



FLEXURAL STRENGTH OF CONCRETE CONTAINING RICE HUSK ASH WITH A CONSTANT 2% PALM KERNEL SHELL ASH AS PARTIAL CEMENT REPLACEMENT

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ABSTRACT

Flexural strength governs the performance of concrete pavements and slabs, yet the combined effect of rice husk ash (RHA) and palm kernel shell ash (PKSA) on it has received little attention. This study evaluated the workability and flexural strength of concrete in which Ordinary Portland Cement (OPC) was partially replaced by 5%, 10%, 15% and 20% RHA with a constant 2% PKSA, relative to a plain OPC control. Thirty 100 mm × 100 mm × 500 mm beams (nominal 1:2:4 mix, water–binder ratio 0.50) were water-cured and tested in centre-point flexure to BS EN 12390-5 at 7, 14 and 28 days. Slump decreased from 70 mm for the control to 60 mm at 20% RHA, but all mixes remained within the S2 consistence class. At 7 days, all blended mixes were weaker than the control. At 28 days, the mix with 5% RHA and 2% PKSA gave the highest flexural strength, 43.3% above the control; 15% and 20% RHA gave increases of 0.6% and 14.0%, whereas 10% RHA reduced the strength by 18.5%. The measured 28-day strengths (6.1–10.8 N/mm²) were 1.7–3.9 times the Eurocode 2 estimates derived from companion cubes from the same batches, so their absolute values need confirmation; the conclusions therefore rest on changes relative to the control, which depend only on failure-load ratios. A blend of 5% RHA and 2% PKSA was the most favourable of the levels studied, subject to confirmation by a larger test programme.

Keywords: Flexural strength; Modulus of rupture; Palm kernel shell ash; Rice husk ash; Workability

1 INTRODUCTION

Concrete is the most widely used construction material, but its principal binder, Ordinary Portland Cement (OPC), is energy-intensive to produce, and cement manufacture accounts for about 8% of global carbon dioxide (CO₂) emissions [1]. In Nigeria, the rising cost of cement also constrains the delivery of affordable housing and infrastructure. Partial replacement of cement with supplementary cementitious materials (SCMs) derived from agricultural wastes offers a way to reduce both the cost and the carbon footprint of concrete while making use of residues that would otherwise be burnt in the open [2].

Rice husk and palm kernel shell are two such residues that are abundant in Nigeria. When completely incinerated under appropriate conditions, rice husk yields rice husk ash (RHA) containing 90–96% amorphous silica [2], and palm kernel shell yields palm kernel shell ash (PKSA), also referred to as palm kernel ash, which is rich in pozzolanic oxides [3]. Both ashes can react with the calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H), the main strength-giving phase of hardened cement paste [4].

Most studies of these ashes have concentrated on compressive strength [5,6], whereas flexural strength, which governs the performance of beams, slabs and pavements, has received comparatively little attention; the review of Fapohunda et al. [7] identified the bending response of RHA concrete as a gap in knowledge. This paper reports the flexural strength of beams cast from the same concrete batches as the cubes of a companion study of compressive strength [8], in which cement was partially replaced by RHA at 0–20% together with a constant 2% PKSA.

The aim of the study was to evaluate the effect of this combined replacement on the workability and flexural strength of concrete, with specific objectives to:

- Produce concrete beams containing 0%, 5%, 10%, 15% and 20% RHA with 2% PKSA as partial replacements of OPC;
- Evaluate the workability of the fresh concrete;
- Determine the flexural strength (modulus of rupture) at 7, 14 and 28 days; and
- Identify the replacement level that gives the best flexural performance.
- Compressive strength is reported in the companion paper [8], and durability was outside the scope of this study.

2 LITERATURE REVIEW

2.1 Pozzolans and Agricultural Ashes

A pozzolan is a siliceous or siliceous-aluminous material that, in finely divided form and in the presence of moisture, reacts with calcium hydroxide at ordinary temperatures to form compounds with cementitious properties [9]. The secondary reaction converts portlandite into additional C-S-H, refining the pore structure of the paste and the interfacial transition zone between paste and aggregate [4]. Agricultural ashes are attractive SCMs in developing countries, where industrial by-products such as fly ash and slag are scarce or unevenly available [2].

2.2 Rice Husk Ash

Controlled incineration is required to produce a reactive RHA [7], and completely burnt ash contains 90–96% amorphous silica [2]. RHA increases the water demand of concrete [7]. Hasan et al. [10] found that 5–20% RHA reduced the workability of high-strength concrete while increasing its compressive, splitting tensile and flexural strengths by up to 7.16%, 7.03% and 3.82%, respectively, with 10% RHA giving the best performance. In high-strength concrete containing 10% micro silica, Zareei et al. [11] obtained the best strength and durability at about 20% RHA, beyond which strength decreased by about 4.5%. Replacement levels typically range from 10% to 30% by weight of cement, the optimum depending on the ash and the application [12], and Bheel et al. [13] confirmed that RHA can improve the strength of concrete when used as a cementitious material.

2.3 Palm Kernel Shell Ash

PKSA is obtained by burning the hard shells that remain after palm oil extraction. Kilani et al. [3] reported that PKSA contains about 85% pozzolanic oxides, suggested 8–25% palm kernel shell or PKSA for green concrete, and recommended blending it with other highly pozzolanic materials. Using a 1:2:4 mix with a water–cement ratio of 0.5, Olutoge et al. [5] obtained a 28-day compressive strength of 22.8 N/mm² with 10% PKSA, although the PKSA concrete did not exceed the strength of the OPC control. Ikponmwosa et al. [6] found that strength decreased as PKSA replaced 0–50% of the cement, and Babatola [14] reported that PKSA concrete continued to gain strength up to 56 days, immersion curing giving the highest strengths. In flexure, Armah et al. [15] found that the strength of concrete containing 20–60% ground palm kernel shell decreased with the replacement level but increased with curing age.

2.4 Flexural Strength of Concrete

Flexural strength, or modulus of rupture, is the maximum tensile stress at the extreme fibre of a beam at failure; it governs the design of pavements and the cracking of beams and slabs [4]. BS EN 12390-5 determines it on prismatic specimens under two-point or centre-point loading, with the supporting rollers set three times the specimen depth apart [16]. Design codes relate tensile to compressive strength: Eurocode 2 gives the mean axial tensile strength as $f_{ctm} = 0.30f_{ck}^{2/3}$ and the flexural tensile strength as $\max\{(1.6 - h/1000)f_{ctm}; f_{ctm}\}$ [17], whereas ACI 318 gives the modulus of rupture as $0.62\lambda\sqrt{f'_c}$ [18]. For blended agricultural ashes, Sulaiman et al. [19] reported that the flexural strength of

concrete containing a sesame straw ash–RHA blend decreased with ash content but increased with curing age up to 90 days.

2.5 Research Gap

The literature shows that RHA and PKSA are pozzolanic, but most studies used a single ash, reported compressive strength only, or used palm kernel shell as an aggregate rather than as an ash. The effect of varying the RHA content at a fixed low PKSA content on the flexural strength of concrete at different curing ages has not been reported, and this study addresses that gap.

3 MATERIALS AND METHODS

3.1 Materials

The materials and their preparation were the same as in the companion study [8]. Ordinary Portland Cement (CEM I 42.5N) conforming to BS EN 197-1 [20] was obtained from a single batch from a supplier in Bauchi State, Nigeria. Rice husk from a rice processing mill in Bauchi State was cleaned, sun-dried and calcined in a muffle furnace at 600 °C for 4 h, and the resulting ash was cooled and passed through a 75 µm sieve. Palm kernel shells from an oil palm processing plant in Bauchi State were washed with detergent and water, sun-dried and incinerated at 350–750 °C, and the ash was cooled, ground and passed through the same sieve. The fine aggregate, from Sabon Kaura, Bauchi State, was passed through a 4.75 mm sieve in accordance with BS 1377-2 [21], and the coarse aggregate was crushed granite with a nominal maximum size of 20 mm from a quarry in Bauchi State, graded in accordance with BS 812-103.1 [22]. Potable water from the mains supply of Abubakar Tafawa Balewa University (ATBU), Bauchi, was used for mixing and curing. All materials were obtained from single batches and stored under controlled conditions to prevent contamination.

3.2 Mix Proportions

Five mixes were prepared (Table 1). The control (M1) contained OPC only; in M2–M5, 2% of the cement by mass was replaced by PKSA and a further 5%, 10%, 15% or 20% by RHA. A nominal mix of 1:2:4 (binder : sand : granite) by mass with a water–binder ratio of 0.50 was used for all mixes, targeting a characteristic 28-day cube strength of 25 N/mm² (C25). The material quantities per batch are given in Table 2. The beams were cast from the same batches as the cubes of the companion compressive-strength study [8].

Table 1: Mix Designations and Binder Composition

Mix	OPC (%)	RHA (%)	PKSA (%)	Total replacement (%)
M1 (control)	100	0	0	0
M2	93	5	2	7
M3	88	10	2	12
M4	83	15	2	17
M5	78	20	2	22

Table 2: Material Quantities per Batch (kg)

Mix	OPC	RHA	PKSA	Sand	Granite	Water
M1	7.71	0.00	0.00	15.43	30.86	3.86
M2	7.17	0.39	0.15	15.43	30.86	3.86
M3	6.78	0.77	0.15	15.43	30.86	3.86
M4	6.40	1.16	0.15	15.43	30.86	3.86
M5	6.01	1.54	0.15	15.43	30.86	3.86

3.3 Specimen Preparation and Curing

The constituents were weighed on a calibrated electronic balance and mixed in a laboratory drum mixer: the dry materials for 2 min, followed by gradual addition of the water over 1 min and a further 3 min of wet mixing. Prismatic steel moulds of 100 mm × 100 mm × 500 mm conforming to BS EN 12390-1 [23] were cleaned, lightly oiled, filled in two equal layers and compacted on a vibrating table for 20 s per layer in accordance with BS EN 12390-2 [24]. The

specimens were left undisturbed at room temperature for 24 h, demoulded and cured fully immersed in water at ambient temperature until testing. Two beams were cast for each mix and curing age, giving 30 beams in total (5 mixes $\times$ 3 ages $\times$ 2 beams). All test equipment was calibrated before use.

3.4 Test Methods

The slump of each fresh mix was measured immediately after mixing in accordance with BS EN 12350-2 [25]. Flexural strength was determined at 7, 14 and 28 days in accordance with BS EN 12390-5 [16], using the centre-point loading arrangement in a universal testing machine. Each beam was placed centrally on two supporting rollers set 300 mm apart, i.e. three times the specimen depth as required by the standard, and loaded at mid-span at a constant stress rate of 0.05 ± 0.01 N/mm²/s (within the specified 0.04–0.06 N/mm²/s; about 111 N/s for this specimen size and span) until failure. The flexural strength was calculated using Equation (1):

$$f_{cf} = 3Fl / (2d_1d_2^2) \quad (1)$$

where f_{cf} is the flexural strength (N/mm²), F is the maximum load (N), l is the distance between the supporting rollers (mm), and d_1 and d_2 are the lateral dimensions of the specimen (mm) [16]. The result for each mix and age is the mean of two beams, expressed to the nearest 0.1 N/mm² as required by BS EN 12390-5.

4 RESULTS AND DISCUSSION

4.1 Workability

All mixes exhibited a true slump. The slump decreased from 70 mm for the control to 60 mm at 20% RHA, a reduction of 14.3% (Table 3 and Figure 1); M2 and M3 gave the same slump of 67 mm. All mixes remained within the S2 consistence class (50–90 mm) of BS EN 206 [26], so they could be placed and compacted without admixtures. The reduction is consistent with the higher water demand of RHA [7,10], which arises from the fineness and porous particle structure of the ash. Because the beams and the cubes of the companion study were cast from the same batches, these slump results are common to both studies [8].

Table 3: Slump of Fresh Concrete

Mix	RHA (%)	PKSA (%)	Slump (mm)	Change vs control (%)	Class (BS EN 206)
M1	0	0	70	–	S2
M2	5	2	67	–4.3	S2
M3	10	2	67	–4.3	S2
M4	15	2	65	–7.1	S2
M5	20	2	60	–14.3	S2

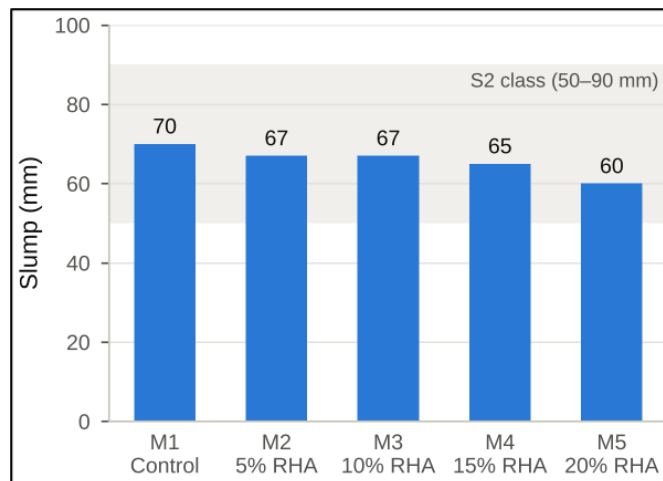


Figure 1: Slump of the fresh concrete mixes (shaded band: S2 consistence class, 50–90 mm)

4.2 Flexural Strength

Table 4 gives the mean maximum loads and flexural strengths, Table 5 the changes relative to the control, and Figure 2 compares the results. At 7 days, the control gave the highest flexural strength (10.0 N/mm^2), and all blended mixes were weaker: by 20.1–23.7% for M3–M5 and by 50.3% for M2 (5.0 N/mm^2). Lower early strength in ash-blended concrete is consistent with the slow pozzolanic reaction of the ashes, whose contribution increases as cement hydration releases more calcium hydroxide [14,19]. At 14 days, M2, M4 and M5 exceeded the control (6.0 N/mm^2) by 8.2%, 10.4% and 25.0%, respectively, while M3 was 1.1% lower. At 28 days, M2 recorded the highest flexural strength of 10.8 N/mm^2 , 43.3% above the control (7.5 N/mm^2), followed by M5 (8.6 N/mm^2 , +14.0%) and M4 (7.6 N/mm^2 , +0.6%), whereas M3 was 18.5% below the control (6.1 N/mm^2).

Table 4: Mean Maximum Load (kN) and Flexural Strength (N/mm^2)

Mix	7 days		14 days		28 days	
	F	f_{cf}	F	f_{cf}	F	f_{cf}
M1	22.15	10.0	13.40	6.0	16.75	7.5
M2	11.00	5.0	14.50	6.5	24.00	10.8
M3	17.70	8.0	13.25	6.0	13.65	6.1
M4	16.90	7.6	14.80	6.7	16.85	7.6
M5	17.60	7.9	16.75	7.5	19.10	8.6

F = mean maximum load of two beams (kN); f_{cf} = flexural strength from Equation (1) to the nearest 0.1 N/mm^2 (BS EN 12390-5). Percentage changes are calculated from unrounded values.

Table 5: Change in Flexural Strength Relative to the Control (%)

Mix	7 days	14 days	28 days
M2	-50.3	+8.2	+43.3
M3	-20.1	-1.1	-18.5
M4	-23.7	+10.4	+0.6
M5	-20.5	+25.0	+14.0

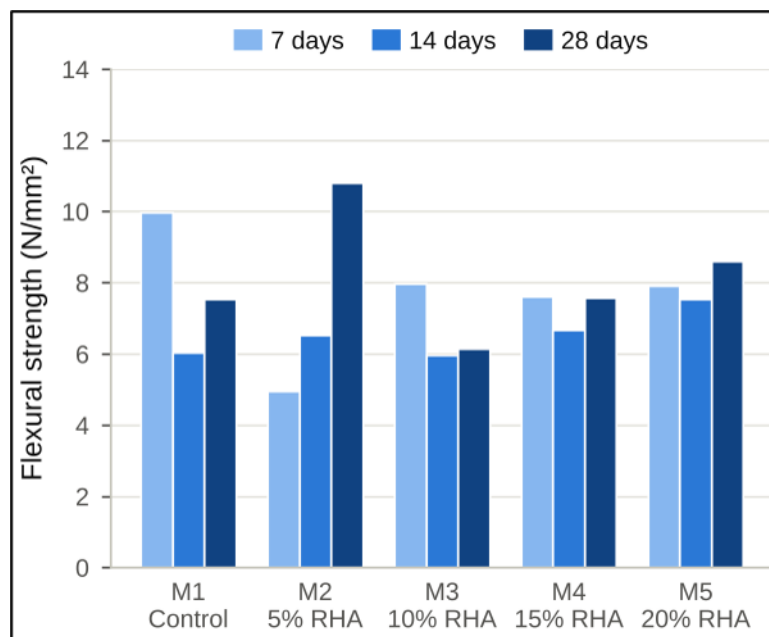


Figure 2: Mean flexural strength of the mixes at 7, 14 and 28 days (two beams per mix and age)

4.3 Strength Development with Curing Age

Figure 3 shows the development of flexural strength with age. Only M2 gained strength continuously, from 5.0 N/mm² at 7 days to 10.8 N/mm² at 28 days (an increase of 118.2%), a pattern of low early and high later strength that is typical of pozzolanic systems. In contrast, the control, M3, M4 and M5 all decreased between 7 and 14 days (by 39.5%, 25.1%, 12.4% and 4.8%, respectively) before increasing again by 28 days; the 28-day strength of the control was 24.4% below its 7-day value. A loss of flexural strength under continuous water curing is not expected from the hydration and pozzolanic mechanisms, so these reversals are attributed to specimen-to-specimen variability, which cannot be averaged out with only two beams per mix and age. The 7-day results in particular should therefore be interpreted with caution.

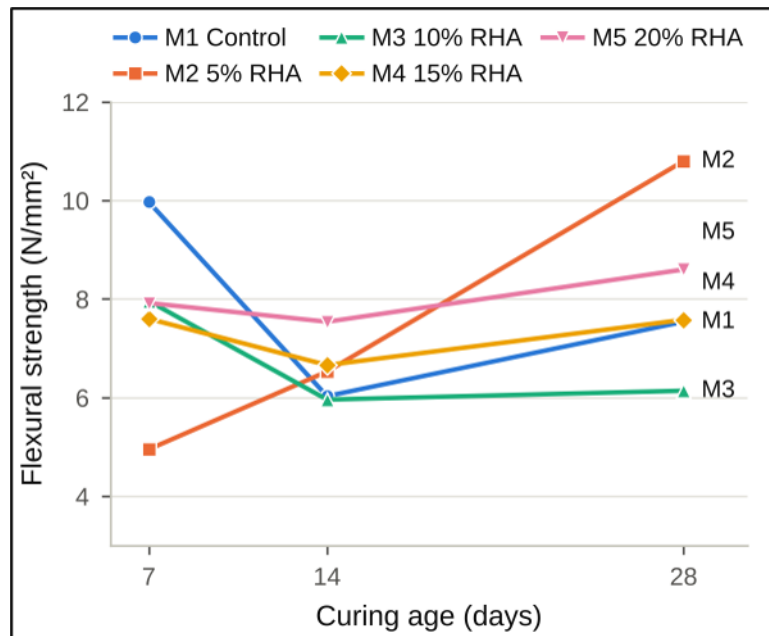


Figure 3: Development of mean flexural strength with curing age for the five mixes

4.4 Effect of RHA Content and Most Favourable Replacement Level

At 28 days, the flexural strength did not vary systematically with RHA content: the ranking was M2 > M5 > M4 > M1 > M3. The highest strength at the lowest RHA content (5%) suggests that a small addition of RHA together with 2% PKSA supplies enough reactive silica to consume calcium hydroxide and densify the paste and the interfacial transition zone without excessively diluting the cement [2,4], while the calcium oxide in PKSA may add mild cementitious activity. However, the low strength of M3 and the higher strength of M5 do not follow a consistent trend, and because only the mean of two beams was available for each mix and age, the statistical significance of the differences could not be assessed. M2 (5% RHA + 2% PKSA) is therefore identified as the most favourable mix among those tested rather than as a definitive optimum.

4.5 Comparison with Eurocode 2

Because the beams and the cubes of the companion study [8] were cast from the same batches, the measured flexural strengths can be checked against the values expected from the measured compressive strengths. Table 6 compares the 28-day results with Eurocode 2 estimates obtained from the companion mean cube strengths f_{cu} , taking the mean cylinder strength f_{cm} as $0.8f_{cu}$, $f_{ck} = f_{cm} - 8$ N/mm², the mean axial tensile strength $f_{ctm} = 0.30f_{ck}^{2/3}$ and the flexural tensile strength $f_{ctm,fl} = (1.6 - h/1000)f_{ctm}$ with $h = 100$ mm [17]. The measured values are higher than expected: they are 1.7–3.9 times the Eurocode 2 estimates of 2.6–3.6 N/mm², and the ACI 318 relationship, with f'_c taken as $0.8f_{cu}$, gives similar estimates of 2.9–3.4 N/mm² [18]. Likewise, the ratio of flexural to compressive strength (0.16–0.37) is well above the ratio of about 0.09 implied by Eurocode 2. Centre-point loading gives somewhat higher moduli of rupture than two-point loading [4], and the effect of specimen size is already included in the Eurocode 2 expression, so neither explains differences of this magnitude. The ranking of the mixes also differs from that for compressive strength, in which M3 was the strongest [8]. The absolute flexural strengths reported here should therefore be treated with caution and confirmed by further testing. The comparisons between mixes are not affected: for beams of the same size tested on the same span, the percentage change relative to the control depends only on the ratio of the failure loads, and the conclusions of this study are based on these relative changes.

Table 6: Measured 28-Day Flexural Strength and Eurocode 2 Estimates

Mix	f_{cu} (N/mm ²)	f_{cf} (N/mm ²)	$f_{ctm,fl}$ EC2 (N/mm ²)	$f_{cf} / f_{ctm,fl}$
M1	33.30	7.5	3.2	2.4
M2	28.99	10.8	2.8	3.9
M3	38.22	6.1	3.6	1.7
M4	32.79	7.6	3.1	2.4
M5	26.95	8.6	2.6	3.4

f_{cu} = mean 28-day cube strength from the companion study [8]; f_{cf} = measured flexural strength (BS EN 12390-5); $f_{ctm,fl}$ = Eurocode 2 (EC2) flexural tensile strength with $f_{ck} = 0.8f_{cu} - 8$ N/mm² and $h = 100$ mm [17]. Ratios are calculated from unrounded values.

4.6 Comparison with Previous Studies

Table 7 compares the present results with related studies. The 43.3% increase in 28-day flexural strength obtained with 5% RHA and 2% PKSA is much larger than the maximum gain of 3.82% reported by Hasan et al. [10] for 10% RHA in high-strength concrete, and the most favourable RHA content is lower than those reported by Hasan et al. (10%) and Zareei et al. [11] (about 20%, with 10% micro silica). Studies at higher replacement levels found that flexural strength decreased as the ash content increased: Sulaiman et al. [19] for 10–30% of a sesame straw ash–RHA blend and Armah et al. [15] for 20–60% ground palm kernel shell. The present results agree with these studies in showing that low replacement levels are the most favourable, but the magnitude of the improvement at 5% RHA should be confirmed by a larger test programme.

Table 7: Comparison with Related Studies

Study	Material	Replacement	Flexural result
Present study	RHA + 2% PKSA	5–20% RHA	+43.3% at 5% RHA (28 days)
Hasan et al. [10]	RHA, high-strength concrete	5–20%	Up to +3.82%; 10% best
Zareei et al. [11]	RHA + 10% micro silica	5–25%	Best strength at about 20%
Sulaiman et al. [19]	Sesame straw ash–RHA blend	10–30%	Decreased with ash content
Armah et al. [15]	Ground palm kernel shell	20–60%	Decreased with replacement

5 CONCLUSION

Partial replacement of cement by 5–20% RHA with a constant 2% PKSA reduced the slump of concrete from 70 mm to 60 mm, but all mixes remained within the S2 consistence class and were workable without admixtures. At 7 days, all blended mixes had lower flexural strength than the control. At 28 days, the mix with 5% RHA and 2% PKSA (M2) had the highest flexural strength, 43.3% above the control; the mixes with 20% and 15% RHA were 14.0% and 0.6% above the control, and the mix with 10% RHA was 18.5% below it. Only M2 gained strength continuously with age. The measured flexural strengths were 1.7–3.9 times the Eurocode 2 estimates, so their absolute values need to be confirmed, but the comparisons between mixes, which depend only on the ratios of the failure loads, are not affected. Low-level combined replacement of cement by RHA and PKSA can therefore maintain or improve the flexural strength of concrete while reducing its OPC content, with 5% RHA and 2% PKSA the most favourable of the levels studied.

Recommendations

Based on the findings, the following are recommended:

- A blend of 5% RHA and 2% PKSA should be considered for trial use where flexural strength is important, such as in pavements and slabs, once the results have been confirmed by a larger test programme.
- Rice husk and palm kernel shells should be burnt under controlled conditions (the RHA used here was calcined at 600 °C) and the ashes passed through a 75 µm sieve before use, since poorly burnt or coarse ash contributes little to strength.
- Further work should confirm the absolute flexural strengths by repeat tests, checking the loading arrangement and specimen dimensions against BS EN 12390-5; test at least three beams per mix and age with statistical analysis; extend testing to 90 and 180 days; characterise the ashes by X-ray fluorescence, X-ray diffraction and scanning electron microscopy; vary the PKSA content; and evaluate durability and life-cycle cost.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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