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Prediction of Compressive Strength of Rice Husk Ash Blended Concrete Using Non-Linear Regression Models

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Abstract

Ordinary Portland Cement (OPC) production is a major contributor to global CO_2 emissions, motivating interest in supplementary cementitious materials such as Rice Husk Ash (RHA), a silica-rich agricultural by-product with pozzolanic properties. This study investigated the effect of RHA as a partial cement replacement (2.5%, 5%, 12%, and 15% by weight) on the compressive strength of concrete cured for 7 to 28 days, and compared the predictive performance of three non-linear regression models — Spline, Polynomial, and Physics-Based — against experimental results. X-ray fluorescence analysis confirmed a silica content of 85.00% in the RHA used, consistent with a reactive natural pozzolan. The highest average compressive strength (39.09 N/mm²) was recorded at 5% RHA replacement after 21 days of curing, while higher replacement levels produced lower strengths. The Spline and Polynomial models achieved identical coefficients of determination (R^2 = 0.8310), with the Spline model recording lower mean absolute error (6.0425) and mean absolute percentage error (18.52%) than the Polynomial model. The Physics-Based model recorded the lowest R^2 (0.5946) despite the lowest bias. Because the four experimental mixes were not varied independently across replacement level, curing age, and water-cement ratio, and because the dataset was limited to four points, these findings are presented as a preliminary comparative assessment rather than a validated predictive framework. The Spline model showed the most balanced performance among the three approaches. Further work with an independently varied, larger dataset is recommended to confirm these findings and support field application of RHA in sustainable concrete production.

Keywords: rice husk ash, compressive strength, concrete, partial cement replacement, regression model, spline regression, pozzolanic material.

Introduction

Concrete remains the most widely used construction material globally, valued for its strength, durability, and versatility in infrastructure development [1]. Its principal binder, Ordinary Portland Cement (OPC), is however associated with substantial environmental cost: cement manufacturing is energy-intensive and accounts for approximately 5–8% of global CO_2 emissions [2]. This has intensified interest in supplementary cementitious materials (SCMs) capable of partially replacing OPC without compromising performance.

Rice Husk Ash (RHA), an agricultural by-product of controlled rice husk combustion, is one such material. RHA is rich in amorphous silica, which reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H) — the compound primarily responsible for concrete strength [3]. This pozzolanic behavior makes RHA a technically viable and environmentally attractive partial cement substitute, particularly in rice-producing regions such as Nigeria. Prior studies report that RHA incorporation can improve long-term compressive strength when used at appropriate proportions, while finer RHA particles further densify the concrete microstructure [4], [5].

However, RHA-concrete performance is sensitive to several interacting variables — silica content, particle fineness, water-to-binder ratio, curing regime, and replacement level — making standardized mix design difficult. Conventional trial-and-error experimental approaches to resolving this are costly and time-consuming. Regression-based predictive modelling offers an alternative: by relating measurable input variables (replacement percentage, curing age, water-cement ratio) to compressive strength outcomes, engineers can estimate performance without exhaustive physical testing. Prior studies combining RHA substitution with regression modelling have reported strong correlations between predicted and experimental strength values [6].

Despite this progress, most published RHA prediction models are calibrated on relatively large, systematically varied datasets and rarely compare multiple non-linear modelling approaches — spline-based, empirical physics-based, and polynomial — side by side on the same dataset. There remains limited evidence on which non-linear technique offers the most reliable compressive strength prediction for RHA-blended concrete under constrained, low-to-moderate replacement conditions (≤15%), which is the practically relevant range given that excessive replacement is already known to reduce strength through increased water demand and reduced density.

This study addresses that gap. It investigates the effect of RHA as a partial cement replacement (2.5%, 5%, 12%, and 15% by weight) on the compressive strength of concrete cured over 7–28 days, and compares the predictive performance of three non-linear regression models — Spline, Polynomial, and a Physics-Based formulation — against experimental results. The specific objectives are to: (i) characterize the physical and chemical properties of the RHA used; (ii) develop regression models relating replacement percentage, curing age, and water-cement ratio to compressive strength; (iii) compare predicted against experimental strength values; and (iv) identify the best-performing model using standard statistical accuracy measures. Given the constrained sample size, this work is positioned as a preliminary comparative modelling study intended to inform, rather than conclusively establish, best-practice predictive approaches for RHA-concrete — a limitation addressed explicitly in Section 3.

Materials

Ordinary Portland Cement (OPC) conforming to ASTM C150 [8] was used as the primary binder.

Rice Husk Ash (RHA) was obtained from controlled combustion of rice husk and processed into a fine powder conforming to natural pozzolan requirements [9]. Natural river sand, free of organic impurities, was used as fine aggregate, and crushed granite of 20 mm nominal size was used as coarse aggregate. Potable water free from impurities was used for mixing and curing.

Chemical Characterization of RHA

The oxide composition of the RHA was determined by X-ray Fluorescence (XRF) analysis, conducted at the Department of Chemical Engineering, Ahmadu Bello University, Zaria.

Mix Design and Specimen Preparation

Concrete mixes were proportioned in accordance with the ACI mix design procedure [11]. RHA was used to replace OPC by weight at four levels: 2.5%, 5%, 12%, and 15%. Corresponding water-cement ratios of 0.40, 0.50, 0.65, and 0.45 were applied to the respective mixes. For each replacement level, three cube specimens measuring 100 mm × 100 mm × 100 mm were cast, compacted using a vibrating table, and demolded after 24 hours, giving twelve specimens in total. Specimens were subsequently cured in water maintained at 25 ± 2 °C.

Compressive Strength Testing

Compressive strength tests were conducted in accordance with BS EN 12390-3 [10] using a hydraulic compression testing machine. The three replicate cubes for each RHA replacement level were tested at the single curing age associated with that mix (7, 14, 21, or 28 days), and the reported compressive strength for each mix was taken as the average of the three replicate values. Compressive strength was calculated as:

$$f_c = P / A \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where f_c is the compressive strength (N/mm²), P is the failure load (N), and A is the cross-sectional area of the loaded face (mm²).

Regression Model Development

Three non-linear regression models were developed to predict compressive strength as a function of RHA replacement percentage (R), curing age (T), and water-cement ratio (WC): a natural cubic spline model, an empirical physics-based exponential model, and a polynomial regression model. Model fitting and evaluation were performed in R statistical software. Model performance was assessed using the coefficient of determination (R^2), standard error, mean absolute error (MAE), mean absolute percentage error (MAPE), and mean bias error. The three models were formulated as follows.

(i) Spline model. A natural cubic spline model was fitted using basis-function expansions of each predictor:

$$f_c = \beta_0 + \Sigma_i \beta_{1i} B_{1i}(WC) + \Sigma_i \beta_{2i} B_{2i}(R) + \Sigma_i \beta_{3i} B_{3i}(T) \quad (2)$$

where B_{1i}, B_{2i}, and B_{3i} denote natural cubic spline basis functions (three degrees of freedom each) for water-cement ratio, RHA replacement percentage, and curing age, respectively, and β_0, β_{1i}, β_{2i}, β_{3i} are the fitted regression coefficients.

(ii) Physics-Based model. An empirical exponential model, structured to reflect strength gain with curing age and strength loss with water-cement ratio and replacement level, was fitted as:

$$F_c(T) = a \cdot e^{\wedge}(-b \cdot WC) \times (1 - c \cdot R) \times (1 - e^{\wedge}(-d \cdot T)) \quad (3)$$

where a, b, c, and d, are model parameters estimated by non-linear least squares fitting (a = 47.37, b = 0.97, c = 1.2, d = 0.16), WC is the water-cement ratio, R is the RHA replacement fraction, and T is the curing age in days.
(iii) Polynomial model. A second-order polynomial model incorporating two-way interaction terms was fitted as:

$$f_c = 32.725 - 45.453 \cdot WC + 12.375 \cdot WC^2 - 0.191 \cdot R - 0.006 \cdot R^2 + 0.629 \cdot T - 0.013 \cdot T^2 + 0.585 \cdot WC \cdot T + 0.118 \cdot WC \cdot R \quad (4)$$

where WC, R, and T retain the same definitions as above and the numerical coefficients were obtained by ordinary least squares regression.

Study Limitations in Design

Each of the four RHA replacement levels was tested at a single, distinct combination of curing age and water-cement ratio rather than at a full factorial combination of all three variables. Consequently, the effects of replacement percentage, curing age, and water-cement ratio are confounded across the four mixes and cannot be statistically isolated from one another, even though each individual mix result is itself the average of three replicate cubes. The regression models presented here should therefore be interpreted as an exploratory, small-sample comparison of model forms rather than as validated predictive tools for general use. This limitation is discussed further in Section 3.

3.1 Physical and Chemical Properties of RHA

Table 1 presents the oxide composition of the RHA used in this study, as determined by XRF analysis.

Table 1: Oxide Composition of Rice Husk Ash

Oxide	Symbol	Weight (%)
Silicon Oxide	SiO_2	85.00
Aluminium Oxide	Al_2O_3	0.85
Ferric Oxide	Fe_2O_3	0.80
Calcium Oxide	CaO	0.60
Magnesium Oxide	MgO	0.35
Potassium Oxide	K_2O	4.70
Manganese Oxide	MnO	0.02

The RHA exhibited a silica (SiO_2) content of 85.00%, with combined CaO and MgO content below 1%. According to ASTM C618 classification criteria [9], this composition is consistent with a Class N natural pozzolan, indicating strong potential for pozzolanic reactivity when used as a partial cement replacement.

Average Compressive Strength

Table 2 presents the average compressive strength (of three replicate cubes) recorded for each RHA replacement level, together with the associated water-cement ratio and curing age.

Table 2: Average Compressive Strength by Mix

Sample	RHA Replaced (%)	Water-Cement Ratio	Curing Age (days)	Average Compressive Strength (N/mm²)
A	2.5	0.40	7	20.12
B	15	0.45	14	23.18
C	5	0.50	21	39.09
D	12	0.65	28	29.47

The highest average compressive strength (39.09 N/mm²) was recorded for Sample C (5% RHA replacement, 21 days curing). Sample A (2.5% RHA, 7 days curing) recorded the lowest average strength (20.12 N/mm²), consistent with its shortest curing period among the four mixes.

This pattern is broadly consistent with the pozzolanic mechanism described in the literature: at low-to-moderate replacement levels, the high silica content of RHA reacts with calcium hydroxide released during cement hydration to form additional C-S-H gel, densifying the microstructure and enhancing strength [3], [4]. At higher replacement levels, the increased surface area of RHA particles raises water demand, which can increase porosity and offset the pozzolanic benefit [5]. However, this interpretation must be qualified: because each replacement level in this dataset was tested at a different curing age and water-cement ratio (Section 2.6), the observed strength differences cannot be attributed to RHA content alone. Sample C's peak strength coincided with the longest curing age among the lower-replacement mixes (21 days) and a mid-range water-cement ratio (0.50), both of which independently favor higher strength. The apparent optimal RHA level identified here is therefore a plausible but not isolated finding, and should be read as consistent with the wider literature on RHA optimum replacement ranges [4].

Experimental versus Predicted Compressive Strength

Table 3 compares the experimental compressive strength values with predictions from the Spline, Physics-Based, and Polynomial regression models (Equations 2–4).

Table 3: Experimental and Predicted Compressive Strength (N/mm²)

Sample	Experimental	Spline Model	Physics-Based Model	Polynomial Model
A	20.12	21.16	15.35	21.93
B	23.18	20.39	22.42	25.51
C	39.09	24.58	26.47	26.71
D	29.47	23.62	21.35	26.47

The Spline model predictions ranged from 20.39 to 24.58 N/mm², the Physics-Based model from 15.35 to 26.47 N/mm², and the Polynomial model from 21.93 to 26.71 N/mm². All three models underpredicted the peak experimental value recorded for Sample C.

Model Performance Statistics

Table 4 summarizes the statistical performance of the three regression models across the four data points.

Table 4: Model Performance Statistics

Model	R^2	Standard Error	MAE	MAPE (%)	Bias (Mean Error)
Spline	0.8310	7.9611	6.0425	18.52	5.5225
Polynomial	0.8310	7.8819	6.5625	21.69	6.5625
Physics-Based	0.5946	6.5396	4.8850	15.25	2.8050

The Spline and Polynomial models achieved identical R^2 values (0.8310), while the Physics-Based model recorded a notably lower R^2 (0.5946). On error metrics, the Spline model outperformed the Polynomial model (MAE 6.04 vs. 6.56; MAPE 18.52% vs. 21.69%), suggesting it fit the trend in the data slightly more efficiently despite the shared R^2. The Physics-Based model, despite its low R^2, recorded the lowest MAE (4.885) and bias (2.805) — an apparent contradiction explained by the small sample size: with only four data points, a model can track individual values reasonably closely in absolute terms while still explaining a smaller share of total variance, particularly if its errors are inconsistently distributed across the range of the data.

This tension is itself informative. It illustrates a known limitation of R^2 as a sole performance indicator in small-sample regression: R^2 is highly sensitive to the total variance present in a tiny dataset and can be misleading in isolation. A combined reading of R^2, MAE, and MAPE — rather than any single metric — supports the Spline model as the most balanced performer among the three tested, but this conclusion carries low statistical confidence given n = 4.

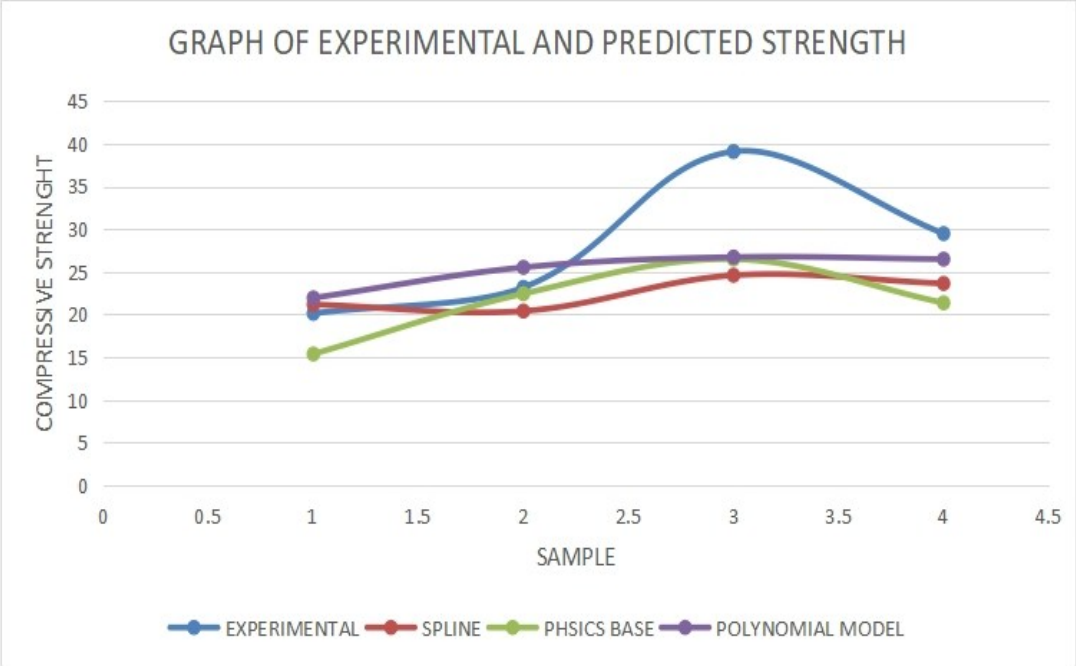


Figure 1: Graph of experimental vs predicted strength of the three (3 models)

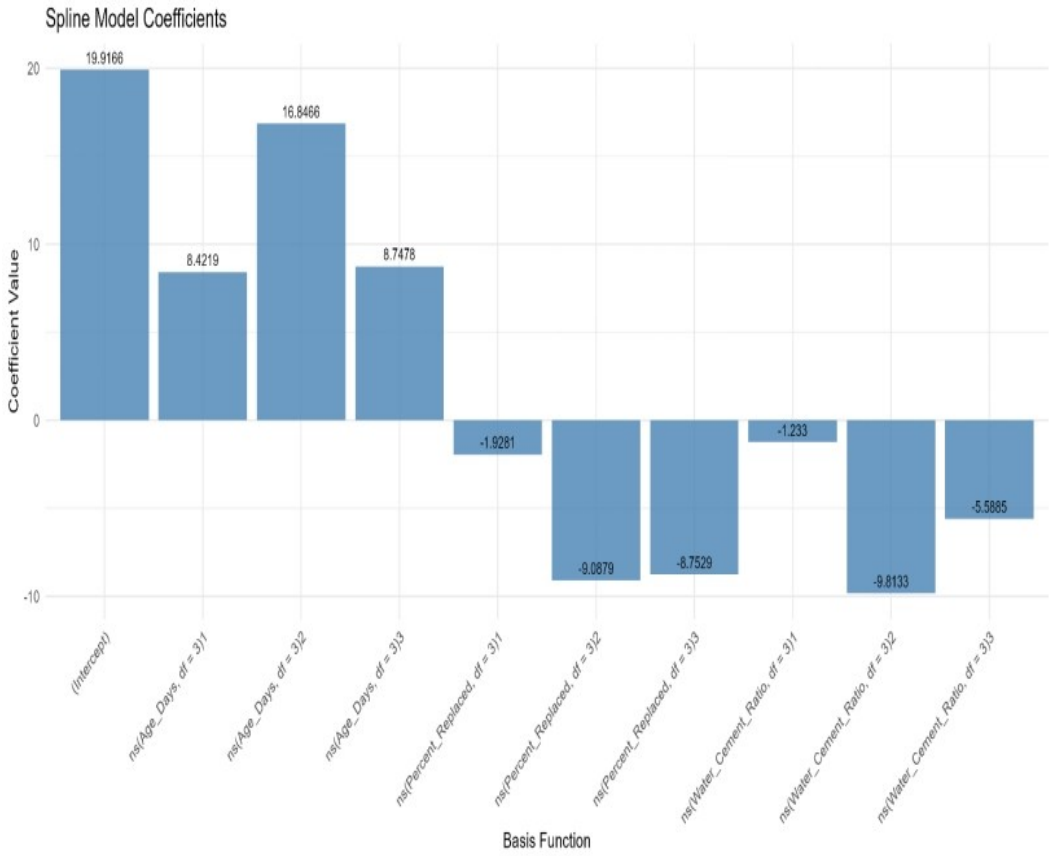


Figure 2: spline coefficient chart

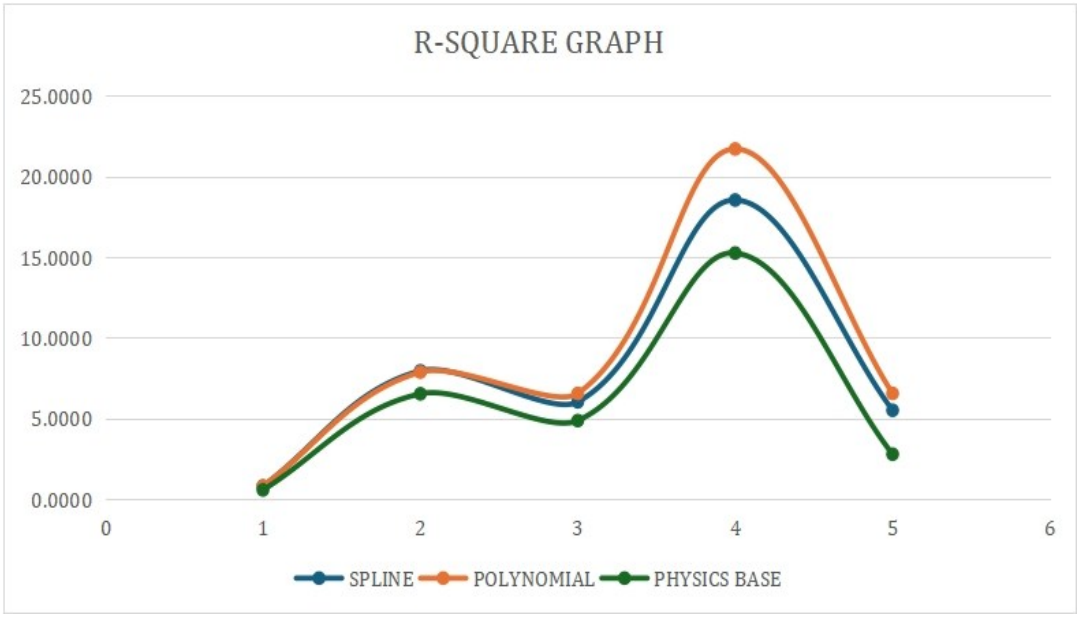


Figure 3: R-Square graph of the three (3) models

Comparison with Prior Studies

The general finding that moderate RHA replacement (around 5%) enhances strength while higher replacement reduces it aligns with previous experimental work on RHA-blended concrete [4], [5]. Likewise, the use of regression-type models to predict RHA-concrete strength is well established, with prior studies reporting strong correlations between predicted and experimental values [6]. However, most of that prior work relied on substantially larger, systematically varied datasets than the four-point dataset used here, which limits the extent to which the present spline and polynomial models can be considered validated in the same sense.

Limitations

This study has three material limitations that constrain the strength of its conclusions:

1. Confounded design: RHA replacement percentage, curing age, and water-cement ratio were not varied independently; each of the four mixes represents a unique combination of all three variables. This makes it statistically impossible to isolate the individual effect of RHA content on strength from the effects of curing age or water-cement ratio using this dataset alone.
2. Small sample size: with only four data points, the regression models, particularly the multi-parameter spline and polynomial forms, are close to interpolating through the available data rather than fitting a generalizable relationship. R^2 and error statistics calculated from four points carry substantial uncertainty and should not be read as equivalent to model validation on a properly sized dataset.

These limitations mean the findings should be treated as preliminary and hypothesis-generating rather than as a validated predictive framework ready for field application. A properly powered follow-up study — with RHA content, curing age, and water-cement ratio varied independently across a full factorial design, and a genuinely held-out test set — would be needed to confirm both the optimum replacement level and the relative performance of the three model types.

Conclusion

This study examined the effect of Rice Husk Ash (RHA) as a partial cement replacement on the compressive strength of concrete, and compared three non-linear regression approaches — Spline, Polynomial, and Physics-Based models — for predicting that strength. Based on the experimental and modelling results, the following conclusions are drawn:

1. XRF analysis confirmed the RHA used had a high silica content (85.00%) with low combined CaO and MgO content, consistent with a reactive pozzolanic material suitable for partial cement replacement.
2. Compressive strength was highest at 5% RHA replacement (39.09 N/mm² at 21 days) and lower at higher replacement levels (12% and 15%), a pattern consistent with the known pozzolanic behavior of RHA at moderate dosages and increased water demand at higher dosages. Because replacement level, curing age, and water-cement ratio were not varied independently in this dataset, this finding should be read as consistent with the established mechanism rather than as independent proof of an optimum replacement level from this study alone.
3. Among the three regression models tested, the Spline model showed the most balanced performance, combining a comparatively low mean absolute error and MAPE with the highest R^2 (tied with the Polynomial model). The Polynomial model showed a tendency toward larger errors despite matching R^2, and the Physics-Based model, while recording the lowest bias and MAE, explained the least variance ($R^2 = 0.5946$).

4. Given the limited sample size (n = 4) and the confounded experimental design, these modelling results are preliminary. They indicate the relative promise of spline-based regression for this application but do not constitute a validated predictive tool.

Recommendations

For practice:

1. Where field trials support it, RHA replacement in the range of approximately 2.5–5% by weight may be considered for applications prioritizing compressive strength, subject to local validation.
2. A well-controlled, moderate water-cement ratio should be maintained when incorporating RHA, given the sensitivity of RHA-blended mixes to water demand.

For future research:

1. A full factorial experimental design — independently varying RHA replacement percentage, curing age, and water-cement ratio, with adequate replication at each combination — is needed to properly isolate the individual effect of each variable and to validate the regression models proposed here.
2. A larger dataset, ideally with a held-out validation set, should be used to confirm which non-linear regression approach generalizes best for RHA-concrete strength prediction.
3. Future work should extend beyond compressive strength to include durability performance (e.g., resistance to sulfate and chloride attack) and microstructural analysis (e.g., SEM, XRD) to better characterize the pozzolanic reaction products.
4. Standardization of RHA sourcing and processing conditions would improve the comparability of results across studies and support broader industry adoption.

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