

Optimisation of the properties of concrete incorporating Rice husk ash and sheep wool fibres using Response Surface Methodology

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ABSTRACT : The increasing demand for sustainable construction materials has encouraged the incorporation of agricultural and natural fibre into cementitious composites. This study investigates the combined influence of Rice Husk Ash (RHA), a pozzolanic agro-waste, and Sheep Wool Fibre (SWF), a renewable natural fibre, on the mechanical properties of concrete. The experimental program employed Response Surface Methodology (RSM) with a Central Composite Design (CCD) to optimize the mix proportions of RHA (5–25% replacement of cement) and SWF (0.5–2.5%) by weight. Key performance indicators including workability, compressive strength, split tensile and flexural strength, were evaluated. X-ray diffraction (XRD) analysis confirmed the presence of amorphous silica in RHA, indicating high pozzolanic potential, while SWF exhibited crystalline patterns characteristic of structural reinforcement rather than chemical reactivity. Results showed that partial replacement of cement with RHA significantly improved the mechanical properties, while SWF enhanced toughness and crack resistance. However, excessive levels of either component reduced workability and strength. The RSM predictive models demonstrated strong correlation with experimental results, allowing the identification of optimal mix proportions that produce an achievable strength. Overall, the integration of RHA and SWF provides an eco-friendly pathway for producing sustainable concrete composites with improved performance.

KEYWORDS Rice Husk Ash, Sheep wool Fibre, Response Surface Methodology, Fresh properties, Mechanical Property.

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I INTRODUCTION

The combined needs of servicing growing infrastructure demands 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 [Zhang, and Malhotra, 1996] and [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 [Neville, 2011]. Additionally, LWC has better fire resistance and thermal insulation qualities [Chandra and Berntsson, 2002]. 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 and 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 and 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 [Chandra and Berntsson, 2002],[Mehta and 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 [Chandra and Berntsson, 2002]..

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 and Mahmud,2010]. Therefore, a major and challenging engineering problem is to Fig. 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 and 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], [Adamu, et al, 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 [Khalid et al, 2024]. Using

fly ash and quarry dust [Montgomery, 2017], conducted a multi-objective optimization research on concrete, effectively identifying Pareto-optimal solutions that met the competing objectives of maximizing strength and minimizing cost [STM, 2016]. A noteworthy development was made by [Zhang, and Malhotra, 1996], who optimized a ternary mix of cement substituted with fly ash and glass powder using RSM in conjunction with a genetic algorithm, producing a very accurate model for predicting echo-mechanical performance [Myers, 216]. Similarly, [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 [Adamu, et al, 2020]. However, a study of hybrid systems such as rice husk ash and recycled aggregate by [Habeeb and Mahmud,2010] identified a common flaw: many research 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 under utilization 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 [STM, 2016].

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 [Zhang, and Malhotra, 1996] and [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.

II. 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 μ m 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 188].

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 with 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. Elasticity is a key component of wool fiber's mechanical qualities, felting, and resilience. Alpha helical cells give wool fibre its elastic quality and operate as a spring for up to 2.5 percent of its length; however, they are more easily expanded in acidic or alkaline environments than in neutral ones. When the wool polymer's peptide chains are broken by acid or alkali, they take on the elasticity of rubber; however, when they are removed, their side linkage spontaneously repairs, decreasing elasticity. Wool fiber's comfort qualities are improved by its elastic recovery quality, which also keeps it from crinkling readily

Sieve Analysis

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

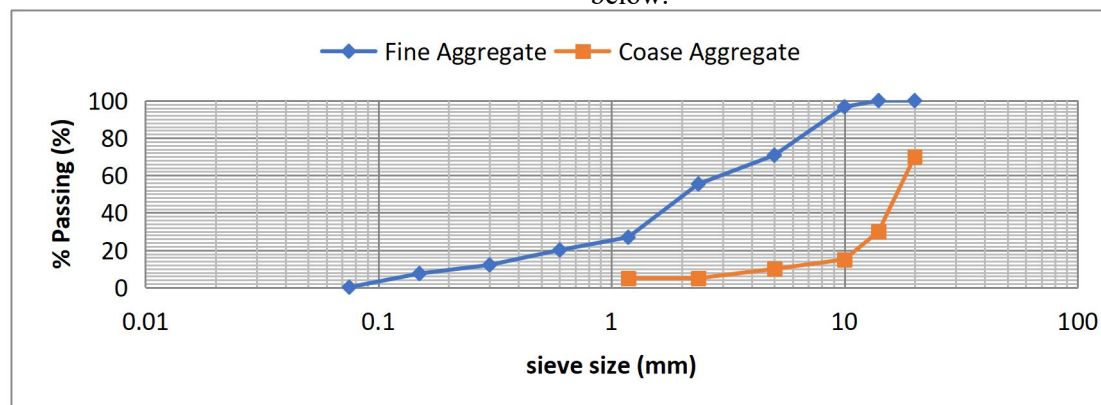


Fig. 1: Particle size distribution curve of Aggregates

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.

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

(1)

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 [20]. 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: Mix design proportioning using RSM.

Runs	Coded Values		Actual Values	
	RHA%	SWF%	RHA%	SWF%
1			0	0
2	0	0	0	1.0
3	-1	-1	10	1.0
4	1	-1	20	2.0
5	-1	1	10	2.0
6	1	1	20	1.5
7	-1.41	0	5	1.5
8	1.41	0	25	1.5
9	0	-1.41	15	0.5
10	0	1.41	15	2.5
11	0	0	15	1.5
12	0	0	15	1.5
13	0	0	15	1.5
14	0	0	15	1.5

Table 2. 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 (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],[Adamu et al, 2021], [Adamu et al, 2022].

III. RESULT AND DISCUSSION

Slump Test Result

The slump test results presented in Fig. 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 has 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. [Zhang and Malhotra, 1996] 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 those wool fibre, though reducing flow, can improve the cohesiveness of the mix and minimize segregation—an advantage in lightweight concretes.

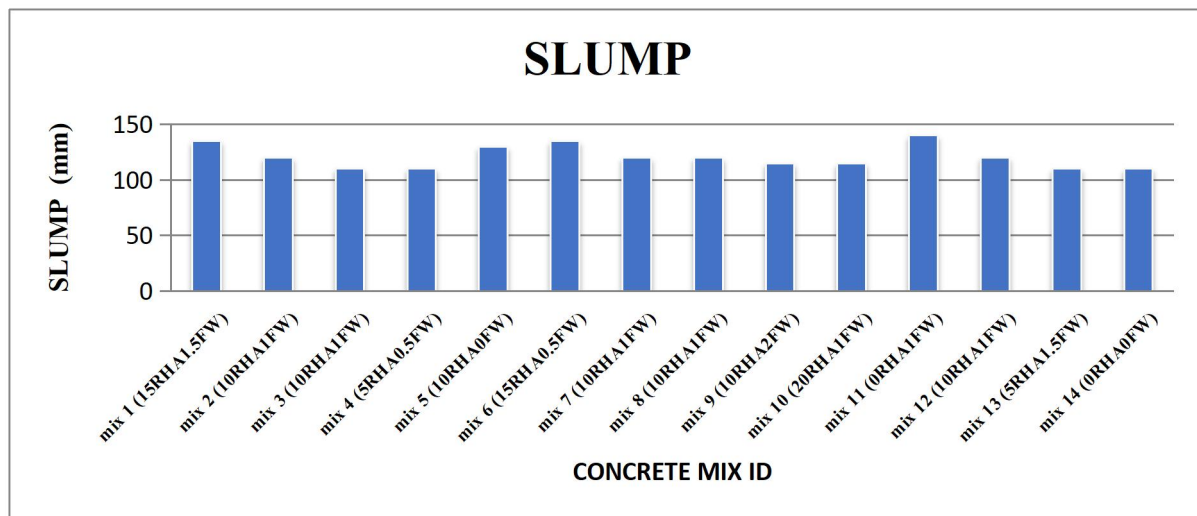


Fig. 2: Slump Test Result

Mechanical Properties

Compressive Strength

The compressive strengths of concrete containing various portions of RHA and SWF tested at 14- and 28-days curing ages are shown in Fig. 3. The results indicated that all concrete samples experience an increase in compressive strength with age regardless of their replacement amount. The compressive strength of the control sample (Mix 14: 0RHA0SWF) at 14 and 28 days were found to be 12.3 and 16.6 MPa, respectively. Mix 1 concrete samples with 15% RHA and 1.5% SWF have the highest compressive strength at 14 and 28 days, which were 17.4 MPa and 24.6 MPa respectively. Conversely, mix 4 which contains 5% RHA and 0.5% SWF revealed the lowest compressive strength of 10 MPa and 13.5 MPa at 14, and 28 d of curing age respectively. The lower strength of Mix 4 was attributed to the negative effect of RHA which decrease the compressive strength and the lower SWF content and was unable to mitigate the loss of strength in the mix. The compressive strength significantly increased by adding SWF content. An increased in water volume was also due to an increase in RHA and SWF addition, this could be attributed to the mix's greater surface area and lower water content.

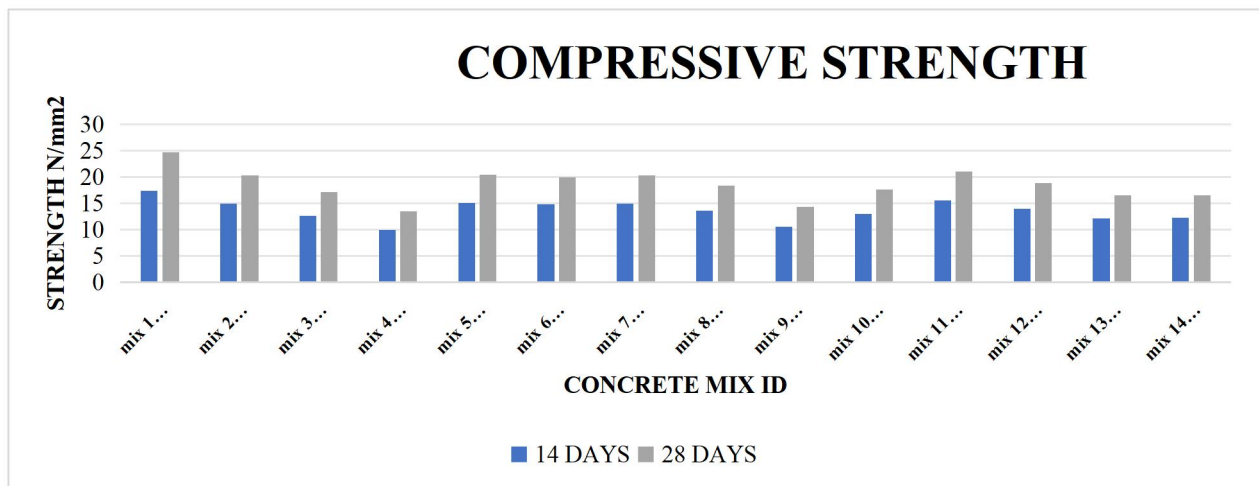


Fig. 3: Compressive Result of RHA +SWF

Split-Tensile Strength

The splitting tensile of the concrete modified with different RHA and SWF content tested at 14 and 28 days. As seen in Fig. 4, it can be noted that splitting tensile strength properties follow a similar behavior to compressive strength. The persistent cement hydration reaction during curing causes the splitting tensile strength to increase with curing age gradually. Mix 1 (15RHA1.5SWF) demonstrated the highest splitting tensile strength at 14 and 28 days to be 3.1MPa and 6.7MPa respectively compared to other mixes. However, the splitting tensile strength decreased with an

increased in RHA and SWF content. This could be as a result of the weak link between the RHA particles and the matrix of solidified concrete paste, which causes tiny cracks and a sudden loss of strength. The cement pastes and aggregate bond failure consequently resulted in a reduction in the splitting tensile strength. Furthermore, this is consistent with the findings of [15]. Moreover, the large surface area of SWF which fortifies the bond between the aggregate particles and the cement matrix which causes the splitting tensile strength to decrease.

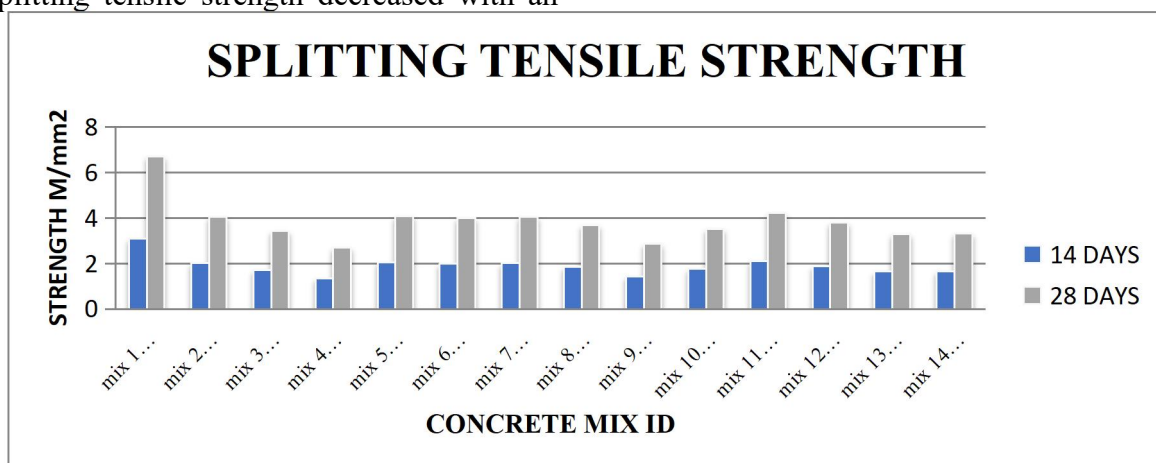


Fig. 4: Split Tensile Result of RHA +SWF

Flexural Strength

The results of the flexural strength test are shown in Fig. 5. Just like the compressive strength test results, a similar trend is observed for flexural strength. As the proportion of RHA and SWF increases in the matrix, the flexural strength decreases. It was observed that for all the mixes there was marginal increase in the flexural strength. The highest flexural strength

obtained after 14 days was 2.79 MPa as mix 7 with 10%RHA and 1%SWF and for the 28 days of curing was 4.35MPa while the lowest was MIX 9 and 10 to be 1.3 and 2.028 MPa with 10%RHA and 2%SWF then 20%RHA and 1%SWF replacement at 14 and 28 days respectively. This may also be attributed to the surface texture of RHA and SWF which affects proper bonding and cohesion of the mix.

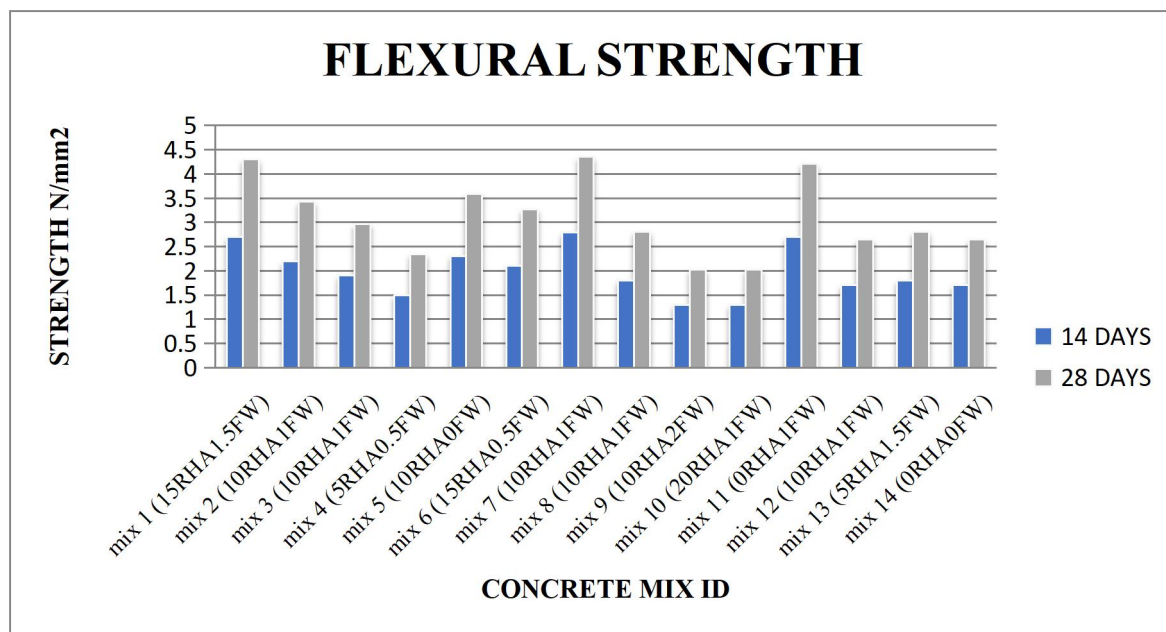


Fig. 5: Flexural Strength Result of RHA +SWF

Statistical Analysis of Responses

RSM Model for Workability and Mechanical properties

The interaction between the variables (RHA and SWF) and the responses (workability and mechanical properties) was evaluated using ANOVA. The coefficient of determination (R^2) assessed the validity of the quadratic function of the CCD model, which was evaluated and validated using the probability function (p-value) at a 95% confidence level. The model was developed according to the coded factors. The slump, the 14 and 28-days compressive strength, split-Tensile strength and the flexural strength responses were utilized to generate

the prediction model. The following second-order polynomial Equations represent the empirical relationship between the variables and the responses:

$$S = 113 + 3.54A - 6.04B + 5.000AB + 6.63A^2 + 4.13B^2 \quad (2)$$

$$f_{C-14} = 11.82 + 0.6078A - 0.6682B + 0.7000AB + 1.49A^2 + 1.04B^2 \quad (3)$$

$$f_{C-28} = 15.96 + 0.8389A - 0.8993B + 0.9500AB + 2.02A^2 + 1.42B^2 \quad (4)$$

$$f_{Ct-14} = 1.60 + 0.0839A - 0.0899B + 0.0950AB + 0.2020A^2 + 0.1420B^2 \quad (5)$$

$$f_{Ct-28} = 3.19 + 0.1678A - 0.1799B + 0.1900AB + 0.4040A^2 + 0.2840B^2 \quad (6)$$

$$f_{Cf-14} = 1.40 + 0.3005A - 0.2902B + 0.0025AB + 0.3444A^2 + 0.0944B^2 \quad (7)$$

$$f_{Cf-28} = 2.59 + 0.4688A - 0.4527B + 0.0039AB + 0.5372A^2 + 0.1472B^2 \quad (8)$$

where A and B stand for the corresponding percentages of the RHA and SWF components and S, f_{C-14} , f_{C-28} , f_{Ct-14} , f_{Ct-28} and f_{Cf-14} , f_{Cf-28} indicate the concrete's slump, 14, 28-days compressive strengths, split tensile and flexural respectively. It can be seen in Equations (2) to (8) the parameters and interactions considerably impacted the workability and the mechanical properties.

Table 3 summarizes the ANOVA result of quadratic models for estimating the responses. It can be noted that most of the model's terms revealed the p-values less than 0.05, for instance, the terms A^2 , B^2 and AB for the 14-days response which were significant. Generally, the model terms in both cases have p-values of less than 0.05, showing they are significant. Table 4 presents the performance evaluation of the responses model. The coefficient of regression is the main statistical indicator to assess the performance of the developed model. The 14-day split tensile strength model has the highest R^2 value, which clarifies and validates its greater significance than the other models. The difference between each model's predicted and adjusted R^2 values were lower than 0.2, indicating that the model terms substantially agreed. Moreover, a lower standard deviation indicates the model's fitness and suitability with their mean values.

Table 3. ANOVA result of workability and Mechanical properties models.

Response	Source	Sum of Squares	Mean Square	F-Value	p-Value	Remark
<i>Slump</i>	Model	872.00	174.40	4.05	0.0477	Significant
	A-RHA	100.00	100.00	2.32	0.1711	
	B-SWF	291.42	291.42	6.78	0.0353	
	AB	100.00	100.00	2.32	0.1711	
	A^2	305.33	305.33	7.10	0.0323	
	B^2	118.37	118.37	2.75	0.1411	
	Lack of Fit	221.08	73.69	3.68	0.1200	Not Significant
<i>Compressive Strength at 14-Days</i>	Model	28.99	5.80	4.56	0.0361	Significant
	A-RHA	2.96	2.96	2.32	0.1714	
	B-SWF	3.57	3.57	2.81	0.1378	
	AB	1.96	1.96	1.54	0.2546	
	A^2	15.44	15.44	12.13	0.0102	
	B^2	7.52	7.52	5.91	0.0453	
	Lack of Fit	0.0223	0.0074	0.0033	0.9997	Not Significant

<i>Compressive Strength at 28-Days</i>	Model	53.56	10.71	4.57	0.0358	Significant
	A-RHA	5.63	5.63	2.40	0.1651	
	B-SWF	6.47	6.47	2.76	0.1405	
	AB	3.61	3.61	1.54	0.2545	
	A ²	28.39	28.39	12.11	0.0103	
	B ²	14.03	14.03	5.99	0.0443	
	Lack of Fit	0.0505	0.0168	0.0041	0.9996	
<i>Split Tensile Strength at 14 Days</i>	Model	0.4807	0.1071	4.57	0.0358	Significant
	A-RHA	0.1862	0.0563	2.40	0.1651	
	B-SWF	0.0092	0.0647	2.76	0.1405	
	AB	0.0600	0.0361	1.54	0.2545	
	A ²	0.2025	0.2839	12.11	0.0103	
	B ²	0.0082	0.1403	5.99	0.0443	
	Lack of Fit	0.0005	0.0002	0.0041	0.9996	
<i>Split Tensile Strength at 28 Days</i>	Model	2.14	0.4285	4.57	0.0358	Significant
	A-RHA	0.2252	0.2252	2.40	0.1651	
	B-SWF	0.2588	0.2588	2.76	0.1405	
	AB	0.1444	0.1444	1.54	0.2545	
	A ²	1.14	1.14	12.11	0.0103	
	B ²	0.5611	0.5611	5.99	0.0443	
	Lack of Fit	0.0020	0.0007	0.0041	0.9996	
<i>Flexural Strength at 14 Days</i>	Model	2.24	0.4477	6.93	0.0122	Significant
	A-RHA	0.7225	0.7225	11.19	0.0123	
	B-SWF	0.6736	0.6736	10.43	0.0145	
	AB	0.0000	0.0000	0.0004	0.9848	
	A ²	0.8250	0.8250	12.78	0.0090	
	B ²	0.0620	0.0620	0.9597	0.3599	
	Lack of Fit	0.1999	0.0666	1.06	0.4596	
<i>Flexural Strength at 28 Days</i>	Model	5.45	1.09	6.93	0.0122	Significant
	A-RHA	1.76	1.76	11.19	0.0123	
	B-SWF	1.64	1.64	10.43	0.0145	

AB	0.0001	0.0001	0.0004	0.9848	
A ²	2.01	2.01	12.78	0.0090	
B ²	0.1508	0.1508	0.9597	0.3599	
Lack of Fit	0.4866	0.1622	1.06	0.4596	Not Significant

Table 4. Performance indicators for workability and Mechanical properties models.

Factors	Slump	CS at 14-Days	CS at 28-Days	ST at 14 Days	ST at 28 Days	FS at 14 Days	FS at 28 Days
Std. Dev.	6.56	1.13	1.53	0.1531	0.3062	0.2541	0.3964
Mean	119.62	13.38	18.08	1.81	3.62	1.93	3.01
CoV. (%)	5.48	8.43	8.47	8.47	8.47	13.17	13.17
R ²	0.7433	0.7649	0.7656	0.7656	0.7656	0.8320	0.8320
Adjusted R ²	0.5600	0.5970	0.5981	0.5981	0.5981	0.7120	0.7120
Predicted R ²	-0.4467	0.6294	0.6297	0.6297	0.6297	0.3252	0.3252
Adequate precision	4.9537	5.0094	5.0257	5.0257	5.0257	7.7359	7.7359

3D response surface and 2D contour plots for the various responses

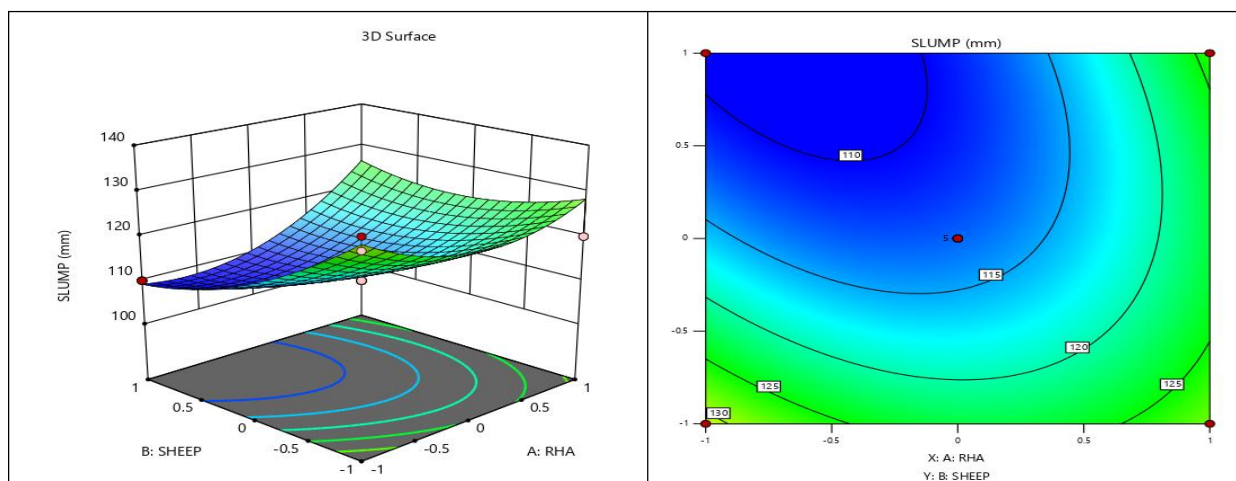


Fig. 6: 3D and contour plot for Slump

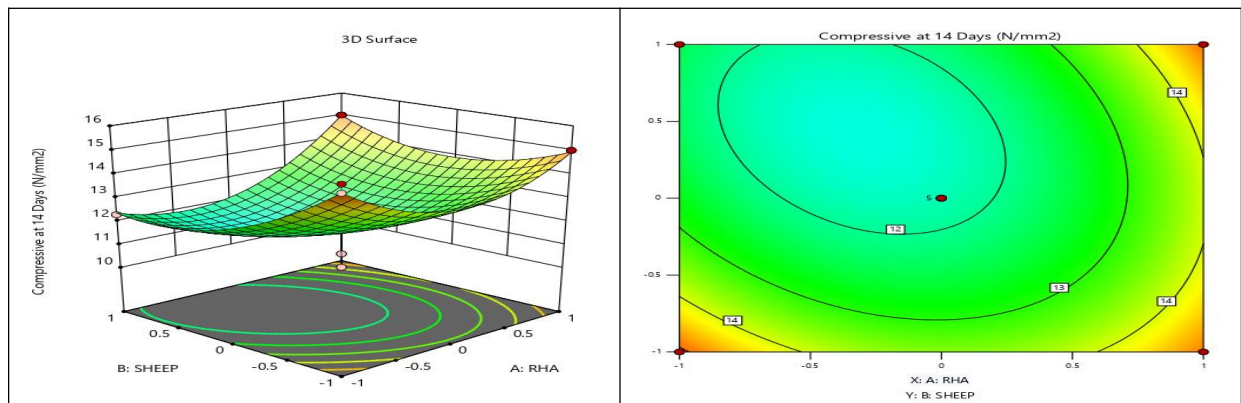


Fig. 7: 3D and contour plot for Compressive Strength at 14 Days

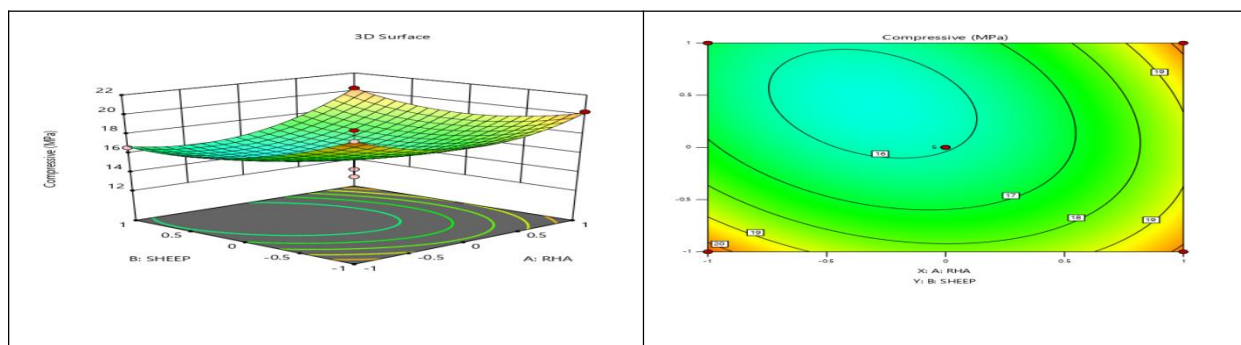


Fig. 8: 3D and contour plot for Compressive Strength at 28 Days

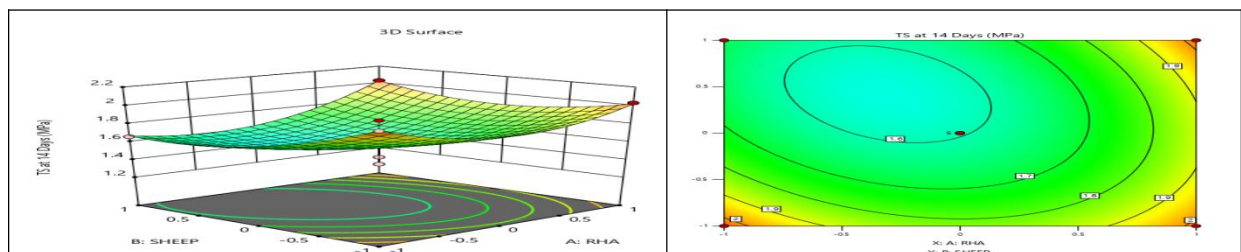


Fig. 9: 3D and contour plot for Split Tensile Strength at 14 Days

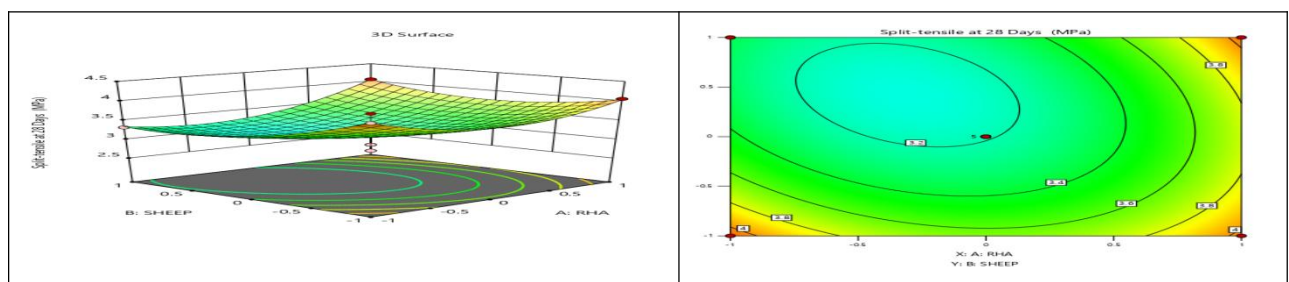


Fig. 10: 3D and contour plot for Split Tensile Strength at 28 Days

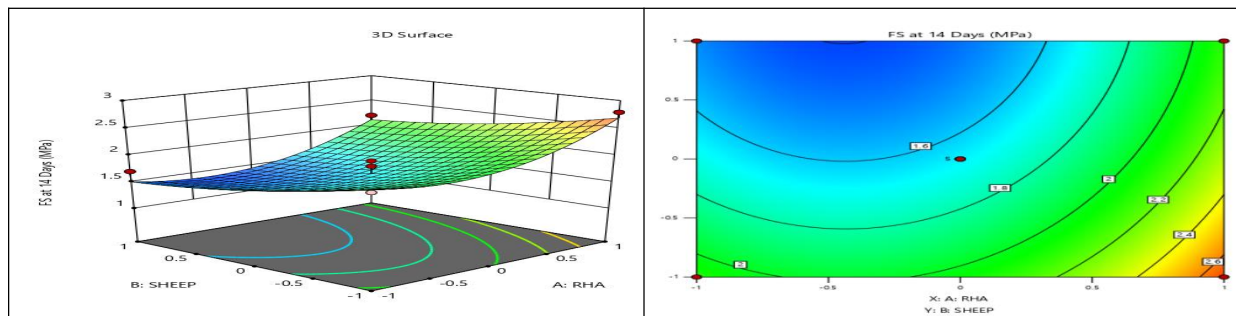


Fig. 11: 3D and contour plot for Flexural Strength at 14 Days

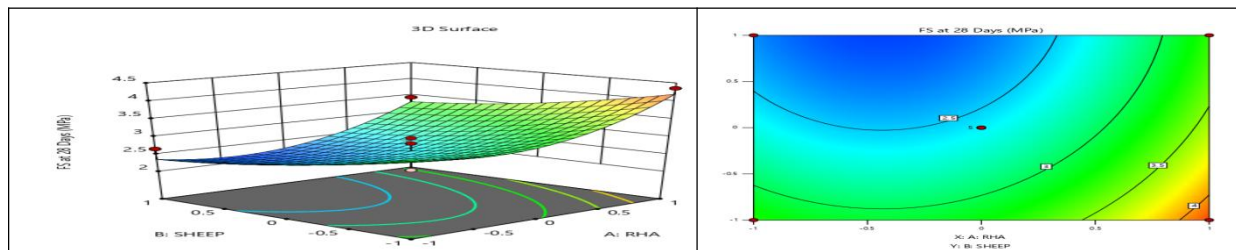


Fig. 12: 3D and contour plot for Flexural Strength at 28 Days

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 a 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 5 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 coarse aggregate with 1% SWF can produce significant increases in the fresh, mechanical 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 5, 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 (9) [15], the discrepancy between the experimental and predicted results was computed.

$$\varepsilon = 1 - \frac{Y}{X} \times 100$$

(9)

Where (Y) stand for *Predicted value* and (X) for *Experimental value* from each of the responses that were taken into consideration. Table 5 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 5: Multi-objective Criteria and Outcomes of the Optimization.

Variables and responses	Units	Criteria for optimization			Results and verification		
		<i>Desired goal</i>	<i>Lower limit</i>	<i>Upper limit</i>	<i>Predicted result (Y)</i>	<i>Experimental result (X)</i>	<i>Error (ε)(%)</i>
<i>RHA</i>	%	In range	0	20	10	10	-
<i>SWF</i>	%	In range	0	2	1	1	-
<i>Slump</i>	mm	Maximize	110	140	127.343	128.543	0.93
<i>CS at 14-days</i>	MPa	Maximize	10	15.6	14.404	14.832	2.89
<i>CS at 28-days</i>	MPa	Maximize	13.5	21.1	19.451	20.223	3.82
<i>ST at 14-days</i>	MPa	Maximize	1.35	2.11	1.945	1.979	1.72
<i>ST at 28-days</i>	MPa	Maximize	2.7	4.22	3.890	3.99	2.51
<i>FS at 14-days</i>	MPa	Maximize	1.3	2.79	1.992	2.016	1.19
<i>FS at 28-days</i>	MPa	Maximize	2.028	4.3524	3.107	3.211	3.24
Desirability		87.5%					

IV. CONCLUSIONS

Conclusively, the following takeaways were extracted from the research as follows:

- i. The XRD analysis of the SWF and RHA samples shows that SWF is dominantly crystalline which implies its less reactivity and again in RHA sample, crystalline which is majorly 70% Quartz revealed it's less puzillanicity.
- ii. A higher replacement amount of RHA and SWF results in a more workable concrete mix. The remarkable rise in slump might perhaps be ascribed to the particle packing effect of SWF, which decreases the water content needed for plasticization.
- iii. Regardless of the replacement level, samples produced with RHA and SWF exhibit increase in the compressive, splitting

tensile and flexural strength with age. Nevertheless, it does not appear that the curing medium has a bigger impact on their strength at an early age. The compressive, splitting tensile and flexural strength of RHA-SWF concrete has been greatly increased compared to the control sample by using RHA and SWF up to a 20% substitution of the coarse aggregate content.

- iv. The RSM-based optimization produced the optimal mix of 2% RHA (replacement of cement) and 10% SWF (replacement of coarse aggregate), maximizing workability(126.5mm), compressive strength at 14days (17.1MPa) and 28days(24.2MPa), split tensile strength at 14

days(1.84MPa) and at 28 days(2.79MPa) and flexural strength at 14 days(2.02MPa) and at 28 days(2.87MPa) with 87.5% desirability. The experimental validation of this result revealed that the discrepancy between the predicted and experimental results was less than 5%. This indicates the potential of RHA-SWF lightweight concrete.

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Conflict of Interest

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

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