

Proportioning Fly Ash and Rice Husk Ash in Binary and Ternary Blended Concrete: Statistical Response Modelling and an Experimental Framework for Nano-Silica Modification

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Highlights

- Thirteen FA, RHA and FA–RHA concretes at 0–30% cement replacement were analysed statistically.
- 22.5% FA + 7.5% RHA gave the highest 28-d compressive (39.41 MPa) and flexural (7.33 MPa) strengths.
- A constrained second-order response surface explained 86% (compressive) and 95% (flexural) of the variance.
- Ternary FA–RHA blends reduced cement intensity from 11.78 to 7.99 kg·m⁻³·MPa⁻¹ (–32%).
- A replicated, statistically powered test matrix is defined for 0–3% nano-silica modification.

Abstract

Fly ash (FA) and rice husk ash (RHA) are complementary pozzolans: FA is a slowly reacting aluminosilicate, whereas RHA is a highly reactive, high-surface-area amorphous silica. How they should be proportioned in a ternary binder, and whether such a binder is a suitable host for nano-silica (NS), are not yet settled. This study re-analyses a 13-mix experimental programme (450 kg/m³ binder, w/b = 0.42) comprising a control, binary FA and RHA mixes at 10–30% replacement and six ternary mixes at a constant 30% total replacement. Compressive strength at 7 and 28 days and 28-day splitting tensile and flexural strengths were modelled with a constrained second-order response surface, validated by leave-one-out cross-validation, and evaluated against code-based tensile relationships and eco-efficiency indicators. FA alone was strength-neutral up to 20%, whereas RHA alone reduced 28-day compressive strength by 20–34%. The ternary mix with 22.5% FA and 7.5% RHA reached 39.41 MPa compressive, 2.73 MPa splitting tensile and 7.33 MPa flexural strength (+3.2%, +0.7% and +30.7% over the control) while cutting cement intensity by 32%. The response surface explained 86% and 95% of the variance in compressive and flexural strength ($Q^2 = 0.62$ and 0.80), but the six-point quadratic for the 30% series was not significant at $\alpha = 0.05$ ($p = 0.09$), so the optimum RHA fraction of about 7% should be treated as indicative. No NS was present in the dataset; a replicated 3×4 factorial programme with fixed water content and a statistical model capable of isolating the NS effect is therefore proposed rather than inferred.

Keywords: fly ash; rice husk ash; ternary blended concrete; nano-silica; response surface methodology; eco-efficiency; cement intensity

1. Introduction

Portland cement production accounts for a substantial share of anthropogenic CO₂ emissions, and replacing part of the clinker with supplementary cementitious materials (SCMs) remains the most practical route to lower-carbon concrete in the near term [1,2]. SCMs reduce clinker demand, consume portlandite through the pozzolanic reaction and refine the pore structure, but they also dilute the clinker and slow early strength development [3,4]. The net mechanical effect therefore depends on the reactivity, fineness and dosage of the SCM and on how different SCMs interact when used together.

Class F fly ash is the most widely used SCM in India. Its spherical particles improve workability, but its glassy aluminosilicate phase reacts slowly, so strength gains are generally realised after 28 days and high replacement levels penalise early-age strength [5,6]. Rice husk ash, produced by controlled combustion of an agricultural residue, is dominated by amorphous silica with a very high specific surface; when ground and burned appropriately it is among the most reactive natural pozzolans [7–9]. Its high water demand and the variability of field-burnt ash, however, often reduce workability and strength at replacements above about 10% [9,10].

Combining the two ashes in a ternary binder is attractive because the fast-reacting RHA can partly offset the slow early reaction of FA, while the FA improves the packing and workability lost through RHA. Chindaprasirt and Rukzon reported that ternary Portland–RHA–FA mortars had lower porosity and better corrosion resistance than binary mixes [11]. Nano-silica (NS) has been proposed as a third modifier for such systems: owing to its nanometre size and high amorphous silica content it acts as a nucleation site for C–S–H, accelerates hydration and consumes portlandite at early ages [12–14]. NS has been shown to restore the early strength of high-volume FA concretes [15–17] and to improve the strength and transport properties of RHA-blended systems [18–21].

Three gaps limit the design of FA–RHA–NS concretes. First, most ternary FA–RHA studies report the best-performing mix but do not model the response over the composition space, so the sensitivity of strength to the FA:RHA ratio is not quantified. Second, the eco-efficiency of the blends is rarely expressed per unit of strength delivered, which is the basis on which binders should be compared [22]. Third, NS studies differ in base binder, w/b ratio and admixture dosage, so their reported optima cannot be transferred to a specific FA–RHA blend without new tests [10].

This paper addresses the first two gaps directly and the third methodologically. Its objectives are to (i) quantify the mechanical response of binary and ternary FA–RHA concretes over 0–30% replacement; (ii) fit and cross-validate a constrained second-order response surface linking FA and RHA content to strength; (iii) evaluate the blends using code-based tensile relationships and cement and CO₂ intensity indicators; and (iv) define, on the basis of the measured baseline, a statistically powered experimental framework for 0–3% NS modification. The work is presented explicitly as a baseline analysis: no NS response is inferred from data that contain no NS.

2. Materials and Methods

2.1 Experimental programme and data source

The experimental data were generated in a Master's programme on FA–RHA concrete [23] and are re-analysed here with the statistical and eco-efficiency methods described in Sections 2.3–2.4. The constituents were ordinary Portland cement, Class F fly ash, rice husk ash, natural river sand and crushed coarse aggregate. The nominal control mix contained 450 kg/m³ cement, 189 kg/m³ water (w/b = 0.42), 554 kg/m³ fine aggregate and 1139 kg/m³ coarse aggregate. FA and RHA replaced cement by mass with water and aggregate contents held constant. The programme comprised one control (M0), three binary FA mixes (M1–M3, 10–30% FA), three binary RHA mixes (M4–M6, 10–30% RHA) and six ternary mixes at a constant 30% total replacement in which RHA rose from 2.5% to 15% in 2.5% steps (M7–M12). The resulting binder compositions are listed in Table 1.

Table 1. Binder composition of the 13 concretes (total binder 450 kg/m³; water 189 kg/m³; w/b = 0.42; fine and coarse aggregate 554 and 1139 kg/m³).

Mix	FA (%)	RHA (%)	Cement (kg/m ³)	FA (kg/m ³)	RHA (kg/m ³)	w/c
M0	0	0	450.0	0.0	0.0	0.42
M1	10	0	405.0	45.0	0.0	0.47
M2	20	0	360.0	90.0	0.0	0.53
M3	30	0	315.0	135.0	0.0	0.60
M4	0	10	405.0	0.0	45.0	0.47
M5	0	20	360.0	0.0	90.0	0.53
M6	0	30	315.0	0.0	135.0	0.60
M7	27.5	2.5	315.0	123.8	11.2	0.60
M8	25	5	315.0	112.5	22.5	0.60
M9	22.5	7.5	315.0	101.2	33.8	0.60
M10	20	10	315.0	90.0	45.0	0.60
M11	17.5	12.5	315.0	78.8	56.2	0.60
M12	15	15	315.0	67.5	67.5	0.60

2.2 Test methods

Compressive strength was determined on cubes at 7 and 28 days in accordance with IS 516 [24], splitting tensile strength on cylinders at 28 days in accordance with IS 5816 [25], and flexural strength on prisms at 28 days under the IS 516 procedure. The values analysed here are the mean values reported for each mix in the source programme [23]; individual specimen results and their dispersion were not available for re-analysis, which is addressed as a limitation in Section 5.

2.3 Statistical modelling

Because the FA and RHA contents were varied jointly over a constrained region (FA + RHA ≤ 30%), the 28-day responses y (compressive, splitting tensile and flexural strength) were described by a second-order polynomial in the two replacement levels, as in response surface methodology [26]:

$$y = \beta_0 + \beta_1 F + \beta_2 R + \beta_{11} F^2 + \beta_{22} R^2 + \beta_{12} FR + \varepsilon \quad (1)$$

where F and R are the FA and RHA replacement levels (% by binder mass), β are regression coefficients and ε is the residual. Coefficients were estimated by ordinary least squares on the 13 mixes, leaving 7 residual degrees of freedom. Model quality was assessed by the coefficient of determination R^2 , the adjusted R^2_{adj} , the overall F-test and the root-mean-square error (RMSE). Because R^2 always increases with the number of terms, the predictive ability was also assessed by leave-one-out cross-validation, expressed as the predictive coefficient $Q^2 = 1 - \text{PRESS}/\text{SS}_{\text{tot}}$, where PRESS is the sum of squared prediction errors when each mix is omitted in turn [27]. For the six ternary mixes at 30% total replacement a one-variable quadratic in R was also fitted, with 95% confidence intervals on the mean response.

2.4 Tensile relationships and eco-efficiency indicators

Measured flexural strength f_b was compared with the IS 456 estimate $0.7\sqrt{f_{ck}}$ [28], and the coefficients k in $f_b = k\sqrt{f_c}$ and $f_{st} = k\sqrt{f_c}$ were obtained by least squares through the origin. Eco-efficiency was expressed by the cement intensity c_i (kg of cement per m^3 per MPa of 28-day compressive strength) and the CO_2 intensity, following the binder-intensity concept of Damineli et al. [22]. CO_2 intensity was calculated with an emission factor of 0.9 kg CO_2 -eq/kg for Portland cement, the midpoint of the 0.8–1.0 kg CO_2 -eq/kg range reported for CEM I [29]; FA and RHA were treated as by-products with no allocated burden (cut-off approach), and transport and processing were excluded. The CO_2 indicator is therefore a comparative cradle-to-gate binder indicator, not a full life-cycle assessment.

3. Results and Discussion

3.1 Compressive strength development

Table 2. Measured mechanical properties and changes relative to the control (M0).

Mix	$f_{c,7}$ (MPa)	$f_{c,28}$ (MPa)	Δ vs M0 (%)	$f_{c,7}/f_{c,28}$	f_{st} (MPa)	Δ (%)	f_b (MPa)	Δ (%)
M0	27.20	38.20	—	0.71	2.71	—	5.61	—
M1	27.35	38.45	+0.7	0.71	2.91	+7.4	6.31	+12.5
M2	27.50	38.90	+1.8	0.71	2.98	+10.0	7.03	+25.3
M3	26.65	37.18	-2.7	0.72	2.65	-2.2	6.45	+15.0
M4	23.15	30.51	-20.1	0.76	2.51	-7.4	3.40	-39.4
M5	23.27	28.60	-25.1	0.81	2.21	-18.5	3.05	-45.6
M6	24.01	25.13	-34.2	0.96	2.15	-20.7	2.70	-51.9
M7	25.51	34.43	-9.9	0.74	2.51	-7.4	6.09	+8.6
M8	25.94	38.13	-0.2	0.68	2.33	-14.0	6.89	+22.8
M9	21.41	39.41	+3.2	0.54	2.73	+0.7	7.33	+30.7
M10	20.89	34.04	-10.9	0.61	2.42	-10.7	6.52	+16.2
M11	19.61	33.98	-11.0	0.58	2.11	-22.1	5.89	+5.0
M12	19.06	30.10	-21.2	0.63	1.81	-33.2	5.66	+0.9

f_c = cube compressive strength; f_{st} = splitting tensile strength; f_b = flexural strength (all at 28 days unless stated).
 Source data from [23].

Table 2 and Fig. 1 summarise the measured properties. Binary FA mixes were essentially strength-neutral at 28 days: 10% and 20% FA gave 38.45 and 38.90 MPa (+0.7% and +1.8%), and 30% FA gave 37.18 MPa (−2.7%). Their 7-day strengths (26.65–27.50 MPa) were also close to that of the control (27.20 MPa), giving 7/28-day ratios of 0.71–0.72. This indicates that, at $w/b = 0.42$, the filler and dispersion effects of FA largely compensated for clinker dilution even before its pozzolanic reaction became significant [5,6].

Binary RHA mixes behaved very differently. The 28-day compressive strength fell to 30.51, 28.60 and 25.13 MPa at 10%, 20% and 30% RHA (−20.1% to −34.2%), while 7-day strength changed little (23.15–24.01 MPa). The resulting 7/28-day ratios (0.76–0.96) are higher than for the control, i.e. the RHA mixes gained comparatively little strength between 7 and 28 days. This is the opposite of what a well-reacting pozzolan should show, and it points to a coarse or partly crystalline ash, or to an increase in effective water demand that was not compensated, since water content was fixed and no superplasticiser adjustment was reported [8,9]. Without the RHA's particle size, amorphous silica content and loss on ignition, the cause cannot be identified with certainty, and these properties should be reported in any subsequent programme.

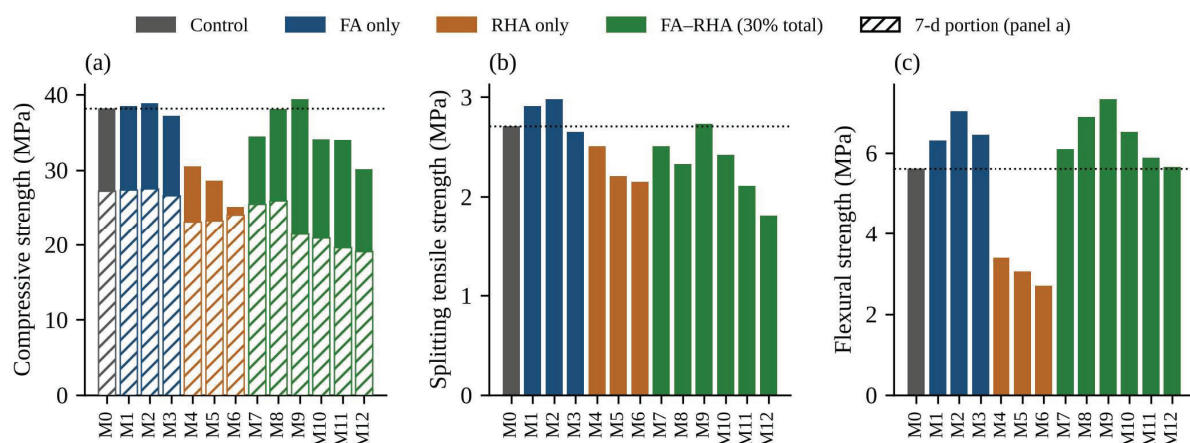


Figure 1. Measured (a) compressive, (b) splitting tensile and (c) flexural strengths of all mixes.

In the ternary series the 28-day strength rose from 34.43 MPa (M7, 2.5% RHA) to a maximum of 39.41 MPa (M9, 22.5% FA + 7.5% RHA) and then fell to 30.10 MPa at 15% RHA (M12). M8 and M9 were the only 30%-replacement mixes to equal or exceed the control. The ternary mixes, however, had markedly lower 7-day strengths (19.06–25.94 MPa) and 7/28-day ratios of 0.54–0.74; between 7 and 28 days M9 gained 84% over its 7-day strength, compared with 40% for the control. A synergistic late-age contribution of RHA within an FA-rich matrix is consistent with the faster pozzolanic reaction of RHA once portlandite has accumulated [3,11], but a 7/28-day ratio of 0.54 is unusually low for a Portland-based concrete at $w/b = 0.42$. The 7- and 28-day strengths were only weakly correlated across the dataset ($r = 0.45$), and the M9 7-day value in particular should be confirmed against the original test records before the early-age behaviour is generalised.

3.2 Tensile and flexural behaviour

Splitting tensile strength ranged from 1.81 to 2.98 MPa and followed compressive strength more weakly than flexural strength (Table 2). FA at 10–20% increased f_{st} by 7.4–10.0%, whereas all RHA and most ternary mixes reduced it; M9 was the only ternary mix to match the control (2.73 versus 2.71 MPa). The least-squares coefficient for $f_{st} = k\sqrt{f_c}$ was 0.42, with the lowest values (0.33–0.38) for the RHA-rich ternary mixes M8, M11 and M12 (Fig. 4a).

Flexural strength was the most composition-sensitive property. FA alone raised f_b by 12.5–25.3%, the ternary mixes M7–M10 by 8.6–30.7%, and RHA alone reduced it by 39.4–51.9%. Except for the RHA-only mixes, all measured flexural strengths exceeded the IS 456 estimate $0.7\sqrt{f_{ck}}$ by a wide margin, with $f_b/\sqrt{f_c}$ between 0.91 and 1.17 (Fig. 4a), and f_b/f_c ratios for the FA and ternary mixes (0.16–0.19) were above the 0.10–0.15 typically reported for normal-strength concrete [30]. This suggests either a genuine improvement of the paste–aggregate interface by the fine ashes or a systematic effect of the prism size and loading configuration in the source tests. The RHA-only mixes, by contrast, fell well below the code estimate, which is consistent with a weak interfacial transition zone under fixed water content [4]. Code-based conversion from compressive to flexural strength is therefore not safe for these binders without project-specific calibration.

3.3 Response surface models

Table 3. Coefficients and diagnostics of the second-order response surface models (Eq. 1; $n = 13$, 7 residual d.f.).

Term	$f_{c,28}$: coefficient	p-value	f_b : coefficient	p-value	f_{st} : coefficient	p-value
β_0 (intercept)	37.7332	0.000	5.4558	0.000	2.7140	0.000
β_1 (F)	0.1464	0.682	0.1376	0.081	0.0344	0.317
β_2 (R)	-0.6993	0.085	-0.2207	0.015	-0.0271	0.432
β_{11} (F ²)	-0.0050	0.650	-0.0034	0.147	-0.0011	0.286
β_{22} (R ²)	0.0092	0.436	0.0043	0.091	0.0002	0.847
β_{12} (F·R)	0.0106	0.541	0.0068	0.075	-0.0022	0.189
R ²	0.858		0.952		0.775	
R ² _{adj}	0.757		0.918		0.614	
Model F-test p	0.0070		0.0002		0.0315	
RMSE (MPa)	2.256		0.444		0.210	
Q ² (LOO)	0.624		0.803		-0.106	
RMSE _{LOO} (MPa)	2.695		0.661		0.342	

F and R in % of binder mass. Q² = leave-one-out predictive coefficient.

The fitted models are summarised in Table 3 and Fig. 3. The compressive model was significant (F-test $p = 0.007$) with $R^2 = 0.86$, $R^2_{adj} = 0.76$ and $Q^2 = 0.62$; the flexural model was stronger ($p < 0.001$, $R^2 = 0.95$, $R^2_{adj} = 0.92$, $Q^2 = 0.80$). Only the RHA terms were individually significant or near-significant (β_2 $p = 0.085$ for compressive and 0.015 for flexural strength), confirming that RHA content was the dominant factor and FA a secondary one over the range tested. The

positive interaction coefficients ($\beta_{12} = 0.0106$ and 0.0068) indicate that the strength penalty of RHA is smaller when it is combined with FA, which is the statistical expression of the FA–RHA synergy. The splitting tensile model, although significant in-sample ($p = 0.032$), had a negative Q^2 (-0.11) and therefore no predictive value; it is reported for completeness only.

Across the composition space the compressive surface reaches its maximum of about 38.8 MPa near 15% FA without RHA, and the flexural surface peaks at about 6.8 MPa near 20% FA (Fig. 3). These model maxima lie below the measured maximum at M9 (39.41 and 7.33 MPa) because a second-order surface fitted to 13 points smooths the local peak of the ternary series. The response surface is therefore best used to locate the region of good performance — FA-dominant binders with RHA at or below about 7.5% — rather than to predict a precise optimum.

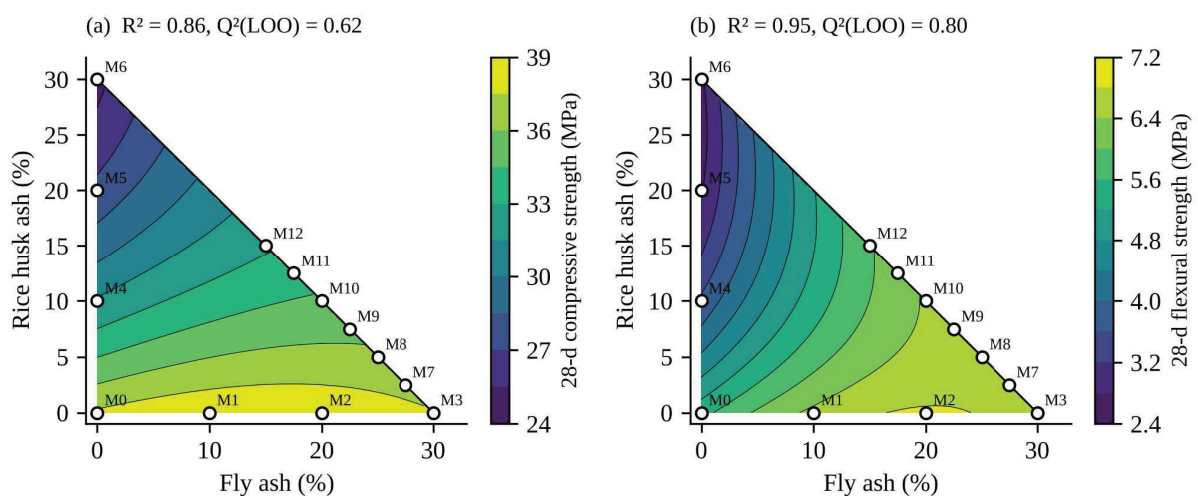


Figure 2. Response surfaces for 28-day (a) compressive and (b) flexural strength.

3.4 Optimum RHA fraction at constant 30% replacement

For the six ternary mixes, the quadratic regression of 28-day compressive strength on RHA content was:

$$f_{c,28} = -0.1236R^2 + 1.7119R + 31.752 \text{ (MPa; } 2.5 \leq R \leq 15\%) \quad (2)$$

with $R^2 = 0.80$, $R^2_{adj} = 0.67$ and F-test $p = 0.088$ (Fig. 2a). The stationary point lies at $R = 6.9\%$, i.e. about 23% FA + 7% RHA, close to the measured best mix M9. The corresponding flexural model gives an optimum at $R = 7.5\%$ ($R^2 = 0.77$, $p = 0.11$). With only three residual degrees of freedom, however, neither model is significant at $\alpha = 0.05$, and the 95% confidence band of the mean response is wide (Fig. 2). The data support the conclusion that the optimum RHA fraction within a 30% FA–RHA binder lies between about 5% and 7.5%, but a precise optimum would require replicated tests at intermediate compositions.

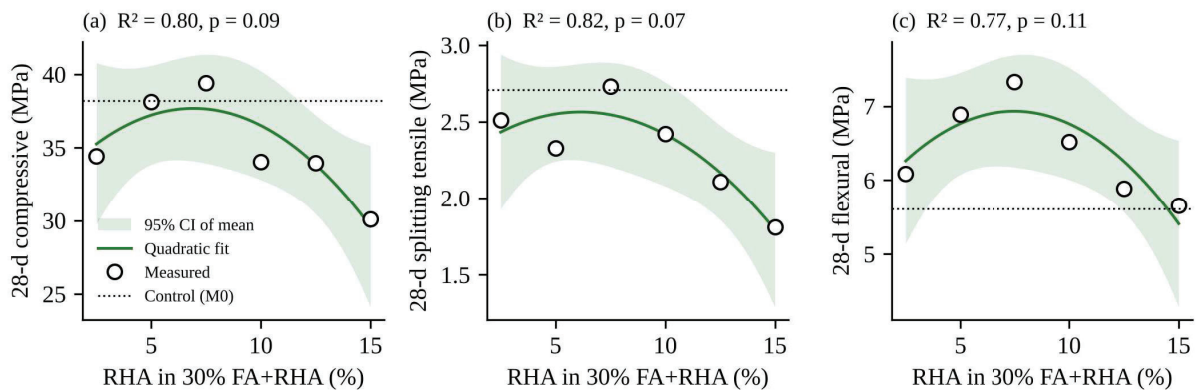


Figure 3. Quadratic fits for the constant-30% FA-RHA series with 95% confidence bands.

3.5 Eco-efficiency

Cement intensity fell from $11.78 \text{ kg} \cdot \text{m}^{-3} \cdot \text{MPa}^{-1}$ for the control to 9.25 for 20% FA and 7.99 for M9 (Fig. 4b), a reduction of 32%. With the stated emission factor, the corresponding CO_2 intensity fell from 10.60 to $7.19 \text{ kg CO}_2\text{-eq} \cdot \text{m}^{-3} \cdot \text{MPa}^{-1}$; across the 0.8–1.0 kg/kg range of the cement factor the M9 value lies between 6.39 and 7.99. The RHA-only mixes were the least efficient of all replacement mixes ($12.53\text{--}13.27 \text{ kg} \cdot \text{m}^{-3} \cdot \text{MPa}^{-1}$) and were all less efficient than the control, because their strength loss exceeded their cement saving. The comparison illustrates why SCM binders should be compared per unit of performance rather than per unit volume [22]: at equal 30% replacement, M9 and M6 contain the same cement but differ by a factor of 1.57 in cement intensity.

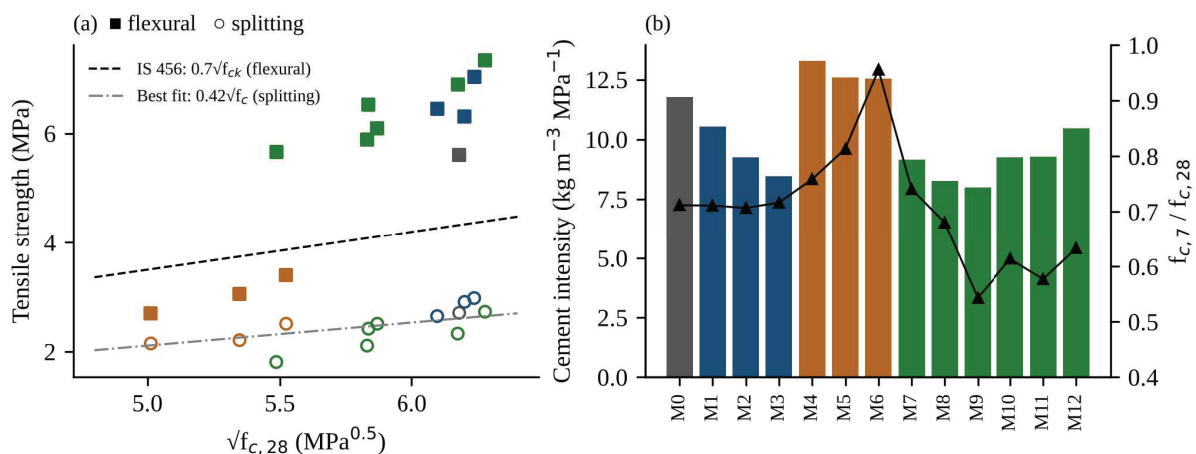


Figure 4. (a) Tensile strengths versus $\sqrt{f_c}$; (b) cement intensity and 7/28-day strength ratio.

3.6 Comparison with the literature

Table 4. Selected literature on FA–RHA ternary and NS-modified binders.

Study	Binder system	Main reported finding	Relevance to present work
Chindaprasirt and Rukzon [11]	OPC–RHA–FA mortar	Ternary blends reduced porosity and improved corrosion resistance relative to binary blends	Supports FA–RHA synergy found here ($\beta_{12} > 0$)
Li [15]	High-volume FA concrete + NS	NS increased early and long-term strength of HVFA concrete	NS may offset the low 7-d strength of M7–M12
Zhang and Islam [16]	High-volume FA or slag concrete + NS	NS shortened setting time and increased early strength	Same mechanism targeted for FA-rich ternary mixes
Zahedi et al. [20]	Mortar with RHA + NS	10% RHA with 5% NS gave the best performance at 28 and 90 days	Optimum NS differs by system; must be re-established
Avudaiappan et al. [19]	M20 concrete with RHA + NS	1% NS with 10% RHA identified as optimum	NS window of 0–2% is reasonable
Tran et al. [31]	High-strength concrete with RHA-derived NS	Strength optimum near 1.5% NS	Upper NS levels (>2%) may be past optimum
Anto et al. [18]	Ternary paste, RHA + NS	10% RHA + 3% NS raised compressive strength by 14.2% (w/b 0.35) and 20.9% (w/b 0.55); acid-attack mass loss reduced by 27.5%	Larger NS benefit at higher w/b relevant to w/b = 0.42

Table 4 places the present results in context. The synergy observed between FA and RHA agrees with the improved pore structure of ternary Portland–RHA–FA mortars [11]. The NS literature consistently identifies optimum dosages in the 1–3% range, but the optimum depends on the base binder, w/b ratio and dispersion method: 1% NS with 10% RHA in M20 concrete [19], about 1.5% in high-strength concrete [31], and 3% in RHA pastes, with a larger relative benefit at w/b = 0.55 than at 0.35 [18]. Agglomeration of NS at higher dosages and its high water demand are the usual explanations for performance declining beyond the optimum [13,32]. These studies justify a 0–3% NS test window for the FA–RHA system, but they do not provide responses for the specific blends studied here.

4. Experimental Framework for Nano-Silica Modification

The baseline results indicate two specific roles for NS in FA–RHA concrete: compensating the low 7-day strength of the ternary mixes, and reducing the strength penalty at higher RHA contents. NS is expected to act on early-age hydration through nucleation and rapid pozzolanic consumption of portlandite [12,14], which is precisely where the ternary blends were weakest (7/28-day ratios of 0.54–0.74). The planned dissertation design [33] combines three FA:RHA blends with four NS dosages (Table 5).

Table 5. Planned FA–RHA–NS experimental matrix (NS replaces cement by mass).

Group	FA (%)	RHA (%)	Total SCM (%)	NS dosages (%)	Cement at NS = 0 (%)	Within tested domain?
Control	0	0	0	0	100	Yes
F1 (N0, N1, N4, N7)	10	5	15	0, 1, 2, 3	85	Yes (interpolation)
F2 (N0, N2, N5, N8)	20	10	30	0, 1, 2, 3	70	Yes (on 30% line; close to M10)

Group	FA (%)	RHA (%)	Total SCM (%)	NS dosages (%)	Cement at NS = 0 (%)	Within tested domain?
F3 (N0, N3, N6, N9)	30	15	45	0, 1, 2, 3	55	No (extrapolation)

Three design features are needed for the NS effect to be identifiable. First, the F3 blend (45% total SCM) lies outside the 0–30% domain of the present data, so its NS-free reference (F3-N0) must be cast and tested; the response surface of Section 3.3 cannot be extrapolated to it. Similarly, F1 and F2 should each include an NS = 0 reference cast in the same campaign. Second, water content and w/b should be held constant across NS levels, with superplasticiser adjusted to a target slump band and recorded as a covariate; otherwise the NS effect is confounded with changes in water demand. Third, each mix should be tested in at least triplicate at 7, 28 and preferably 56 or 90 days, so that a two-way analysis of variance (blend $\times$ NS dosage) with interaction can be performed [27]. With 13 mixes, three ages and three replicates, the full programme involves 117 cubes for compressive strength alone, plus cylinders and prisms for tensile and flexural tests. The resulting data would allow Eq. (1) to be extended with linear and quadratic NS terms and FA $\times$ NS and RHA $\times$ NS interactions, and cross-validated in the same way as the baseline models.

In addition to strength, the NS programme should report the properties needed to interpret it: the particle size, specific surface, amorphous silica content and loss on ignition of the FA, RHA and NS; NS dispersion method; fresh properties (slump and setting time); and microstructural and durability indicators such as water absorption, sorptivity, rapid chloride penetration, XRD and SEM. Eco-efficiency should be re-evaluated including the embodied CO₂ of NS, which is far higher per kilogram than that of FA or RHA.

5. Limitations

The study is a secondary analysis of mean values from a single experimental programme; individual specimen results and standard deviations were not available, so the regression residuals combine experimental scatter with model error and the significance levels should be read with this in mind. The physical and chemical properties of the FA and RHA, curing details and specimen dimensions were not available for all tests. The unusual early-age behaviour of the ternary mixes, notably M9, requires confirmation against the original records. The CO₂ indicator excludes transport, grinding of RHA and end-of-life, and assigns no burden to the ashes. Finally, no NS was present in the data, and no NS effect is claimed.

6. Conclusions

(1) Fly ash alone was strength-neutral at 28 days up to 20% replacement (38.45–38.90 MPa versus 38.20 MPa) and raised flexural strength by up to 25.3%. Rice husk ash alone reduced 28-day compressive strength by 20.1–34.2% and flexural strength by 39.4–51.9% under fixed water content.

- (2) At a constant 30% replacement, combining the ashes recovered and exceeded the control strength. The mix with 22.5% FA and 7.5% RHA gave the highest 28-day compressive (39.41 MPa, +3.2%) and flexural (7.33 MPa, +30.7%) strengths and equalled the control in splitting tensile strength (2.73 MPa).
- (3) A constrained second-order response surface explained 86% and 95% of the variance in 28-day compressive and flexural strength, with cross-validated Q^2 of 0.62 and 0.80. RHA content was the dominant factor, and the positive FA×RHA interaction quantifies the synergy between the ashes. The splitting tensile model had no predictive value.
- (4) Within the 30% ternary series, the optimum RHA fraction was about 7% (stationary point of the quadratic fit), but the fit was not significant at $\alpha = 0.05$ ($p = 0.09$); the optimum is therefore indicative and lies between about 5% and 7.5% RHA.
- (5) Flexural strengths of FA and ternary mixes exceeded the IS 456 estimate $0.7\sqrt{f_{ck}}$ substantially, whereas RHA-only mixes fell well below it; code-based conversion should be calibrated for these binders.
- (6) The best ternary mix cut cement intensity by 32% (11.78 to 7.99 $\text{kg}\cdot\text{m}^{-3}\cdot\text{MPa}^{-1}$) relative to the control, whereas RHA-only mixes were the least eco-efficient replacement mixes.
- (7) The ternary blends had low 7-day strengths (7/28-day ratio 0.54–0.74), which is the property NS is most likely to improve. A replicated 3×4 factorial NS programme with fixed water content, NS-free references for every blend and a two-way ANOVA is required; the 45% SCM blend lies outside the present data domain and must be treated as a new system.

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