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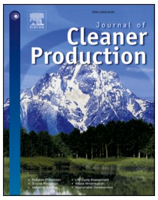

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Combined reusing of sorghum husk ash and recycled concrete aggregate for sustainable pervious concrete production

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ARTICLE INFO

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Carbon dioxide emission
Pervious concrete
Recycled concrete aggregates
Sorghum husk ash
Sustainability efficiency

ABSTRACT

The huge amounts of natural resources and high level of energy consumption in concrete production necessitate the use of agricultural and demolition wastes as alternative construction materials. The present study explores pervious concrete (PC) that includes sorghum husk ash (SHA) and recycled concrete aggregate (RCA) as alternatives to cement and natural aggregate (NA) in standard PC mixtures. PCs were prepared from mixtures derived from replacement levels 0%, 5%, 10%, 15%, 20% and 25% of cement with SHA and 0%, 20%, 40%, 60%, 80% and 100% of NA with RCA. The density, compressive strength and hydraulic properties (void ratio and hydraulic conductivity) of the samples were determined at 28-day using ACI standards. Sustainability efficiency of incorporating SHA and RCA on PC was also investigated using structural efficiency and carbon dioxide (CO_2) emission. Their cost effectiveness was equally examined. Results revealed that densities of PC decreased with increase in SHA and RCA amount. Compressive strength and structural efficiency reduced with increase in SHA except at 5% where they were higher than the control. On the other hand, the incorporation of RCA decreased the compressive strength but improved the PC hydraulic properties. CO_2 emission and production cost were found reduced with increase in SHA as well as RCA. The maximum reduction of CO_2 emission (38.23%) and production cost (51.29%) were obtained when 25% SHA was combined with 100% RCA. The combined usage of SHA and RCA as raw materials in PC was found to be effective in boosting PC's hydraulic properties at an appropriate compressive strength. The reduction of CO_2 discharge and in production cost attributed to the construction materials demonstrates their impacts on mitigating global warming problems and lowering costs of PC production.

1. Introduction

Because of its widespread use, the concrete industry is one of the world's largest consumers of natural resources and a major source of anthropogenic carbon dioxide emissions. According to de Brito and Kurda (2020), the global warming potential of cement and aggregates used for concrete construction is alarming. Cement and aggregates consumed in 2018 alone were about 4.1 and 48.3 billion tonnes respectively. Thus, to lessen the effect of concrete construction on the environments, researchers have focused on developing novel sustainable materials for concrete production from wastes. Consequently, through widespread research, supplementary cementitious materials have been incorporated in concrete construction (Oyejobi et al., 2016; Opeyemi et al., 2017; Tijani et al., 2018a; Ahsan and Hossain, 2018). Sorghum husk ash (SHA) is one of the supplementary cementitious material that can be used as an alternative to cement in concrete production. The United States Department of Agriculture (USDA United States, 2017) estimated the world sorghum production at 59.35 million metric tons. The breakdown of the data shows that USA's input is 8,408,000 metric tons while Nigeria is following with 6,550,000 metric tons and Mexico in the third position with 6,000,000 metric tons. Disposition of husks from significant amount of sorghum mostly occur by setting them ablaze in open air and then dumped as a dregs, causing annoyance and pollution to the environment. As a result, a number of studies have been conducted on the use of SHA as supplementary cementitious material in concrete production (Williams et al., 2014; Ogork and Danja,

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Abbreviations: ACI, American Concrete Institute; CO_2, Carbon dioxide; NA, Natural Aggregate; PC, Pervious Concrete; RCA, Recycled Concrete Aggregate; SE, Structural Efficiency; SHA, Sorghum Husk Ash.

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https://doi.org/10.1016/j.jclepro.2022.131015
Received 16 September 2021; Received in revised form 13 February 2022; Accepted 16 February 2022
Available online 20 February 2022
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2018; Tijani et al., 2021). According to Tijani et al. (2018b), thermal decomposition of sorghum husk could provide about 11% of SHA content having optimum property of pozzolan. This in their view, can thus bring proper control of the release of hazardous components into the environment.

In order to reduce the detrimental effect of sourcing of aggregate for concrete, the concrete industry has explored different ways in which solid wastes can be recycled and incorporated as aggregate in concrete (Adeyemi, 2020). The high quantity of wastes generated from construction and demolition of concrete structure kept increasing due to urbanisation and population increase. More than 3 billion tonnes of construction and demolition wastes are generated annually in 40 countries (Akhtar and Sarmah, 2018). A large quantity of RCA from construction and demolition rubbles is typically stockpiled and then dumped as leftovers, posing a nuisance and polluting the environment. As a result, using these materials for construction is considered an environmentally benign manner of disposal. In the same vein, it will also reduce the cost of production, thus enhancing sustainability. Typically, RCA particles contain 30–60% old cement paste or mortar, depending on the aggregate size (ECCO, 1999). The use of RCA in production of concrete minimises wastes to landfill, reduces the depletion of natural material resources and keeps the construction cost down (Aiyewalehinmi and Adeoye, 2016). Subsequently, studies have been conducted on the use of RCA as replacement for NA in concrete production by a number of authors (Okafor, 2010; Serres et al., 2016; Tam et al., 2016; Aiyewalehinmi and Adeoye, 2016). Their results revealed that concrete prepared with RCA possesses lower physical and mechanical properties but, when compared to conventional concrete, has impacted environmental sustainability. The increased number of studies on the usage of RCA is primarily intended to broaden awareness of the materials' potentials in order to increase their use in the construction industry. Recently, pervious concrete (PC) has been recommended by Environmental Protection Agency (EPA) of the US as the vital and Best Management Practice for water runoff and storms contaminants regulation. It is categorized as distinct highly permeable material which can easily be made through the removal or reduction of the amount of fine aggregate contained in the concrete (Qin et al., 2015). Its permeability, porosity, density and compressive strength ranges from 1.4 to 12.2 mm/s, 15–35%, 1600–2000 kg/m^3 and 2.8–28 MPa (Tennis et al., 2004; ACI 522R, 2010). Some of the environmental benefits of PC include storm water runoff reduction, groundwater restoration, water quality improvement, as well as water and soil pollution reduction (Yahia and Kabagire, 2014; Ajagbe et al., 2018). It is usually utilized in low traffic roads, parking areas, sidewalks and joggers' tracks (Yang and Jiang, 2003; Tennis et al., 2004).

Consequently, only a few studies on the properties of PC made with supplementary cementitious material, especially SHA (Khankhaje et al., 2018; Tijani et al., 2019a) have been conducted. Khankhaje et al. (2018) reported that the inclusion of palm oil fuel ash as substitute for cement enhanced the hydraulic properties of PC but reduced its strength. According to Tijani et al. (2019b), the filler effect and the pozzolanic interaction with cement hydration by-product improve PC characteristics. Few more studies have been reported on the incorporation of RCA as replacement for NA in PC production (Rizvi et al., 2010; Sriravindrarajah et al., 2012; Kareem and Thesis, 2014; Güneyisi et al., 2016; Yap et al., 2018; Tijani et al., 2019b). All of them agreed that incorporation of RCA in PC improve the hydraulic characteristics but reduced its mechanical properties. However, all of these studies focused on replacing NA with RCA without incorporating any supplementary cementitious material. Because of SHA's benefits as a mineral additive, combining it with RCA will almost certainly improve PC quality. The additional calcium-silicate-hydrate (C-S-H) gel created by SHA pozzolanic activity during cement hydration refines PC pores and enhances the interfacial transition zone between cement paste and aggregate, resulting in a denser inner structure in PC. As a result, PC's strength is projected to increase.

The strength and hydraulic features of embedding RCA in PC have been researched based on the literature. However, only few studies have reported for SHA incorporation in PC. Moreover, to our knowledge, no attention has been paid to estimating the sustainability and cost efficiency of RCA or SHA on PC. Furthermore, no research has been done on the characteristics of SHA-RCA-PC. As a result, the density, compressive strength, hydraulic characteristics (void ratio, hydraulic conductivity), sustainability efficiency (structural efficiency, CO_2 emission) and cost effectiveness of PC produced with SHA as a fractional substitute for cement up to 25% and RCA as a substitute for NA up to 100% are investigated in this work. The outcomes from this study would be useful for further investigations into the production of concrete materials that are both cost efficient and sustainable.

2. Materials and methods

2.1. Materials preparations and properties

This study employed Portland limestone cement of grade 32.5R which has good conformity with what is required by ASTM C150 (2016). The physical characteristics of cement used were fineness (330 m^2/kg), initial setting time (150 min), final setting time (250 min), soundness (0.4 mm) and loss on ignition (1.69%). Whereas, ASTM C150 requires that cement satisfies minimum of 280 m^2/kg fineness, minimum of 45 min initial setting time, maximum of 375 min final setting time, 0.8 mm soundness and 3% loss on ignition. Natural aggregate (granite) was acquired from a quarry and RCA was sourced from demolished buildings while sorghum husk was obtained from an indigenous sorghum farm, all in some selected locations in Nigeria. Fig. 1 shows the pictorial image of NA, RCA, sorghum husk and SHA used for the study. Adhered mortar could be observed on RCA. NA and RCA that could have easy passage via 10 mm mesh but retained on the 5 mm mesh was used for PC making. The main physico-mechanical properties of both aggregates used are presented in Table 1. The specific gravity of RCA was low and its water absorption was high due to the existence of old cement paste within the aggregate units as compared with NA. Kevern (2008) suggested that aggregate for high durability pervious concrete mixtures (i.e. heavy traffic loading or hard wet freeze environments) should have specific gravity greater than 2.5 and absorption of less than 2.5%. Both NA and RCA can be classified as normal weight aggregates since their bulk densities fell between 1200 and 1760 kg/m^3. Their AIV and ACV values shows that the aggregates are tough enough for PC production. Maximum value of 30% AIV and ACV was specified for concrete used in pavement wearing surfaces by IS 383 (2016). The water used in this experiment was ordinary tap water. For all these mixes, water/cement ratio of 0.4 was maintained.

The sorghum husk sample was calcined in an electric furnace at about 600–700 °C to obtain SHA. After that, the SHA was sieved with a 75 m sieve to yield ash with a specific gravity of 2.1. X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM) investigations were used to characterize the SHA. Comparative analyses of SHA and cement for each chemical constituent of the sample are demonstrated in Table 2. SHA had SiO_2 (70.48%) as its major chemical constituent. The SO_3 content of SHA (0.41) does not exceed the ASTM C618 (2012) standard of 5% for cementitious materials. These findings back up Tijani et al. (2019a, 2020) earlier findings. As defined by ASTM C618 (2012) for class F pozzolans, the sum of SiO_2, Al_2O_3, and Fe_2O_3 for SHA was 74.94%, which is more than 70%, with a LOI of 5.68, which is lower than 6%. Moreover, the SEM image of SHA shown in Fig. 2 revealed micro-porous and angular structure with irregular surfaces and variety of particle sizes. Some these particles agglomerated and clumped together to form clustering structure while several are relatively finer with small size capable of filling existing pores in PC. It is anticipated that the higher amounts of small SHA particles will ensure an active participation in the pozzolanic reaction (Tijani et al., 2019a). In addition, the XRD result indicates the prevalence of silica in SHA as the

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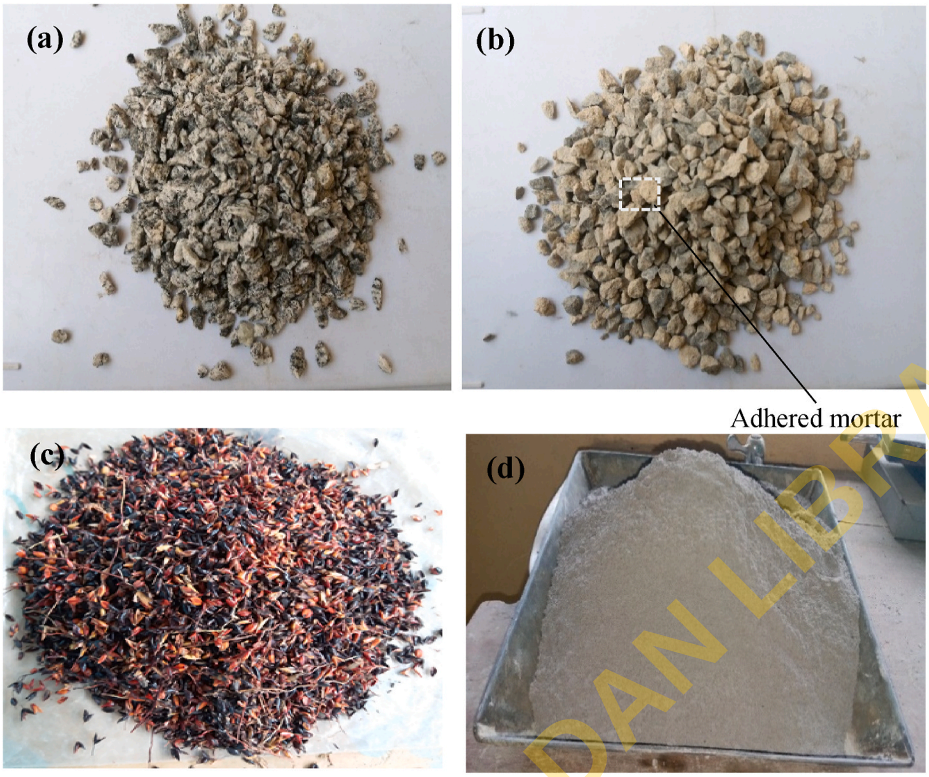

Fig. 1. (a) NA (b) RCA (c) Sorghum husk (d) SHA.

Table 1
Main physical and mechanical properties of Aggregates.

Aggregates	Properties					
	Specific gravity	Water absorption (%)	Bulk density (kg/m^3)	Void ratio (%)	ACV (%)	AIV (%)
NA	2.76	0.3	1559	43.51	19.05	12.19
RCA	2.53	2.80	1301	48.58	26.96	24.02

Table 2
Chemical composition of SHA and Cement.

Chemical constituents	Percentage composition (%)	
	SHA	Cement
SiO_2	70.48	19.02
Al_2O_3	2.80	3.10
Fe_2O_3	1.66	4.80
SO_3	0.41	1.82
MgO	2.75	1.48
K_2O	4.56	0.35
P_2O_5	1.82	0.32
CaO	1.39	67.40
$SiO_2 + Al_2O_3 + Fe_2O_3$	74.94	26.92
Loss on ignition	5.68	1.25
Specific gravity	2.1	3.15

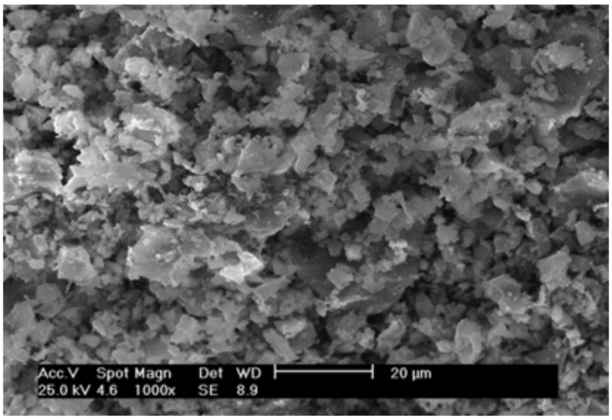

Fig. 2. SEM image of SHA.

principal element that could contribute to its pozzolanic activity. From the pattern, several noises were observed with emanation of few peaks. These characteristics shown from the XRD pattern demonstrated that the silica structure is highly amorphous in nature with few crystallinity. This results corroborate the features revealed from the SEM micrograph shown (Fig. 2). The characteristic peaks depicted from the XRD plot also match well with those attributable to that of quartz and cristobalite crystal structure. The diffused peaks of 1700 and 1200 counts at about $2\theta = 27^\circ$ and 50° respectively in XRD confirm the crystalline phase of silica (quartz) content of the SHA.

2.2. *Mixture proportions and procedures*

For SHA-RCA-PC, a total of 36 mixes were created. Table 3 shows the proportions of the combinations in detail. Pervious concrete specimens were cast in several plastic cylinder (dimension: 100 × 200 mm) moulds for density, compressive strength, void ratio, and hydraulic conductivity evaluations. The cylinders were filled in three layers with 25 drops of a 16 mm diameter steel rod and 10 drops of a standard proctor hammer weighing 2.5 kg for compactness, while maintaining the water/cement mixing ratio constant (0.4) for all mixes. Following casting, all samples were cured for 24 h at room temperature in the lab. They were thereafter taken out and cured for 7, 28 and 56 days in water. Average of the results obtained for minimum of three specimen are used for property testing.

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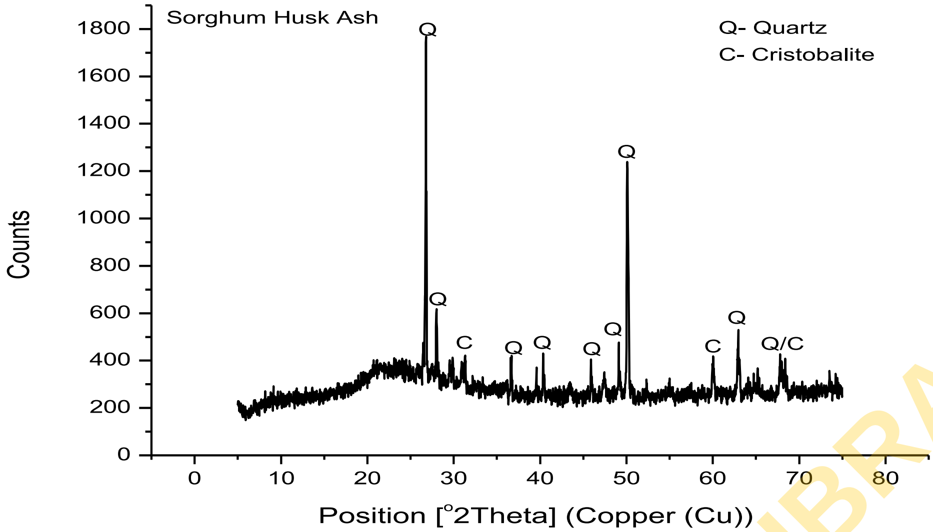

Fig. 3. XRD analysis of SHA.

Table 3
Mix proportions.

Mix	% SHA	Cement (kg/m^3)	SHA (kg/m^3)	Coarse Aggregates (kg/m^3)		Water (kg/m^3)
				NA	RCA	
0SNA100RCA0				1563.40	0	
0SNA80RCA20				1250.72	312.68	
0SNA60RCA40	0	390.83	0	938.04	625.36	156.33
0SNA40RCA60				625.36	938.04	
0SNA20RCA80				312.68	1250.72	
0SNA0RCA100		331.01	0	0	1324.03	132.40
5SNA100RCA0				1563.40	0	
5SNA80RCA20	5	371.29	19.54	1250.72	312.68	156.33
5SNA60RCA40				938.04	625.36	
5SNA40RCA60				625.36	938.04	
5SNA20RCA80				312.68	1250.72	
5SNA0RCA100		314.46	16.55	0	1324.03	132.40
10SNA100RCA0				1563.40	0	
10SNA80RCA20	10	351.75	39.08	1250.72	312.68	156.33
10SNA60RCA40				938.04	625.36	
10SNA40RCA60				625.36	938.04	
10SNA20RCA80				312.68	1250.72	
10SNA0RCA100		297.91	33.10	0	1324.03	132.40
15SNA100RCA0				1563.40	0	
15SNA80RCA20	15	332.21	58.63	1250.72	312.68	156.33
15SNA60RCA40				938.04	625.36	
15SNA40RCA60				625.36	938.04	
15SNA20RCA80				312.68	1250.72	
15SNA0RCA100		281.36	49.65	0	1324.03	132.40
20SNA100RCA0				1563.40	0	
20SNA80RCA20	20	312.66	78.17	1250.72	312.68	156.33
20SNA60RCA40				938.04	625.36	
20SNA40RCA60				625.36	938.04	
20SNA20RCA80				312.68	1250.72	
20SNA0RCA100		264.81	66.20	0	1324.03	132.40
25SNA100RCA0				1563.40	0	
25SNA80RCA20	25	293.12	97.71	1250.72	312.68	156.33
25SNA60RCA40				938.04	625.36	
25SNA40RCA60				625.36	938.04	
25SNA20RCA80				312.68	1250.72	
25SNA0RCA100		248.26	82.75	0	1324.03	132.40

2.3. *Testing methods*

In accordance with ASTM C138/C138M, the density of all specimens was estimated by computing the ratio of the specimens' measured dry weight to their volume (2017). Fresh PC density was determined after 24 h of demoulding before being water cured in a curing chamber, whereas hardened density was determined after 28 days of curing. All the 324 PC specimens cast for compressive strength were tested at 7, 28, and 56 days, according to ASTM C39/C39M (2015). Prior to the test, the samples were dried for roughly 2 h at room temperature before being crushed in the machine at 0.06 MPa/s. ASTM C1754 (2012) was used to determine the void ratio of the PC samples. Volume of the containing cylinder was determined by measuring its length and diameter. Weights of the samples (both dry (X) and submerged conditions (Y)) were then measured and the void content was deduced with the aid of the relation in Equation (1),

$$VR\ \% = \left[1-\left(\frac{X-Y}{\rho w\ \ Vol}\right)x\ 100\%\right] \tag{1}$$

where VR, X, Y, Vol and ρ_w are Void ratio, dry weight (g), weight under water (g), volume of sample (cm^3) and density of water (kg/cm^3), respectively. A falling-head permeameter was used to determine the specimens' hydraulic conductivity (also known as coefficient of permeability) in accordance with ASTM D5084 (2016). Before testing, the specimens were completely wet. To assure accuracy, the hydraulic conductivity test was done three times for each specimen and the average was calculated. The test scheme for the falling-head hydraulic conductivity test is shown in Fig. 4. Consequently, Darcy's law given in

Fig. 4. Scheme of hydraulic conductivity test.

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equation (2) was used to obtain coefficient of water permeability,

$$K = \frac{A_{tube}\ x\ L}{A\ x\ t} \times ln\frac{h1}{h2} \tag{2}$$

where K is the water permeability coefficient in mm/s, A and A_{tube} are the areas of the sample and tube cross-sections in mm^2, L is the sample length in mm, and t is the time it takes for water to decrease from an initial water level h_1 to a final water level h_2 (mm). The relationship between structural efficiency and CO_2 emission was used to assess the PC mixes' sustainability efficiency. Structural Efficiency (S.E) is the ratio of concrete compressive strength to density after 28 days of curing, measured in MPa/kgm^3 (Choi, 2006). For the evaluation and study of CO_2 emissions from PC mixtures, the mix design quantity was used. Collins (2010) and Miliutenco (2009) based their carbon emission factors (Table 4) on the UK Mineral Products Association and the Australian National Pollutant Inventory Emission Estimation Technique Manual for Mining. The SHA was considered as a carbon-neutral supplementary cementitious material, for the net CO_2 produced in the combustion of sorghum husk is compensated for by the consumption of CO_2 by the sorghum plant in the photosynthesis process required for its growth.

The cost of making 1 m^3 each of PC, with 5–25% replacement of cement with SHA as well as 20–100% replacement of NA with RCA were likened as a way of measuring the relative cost effectiveness. The rates adopted are considered, being the current attainable rate in Nigeria. RCA was obtained for free but the cost of transporting and reducing them to required size amount to approximately 1000 naira/ton which is 1 naira/kg ($0.0024/kg). Cement is sold at 4, 000 naira/50 kg and this amounts to 80 naira/kg ($0.1920/kg), granite (NA) goes for 8, 000 naira/ton that is 8 naira/kg ($0.0192/kg) and water is assumed to be 1 naira/kg ($0.0024/kg). SHA was obtained for free but the cost of transporting, calcinating and sieving them to required fineness amount to approximately 1000 naira/ton which is 1 naira/kg ($0.0024/kg).

3. Results and discussion

3.1. Fresh and Hardened Density

Fig. 5 presents the fresh and hardened densities of SHA-PC with RCA mixtures. It was observed that the values of hardened density were lower than that of fresh density for every mixtures as anticipated. This is because of the presence of some water that have not been used for hydration in fresh concrete. Careful examination of the figure clearly showed that both fresh and hardened densities decrease as the proportion of RCA increases from 0 to 100% at every replacement level of cement with SHA. The fresh density of 2154 kg/m^3 and hardened density 2129 kg/m^3 were recorded for the control mix (0SNA100RCA0), respectively. However, the fresh density was found reduced by 3, 8, 11, 14 and 18% while hardened density declined by 3, 7, 12, 15 and 18% for mixtures containing 20, 40, 60, 80 and 100% RCA replacement, respectively. The mixtures with 5, 10, 15, 20 and 25% SHA replacement followed the same trend with the control. The lowest fresh and hardened densities (1733 and 1714 kg/m^3) were obtained at 25SNA0RCA100 mixture. It is obvious that both fresh and hardened densities slightly declined as the amount of SHA increased. The lower specific gravity (2.1) of SHA compared to cement (3.15) could explain the drop in densities as SHA content increases, as shown in Table 2. The decrease in the values of fresh and hardened densities as the proportion RCA increases might be attributed to the existence of attached mortar in RCA as shown in Fig. 1. The observed trend can be ascribed to lower specific gravity of RCA when compared to NA (Table 1). However, the values of densities obtained were within the range of 1600–2000 kg/m^3 specified by Tennis et al. (2004). Similar features have been obtained and reported by several authors (Rizvi et al., 2010; Sriravindrarajah et al., 2012; Güneyisi et al., 2016; Yap et al., 2018; Tijani et al., 2019a, 2019b).

Table 4
CO_2 emission factors.

Materials	CO_2 emission factor ($kgCO_2e/kg$)	References
Cement	0.82	Collins (2010),
Granite	0.046	Turner and Collins (2013), Collins (2010), Miliutenco (2009)
RCA	0.0015	Turner and Collins (2013), Collins (2010)

3.2. Compressive strength

The 7-, 28- and 56-days compressive strengths of SHA PC with RCA are presented in Fig. 6. It was observed that the compressive strength of PC mixtures increased with curing. Meanwhile the strengths were generally found to decrease at every RCA replacement levels (0–100%) for all SHA substitutions (0–25%). At 0% SHA substitution, the 28-day compressive strengths decreased by 10.7, 19.8, 32.1, 41.8 and 47.9 N/mm^2 for 20, 40, 60, 80 and 100% RCA incorporation respectively compared to the control. At 5, 10, 15, 20 and 25% SHA substitution, the strength decreased from 8.5 to 43.9, 12.3–46.2, 3.2–38.9, 7.9–44.4 and 14.6–53.8% for 20, 40, 60, 80 and 100% RCA incorporation, accordingly as compared to the control. The decrease in strength with increasing RCA substitution is attributed to weak bond that formed between the old mortar and the new one as opined by Güneyisi et al. (2016). The compressive strengths of all mixtures were also found within the ACI522R (2010) specification. Moreover, the compressive strength at 5% SHA substitution were greater than the control irrespective of number of days of curing and RCA content. This suggests 5% as the optimum replacement level of cement. The compressive strengths at 10% SHA replacement were slightly higher than the control at 56 days, at every RCA replacement levels. This suggests that strength can be attained at later age due to pozzolanic reaction of SHA. This feature shows consistency as with the result obtained from the XRD pattern (Fig. 3) revealing the prevalence of silica in SHA as the principal element and consequently indicating pozolanic activity. The production of additional calcium-silicate-hydrate (C-S-H) gel in PC as a result of SHA pozzolanic activity during cement hydration can be linked to the improvement in strength at low SHA substitution. This refines the pores and improves the interfacial transaction zone between the aggregates and the cement paste, resulting in a PC with a denser internal structure. The decrease in strength at higher replacement of SHA could be due to dilution effect of cement, formation of weaker C-S-H gel as a result of pozzolanic reaction and porous structure of ash particles as observed in Fig. 2. Khankhaje et al. (2018) have given similar report with the use of palm oil fuel ash cement replacement in PC. The same output was also reported for self-compacting concrete with untreated rice husk ash as partial cement substitute (Sathurshan et al., 2021).

3.3. Void ratio and hydraulic conductivity

Fig. 7 depicts the void ratio of SHA-RCA-PC as a function of SHA content. It was observed that increase in the substitution of SHA with cement lead to increase in void ratio at every replacement value of RCA. At 0% SHA replacement level, the void ratio was 20.14% and increased by 3.87, 13.61, 15.24, 16.88 and 20.46% for 20, 40, 60, 80 and 100% RCA respectively. The mixture of 5, 10, 15, 20 and 25% SHA replacement followed the same trend with increased void ratio from 1.6 to 19.1, 2.8 to 21.3, 0.6 to 13.8, 0.3 to 13.6 and 1.1–15.1% for 20–100% RCA replacement, respectively when compared to the control mixture. Typical void ratio for PC is within the range of 18–35% (ACI522R, 2010 and Tennis et al., 2004). This range is considered perfect to offer adequate strength with provision for sufficient hydraulic conductivity. The hydraulic conductivity of SHA-RCA-PC is presented in Fig. 8. It was revealed that hydraulic conductivity values rise as the SHA additions increases at every replacement level of RCA. At 0, 5, 10, 15, 20 and 25% SHA replacement, the hydraulic conductivity values increased up to 84,

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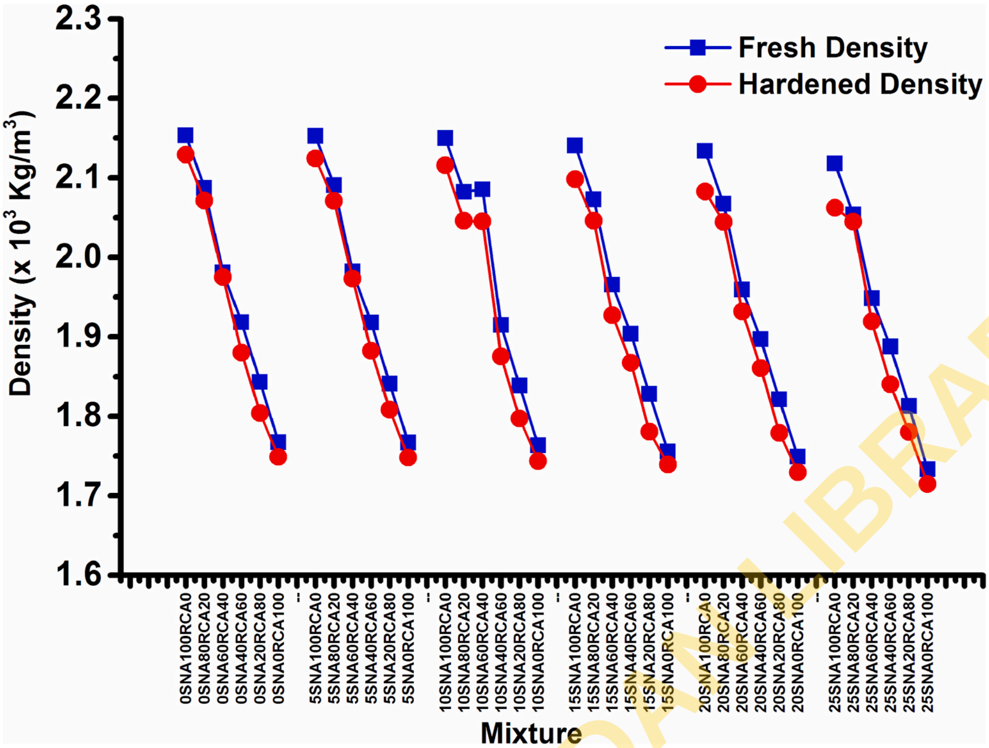

Fig. 5. Fresh and hardened density of SHA-RCA-PC.

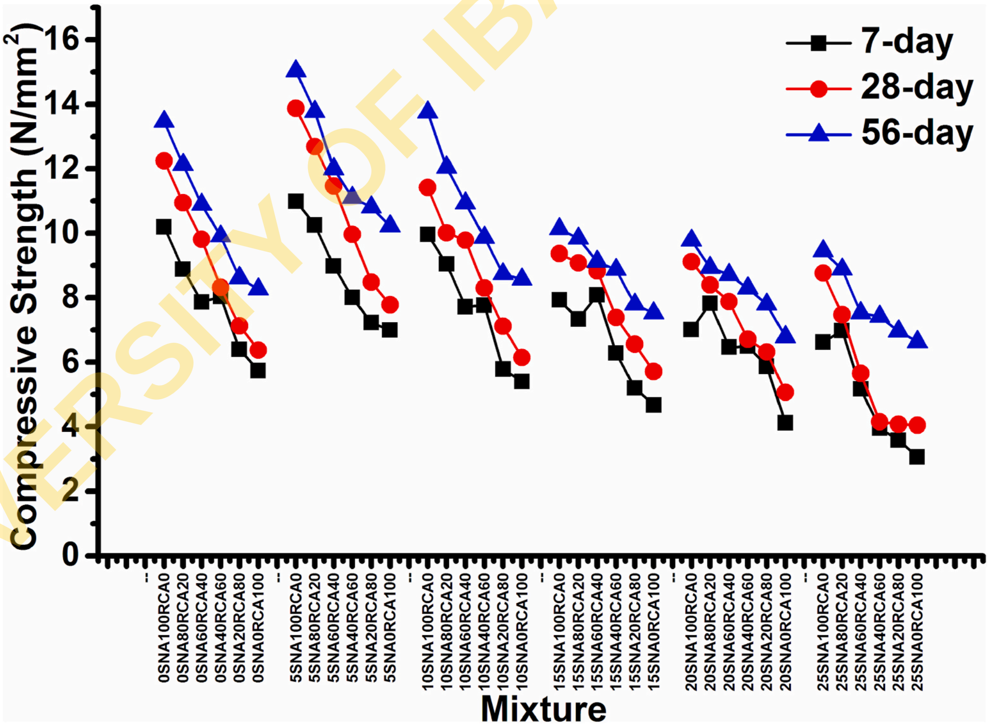

Fig. 6. Compressive strength of SHA-RCA-PC

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86, 73, 64, 68 and 55% for 0, 20, 40, 60, 80 and 100% RCA replacement, respectively. The increase in the values of void ratio and hydraulic conductivity as the proportion RCA increases could be attributed to the presence of already used mortar in RCA (Fig. 1(b)). However, the values of void ratio and hydraulic conductivity obtained were within the range specified by ACI 522R (2010) and Tennis et al. (2004). Similar results were also obtained by Yap et al. (2018), Sriravindrarajah et al. (2012) and Rizvi et al. (2010) where void ratio and hydraulic conductivity of PC increased as the percentage of RCA replacement increased. It was obvious that both void ratio and hydraulic conductivity were slightly raised with increasing SHA contents. This observable trend could be attributed to the high porous nature of SHA as shown in Fig. 2. Similar

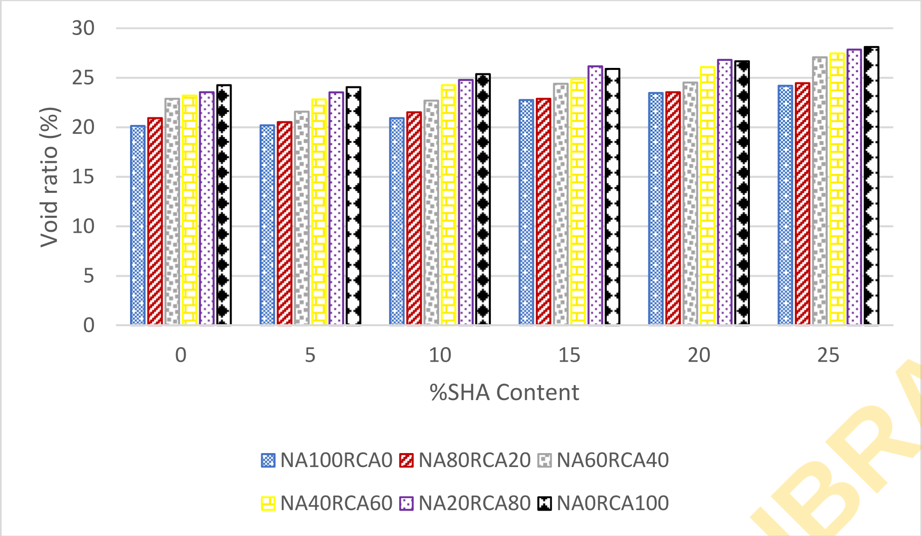

Fig. 7. Void ratio of SHA-RCA-PC.

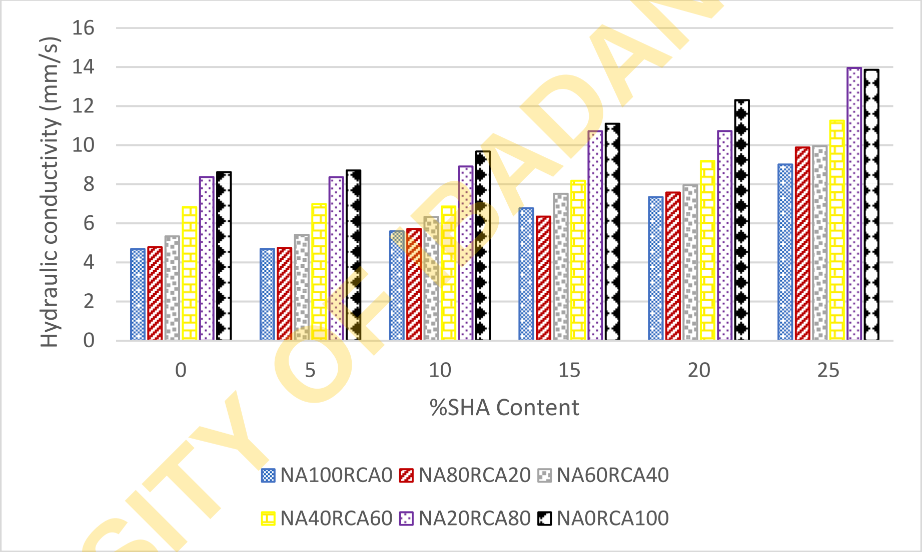

Fig. 8. Hydraulic conductivity of SHA-RCA-PC.

results were obtained by Khankhaje et al. (2018) using palm oil fuel ash as cement replacement in PC.

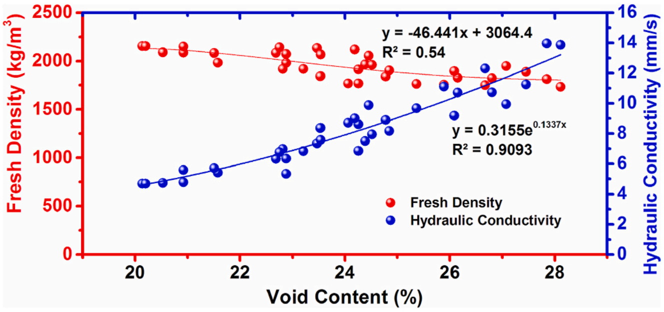

Fig. 9. Relationship among fresh density, hydraulic conductivity and void content of SHA-RCA-PC.

3.4. Relationship among the measured properties

In order to designing the mix properties for structural works in PC, there is a strong need to find a balance between the basic characteristic attributes of void content, hydraulic conductivity and the (desired) strength of the PC. The 28 day values of compressive strength have been recommended as an efficient tool to generally suggest the strength of PC (Kevern et al., 2009). The fresh density of PC is a pointer of the strength and hydrological properties, and offers the top predictable test for watching quality (Kevern, 2008). Fig. 9 shows the relationship among fresh density, hydraulic conductivity and void content of SHA-RCA-PC. The figure shows that the fresh density decreases linearly as the void content increases while hydraulic conductivity exponentially increases with void content irrespective of SHA or RCA replacements. There is a definite correlation between the void content and fresh density as well as void content and hydraulic conductivity. Kevern (2008) stated that once fresh unit weight is established, void content of PC can be easily evaluated since it declined linearly as unit weight rises. Monrose (2020) revealed in his work that the lesser the unit weight value of a PC, the higher the void ratio. Lu et al. (2019) stated that permeability rapidly increased with increase in porosity of PC. Fig. 10 shows the relationship

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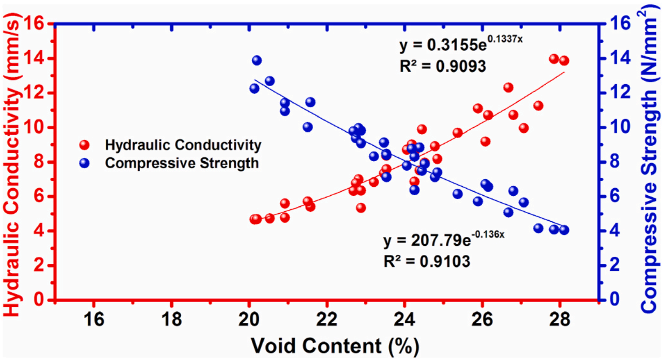

Fig. 10. Relationship among 28 day compressive strength, hydraulic conductivity and void content of SHA-RCA-PC.

among compressive strength, hydraulic conductivity and void content of SHA-RCA-PC to determine optimum mix. It shows that when the void content increases, the compressive strength decreases and hydraulic conductivity increases. Chen et al. (2019) stated that strength of PC are mostly affected by void content. Influence of SHA in the mix improve the compressive strength at 5% cement substitution while replacement of NA with RCA in the mix increases the void ratio and hydraulic conductivity of PC but decreases the compressive strength. Balancing the compressive strength and hydraulic conductivity, optimum mix is determined. Both the compressive strength and hydraulic conductivity are found to be around 8 N/mm^2 and 8 mm/s while the void content is approximately 24%. With reference to the above values, mix with 5% SHA, 20% NA and 80% RCA (5SNA20RCA80) is identified as optimum.

3.5. *Sustainability efficiency*

The sustainability efficiency of incorporating RCA and SHA on PC mixtures were investigated using structural efficiency and CO_2 emission. Fig. 11 shows the relationship between CO_2 emission and structural efficiency of SHA-RCA-PC mixtures. It could be seen from the figure that CO_2 emission slightly reduces linearly with increase in the percentage replacement of SHA from 0 to 25%. This observation is similar to what Kanadasan and Razak (2015) obtained for palm oil mill incinerated waste concrete. Ibrahim and Razak (2016) also reported reduced CO_2 emission when palm oil clinker was incorporated in PC. Interestingly, significant reductions in CO_2 emission was noticed as the percentage replacement of NA with RCA increases from 0 to 100%.

Summarily, at 0% SHA addition, the value of CO_2 emission obtained for 0% RCA was 0.3924 tCO_2-e/m^3, this reduces by 3.5, 7.1, 10.6, 14.2 and 17.8% for 20, 40, 60, 80 and 100% RCA replacement level respectively. Also, the value of structural efficiency obtained at this 0% SHA addition was 0.005751 MPa/kg/m^3 and reduces by 8.1, 13.6, 23.1, 31.32 and 36.6% for 20, 40, 60, 80 and 100% RCA replacement level, respectively. At 5% SHA replacement, CO_2 emission of 0.3764 tCO_2-e/m^3 was obtained for mixture containing 0% RCA. The emission reduced by 3.7, 7.4, 11.1, 14.8 and 18.6% for 20, 40, 60, 80 and 100% RCA replacement level respectively. Furthermore, the value of structural efficiency obtained was 0.006531 MPa/kg/m^3 and reduces for 20, 40, 60, 80 and 100% RCA by 6.2, 11.1, 18.9, 28.2 and 31.9% respectively. Considering 10% SHA replacement, the value of CO_2 emission obtained for 0% RCA was 0.3603 tCO_2-e/m^3 and reduced by 3.9, 7.7, 11.6, 15.4 and 19.4% for 20, 40, 60, 80 and 100% RCA replacement level respectively. For the structural efficiency, 0.005395 MPa/kg/m^3 was obtained for no RCA replacement. This value reduced by 9.3, 11.4, 17.9, 26.6 and 34.7% for 20, 40, 60, 80 and 100% RCA replacement level respectively.

The results obtained for 15, 20 and 25% replacement followed same trend. At 15% SHA addition, CO_2 emission of 0.3443, 0.3304, 0.3164, 0.3026, 0.2887 and 0.2744 tCO_2-e/m^3 (20.3% maximum CO_2 emission reduction) were recorded while structural efficiency obtained were 0.004463, 0.004437, 0.004582, 0.003957, 0.003683 and 0.003286 MPa/kg/m^3 (26.4% maximum structural efficiency reduction) for 20, 40, 60, 80 and 100% RCA replacement level respectively. At 20% SHA addition, CO_2 emission values were 0.3283, 0.3144, 0.3004, 0.2866, 0.2727 and 0.2584 tCO_2-e/m^3 (21.3% maximum CO_2 emission reduction) while structural efficiency obtained were 0.004378, 0.004106,

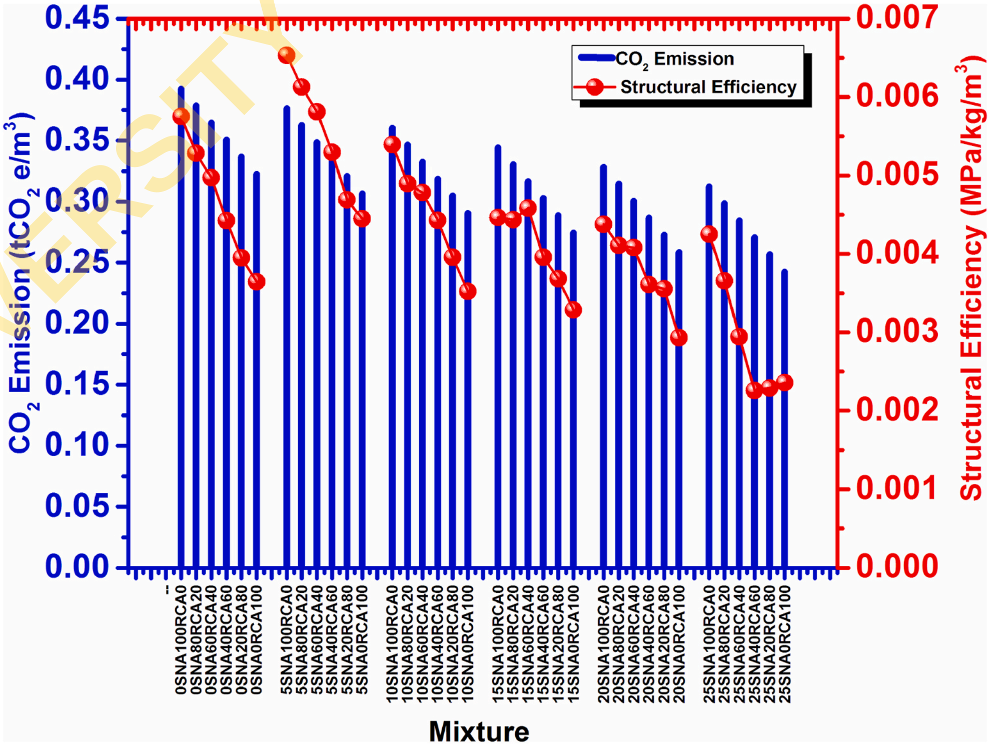

Fig. 11. Relationship between CO_2 emission and structural efficiency of SHA-RCA-PC.

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0.004079, 0.003607, 0.003552 and 0.002932 MPa/kg/m^3 (33.0% maximum structural efficiency reduction) for 20, 40, 60, 80 and 100% RCA replacement level respectively. Finally, at 25% SHA addition, CO_2 emission values were 0.3123, 0.2984, 0.2844, 0.2706, 0.2567 and 0.2424 tCO_2-e/m^3 (22.4% maximum CO_2 emission reduction) while structural efficiency obtained were 0.004248, 0.003657, 0.002946, 0.002259, 0.002290 and 0.002360 MPa/kg/m^3 (44.4% maximum structural efficiency reduction) for 20, 40, 60, 80 and 100% RCA replacement level respectively. Thus incorporating RCA into SHA-PC mix will help reduce discharge of CO_2 which is harmful to the environment.

3.6. *Economic analysis*

The cost efficiency of SHA-RCA-PC was investigated. Table 5 presents the summary of estimated costs per cubic meter for SHA-RCA-PC mixtures. At 0% SHA cement replacement, the cost of making one cubic meter of PC with 100% NA and 0% RCA was $105.43 which reduced by 4.98, 9.96, 14.95, 19.93, and 36.40% for 20, 40, 60, 80 and 100% RCA replacements of NA respectively. Total replacement of NA by RCA produced the least unit cost of PC with the value which equals $67.05. The costs of cement and that of water remained constant at $75.04 and $0.38, respectively until when the batching ratio of NA and RCA was 0:100, at this, the cost of cement and that of water were $63.55 and $0.32 respectively. Also, the cost of making one cubic meter of PC with 100% NA and 0% RCA at 5% SHA cement replacement, was $101.73 which reduced by 5.17, 10.33, 15.49, 20.66, and 37.18% for 20, 40, 60, 80 and 100% RCA replacements of NA respectively. The least unit cost of PC with the value which equals $63.91 was produced by total replacement of NA with RCA. The costs of cement, SHA and that of water remained constant at $71.29, $0.05 and $0.38 respectively until when the batching ratio of NA and RCA was 0:100, at this level, the cost of cement, SHA and that of water were $60.38, $0.04 and $0.32 respectively.

Table 5
Summary of estimated costs per cubic meter for SHA-RCA-PC.

Mix	Cement Cost ($)	SHA Cost ($)	Water Cost ($)	NA Cost ($)	RCA Cost ($)	Total Cost ($)
0SNA100RCA0	75.04	0.00	0.38	30.02	0.00	105.43
0SNA80RCA20	75.04	0.00	0.38	24.01	0.75	100.18
0SNA60RCA40	75.04	0.00	0.38	18.01	1.50	94.93
0SNA40RCA60	75.04	0.00	0.38	12.01	2.25	89.67
0SNA20RCA80	75.04	0.00	0.38	6.00	3.00	84.42
0SNA0RCA100	63.55	0.00	0.32	0.00	3.18	67.05
5SNA100RCA0	71.29	0.05	0.38	30.02	0.00	101.73
5SNA80RCA20	71.29	0.05	0.38	24.01	0.75	96.47
5SNA60RCA40	71.29	0.05	0.38	18.01	1.50	91.22
5SNA40RCA60	71.29	0.05	0.38	12.01	2.25	85.97
5SNA20RCA80	71.29	0.05	0.38	6.00	3.00	80.71
5SNA0RCA100	60.38	0.04	0.32	0.00	3.18	63.91
10SNA100RCA0	67.54	0.09	0.38	30.02	0.00	98.02
10SNA80RCA20	67.54	0.09	0.38	24.01	0.75	92.77
10SNA60RCA40	67.54	0.09	0.38	18.01	1.50	87.52
10SNA40RCA60	67.54	0.09	0.38	12.01	2.25	82.26
10SNA20RCA80	67.54	0.09	0.38	6.00	3.00	77.01
10SNA0RCA100	57.20	0.08	0.32	0.00	3.18	60.77
15SNA100RCA0	63.78	0.14	0.38	30.02	0.00	94.32
15SNA80RCA20	63.78	0.14	0.38	24.01	0.75	89.06
15SNA60RCA40	63.78	0.14	0.38	18.01	1.50	83.81
15SNA40RCA60	63.78	0.14	0.38	12.01	2.25	78.56
15SNA20RCA80	63.78	0.14	0.38	6.00	3.00	73.31
15SNA0RCA100	54.02	0.12	0.32	0.00	3.18	57.64
20SNA100RCA0	60.03	0.19	0.38	30.02	0.00	90.61
20SNA80RCA20	60.03	0.19	0.38	24.01	0.75	85.36
20SNA60RCA40	60.03	0.19	0.38	18.01	1.50	80.10
20SNA40RCA60	60.03	0.19	0.38	12.01	2.25	74.85
20SNA20RCA80	60.03	0.19	0.38	6.00	3.00	69.60
20SNA0RCA100	50.84	0.16	0.32	0.00	3.18	54.50
25SNA100RCA0	56.28	0.23	0.38	30.02	0.00	86.91
25SNA80RCA20	56.28	0.23	0.38	24.01	0.75	81.65
25SNA60RCA40	56.28	0.23	0.38	18.01	1.50	76.40
25SNA40RCA60	56.28	0.23	0.38	12.01	2.25	71.15
25SNA20RCA80	56.28	0.23	0.38	6.00	3.00	65.89
25SNA0RCA100	47.67	0.20	0.32	0.00	3.18	51.36

The results obtained for 10 and 15% SHA replacement followed same trend. At 10% SHA cement replacement, the cost of making one cubic meter of PC were $98.02, $92.77, $87.52, $82.26, $77.01 and $60.77 (38.00% maximum cost reduction) for 0, 20, 40, 60, 80 and 100% RCA replacement level respectively. On the other hand, the respective cost obtained for 0–100% RCA replacement level at 15% SHA cement replacement were $94.32, $89.06, $83.81, $78.56, $73.31 and $57.64 (38.89% maximum cost reduction). Similarly, at 20% SHA cement replacement, the cost of PC with 100% NA and 0% RCA was $90.61 which reduced by 5.79, 11.60, 17.39, 23.19 and 39.85% for 20–100% RCA replacements of NA respectively. Lastly, at 25% SHA cement replacement, the cost of making one cubic meter of PC with 100% NA and 0% RCA was $86.91 which reduced by 6.05, 12.09, 18.13, 24.19 and 40.90% for 20–100% RCA replacements of NA respectively. Total replacement of NA by RCA produced the least unit cost of PC with the value which equals $51.36. The costs of cement, SHA and that of water remained constant at $56.28, $0.23 and $0.38 respectively until when the batching ratio of NA to RCA was 0:100, at this, the cost of cement, SHA and that of water were $47.67, $0.2 and $0.32 respectively.

Generally, the highest cost of making one cubic meter of PC ($105.43) was obtained in the control mixture (0SNA100RCA0) while the lowest cost ($51.36) was obtained when 25% SHA was combined with 100% RCA (25SNA0RCA100) which amounts to 51.29% cost reduction. Therefore, the findings of the cost evaluation revealed that incorporating RCA into SHA-PC mix will contribute to the development of low-cost PC production without any detrimental effect to adequate strength and hydraulic properties.

4. Conclusion

The study prepared a novel mixed proportions of SHA-RCA-PC. The effect of SHA and RCA on density, compressive strength and hydraulic properties of PC made with NA was investigated in order to produce a more environmentally-sustainable and cost-efficient structures. At different levels, SHA was used as partial replacement for cement and its influence on PC mixes produced with NA and RCA was investigated. Lastly, sustainability and cost efficiency of using wastes; SHA and RCA in PC production were established. The study demonstrated the impact of incorporating SHA as a fractional substitute for cement and RCA as a substitute for NA on the improvement of the hydraulic properties at appropriate strength and the reduction of CO_2 emission. Effectiveness in cost of PC production was also established. The following conclusions were drawn from the study:

- The replacement of NA with RCA increased the void ratio and hydraulic conductivity of PC but decreased the fresh and hardened densities and compressive strength (7, 28 and 56 days) irrespective of the substitution of cement with SHA. Moreover, the 28 day compressive strength at 5% SHA replacement were greater than the control irrespective of RCA incorporation. This suggests that the 5% is the optimum replacement level of cement. Amazingly at later curing age of 56 days, the compressive strength at 10% SHA replacement were slightly higher than the control at every RCA replacement levels. This suggests that more strength can be attained at later age due to pozzolanic reaction of SHA.
- Mix with 5% SHA, 20% NA and 80% RCA was identified as optimum when the balance between the basic characteristic attributes of void content, hydraulic conductivity and compressive strength of the PC was sought.
- Sustainability assessment showed that CO_2 emission reduced as the percentage of SHA and RCA increases for all PC mixtures. The CO_2

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emission of 100% RCA plus 25% SHA was 38.23% lower than control mixture. The structural efficiency decreased for all PC mixtures as the percentage substitution of SHA and RCA increased except at 5% SHA addition where it increased slightly suggesting it as the optimum cement replacement level because of the improved structural efficiency at the same time with reduced CO_2 emission.

- Economic analysis showed that production costs reduced as the percentage SHA and RCA increase for all PC mixtures. The production cost of 100% RCA plus 25% SHA was 51.29% lower than control mixture.
- The incorporation of SHA and RCA reduce CO_2 discharge from construction materials and their cost implications, thus forming an integral part of the urgent actions to combat climate change and its impacts.

CRediT authorship contribution statement

Murtadha Adekilekun Tijani: Conceptualization, Data curation, Methodology, Investigation, Formal analysis, Resources, Visualization, Writing – original draft, review & editing, process, Conceived the presented idea; Developed and designed the, Conducted the research and, specifically performed the experiments, data/evidence collection and wrote the manuscript. **Wasiu Olabamiji Ajagbe:** Conceptualization, Methodology, Visualization, Validation, Supervision, Writing – review & editing, verifications of the activities, of the overall replication/ reproducibility of results/experiments and other research outputs. **Oluwole Akinyele Agbede:** Supervision, Project administration, Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team; Management and coordination of responsibility for the research activity planning and execution.

Declaration of competing 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.

Acknowledgements

The authors would like to thank Dr. Saheed Adewinbi (Osun State University) for comments on the manuscript.

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