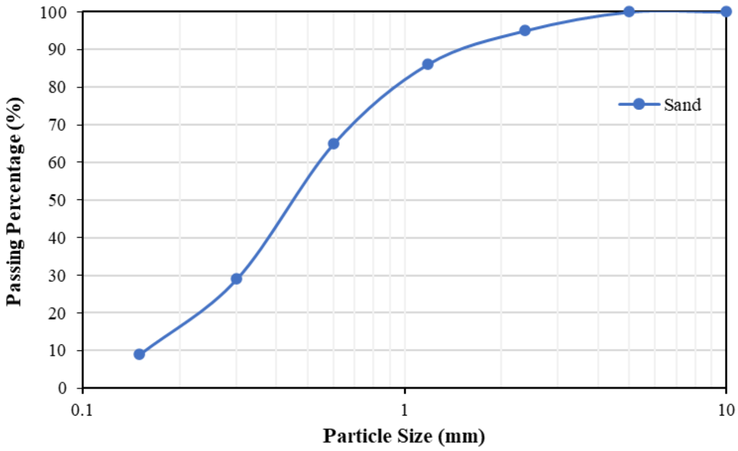


Fig. 5 *Particle size distribution analysis of sand and agricultural waste ashes*

Table 2 *Specification of fine aggregate*

List of properties	Value
Fineness modulus	2.72
Specific gravity	2.31
Water absorption (%)	3.09
Water content (%)	3.45
Mass density g/cm^3	1.54
Mud content (%)	2.60

3.2 Mix Proportions

This study focuses on replacing three distinct agricultural by-products were utilized as partial replacements for cement in the production of paving blocks. The size of the paving blocks used in this research is 20 x 10 x 6 cm^3 (length x width x height). The variations for each waste ash used as a cement replacement consisted of 0%, 10%, 15%, and 20% of the total volume of binder. The mix design was derived from the results of field investigations, which revealed that the paving block industry in the Yogyakarta district of Indonesia typically produces paving blocks with a cement-to-sand volume ratio of 1:9. Then, based on the results of field investigation, the proportion of the mixture was transformed to weight units as shown in Table 3. The mix proportion shown in Table 3 is a paving block mixture to produce 18 specimens, including the safety factor. It should be noted that a water to binder ratio of 0.50 was used in this study. This value water to binder ratio was obtained through initial investigations regarding water requirements to produce paving blocks. Initial investigation reveals that an increase in the proportion of waste ash leads to a corresponding rise in water demand, due to the higher water absorption capacity of waste ashes compared to that of cement. A constant water-to-binder ratio was applied to all specimens to verify the quality of the paving blocks, thereby enabling a more reliable comparison of the results. This study utilize 10%; 15% and maximum of 20% by volume of cement of each waste due to the simplicity calculation for the mix proportion. Furthermore, preliminary investigations and literature from past investigations [75, 76] indicate that incorporating agricultural waste ashes in more than 20% significantly diminishes the mechanical properties of mortar/concrete and adversely affects workability, thereby complicating the mixing process. Thus, this study only utilize agricultural by-product ashes as cement substitute for paving blocks production not more than 20% of cement.

Table 3 *Mix proportions for each specimen in kg*

Specimen ID	Cement	Water	Sand	RHA	SBA	CCA
100PPC	8.56	4.28	38.44	-	-	-
90PPC10RHA	7.70	4.17	38.44	0.65	-	-
85PPC15RHA	6.84	4.07	38.44	1.29	-	-
80PPC20RHA	5.99	3.96	38.44	1.94	-	-
90PPC10SBA	7.70	4.17	38.44	-	0.65	-
85PPC15SBA	6.84	4.07	38.44	-	1.29	-
80PPC20SBA	5.99	3.96	38.44	-	1.94	-
90PPC10CCA	7.70	4.17	38.44	-	-	0.65
85PPC15CCA	6.84	4.07	38.44	-	-	1.29
80PPC20CCA	5.99	3.96	38.44	-	-	1.94

3.3 Experimental Procedures

The present study comprises two primary components, specifically the investigation of engineering properties and the assessment of production costs. The investigation of engineering properties was conducted through the examination of both fresh and hardened properties. The assessment of fresh properties involved slump flow testing, while the assessment of hardened properties included various aspects such as compressive strength, split tensile strength, flexural strength, mass density, mass loss, water absorption, porosity, and IRS. The inspection of fresh characteristics is conducted for each mix proportion by the measurement of the flow table. The flow table testing was conducted according to the guidelines set out by ASTM C230 standards [79]. After the flow table tests were completed, the specimens in each variation were placed into the mold and removed from it when they had taken their intended cube shape. The specimens were then covered with plastic wrap for 24 hours to prevent evaporation. The specimens were then water-cured for seven days to produce paving blocks with improved performance so that the hydration process could run well. Then, all specimens were deposited in a controlled room until the test period.

Compressive strength, flexural strength and split tensile strength tests were conducted on specimens aged 7, 14, and 28 days, with an average of three specimens represented for each result (90 specimens for each test with total 270 specimens). It should be noted that all specimens for compressive strength, split tensile strength, and flexural strength tests have the same dimension of 20 × 10 × 6 cm^3 (length × width × height). Fig. 6 shows the setup for each test carried out in this study. The compressive strength test in this study was adapted from ASTM C109 [80], which is used for the compressive strength test of mortar. Meanwhile, splitting tensile strength testing refers to ASTM C496 [81], and flexural strength testing refers to ASTM C78 [82]. It is expected that the investigation of compressive strength, tensile strength, and flexural strength will be able to determine the mechanical properties of paving blocks. In addition, physical properties measurements, such as mass density, mass loss, water absorption, porosity, and IRS, are conducted on 28-day-old pavers. The results of this physical properties test were the average of the results from three specimens. The water absorption and IRS test were conducted following through ASTM C1403 [83], while the mass density and porosity of the hardened mortar were evaluated in accordance with ASTM D604 [84]. The purpose of the physical properties investigation was to collect more information about the quality of paving blocks manufactured with agricultural waste ash as a cement substitute. In addition, the costs of production in each mixture variation were analyzed. It should be noted that the costs used in this study are expressed in Indonesian rupiah.

(a) Slump flow test

(b) Compressive strength

(c) Splitting tensile strength

(d) Flexural strength

Fig. 6 *Setting up for the experiment of fresh and hardened properties for paving block*

4. Results and Discussion

4.1 Fresh Properties

Slump flow testing is one of the methods used to evaluate the workability of fresh mortar and water requirements for paving block production. This inspection aims to determine the water requirements and water to binder ratio for mixing paving blocks effectively during the manufacturing process. It should be noted that a consistent water-to-binder ratio was applied across all mixture variations in this study. The standard and classification of slump flow testing for paving blocks is ASTM C230 [79] due to the similarity in the materials used between paving blocks and mortar. The slump flow test results for each proportion can be seen in Fig. 7. This test shows that paving blocks with standard proportions (no replacement material) generate the highest slump flow of 118.25%. The slump flow tends to decrease with the increasing proportion of waste used as a substitute for cement. These results also indicate an insignificant difference in slump values between using RHA, SBA, and CCA waste.

When using an amount of waste of 20%, it produces the lowest slump flow, ranging from 106% to 108%. However, the reduction in slump flow is acceptable. Because this research intended to use similar water to binder ratio for all different mixtures, it was discovered that using more than 20% waste could substantially reduce slump flow. The finding reveals that the maximum proportion of waste used as a cement replacement was determined to be 20%. With a constant water to binder ratio of 0.5, it can be concluded that 10%, 15%, and 20% waste ashes can produce paving blocks that satisfy the slump flow requirements. In addition, A water-to-binder ratio of 0.5 was selected following a series of slump flow tests conducted using a trial-and-error approach. Using a higher water to binder ratio results in an excessively high slump flow, particularly in normal paving mix proportions, while using a lower water to binder ratio results in an excessively low slump flow, particularly in a mix proportion containing 20% waste ashes.

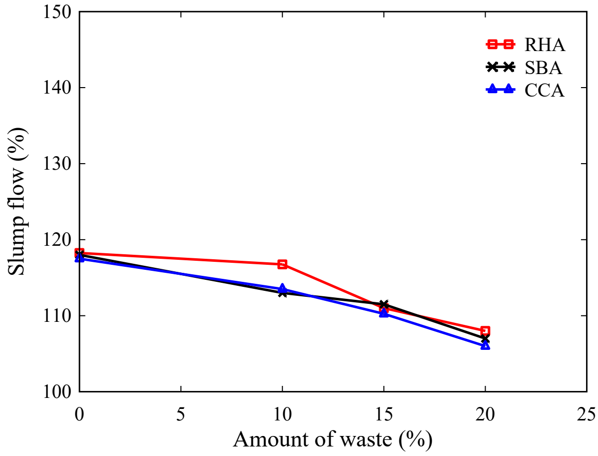
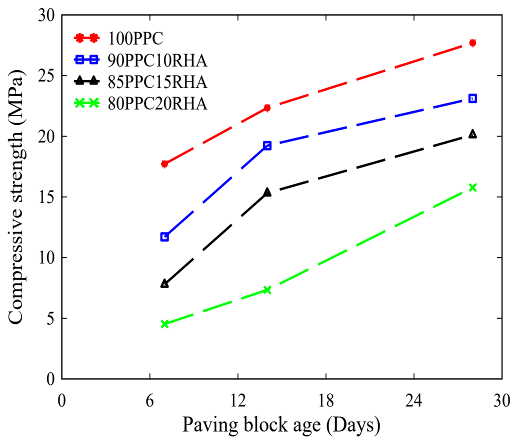


Fig. 7 *Relationship between the amount of waste and results of slump flow*

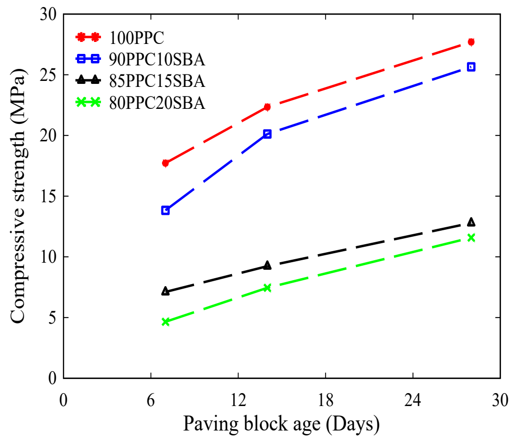
4.2 Compressive Strength

The compressive strength of specimens aged 7, 14, and 28 days was measured. Each result of a compressive strength test is the average of three specimens Fig. 8 illustrates the compressive strength performance of paving blocks incorporating different types of agricultural waste. Specifically, Fig. 8a presents the results for mixtures containing rice husk ash (RHA), Fig. 8b for sugarcane bagasse ash (SBA), and Fig. 8c for corn cob ash (CCA). The findings indicate that compressive strength generally improves with longer curing durations. Despite the ongoing hydration process, an inverse relationship was observed at 7 days between the amount of agricultural waste and compressive strength, as higher replacement levels tended to reduce strength. A similar trend is evident at 28 days, where increasing the proportion of waste material continues to result in lower compressive strength values. The compressive strength decreased due to the natural behavior of the waste, which is a pozzolanic material that does not instantaneously react when mixed with water. By utilizing a larger amount of waste, this waste requires a lengthier duration to harden. In addition, compressive strength decreases because these wastes are porous materials, and as the amount of waste utilized increases, so does the volume of pores in hardened paving blocks.

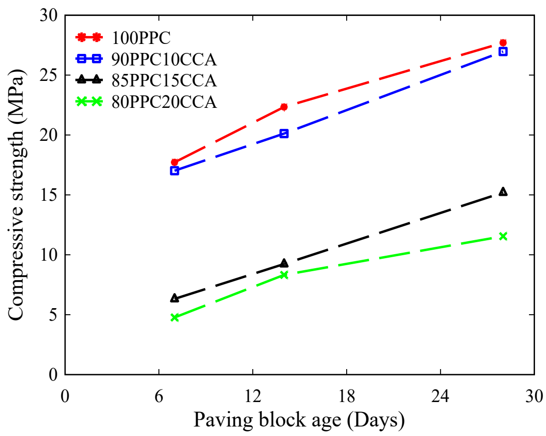
Fig. 9 illustrates the relationship between the compressive strength of paving blocks and the proportion of waste used as a cement substitute. The results indicate that an increase in waste content leads to a corresponding decrease in compressive strength. Notably, the incorporation of 15% waste resulted in a marked reduction in strength, highlighting the adverse impact of higher replacement levels. Meanwhile by substituting of 10% waste as a cement results in compressive strength of paving blocks either comparable or negligible decrease to normal paving blocks. Several previous studies have also proven that the use of 10% waste as a cement substitute is capable of producing comparable compressive strength in both mortar and concrete, including in rice husk ash [85-89], sugarcane bagasse ash [90-95], and corn cob ash [96-98]. The reduction of compressive strength in paving blocks made with agricultural waste is likely due to the low pozzolanic content of agricultural waste ashes, which slows the development of compressive strength, or the hydration process of pavers compared to normal pavers [75, 99, 100]. In addition, the use of waste from open field burning makes it challenging to control the combustion process, which makes it difficult to control the quality of the waste used, thereby decreasing the compressive strength of the paving blocks.



(a) RHA

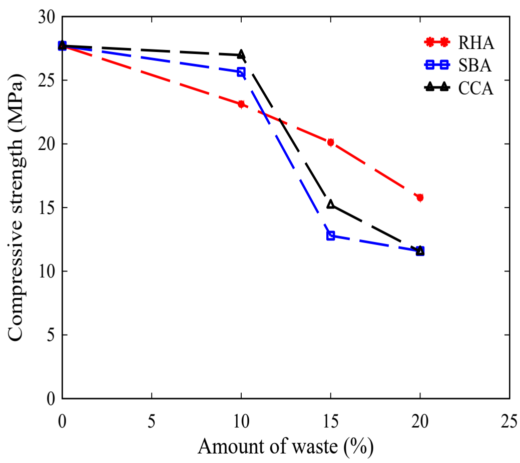


(b) SBA

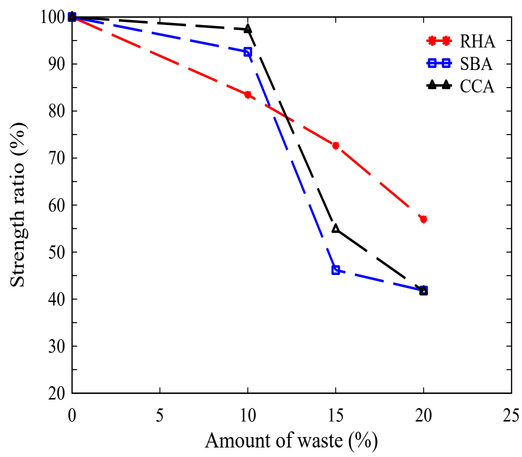


(c) CCA

Fig. 8 *Relationship between compressive strength and age of paving block*



(a) Compressive strength at 28 days



(b) Compressive strength ratio at 28 days

Fig. 9 *Compressive strength and strength ratio at 28 days with different types of waste ashes*

This experiment demonstrates that using 10% RHA as a cement substitute produces lower compressive strength than using 10% SBA and CCA. The strength produced for 10% RHA is only 85% of the total strength of the normal paving block, while using 10% SBA and CCA produces a compressive strength that is very close to that of the normal paving block, i.e., over 90% of the total strength of the normal paving block. This indicates that using 10% SBA and CCA allows the produce paving with a higher compressive strength than when using 10% RHA. However, it is also necessary to consider the mechanical properties of the used waste and the waste processing method. When using 15% to 20% waste, it can be seen that the compressive strength performance of RHA is much higher than using SBA and CCA. The compressive strength performance of paving using SBA and CCA waste is only approximately 40% of the total when 20% waste is used while using 20% RHA waste produces paving blocks with a compressive strength that is approximately 50% of the normal compressive strength of paving blocks at 28 days. This significant reduction occurred due to a significant reduction in the amount of cement, allowing it to have a larger volume of pores.

4.3 Splitting Tensile Strength

The splitting tensile strength test was performed on paving block specimens after 7, 14, and 28 days of curing. As with the compressive strength test, each reported value represents the average of three specimens. Fig. 10 presents the splitting tensile strength results for all agricultural waste ashes across the different curing ages. Fig. 11 illustrates the relationship between the amount of agricultural waste and the corresponding splitting tensile strength, along with the strength ratio. The test was conducted using the same specimen dimensions as those used for compressive strength testing and was carried out in accordance with procedures adapted from previous studies [101-103].

The results of the splitting tensile strength test on paving blocks incorporating RHA and CCA indicate a reduction in strength with increasing waste content across all curing ages (7, 14, and 28 days). In contrast, specimens containing 10% SBA demonstrated a higher splitting tensile strength compared to the control mixture. However, further increasing the SBA content to 15% and 20% resulted in lower tensile strength than that of the control. At 7 days, the splitting tensile strength for all mixtures ranged from 3 MPa to 5.8 MPa, while at 28 days, the values increased to between 5 MPa and 10 MPa. As shown in Fig. 10, although a general decline in splitting tensile strength is observed with higher waste substitution levels, all three waste materials produced satisfactory results particularly SBA at the 10% replacement level, which exhibited a notable improvement.

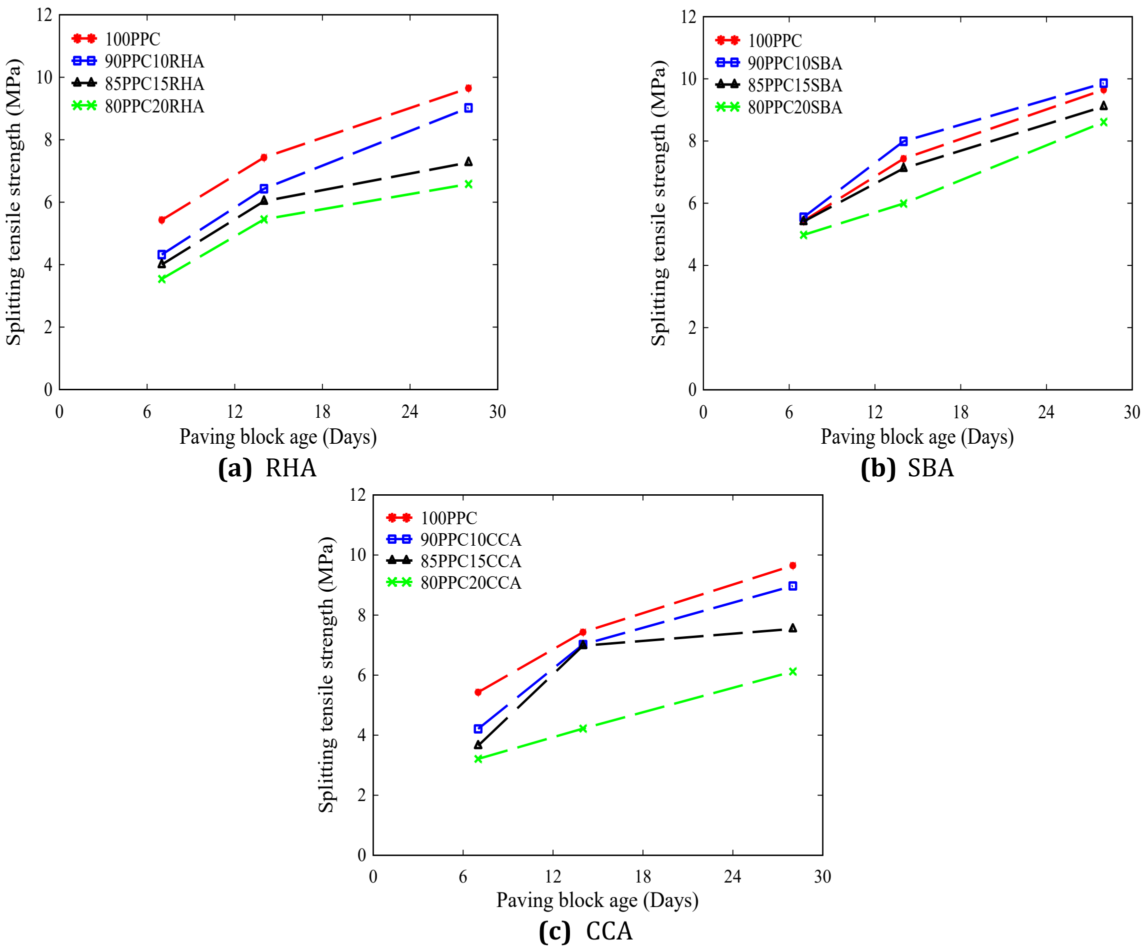
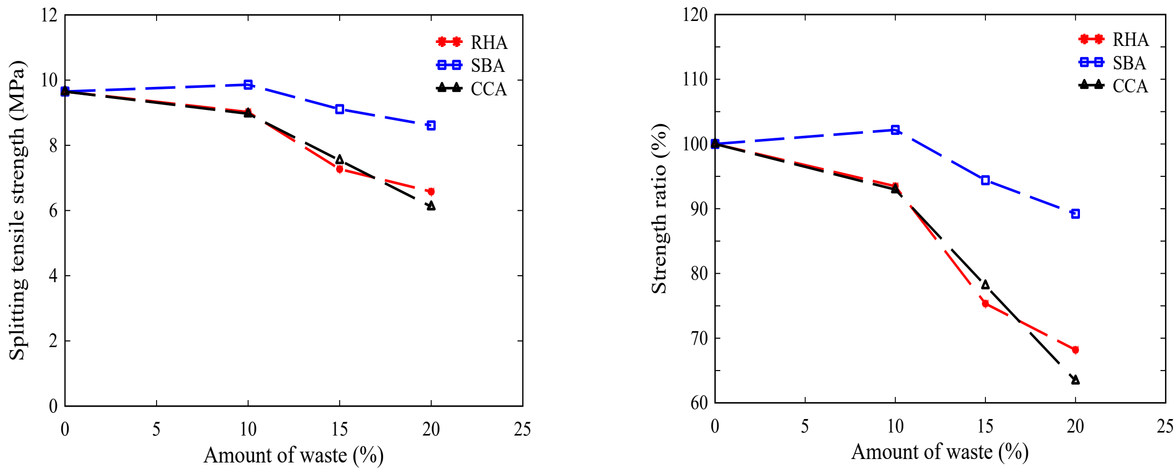


Fig. 10 *Relationship between splitting strength and age of paving block*



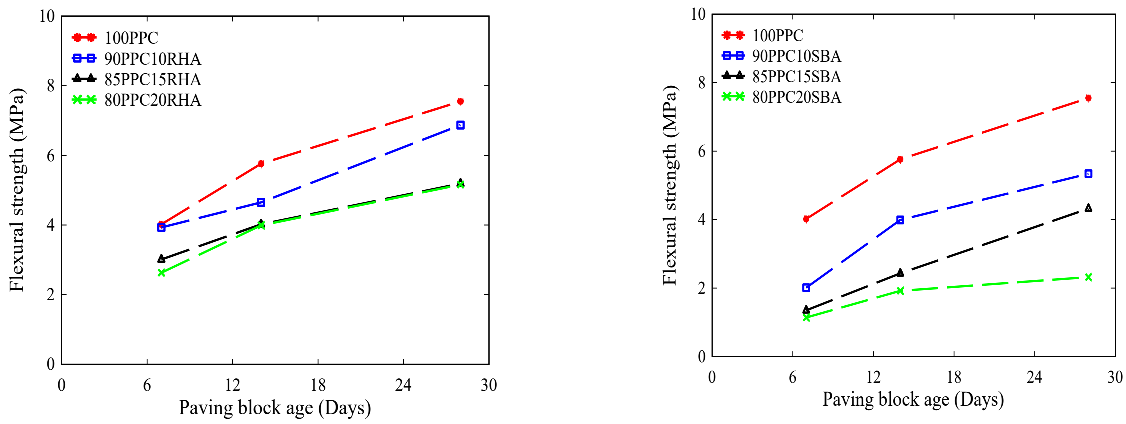
(a) Splitting tensile strength at 28 days **(b)** Splitting tensile strength ratio at 28 days

Fig. 11 *Splitting tensile strength and strength ratio at 28 days with different types of waste ashes*

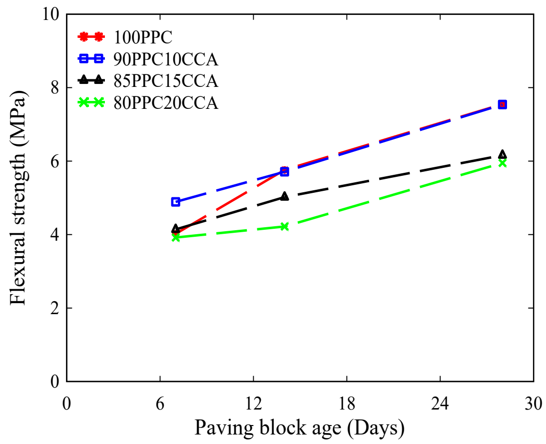
Fig. 11 shows that paving blocks made from SBA waste produced the highest splitting tensile strength compared to RHA and CCA, which produced splitting tensile strengths (RHA and CCA) that were almost identical. This measurement of splitting tensile strength shows that paver blocks made from SBA have superior splitting tensile performance compared to those made from RHA and CCA waste. From the ratio of the splitting tensile strength of waste ashes paving blocks to normal paving blocks, it can be determined that the lowest splitting tensile strength value generated when substituting SBA for cement in the production of pavers is approximately 90% of the splitting tensile strength of normal paving blocks. Meanwhile, paver blocks made with RHA and CCA have the lowest splitting tensile strength values, ranging from 60% to 70% of normal paver blocks. It should be noted that the decrease in the strength ratio of tensile strength is less than that of compressive strength in the entire series of tests. This decrease in splitting tensile strength is attributed to the same cause as the decrease in compressive strength of paver blocks, which is an increase in pore volume. Using a mixed proportion of 1:9 (cement to sand) produces paving blocks with a high porosity, reducing the quantity of cement to 15-20% of the total binder increases the possibility of increasing the pore volume. However, using 10% waste shows splitting tensile strength results comparable to or close to splitting tensile strength with 100% PPC binder.

4.4 Flexural Strength

Fig. 12 demonstrates the flexural strength results for all types of agricultural waste in relation to the test age. The results of this test show that as age increases, the flexural strength increases. The flexural strength decreases as the amount of rice husk ash waste utilized increases. However, the flexural strength results between 15% and 20% RHA waste produce nearly the same flexural strength, although it is still lower than the flexural strength of normal paving without waste utilized. Meanwhile, SBA waste shows a significant decrease in flexural strength, from 10% to 20% of waste used. While using CCA as a cement replacement material for paving blocks, flexural strength decreases, but it is not as significant as when rice husk ash and sugarcane bagasse ash were used. Through this investigation, it can be concluded that several types of waste significantly reduce flexural strength, particularly SBA. However, some variations produce flexural strength that is comparable to that of normal paving blocks.



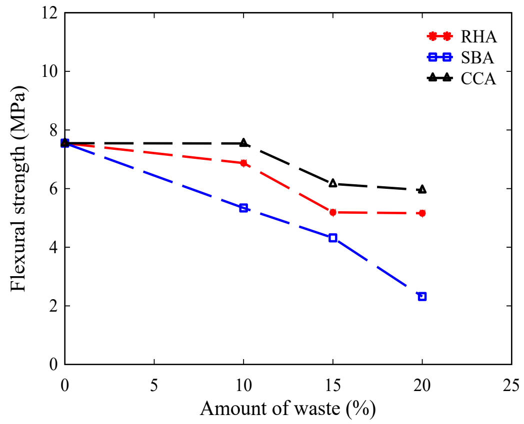
(a) RHA **(b)** SBA



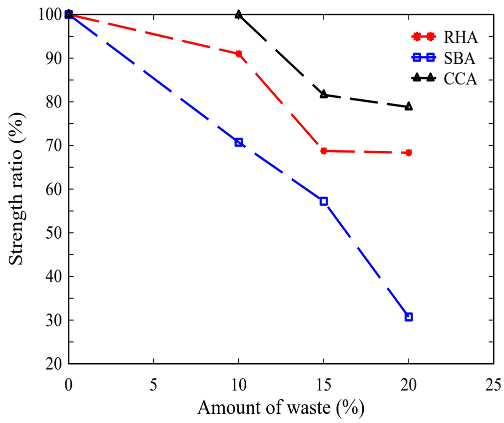
(c) CCA

Fig. 12 *Relationship between flexural strength and age of paving block*

The relationship between flexural strength and the different waste replacement levels, along with the corresponding development of the strength ratio, is illustrated in Fig. 13. The results of this investigation indicate that CCA waste ashes produce a higher flexural strength than RHA and SBA, with 20% CCA producing the lowest flexural strength, which is 80% of the total flexural strength of normal paving blocks. In contrast, the flexural strength tests on SBA waste decreased significantly as the amount of waste used as a cement replacement increased. The lowest flexural strength generated by SBA paving blocks containing 20% SBA waste is approximately 30% of the flexural strength of conventional paving blocks. This significant reduction is possible due to several factors, including the waste processing process, the accuracy with which test objects are manufactured, and the influence of the resulting pore volume, which causes the flexural strength of the paving blocks to decrease significantly. Therefore, using paving blocks made from RHA waste on infrastructure that can withstand heavy bending loads is not recommended.



(a) Flexural strength at 28 days

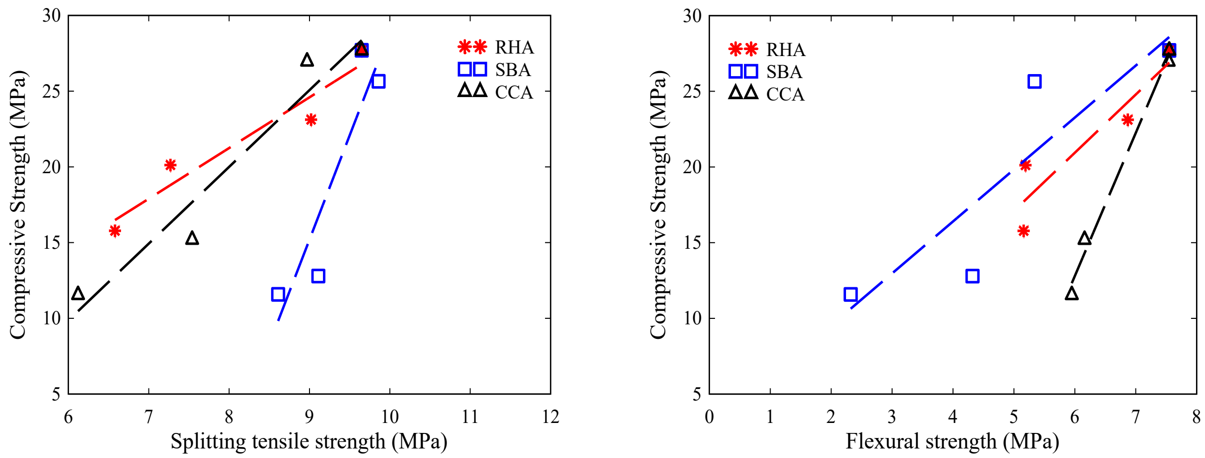


(b) Flexural strength ratio at 28 days

Fig. 13 *Flexural strength and strength ratio at 28 days with different types of waste ashes*

4.5 Relationship Between Compressive Strength with Tensile Splitting and Flexural Strength

This section discusses the relationship between the mechanical properties of paver blocks, particularly the relationship between compressive strength and splitting tensile strength in Fig. 14a and the relationship between compressive strength and flexural strength in Fig. 14b. A reasonably linear relationship can be observed from the results of the relationship between compressive strength with splitting tensile strength and flexural strength. As the compressive strength increases, its flexural strength and splitting tensile strength also increase. It can be concluded that using waste with a 10% cement replacement can produce pavers with nearly the same mechanical properties as conventional pavers, while using agricultural waste ash with 15% and 20% tends to produce pavers with lower mechanical properties.



(a) Compressive to splitting tensile strength **(b)** Compressive to flexural strength

Fig. 14 *Relationship between compressive to splitting tensile and flexural strength*

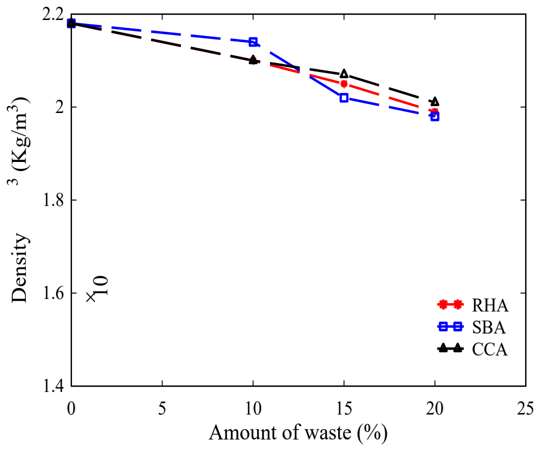
The differences in mechanical properties of paving blocks were related to the use of different types of waste and an uncontrolled waste processing procedure that employs waste originating from open field burning. The agricultural waste ashes utilized serve as an alternative material that substitutes cement, revealing pozzolanic properties. The increasing quantity of agricultural waste ashes decreases the cement content, potentially impairing the engineering characteristics of paving. Additionally, the influence of untreated agricultural waste ashes, which may possess inferior quality compared to cement, can also contribute to a decrease in the engineering characteristics of paving blocks. This is also supported by several previous research results which show the same trend [75, 76]. However, it can be concluded that these three wastes have positive value for use as a cement substitute for paving blocks. By incorporating 10% waste, it is possible to produce mechanical properties comparable to those obtained without waste, thereby reducing cement utilization. In addition, larger amounts of waste can also be used for infrastructure that receives a lower load. Meanwhile, the damage patterns from each test result for compressive strength, splitting tensile strength, and flexural strength can be seen in Fig. 15. Each test form on the three used wastes produced nearly identical damage patterns. It should be noted that using waste to replace cement above 20% is not recommended. The hardening process takes longer, resulting in a more extended curing period. Additionally, there is the possibility of a significant reduction in mechanical properties if more than 20% of waste, such as rice husk ash, sugar cane bagasse ash, and cob corn ash, is used as a cement substitute.

(a) Compressive strength **(b)** Splitting tensile strength **(c)** Flexural strength

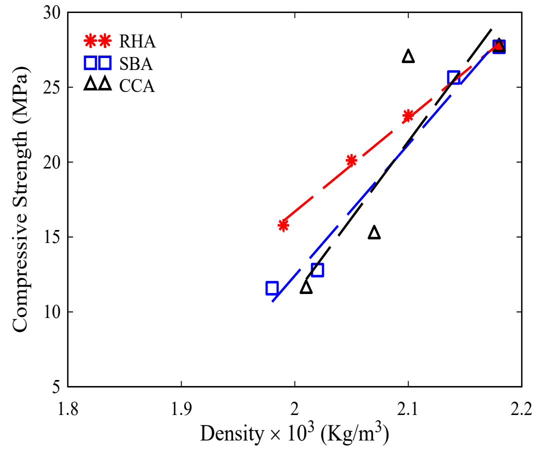
Fig. 15 *Specimen conditions after the test*

4.6 Mass Density and Mass Loss

In addition to investigating the mechanical properties, this study examined the physical properties of hardened concrete through mass density and mass loss. Fig. 16 shows the mass density examination results and their relationship with compressive strength. The mass density test results indicate that the mass density of paving blocks decreases as the amount of agricultural waste ashes used increases. Normal paving blocks with a mixed ratio of 1:9 produce a mass density of 2813 kg/m³, while paving blocks containing 20% agricultural waste produce a mass density of 1991 kg/m³ (RHA), 1983 kg/m³ (SBA) and 2008 kg/m³ (CCA). Agricultural waste ashes density influenced this decrease in paving block mass density.



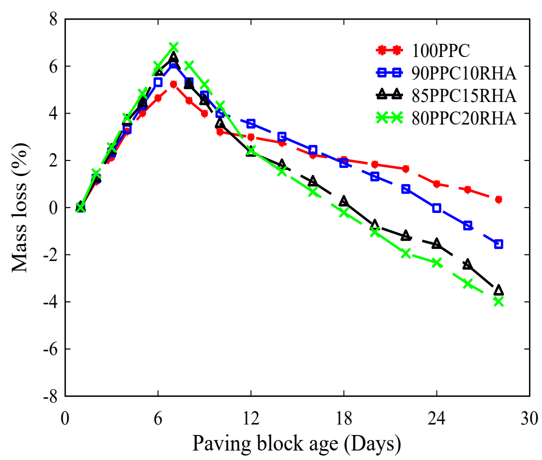
(a) Mass density



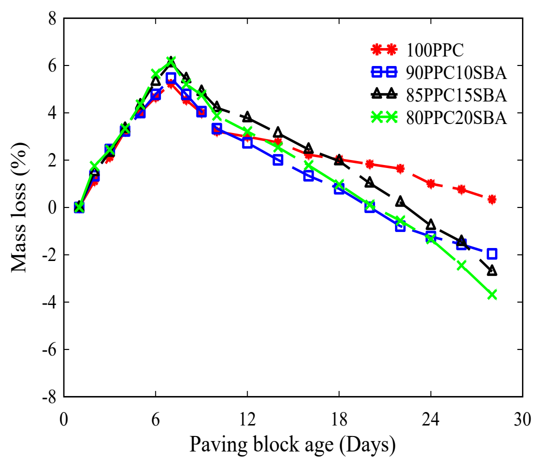
(b) Relationship of mass density with compressive strength

Fig. 16 *Results of mass density and its relationship with compressive strength*

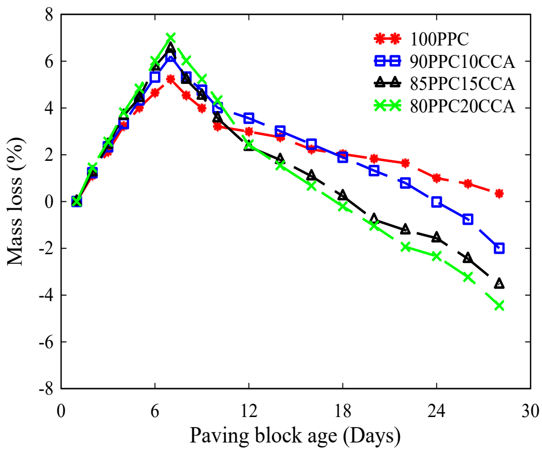
In addition, this research also analyses the relationship between the mass density and compressive strength of paving blocks. Notably, the correlation between mass density and compressive strength analysed in this study was only for 28-day-old specimens. The research indicates that the compressive strength of paving blocks increases as the mass desiccation generated by hardened paving blocks increases. Meanwhile, Fig. 17 shows the results of the mass change percentage on paving blocks for 28 days. During the seven-day water-curing process, the mass of the paving blocks increased by 6% to 7% on the seventh day (the final day of curing). This is due to the influence of water absorption during the curing process, causing an increase in mass. The mass decrease occurs very significantly after the water-curing process is completed. This is because all specimens are placed in a room in dry conditions (air curing) for up to 28 days. As a result of this change in curing type, the water in the paving blocks is also quickly evaporated. Fig. 17 shows the mass increase tends to increase substantially with increasing waste content. When using curing water, the mass decrease in paving containing 20% waste is the highest compared to other specimens. This was also discovered by several previous researchers who applied this type of waste to make mortar or concrete [11, 75]. This is because the waste used is a porous material, thus ensuring water absorption and evaporation occur more quickly compared to normal paving blocks. The use of high amounts of waste also allows significant mass changes to occur relatively quickly.



(a) RHA



(b) SBA

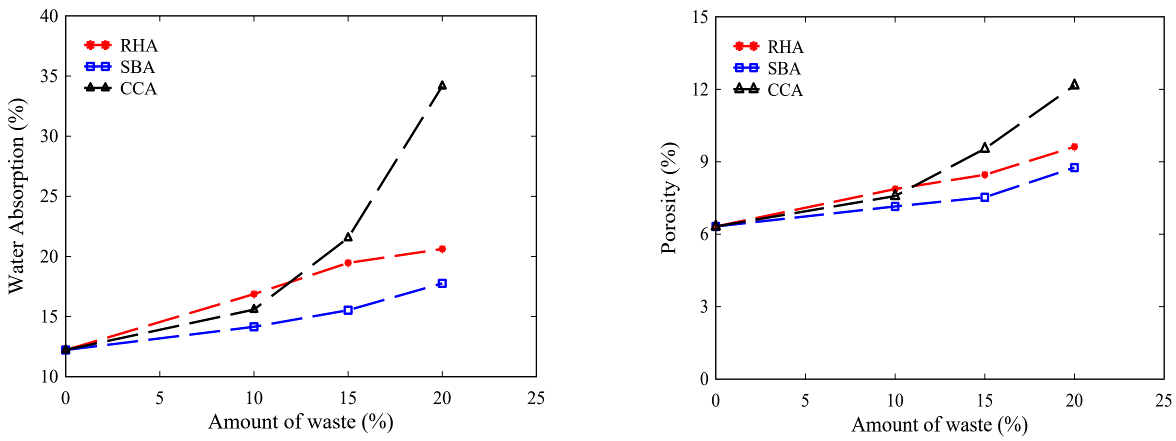


(c) CCA

Fig. 17 *Development of mass of paving block for 28 days*

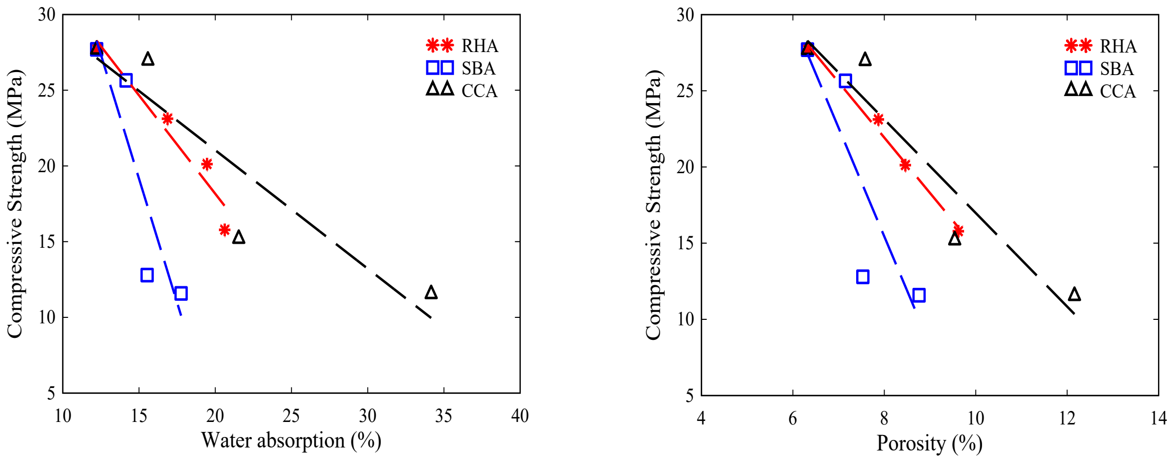
4.7 Water Absorption and Porosity

The results of water absorption and porosity measurement of paving blocks with variations in the amount of agricultural waste can be seen in Fig. 18. Notably, water absorption and porosity measurements were performed only on specimens that were 28 days old, with an average of three specimens for each variation represented in the results. The results of the water absorption and porosity measurements indicate that as the amount of waste increases, the water absorption and porosity values increase. This demonstrates that water absorption has increased due to using agricultural waste for paving. The increase in water absorption is closely related to the porosity properties of paving blocks. Moreover, paving blocks containing 20% CCA as a cement substitute exhibit the highest water absorption and porosity increase. Meanwhile, the most negligible porosity and water absorption were produced by SBA compared to RHA and CCA. Fig. 19 shows the relationship between compressive strength with water absorption and porosity. The results of this study indicate that the compressive strength of paving blocks decreases as their porosity and water absorption increase. Therefore, the compressive strength of paving blocks decreases as the amount of agricultural waste ashes used in their production increases, whether rice husk ash, sugarcane bagasse ash, or cob corn ash is used. It can be concluded that waste as porous material significantly influences the compressive strength of paver blocks.



(a) Water absorption **(b)** Porosity

Fig. 18 *Relationship of water absorption and porosity to the amount of agricultural waste ashes*

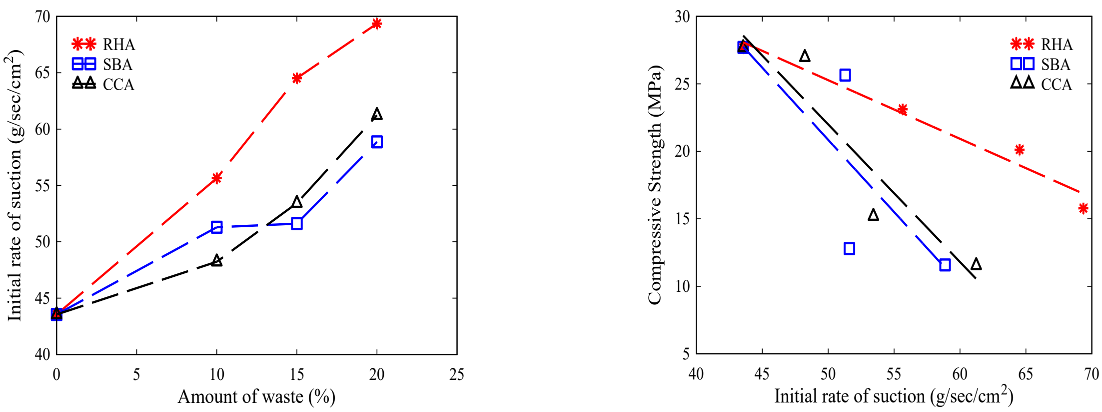


(a) Water absorption **(b)** Porosity

Fig. 19 *Relationship between compressive strength with water absorption and porosity*

4.8 Initial Rate of Suction

The Initial Rate of Suction (IRS) refers to the capacity of paving blocks to absorb water within the first minute of exposure. This test is used to assess the moisture absorption characteristics of the blocks. Fig. 20 presents the IRS values for specimens incorporating varying amounts of agricultural waste ashes, namely RHA, SBA, and CCA, along with the observed correlation between IRS and compressive strength.



(a) Relationship between the amount of waste with IRS **(b)** Relationship between compressive strength with IRS

Fig. 20 *Relationship between amount of waste and compressive strength with initial rate of suction*

The results of this experiment indicate that the IRS value has considerably increased as the amount of agricultural waste ashes used as a substitute for binder in the production of paving blocks has increased. This occurs because higher amounts of waste accelerate water absorption in the pavers. This investigation also revealed that pavers made from RHA waste had the highest IRS values compared to those made from SBA and CCA waste. This shows that paving blocks using RHA as a cement substitute experience a faster water absorption process. In addition, through this research, it can also be concluded that compressive strength decreases if the IRS value increases. Although compressive strength decreases as the IRS value increases in paving blocks made from SBA and CCA, there is no significant difference between the results for paving blocks made from these waste types.

4.9 Estimation of Manufacturing Cost

The cost of production is an essential consideration when using agricultural waste ash as a substitute for cement in the production of paving blocks. The results of the production cost analysis for each variation are shown in Table 4. It is important to note that the conditions in rural areas of the Yogyakarta region in Indonesia determine the price of this waste process. This research indicates that production costs have decreased, but this must be considered towards the quality of the manufactured paving blocks. Table 5 shows the total cost savings percentage achieved by substituting waste for cement to produce paving blocks. Utilizing 10% waste can reduce paving production costs by between 2.25% to 2.43%. Using 20% waste can reduce the price of paving block production by 8.92% to 9.29%. CCA waste has the lowest production costs when compared to other wastes.

Table 4 *Production cost for one paving block made from agricultural waste ashes*

Amount of waste	Manufacturing cost in IDR Rupiah		
	RHA	SBA	CCA
0	941.52	941.52	941.52
10	920.36	919.08	918.63
15	909.60	907.66	906.99
20	857.51	854.95	854.05

Table 5 *Percentage cost saving for one paving block made from agricultural waste ashes*

Specimen ID	Percentage cost saving		
	RHA	SBA	CCA
10	2.25	2.38	2.43
15	3.39	3.60	3.67
20	8.92	9.20	9.29

Based on these investigations, further study can be carried out regarding the relationship between the engineering properties of paving blocks and the estimation of manufacturing costs. In general, the mechanical properties of paving blocks indicates that an increased substitution of waste for cement leads to a reduction in engineering properties, including compressive strength, splitting tensile strength, and flexural strength. On the other hand, the increasing volume of agricultural waste ashes employed is projected to be able to reduce the production costs of paving blocks significantly. Thus, a comprehensive analysis of the optimal point is essential, taking into account production costs (economic value) and engineering properties, to achieve high-quality paving block production and reduced prices while effectively minimizing agricultural wastes.

According to the criteria applicable in Indonesia, where this research was conducted (SNI 6882:2014) [104], mortar-based paving blocks are categorized into four different groups depending on their compressive strength. The finest grade paving block, classified as type M, possesses a compressive strength above 17 MPa. The medium class includes two categories: type S with a compressive strength ranging from 12 to 17 MPa, and type N with a compressive strength ranging from 5 to 12 MPa. While, the lowest classification (type O) has a compressive strength of 2 to 5 MPa. Through the compressive strength results, it can be demonstrated (see Fig. 9) that utilizing 10% of CCA, RHA, and SBA provides a compressive strength above 17 MPa at the age of 28 days. In addition, replacing 10% of cement with agricultural waste ashes can decrease manufacturing costs by 2.25%-2.43%. Meanwhile, the utilization of 15% RHA waste produces a compressive strength above 17 MPa, but the incorporation of CCA and SBA (15%) results in a reduction of the compressive strength classification to type S (medium strength class). The utilization of these wastes up to 15% as cement replacement may decrease production costs by 3.39%-3.67%. Meanwhile, utilizing 20% waste as a cement substitute in the production of paving blocks produces a compressive strength at 28 days classified as type S (medium class) for all varieties of agricultural waste ashes based paving blocks. However, the decrease in manufacturing costs could be achieved between 8.92% to 9.29% by utilizing 20% waste as a substitute for cement. Thus, this summary is tailored to the requirements of the industry and consumer demands. Incorporating 10% waste produces compressive strength that remains within the highest classification of pavers (equivalent to 100% cement pavers), but the decrease in production costs is not significant, as seen in Table 5. In addition, the production of type S paving blocks, the incorporation of 15-20% waste can lead to a substantial decrease in manufacturing costs.

In addition, utilizing these wastes (RHA, CCA, SBA) as a replacement for cement in the production of paving blocks will mitigate the disposal of agricultural waste generated by open field burning. The burned waste can subsequently be utilized in the paving block industry for local communities, thereby acquiring economic value. Additionally, the utilization of these wastes may minimize the discharge of combustion byproducts, allowing them to be repurposed as construction materials. However, further study and investigation are required to quantitatively assess the potential for minimizing pollution and environmental impacts through the utilization of this waste as paving block material.

5. Conclusions

This study investigates the influence of agricultural waste ash from open field burning for cement replacement in the production of paving blocks. Paving blocks are examined in a laboratory to determine their fresh and hardened properties. The engineering properties are evaluated using a flow table, compressive strength, splitting tensile strength, flexural strength, mass density, mass loss, water absorption, porosity, and initial suction rate. In addition, production costs for paving blocks made with each waste material as a substitute for cement were calculated. The conclusions that can be obtained through this investigation are as follows.

a) Fresh properties are one of the factors that must be considered during the production of paving blocks. If the water-to-binder ratio is too high, the fresh properties will also be high, but the hardening process will take longer. This investigation utilized a water to binder ratio of 0.5 for all test object variations. The increase in the use of waste ashes indicates that slump flow has decreased so that the maximum percentage of waste ashes that can be used to produce paving blocks is 20% of the total binder in a mixture ratio of 1:9 (binder: sand).
b) The results of mechanical properties testing (compressive strength, splitting tensile strength, and flexural strength) show that an increase in agricultural waste causes a decrease in mechanical properties. However, using waste of 10% of the total binder produces mechanical properties comparable to normal paving blocks. As a result, a volume of 10% is recommended for use as a cement replacement in paver blocks.
c) The results of the physical properties test indicate that an increase in waste amount increases mass loss, water absorption, porosity, and IRS, but a decrease in mass density. This is because agricultural waste ash is a porous pozzolanic material that produces more pores than cement.
d) Using 10% agricultural waste to manufacture paving blocks can reduce production costs by 2.25% to 2.43%, while using 20% can reduce costs by 8.92% to 9.29%.

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Conflict 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.

Author Contribution

Hakas Prayuda*: Conceptualization, Data curation, Investigation, Project administration, Funding acquisition, Methodology, Supervision, Writing original draft.* ***Fanny Monika****: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing review & editing.* ***Martyana Dwi Cahyati****: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing review & editing.* ***Bagus Arya Nurega****: Data curation, Investigation, Writing original draft.* ***M Fathurrahman****: Data curation, Investigation, Writing original draft.* ***Achmad Yusuf Firman Hidayat Subani****: Data curation, Investigation, Writing original draft.*

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