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ASSESSMENT OF CHLORIDE ION PENETRATION OF COCONUT SHELL AND RICE HUSK ASH MODIFIED CONCRETE

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ABSTRACT

This is because the corrosion of embedded steel reinforcements in concrete because of the ingress of chloride ions is one of the most important durability factors in the construction sector. This experiment was used to test the efficacy of Coconut Shell (CSh) as a partial substitute to coarse aggregate and Rice Husk Ash (RHA) as a partial substitute to cement to minimize chloride ion induced corrosion in reinforced concrete. The research was a response to the necessity to find long-term building material and discuss its usefulness in the sustainable construction, by substituting the 1:2:4 mix ratio CSh with RHA by weight at 0%, 5%, 10%, 15% and 20%. Prism samples 100 x 100 x 500 mm of reinforced concrete were placed in a solution of 5.844g/L NaCl to replicate a chloride rich environment and 150 mm cube samples were left to cure under normal laboratory conditions. The ingress of chloride ions was measured using the gravimetric analysis of the weight loss of the steel reinforcement, compressive strengths were measured at 7, 14, and 28 days. The findings indicated that compressive strength reduced progressively with the replacement rates with the 10 per cent mix providing a good compromise of 16.09 MPa at 28 days. The corrosion rates reduced considerably to 18.52 mm/year in the control mix and 6.17 mm/year in 10 percent replacement, which demonstrates the beneficial effect of RHA and CSh on the corrosion resistance of concrete. Nonetheless, corrosion rates were higher in 15-percent and 20-percent levels, meaning that the matrix integrity was reduced with the increase in the replacements.

KEYWORDS

Chloride ingression, coconut shell aggregate, rice husk ash, reinforced concrete, corrosion resistance, sustainable materials.

1. INTRODUCTION

Modern infrastructure has largely relied on reinforced concrete, which has been characterized by high compressive strength, formability, durability, and relatively low cost (Coppola et al., 2022). Nonetheless, it is highly associated with its long term performance, which is directly related to the existence of embedded steel reinforcements, especially corrosion resistance (Chen et al., 2023; Gorgis et al., 2018). Chloride ion ingress is also one of the most serious threats to the structural integrity and service life of reinforced concrete (Sai et al., 2024) particularly in the marine structure, coastal areas, and areas with de-icing salts (Afolabi et al., 2021). When the chloride ions enter the porous matrix of the concrete, they break the passive oxide film on the surface of the steel, and corrosion is started, which causes cracking and the ultimate failure of the concrete elements (Al-Mamoori et al., 2018; Ikumapayi et al., 2020).

A number of measures have been implemented over the decades to fight against reinforcement corrosion, such as concrete cover augmentation, corrosion inhibitors, low-permeability concrete, and protective coatings (Heiyantuduwa-Beushausen, 2022; Yan et al., 2022). Although such approaches offer different degrees of efficiency, most of them are either expensive or unsustainable to the environment (Aljibori et al., 2023). Also, the rising production of concrete has been accompanied by environmental issues, such as, natural aggregates), as well as, environmental emissions due to cement production (Flower and Sanjayan, 2007). When the construction industry moves towards the practices of sustainability (von Freeden et al., 2022), it has become popular to use agricultural waste materials and industrial by-products (Adeniji A. et al., 2025; Chen et al., 2024). The substitution of traditional concrete materials with other environmentally friendly constituents is one of the potential areas of research that will yield promising results (Afrin et al., 2021).

Rice Husk Ash (RHA) and Coconut Shell (CSh) are examples of agricultural wastes with a high degree of interest since they are cheap, accessible, and have pozzolanic or filler properties (Vivek et al., 2024). RHA is a by product of the rice milling process and contains amorphous silica which has shown pozzolanic behavior as an enhancer to the microstructure of cement based composites (Natarajan et al., 2022). It reacts with calcium hydroxide in hydrated cement to produce more calcium silicate hydrate (CSH) (Abolhasani et al., 2022) to refine the pore structure and make them less permeable. In a similar manner, coconut shells as waste can be used as lightweight coarse aggregate alternatives because they are hard, tough, and have a cellular structure (Trinh et al., 2024). They can be used to minimize the reliance on natural stone aggregates and assist in the minimization of waste (Sarangi & Suganya, 2024). A number of studies have been conducted on the use of either RHA or CSh in concrete. RHA has been found to enhance compressive strength, decrease permeability, and sulphate resistance when applied partially as a cement replacement (Hamada et al., 2023; Zhang et al., 2019). Similarly, addition of CSh as a coarse aggregate has been found to decrease the concrete density and augment concrete sustainability index (Gunasekaran, 2011). A significant portion of the current studies has, however, studied these materials individually. The synergistic performance of RHA and CSh in reinforced concrete has had very little studies, especially in regards to chloride ingress and performance in the case of corrosion (Amran et al., 2021). What is still missing is the knowledge of how these two wastes of agriculture when used as a separate mixture as partial replacement of cement and aggregate respectively affect the mechanical as well as the durability properties of reinforced concrete in presence of hostile chloride environments.

The study examines the cumulative impact of Rice Husk Ash and Coconut Shell aggregate to the chloride ion infiltration into reinforced concrete samples and their compressive strength. The study offers the input on the best combination of these materials that will result in the balance of structural performance and increased resistance to chloride induced corrosion. The research gives empirical evidence on the use of RHA and CSh together in reinforced concrete, suggests a cost effective and environmentally friendly solution by using agro waste materials in the manufacture of sustainable construction composites, which could help address the issue of infrastructure deterioration and contribute to long-term stability. To sum up, this paper has indicated that partial substitution of cement with RHA and coarse aggregate with CSh can be greatly helpful to the reinforced concrete resistance to chloride ion penetration with insufficient compression level.

2. MATERIALS AND METHODS

2.1. Materials

This study utilised sustainable agricultural waste materials. Rice Husk Ash (RHA) in Fig. 1 (a and b), and Coconut Shell (CSh) in Fig.1c as partial replacements for cement and coarse aggregate, respectively, in the production of reinforced concrete. CEM II 42.5N grade of Portland Lime Cement (PLC), which conforms to the Nigerian Industrial Standard (NIS 444-1:2003), served as the primary binder. The RHA was obtained through the controlled combustion of rice husks in a laboratory furnace to ensure the production of high-reactivity ash rich in amorphous silica, as shown in Fig.1a. The ash was subsequently ground and sieved to a uniform fineness to enhance its pozzolanic activity, its chemical and physical properties are given in Table 1a as reported by (Habeeb & Mahmud, 2010). For the aggregate materials with their properties in Table 1b, the fine aggregate used was mining sand passing 4.75 mm sieve.

The coarse aggregate was crushed granite with a nominal maximum size of 19 mm in Fig.1e was used as the conventional coarse aggregate, while clean, well-graded river sand was employed as fine aggregate. The coconut shells were sourced from local coconut processing facilities in Nigeria. These were cleaned, sun-dried, crushed, and sieved to a particle size distribution similar to that of the granite to ensure compatibility in the concrete mix. The properties of the CSh are presented in Table 1b. The solution of NaCl in Fig.1d was used to simulate a chloride-rich environment while Fig.1f shows the freshly produced reinforced concrete samples. The reinforcement was high yield 12 mm diameter bar with its chemical composition details in Table 1c.

Fig. 1a. Control burning of Rice husk

Fig. 1b. Rice husk Ash sample

Fig. 1c. Coconut Shell sample

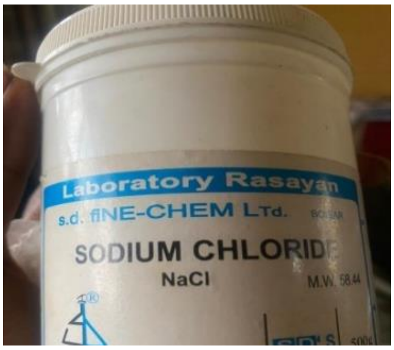

Fig. 1d. Sodium Chloride

Fig. 1e. Coarse aggregate

Fig. 1f. Freshly mixed concrete samples

Table 1a. Chemical composition of the PLC and RHA

Chemical Constituents (% by mass)	PLC	RHA
SiO_2	20.7	88.32
Al_2O_3	5.28	0.46
Fe_2O_3	3.29	0.67
CaO	62.5	0.67
MgO	2.62	0.44
Na_2O_3	0.0	0.12
K_2O	0.11	2.91
LOI	1.73	5.81
Lime Free	0.98	-
Specific gravity	2.94	2.11

Source:(Habeeb & Mahmud, 2010), (Raheem & Kareem, 2017)

Table 1b. Properties of aggregates and CSh

Properties	Fine aggregate (Sand)		Coarse aggregate (Crushed granite)		CSh
Specific gravity	2.61		2.65		1.54
Water absorption (%)	0.76		0.50		26.1
Moisture content (%)	-		-		4.6
Bulk density (kg/m³)	1410		1520		592
Particle size (mm)	-		-		10-19
	Sieve size (mm)	Cumulative Retained (%)	Sieve size (mm)	Cumulative Retained (%)	
-	4.750	0.00	19.00	0.00	
-	2.360	16.91	13.20	43.80	
-	1.180	35.31	9.50	68.69	
-	0.600	58.12	4.75	100.00	
-	0.300	81.39	-	-	
-	0.150	93.10	-	-	
-	0.075	97.18	-	-	
-	Pan	100.00	-	-	

Source: (Habeeb & Mahmud, 2010; Stel'makh et al., 2023)

Table 1c. Chemical composition of 12 mm diameter high yield steel

Element	**C**	**Mn**	**N**	**V**	**Si**	**Cu**	**P**	**S**	**Cr**	**Mo**	**Ni**
Composition (%)	0.33	0.68	0.008	0.004	0.25	0.20	0.034	0.06	0.20	0.022	0.11

Element	**B**	**Al**	**Ca**	**Ti**	**Pb**	**Co**	**Fe**	**Sn**	**Sb**
Composition (%)	0.0002	0.003	0.0007	0.0008	0.0008	0.011	98.10	0.023	0.009

Table 1d. Properties of Portland Lime Cement

Fineness (%)	3.9
Initial Setting time (min)	45
Final Setting time (min)	380
Consistency (%)	26.5

Source: (Adeniji A. et al., 2025)

Table 1e. Properties of the RHA

Grinding time (minutes)	360
Average particle size (µm)	11.5
BET nitrogen adsorption (m^2g^{-1})	30.3
Moisture content (%)	10.20
Bulk density (kg/m^3)	105
Proximate analysis	18.70

Source: (Habeeb & Mahmud, 2010; Mansaray & Ghaly, 1997)

2.2. Methods

The experimental procedure was designed to assess the influence of combined Rice Husk Ash (RHA) and Coconut Shell (CSh) substitutions on the mechanical performance and chloride ion ingress resistance of reinforced concrete samples. The study followed a systematic approach involving specimen preparation, curing, exposure to chloride solution, and subsequent testing. Concrete mixes were produced using a mix ratio of 1:2:4 (cement: sand: coarse aggregate) with a constant water-to-cement (w/c) ratio of 0.55. The RHA and CSh were introduced as partial replacements for cement and coarse aggregate, respectively, at five replacement levels: 0%, 5%, 10%, 15%, and 20% by weight. Each replacement level maintained a balanced substitution of both RHA and CSh. Also, it was designed to evaluate their incremental effects on concrete performance and based on previous research. The materials were weighed, batched, and thoroughly mixed using a mechanical concrete mixer to ensure homogeneity as shown in Table2. The fresh concrete was cast into 150 mm cubes for compressive strength testing and 100 mm × 100 mm × 500 mm prism containing embedded 12 mm diameter steel bars 40mm reinforcement concrete cover for corrosion testing. The corrosion penetration test was conduction using gravitational method.

Table 2a. Mixture proportion of modified concrete aggregates (kg/m3)

Mix ID (%)	w/c	Water	Cement	RHA	Sand	Granite	CSh
0	0.5	158	317	0	620	1338	0
5	0.5	158	301.15	15.85	620	1271.10	66.90
10	0.5	158	285.30	31.70	620	1204.20	133.80
15	0.5	158	269.45	47.55	620	1137.30	200.70
20	0.5	158	253.60	63.40	620	1070.4	267.60

2.3. Gravimetric method for chloride penetration rate test

In order to determine the corrosion resistance of reinforced concrete samples, the gravimetric analysis approach was used to determine the rate of corrosion penetration of embedded steel reinforcements (Malaret and Yang, 2022). Before casting, the high yield steel bars of 12 mm diameter were cut into 450 mm long, cleaned, and weighed using a precision balance. These bars were incorporated in prism 100 × 100 × 500 mm concrete samples, as explained in the mix design procedures. Fig.2a shows that after initial curing, the reinforced concrete samples were left in a 0.1 M sodium chloride (NaCl) solution (equivalent 5.844 g/L) to a maximum of 28 days to mimic a chloride corrosive environment. Corrosion was induced by adding NaCl solution to the concrete that helped the solution to penetrate the concrete samples via the pore and, in this way, helped the steel to be depassivated and therefore, led to electrochemical corrosion. The prism specimens were then carefully fractured in order to remove the bars of steel embedded in them at the end of the exposure period Fig. 2b. Then the steel bars were cleaned on base of ASTM G103 protocols to eliminate the corrosion rusts without damaging the base metal. Final weights of the steel bars were determined and the weight loss recorded on each sample. The rate of corrosion penetration was determined according to the mass loss of the steel reinforcement during the period of exposure using the Eq. 1. This gave a quantitative rating on the rate of corrosion in millimetres per year (mm/year), which provides a direct comparison on the performance of the various RHA and CSh replacement percentages. The findings provided the necessary insight on the capacity of modified concrete to withstand chloride induced corrosion.

Fig. 2a. Samples exposed to Corrosive environment

Fig. 2b. Steel reinforcement for ion penetration test

$$\text{C.R (mm/yr)} = \frac{8.76\ x\ 10^4 \times \Delta W}{D \times A \times T} \quad \text{(Malaret \& Yang, 2022)} \qquad (1)$$

Where

C.R = Corrosion Rate

ΔW = Weight Loss (g)

T /365 = exposure time in days extrapolated to year

A = surface area of the specimen (mm2)

D = Density of the specimen or sample

2.4. Compressive strength test

The cubes were tested for compressive strength on the 7, 14, and 28 days following the standards in BS EN 12390-3: 2002. The testing was conducted using a Digital Compression test machine. The concrete cube samples were removed from the curing tank, 24 hours before the test and moisture on their surfaces was allowed to evaporate. Each sample was weighed and then positioned in the machine as shown in Fig.3 so that the load was applied to the cubes, aligned centrally on the base plate of the machine. The load was applied gradually and continuously, without shock, until each specimen was crushed. The maximum load at which each cube failed was recorded, and the compressive strengths were calculated using Eq. 2.

Fig. 3. Compression testing of samples

Compressive Strength, fc = F/Ac (2)

Where

Fc = maximum compressive stress in mega pascals (MPa or N/mm')

F = Maximum load at failure in Newton (N)

Ac = Cross sectional area of the specimen on which the compressive force acts, calculated from the designated size of the specimen.

3. RESULTS AND DISCUSSIONS

3.1. Chloride ion penetration rate

The test involved the calculation of the initial and final weight of steel bars in concrete samples after 28 days of the exposure to the solution of 0.1 M NaCl and the density of the concrete. Based on these parameters, the corrosion penetration rate in mm/year was determined as presented in Table 3. The control sample, which had no RHA or CSh, had a corrosion rate of 18.52 mm/year which was the baseline level of deterioration caused by corrosion by chloride. Great decrease in corrosion was seen at the 5-percent and 10-percent replacement levels. The 5 percent mix exhibited the rate of corrosion at 12.35 mm/per year, which is 33 percent better than the control. The biggest improvement was at 10% replacement which registered the lowest recorded corrosion rate of 6.17 mm/year, which is about 67 percent lower as compared to the control mix. This significant increase has been explained by the fact that the RHA acts as a pozzolanic material refining the pore structure and decreasing the permeability and the low porosity and high water absorption of the CSh, which could restrain the chloride ion movement in the concrete. Amorphous silica is abundant in the RHA and chemically reacts with calcium hydroxide in hydration of cement to create further calcium silicate hydrate. This response improves the microstructure in that voids are filled and the pore structure is made finer thus lowering the permeability. A thicker matrix hinders considerably the infiltration of harmful ions including chlorides. Also, the addition of CSh is added because of its comparatively low porosity and high water absorption capacity. This protective effect however seems to reduce at higher replacement levels. The replacement level of 15 percent had a higher rate of corrosion of 24.69 mm/year with the 20 percent mix having the highest rate of 43.22 mm/year, which was more than twice the control. These mixes were also worse in their corrosion resistance perhaps because they were over-substituted, thereby having a deleterious impact on the compaction of concrete and pore connectivity. This implies that though moderate replacement of RHA and CSh enhance the durability performance of reinforced concrete, overreplacement can add to the vulnerability of the materials to chloride ingress due to its destruction of the microstructure. The data shows clearly that a replacement level of 10 percent provides a good balance between material integrity and corrosion resistance. The obtained results of corrosion resistance are similar to the past research by (Andrade et al., 2013) and (Boğa and Topcu, 2012), which underscored the success of pozzolanic materials in minimizing chloride ingress. The replacement level of 10% in the current study is comparable to the 15 percent fly ash replacement used in the study by Boğa and Topcu. This has greatly reduced the corrosion rate as indicated, and this is evidence that agro-waste-based concrete is very effective in the hostile environment, particularly in places where chloride attack is a worry.

Table 3. Chloride ion penetration rate

Percentage replacement (%)	Initial Weight (kg)	Final Weight (kg)	Weight Loss (kg)	Density (kg/m³)	Weight loss (kg)	Corrosion Rate (mm/yr)
0	0.341	0.338	0.003	2.52	0.003	18.52
5	0.341	0.336	0.002	2.51	0.002	12.35
10	0.341	0.340	0.001	2.49	0.001	6.17
15	0.340	0.334	0.004	2.47	0.004	24.69
20	0.341	0.333	0.007	2.42	0.007	43.22

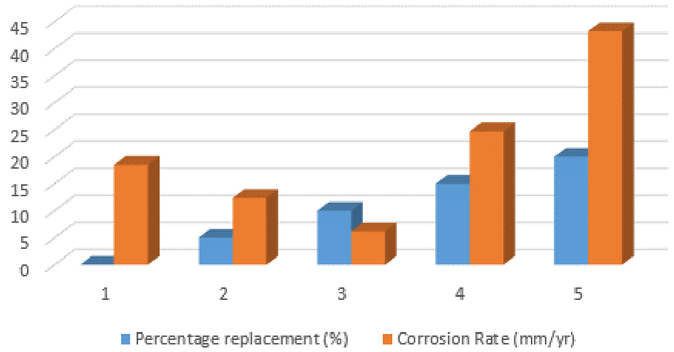

Fig. 4. Corrosion rate of percentages of the mix

3.2. Compressive strength

It can be seen that control mix, always recorded the highest strength values at all curing ages of 11.29 MPa at 7 days, 14.60 MPa at 14 days, and 17.10 MPa at 28 days, which indicates that compressive strength performance of reinforced concrete modified with the RHA and CSh as partial replacement of cement and coarse aggregate. Compressive strength was gradually decreasing as the replacement percentage rose with a 5 percent to 20 percent. The shrink at the lower replacement levels was however small and within acceptable structural boundaries. The compressive strength was 16.48 MPa at a 5% replacement at 28 days which is a low 3.6% reduction as compared to the control. On the same note, the replacement mix with 10 percent reached 16.09 MPa at 28 days implying that a few losses in strengths can be made at this point at the expense of sustainability. It is interesting to note that even the 10% mix performed better than the 5percent mix at 14 days of strength gain, which is a sign that strength gain is always positive with time, probably because of the synergetic effect of sustained cement hydration and the pozzolanic activity of RHA, which refines the microstructure of the concrete. At 14 days, the RHA and CSh 10% mix were more effective than 5 percent mix since there was increased pozzolanic activity. RHA is more reactive with calcium hydroxide at this stage, giving rise to further C-S-H, and a combination of this synergy with the continued cement hydration offers a denser structure and ensures a steady increase in strength post early curing producing better mechanical performance. When increased replacement levels (15% and 20%) were used, the deterioration was more evident and the 20 percent mix had reached 14.11 MPa after 28 days. This means that over- replacements affect performance. The progressive increase in strength with time was observed in all mixes even emphasizing the long-term efficacy of pozzolanic materials in concrete (Ikumapayi et al., 2020). The uniform rise in the mixes of 7 to 28 days is in justification of the fact that the alteration of RHA and CSh does not hinder the hydration process but can slow down the attainment of maximum strength. In general, the replacement level of 10% provided the most suitable compromise between the strength maintenance and sustainability, which proves that it can be used in long-lasting and environment-friendly concrete. This replacement level assists in the creation of structural concrete and the decrease of dependence on natural assets and the use of agricultural waste, which are consistent with the global initiatives to foster the circulation of economy practices in the construction sector. The present research is associated with those findings detailed by (Lee et al., 2024), in which the mixture of 10% Rice Husk Ash (RHA) and 5% Coconut Shell (CSh) demonstrated the most positive result in terms of performance of modified concrete mixes. This composition gave great balance in both studies on the retention of strength. The mixture in the research of Lee recorded a compressive strength of 28 days at 15 MPa and the compressive strength of 16.09 Mpa was also registered in the current research. These relationships affirm that moderate levels of RHA and CSh, in addition to making concrete to be sustainable, increases the microstructural integrity of concrete. On the other hand, both experiments reported lower replacement (more than 15 percent) resulted in lower compressive strength and supporting the idea that the best substitution was at moderate proportions of substitution (10 percent).

Table 4. Result of compressive strength test

Percentage Replacement (%)	Failure Load (kN)			Compressive Strength (MPa)		
	7 days	14 days	28 days	7 days	14 days	28 days
0	385.60	477.65	517.73	11.29	14.60	17.10
5	376.00	418.05	465.3	10.49	14.14	16.48
10	362.00	444.40	535.80	10.12	13.24	16.09
15	305.40	367.85	419.95	9.80	12.22	15.23
20	269.75	334.40	365.40	9.20	11.10	14.11

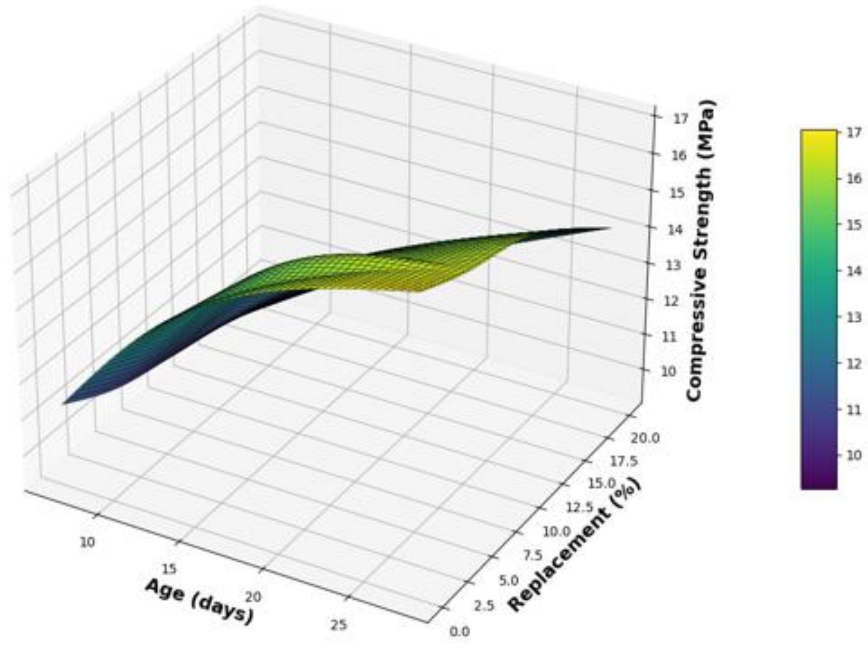

Fig. 5a. Surface Plot of Compressive strength

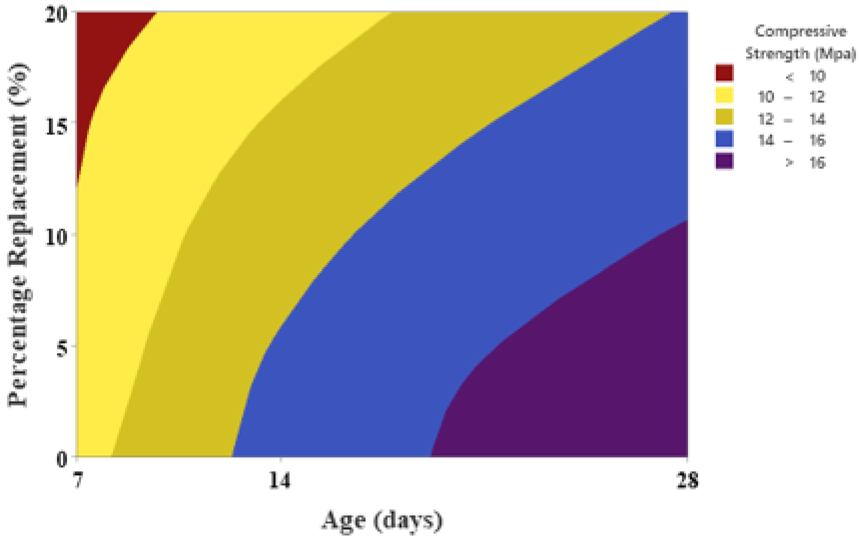

Fig. 5b. Contour Plot of Compressive Strength against Percentage Replacement and Age

4. CONCLUSION

This paper has shown that partially replacing cement and coarse aggregate, respectively, by Rice Husk Ash (RHA) and Coconut Shell (CSh) can go a long way in increasing the life of reinforced concrete structure in chloride prone environments besides making construction sustainable. The incorporation of the RHA, which is reactive silica-loaded, optimized the pore network with the help of the reaction of pozzolans, as well as the cellular structure and high solubility of the CSh inhibited the mobility of chloride ions. Out of all the mix combinations tried, the 10% replacement level was found to be the most optimal mix design with a significant compressive strength of 16.09 Mpa after 28 days and the lowest corrosion rate of 6.17 mm/year, compared to other replacement ratios in the kind of structural performance as well as the ability to resist corrosion. These results are a confirmation that moderate quantities of agricultural waste incorporation not only make us less reliant on traditional raw materials and minimize carbon emissions related to cement production but lead to sustainable and cost effective building materials. The maximum percentage replacement was however found to result in performance deterioration probably because of degraded matrix integrity and high porosity. The study fills an urgent knowledge gap in the usage of agro waste in combination with other types and offers empirical data that justifies the principles of the circular economy in reasoned civil infrastructure. It preconditions the creation of the next generation sustainable concretes and motivates the engineering community to accept the waste valorization strategies as the means of fighting the material degradation and resources shortage.

AUTHOR'S CONTRIBUTION STATEMENT

All authors have made substantive contributions to the article.

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