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Performance of Binary Cementitious Matrix Concrete Containing Coconut Shell Ash as Partial Replacement of Cement Under Aggressive Environment

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Abstract

Magnesium sulphate attack is one of the major causes of durability deterioration in concrete structures due to the ingress of sulphate ions through interconnected pore networks. Leading to the formation of expansive compounds and progressive internal damage. This study investigates the performance of binary cementitious matrix concrete incorporating Coconut Shell Ash (CSA) as partial replacement of Ordinary Portland Cement (OPC) under aggressive sulphate exposure. CSA was used at 10% and 15% replacement levels after preliminary trial mixes. Concrete specimens were cured in 2.5% $MgSO_4$ *solution to simulate a sulphate-rich environment, and compressive strength was evaluated up to 180 days. Sorptivity and water absorption tests were also conducted to assess durability characteristics. Results indicated that although CSA-blended concrete exhibited lower early-age compressive strength compared to the control, significant strength improvement was observed at later curing ages due to pozzolanic activity. At 180 days, the control sample recorded a strength loss of 17.7% under sulphate exposure, whereas 10% and 15% CSA replacements showed lower strength losses of 3.8% and 4.75%, respectively. Additionally, CSA incorporation reduced sorptivity and water absorption, indicating improved pore refinement and resistance to ingress of harmful agents. Among the mixtures tested, 10% CSA replacement demonstrated the best overall performance under prolonged sulphate exposure. The study concludes that CSA can effectively enhance sulphate resistance and durability of concrete, with 10% replacement recommended for structural applications in aggressive environments.*

Keywords: Aggressive Environment, Coconut Shell Ash, Durability, Magnesium Sulphate, Sorptivity.

Introduction

Ordinary Portland Cement (OPC) concrete is the most popular and widely used **construction material**, due to availability of the raw materials all over the world, its ease in preparation and fabrication in all sorts of conceivable shapes. Concrete is the most widely used material after water (Ata, 2020). The adverse effects of aggressive environmental conditions on the durability of concrete can be reduced through the incorporation of pozzolanic materials in concrete Hence this study is therefore of significant interest. An aggressive environment can be defined as an environment which involves dissolved injurious substances which negatively alter concrete and reinforcements structural integrity therefore reducing load bearing capacity of the concrete products (Gupta et al., 2019) and (Fedosov et al., 2022). The aggressive environments affecting the setting and hardening characteristics of cement may exist naturally in soil or waste product from industries. Sulphuric and nitric acid have much negative influence on the fundamental properties of cement. Similarly, pollution due to indiscriminate disposal of industrial and urban wastes on earth surface are responsible for the presence of acids, bases and salts in soil (Gana et al., 2020).Sulfate attack is one of the most aggressive environmental deteriorations that affect the long-term durability of concrete structures. The sulfate attack of concrete leads to expansion, cracking, and deterioration of infrastructure (Gana et al., 2020)

When concrete infrastructure piers, bridges, foundations, concrete pipes, are exposed to sulphate rich environment. The sulphate ions in the solution which come from soil, Groundwater, and seawater, are found in combination with other ions such as sodium, potassium, magnesium and calcium ions. The sulfate ions react with C_3A and $Ca(OH)_2$ to produce expansive and softening types of deterioration (Wang et al., 2024). Incorporation of mineral admixtures, as a partial cement replacement both in concrete and mortar is one effective way to improve concrete performance in aggressive environment, which results to cost reduction, conserve energy, and minimize waste generated. Mineral admixtures, including blast furnace slag, fly ash, and silica fume (Santhish et al., 2016) and (Chikhi etal., 2024). The use of mineral admixtures improves the compressive strength, pore structure, and permeability of mortars and concrete because total porosity decreases as hydration time increases (Santhish et al., 2016).

The concept of Supplementary Cementitious Materials (SCMs) is widely recognized worldwide. Several agricultural and industrial waste ashes meet the criteria for SCMs, including Rice Husk Ash (RHA), Bagasse Ash (BA), Wood Ash (WA), Palm Oil Fuel Ash (POFA), Fly Ash (FA), and Olive Ash (OA). Previous research has reported that the use of SCMs improves both the strength and durability of cementitious systems (Pacewska and Wilińska, 2020). The pozzolanic reaction consumes portlandite, calcium hydroxide ($Ca(OH)_2$), thereby reducing the formation of gypsum. It also produces secondary calcium silicate hydrate (C–S–H), which densifies the pore structure and reduces permeability, since most harmful chemicals are transported in liquid form. In addition, the reduction of tricalcium aluminate (C_3 A) content decreases the amount of aluminate-bearing phases in concrete (McCarthy and Dyer,2019).Other advantages of using pozzolans in concrete include improved workability at low replacement levels, reduced bleeding and segregation, lower heat of hydration, reduced creep and shrinkage, greater resistance to chemical attack at later ages, and a lower rate of chloride ion diffusion, which enhances the corrosion resistance of reinforcing steel (Becerra & Rojas, 2022).

Pozzolans are siliceous or siliceous and aluminous materials which, by themselves, possess little or no cementitious properties. However, when finely divided and in the presence of moisture, they chemically react with calcium hydroxide (lime) at ordinary temperature to form compounds with low solubility that exhibit cementitious properties (Waghmare et al., 2021). Some pozzolanic materials cannot react chemically with water on their own (that is, they do not exhibit hydraulic activity) unless they are combined with Portland cement. When mixed with Portland cement, pozzolans react with the calcium hydroxide released during cement hydration to form calcium silicate hydrate (C–S–H) and other cementitious compounds (McCarthy & Dyer, 2019). Pozzolanic activity therefore refers to the chemical reaction between aluminous–siliceous materials and calcium hydroxide in the presence of water, resulting in the formation of cementitious products (McCarthy & Dyer, 2019).

Coconut shell ash is a very fine material. The average particle size of Coco nut shell ash ranges from 5 to 10µm, coconut shell ash is rich in silica content, it is generally around 40%. For coconut shell ash to be used as pozzolana in cement and concrete. It must satisfy the chemical composition of pozzolana according to ASTM C618. The combined proportion of silicon dioxide (SiO_2), Aluminium Oxide (Al_2O_3) and iron oxide (Fe_2O_3) in the ash should not be less than 70% as stipulated in the ASTM requirement (Rajesh, 2019). Although numerous studies have been conducted on the use of Supplementary Cementitious Materials (SCMs) such as fly ash, rice husk ash, silica fume, and palm oil fuel ash in improving the durability of concrete. Research on the performance of Coconut Shell Ash (CSA) under aggressive sulphate environments is limited. Most existing studies on CSA primarily focus on its effects on compressive strength and general mechanical properties under normal curing conditions. (Ranatunga et al.,2023; Vasanthi, et al.,2020). Sufficient attention has not been given to long-term durability performance, particularly under magnesium sulphate exposure.

Furthermore, there is inadequate data on the optimal replacement level of CSA that can effectively enhance sulphate resistance while fulfilling satisfactory mechanical properties. The mechanisms governing strength retention, permeability reduction, and resistance to sulphate-induced deterioration in CSA-blended concrete are not yet fully established. Therefore, this study investigates the performance of concrete incorporating Coconut Shell Ash as a partial replacement for cement under a magnesium sulphate aggressive environment. Specifically, the study evaluates compressive strength development, Strength loss under Sulphate exposure, Sorptivity, and water absorption characteristics in order to determine the optimum replacement level of CSA for improved durability.

Materials and Methods

Materials

Ordinary Portland cement was used for the experimental work (OPC, Dangote Brand) conforming to the requirement of BS 12 (1996). The fine aggregate used was natural sand. It was sieved with a 4.75mm BS sieve to remove impurities and larger aggregates. The fine aggregate was obtained from Ahmadu Bello University (ABU) Dam. It complies with provisions of BS EN 12620 (2013). The coarse aggregate used was crushed gravel obtained from Abdul quarry site along Samaru Road. It conforms with the requirement of BS EN 12620 (2013). The water used for mixing the concrete was clean, tap water free from impurities, complying with the provisions of BS EN 1008 (2002). Newly discarded coconut shells, obtained as domestic agricultural waste, were used in this study to produce coconut shell ash (CSA). The shells were first cleaned and sun-dried for 6 hours to remove moisture. They were then incinerated at 800 °C for 3 hours in an incinerator, with the burning time carefully controlled to minimize environmental impact. The resulting ash was milled using a grinding machine to obtain finer particles, with the milling time limited to 5 minutes per kilogram of CSA. Finally, the grinded sample was sieved through a 75 µm sieve in order to achieve the desired particle size. This was done in accordance to the procedure of (Ranatunga et al., 2023). The coconut shell Ash sample was then taken for X - ray diffraction test (XRD) at Defence Industry corporation (DICON) at Kakuri, Kaduna south local Government Area, Kaduna State.

Methods

The concrete mixes were prepared in accordance with the approved mix design of BRE method and design mix was 1:1.7:2. A water–cement ratio of 0.5 was arrived at, and all materials were thoroughly mixed using a mechanical concrete mixer. The weight batching method was employed to ensure accuracy in proportioning. Ordinary Portland Cement (OPC) was partially replaced with coconut shell ash (CSA) at varying replacement levels of 0%, 5%, 10%, 15%, 20%, 25%, and 30%, corresponding to mix ratios of 100:0, 95:5, 90:10, 85:15, 80:20, 75:25, and 70:30 (OPC:CSA), respectively. For each replacement level, five cube specimens were cast. All specimens were cured in water and tested at 7-day intervals up to 28 days. Based on the compressive strength results at 28 days, the 10% and 15% CSA replacement levels exhibited appreciable strength and were therefore selected for further durability studies. Additional specimens were produced using the same mould dimensions under strict laboratory conditions for 10% and 15% CSA replacements. These specimens were cured for up to 180 days and subjected to aggressive environmental conditions. A severe magnesium sulphate environment was simulated by curing the specimens in a 2.5% $MgSO_4$ solution.

Another set of samples were casted (based on the replacement levels) and were cured in water up to 90 days and were subjected to Sorptivity test and Water absorption test at 28days, 56 days and 90 days respectively.

Testing of the Specimen

Compressive Strength

Compressive strength was carried out after different curing ages of 7, 14, 28, 56 , 90 and 180 days for all the concrete samples (control, 10% and 15% CSA Samples). Compressive strength test was done as stipulated by ASTM C 39-05. Three cubes were tested to failure for all specimens. The maximum failure load was then recorded and the compressive strength was calculated using the equation below.

$$f_c = \frac{P}{A} \quad (1)$$

Where;

P = failure load (N)

A = cross sectional area (mm^2)

Water Absorption

The water absorption test was carried as outlined BS 1881-122(1983). The apparatus used for carrying out the experiment includes a weighing balance, Oven and water tank. Three specimens from each sample were placed in an oven at 105^0C for 72 hours. The specimens were removed and cooled to room temperature in an airtight container. The specimens were weighed (W_1) and submerged in a water tank for 24 hours. After 24 hours, the specimens were removed from the water tank and surface dried with cloth. The specimens were then weighed, and the values were recorded. The results were evaluated as the increase in mass resulting from the submersion of the concrete specimens in the water tank and expressed as the percentage of the dried specimen as presented in equation 2.

$$\text{Water absorption} = \frac{(W2 - W1)}{W1} \times 100 \quad (2)$$

Where;

W_1= Oven dry weight of cylinder (ingrams)
W_2 = After 24 hours, the wet weight of the cylinder (in grams).

Sorptivity

The sorptivity can be determined by measuring the capillary rise absorption rate on reasonably homogeneous material (Jayesh & Umrigar, 2013). Water was used as the test fluid. The cubes, after casting, were immersed in water for 90 days curing. The specimen dimensions are 100 mm × 100 mm × 100 mm. were dried in oven at temperature of 100 + 5 °C for 72 hours, the samples were removed and allowed to cool in an airtight container. The samples were drowned in a water container with a water level not more than 5 mm above the base of the specimen, and the flow from the peripheral surface was prevented by sealing it properly with a non-absorbent coating (Silicon Sealant). The quantity of water absorbed after 48 hours was measured by weighting the specimen on a top pan balance weighting up to 0.1 mg (W_2). Surface water on the specimen was wiped off with a dampened tissue, and each weighting operation was completed within 30 seconds. Sorptivity (S) is a material property that characterizes a porous material's tendency to absorb and transmit water by capillarity. The cumulative water absorption (per unit area of the inflow surface) increases as the square root of elapsed time (t) as shown in equation 3.

$$S = \frac{Q}{A X d} \qquad (3)$$

Where;
S = sorptivity coefficient
Q = Change in Mass (g)
A = exposed surface area (mm^2)
D = density of water (g/mm^3)

Result and Discussion

Physical Properties of Materials

Table 2 presents the results of the specific gravity tests conducted on the materials used in this study. The specific gravity of the coarse aggregate (gravel) was determined to be 2.76, which is higher than the value of 2.63 reported by (Umamaheswari and Vignesh, 2018). The specific gravity of the fine aggregate (sand) was found to be 2.51, which falls within the acceptable threshold specified by BS 882 (2.4–2.9). Furthermore, the specific gravity of coconut shell ash (CSA) was determined to be 2.23. This value exceeds the 1.33 reported by (Umamaheswari and Vigneshkumar, 2018). The variation in the obtained values may be attributed to differences in geographical location and material processing methods.

Table 1: Physical properties: Specific Gravity of Materials

Materials	Specific Gravity (g)	Bulk Density (kg/m^3)	Water Absorption	Moisture Content
Fine Aggregate	2.51	1498	1.69	0.89
Coarse Aggregate	2.76	1767	1.02	0.4
Cement	3.20	1620	_	_
Coconut Shell Ash	2.23	1006	_	_

Chemical Composition of Coconut Shell Ash

The chemical composition of the coconut shell ash used in this study shows that the combined percentage of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) is 77.89%, as presented in Table 3. This value exceeds the 71.21% reported by (Priya, et al.,2024). The observed variation may be attributed to differences in geographical location and research methodology. Furthermore, the result satisfies the ASTM C618-05 requirement, which specifies that for a material to be classified as a pozzolan, the combined content of SiO_2, Al_2O_3, and Fe_2O_3 must be at least 70.0%.

Table 2: Chemical Composition of Coconut Shell Ash

Elements	**% Composition**	**% Composition Cement**
Silicon Oxide (SiO_2)	37.97	22.0
Aluminum Oxide (Al_2O_3)	24.12	5.02
Iron Oxide (Fe_2O_3)	15.80	4.60
Sodium Oxide (Na_2O)	4.98	0.19
Calcium Oxide (CaO)	0.81	62.0
Magnesium Oxide (MgO)	0.95	2.06
Potassium Oxide (K_2O)	0.83	0.40
Sulfur Oxide	0.71	1.43
LOI	10.3	11.17

Compressive Strength of samples cured in water

Figure 1 shows the compressive strength of samples cured in water. The samples contained 10% and 15% CSA as partial replacement. For the 10% CSA sample, the compressive strength values were 12.61 N/mm², 21.21 N/mm², 31.84 N/mm², 37.71 N/mm², 41.46 N/mm², and 45.56 N/mm² at 7, 14, 28, 56, 90, and 180 days, respectively. The Pozzolanic activity index values were 72.5%, 90%, 94%, 105%, 109%, and 118% at 7, 14, 28, 56, 90, and 180 days, respectively. For the 15% CSA sample, the compressive strength values were 10.86 N/mm², 16.73 N/mm², 27.01 N/mm², 32.95 N/mm², 39.62 N/mm², and 41.46 N/mm² at 7, 14, 28, 56, 90, and 180 days, respectively. The Pozzolanic activity index values were 62.46%, 71%, 79%, 92%, 105%, and 108% at 7, 14, 28, 56, 90, and 180 days, respectively.

Overall, the compressive strength increased with curing age for both mixtures. However, the 10% CSA sample showed higher strength values compared to the 15% CSA sample at all curing ages. At 90 and 180 days, the compressive strength increased by 5% and 8%, respectively, compared with the control sample. However, the strength gain decreased as the pozzolan content increased. This reduction may be attributed to the slower consumption of calcium hydroxide ($Ca(OH)_2$) during the pozzolanic reaction. The low early strength can be linked to delayed hydration at the initial stage of curing. Therefore, pozzolana-blended cement concrete requires a longer curing period to achieve its full-strength potential. These findings are consistent with the results reported by (Rajesh, 2018) observed that 10 to 15 % replacement of cement with coconut shell Ash improves compressive strength of concrete and other physical properties and Charitha et al., (2021), CSA with 10% replacement has shown the highest strength properties.

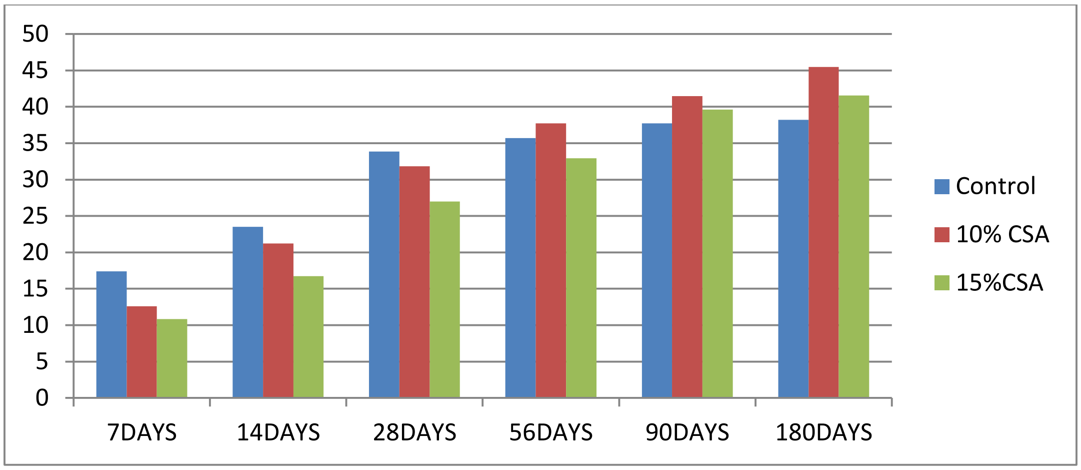

Figure 1 Compressive Strength of Samples cured in water

Compressive Strength of Samples Specimens Exposed to Sulphate

Figure 2. shows the compressive strength of concrete samples cured in 2.5% $MgSO_4$ solution at 7, 14, and 28 days. The results indicate that none of the samples exhibited significant strength loss during the early curing period, except the control sample, which recorded a 7.56% increase in compressive strength. The observed reduction in strength in some samples can be attributed to the formation of expansive reaction products such as gypsum and ettringite, which develop within the voids and micro pores of the cement matrix. At 56 days, only the control sample experienced a noticeable strength reduction of 3.72%. Generally, a reduction in compressive strength was observed when compared with specimens cured in water. At 180 days, the control sample recorded a significant strength loss of 17.7%, indicating severe deterioration due to prolonged magnesium sulphate attack. In contrast, the blended cement concrete containing 10% and 15% Coconut Shell Ash (CSA) replacements exhibited much lower strength reductions of 3.8% and 4.75%, respectively.

This result suggests that the incorporation of CSA as a supplementary cementitious material improves the sulphate resistance of concrete. The improved durability may be attributed to the pozzolanic reaction, which consumes calcium hydroxide and forms additional calcium silicate hydrate (C–S–H) gel. This process refines the pore structure and reduces permeability, thereby limiting sulphate ion penetration. Therefore, the blended cement concrete demonstrated better resistance to magnesium sulphate attack than ordinary Portland cement concrete, which is consistent with the findings reported by (Rouzudeen and Sha, 2025) and conforms with the findings Kassar and Momoh (2018) stated that incorporation of coconut Shell Ash as partial replacement of cement in concrete help diminish the attack caused by sulphate compounds available in the soil.

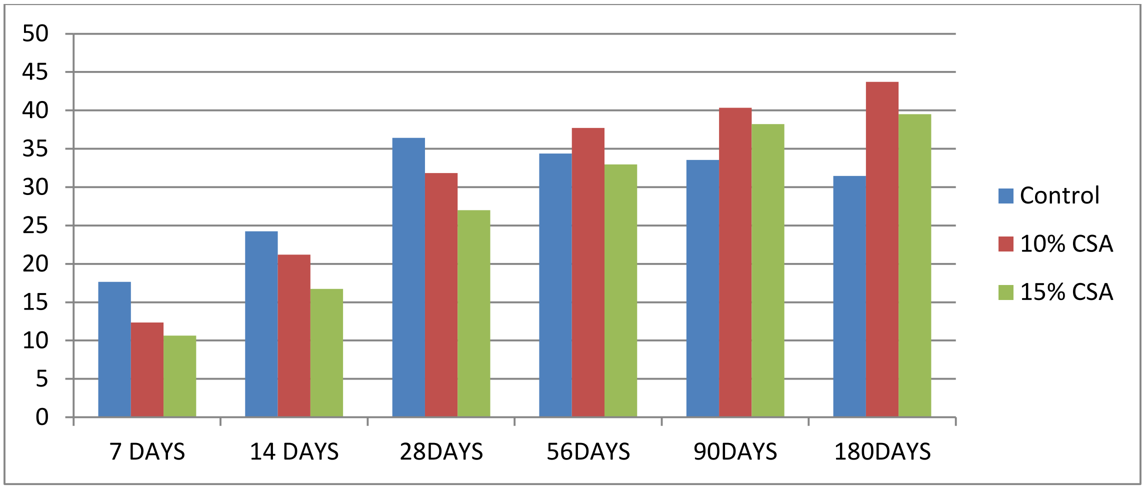

Figure 2. Compressive Strength of Samples exposed to Magnessium sulphate

Sorptivity

Figure 3 presents the sorptivity test results of the concrete samples. The results indicate that specimens incorporating pozzolanic material (10% CSA and 15% CSA) exhibited lower sorptivity values compared to the control mix. This suggests that the inclusion of coconut shell ash improved the resistance of the concrete to capillary water absorption. For the 10% CSA replacement level**,** sorptivity values of 11.91×10^{-5} , 10.43×10^{-5} , and6.72×10^{-5} were recorded at 28, 56, and 90 days, respectively. These values correspond to reductions of 38.47%, 40.1%, and 45% relative to the control mix. Similarly, the 15% CSA replacement level produced sorptivity values of 12.42×10^{-5} , 12.17×10^{-5} , and 7.94×10^{-5} at 28, 56, and 90 days, representing percentage reductions of 35.34%, 37.04%, and 39%**,** respectively. Although both replacement levels improved the resistance of the concrete to sorptivity when compared with the control mix, the results show that increasing the replacement level from 10% to 15% slightly reduced the resistance to water absorption, as indicated by the relatively higher sorptivity values.

The reduction in resistance to capillary suction at higher replacement levels may be attributed to the limited availability of calcium hydroxide ($Ca(OH)_2$) required to sustain the pozzolanic reaction. When insufficient $Ca(OH)_2$ is available, the pozzolanic reaction becomes less effective, resulting in reduced pore refinement and consequently lower resistance to capillary water ingress. These findings are consistent with the studies of Charitha et al., (2021) and Priya and Padmanaban (2024), who reported that the incorporation of pozzolanic materials improves resistance to capillary suction by densifying the pore structure and reducing the rate of water absorption. The results also agree with the observations of (Santhish et al., 2016**)**.

Overall, the results indicate that the incorporation of pozzolana reduces the rate of capillary suction, thereby making the concrete less susceptible to deterioration caused by the ingress of harmful substances. However, the sorptivity values were observed to vary with exposure time, reflecting the influence of curing age on the pore structure development of the concrete.

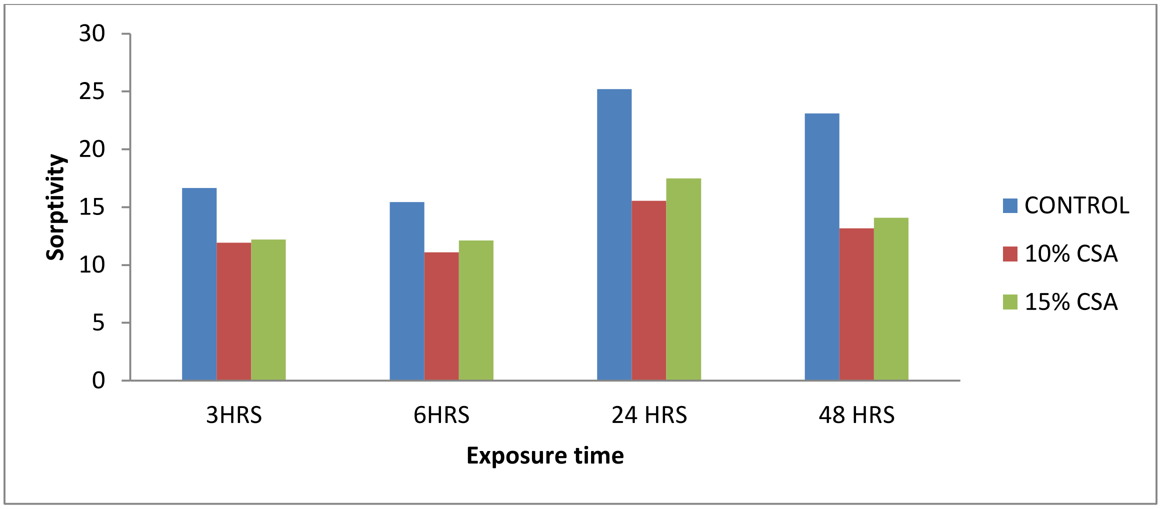

Figure 3.1 28 days sorptivity test

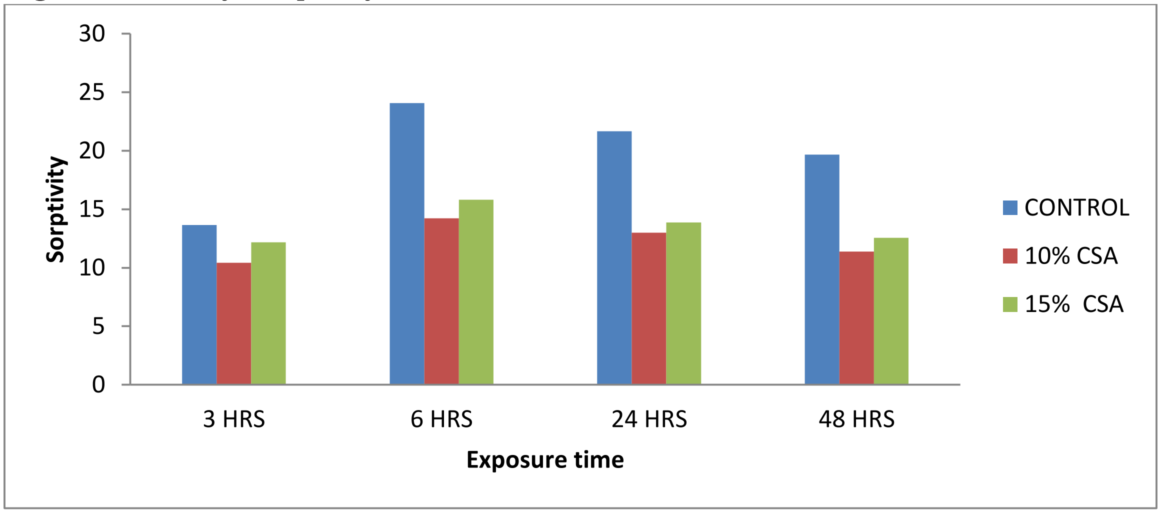

Figure 3.2 56 days sorptivity test

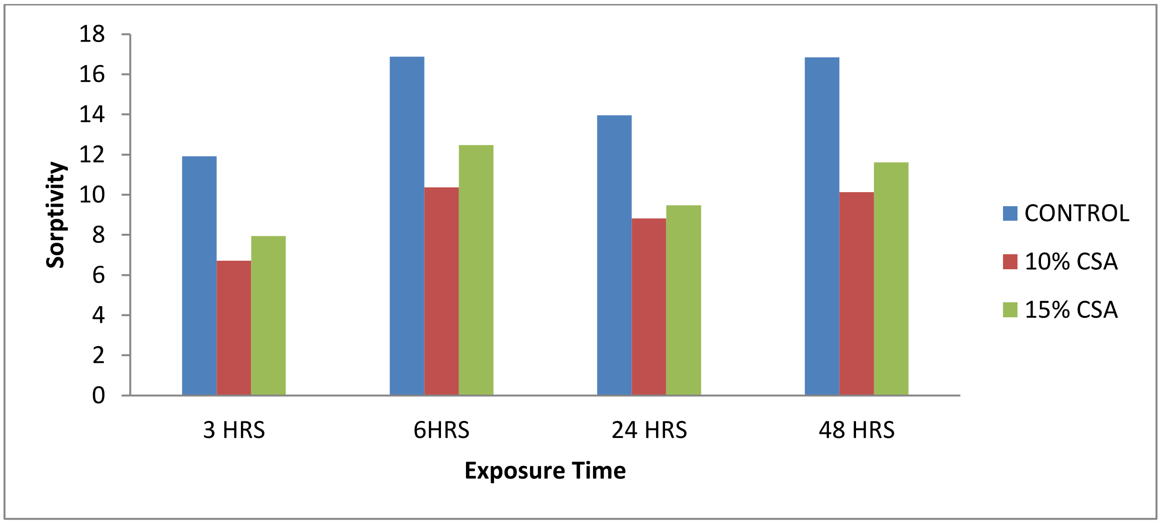

Figure 3.3. 90 days sorptivity test

Water Absorption

The water absorption results indicate that the incorporation of coconut shell ash (CSA) as a partial replacement for cement influenced the permeability characteristics of the concrete**.** The 10% CSA specimens recorded water absorption values of 3.41%, 2.92%, and 1.45% at 28, 56, and 90 days**,** respectively. These values correspond to reductions of 33.6%, 40%, and 46.29%**,** respectively, when compared with the control mix.

Similarly, the 15% CSA specimens exhibited water absorption values of 3.67%, 3.0%, and 2.56% at 28, 56, and 90 days**,** representing reductions of 28%, 32.6%, and 36%**,** respectively, relative to the control. Although both replacement levels improved the resistance of the concrete to water absorption compared to the control mix, the results indicate that water absorption slightly increased with higher pozzolanic replacement levels. This may be attributed to the insufficient availability of calcium hydroxide ($Ca(OH)_2$) required to sustain an effective pozzolanic reaction at higher replacement levels, thereby limiting the extent of pore refinement within the cement matrix.

However, it was also observed that water absorption decreased with increasing curing age**.** This trend can be attributed to the continued hydration and pozzolanic reactions occurring over time, which contribute to improved microstructural development and reduced permeability of the concrete**.** These findings are consistent with the studies of **(**Santhish et al.,2016) and **(**Priya and Padmanaban,2024)**,** who reported that the incorporation of 10% pozzolanic material in blended cement concrete significantly reduces water absorption**.** This improvement is primarily associated with the densification of the internal pore structure, which restricts the ingress of water into the concrete matrix

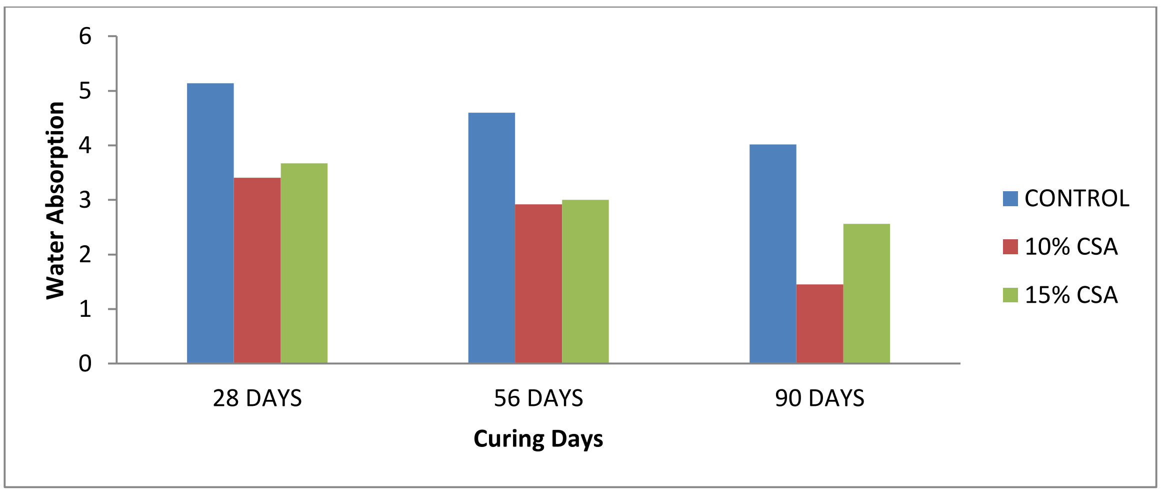

Figure 4. Water Absorption of Samples.

Conclusion

This study was conducted to assess whether the incorporation of Coconut Shell Ash as partial replacement of cement will improve the performance of concrete when exposed to aggressive environment. Based on the experimental findings, the following conclusions can be deduced:

The chemical composition of CSA meets ASTM requirements for pozzolanic materials, with the combined SiO_2 , Al_2O_3 , and Fe_2O_3 content totaling 77.89%, confirming its applicability as a supplementary cementitious material. CSA-blended concrete developed lower early-age compressive strength compared to the control due to delayed hydration and slower pozzolanic reaction. However, significant strength was developed at later curing ages. Under 2.5% $MgSO_4$

exposure, the control concrete experienced substantial strength deterioration (17.7% loss at 180 days), whereas CSA-modified concrete showed significantly improved sulphate resistance. Strength losses were limited to 3.8% and 4.75% for 10% and 15% CSA replacements, respectively.

Incorporation of CSA reduced sorptivity and water absorption, indicating improved pore structure refinement and reduction of permeability. This improvement limits the ingress of aggressive ions and contributes to better durability performance. Among the replacement levels investigated, 10% CSA demonstrated optimal performance in terms of compressive strength retention, resistance to sulphate attack, and durability indices.

Therefore, CSA can be effectively utilized as a sustainable supplementary cementitious material. A 10% replacement level is recommended for structural concrete in sulphate-rich or aggressive environments, while 15% replacement may be suitable for less aggressive conditions. In addition to enhancing durability, CSA incorporation contributes to environmental sustainability through reduction in cement consumption and associated CO_2 emissions and also contributes to the enhancement of economic value of Coconut Shell Ash and conservation of wealth and resources through elimination of unproductive dumping of coconut shell in landfill.

The findings of this study therefore demonstrate the potential of Coconut Shell Ash as a sustainable and environmentally friendly supplementary cementitious material capable of improving the durability performance of concrete in aggressive sulphate environment.

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