

Multi-Objective Optimization of Workability and Durability Properties of Eco-Friendly Lightweight Concrete Incorporating Rice Husk Ash and Sheep Wool Fibre

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Abstract

The rising demand for sustainable construction materials has encouraged the incorporation of agricultural and natural fibres into cementitious composites. This study investigated the combined effects of Rice Husk Ash (RHA, 0–20% cement replacement) and Sheep Wool Fibre (SWF, 0–2% by weight) on the properties of lightweight concrete. Central Composite Design (CCD) and Response Surface Methodology (RSM) were used to evaluate workability, water absorption, and resistance to acid attack. Quadratic models successfully predicted the responses. Multi-objective optimization identified the ideal mix of 10% RHA and 1% SWF, achieving a slump of 128.5 mm, water absorption of 2.3% (14-days) and 3.88% (28-days), and residual compressive strengths of 3.65 MPa (14 days) and 4.9 MPa (28 days) after acid exposure, with 75.1% desirability. Experimental validation showed prediction errors below 5%. The results highlight the potential of RHA-SWF lightweight concrete as an affordable and environmentally friendly option for sustainable construction in resource-limited areas.

Keywords: *Rice Husk Ash, Sheep wool Fibre, Response Surface Methodology, Fresh properties, Durability Property, lightweight concrete*

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Background to the Study

The combined needs of servicing growing infrastructure demand and reducing its substantial environmental impact present a perpetual challenge to the global construction sector. Agricultural by-products are one of the most widely used materials in the production of conventional concrete which mainly replace cement and natural aggregates. Approximately 5-8% of the world's anthropogenic carbon dioxide (CO₂) emissions originate from the production of ordinary Portland cement (OPC), a process that is both energy-intensive and environmentally detrimental (Scrivener et al. 2018). Concurrently, widespread natural coarse aggregate quarrying results in resource depletion, ecological devastation, and landscape deterioration (Monteiro et al. 2017). At the same time, a serious waste management dilemma is brought on by the growing amount of industrial and agricultural waste.

Rice husk is an agricultural waste product which causes environmental issues such as air and water pollution during high winds and transported into sewers, contributing to sewer flooding within the neighborhood during intense rainfall. The rice husk has a disposal issue in most countries. Wool fibers have gained attention for their unique properties, including low thermal conductivity, biodegradability, and sustainability. While wool has been extensively used in textiles, its application in construction materials is a relatively newer area of exploration. Studies by Adefisoye et al. (2025); Sonebi and Kwasny (2018) have demonstrated the potential of wool fibers in improving the mechanical properties of cement-based materials and reducing their environmental impact. The development of structural lightweight concrete (LWC) is a key tactic in this green construction trend. One of LWC's many benefits is a lower dead load, which enables smaller foundations and structural components and saves money. Additionally, LWC has better fire resistance and thermal insulation qualities (Neville, 2011). In order to produce LWC, traditional normal-weight aggregates are usually partially or completely replaced with lighter substitutes. By turning waste into useful resources, the idea of using industrial and agricultural by-products as partial substitutes for cement has gained significant popularity (Mehta & Monteiro, 2014). This method significantly lowers the total embodied energy and carbon footprint of concrete while also preserving virgin resources and easing waste disposal issues (Schneider, 2011).

Among the many possible waste products, Rice Husk Ash (RHA) and Sheep wool Fibre (SWF) stand out as particularly attractive options due to their availability, affordability, and unique material properties. RHA, a large by-product of the world's rice processing industries is frequently disposed of expensively. The ash that results from controlled combustion however, has pozzolanic qualities, which means that it includes siliceous and aluminous elements that can react with calcium hydroxide, a byproduct of cement hydration, to generate more cementitious compounds or C-S-H gel (Nascimento, et al, 2023; Raheem & Adenuga, 2013). For partial cement substitution, this makes RHA a feasible supplementary cementitious material (SCM), comparable to more well-known alternatives like fly ash and Sawdust ash. In addition, Sheep wool Fibre, a hard and resilient animal waste from the thriving wool industry, has qualities that make it a promising candidate to function as an

additive in concrete. Research has indicated that SWF has low weight, toughness, and inherent susceptibility to water and deterioration can help produce structural lightweight concrete that is strong enough, (Mehta & Monteiro, 2014).

The investigation of locally accessible waste materials has accelerated recently, progressing from traditional supplemental cementitious materials (SCMs) to more innovative substitutes. In recent years, the pozzolanic potential of RHA has been further clarified and verified. By optimizing the use of RHA and quarry dust in concrete, Sonebi and Kwasny (2018) showed that an acceptable compressive strength could be achieved with up to 15% RHA substitution. Nevertheless, incorporating these minerals into concrete is not a simple replacement. The proportions of its component constituents have a complicated and non-linear effect on the final concrete's performance. The replacement amounts of both RHA and SWF have a significant impact on the final mechanical characteristics (compressive strength, split tensile strength, and flexural strength), workability, setting time, and water consumption (Montgomery, 2017). An ideal blend is essential; too much RHA and Sheep wool Fibre replacement in cement can result in a dilution effect and slower pozzolanic reactions, which can reduce early strength (Montgomery, 2017; Habeeb & Mahmud, 2010). Therefore, a major and challenging engineering problem is to figure out the exact mix that maximizes the advantages—achieving the intended lightweight qualities while meeting the target mechanical performance.

Conventional experimental methods for concrete mix optimization, which change one factor at a time (OFAT), are ineffective, resource-intensive and time-consuming. Furthermore, the intricate synergistic relationships between many mix design elements cannot be captured by OFAT approaches (Raheem & Adenuga, 2013). Applying sophisticated statistical and an optimization method, a potent set of statistical and mathematical techniques known as Response Surface Methodology (RSM) is capable of modeling, analyzing and optimizing processes in which a response of interest is impacted by several independent factors (Adamu et al. 2021). RSM may be used to generate exact prediction models for mechanical properties as functions of RHA and SWF substitute levels within the context of concrete mix design.

Additionally, depending on predetermined criteria, it may determine the percentage that provides the highest overall performance and produce numerical optimization solutions to detect significant correlation effects between these variables (Adamu et al. 2020; 2022). The practice of integrating various waste products is becoming more popular, and Response Surface Methodology is being used in more complex ways. By using RSM to optimize a lightweight concrete mix with calcium carbide and oil lateritic soil aggregate, Khalid, et al (2024) showed how effective the approach is at balancing several responses, including cost, density, and strength. Using fly ash and quarry dust, Montgomery (2017) conducted multi-objective optimization research on concrete, effectively identifying Pareto-optimal solutions that met the competing objectives of maximizing strength and minimizing cost. Adamu, et al (2021) successfully modeled the interaction between flow ability, passing ability and strength by using RSM to create self-compacting concrete that included waste marble

powder and copper slag. However, a study of hybrid systems such as rice husk ash and recycled aggregate by Habeeb and Mahmud (2010) identified a common flaw: many researches do not take a systematic approach to modeling the interactions between the combined materials, which frequently results in less-than-ideal combinations (Ali, et al. 2018). Additionally, a gap noted by Habeeb and Mahmud (2010) is the underutilization of RSM for novel hybrid waste combinations, especially those that involve an agriculturally based lightweight aggregate and an agriculturally based SCM, where the performance critical interaction effects are largely unknown.

Recent research demonstrates the effectiveness of RSM for concrete optimization while confirming the separate advantages of RHA and SWF. A rigorous examination, however, identifies an important, unexplored area. Although research like Neville (2011) highlight RSM for waste-derived concrete, they focus on other, more well-known material combinations (such as fly ash and oil palm shell). Critically, there is a glaring lack of studies that employ a strong statistical framework to systematically examine the synergistic effects of mixing rice husk ash (RHA) and Sheep wool Fibre (SWF) within a single concrete matrix. The goal of this study is to close this crucial gap by offering a thorough, data-driven examination of this innovative hybrid lightweight concrete and using RSM to maximize its sustainable performance. In light of this, the main goal of this research is to use Response Surface Methodology to predict and optimize the mechanical and workability characteristics of lightweight concrete that contains rice husk ash and Sheep wool Fibre.

Materials and Methods

Materials

Grade 42.5N Portland limestone cement manufactured in Nigeria as Dangote brand was used for this experimental investigation, the river sand used as fine aggregate was procured within Kano state Nigeria. Sieve analysis and specific gravity of the aggregates were also determined in accordance with BS 1881. The coarse aggregate used for this research were typically angular in shape, well graded for conventional concrete. Water used for this research was obtained from the laboratory tap and was found adequate for the experiment. The rice husk used in this research was procured in a nearby rice milling factory in Kano state Nigeria. It was sun-dried for 10 days to remove excess moisture to aid the burning process. The samples were burnt openly and then rice husk Ash was obtained at a control temperature ranging from 600°C for 2hrs. The ash was allowed to cool before sieving through sieve 75 µm and the retained material obtained was used for the experiment. The characterization test and specific gravity test for the sample was observed in accordance with BS 1881.

Fine Aggregate is an essential material of concrete, for this study, the river sand in Kano was considered for the experiment. Sieve analysis and specific gravity of the aggregates were also determined. The coarse aggregate chosen for the concrete was typically angular in shape, well graded and smaller than maximum size suited for conventional concrete conformed to BS 1881. Water is an important ingredient of concrete as it actually participates in the chemical reaction with the cement. Since water improves the strength of cement in concrete, the

quantity and quality of water are required to be looked in to very carefully. Fiber reinforced cementitious composites are gaining attention in construction industry because of the high strength, ductility and energy absorption capacity. Concrete production is still under consideration to improve the sustainability and environmental safety. Therefore, natural fiber reinforced concrete is the good alternative. Although sheep wools are producing a huge amount of waste, which can be utilized as building material in concrete if properly recycled. The addition of sheep wool in concrete mix was not very new; it has been used for insulation purposes. In this research, the utilization of sheep wool fiber in the production of lightweight concrete is considered.

Sieve Analysis

The sieve analysis results of the coarse and fine aggregates are presented in Figure 1 below.

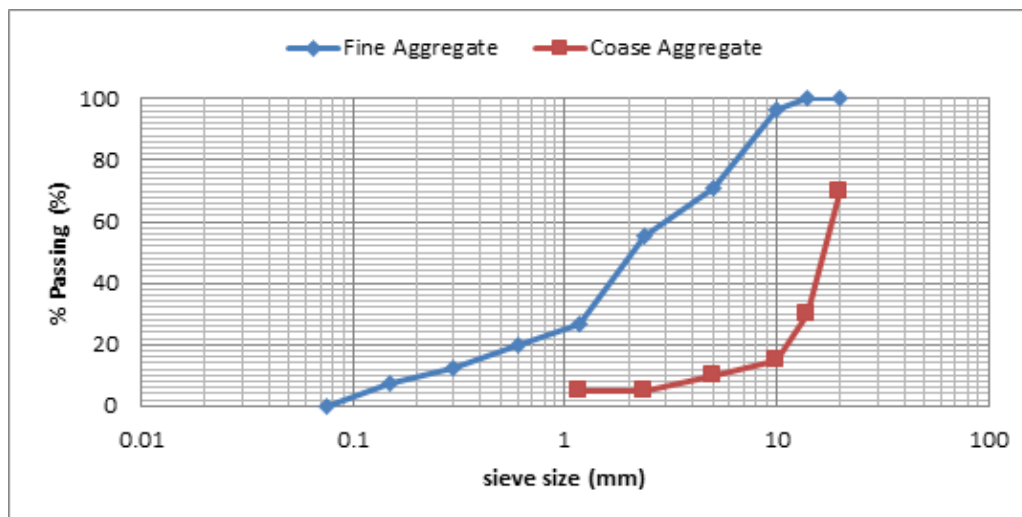


Figure 1: Particle size distribution curve of Aggregates

Specific Gravity

The specific gravity test on RHA, SWF, fine aggregate and coarse aggregate were conducted in accordance with BS EN 12620 (2013), their result were found to be 1.03, 0.18, 2.59 and 2.34 respectively using equation 1 below:

$$SG = \frac{w_2 - w_1}{(w_4 - w_1) - (w_3 - w_2)}$$

Where; W_1 = Weight of empty bottle, W_2 = Weight of bottle + Sample, W_3 = Weight of bottle + Sample + Water, W_4 = Weight of bottle + Full Water

Mix Design

Response Surface Methodology analysis was used to establish appropriate portions of cement, RHA, SWF, coarse aggregate, fine aggregate and water to obtain the desirable

workability and mechanical properties of the lightweight concrete. The concrete's mix proportion was formulated using the principles specified in the building research establishment (BRE) mix design method (Formerly known as the DOE method). In this study, Response Surface Methodology analysis was performed using Design Expert version 13 to develop a statistical model of lightweight concrete modified with Sawdust Ash and Coconut Shell using a central composite design (Adamu et al. 2022). Rice Husk Ash and sheep wool fibre serving as independent variables at Five (5) levels correspond to each parameter: 0% to 20% Rice Husk Ash in place of cement and likewise, the percentages of sheep wool fibre in 0% to 2% as additive.

Table 1: The Mix Proportion of concrete materials based on RSM Analysis

MIX ID	OPC Kg/m ³	F Agg Kg/m ³	C Agg Kg/m ³	Water (kg/m ³)	RHA Kg/m ³	SWF Kg/m ³
mix 1 (15RHA1.5SWF)	462.924	577.5	1312	180.26	83.16	8.316
mix 2 (10RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 3 (10RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 4 (5RHA0.5SWF)	523.908	577.5	1312	180.26	27.72	2.772
mix 5 (10RHA0SWF)	498.96	577.5	1312	180.26	55.44	0
mix 6 (15RHA0.5SWF)	468.468	577.5	1312	180.26	83.16	2.772
mix 7 (10RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 8 (10RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 9 (10RHA2SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 10 (20RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 11 (0RHA1SWF)	548.856	577.5	1312	180.26	0	5.544
mix 12 (10RHA1SWF)	493.416	577.5	1312	180.26	55.44	5.544
mix 13 (5RHA1.5SWF)	518.364	577.5	1312	180.26	27.72	8.316
mix 14 (0RHA0SWF)	554.4	577.5	1312	180.26	0	0

The above table shows the mix proportion of the concrete materials used to prepare the lightweight concrete. Design Expert software was used to generate 13 mixes by the various combinations of factors summarized in Table 1. There are four (4) factorial points, four (4) axial points and five (5) center points in the Thirteen (13) mixes. The center points are mixed combinations that are repeated. The repeated mixes also known as duplicated design points used to determine the model's lack of fit. The "Lack of Fit Tests" chart contrasts the "Pure Error" from duplicated design points with the residual error. The model should not be utilized as a response predictor if there is a significant lack of fit, as shown by a low probability value ("Prob > F") (Adamu et al. 2020; 2021; 2022).

Result and Discussion

Slump Test Result

The slump test results presented in Figure 6 below indicate that the workability of the concrete mixes varied between 100 mm and 170 mm across different proportions of RHA

and SWF. Furthermore, mixes containing higher levels of RHA and SWF showed reduced slump values compared to mixes with lower replacement levels. The results indicate that the addition of these materials has a significant influence on fresh concrete workability. The reduction in slump can be as a result of two main factors: Effect of RHA and SWF have a high specific surface area and is highly porous. When incorporated as a partial cement replacement, it tends to absorb more mixing water, reducing the free water available in the mix. This leads to a stiffer mix and hence lower slump values. Similar findings were reported by Scrivener, et al (2018) who observed a consistent reduction in workability with increasing RHA content. The Effect of SWF increases the internal friction within the concrete, reducing its flow ability. The fibre also absorb water and promote interlocking effects, further reducing slump. Adefisoye et al. (2025) reported that natural fibre generally reduces workability due to balling effects and increased viscosity of the fresh mix. Despite the reduction in slump, certain mixes (e.g., those around 160–170 mm) exhibited good workability. This could be due to the balance between RHA's fine particles filling voids and the moderate content of SWF improving cohesion without causing excessive stiffening. Ali, et al (2018) highlighted that wool fibre, though reducing flow, can improve the cohesiveness of the mix and minimize segregation—an advantage in lightweight concretes.

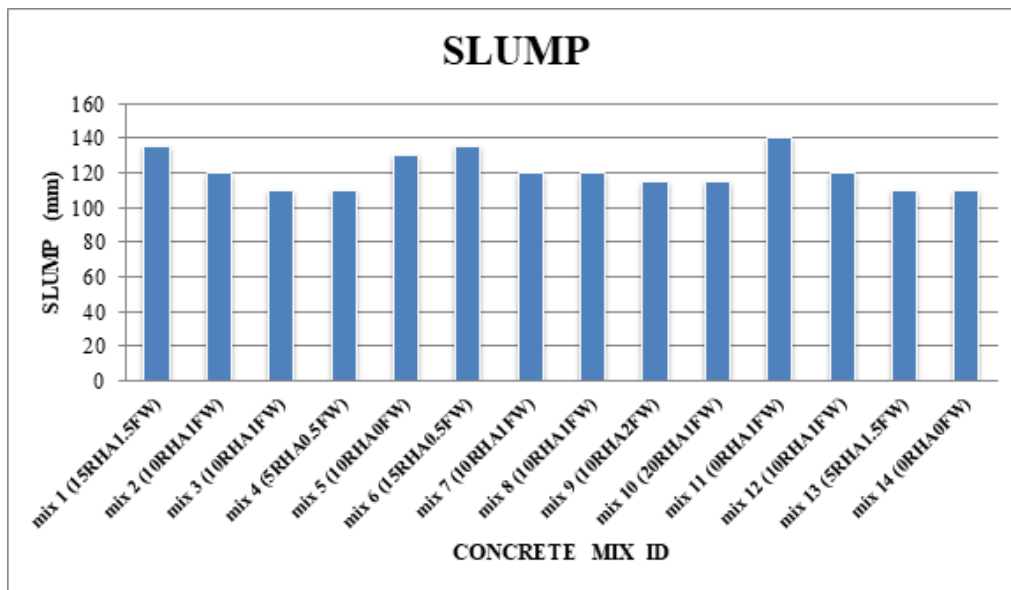


Figure 2: Slump Test Result

Durability Properties

Water Absorption

The durability performance of RHA-SWF concrete mixes containing RHA and SWF was also assessed using water absorption test; the findings are shown in Figure 3. The percentage of RHA and SWF content was shown for each mix. Mix 1 (15RHA1.5SWF) for example, which contains 15% RHA and 1.5% SWF, has a water absorption value of 4.2% at 14 days and 9.3% at

28 days. On the other hand, Mix 7 (10RHA1SWF), which includes 10% RHA and 1% SWF had a water absorption capacity of 3.8% at 14 days and 6.7% at 28 days, while Mix 14 (0RHA0SWF) which contains 0% RHA and 0% SWF, demonstrated a water absorption capacity of 2.3% and 4.08%. The water absorption capacity value of Mix 1 (15RHA1.5SWF) was the greatest surpassing that of the control mix. The results clearly show that the water absorption rate rises as the percentage replacement of a larger amount of RHA and a lesser percentage of SWF increases. Moreover, as comparison to Mix 14 (control mix), the water absorption rate falls with a larger proportion of SWF and a smaller proportion of RHA. This might be explained by the high specific surface area of SWF, which would raise the water requirement, and its low specific gravity, which results in a decrease in mass per unit volume.

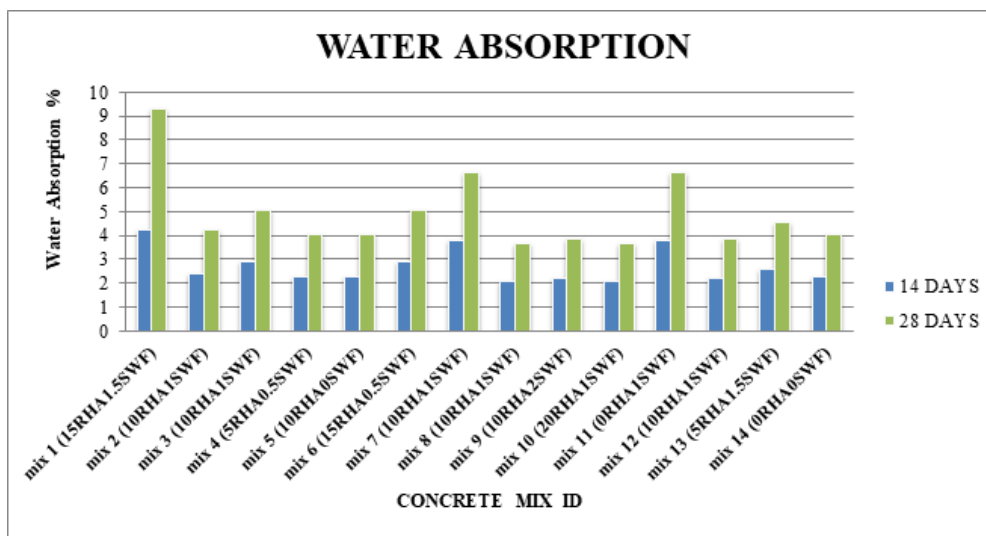


Figure 3: Water Absorption Result of RHA+ SWF

Resistance to Hydrochloric Acid (HCl) media

The compressive residual strength of concrete samples exposed to acidic media is shown in Figure 4. The figure clearly shows that the concrete samples' compressive residual strength significantly drops as the acid exposure period increases. The results clearly demonstrate that at 14 and 28 days, the control concrete sample showed a decrease of compressive residual strength ranging from 5.2 N/mm² to 2.3 N/mm². Conversely, the compressive residual strength of RHA-SWF concrete sample with mix ID 1 decreased from 5.3 N/mm² to 10.15 N/mm². Figure 4 illustrates the loss in compressive residual strength for RHA-SWF concrete samples exposed to acidic media. It also makes it evident that as the immersion period increased the samples' compressive residual strength which was greatly affected by the acidic conditions.

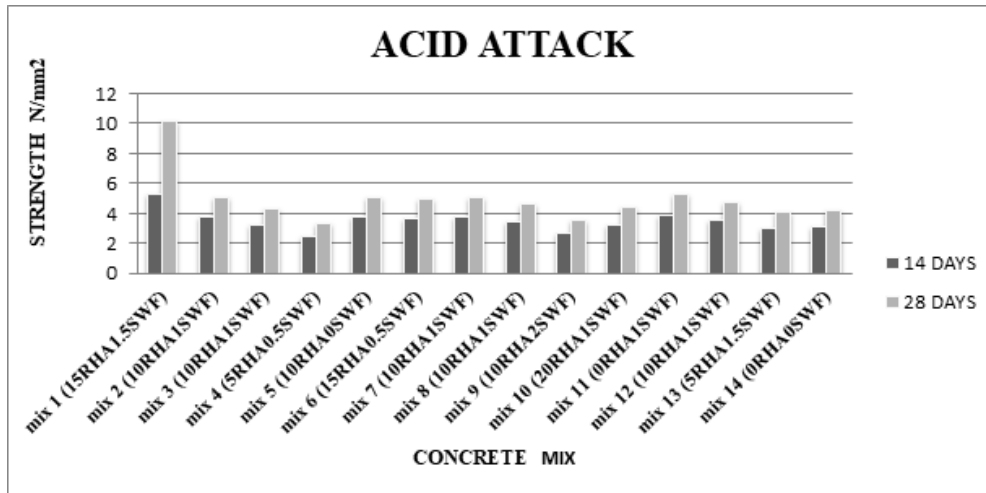


Figure 4: RHA+SWF Resistance to Acid (HCl)

Multi-objective Optimization and Validation

A numerical optimization was conducted using the desirability function approach which is frequently used in multi-objective optimization scenarios, to determine the ideal mix proportions of RHA and SWF for improved concrete durability. The goal of this study's optimization was to determine the best mix of independent factors to produce an RHA-SWF concrete mixture that minimizes acid attack and water absorption while maximizing the mechanical properties and the workability. To optimize the responses and capture all possible solutions, all parameters were established within a certain range. Table 2 defines the multi-objective optimization constraints for the variables and responses. According to the optimization findings, if the ratios are maintained within the statistically established ideal range, a partial substitution of cement with 10% RHA and 1% SWF can produce significant increase in the fresh and durability of concrete. In addition to helping to conserve resources and reduce waste, this approach supports the development of sustainable building materials. Using the optimized mixture ratios shown in Table 2, a second series of laboratory tests was carried out to confirm the sufficiency of the optimization data retrieved from the Design-Expert program and all of the response models. The latter step was done to ensure that the proportions of the optimized mixture were accurate. Three specimens were produced for each test parameter, and the mean values of each were reported. After 28 days, results were evaluated and contrasted with the predicted results. Using Equation (1), Khalid, et al (2024), the discrepancy between the experimental and predicted results was computed.

$$\varepsilon = 1 - \frac{y}{x} \times 100 \tag{1}$$

Where y stand for *Predicted Value* and x stand for *Experimental value* for each of the responses that were taken into consideration, Table 2 displays the RSM predicted findings together with the corresponding experimental data. With an average percentage error of less than 5%, the computed percentage errors showed that the actual results and predicted results agreed well.

Table 2: Multi-objective Criteria and Outcomes of the Optimization

Variables and responses	Units	Criteria for optimization			Results and verification		
		Desired goal	Lower limit	Upper limit	Predicted result (Y)	Experimental result (X)	Error (%)
RHA	%	In range	0	20	10	10	-
SWF	%	In range	0	2	1	1	-
Slump	mm	Maximize	110	140	127.343	128.543	0.93
Acid attack at 14 Days	MPa	Minimize	2.5	3.9	3.601	3.6512	1.37
Acid attack at 28 Days	MPa	Minimize	3.375	5.275	4.863	4.902	0.80
Water absorption at 14	%	Minimize	2.1	3.8	2.214	2.312	4.24
Water absorption at 28 Days	%	Minimize	3.675	6.65	3.875	3.882	0.18
Desirability	%				75.1%		

Conclusion

This study investigated the potential of Rice Husk Ash (RHA) and Sheep Wool Fibre (SWF) as a partial replacement for cement in the production of lightweight concrete, with a focus on workability, water absorption, and resistance to acid attack. The key findings demonstrate that the incorporation of RHA and SWF significantly influences the fresh and hardened properties of concrete. Higher replacement levels of RHA and SWF reduced workability due to the particle packing effect of SWF, which reduced the water demand for plasticization. However, increased replacement levels also led to higher water absorption and reduced resistance to acidic environments, primarily due to increased pore volume and permeability. The Response Surface Methodology (RSM) proved effective in modeling these durability properties, showing good predictive accuracy with less than 5% discrepancy between predicted and experimental results.

This study contributes to sustainable construction practices by promoting the valorization of agricultural and industrial wastes (RHA and SWF) in concrete production, thereby reducing reliance on conventional materials, minimizing environmental waste disposal issues, and lowering the carbon footprint associated with cement use. The optimal mix identified was 10% RHA and 1% SWF (cement replacement) which maximized workability while keeping water absorption and acid attack within acceptable limits. This mix offers a practical and eco-friendly alternative for producing lightweight concrete suitable for non-structural or semi-structural applications. While the study provides valuable insights, it was limited to specific replacement levels and short-term durability tests (up to 28 days). Future research should

explore higher replacement percentages, long-term durability performance, and the mechanical strength properties (compressive, tensile, and flexural) of RHA-SWF lightweight concrete under various environmental conditions. In conclusion, the successful utilization of RHA and SWF in lightweight concrete presents a promising pathway toward more sustainable and environmentally responsible construction materials, contributing to both waste management and green building initiatives.

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Conflict of Interest

Authors have no any conflict of interest associated with this work.

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