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Compressive Strength Optimisation of Lateritic Concrete Incorporating Fly Ash and Rice Husk Ash Using a Scheffé Mixture Design

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ABSTRACT

Lateritic concrete blended with industrial and agricultural by-products offers a locally available route to reduce Portland-cement demand in tropical regions. This study investigated the compressive strength, workability and water absorption of lateritic concrete in which ordinary Portland cement was partially replaced by fly ash (FA) and rice husk ash (RHA). Eighty-four mixtures were generated by a Scheffé simplex-lattice design and tested at 28 days. The highest measured mean compressive strength among the blended mixtures was 20.67 MPa (approximately 68 % of the 30.38 MPa control). Balanced FA:RHA proportions near 2:1–3:1 at moderate total cement replacement retained the highest strengths, while mixtures dominated by RHA or containing very high total ash contents exhibited marked strength loss, high slump and reduced density. A third-degree Scheffé polynomial described the response surface with a reported coefficient of determination of 99.4 %; however, the model was nearly saturated (84 model degrees of freedom, 1 residual degree of freedom) and the reported R^2 is not fully reproduced by the published sums of squares. Predicted optimum strengths exceeded the best measured values, underscoring the necessity of independent confirmation mixtures. The results demonstrate that carefully proportioned FA–RHA lateritic concrete can achieve strengths suitable for many non-structural and lightly loaded structural applications while valorising two abundant waste streams. Full mix-design tables, material characterisation and confirmation testing are required before the optimised mixtures can be recommended for routine structural use.

Keywords: lateritic concrete; fly ash; rice husk ash; Scheffé mixture design; compressive strength; supplementary cementitious materials; sustainable construction

INTRODUCTION

Concrete remains one of the principal materials used in civil engineering because of its versatility, strength and broad range of applications. However, conventional concrete production is associated with environmental pressures arising from cement manufacture, consumption of natural resources and disposal of industrial and agricultural residues. The use of supplementary cementitious materials (SCMs) is therefore an important pathway for reducing dependence on Portland cement while improving resource efficiency [1–3].

Lateritic materials are particularly relevant in tropical regions because of their wide availability and potential for partial substitution of conventional concrete constituents. Previous studies have reported that lateritic materials can be incorporated into concrete while maintaining useful mechanical performance when their proportion and material characteristics are appropriately controlled [4–7]. Fly ash and rice husk ash are two SCMs with established potential in cement-based materials.

Fly ash can contribute to later-age strength development through pozzolanic reactions, while rice husk ash, when appropriately processed, provides a silica-rich fine material capable of participating in secondary cementitious reactions [8–10]. Studies on blended cement systems also show that the performance of SCM

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combinations depends strongly on their relative proportions, particle characteristics, curing conditions and total replacement level [11–13].

Despite this body of research, the combined use of laterite, fly ash and rice husk ash presents a mixture-design problem in which mechanical performance must be balanced against workability, density and moisture-related behaviour.

Systematic optimisation of the ternary laterite–FA–RHA combination remains limited. In particular, the interaction between the high-silica, high-water-demand RHA and the more spherical, lower-water-demand FA within a lateritic matrix has not been mapped with a statistically designed mixture experiment. The present work therefore applies a Scheffé simplex-lattice design to 84 lateritic concrete mixtures, measures compressive strength, slump and water absorption, and evaluates a third-degree polynomial response surface.

Research Objectives

The specific objectives of this study are:

- to determine the optimal mix ratios of fly ash and RHA for enhancing the compressive strength of lateritic concrete;
- to analyse the effects of curing time on the strength development of the blended concrete;
- to compare the compressive strength of SCM-blended lateritic concrete with the conventional control mixture; and
- to assess the sustainability implications of using these materials in concrete production within the limits of the experimental evidence.

MATERIALS AND METHODS

Materials

Ordinary Portland cement conforming to ASTM C150 was used as the primary binder. Lateritic soil was obtained from a local borrow pit in the Federal Capital Territory, Nigeria, air-dried and sieved to remove oversized particles. Fly ash was characterised by X-ray fluorescence; the principal oxides were SiO_2 51.98 %, Al_2O_3 11.39 % and Fe_2O_3 15.13 %, placing the material within the compositional range of Class F fly ash according to ASTM C618.

Rice husk ash was produced by controlled combustion of rice husks; the source documents note its high silica content and angular particle morphology but do not report the precise burning temperature, grinding regime or complete oxide analysis. Fine and coarse aggregates satisfied the grading requirements of ASTM C33. Potable water was used for mixing and curing.

Mixture Design

A Scheffé simplex-lattice design was adopted to explore the binder space defined by OPC, FA and RHA while laterite, fine aggregate, coarse aggregate and water were held within prescribed bounds. Eighty-four real-component mixtures were generated. The control mixture (labelled Z1) contained 100 % OPC as the binder. Subsequent mixtures systematically varied the pseudo-component proportions of FA and RHA.

Exact mass proportions for every mixture, the water-to-binder ratio, the precise role of laterite (fine-aggregate replacement versus coarse-aggregate replacement), and the upper and lower bounds of each

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component are summarised in Table 1 for selected representative mixtures. The complete 84-mixture design matrix should be supplied as supplementary material in any archival submission.

Table 1. Selected mixture proportions and pseudo-component distribution (representative mixes from the Scheffé design)

Mix ID	OPC (%)	FA (%)	RHA (%)	Laterite	W/B*	Notes
Z1 (Control)	100	0	0	Baseline	0.50	Reference mix
Z36	~70–75	Balanced	Balanced	Included	~0.50	High measured strength
Z114	~70–75	~2:1 ratio	~2:1 ratio	Included	~0.50	Best measured CS group
Z115	~70–75	~2:1–3:1	~2:1–3:1	Included	~0.50	Best measured CS group
Z116	~70–75	~2:1–3:1	~2:1–3:1	Included	~0.50	Best measured CS group
Z117	~70–75	~2:1–3:1	~2:1–3:1	Included	~0.50	Best measured CS group
Z125	Low	Low FA	High RHA	Included	Elevated	Low density / low CS
Z126	Low	Low FA	High RHA	Included	Elevated	Low density / low CS
Z127	Low	Low FA	High RHA	Included	Elevated	Low density / low CS
Mix-6 (opt.)	—	7.05*	27.67*	—	—	Predicted optimum (pseudo)
Mix-7 (opt.)	—	3.80*	33.16*	—	—	Narrative optimum (pseudo)

*W/B = water-to-binder ratio (approximate; exact values and full 84-mix matrix to be supplied as supplementary data). Pseudo-component percentages for Mix-6 and Mix-7 are as reported in the optimisation table of the source study. Exact mass proportions of laterite, fine and coarse aggregates for every mix are not fully tabulated in the available documents.

Specimen Preparation and Testing

Materials were batched by mass, mixed mechanically, placed in moulds and compacted. Cubes were demoulded after 24 h and cured in water until the age of testing. Compressive strength was determined at 28

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days in accordance with ASTM C39; three replicate cubes were tested for each mixture and the mean and standard deviation recorded. Workability was measured by the slump test (ASTM C143). Water absorption was determined after 28 days of curing. Density was calculated from the mass and volume of the hardened cubes. Specimen size followed standard laboratory cube practice (typically 100 mm or 150 mm); the precise dimension used in the experimental programme should be confirmed and reported in the archival version of the paper.

Statistical Analysis – Scheffé Model

A third-degree Scheffé polynomial was fitted to the compressive-strength data:

$$\hat{y} = \Sigma\, \beta_i x_i + \Sigma\, \beta_{ij} x_i x_j + \Sigma\, \gamma_{ij} x_i x_j (x_i - x_j) + \Sigma\, \beta_{ijk} x_i x_j x_k$$

where x_i are the pseudo-component proportions and the β and γ coefficients are estimated by least squares. Analysis of variance was performed on the fitted model. The source documents report 84 model degrees of freedom, 1 residual degree of freedom, model sum of squares 13 801.6 and residual sum of squares 190.201, together with an average R^2 of 99.423 %. These statistics indicate an almost saturated model; the reported R^2 is not exactly reproduced by the published sums of squares (approximately 98.6 %). Adjusted and predicted R^2 values and lack-of-fit tests are not available and should be supplied in a revised submission.

RESULTS AND DISCUSSION

Fresh and Physical Properties

Slump values ranged from 61 mm (control) to approximately 245 mm for the most fluid mixtures. Many FA-containing mixtures exhibited higher workability than the control, consistent with the spherical particle morphology of fly ash. Extremely high slumps (>200 mm) were accompanied by low densities (approximately 1 700 kg m^{-3}) and low compressive strengths, suggesting segregation or excessive water demand rather than beneficial lubrication.

Mean water absorption of the control was 0.37 %. The best-performing blended mixtures (Z114–Z117) recorded absorptions of 1.60–1.73 %, while several low-strength, high-RHA mixtures showed comparable or only marginally higher absorption. The data therefore do not support a simple causal link between elevated absorption and the strength loss observed in Z125–Z127; the dominant factors appear to be binder dilution, high water demand of RHA, and consequent low density.

Compressive Strength – Laboratory Results

The control mixture achieved a mean 28-day compressive strength of 30.38 MPa. Among the blended mixtures the highest measured means were in the range 20.2–20.7 MPa. Table 2 presents the key laboratory test results for selected mixtures, including slump, density, moisture absorption and compressive strength.

Table 2. Laboratory test results for selected lateritic concrete mixtures (mean values of three replicates)

Mix ID	Slump (mm)	Density (kg/m³)	Mean MA (%)	Mean CS (MPa)	% of Control
Z1 (Control)	61.01	2363.03	0.37	**30.384**	**100.0**
Z36	163.35	2159.19	2.84	20.476	67.4

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Z114	112.75	2177.19	1.70	**20.673**	**68.0**
Z115	111.24	2177.13	1.73	20.647	67.9
Z116	110.61	2182.90	1.68	20.232	66.6
Z117	105.83	2198.59	1.60	20.218	66.5
Z125	244.77	1719.51	1.63	5.574	18.3
Z126	228.20	1705.60	1.60	4.906	16.1
Z127	209.46	1683.80	1.54	3.957	13.0

Note: MA = moisture absorption; CS = compressive strength. Values are means of three replicate tests. The Z114–Z117 group represents the highest measured strengths among the blended mixtures (approximately 66–68 % of control). Z125–Z127 illustrate the performance penalty associated with high RHA content, elevated slump and low density.

The contrast between Z114–Z117 and Z125–Z127 illustrates the decisive effect of mixture balance. The former group combined relatively high density (approximately 2 180 kg m^{-3}), moderate slump (105–113 mm) and compressive strengths above 20 MPa. The latter group recorded densities near 1 700 kg m^{-3}, slumps of 209–245 mm and compressive strengths below 6 MPa. The source study associates the poor performance of high-RHA or highly substituted mixtures with increased water demand, porosity and less favourable binder dilution. However, the moisture-absorption values of Z125–Z127 (1.54–1.63 %) are actually comparable to or lower than those of the best blends (1.60–1.73 %). Consequently, the strength loss cannot be attributed primarily to increased porosity as measured by water absorption; segregation, low density and excessive binder dilution are more consistent explanations.

Mixture Optimisation

The mixture-optimisation exercise generated eight candidate mixture combinations. Predicted compressive-strength values ranged from 20.585 MPa to 25.734 MPa (Table 3). The highest predicted value (25.734 MPa) corresponds to Mix-6, while the narrative of the source documents identifies Mix-7 (predicted 23.964 MPa) as the optimum. Because the predicted values exceed the highest measured strength (20.67 MPa) and no independent confirmation mixtures were cast, the optimisation results must be regarded as provisional.

Table 3. Candidate optimised mixture combinations from the Scheffé response surface (pseudo-component basis)

Mixture	FA (pseudo %)	RHA (pseudo %)	Predicted CS (MPa)
Mix-1	9.98	36.68	22.599
Mix-2	4.68	36.93	23.038
Mix-3	8.81	47.95	20.585
Mix-4	11.45	41.05	20.913
Mix-5	4.61	26.17	22.123
Mix-6	**7.05**	**27.67**	**25.734**

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Mix-7	**3.80**	**33.16**	**23.964**
Mix-8	10.92	41.68	20.693

Note: Mix-6 has the highest predicted strength; Mix-7 is identified as optimum in the source narrative. Both predictions exceed the best measured laboratory strength (20.67 MPa). Independent confirmation testing is required before either candidate can be recommended.

A single measured optimum based on the experimental data is therefore preferred for practical purposes: the group of mixtures Z114–Z117, characterised by balanced FA:RHA proportions (approximately 2:1 to 3:1) and compressive strengths of 20.2–20.7 MPa. These mixtures also exhibited moderate workability and densities above 2 170 kg m^{-3}, indicating a more stable microstructure than the high-slump, low-density mixtures.

Statistical Model Performance

Table 4 summarises the ANOVA results reported for the third-degree Scheffé compressive-strength model.

Table 4. ANOVA summary for the Scheffé third-degree polynomial compressive-strength model

Source	DF	Sum of Squares	Remarks
Model	84	13 801.6	Nearly saturated
Error (Residual)	1	190.201	Very limited residual DF
Total	85	—	Does not match 84 mixtures exactly
Reported R^2	—	99.423 %	Not fully reproduced by SS ratio (~98.6 %)

The near-saturation of the cubic model (84 model degrees of freedom, 1 residual degree of freedom) and the minor discrepancy between the reported R^2 and the value calculated from the published sums of squares limit the interpretability of the individual regression coefficients. The model is useful for ranking mixtures inside the experimental domain but should not be extrapolated without confirmation testing. Adjusted R^2, predicted R^2 and lack-of-fit statistics are recommended for any revised submission.

Influence of Curing and SCM Interaction

The source documents state that SCM-blended mixtures generally developed strength more slowly than the OPC control at early ages. This behaviour is consistent with the delayed contribution of pozzolanic reactions. With continued curing, the SCM-containing mixtures are reported to show improved strength as secondary hydration and microstructural refinement progressed. However, no tabulated strength-versus-age data (7, 14 and 28 days) are provided in the available documents, so the claim cannot be verified quantitatively from the present dataset. Extended curing is therefore recommended on the basis of established SCM behaviour rather than on direct evidence from this experimental programme.

The interaction between FA and RHA was also important: fly ash contributed to workability and later-age strength development, while the fine silica-rich RHA was associated with pore refinement and additional pozzolanic activity when used in moderation. Excessive RHA, however, was associated with greater water demand, lower density and lower strength. Balanced FA:RHA proportions around 2:1 to 3:1 consistently outperformed mixtures dominated by a single SCM.

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Mechanism Considerations

Pozzolanic reaction, pore refinement and secondary C-S-H formation are plausible explanations for the performance of the better-balanced mixtures and are supported by the broader literature on FA and RHA [8–13]. In the absence of X-ray diffraction (XRD), scanning electron microscopy (SEM), thermogravimetric analysis (TGA) or mercury-intrusion porosimetry data from the present experimental programme, these mechanisms remain hypotheses. Future work should include microstructural characterisation of the optimised mixtures to confirm the contribution of secondary hydration products.

Sustainability and Practical Implications

Partial replacement of OPC by FA and RHA reduces the clinker factor and utilises two abundant waste streams—one industrial and one agricultural. Reduced OPC consumption can lower the material demand associated with cement production, while the beneficial use of ash residues can reduce dependence on disposal pathways. The use of lateritic material also supports the utilisation of locally available resources in tropical regions.

A quantitative embodied-carbon or cost calculation per cubic metre was not performed in the present study; such an assessment is required before firm environmental or economic claims can be made. The measured strengths of 20–21 MPa place the better mixtures within the range of lower structural grades recognised by many national codes (for example, C20/25 class concrete), provided that characteristic strength, specimen geometry and long-term durability are confirmed. The mixtures are therefore considered potentially suitable for non-structural elements and lightly loaded structural members once the outstanding experimental gaps (confirmation testing, durability indicators and full mix-design documentation) are closed.

CONCLUSIONS

- The highest measured mean compressive strength among the FA–RHA lateritic mixtures was 20.67 MPa (approximately 68 % of the 30.38 MPa control).
- Balanced FA:RHA proportions near 2:1–3:1 at moderate cement replacement levels retained the highest strengths; high-RHA or highly substituted mixtures suffered severe strength loss and density reduction.
- A third-degree Scheffé model described the experimental response surface with a high coefficient of determination, but the model was nearly saturated and the reported R^2 is not fully consistent with the published sums of squares.
- Predicted optimum strengths exceeded measured values; independent confirmation mixtures are essential before any optimised mix can be recommended.
- The experimental dataset is potentially valuable for tropical regions, but full methodological detail, quantified sustainability metrics and durability data are required before the optimised mixtures can be recommended for structural use.

Recommendations for Further Work

- Publish the complete mix-design table, water-to-binder ratios, component bounds and material characterisation (including RHA oxide composition, LOI, fineness and processing parameters) as supplementary material.
- Cast and test at least three independent confirmation mixtures at the measured optimum proportions (Z114–Z117 group) and report prediction error relative to the Scheffé surface.

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- Provide strength–age curves (7, 14 and 28 days) for the control and the best blended mixtures to substantiate claims concerning early-age lag and later recovery.
- Quantify embodied carbon and cost per cubic metre of the optimised mixture relative to the control.
- Perform microstructural (XRD, SEM, TGA) and durability testing (chloride ingress, sulphate resistance, shrinkage) on the optimised mixtures.
- Compare results systematically with previously published laterite–SCM studies to strengthen the research-gap narrative and demonstrate novelty.

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