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RICE HUSK ASH AS PARTIAL REPLACEMENT OF CEMENT IN SUSTAINABLE CONSTRUCTION

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ABSTRACT

Alternative construction materials derived from agricultural waste, such as rice husk ash (RHA) and groundnut shell ash, have enhanced the sustainability and performance of concrete structures. The use of these ash materials, with their inherent pozzolanic and mineral admixture properties, has received much attention in the construction industry due to their potential benefits. In this experimental investigation, we assessed the attributes of cement paste incorporating RHA as a pozzolanic substitute. Various replacement ratios, ranging from 0% to 25% by weight of the binder, were examined at different water-to-binder ratios (0.40, 0.45, 0.50, and 0.55). Cementitious specimens were cast in 50mm x 50mm x 50mm cube molds, cured for seven days, and subjected to compressive strength testing. The findings highlight the impact of water-to-binder ratios and cement replacement levels on the compressive strength of cement paste. Higher water-to-binder ratios were associated with reduced compressive strength in the hardened paste. The optimal cement replacement levels were observed at 15% for the hardened blended paste specimens for all water-to-binder ratios. Two empirical regression models (polynomial and power) were employed to analyze the relationships between the paste's replacement ratios, water-to-binder ratios, and compressive strength. The models revealed consistent findings, with the power model demonstrating an inverse relationship between compressive strength and water-to-binder ratios, while the polynomial model's coefficients indicated a positive correlation between replacement ratios and compressive strength.

Keywords: Rice Husk Ash (RHA), Compressive Strength, Partial Replacement of cement, Cement-RHA Blended paste, and Empirical modeling

INTRODUCTION

In the early days of concrete technology, the use of admixtures and partial replacements of cement with supplementary cementitious materials (SCMs) were rare. Conventional concrete was made solely with cement, aggregates, and water, with Portland cement being the only binding material. Due to the global population increase and the need to build more civil engineering infrastructures, cement-based construction materials have increased exponentially. Cement production produces significant CO_2 emissions, contributing to global warming and climate change [Khan *et al*.,2012; Leung *et al*., 2014]. In response, modern concretes now almost universally incorporate mineral admixtures. Research has demonstrated that the partial replacement of ordinary Portland cement (OPC) with SCMs can bring numerous benefits, including improved mechanical properties, durability, cost savings, and environmental sustainability [Ahsan *et al*., 2018]. These advancements in concrete technology make the partial replacement of cement with SCMs a crucial area of research for engineers. As a result of the increasing global focus on reducing CO_2 emissions and improving the sustainability of construction materials, many researchers are now studying the potential of agricultural waste as a source of pozzolanic materials. One of the most promising sources among these agricultural waste components is rice husk and groundnut shell, which are readily available in large quantities and have been found to significantly improve the properties of concrete due to their high silica and or calcium oxide content. For example, rice husk is a by-product of rice production, and its ash has the potential to be used as a supplementary cementitious material due to its high silica content [Ahsan *et a*l., 2018]. For every ton of rice produced, 200 kg of rice husk can be obtained after tilling[Muleya *et al*., 2021]. Researchers are keenly exploring the advantages of partial cement replacement with rice husk ash (RHA) or blended RHA regarding both short-term and long-term effects on concrete. A study by [Viera *et al*., 2020; Venkatanarayanan *et al*., 2015] evaluated the impact of particle size and porous structure of RHA on the compressive strength, concluding that the evolution of strength at early ages (28 days) is influenced by particle size while the replacement ratio plays a significant role in strength evolution at later ages (after 28 days). Another study by [Ramezanianpour *et al*., 2009] found that concrete with RHA exhibited higher compressive strength, splitting tensile strength, and modulus of elasticity than ones without RHA. Furthermore, the presence of RHA in the mix improved durability and reduced chloride diffusion in concrete. Another study by [Ambedkar *et al*., 2017] found that incorporating RHA into cement concrete improved its durability compared to plain cement concrete.

A recent study by [Zaid *et al*., 2021]delivering energy through direct combustion as well as by gasifying. Annually, 7.4 million tons of Rice Husk Ash (RHA revealed that a 10% replacement of cement with RHA mixed with steel fibers gives the same compressive strength as the control specimen mix with zero percent replacement. In a similar study, [Singh *et al*., 2001] reported 10%, whilst [Chao-Lung *et al.*, 2011; Muthadni and Kothandaraman, 2013] reported that 20% of ground RHA could be beneficially blended with cement without adversely affecting the strength and durability properties of concrete. These findings emphasize the potential of RHA as a valuable supplementary cementitious material in sustainable concretes. Building upon the previous findings in the literature, this study delves into the impact of the partial replacement of cement with rice husk ash and water-to-binder ratio on the compressive strength of cement paste at an early age. Rice husk ash, a pozzolanic material, has been shown to enhance the cementitious properties of concrete in the presence of a lime-rich medium such as calcium hydroxide. The strength development of the concrete results from the reaction between silicates and lime, leading to the formation of secondary cementitious phases of calcium silicate hydrates, which show gradual strengthening after seven days. The extent of the strength development depends on the chemical composition of the pozzolanic material, with higher alumina, silica and vitreous phase content resulting in a stronger pozzolanic reaction. This study focuses on the impact of the partial replacement of cement with rice husk ash produced at a temperature of 600^{0}C and the water-to-binder ratio on the compressive strength of cement paste.

In this research, cement paste was used instead of mortar or concrete because cement paste provides a simplified and controlled material system consisting solely of cement and water, facilitating precise manipulation of composition and properties. Furthermore, this simplicity allows us to isolate and study the effects of RHA on cement at a fundamental level without the complicating factors introduced by aggregates found in mortar and concrete. Moreover, the findings from this study will provide a starting point for understanding how RHA interacts with cementitious materials, laying the foundation for future studies in mortar and concrete to explore practical applications and performance enhancements based on this foundational knowledge.

MATERIALS AND METHODS

Rice Husk Ash (RHA.)

Locally sourced rice husk was burnt to ash and utilized to replace cement in paste mixtures partially. A special furnace (Figure 1a) was designed and constructed at Kwame Nkrumah University of Science and Technology (KNUST.) Mechanical Engineering Laboratory for use in shift burning. This first shift burning was done in the open because of the release of smoke accompanied by the burning. The temperature during this burning ranges from 400 to 500^{0}C. The hotplate electric burner (Figure 1c) was used for the second shift burning inside the laboratory for one hour at a controlled temperature of 600^{0}C. The grinding process was carried out manually for about 30 minutes, and the resulting material was sieved through a BS standard sieve size 75μm. The chemical composition of the rice husk ash produced at the end of the two burning shifts is presented in Table 2. Table 1 shows the chemical content of the rice husk ash used for this study compared to that of other researchers. The rice husk production process is shown in Figure 1.

a. b. c.

Figure 1. Rice husk ash production- a. First-shift burning b. charred RHA c. Second-shift burning

Table 1 Chemical composition of rice husk ash in the current study compared to the results of other researchers.

Author/s	Incineration condition	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	Na_2O	K_2O	SO_3		TiO_2	LOI
[Thiedeitz *et* al., 2020]	500^{0}C for 3 hours	93.78	0.72	2.07	0.48	0.52	0,38	1.89	-	-	0.88	-
	600^{0}C for 4 hours	61.90	11.40	5.40	1.20	1.40	2.10	12.80	-	1.70	-	-
[Zaid *et al.*, 2021]	600^{0}C for 4 hours	62.60	5.10	6.90	3.30	3.40	2.50	10.30	-	2.90	-	-
	600^{0}C for 4 hours	59.50	8.80	7.30	2.10	2.20	3.00	12.60	-	2.00	-	-
	550^{0}C for 60 min	75.22	0.14	0.57	0.05	0.36	0.07	1.47	0.37		0.01	0.01
[Ramezanianpour *et al.*,2009]	550^{0}C for 90 min	80.76	0.09	0.66	0.03	0.43	0.05	1.72	0.23		0.01	0.01
	600^{0}C for 90 min	85.60	0.15	0.87	0.06	0.41	0.06	1.53	0.22		0.02	0.02
[Thiedeitz *et al.*, 2020]	650^{0}C for 3 hours	94.97	0.58	0.83	0.97	0.57	0.58	1.66	-	-	0.59	-

Table 1 Continued

	650^0C for 30 min	76.21	0.22	0.86	0.08	0.31	0.08	1.69	0.21		0.01	0.01
	650^0C for 60 min	89.61	0.22	0.91	0.04	0.42	0.07	1.58	0.15		0.02	0.02
	650^0C for 90 min	90.21	0.27	0.85	0.06	0.49	0.08	1.51	0.25		0.02	0.02
[Ramezanianpour *et al.*, 2009]	700^0C for 30 min	81.35	0.15	0.77	0.09	0.33	0.08	1.72	0.18		0.02	0.02
	700^0C for 60 min	89.93	0.11	0.88	0.06	0.39	0.09	1.48	0.14		0.02	0.02
	700^0C for 90 min	92.19	0.10	0.71	0.09	0.41	0.05	1.64	0.09		0.01	0.01
	750^0C for 30 min	84.22	0.18	0.54	0.09	0.38	0.06	1.35	0.17		0.02	0.02
	750^0C for 60 min	93.11	0.27	0.67	0.08	0.44	0.06	1.69	0.11		0.02	0.02
CURRENT STUDY (RHA.)	600 for 60 min	87.00	0.96	0.53	0.52	1.55	-	3.21	0.72	0.17	-	-

Ordinary Portland cement

Ordinary Portland cement (OPC) 42.5R, also known as CEM I 42.5R, as per the requirements of ASTM C150 [ASTM, 1953], was used in this study. It is a type of cement widely used in the construction industry in Ghana and the West African sub-region. GHACEM, the leading cement manufacturing company in Ghana, produces it. The chemical composition of the cement is found in Table 2.

Experimental Investigation

Chemical analysis of cement and RHA

The oxide composition analysis of the rice husk ash and cement was done using the X-ray fluorescence (XRF) test. X-ray fluorescence (XRF) is a common analytical technique used for the chemical analysis of cement and other materials such as pozzolanas. It relies on the interaction between X-rays and the material's atoms being analyzed. According to [Bediako and Amankwah, 2015], the XRF machine uses a polarized energy dispersion. About 4g of the sample was milled and mixed thoroughly to produce a homogeneous mixture. The mixture was then placed in the Spectro X-lab instrument to obtain the results of the chemical analysis. The results for the RHA and cement used in this study are shown in Table 2.

Table 2 Chemical composition of the rice husk ash and cement

Material	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	K_2O	SO_3	MnO
Rice husk ash (RHA.)	87	0.96	0.531	0.524	1.55	3.21	0.715	0.171
OPC (GHACEM 42.5 R)	23.9	3.56	57.6	5.45	3.82	0.75	3.89	0.074

Specimen preparation and description

A batching process was used for the preparation of materials for paste by partially replacing (0%, 5%, 10%, 15%, 20% and 25%) the cement with RHA and studying the effect at 0.40, 0.45, 0.50 and 0.55 w/b ratio for the paste. To ensure complete early-age hydration, the fresh paste was cast into 50mm x 50mm x 50mm molds and allowed to harden for the first 24 hours. After hardening, they were moist-cured for seven days. Table 3 shows the cement paste and mortar mix ratios and specimen descriptions. The effect of RHA on cement paste at different cement replacement ratios and w/b ratios was investigated at this curing age.

a. b. c. d. e.

Figure 2. Specimen preparation procedure (a. binder-cement+RHA, b. binder paste, c. binder paste in Molds, d. hardened binder paste, and e. specimen after compression test)

Table 3 Mix ratios and description of binder paste specimens

Mix ID	Specimen ID	Water-to-cement ratio	Percentage replacement (%)	Mass of cement (kg)	Mass of RHA. (kg)	Mass of water (kg)
M0	P40_00	0.40	0	0.265	0.000	0.106
	P45_00	0.45		0.265	0.000	0.119
	P50_00	0.50		0.265	0.000	0.133
	P55_00	0.55		0.265	0.000	0.146
M5	P40_05	0.40	5	0.252	0.013	0.106
	P45_05	0.45		0.252	0.013	0.119
	P50_05	0.50		0.252	0.013	0.133
	P55_05	0.55		0.252	0.013	0.146
M10	P40_10	0.40	10	0.239	0.024	0.106
	P45_10	0.45		0.239	0.024	0.119
	P50_10	0.50		0.239	0.024	0.133
	P55_10	0.55		0.239	0.024	0.146
M15	P40_15	0.40	15	0.225	0.034	0.106
	P45_15	0.45		0.225	0.034	0.119
	P50_15	0.50		0.225	0.034	0.133
	P55_15	0.55		0.225	0.034	0.146

Table 3 Continued

M20	P40_20	0.40	20	0.212	0.042	0.106
	P45_20	0.45		0.212	0.042	0.119
	P50_20	0.50		0.212	0.042	0.133
	P55_20	0.55		0.212	0.042	0.146
M25	P40_25	0.40	25	0.199	0.050	0.106
	P45_25	0.45		0.199	0.050	0.119
	P50_25	0.50		0.199	0.050	0.133
	P55_25	0.55		0.199	0.050	0.146

Compressive strength test

The test was done per ASTM C109/C109M-02 [ASTM, 2020], and the results are shown in Table 4. It has been reported that concrete exhibiting good compressive strength also shows higher durability [Ambedkar *et al*., 2017]. The specimens were removed from the curing tank a day before the test. A computer-aided Universal Testing Machine (UTM) was used for the compression test. The specimens were carefully placed in the testing machine to achieve uniform load distribution on the chosen contact surfaces.

Empirical modeling

In this section, the empirical modeling undertaken to establish relationships between water-to-binder and RHA replacement ratios and compressive strength are presented. The primary objective was to derive models that could accurately predict compressive strength based on varying water-to-binder and replacement ratios.

Power modeling of compressive strength

To understand the effect of the water-to-binder ratio on compressive strength, we employed a power model given by Equation (1):

$$f_{cu}^{\psi} = \frac{\alpha_1}{(\psi)^{\alpha_2}} \qquad (1)$$

where f_{cu}^{ψ} = compressive strength as a function of water-to-binder ratio, α_1 and α_2 = the model coefficents, and ψ = water-to-binder ratio. MATLAB® was utilized as our modeling tool for this investigation. We derived the coefficients α_1 and α_2 through rigorous regression analysis, ensuring a 95% confidence interval for statistical validity.

Polynomial modeling of compressive strength

The relationship between replacement ratio and compressive strength was explored using polynomial modeling. Specifically, a second-degree polynomial model was employed, as shown in Equation (2):

$$f_{cu}^{r} = \beta_1 r^2 + \beta_2 r + \beta_3 \qquad (2)$$

where f_{cu}^{r} = compressive strength as a function of replacement ratio, β_1 , β_2 and β_3 = the model coefficients. Similarly, MATLAB® was employed to perform this modeling, and the coefficients β_1 , β_2 and β_3 and were obtained with a 95% confidence interval, ensuring robust statistical reliability.

Table 4 Compressive test results of paste for 7 days curing ages

Mix ID	Specimen ID	Water-to-cement ratio	Percentage replacement	Compressive Strength (f_{cu}) MPa)
M0	P40_00	0.40	0	26.3
	P45_00	0.45		23.2
	P50_00	0.50		17.0
	P55_00	0.55		14.7
M5	P40_05	0.40	5	24.2
	P45_05	0.45		19.1
	P50_05	0.50		16.2
	P55_05	0.55		14.7
M10	P40_10	0.40	10	24.4
	P45_10	0.45		19.9
	P50_10	0.50		17.7
	P55_10	0.55		15.5
M15	P40_15	0.40	15	25.8
	P45_15	0.45		23.5
	P50_15	0.50		18.3
	P55_15	0.55		16.6
M20	P40_20	0.40	20	23.6
	P45_20	0.45		20.6
	P50_20	0.50		18.1
	P55_20	0.55		16.5
M25	P40_25	0.40	25	19.8
	P45_25	0.45		17.5
	P50_25	0.50		17.3
	P55_25	0.55		15.7

Model validation and significance

It is worth noting that the models' coefficients were determined with a 95% confidence interval, indicating a high degree of confidence in the accuracy and reliability of the models. These empirical models provide valuable insights into the relationships between water-to-binder ratio, compressive strength, and replacement ratio and compressive strength.

In section 4.3, we will present the results of our empirical modeling, including graphical representations and discussions of the model's significance in the context of our study. These models offer a practical tool for predicting compressive strength based on specific water-to-binder ratios and replacement ratios of hardened paste and specimens manufactured with RHA.

RESULTS AND DISCUSSIONS

Chemical composition of RHA

Based on the chemical analysis of the RHA sample, the sum of Silica (SiO_2), Ferrous oxide (Fe_2O_3) and Aluminium oxide (Al_2O_3) constituted 88.48% per unit weight of the RHA sample, and the Sulphite (SO_3) content was found to be less than 5%. This is in accordance with the minimum standards set by ASTM C-618-03 [ASTM, 2003] for a material to be classified as a pozzolana. This implies that the RHA used in this study meets the standards to be classified under classes N, F and C pozzolana and could partially replace cement in cementitious composites.

Compressive Strength

Table 4 presents the results of compressive strength tests conducted on blended cement paste samples with varying w/b ratios and RHA-replacement ratios. The compressive strength values, measured in MPa, are reported as averages of three specimens for each w/b ratio (0.40, 0.45, 0.50 and 0.55) and mix groups (M0, M5, M10, M15, M20 and M25). The findings in Figures 3 and 6 suggest that an increase in the w/b ratio decreases the compressive strength for all mixes. This could be attributed to the increase in porosity because of the increase in the w/b ratio. This trend is consistent with the behaviour of hydraulic cement paste mixes, where a higher w/b ratio leads to reduced strength due to inadequate hydration products to fill the pores [Zivica, 2009]. The results also indicate that increasing the replacement ratio of RHA typically increases the water demand and reduces the compressive strength of the blended cement paste[Ogork *et al*., 2015]. This is likely due to RHA's lower reactivity than cement, which results in reduced strength gain[Oyekan and Kamiyo, 2011]. However, the impact of RHA on compressive strength varies depending on the replacement ratios (Figures 3 and 5). For example, the strength of the 15% replacement ratio tends to be highest for all w/b ratios. This suggests that the use of RHA has a pozzolanic effect and can have a beneficial effect on strength. In addition, using RHA in blended cement paste can positively and negatively affect compressive strength depending on the replacement ratio and the w/b ratio used. Generally, a decrease in strength is observed as the replacement ratio increases (Figure 5). The general decrease in compressive strength is attributed to the reduction in the cement content, which leads to a decrease in the amount of hydration products available to fill the pores due to the increase in RHA content [Ogork *et al*., 2015]. The lower amount of cement and the higher amount of RHA lead to a reduction in the amount of C-S-H gel and CH, which results in insufficient CH to react with RHA for improved mechanical strength.

The maximum compressive strength for all w/b ratios was observed at the 15% replacement ratio (Figure 3), implying that the 15% RHA replacement ratio was the optimum ratio for all w/b ratios.

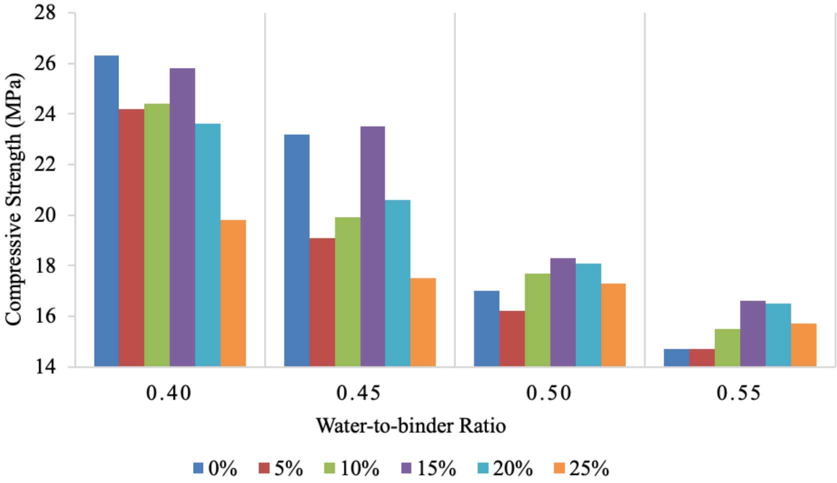

Figure 3 Compressive strength of cement paste for different replacement ratios at different w/b

Empirical modeling

Power model

It can be observed from Figure 4 that the compressive strength decreases non-linearly as the water-to-binder ratio also increases. This is a consistent, well-established inverse relationship between the compressive strength of cementitious composites and the water-to-binder ratio. Moreover, this finding is consistent for all the replacement ratios.

Polynomial model

The relationship between the replacement ratios and compressive strength at different water-to-binder ratios is shown in Figure 5. In general, the compressive strength of the paste increases with an increase in the replacement ratio up to a replacement ratio of 15% and then decreases. Unlike the experimental data that showed a constant optimum replacement ratio for all w/b ratios, the model predicted different values for the optimum replacement ratios ranging from 12,10% to 17.38% (Table 5 and Figure 8)

Models validation and significance

(a) Model coefficients

The coefficients of the polynomial model (Equation (2)), including β_1, β_2, and β_3, offer valuable insights into the model's behaviour. It was found that β_2 consistently exhibits a positive value across all water-to-binder ratios (Figure 7), indicating a direct relationship between the replacement ratio and compressive strength. This observation aligns with concrete mixture expectations, where incorporating supplementary cementitious materials (e.g. RHA) can positively influence compressive strength. Furthermore, the magnitude of β_2 varies across different water-to-binder ratios, suggesting that the specific water-to-binder ratio influences the effect of the replacement ratio on compressive strength. Conversely, β_1 consistently displays a negative value, indicating an inverse relationship between the water-to-binder ratio and compressive strength. As the water-to-binder ratio decreases, compressive strength tends to increase, consistent with well-established principles in concrete mix design. This suggests that the replacement ratios could not alter this well-known fact. Additionally, β_3, representing the constant term, contributes to the overall compressive strength prediction and exhibits variability across different water-to-binder ratios.

The relationship between and the replacement ratio is characterized by a positive correlation (Figure 6), suggesting an increase in the replacement ratio corresponds to an increase in the baseline compressive strength (replacement ratio of 0%), assuming a constant water-to-binder ratio. This positive association aligns with the expectation that higher replacement ratios, substituting more cement with materials like supplementary cementitious materials, enhance compressive strength. Conversely, the relationship between and the replacement ratio demonstrates an inverse connection. As the replacement ratio increases, decreases, indicating a diminishing sensitivity of the compressive strength to changes in the replacement ratio. In other terms, higher replacement ratios yield a reduced impact on the rate of change in compressive strength concerning variations in the replacement ratio. This suggests that as the replacement ratio increases, the changes in replacement ratio influence on the compressive becomes less pronounced.

(b) Optimum Replacement Ratio (r^{opt} (%))

The optimum replacement ratio represents the value of the replacement ratio at which the model predicts the maximum compressive strength. For all water-to-binder ratios, the optimum replacement ratio measured experimentally is 15%, as shown in Figure 3. However, the model predicts an optimum replacement ratio that ranges from 12.10 % to 17.38% (Figure 8). Figure 8 shows the variation of the predicted optimum replacement ratio and the percentage difference over the range of water-to-binder ratios considered in the study. The model underpredicted the optimum replacement ratios for water-to-binder ratios of 0.40 and 0.45 but predicted for 0.50 and 0.55. This information is valuable for concrete mix design, indicating the ideal replacement ratio to achieve the highest compressive strength.

(c) Percentage Difference (ε %)

The percentage difference between the experimental and model-predicted optimum replacement ratio provides insights into the model's accuracy (Figure 8). Positive values indicate that the model underestimates the optimum replacement ratio, while negative values suggest overestimation. The magnitude of the percentage difference varies for different water-to-binder ratios, indicating that the specific water-to-binder ratio influences the model's performance.

(d) Coefficient of Determination (R^2)

The coefficient of determination (R^2) measures how well the models fit the experimental data. A high R^2 value indicates that the model predicts the experimental data well. In the case of the polynomial model, the R^2 values range from 0.7768 to 0.9967, suggesting that the polynomial model best fits the experimental data for each water-to-binder ratio. For the power model, R^2 values are generally relatively high, ranging from 0.9290 to 0.9985. These high R^2 values suggest that the model fits the data well and explains a significant portion of the variability in the compressive strength.

Table 5. Model parameters and model performance index for the model

Water-to-binder ratio,				R^2	Optimum replacement ratio, r^{opt} *(%)*		Percentage difference, ε (%)
					Experimental	Model	
0.40	-0.03314	0.8023	20.64	0.9287	15	12.10	19.33
0.45	-0.04086	1.1760	13.72	0.7768	15	13.34	11.07
0.50	-0.01546	0.5149	14.04	0.9967	15	16.69	-11.27
0.55	-0.01257	0.4371	12.70	0.9356	15	17.38	-15.87

Table 6. Model parameters and model performance index for the model

Repalcement ration, *r* (%)			R^2
5	5.304	-1.640	0.9837
10	6.549	-1.424	0.9914
15	7.011	-1.444	0.9545
20	8.27	-1.143	0.9985
25	10.55	-0.6744	0.9290

CONCLUSION

The study investigated the effect of rice husk ash (RHA) on the mechanical properties of hardened cement paste. Compressive strength tests were conducted on five different blended cement paste samples with varying water-to-binder ratios and percentages of RHA. The findings from the study are summarized as follows:

a. Found that increasing water-to-binder ratios reduce compressive strength while increased RHA content initially enhances it until an optimum replacement ratio is reached.

b.

c. Beyond the optimum ratio, compressive strength decreases, with the most significant decline observed at higher replacement levels beyond 15%.

d. The effects of RHA on compressive strength depend on the water-to-binder ratio, with 15% RHA replacement being optimal for strength improvement due to the pozzolanic effect.

e. The study's findings can be used to optimize RHA usage in blended cement paste production for construction.

f. The empirical modeling study revealed consistent relationships between replacement ratios, water-to-binder ratios, and compressive strength, offering valuable insights for concrete mix design. The models' reliability, coefficient analyses, and practical implications underscore their significance in explaining compressive strength variations.

The authors are currently investigating the effects of rice husk ash in concrete mixtures on other properties, such as the concrete's flexural and shear strengths, tensile strength, and durability.

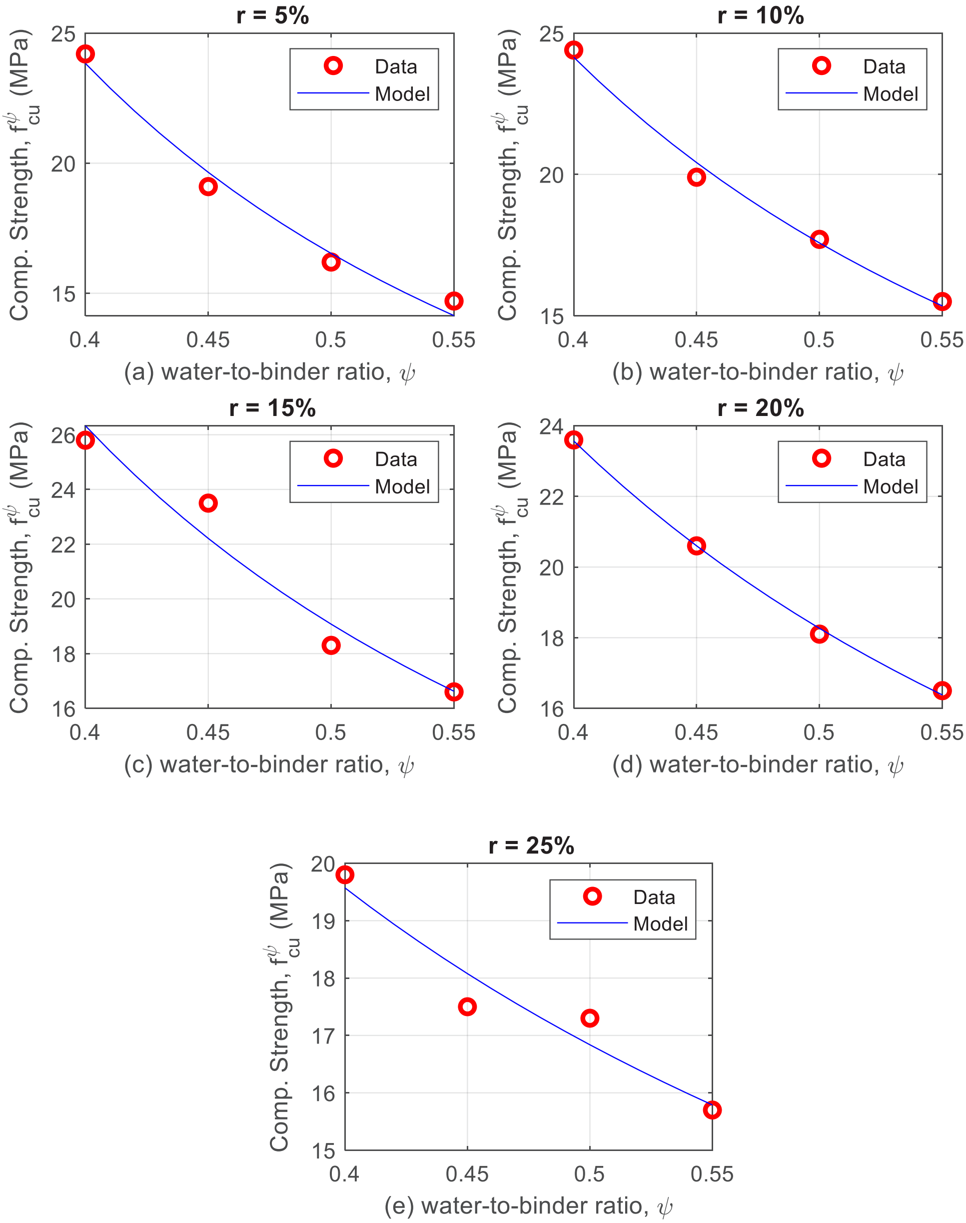

Figure 4. Relationship between water-to-binder ratio and the compressive strength of the hardened paste at different replacement ratios ((a) 5% to (e) 25%)

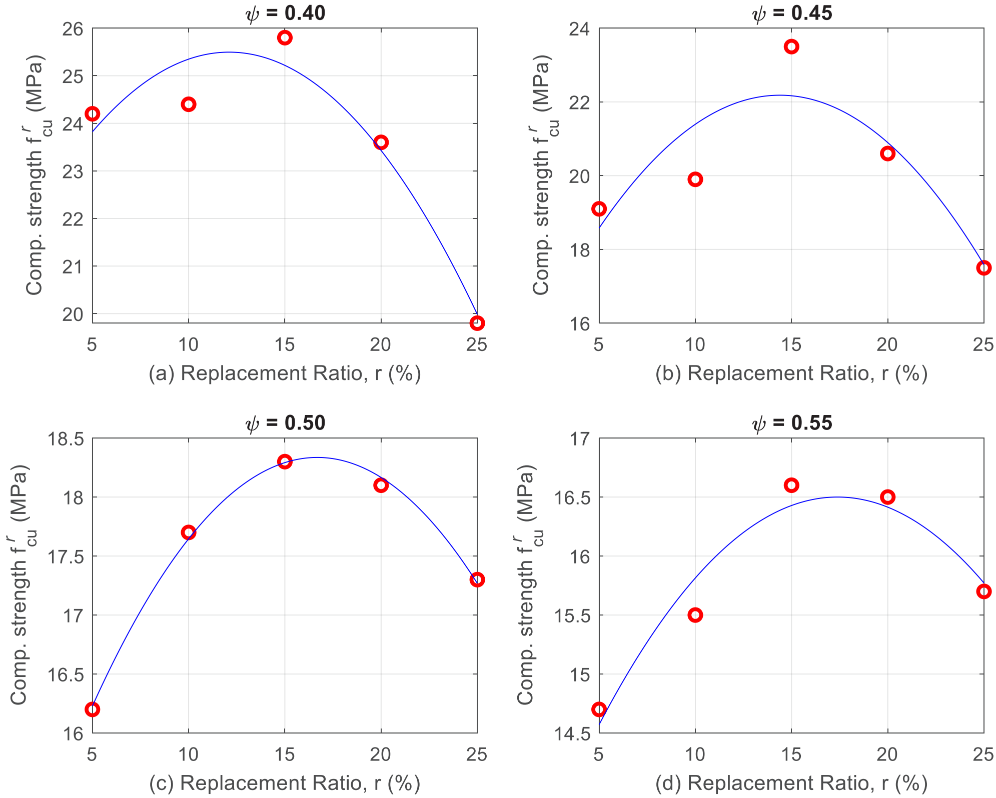

Figure 5. Relationship between cement replacement ratio and the compressive strength of hardened paste at different water-to-binder ratios ((a) 0.40 to (d) 0.55)

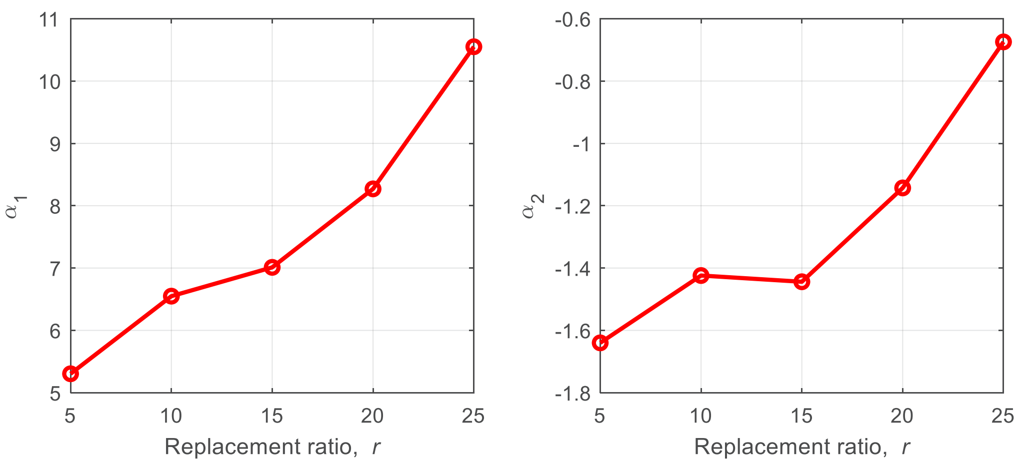

Figure 6. Variation of the model coefficients of the $f_{cu}^{\psi} - \psi$ model with replacement ratio

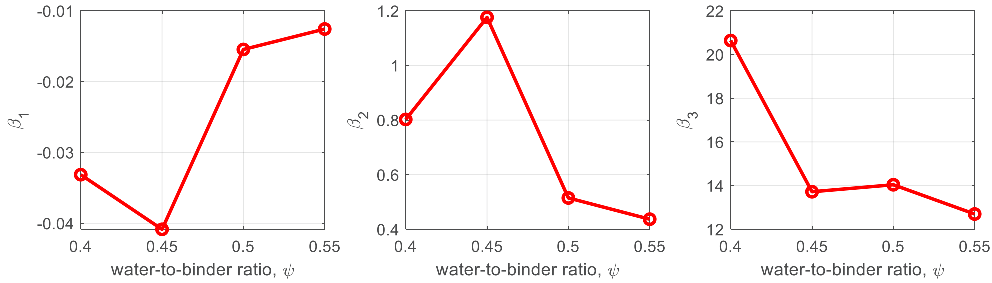

Figure 7. Variation of the model coefficients of the $f_{cu}^{r} - r$ model with replacement ratio

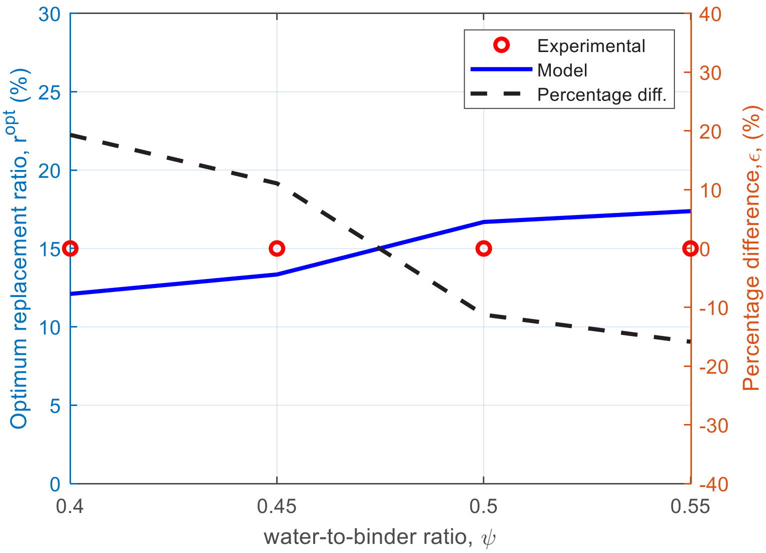

Figure 8. Variation of optimum replacement ratio and percentage difference with water-to-binder ratio

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DECLARATION OF CONFLICT OF INTEREST

No conflict of interest exists.

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