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COMBINED RICE HUSK ASH–FLY ASH AS A SUPPLEMENTARY CEMENTITIOUS BINDER IN CONCRETE: INFLUENCE OF BLENDING RATIO ON WORKABILITY, COMPRESSIVE AND FLEXURAL STRENGTH DEVELOPMENT UP TO 90 DAYS

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Abstract
This study investigated the performance of concrete incorporating combined rice husk ash (RHA) and fly ash (FA) at different blending ratios. Three mixtures were prepared at a constant total cement replacement level of 10%: RF1 (5% RHA + 5% FA), RF2 (3.33% RHA + 6.67% FA), and RF3 (2.50% RHA + 7.50% FA), corresponding to RHA:FA blending ratios of 1:1, 1:2, and 1:3, respectively. A concrete mix ratio of 1:2:4 and a water-to-cementitious-material ratio of 0.57 were used. Workability, compressive strength, and flexural strength were evaluated at 7, 14, 21, 28, 60, and 90 days. X-ray fluorescence analysis showed that the SiO_2 contents of RHA and FA were 72.81% and 56.64%, respectively, while FA contained higher proportions of Al_2O_3 and Fe_2O_3. Slump increased from 136 mm for RF1 to 149 mm for RF3. Both compressive and flexural strengths increased with curing age. At 90 days, compressive strengths were 31.20, 31.60, and 30.70 MPa for RF1, RF2, and RF3, respectively, while flexural strengths were 3.47, 3.49, and 3.44 MPa. Two-way analysis of variance at a significance level of 0.05 indicated significant effects of mixture proportion, curing age, and their interaction on compressive strength ($p = 0.0047$, $p < 0.001$, and $p = 0.0301$, respectively). For flexural strength, curing age had a significant effect ($p < 0.001$), whereas the effects of mixture proportion ($p = 0.474$) and its interaction with curing age ($p = 0.991$) were not statistically significant. RF2 recorded the highest observed 90-day mean compressive and flexural strengths, although a statistically significant flexural-strength advantage over the other mixtures was not established. These findings provide a comparative assessment of the tested RHA–FA blending ratios and their influence on concrete workability and strength development under the experimental conditions investigated.
Keywords: Rice husk ash; fly ash; blended concrete; compressive strength; flexural strength.

1.0 Introduction

The decarbonization of cement-based construction increasingly requires reductions in clinker consumption without compromising the engineering performance of concrete. Supplementary cementitious materials (SCMs) offer a practical approach to achieving this objective because they can partially replace cement and, depending on their characteristics, contribute to concrete performance. The use of agricultural and industrial by-products as SCMs has consequently attracted attention as a means of reducing cement demand while creating beneficial uses for waste-derived materials.

Rice husk ash (RHA), an agricultural residue-derived material, can contain substantial amounts of silica, although its properties and performance depend on factors such as combustion conditions, fineness, silica structure, and mixture proportion. Properly processed RHA has been associated with later-age strength development, while its porous structure and high surface area may influence the water demand and workability of fresh concrete (Siddika et al., 2021; Li et al., 2021). Fly ash (FA), a coal-combustion by-product, has different physical and chemical characteristics that may improve workability in some mixtures but delay early-age strength development, depending on its source and replacement level (Amran et al., 2021). Combining RHA and FA may therefore offer complementary performance characteristics; however, the resulting behaviour depends on the properties of the individual ashes, their relative proportions, the total cement replacement level, and the curing period.

Although previous studies have investigated RHA and FA in concrete, further comparative evidence is needed to establish how different RHA-to-FA (RHA:FA) blending ratios perform when the total cement replacement level is held constant and fresh and hardened concrete properties are assessed together over an extended curing period. The present study addresses this gap by comparing three RHA:FA blending ratios of 1:1, 1:2, and 1:3 at a constant total cement replacement level of 10%. Its contribution lies in evaluating the influence of these selected blending ratios on slump, compressive strength, and flexural strength at six curing ages (7, 14, 21, 28, 60, and 90 days), together with an exploratory statistical assessment of the effects of mixture proportion, curing age, and their interaction. Specifically, the study aims to: (i) characterize the major oxide composition of the RHA and FA used; (ii) determine the effect of RHA blending ratio on concrete slump; (iii) evaluate compressive and flexural strength

development up to 90 days; and (iv) examine the statistical significance of mixture proportion, curing age, and their interaction. The findings provide comparative evidence for the mixtures and experimental conditions investigated, rather than establishing a universally optimal blending ratio. Because only two specimens were tested for each mixture–age combination, both from the same batch, the statistical results are interpreted cautiously. Hydration kinetics and microstructural changes were not directly measured and are therefore not claimed as experimentally established mechanisms.

2.0 Materials and methods

2.1 Materials and Preparation

Portland limestone cement (PLC), grade 42.5N, manufactured by BUA Cement Plc, was used as the primary binder. The cement was obtained from an authorized distributor at Awka Market, Anambra State, and stored under dry conditions before use. The cement was reported as conforming to BS EN 197-1.

Natural river sand was used as the fine aggregate. The sand was obtained from a local supplier in Awka, Anambra State. It was visually inspected and found to be free from excessive organic matter, clay, silt and other deleterious materials. Prior to use, the sand was air-dried and prepared for laboratory testing and concrete production.

Crushed granite with a nominal maximum size of 20 mm was used as the coarse aggregate. The aggregate was obtained from a quarry in Awka, Anambra State. It was clean, hard, durable and substantially free from dust and other harmful impurities. The aggregate was prepared before use and subjected to the relevant physical-property tests.

Rice husks were obtained from a local rice-milling facility in Anambra State. The husks were manually inspected to remove foreign materials and other visible contaminants and were subsequently air-dried under ambient laboratory conditions. The dried husks were combusted in a locally fabricated perforated steel-mesh basket burner until a greyish ash was obtained. After cooling to room temperature, the ash was passed through a 75 μm British Standard sieve to remove coarse particles and unburnt residues. The processed rice husk ash (RHA) was stored in airtight polyethylene bags until characterization and use.

Fly ash (FA) was obtained from Oji River Thermal Power Station, Enugu State, Nigeria. The material was air-dried in the laboratory and passed through a 45 μm sieve to remove coarse particles and promote uniformity. The processed fly ash was stored in sealed containers until required for characterization and concrete production.

Clean potable water obtained from the Civil Engineering Laboratory of Nnamdi Azikiwe University, Awka, was used for concrete mixing and curing. The same water source was maintained throughout the experimental programme to promote consistency.

2.2 Mix Proportions

A nominal concrete mix proportion of 1:2:4, representing cementitious material: fine aggregate: coarse aggregate, was adopted. The water-to-cementitious-material ratio was maintained at 0.57 for all mixtures. The total replacement of Portland limestone cement (PLC) by supplementary cementitious materials (SCMs) was fixed at 10% by mass of the cementitious binder.

Three combined RHA–FA mixtures were investigated based on RHA blending ratios of 1:1, 1:2 and 1:3. These were designated RF1, RF2 and RF3, respectively. RF1 contained 5.00% RHA and 5.00% FA, RF2 contained 3.33% RHA and 6.67% FA, while RF3 contained 2.50% RHA and 7.50% FA. Thus, the total SCM content remained constant at 10% for all three mixtures, while the relative proportions of RHA and FA varied.

All constituent materials were batched by mass. For each batch, the fine aggregate, coarse aggregate and mixing water were maintained at 4.700 kg, 9.420 kg and 1.340 kg, respectively. The quantity of PLC was 2.124 kg for each combined mixture, while the quantities of RHA and FA were adjusted according to the selected blending ratio. The corresponding batch quantities are presented in Table 1.

Table 1. Combined RHA–FA mixture proportions used in the present study.

MIX ID	Total SCM (%)	RHA: FA Ratio	PLC (kg)	RHA (kg)	FA (Kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Water (kg)
RF1	10	1:1	2.124	0.118	0.118	4.700	9.420	1.340
RF2	10	1:2	2.124	0.079	0.157	4.700	9.420	1.340
RF3	10	1:3	2.124	0.059	0.177	4.700	9.420	1.340

The constituent materials were measured using a calibrated digital weighing balance. The same batching procedure was applied to all mixtures to maintain consistency in material proportions during concrete production.

2.3 Concrete Mixing, Casting and Curing

Concrete mixing was carried out manually on a clean, non-absorbent platform. For each mixture, the required quantities of PLC, RHA, FA, fine aggregate and coarse aggregate were measured separately by mass. The dry constituents were first thoroughly mixed until a uniform distribution was obtained. The measured quantity of water was then added gradually while mixing continued until a homogeneous and workable concrete mixture was produced. Separate batches were prepared for each mixture to minimize cross-contamination, and the same mixing sequence was maintained throughout the experimental programme.

Fresh concrete was placed into clean and lightly oiled moulds immediately after mixing. Two types of specimens were produced: 150 mm × 150 mm × 150 mm concrete cubes for compressive strength testing and 100 mm × 100 mm × 500 mm beams for flexural strength testing. The concrete was placed into the moulds in layers and adequately compacted to minimize entrapped air and promote uniformity. The exposed surfaces were levelled and finished after casting.

The moulded specimens were covered to minimize rapid moisture loss and maintained under laboratory conditions for approximately 24 hours before demoulding. After demoulding, the specimens were transferred to the curing tank and completely immersed in clean potable water. The curing water was maintained under laboratory conditions and replaced periodically to minimize contamination.

The curing ages considered were 7, 14, 21, 28, 60 and 90 days. At each designated testing age, the required specimens were removed from the curing tank, allowed to drain briefly and surface-dried before testing. For each mixture and curing age, two replicate cube specimens were used for compressive strength determination and two replicate beam specimens were used for flexural strength determination.

2.4 Testing Procedures

2.4.1 Slump Test

The workability of the fresh concrete mixtures was determined using the slump test in accordance with BS EN 12350-2:2019. The slump cone was placed on a rigid, non-absorbent surface and filled with fresh concrete in three approximately equal layers. Each layer was compacted using 25 strokes of a standard tamping rod. After the top layer had been levelled, the cone was carefully lifted vertically, allowing the concrete to subside freely. The vertical difference between the original height of the cone and the highest point of the slumped concrete was measured and recorded as the slump value in millimetres (mm). The test was conducted immediately after mixing and before casting the specimens.

2.4.2 Compressive Strength Test

Compressive strength was determined using 150 mm × 150 mm × 150 mm concrete cube specimens in accordance with BS EN 12390-3. At each curing age of 7, 14, 21, 28, 60 and 90 days, the specimens were removed from the curing tank and tested using a compression testing machine. Each cube was positioned centrally in the machine and loaded until failure, and the maximum failure load was recorded.

The compressive strength was calculated using:

$$f^c = {}^{P}/_{A} \qquad (1)$$

where:

(f^c) = compressive strength (MPa);

(P) = maximum failure load (N); and

(A) = loaded cross-sectional area (mm^2).

The replicate observations were retained for calculating the mean and standard deviation and for subsequent statistical analysis.

2.4.3 Flexural Strength Test

Flexural strength was determined using 100 mm × 100 mm × 500 mm beam specimens in accordance with ASTM C78/C78M-22. The test was conducted using a third-point loading arrangement, in which each beam was supported on two rollers and loaded through two equally spaced loading points until failure. The maximum failure load was recorded, and the modulus of rupture was calculated from the failure load and specimen dimensions.

For the third-point loading configuration, the flexural strength was calculated as:

$$f_r = \frac{PL}{bd^2} \qquad (2)$$

f_r = flexural strength or modulus of rupture (MPa);
P = maximum applied load at failure (N);
L = span length between the supports (mm);
b = average width of the specimen (mm); and
d = average depth of the specimen (mm).

2.5 Statistical Analysis

The compressive and flexural strength results were summarized using descriptive statistics and reported as mean ± standard deviation (SD) for each mixture and curing age. Two replicate specimens were used for each mixture-age combination.
A two-way analysis of variance (ANOVA) was performed separately for compressive strength and flexural strength to evaluate the effects of mixture proportion and curing age, as well as their interaction. The analysis was based on 36 individual observations for each strength property, comprising three mixtures, six curing ages and two replicate specimens per mixture-age combination.
The statistical model was expressed as:

$$Y_{ijk} = \mu + M_i + A_j + (MA)_{ij} + \varepsilon_{ijk} \quad (3)$$

Where:
Y_{ijk} = observed strength;
μ = overall mean;
M_i = effect of mixture type;
A_j = effect of curing age;
$(MA)_{ij}$ = mixture-by-age interaction effect; and
ε_{ijk} = random error term.

Statistical significance was assessed at a significance level of (α =0.05). Therefore, effects with ($p<0.05$) were considered statistically significant. Partial eta-squared (ηp^2) was reported as a measure of effect size. Because only two replicate specimens were available for each mixture-age combination, the statistical findings were interpreted within the experimental range of the study and were not treated as generalized estimates for all possible RHA and FA sources or processing conditions.

3.0 Results and Discussion

3.1 Oxide Composition

The major oxide compositions of the rice husk ash (RHA) and fly ash (FA) used in the study are presented in Table 2. The results show clear differences in the chemical composition of the two supplementary cementitious materials. RHA contained a higher SiO_2 content of 72.81%, compared with 56.64% for FA. In contrast, FA contained higher Al_2O_3 and Fe_2O_3 contents, with values of 22.52% and 8.58%, respectively, compared with 9.41% and 3.50% in RHA.
The combined SiO_2 + Al_2O_3 + Fe_2O_3 contents were 85.72% for RHA and 87.74% for FA. RHA also recorded higher K_2O and CaO contents, whereas FA contained a higher TiO_2 content. These differences indicate that the two ashes had distinct chemical characteristics, which are relevant when considering their combined use as supplementary cementitious materials.
However, the oxide composition alone does not establish the mechanism responsible for strength development, since other characteristics such as fineness, particle morphology and processing history can also affect the performance of RHA and FA. Therefore, the oxide results in this study are interpreted as a characterization of the specific materials used rather than as universal compositions of RHA or FA.

Table 2. Major oxide composition of the RHA and FA used in the study.

Oxide	RHA (%)	FA (%)
SiO_2	72.81	56.64
Al_2O_3	9.41	22.52
Fe_2O_3	3.50	8.58
CaO	2.46	1.40
MgO	1.96	0.00
K_2O	5.34	0.38
SO_3	1.20	0.23
TiO_2	1.43	4.47
SiO_2 + Al_2O_3 + Fe_2O_3	85.72	87.74

3.2 Workability

The slump values obtained for the combined RHA–FA concrete mixtures are presented in Table 3. The results show that slump increased progressively with increasing fly ash proportion in the blended supplementary cementitious material. RF1, with an RHA:FA ratio of 1:1, recorded a slump of 136 mm, while RF2 (1:2) and RF3 (1:3) recorded 143 mm and 149 mm, respectively.

Thus, at the constant total cement replacement level of 10%, increasing the FA fraction from the 1:1 to the 1:3 blending ratio resulted in a 13 mm increase in slump. This indicates that the blending ratio affected the workability of the fresh concrete under the conditions of the present study.

The increase in slump with increasing FA proportion may be associated with differences in the physical characteristics of RHA and FA, including particle morphology and water-demand behavior. However, the present experimental results do not establish a specific mechanism for the observed trend. The result therefore indicates that the proportion of RHA and FA should be considered when proportioning blended RHA–FA concrete.

Table 3. Slump values of the combined RHA–FA concrete mixtures.

Mixture	RHA: FA	Slump (mm)
RF1 (1:1)	1:1	136
RF2 (1:2)	1:2	143
RF3 (1:3)	1:3	149

3.3 Compressive Strength Development

The compressive strength results for the combined RHA–FA concrete mixtures are presented in Table 4 and Figure 1. All three mixtures showed a progressive increase in compressive strength with curing age. RF1 increased from 15.70 MPa at 7 days to 31.20 MPa at 90 days, while RF2 increased from 14.80 MPa to 31.60 MPa and RF3 increased from 15.30 MPa to 30.70 MPa over the same period.

At 28 days, the compressive strengths were closely grouped, with values of 23.75 MPa, 23.90 MPa and 23.65 MPa for RF1, RF2 and RF3, respectively. At 60 days, the corresponding values increased to 28.70 MPa, 28.90 MPa and 28.20 MPa. By 90 days, RF2 recorded the highest compressive strength of 31.60 MPa, followed by RF1 at 31.20 MPa and RF3 at 30.70 MPa.

The results therefore show that curing age had a substantial effect on compressive strength, while the differences among the three blending ratios were relatively small at most ages. The greater separation observed at 60 and 90 days indicates that the influence of the RHA blending ratio became more apparent at later curing ages.

The continued strength development after 28 days is consistent with later-age strength development discussed in reviews of rice husk ash in cement-based materials and fly-ash-based concrete (Siddika et al., 2021; Li et al., 2021; Amran et al., 2021; Li et al., 2022). However, the present experimental results do not provide direct evidence of the specific hydration or pozzolanic mechanisms responsible for the observed increase.

Table 4. Mean ± standard deviation of compressive strength of the combined RHA–FA mixtures.

Age (days)	RF1 (1:1)	RF2 (1:2)	RF3 (1:3)
7	15.70 ± 0.28	14.80 ± 0.28	15.30 ± 0.28
14	19.80 ± 0.28	19.20 ± 0.28	19.40 ± 0.28
21	22.70 ± 0.28	22.31 ± 0.28	22.13 ± 0.28
28	23.75 ± 0.21	23.90 ± 0.14	23.65 ± 0.21
60	28.70 ± 0.28	28.90 ± 0.28	28.20 ± 0.28
90	31.20 ± 0.28	31.60 ± 0.28	30.70 ± 0.14

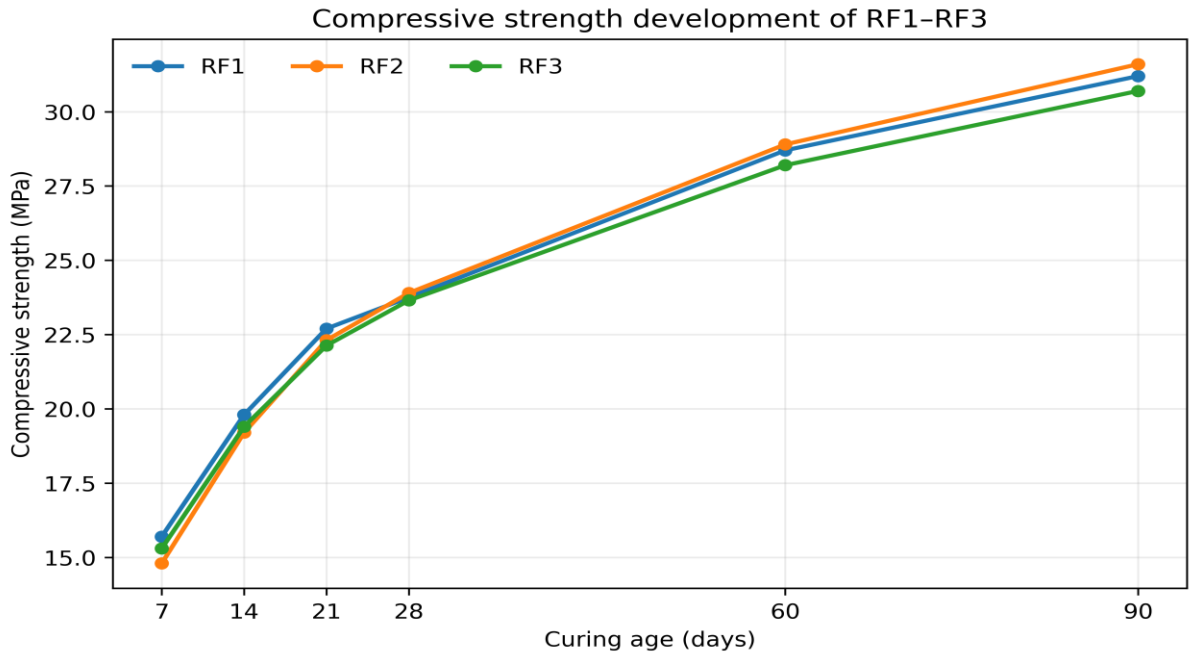


Figure 1. Compressive strength development of RF1–RF3 with curing age.

The strong increase after 28 days is compatible with the observation that blended cement systems containing supplementary cementitious materials may continue developing strength beyond the conventional 28-day reference age. Reviews of RHA discuss its contribution to the properties of cement-based materials, including later-age performance (Siddika et al., 2021; Li et al., 2021). Research and reviews on fly-ash-based concrete describe delayed early-age strength and the potential for later-age improvement, depending on mixture composition and curing conditions (Amran et al., 2021; Li et al., 2022). In the present study, however, the experimental measurements alone do not permit direct attribution of the post-28-day increase to a specific hydration or pozzolanic mechanism.

3.4 Flexural strength development

The flexural strength results of the combined RHA–FA concrete mixtures are presented in Table 5 and Figure 2. All three mixtures showed a progressive increase in flexural strength with curing age. RF1 increased from 2.46 MPa at 7 days to 3.47 MPa at 90 days, while RF2 increased from 2.39 MPa to 3.49 MPa and RF3 increased from 2.43 MPa to 3.44 MPa over the same curing period.

At 28 days, RF1, RF2 and RF3 recorded flexural strengths of 3.15 MPa, 3.14 MPa and 3.11 MPa, respectively. At 60 days, the values increased to 3.32 MPa, 3.34 MPa and 3.29 MPa. At 90 days, RF2 recorded the highest flexural strength at 3.49 MPa, followed by RF1 at 3.47 MPa and RF3 at 3.44 MPa.

The differences in flexural strength among the three blending ratios were relatively small compared with the overall increase associated with curing age. This indicates that curing age had a more pronounced effect on flexural strength than the variation in RHA blending ratio within the mixtures investigated.

The observed increase in flexural strength with curing age is consistent with the overall strength-development pattern observed in the compressive strength results. However, the present experimental results do not establish a specific hydration or pozzolanic mechanism responsible for the increase.

Table 5. Mean ± standard deviation of flexural strength of the combined RHA–FA mixtures.

Age (days)	RF1 (1:1)	RF2 (1:2)	RF3 (1:3)
7	2.46 ± 0.04	2.39 ± 0.07	2.43 ± 0.07
14	2.76 ± 0.06	2.72 ± 0.07	2.73 ± 0.07
21	2.96 ± 0.06	2.93 ± 0.07	2.92 ± 0.07
28	3.15 ± 0.06	3.14 ± 0.06	3.11 ± 0.06
60	3.32 ± 0.06	3.34 ± 0.07	3.29 ± 0.07
90	3.47 ± 0.05	3.49 ± 0.07	3.44 ± 0.07

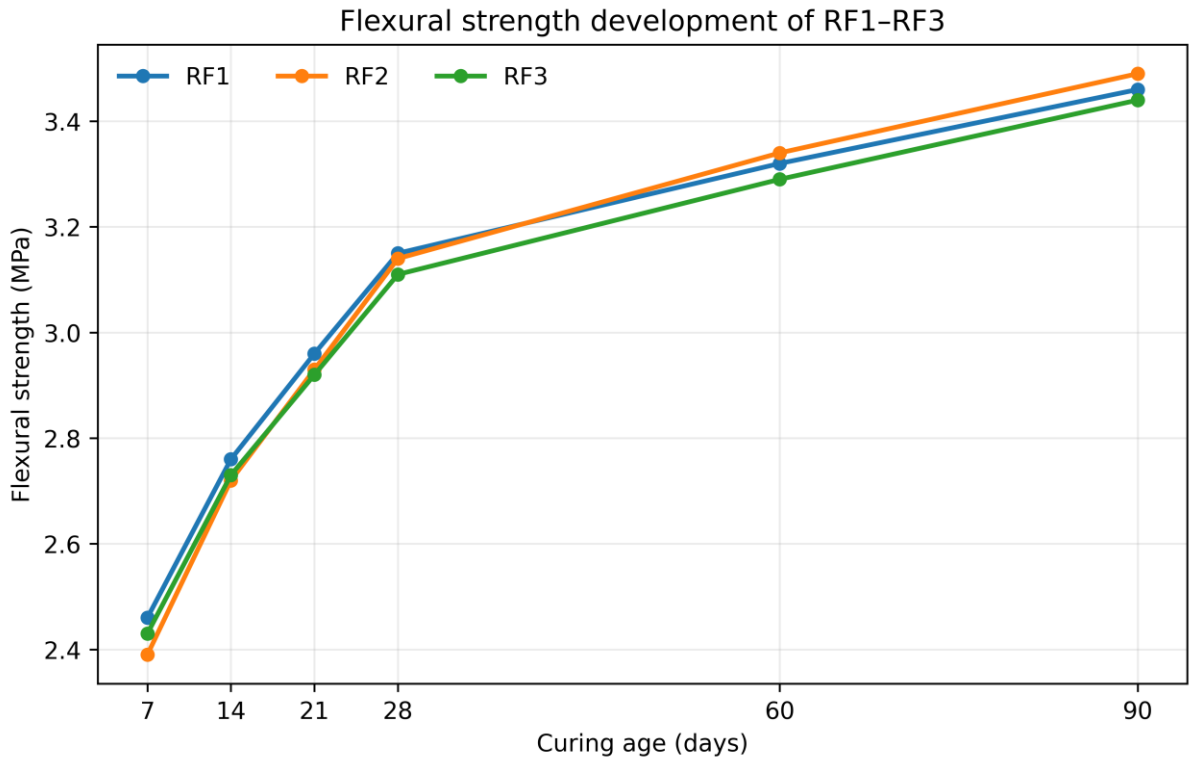


Figure 2. Flexural strength development of RF1–RF3 with curing age.

3.5 Two-way ANOVA

The two-way ANOVA was performed using the 36 individual observations generated from three mixtures, six curing ages and two replicate specimens per mixture-age combination. The analysis evaluated the effects of mixture proportion, curing age and their interaction on compressive and flexural strength at a significance level of $\alpha = 0.05$.

For compressive strength, two-way analysis of variance showed statistically significant effects of mixture proportion, $F(2, 18) = 7.336$, $p = 0.0047$, $\eta p^2 = 0.449$, and curing age, $F(5, 18) = 2940.158$, $p < 0.001$, $\eta p^2 = 0.999$. The interaction between mixture proportion and curing age was also statistically significant, $F(10, 18) = 2.742$, $p = 0.0301$, $\eta p^2 = 0.604$.

Table 6. Two-way ANOVA for compressive strength of RF1–RF3.

Source	SS	df	MS	F	p-value	ηp² / decision
Mixture	1.0188	2	0.5094	7.336	0.0047	0.449; significant
Curing age	1020.8882	5	204.1776	2940.158	<0.001	0.999; significant
Mixture × age	1.9041	10	0.1904	2.742	0.0301	0.604; significant
Error	1.2500	18	0.0694	—	—	—
Total	1025.0612	35	—	—	—	—

For flexural strength, the effect of mixture proportion was not statistically significant, $F(2, 18) = 0.778$, $p = 0.474$, $\eta p^2 = 0.080$. Curing age had a statistically significant effect, $F(5, 18) = 216.532$, $p < 0.001$, $\eta p^2 = 0.984$, whereas the interaction between mixture proportion and curing age was not statistically significant, $F(10, 18) = 0.216$, $p = 0.991$, $\eta p^2 = 0.107$.

Table 7. Two-way ANOVA for flexural strength of RF1–RF3.

Source	SS	df	MS	F	p-value	ηp² / decision
Mixture	0.00635	2	0.00318	0.778	0.4741	0.080; not significant
Curing age	4.41786	5	0.88357	216.532	<0.001	0.984; significant
Mixture × age	0.00882	10	0.00088	0.216	0.9913	0.107; not significant
Error	0.07345	18	0.00408	—	—	—
Total	4.50648	35	—	—	—	—

The ANOVA results should be interpreted cautiously because only two specimens were tested for each mixture–age combination, and both specimens were obtained from the same concrete batch. Consequently, the analysis captures specimen-level variation within the tested batches but does not account for independent batch-to-batch variability. The statistically significant mixture and mixture-by-age effects observed for compressive strength

should therefore be regarded as exploratory findings rather than definitive evidence of reproducible differences across concrete batches. For flexural strength, the analysis did not identify statistically significant effects of mixture proportion or the mixture-by-age interaction. Further investigations using independently prepared batches and increased replication are required to assess the reproducibility and generalizability of these findings.

3.6 Integrated discussion

Taken together, the results indicate that the effects associated with the RHA–FA blending ratio differed by measured property. The increase in slump as the FA proportion increased suggests that the relative proportions of the two ashes influenced fresh-concrete workability under the fixed water-to-cementitious-material ratio of 0.57. However, the oxide results characterize only the specific ashes used and cannot, by themselves, explain the slump trend. Particle-size distribution, morphology, specific surface area and water demand may also be relevant, but these factors were not comprehensively measured in this study. Reviews of RHA and fly-ash-based concrete likewise emphasize that material source, processing and mixture conditions affect performance (Li et al., 2021; Siddika et al., 2021; Amran et al., 2021).

For compressive strength, the reported ANOVA identified statistically significant effects of mixture proportion, curing age and their interaction. This indicates that the observed compressive-strength pattern varied among the tested mixtures and across curing ages within the present experimental programme. The continued increase in strength with age is consistent with literature describing later-age strength development in concrete containing supplementary cementitious materials (Li et al., 2021; Siddika et al., 2021; Amran et al., 2021; Li et al., 2022). Nevertheless, the measurements in this study do not directly establish the reaction products or mechanisms responsible for that development. RF2 recorded the highest observed 90-day mean compressive strength, but the results should not be interpreted as identifying a universally optimal RHA–FA ratio.

The flexural-strength results require a different interpretation. Although RF2 had the highest observed 90-day mean, the reported ANOVA did not identify a statistically significant effect of mixture proportion or a significant mixture-by-age interaction. The evidence therefore supports describing RF2 as having the highest observed mean, not as being statistically superior in flexural strength. In contrast, curing age had a statistically significant effect on flexural strength, indicating that strength development over time was more clearly supported by the reported analysis than differences among the tested blending ratios.

The practical contribution of this study is a comparison of three RHA–FA blending ratios at a constant total cement replacement level of 10%, providing measured evidence on workability and strength development up to 90 days. The findings may inform further evaluation of these combined by-products as supplementary cementitious materials, but they do not establish durability, field performance or the readiness of a particular mixture for broad implementation. The study did not include direct microstructural or hydration analyses; therefore, explanations involving pore refinement, specific hydration products or changes in the interfacial transition zone cannot be confirmed from the available results.

The statistical findings should also be interpreted cautiously because only two specimens were tested for each mixture–age combination and both came from the same concrete batch. The analysis therefore does not capture independent batch-to-batch variability, and the significant compressive-strength effects should be treated as exploratory rather than definitive evidence of reproducible differences. Further work should use independently prepared batches, increased specimen replication, and direct microstructural and hydration analyses. Additional durability testing would also be needed before drawing conclusions about long-term service performance.

4.0 Conclusion

This study investigated the performance of concrete incorporating combined rice husk ash (RHA) and fly ash (FA) at different blending ratios while maintaining a constant total cement replacement level of 10%. Workability, compressive strength, and flexural strength were evaluated at curing ages of 7, 14, 21, 28, 60, and 90 days.

The results showed that slump increased with increasing FA content, from 136 mm for RF1 (5% RHA and 5% FA) to 143 mm for RF2 (3.33% RHA and 6.67% FA) and 149 mm for RF3 (2.50% RHA and 7.50% FA). At 90 days, RF2 recorded the highest observed compressive strength of 31.60 MPa and flexural strength of 3.49 MPa. These values were slightly higher than those recorded for RF1 and RF3, indicating that the 1:2 RHA-to-FA blending ratio performed favourably among the mixtures investigated.

The principal contribution of this study is its comparative evaluation of three RHA–FA blending ratios at a constant total cement replacement level, providing experimental observations on how the relative proportions of these supplementary cementitious materials relate to concrete workability and strength development. The findings suggest that combined RHA and FA may offer a potential approach to reducing cement consumption while maintaining satisfactory measured performance under the conditions investigated. They may also inform further investigations into the use of these materials in concrete production. However, the results do not establish that the identified blending ratio is universally optimal.

The findings should be interpreted cautiously because only two specimens were tested for each mixture–age combination, and both specimens were obtained from the same batch. Further research should therefore include more independent batches, increased specimen replication, and microstructural and hydration analyses to validate the observed trends and investigate the mechanisms influencing strength development.

5.0 Recommendations

Based on the findings of the study, the following recommendations are made:

1. RHA and FA may be considered for partial replacement of PLC where their chemical and physical properties are adequately characterized and controlled.
2. Combined RHA–FA mixtures should be further investigated at different blending ratios and total replacement levels to identify their performance over a wider range of applications.
3. Adequate curing should be maintained for concrete containing RHA and FA because both compressive and flexural strengths continued to increase beyond 28 days.
4. Quality-control procedures should be established for RHA and FA to minimize variations in chemical composition, fineness and processing characteristics.
5. RHA should be produced under controlled burning and processing conditions to improve consistency in its engineering properties.
6. Further studies should investigate durability properties, long-term strength beyond 90 days and microstructural characteristics of RHA–FA blended concrete.

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Nomenclature

RHA = Rice Husk Ash
FA = Fly ash
SCMs = Supplementary cementitious materials
RF1 = Concrete mixture containing 5% RHA and 5% FA
RF2 = Concrete mixture containing 3.33% RHA and 6.67% FA
RF3 = Concrete mixture containing 2.50% RHA and 7.50% FA
w/b = water-to-cementitious-material ratio
XRF = X-ray fluorescence
SiO_2 = Silicon dioxide
Al_2O_3 = Aluminium oxide
Fe_2O_3 = Iron (III) oxide
MPa = Megapascal
Mm = Millimeter
ANOVA = Analysis of variance

Declaration of Generative AI and AI-assisted technologies in the writing process

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