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Assessment of Workability and Compressive Strength of Rice Husk Ash-Blended Palm Kernel Shell Concrete

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Abstract

The evaluation of agro-industrial by-products as alternative construction materials is becoming more significant as the demand for environmentally friendly construction materials increases. In this study, the workability and compressive strength of concrete produced by combining Palm Kernel Shell (PKS) and Rice Husk Ash (RHA) was investigated. Concrete mixes using a fixed content of 15% RHA as replacement for cement and 20, 40, 60, 80 and 100% PKS as replacement for crushed granite by volume with the mix ratios of 1:1½:3, 1:2:4 and 1:3:6 were produced. The water-to-cement ratios of 0.5, 0.6 and 0.7 were used for the respective mix ratios. Concrete without PKS and RHA served as control mix. The fresh concrete workability was evaluated through slump test. The concrete hardened properties determined were the density and compressive strength. The results indicated that the workability and density of PKSC were lower than control concrete, and they decreased as the PKS content in each mix ratio was increased. The compressive strength of concrete at 90 days decreased from 27.8-13.1 N/mm^2, 23.8-8.9 N/mm^{2}and 20.6-7.6 for 1:1½:3, 1:2:4 and 1:3:6, respectively as the substitution level of PKS increased from 0-100%. However, the compressive strength of concrete increased with curing age and the gain in strength of concrete containing RHA and PKSC were higher than the control at the later age. The concrete containing 15% RHA with up to 40% PKS for 1:1½:3 and 20% PKS for 1:2:4 mix ratios satisfied the minimum strength requirements for structural lightweight aggregate concrete (SLWAC) stipulated by the relevant standards. It can be concluded that the addition of 15% RHA is effective in improving the strength properties of PKSC for eco-friendly SLWAC production.

Keywords: Compressive strength, Concrete, Mix ratio, Palm kernel shell, Rice husk ash, Workability.

Introduction

Concrete is a composite material which is produced from the mixture of cement, aggregates (fine and coarse) and water with or without admixture. It is widely used as construction material for the development of structures for human habitation and protection, provision of transportation, education, healthcare, recreation and industrial facilities among others (de Brito and Kurdu, 2021). The popularity of concrete is attributed to its ability to take any shapes while wet and its strength characteristics when hardens (Gupta, 2013). In most cases, the properties of concrete which is the major factor upon which concrete is categorized into different types is governed by the types, properties and proportions of concrete constituents.

The constituent materials used in concrete production are not sustainable since they are derived from non-renewable resources (de Brito and Kurda, 2021). Aggregate is the most voluminous part of the concrete as it occupies about 75% of the total concrete volume. Thus, its influence on the behaviour of hardened concrete cannot be underestimated (Deepa *et al*., 2010). The conventional aggregates used in concrete production exist in their natural aggregates, and generally the main activities involve in extraction of aggregate include mining, harvesting, dredging, processing and transportation. All these activities lead to destruction of ecosystems and habitats and generation of waste as well as excessive use of energy

(Mahamadu *et al*., 2016). Thus, the need to preserve the natural resources and save the environment and its inhabitant from extinction demand for alternative construction materials (Osei and Jackson, 2012; Olanitori and Okesanmi, 2019). In this regard, the search for other solid materials for use as substitute for the natural aggregate led to the investigation of solid agricultural by-products as aggregate for sustainable and eco-friendly concrete production. Palm kernel shell, coconut shell, periwinkle shell, and date seed have all been widely investigated and shown potential as partial or complete substitutes for conventional aggregates in the production of eco-friendly SLWAC (Osei and Jackson, 2012; Regin *et al*., 2016; Aboshio *et al*., 2018; Adefemi *et al*., 2013).

Cement is the main binding component used in concrete production which is produced from non-renewable resources. Substantial CO_2 and greenhouse gasses emanating from cement production processing which include extraction, manufacturing, transporting are also causing destruction of ecosystem and environmental pollution (Mahamadu *et al*., 2016). In addition, the high cost of cement has made building construction unaffordable to the common man in the developing nation. As a result of these considerations, research into the use of alternative materials as substitute for cement in order to lessen the detrimental impact of cement manufacturing on living beings has been ongoing for the past three decades. These alternative materials which are generally known as supplementary cementitious materials occur in their natural state while others are obtained from the processing of agro-industrial by-product materials. These materials include; rice husk ash, palm kernel shell ash, corn cob ash, saw dust ash, mango leave ash (Raheem and Kareem, 2017; Oti *et al*., 2015; Adesanya and Raheem, 2009a; Raheem and Ige, 2019; Ishola *et al*., 2019). The production of low-cost concrete is projected to be accomplished by turning waste into valuable product by incorporating it as raw material during the concrete production (Raheem and Kareem, 2017). Furthermore, waste materials could be used to create more sustainable, cleaner, and greener construction (Onuaguluchi and Panesar, 2014).

Rice is a staple food crop which is cultivated all over the world. RHA is obtained by burning rice husk which is a by-product from rice milling industries. The total estimate of rice produced worldwide was estimated to be 7.41×10^8 tons in 2016 (FAO, 2017). Nigeria was ranked second after Egypt as the second largest rice producer in Africa with the total production of 6.1 million tons in 2016. Rice husks are being generated on daily basis and always found to accumulate large space area over a long period in the vicinity of the industry. The open burning which is the common method of disposing of the husk is not environmentally friendly as its produced foul-smelling effluents while the ash tends to be blown about by the winds and pose threat to public health. This among other factors necessitates the consideration of the husk as valuable material in construction industry and found to be suitable for use as cement replacement material.

Palm Kernel Shell (PKS) are solid by-product obtained by threshing or crushing outside cover of palm kernel fruit to remove the palm kernel seed from which palm kernel oil is extracted. It's comprised of stony, hard endocarps that act as a protective covering for the palm kernel, which comes in a variety of sizes and shapes (Alengaram *et al*., 2011). Concrete in which the normal weight concrete (NWC) is partly or completely replaced by palm kernel shell is known as palm kernel shell concrete (PKSC). As reported in the literature, PKSC has a lower density and strength than NWC (Raheem *et al*., 2008; Olusola and Babafemi, 2013; Fapohunda *et al*., 2015). However, the lower density makes PKSC to be beneficial for use as lightweight concrete (Maghfouri *et al*., 2018; Olanitori and Okesanmi, 2019). Concrete produced from lightweight aggregate (LWA) with the density of less than 2000 kg/m^3 and minimum compressive strength of 17 N/mm^2 are referred to as structural lightweight aggregate concrete (SLWAC) (ASTM C 330/C 330M, 2014; ACI 213R-03, 2003). SLWAC are substantially cost effective in the areas where long span, high self-weight to applied loads are required (Pankhurst, 1993). Findings from the previous studies have shown that PKSC which can be used as SLWAC can be produced by incorporating PKS in to normal weight aggregate at optimum replacement level.

Recently, several researchers have considered the use of mineral admixtures such as fly ash to enhance the properties of PKSC. Mahmud *et al*. (2009) reported high early strength of 80-90% increase from 7-28 day. Islam *et al*. (2016) found maximum increase of 3% in compressive strength of PKSC with 10% palm oil fuel ash content compared to the PKSC without palm oil fuel ash and the trend continues up till 90-day curing age while the compressive strength decreased by 33% for the OPSC with 50% palm oil fuel ash content compared to the PKSC without palm oil fuel ash. In the study by Mo *et al*. (2014), PKSC containing 20% ground granulated blast furnace slag exhibited higher compressive strength than PKSC without ground granulated blast furnace slag at the curing age of 28 days. Shafigh *et al*. (2013) reported the highest 28-day compressive strength for the PKSC containing 10% fly ash content under full water curing and partial early curing before air drying. Foong *et al*. (2015) revealed the early strength development of 20% and 70% of 28-day strength developed at the age of 1 day and 7 days for PKSC containing RHA.

The few studies (Foong *et al*., 2015; Philips *et al*., 2017) which considered the influence of RHA on the properties of PKSC focused on the mechanical properties at the early age of up to 28 days. Therefore, this current study evaluates the workability, density, and compressive strength of RHA-blended PKSC made from three different mix ratios at the curing ages of up to 90 days.

Materials and Methods

Portland limestone cement (PLC), river sand, crushed granite, PKS, rice husk (RH), polyvinyl alcohol (PVA) and water were the materials used in this study. PLC (Grade 32.5 N) conforming to BS EN 197-1 (2011) procured from retail shop within Osogbo, Nigeria served as the binder. River sand sourced from the river bank along Ifon Osun, Osun State Nigeria was the fine aggregate used. Crushed granite sourced from the Quarry site at Ibadan was the main coarse aggregate used. The palm kernel shells (Figure 1) were collected from mini oil palm processing mill at Ogbaagba village, Nigeria. The collected PKSs were first washed with detergent soap and subsequently treated with 5% PVA. Previous research (Thong *et al*., 2017; Traore *et al*., 2018) had demonstrated that this treatment approach improves the water absorption quality of PKS. RH was sourced from mini rice processing mill within Ogbomoso, Nigeria. RHA was produced by calcining the husks in the furnace at the temperature of 600 ^{O}C for 4 hours. At this temperature, ashes with amorphous structures and low carbon content were observed (Raheem and Kareem, 2017). The RHA was subsequently sieved using 75 µm sieve. The potable water used was collected from the tap at the Structural and Material Laboratory, Osun State University, Osogbo, Nigeria.

Figure 1: PKS Samples

Testing of materials: To examine the chemical composition of cement and RHA, X-ray fluorescence analysis was performed as specified in BS EN 196-2 (1995). The physical properties of cement and RHA determined include specific gravity, fineness (specific surface area) and loss on ignition (LOI) in line with BS 1377-2 (1990), BS EN 195-6 (1995).

Sieve analysis was conducted on aggregate (river sand, granite and PKS) to determine particle size distribution as specified in BS 812-103.1 (1989). Water absorption and bulk density of aggregate were determined as specified in BS 812-2 (1995) while specific gravity was carried out as stipulated in BS 1377 (1990). The chemical compositions of cement and RHA were determined as specified in BS EN 196-2 (1995).

Concrete mix proportions and specimens' preparation: Three prescribed mix ratios of 1:1½:3, 1:2:4, 1:3:6 (cement: sand: granite/PKS) with w/c ratios of 0.5, 0.6 and 0.7, respectively were adopted in this study. The constituents of concrete were batched by volume based on the fact that PKS exhibited relatively lower specific gravity than crushed granite. Total six samples were prepared for each mix ratio and the percentage replacement of CA by PKS considered were 20, 40, 60, 80 and 100% as replacement for crushed granite. The sample prepared without PKS and served as the control. The cement used for concrete mixes was replaced with a fixed amount of 15% of RHA except the control. Concrete mixing was done manually according to BS 1881-125 (2013). Concrete mixes were then cast into wooden moulds and placed in the curing room at 27 ± 5 ^{O}C. After 24 hours, the concrete specimens were unmoulded and later cured in water until testing ages were reached.

Testing of concrete specimens: The workability of fresh concrete was determined by conducting slump test as specified in BS EN 12350-2 (2019).

The density of hardened concrete was evaluated after 28 days of curing accordance to BS EN 12390-7 (2009).

Concrete cubes of 100 mm size were used for compressive strength test. The specimens were cast in steel moulds by filling each one in three layers and manually compacting each layer with 25 strokes of a steel tamping rod with a diameter of 25 mm across the cross section of the mould. After 24 hours, the specimens were demoulded and water cured in a curing tank until they were tested at 7, 28, 56 and 90 days. Three specimens for each mix ratio were taken out of the curing tank on each testing age and allowed to rest for two hours before being crushed on a Controls compression machine (maximum capacity 2000 kN). The compressive strength of each specimen was the average of three specimens.

Results and Discussion

Chemical composition: The elemental oxides found in cement and RHA samples are shown in Table 1. The results indicated that the addition of ($SiO_2 + Al_2O_3 + F_2O_3$) for RHA was 94.24% that is more than 70% and LOI of 4.64 which is less than 6% as specified by ASTM C618-12 (2012) for class F pozzolans. Cement showed higher CaO content (62.50%) than RHA (1.38%) but the SiO_2 content of cement (20.92%) was lower than that of RHA (92.40%). The RHA had slightly higher SiO_2 content (92.40%) as against 91, 84.29 and 82.14% reported by Chao-Lung *et al*. (2011), Raheem and Kareem (2017) and Nguyen (2021). In addition, the maximum value of 5 and 6% specified by ASTM C618-12 (2012) for the SO_3 of cementitious material is satisfied by RHA.

Table 1: Chemical Composition and Physico-chemical properties of OPC and RHA

Chemical constituents	Percentage Composition (%)	
	Cement	RHA
SiO_2	20.92	92.40
Al_2O_3	4.84	0.78
F_2O_3	3.24	1.06
CaO	62.50	1.38
MgO	2.53	1.09
SO_3	2.77	0.06
K_2O	0.19	1.63
Na_2O	0.25	0.04
ZnO	0.01	0.23
Cr_2O_3	0.01	0.02
LOI	3.12	4.64
$SiO_2 + Al_2O_3 + F_2O_3$	27	94.24
Physical properties		
Colour	Greenish grey	Brownish grey
Specific gravity	3.19	1.94
Blaine fineness (cm^2/g)	4458	3766

Physical properties of OPC and RHA: Table 1 presents the physical characteristics of cement and RHA. The specific gravity of RHA falls below the range of 2.6 to 2.7 specified Neville and Brook (2010). Thus, it can be categorized as lightweight material. This implies that RHA is porous in nature and there is the tendency that low density concrete will be produced if it is used as raw material in concrete thereby contributing to the reduction in construction cost (Philips *et al.*, 2017). The specific surface area of both the cement and RHA were above the minimum fineness of 250 m^2/kg and 280 m^2/kg specified for cementitious materials by ASTM C 150 (2002) and NIS 439 (2000), respectively.

Sieve analysis: The grading curves of aggregates are shown in Figure 2. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) values were 4.47 and 1.04 for river sand; 1.55 and 1.05 for granite and 1.50 and 0.96 for PKS. The C_u value for sand is greater than 4 and C_c value is greater than 1 but less than 3 as specified by unified soil classification system (USCS) as postulated in ASTM D2487 (2011). Thus, it can be categorized as well graded sand. The C_u gives an indication of the spread of particle size value (Raheem and Ikotun, 2019). The C_u for granite and PKS ranged between 1.0 and 5.0, consequently, they can be classified as uniformly graded. Based on these assessments, river sand, granite and PKS are suitable ingredients for making quality concrete (Bowles, 1992).

Physical characteristic of aggregates: Table 2 shows the aggregates' physical characteristics. PKS was of a size that was comparable to those employed in earlier investigations (Sobuz *et al.*, 2014; Philips *et al.*, 2017; Oti *et al.*, 2017). River sand has a fineness modulus of 2.3-3.1, which is within the range specified by ASTM C33/C33 M (2018) for fine aggregates. A ‘very fine' fine aggregate will raise the concrete mix water requirement, whereas a ‘very coarse' fine aggregate may undermine workability, according to Philip et al. (2017). The specific gravity value of PKS is lower than that of river sand and granite. Therefore, PKS is expected to produce a less dense concrete with better thermal, insulative properties and significant reduction in dead weight than the conventional aggregate when use in concrete (Teo *et al.*, 2007). The specific gravity value of PKS falls outside the range of 2.5-3.0 specified by BS EN ISO 10545 (1997) for normal weight aggregate and can be regarded as LWA. The specific gravity values obtained for granite (2.91) and river sand (2.79) fall within the range of 2.5-3.0. Thus, they can be regarded as normal weight aggregate.

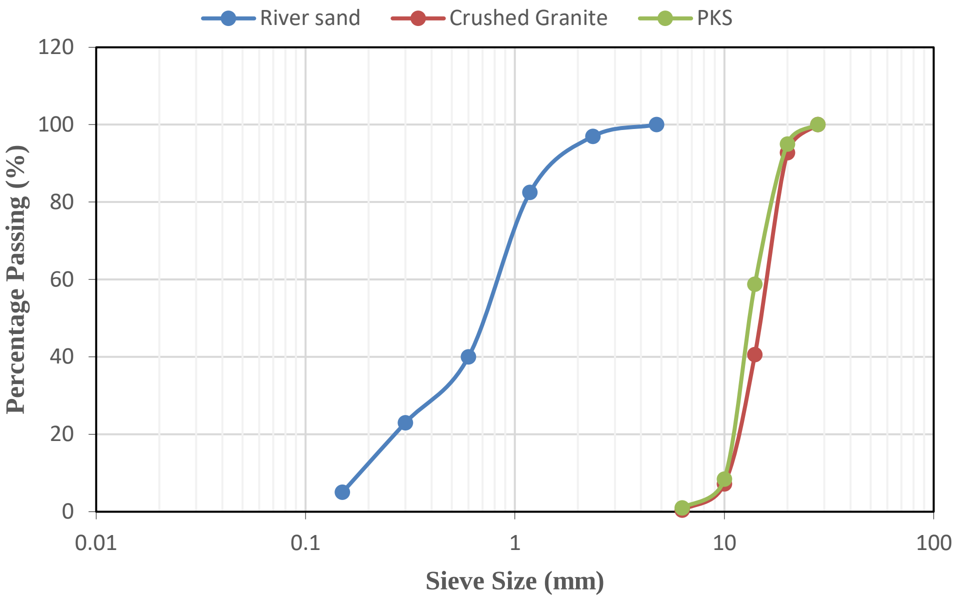

Figure 2: Gradation curves of aggregates

Table 2: Physical characteristics of Aggregates

Properties	Materials		
	River sand	Granite	PKS
Maximum size (mm)	2.36	20	20
Fineness Modulus	2.52	2.59	2.37
Specific gravity	2.79	2.91	1.19
Water absorption (%)	15.03	7.93	16.99
Bulk density	1802	1614	762

The water absorption value of PKS, river sand and granite were 16.99, 15.03 and 7.93, respectively. These results indicated that PKS is more absorptive by approximately 1.1 and 2.1 times higher than that of granite and river sand. The water absorption value of PKS falls outside the range of 0-8%, 0-10% specified by ACI Education Bulletin E1 (1999) and Neville (2008) for conventional aggregate. The cellular structure and porous nature of OPS are largely responsible for PKS's high water absorption and low specific gravity values (Alengaram *et al*., 2011). According to Ogundipe *et al*. (2021), the understanding of the water absorption value of aggregate is essential in developing the ideal water-cement ratio for the concrete mix proportion. PKS exhibited lower bulk density value than river sand and granite as revealed in the results in Table 2. However, the bulk density value of PKS falls within the range of 480-1040 kg/m^3 specified by ACI Education Bulletin E1 (1999) for coarse LWA. Based on this result, PKS can be expected to have a lower density and mechanical strength than the conventional aggregate. The low bulk density is due to the porous nature of PKS which Because of the porous structure of PKS, it has a lower bulk density than conventional aggregates, resulting in lighter concrete (Alengaram *et al*., 2011).

Workability: Table 3 shows the results of the slump test, indicating the workability of RHA-blended PKSC with various mix ratios. The results revealed that for all of the mix ratios studied, the slump values of concrete drop, showing that the workability of fresh concrete reduces as the PKS concentration increases. For 1:1$^1/_2$:3 mix ratio, the slump values decreased from 60-18 mm as the PKS contents increased from 0-100%; while for decreased from 40-16 mm for 1:2:4 mix ratio with increase in PKS contents from 0-100% and the slump values of concrete produced with mix ratio 1:3:6 decreased from 30-6 mm as the PKS contents increased from 0-100%. This is corroborated with the findings of Sobuz *et al*. (2014) and Maghfouri *et al*. (2018) where decrease in slump values were observed as PKS contents increases. These results indicate that the presence of PKS and RHA decrease the workability of concrete compared with the control for in workability is attributed the rough texture, irregular, flaky, elongated or angular shape and higher bulk density of PKS compare to granite (Maghfouri *et al*., 2018). The reduction of workability of RHA-blended PKSC can also be attributed to the increase in replacement level of PKS having higher fine particles leading to increase in its surface area compared with granite as indicated in the gradation curves (Figure 2) can cause an increase in water demand. As a result of these factors, particle friction within concrete increases, requiring more energy for the concrete to flow (Eziefula *et al*., 2017).

Table 3: Slump values of concrete of different mix proportions

	Slump (mm)		
Mix Ratio	1:1½:3	1:2:4	1:3:6
%PKS Replacement			
0	60	40	30
20	35	33	25
40	31	23	20
60	23	15	13
80	20	14	13
100	18	10	6

Due to RHA's lower specific gravity and higher absorptive properties, its presence increased the loss in concrete workability (Philips *et al*., 2017; Nguyen, 2021). For all of the mix ratios examined, the slump values of RHA-blended PKSC are less than the 50-75 mm specified by Mehta and Monteiro (2006) as acceptable for SLWAC. RHA-blended PKSC containing 20% PKS produced with 1:1$^1/_2$:3 mix ratio exhibited the slump value in the neighborhood of the lower limit acceptable for good workable concrete. However, the workability of concrete can be improved by adding effective superplasticizer to the concrete mixes to increase the concrete slump value (Maghfouri *et al*., 2018).

When the effect of mix ratios on workability was taken into account, the behavior of RHA-blended PKSC followed the same pattern as the control. Table 4 further shows that concrete produced with 1:1$^1/_2$:3 mix ratio had higher slump values (workability), followed by 1:2:4 and 1:3:6 mix ratios. The concrete became less workable as a result of the low cement concentration and greater aggregate content in the mix, indicating that more water is required to make the concrete more workable (Adesanya and Raheem, 2009a). This suggests that the aggregate/cement ratio in the richer concrete mixes is lower. As a result, there is more paste available per unit surface area of aggregate to provide lubricating; the mix is therefore made more cohesive and fattier to improve workability (Olusola, 2005).

The results showed that the control and RHA-blended PKSC with 20% PKS for all mix ratios investigated, as well as RHA-blended PKSC with 40% PKS produced with 1:1$^1/_2$:3 mix ratio only having slump values in the range of 25-100 mm, had medium workability. Therefore, they are suitable for concrete construction involving normal reinforced concrete manually compacted (Neville and Brooke, 2010). Low workability concrete includes RHA-blended PKSC with 40% PKS produced with other mix ratios (1:2:4 and 1:3:6), as well as those containing 60% PKS and above for all mix ratios. These are appropriate for vibration-free mass concrete foundations or lightly reinforced sections with vibration.

Density of concrete: The result of density of RHA-blended PKSC with different mix ratios at 28 days of curing are presented in Figure 3. It can be noted from the Figure that the density of concrete declines as the PKS contents rises for all the mix ratios investigated. For 1:1$^1/_2$:3 mix ratio, the density decreased from 2431-1600 kg/m^3 as the PKS contents increased from 0-100%; while for 1:2:4 mix ratio, the density decreased from 2256-1404 kg/m^3 with increase in PKS contents from 0-100% and the slump values of concrete produced with 1:3:6 mix ratio decreased from 2104-1256 kg/m^3 as the PKS contents increased from 0-100%. The trend of oven-dry density values obtained in this study is in consistence with Maghfouri *et al*. (2018) which reported the range of 2337-1900 kg/m^3 for concrete incorporating 0-100% PKS as replacement for conventional aggregate.

The maximum reductions of 34%, 38% and 40% in the density of RHA-blended PKSC were observed for concrete with 1:1½:3, 1:2:4 and 1:3:4 mix ratios, respectively at 100% PKS at 28-day curing age with respect to the control. The lower bulk density of PKS, which is approximately 58% lower than that of granite (Table 2) might be responsible for the reduction in concrete density. As a result, partial substitution of granite with PKS in conventional concrete is projected to increase void content while lowering density. These findings are consistent with previous research (Alengaram *et al*., 2013; Sobuz *et al*., 2014; Philips *et al*., 2017; Maghfouri *et al*., 2018) which found that as the amount of PKS replacement increased, the concrete density declined. The RHA included in concrete contributes to the reduction in concrete density since it exhibited lower specific gravity (1.94) than cement (3.19) (Damdelen *et al*., 2014; Praveenkumar *et al*., 2019). The rise in concrete density with curing age could be ascribed to the increase in hydration products, which fill up the voids and densified the concrete (Montemor *et al*., 2000).

The presented results as shown in Figure 3 suggested that the control of all the mix ratios had density values which is more than 2000 kg/m^3 for NWC at the curing age of 28 days as stipulated by BS EN 206-1 (2000) and Newman and Owen (2003). However, the RHA-blended PKSC containing 20% PKS for 1:1½:3 and 1:2:4 mix ratio mix showed slightly higher oven-dry density above the maximum of 2000 kg/m^3 for lightweight concrete and can be categorized as semi-lightweight concrete according to Abouhussien *et al*. (2015). The RHA-blended PKSC containing 20% PKS for 1:3:6 mix ratio and those containing PKS of 40% above for the three mix ratios had their density lower than 2000 kg/m^3 and they can therefore be categorized as SLWAC.

Considering the effect of mix ratio, it was noted from Figure 3, richer concrete mix (1:1$^1/_2$:3 mix ratio) having lower aggregate/cement ratio exhibited higher density followed by 1:2:4 and then, 1:3:6 mix ratios. This indicates that concrete mix ratio has substantial impact on the concrete density. As the aggregate content decreases, the void content of the

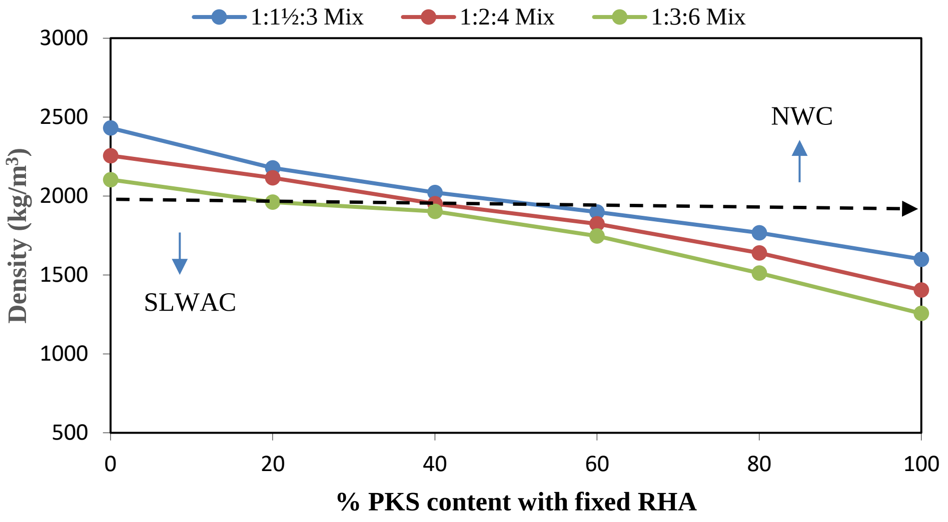

Figure 3. Density of RHA-blended PKSC

concrete mix is expected to decrease while its level of compactness increases. The higher cement content is capable of refining the concrete pores, producing greater amount of calcium-silicate-hydrate (C-S-H) which leads to increase in concrete density (Braga *et al*., 2014; Kareem *et al*., 2021). It can be deduced from the presented results of concrete oven-dry density that the combination of both materials (PKS and RHA) is ideal for use as lightweight and green concrete. Such concrete has the tendency of exhibiting lower self-weight thereby resulting to cost saving on the materials procurement than the conventional concrete. In addition, better thermal properties that guarantee better thermal comfort for human and animals.

Compressive Strength: Figures 4-7 show the compressive strength of RHA-blended PKSC with various mix ratios at curing ages of 7, 28, 56 and 90 days. For all the mix ratios examined, the compressive strength improved with increasing curing ages and declined with increasing PKS substitution.

The results at 7 days as presented in Figure 4 showed that the compressive strength values for 1:1½:3 mix ratio was 20.83 N/mm^2 for control and declined in the range of 17.17- 9.97 N/mm^2 for 20-100% PKS replacement, respectively. This implies a drop in compressive strength of 18-52% as compared to the control after 7 days of curing. For 1:2:4 mix ratio, the compressive strength value was 17.63 N/mm^2 for control and decreased in the range of 15.76-6.5 N/mm^2 for 20-100% PKS replacement. This indicates the decrease of 11-63% in compressive strength with respect to the control at 7 days of curing. For 1:3:6 mix ratio, the compressive strength value was 14.67 N/mm^2 for control and decreased in the range of 12-4.67 N/mm^2 for 20-100% PKS replacement. This corresponds to a decrease of 18-68% compared to the control. The control had the highest compressive strength for all the mix ratios at this stage. The lowest decrease in compressive strength was observed for RHA-blended PKSC containing 20% for all the mix ratios achieving up to 83%, 89% and 82% of the strength of the control strength at 7 days of curing. However, further increase in PKS led to higher reduction in concrete strength. These results agree with the findings from previous studies (Philips *et al*., 2017; Djima *et al*., 2018) on PKSC containing RHA and sugarcane bagasse ash. PKS has a lower bulk density and specific gravity but higher porosity than NWA. As a result, concrete with PKS as coarse aggregate is very porous, has a lower density and lower compressive strength than NWC. Furthermore, because PKS is finer and flakier than NWA, it has a higher surface area, which reduces concrete workability and has a significant impact on the binding between the aggregate and the hydrating cement paste, resulting in lower compressive strength than NWA. About 78%, 74% and 76% of the 28-day strength was achieved by the control with 1:1½:3, 1:2:4 and 1:3:6 mix ratios at the age of 7 days while it was in the range of 85-87%, 86-87% and 83-86% at 20-100% PKS replacement with the corresponding mix ratios. The early strength development strength developed by RHA-blended PKSC can be attributed to the filler effect of RHA which reduced the porosity of concrete and this was suggested to be beneficial in pre-cast concrete where early strength is essential (Foong *et al*. (2015).

Figure 5 showed the compressive strength at the age of 28 days for 1:1½:3 mix ratio was 26.87 N/mm^2 for control and 19.71- 12.71 N/mm^2 for 20-100% PKS replacement. The reduction in compressive strength ranged from 27-53% with respect to control at 28 days curing age. Similar trend was observed for 1:2:4 and 1:3:6 mix ratios with the compressive strength of 22.14 N/mm^2 and 19.32 N/mm^2 for control which decreased in the range of 18.36-8.5 N/mm^2 and 16.4-6.6 N/mm^2 for 20-100% PKS replacement. The reduction in compressive strength were in the range of 17-62% and 15-66% compared with the control for 1:2:4 and 1:3:6 mix ratios, respectively. It could be observed that the results followed similar trend of decrease in compressive strength as the density of concrete decreases. The breakdown of the weaker bond between PKS and cement paste due to the smooth surface and existence of micro pores on the outer surface of PKS was ascribed to the loss in compressive strength of RHA-blended PKSC. (Osei and Jackson, 2012; Tjahono *et al*., 2017; Maghfouri *et al*., 2018). The early age development of compressive strength of RHA-blended PKSC were lower compared to the control as the increase in strength from 7 to 28 days for control was 22%, 20% and 24% for control with 1:1½:3, 1:2:4 and 1:3:6 mix ratios while it ranged between 13-15%, 13-14% and 15-17% for the respective mix ratios. The theory on the gradual evolution of pozzolanic reaction, which governs the strength development of concrete containing pozzolan, also supports the finding. (Chao-Lung *et al*., 2011; Raheem and Kareem, 2017; Nguyen, 2021). Islam *et al*. (2016) provided similar results for PKSC containing palm oil fuel ash caused the delay in hydration rate at early curing age.

The presented results as shown in Figure 5 suggested that the control satisfied the targeted strengths for NWC of M 25 for 1:1½:3 mix ratio, M 20 for 1:2:4 mix ratio and M 15 for 1:3:6 mix ratio at the curing age of 28 days. All the RHA-blended PKSC exhibited the compressive strength below the targeted strength for NWC for the respective mix ratio investigated. However, the RHA-blended PKSC containing 20% PKS showed slight reduction compared with the targeted values while those containing higher PKS content showed higher reduction for the respective mix ratio. In addition, the compressive strength value of 17 N/mm^2 specified by ASTM C 330 (2014) for SLWAC at the curing age of 28 days was satisfied by RHA-blended PKSC containing PKS content up to 40% for 1:1½:3 mix ratio, 20% for 1:2:4 mix ratio, while for 1:3:6 mix ratio, all the PKS replacement considered could not satisfy ASTM C 330 (2014) requirement.

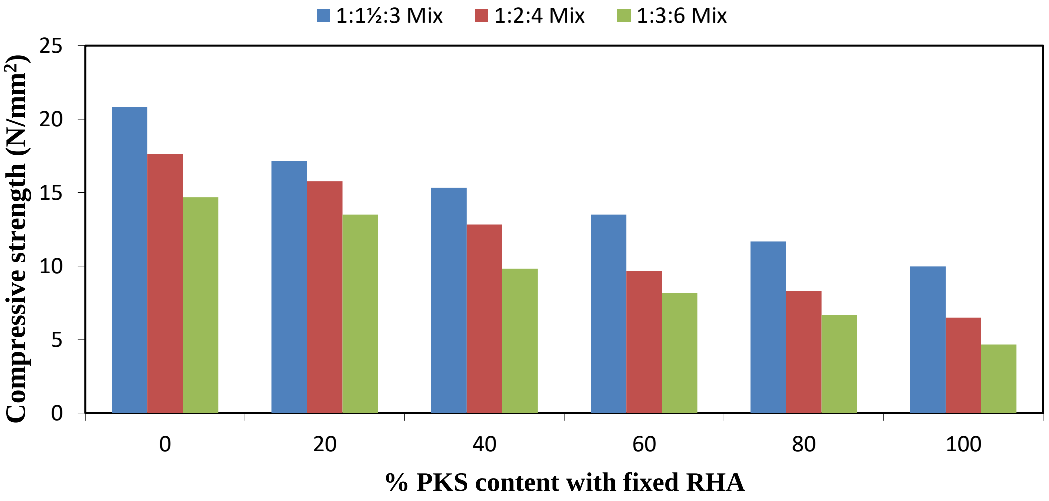

Figure 4. Compressive strength of RHA-blended PKSC at age of 7 days

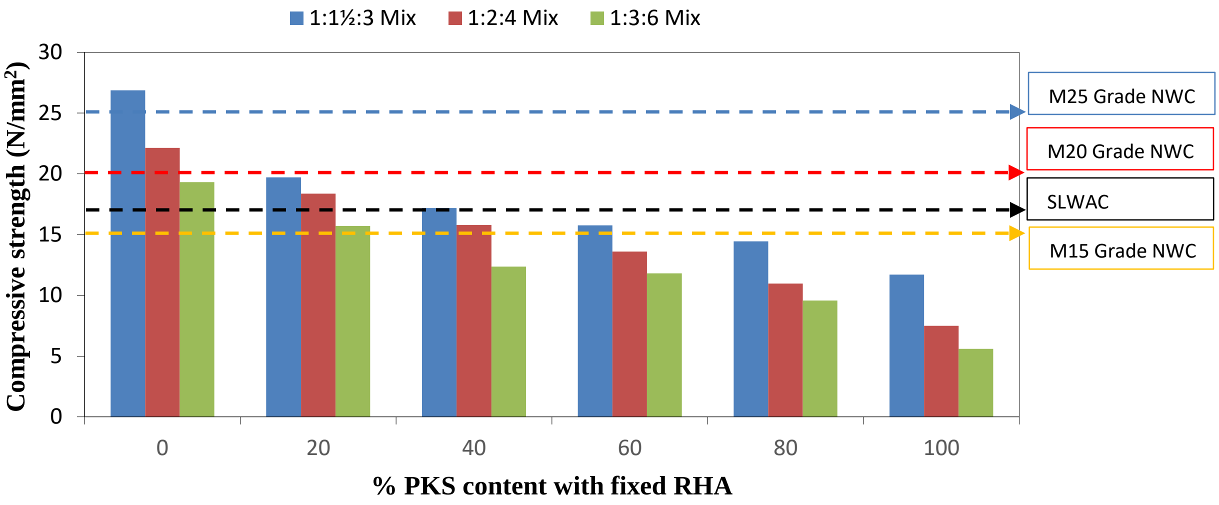

Figure 5. Compressive strength of RHA-blended PKSC at age of 28 days

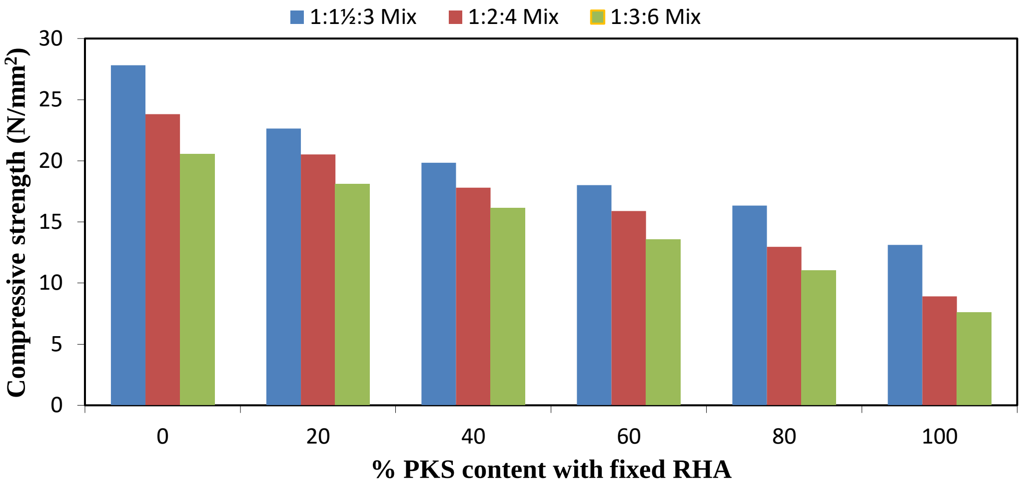

Figure 6. Compressive strength of RHA-blended PKSC at age of 56 days

The results at 56 days as presented in Figure 6 indicated that the compressive strength of RHA-blended PKSC were still lower than the control. With 1:1½:3, 1:2:4, and 1:3:6 mix ratios, the gain in compressive strength at 56 days compared to the 28-day strength for control were 4%, 7%, and 6%, respectively, while it ranged between 11-13%, 10-16%, and 13-15% for RHA-blended PKSC with the corresponding mix ratios. Although the RHA-blended PKSC had a lower compressive strength than the control, it had a slightly higher percentage of strength gain, indicating that RHA's pozzolanic effect had begun. According to Chao-Lung *et al*. (2011), the pozzolanic reaction begins after 28 days, reducing the amount of calcium hydroxide and improving densification, resulting in increased compressive strength at a later age.

At 90 days, the compressive strength of concrete continued to improve with significant strength gain compared to 56 days as illustrated in Figure 7. The gain in compressive strength from 28 to 90 days for control was 7%, 13%, and 16% for control with 1:1½:3, 1:2:4, and 1:3:6 mix ratios, respectively, while it ranged from 18-24%, 15-23%, and 18-27% for RHA-blended PKSC with the respective mix ratios. The continued pozzolanic action of concrete containing RHA was proven by the increase in the strength development of RHA-blended PKSC. In conventional concrete using RHA as a partial replacement for cement, Chao-Lung *et al*. (2011) achieved equivalent results. This suggests that as the curing progresses, the rate of strength development will accelerate. The increase in strength gain discovered for RHA-blended

PKSC compared to those without RHA was attributable to the higher C-S-H gel formed due to the pozzolanic action of RHA, which enhanced particle packing and hence improved the microstructure of PKSC. It was also noted that at 90 days, the RHA-blended PKSC containing 20% PKS had the closest compressive strengths than those with higher PKS substitutions. The compressive strengths were 24.08 N/mm^2, 21.49 N/mm^2, and 19.06 N/mm^2 for 1:1½:3, 1:2:4, and 1:3:6 mix ratios and correspond to 83%, 84% and 83% of the control of the respective mix ratios at 90 days.

Regarding the influence of mix ratio, the richer concrete mix (1:1½:3) with lower aggregate/cement ratio displayed higher compressive strength, followed by 1:2:4 and then 1:3:6 mix ratios. This demonstrates that the concrete mix ratio has a considerable influence on the strength of the concrete. The void content of the concrete mix is intended to decrease as the aggregate content drops, while the level of compactness improves. As a result, fine cement particles fill up the spaces in the aggregate, improving the physical packing of the aggregate and producing more C-S-H, which enhances the compressive strength of concrete (Braga *et al.*, 2014; Kareem *et al.*, 2021).

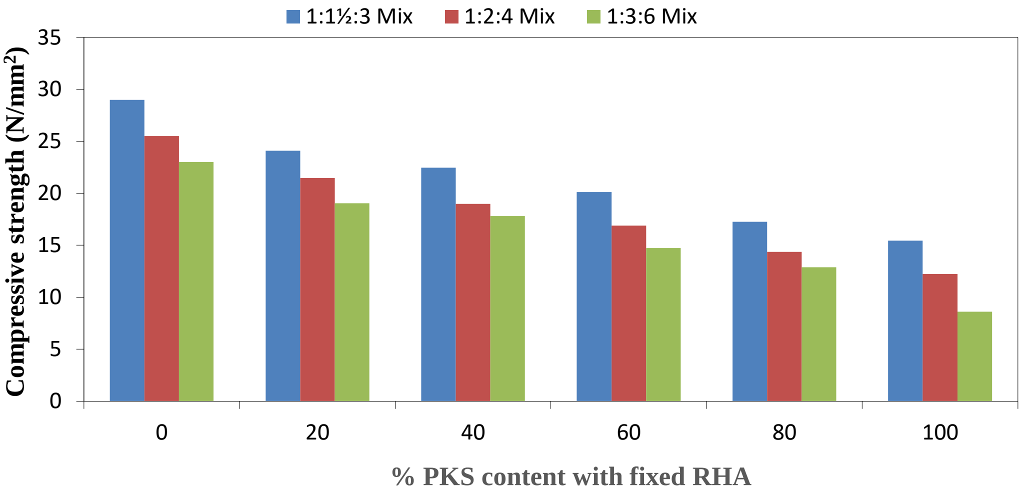

Figure 7. Compressive strength of RHA-blended PKSC at age of 90 days

Conclusion

The following conclusions were drawn based on the study's findings.

(i) RHA is suitable for use as mineral admixture in concrete as the addition of SiO_2, Al_2O_3 and Fe_2O_3 contents present in it was above 70%

(ii) The specific gravity and bulk density of PKS were lesser than that of crushed granite. Hence, it is suitability for lightweight aggregate concrete production.

(iii) For all mix ratios, the workability of fresh concrete decreased as the PKS substitution level increased.

(iv) RHA-blended PKSC had lower density than the control for all the mix ratios. Thus, the combination of RHA and PKS is suitable for producing lightweight concrete.

(v) The compressive strength of concrete declined as the percentage of PKS increased but increased as the curing age increases and also exhibited higher gain in strength than the control at the later age. The concrete containing 15% RHA and 20% PKS as partial substitutes for cement and crushed granite achieved the highest 90-day compressive strength, which was the closest to the control.

(vi) The concrete containing 15% RHA as substitute for cement with up to 40% or 20% as partial replacement for crushed granite for 1:1½:3 or 1:2:4 mix ratio is suitable for the production of SLWAC.

(vii) It is possible to improve the strength qualities of PKSC using 15% RHA as a substitute for cement.

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