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# PERFORMANCE ENHANCEMENT OF RECYCLED AGGREGATE CONCRETE USING COCONUT STEM ASH

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## ABSTRACT

The increasing demand for cement and natural aggregates has raised concerns about carbon emissions, resource depletion, and waste management. This study investigates the potential of coconut stem ash (CSA) as a partial cement replacement and recycled coarse aggregate (RCA) as a substitute for natural aggregate to develop sustainable concrete. CSA was incorporated at 0%, 5%, 10%, and 15% by weight of cement, while RCA replaced natural coarse aggregate at 50% and 100% levels. Recycled aggregate concrete (RAC) offers a sustainable alternative by utilizing 100% recycled coarse aggregate, but its inferior strength and durability compared to conventional concrete limit its application. This study explores the use of coconut stem ash (CSA), derived from the monitored open air burning of coconut palm stems, as a partial replacement for cement to enhance the performance of RAC. Cement was replaced with CSA at 0%, 5%, 10%, 15%, and 20% by weight, and mixes were evaluated for workability, compressive strength, and splitting tensile strength after 28 days of curing. Durability performance was evaluated by immersing specimens in a 10% sodium chloride (NaCl) solution to examine resistance against chloride ion penetration. Results showed a minor reduction in slump with increasing CSA content due to its fine texture and higher water demand. Mechanical performance improved at 10% CSA replacement, where compressive, tensile, and flexural strengths were comparable to or exceeded those of control RAC. Durability assessments also revealed improved resistance to chloride attack at the same level. Overall, the findings demonstrate that the combined use of CSA and RCA can produce concrete with satisfactory strength and durability characteristics while promoting resource conservation and waste utilization offers a viable pathway toward low-carbon and environmentally sustainable construction materials.

***Keywords:*** *Coconut stem ash (CSA), Recycled Coarse Aggregate (RCA), Sustainable Concrete, Chloride Ion Penetration, Durability assessments Pozzolanic Activity, Chloride Durability*

## 1. INTRODUCTION

The global cement and concrete industry stand at a critical juncture in the pursuit of sustainable development, compelled to address its substantial environmental footprint, particularly the release of carbon dioxide ($CO_2$). With concrete consumption projected to exceed 20 billion tons annually by 2030, the extraction of virgin aggregates and energy-intensive clinker manufacturing exacerbate resource depletion, habitat destruction, and greenhouse gas accumulation **(Handayani et al., 2021)**. With sustainability becoming a global priority, efforts to decrease the environmental impact of construction materials continue to gain momentum**(Adamu Umar et al., 2021; Oyebisi et al., 2022)** .Rising fuel demands, raw-material depletion, and carbon emissions are threatening the cement sector's long-term viability **(Benhelal et al., 2013)**, making the search for greener alternatives essential**(Oyebisi et al., 2022)**. To address this challenge, researchers have explored the incorporation of alternative materials in concrete to reduce cement consumption and environmental impacts**(Siddique, 2014)**. Adopting such strategies is not only cost-effective but also environmentally beneficial **(Brito & Silva, 2014)**.

Recycled aggregate concrete (RAC) has emerged as a promising solution to address the dual challenges of construction and demolition (C&D) waste management and natural resource conservation. Globally, C&D waste accounts for approximately 35% of total waste generation, with concrete comprising the largest fraction **(Handayani et al., 2021)**. In the United States alone, approximately 600 million tons of C&D debris are generated annually, with concrete and masonry materials constituting about 70% of this waste (EPA, 2018). By utilizing demolished concrete structures as coarse aggregate, RAC not only reduces the burden on landfills but also conserves natural aggregate resources, addressing a critical sustainability challenge**(Brito & Silva, 2014; Su et al., 2019)**. Despite these advantages, RAC typically exhibits 15–30% lower mechanical strength and heightened permeability compared to conventional concrete, primarily due to the porous adhered mortar on recycled coarse aggregates (RCA), which weakens the interfacial transition zone (ITZ) and increases susceptibility to chloride ingress and sulfate attack **(Kisku et al., 2017)**. To overcome these limitations without compromising sustainability, researchers have increasingly turned to supplementary cementitious materials (SCMs) derived from agricultural and agro-industrial by-products—materials that not only reduce cement demand but also enhance long-term performance through pozzolanic reactivity**(Aprianti et al., 2015)**.

The use of agricultural waste ashes as partial cement replacements has gained considerable research attention over the past two decades. Rice husk ash (RHA), perhaps the most extensively studied agricultural ash, has demonstrated excellent pozzolanic properties when burned at controlled temperatures (600-700°C) and ground to appropriate fineness**(Singh & Singh, n.d.)**.Studies have reported that 10-20% cement replacement with RHA can enhance compressive strength by 10-25% at later ages and significantly improve durability properties**(Siddika et al., 2021)** .Similarly, sugarcane bagasse ash has shown promising results when used at 10-20% replacement levels, with improvements in long-term strength and resistance to sulfate attack **(Rukzon & Chindaprasirt, 2012)**. Despite the substantial research on various agricultural ashes, coconut stem ash remains relatively unexplored in the scientific literature. While coconut stem has been investigated as a lightweight aggregate replacement**(Gunasekaran et al., 2011)** , the potential of coconut stem ash as a cementitious material has received limited attention.

Global coconut production exceeds 60 million tons annually, generating substantial lignocellulosic residues that are often openly burned, contributing to particulate emissions and soil degradation **(Stelte et al., 2022)**. CSA is characterized by high amorphous silica content (60–70%), low loss on ignition, and fineness comparable to Class F fly ash, rendering it capable of reacting with portlandite to form additional calcium silicate hydrate (C-S-H) and refine pore structure **(Šupić et al., 2021)**. Preliminary studies on coconut stem ash and related biomass ashes suggest optimal cement replacement levels of 5–15% for strength enhancement in normal concrete **(Umoh & Ujene, 2015)**, yet systematic evaluation of CSA in 100% RAC remains scarce.

While coconut shell ash (CSA-shell) has been widely investigated as a partial cement replacement in concrete incorporating recycled coarse aggregate (RCA) as a substitute for natural aggregate to promote sustainability (Umoh & Ujene, 2015), the use of coconut stem ash (CSA-stem) as a cementitious material has not yet been reported in the literature**.** The utilization of coconut stem as reinforcement in concrete slabs has been explored; however, coconut stem ash has not before been employed as an aggregate or cementitious material. Different CSA replacement levels were examined to evaluate their effects on workability, compressive strength, tensile strength, flexural strength, and durability. Durability performance was further assessed through chloride and sulfate exposure. The study aims to identify an optimum CSA dosage that can enhance both mechanical and durability properties while reducing cement usage and promoting waste valorisation. The results are expected to support sustainable concrete development by combining agricultural and construction waste materials into a durable, environmentally responsible construction solution.

## 2. MATERIALS AND METHODS

### 2.1 Cement

Ordinary Portland cement (OPC) of type CEM-I 52.5 N, according to BDS EN 197-1, was used. Its physical properties were measured following ASTM standards and are listed in Table 1 (ASTM C187; ASTM C191-08).

**Table 1: Physical properties of cement**

| Specific gravity | Blaine Fineness ($g/cm^2$) | Normal consistency (%) | Initial setting time (min) | Final setting time (min) |
|---|---|---|---|---|
| 3.17 | 3994 | 27.2 | 104 | 248 |

### 2.2 Aggregates

19 mm downgrade recycled brick aggregates were used. They were obtained from demolished partition walls, while new brick aggregates were used as a reference. Both types of aggregates were tested for their physical properties following ASTM standards to evaluate suitability for concrete production. Sylhet sand was used as fine aggregate (FA). The properties of aggregates was determined as per ASTM standards are listed in Table 2 (ASTM C127-24; ASTM C136-06).

**Table 2:** Physical properties of fine aggregates (FA), normal brick coarse aggregates (CA) and RCA

| | Specific gravity (SSD) | Dry unit weight ($kg/m^3$) | Fineness modulus (FM) | Water absorption (%) | Coefficient of uniformity ($C_u$) | Coefficient of curvature ($C_c$) |
|---|---|---|---|---|---|---|
| FA | 2.67 | 1495.82 | 2.55 | - | 2.20 | 1.08 |
| CA | 2.65 | 1226.26 | 4.59 | 19.91 | 2.09 | 1.15 |
| RCA | 2.48 | 1185.82 | 4.54 | 21.92 | 1.98 | 1.07 |

The coconut stems were thoroughly washed, air-dried under sunlight for 7 days, and subsequently burnt in an open environment until complete ash (Fig. 1). The resulting ash was allowed to cool, then ground using a laboratory ball mill and sieved through a 75 µm sieve to achieve fine particles suitable for cementitious applications. The ash was incorporated as a partial replacement of ordinary Portland cement at levels of 0%, 5%, 10%, and 15% by weight. The surface area, specific gravity, and bulk density of the coconut stem ash (CSA) were determined as 312 $m^2/kg$, 2.14, and 720 $kg/m^3$, respectively. The fineness of cement was assessed using Blaine fineness, while the specific surface area was used to evaluate the fineness of coconut stem ash. Despite employing various measurement methods, the surface area reported for CSA suggests a level of fineness similar to that of supplementary cementitious materials found in earlier research. Although EDS provides semi-quantitative elemental composition, it was used here to confirm the dominance of silica, alumina, and iron oxides and the pozzolanic suitability of CSA. Previous studies have shown that coconut-based biomass ashes can behave as pozzolanic materials because of their high amorphous silica content and the combined presence of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$, which are known to contribute to secondary C–S–H formation in cementitious systems. (Rukzon & Chindaprasirt, 2012)The chemical composition of CSA was analysed using Energy Dispersive X-ray Spectroscopy (EDS) and is presented in Table 3.

**Table 3:** Chemical properties of coconut stem ash

| Constituents | Composition (%) |
|---|---|
| $SiO_2$ | 55.4 |
| CaO | 11.13 |
| MgO | 2.14 |
| $Al_2O_3$ | 8.68 |
| $Na_2O$ | 0.39 |
| $Fe_2O_3$ | 7.58 |
| $K_2O$ | 9.86 |
| Others | 4.82 |

The summation of $SiO_2 + Al_2O_3 + Fe_2O_3 = 71.66\%$ which exceeds the minimum requirement of 70% as stipulated by ASTM C618-23 for Class F pozzolanic materials. Additionally, $SO_3 < 5\%$ and $LOI < 6\%$ further confirm the suitability of CSA as a supplementary cementitious material (SCM) in concrete.

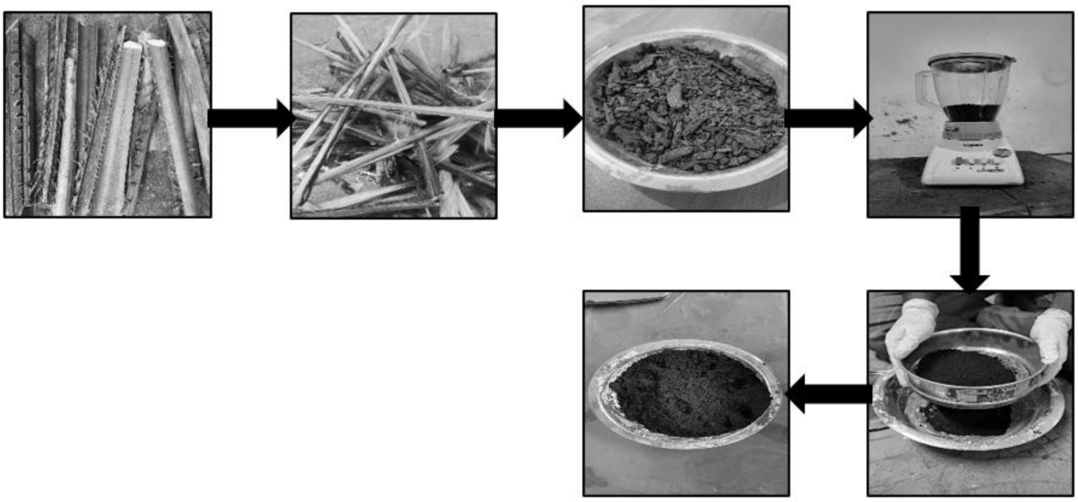
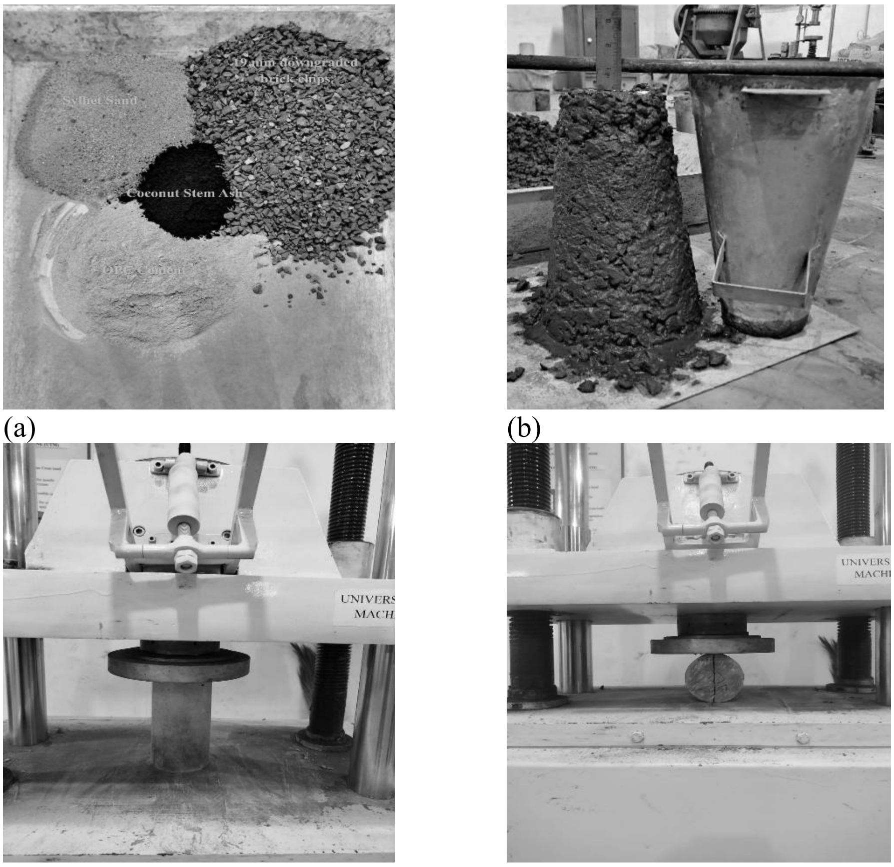


Figure 1: Preparation of coconut stem ash

## 2.3 Experimental Test Procedure

Workability test was conducted as per ASTM C143 (ASTM C143/C143M-12). In order to perform, compressive and splitting tensile strength 100 mm × 200 mm size cylinder was prepared. Both the tests were done after 28 days normal curing period using Universal testing machine (UTM). ASTM standards procedure (ASTM C39/C39M-21; ASTM C496-96) were followed to conduct the tests. For durability testing, chloride ion penetration and wet-dry cycle tests were conducted. After normal curing, cylindrical specimens were immersed in a 10% NaCl solution for 28 days. Then, they were brought to SSD condition and split at the midpoint following the colorimetric method (He et al., 2012). A 0.1N silver nitrate ($AgNO_3$) solution was sprayed on the split surface. The $AgNO_3$ reacted with chloride ions to form white silver chloride (AgCl), while deeper areas formed brown silver oxide ($Ag_2O$). The brown colour appeared within 10–15 minutes, showing the chloride penetration depth. The boundary was marked, and the specimen with the maximum chloride penetration was identified. Compressive and split tensile strengths were also measured as described earlier. A 10% NaCl solution was used to accelerate chloride attack, as it is higher than normal marine salinity (~3.5% NaCl). This helps simulate long-term exposure in a shorter time (Al Mamun & Islam, 2017). The method is common in durability research to assess performance under severe chloride conditions, similar to tidal, splash, or de-icing environments. Such conditions are relevant to Bangladesh's coastal regions, where salinity often rises due to tidal changes and evaporation (Bosunia & Chowdhury, 2001). Testing under these harsh conditions provides conservative and reliable performance results for real marine and saline environments.



(a) (b)

(c) (d)

Figure 2: Materials and tests (a) Mix materials; (b) Slump test; (c) Compressive strength test and (d) Split tensile strength test

The concrete mix designations used in the study based on aggregate type and coconut stem ash (CSA) content. The mixes are grouped into three categories: conventional concrete with 100% natural aggregate (N0), blended aggregate concrete with 50% recycled aggregate and 50% natural aggregate (RA50N50), and recycled aggregate concrete with 100% recycled aggregate (RA100). For each aggregate category, cement was partially replaced with CSA at levels of 0%, 5%, 10%, and 15% to evaluate its influence on fresh, mechanical, and durability properties. This systematic labelling allows clear comparison of the combined effects of recycled aggregate and CSA replacement.

**Table 4**: Description of the Mix Ratio

| Mix ID | Description |
|---|---|
| N0CS0 | 100% normal aggregate, 0% CSA |
| N0CS5 | 100% normal aggregate, 5% CSA |
| N0CS10 | 100% normal aggregate, 10% CSA |
| N0CS15 | 100% normal aggregate, 15% CSA |
| RA50N50CS0 | 50% RA + 50% N, 0% CSA |
| RA50N50CS5 | 50% RA + 50% N, 5% CSA |
| RA50N50CS10 | 50% RA + 50% N, 10% CSA |
| RA50N50CS15 | 50% RA + 50% N, 15% CSA |
| RA100CS0 | 100% RA, 0% CSA |
| RA100CS5 | 100% RA, 5% CSA |
| RA100CS10 | 100% RA, 10% CSA |
| RA100CS15 | 100% RA, 15% CSA |

## 3. RESULTS AND DISCUSSION

For the experimental test a total of 12 different mixes was prepared (Table 4). Each mix was then tested for workability, compressive and splitting tensile strength. The test results are described in the following section.

### 3.1 Slump Value

The slump test results showed a gradual decrease in workability with the increase in recycled brick aggregate (RA) and coconut stem ash (CSA) content. The control mix (N0C0) exhibited the highest slump value of 35.67 mm, indicating comparatively better workability. With the addition of coconut stem ash, the slump values slightly decreased to around 33.13 mm, 30.58 mm, and 28.93 mm for N0C5, N0C10, and N0C15, respectively. When 50% of the normal aggregate was replaced by recycled brick aggregate, the slump values further dropped to approximately 30.11 mm, 28.34 mm, 26.67 mm, and 24.45 mm for RA50N50CS0, RA50N50C5, RA50N50CS10, and RA50N50CS15, respectively.

**Table 5: Slump value of the test sample mix**

| Mix ID | Description | Slump (mm) |
|---|---|---|
| N0CS0 | 100% normal aggregate, 0% CSA | 35.67 |
| N0CS5 | 100% normal aggregate, 5% CSA | 33.13 |
| N0CS10 | 100% normal aggregate, 10% CSA | 30.58 |
| N0CS15 | 100% normal aggregate, 15% CSA | 28.93 |
| RA50N50CS0 | 50% RA + 50% N, 0% CSA | 30.11 |
| RA50N50CS5 | 50% RA + 50% N, 5% CSA | 28.34 |
| RA50N50CS10 | 50% RA + 50% N, 10% CSA | 26.67 |
| RA50N50CS15 | 50% RA + 50% N, 15% CSA | 24.45 |
| RA100CS0 | 100% RA, 0% CSA | 25.22 |
| RA100CS5 | 100% RA, 5% CSA | 23.41 |
| RA100CS10 | 100% RA, 10% CSA | 21.34 |

| **Mix ID** | **Description** | **Slump (mm)** |
|---|---|---|
| RA100CS15 | 100% RA, 15% CSA | 20.97 |

The lowest slump values were observed in mixes containing 100% recycled brick aggregate, where the slump reduced to about 25.22 mm for RA100CS0 and further declined to 23.41 mm, 21.34 mm, and 20.97 mm for RA100CS5, RA100CS10, and RA100CS15, respectively. The reduction in slump with higher RA content is mainly due to the rough surface texture and high-water absorption of recycled brick aggregates, which reduce the available free water in the mix. Similarly, the inclusion of coconut stem ash increases the surface area of fine materials, raising the water demand and making the mix stiffer. The combined use of RA and CSA intensifies this effect, resulting in a significant reduction in workability compared to the control mix.

### 3.2 Compressive Strength Test Results

The compressive strength of concrete of the test samples after 28 days normal curing period is shown in Fig. 3. The compressive strength of concrete decreased with higher recycled brick aggregate (RA) content and slightly improved with the addition of coconut stem ash (CSA) up to 10% replacement. The control mix (N0C0) showed a strength of 21.91 MPa, which increased slightly to 24.85 MPa for N0C10, then decreased to 24.14 MPa for N0C15. This indicates that a small amount of CSA can enhance strength due to its pozzolanic reaction, but excessive replacement reduces it. When 50% of normal aggregate was replaced by RA, the strength dropped to 20.22 MPa but improved to 22.52 MPa at 10% CSA, showing partial recovery. Similarly, mixes with 100% RA had the lowest strength of 18.35 MPa, but strength increased to 21.04 MPa at 10% CSA. The overall trend shows that recycled aggregates reduce compressive strength because of their porous and weak structure, while moderate CSA addition helps improve bonding and strength through secondary hydration. However, beyond 10% CSA, strength decreased again due to dilution of cementitious material.

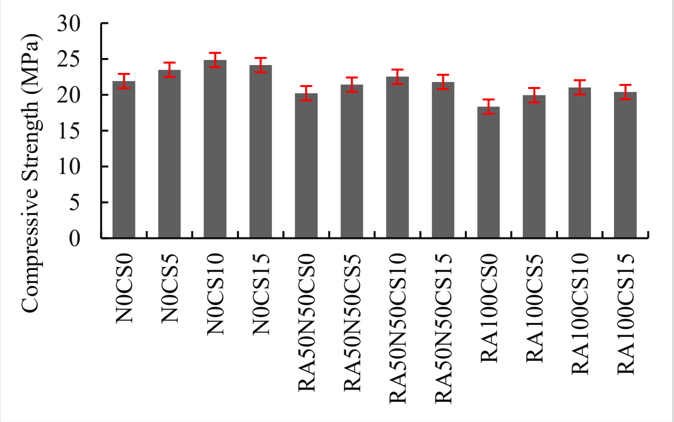


Figure 3: Compressive strength of concrete samples after 28 days normal curing period

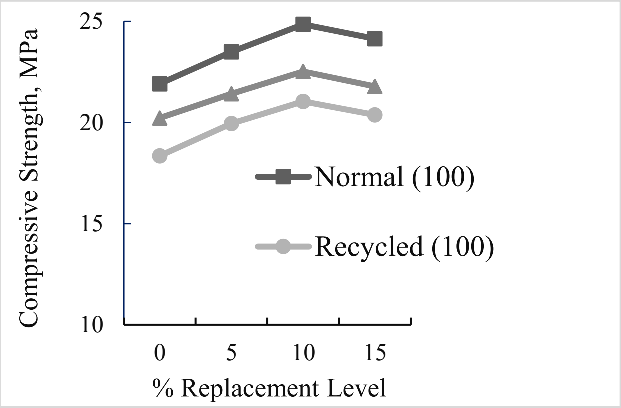


Figure 4: Effect of % replacement level of cement by coconut stem ash on compressive strength

The Fig. 4 shows that the compressive strength increases slightly with the addition of coconut stem ash up to around 10–15% replacement, after which it becomes almost constant. The Normal (100) mix gives the highest strength, while the Recycled (100) mix shows slightly lower values, indicating that recycled aggregates may reduce the strength. The combined Normal (50) + Recycled (50) mix performs moderately between the two. It can be summarized that compressive Strength and durability of concrete with coconut stem ash as cement replacement (Adajar et al., 2020) found that partially replacing ordinary Portland cement (OPC) with coconut stem ash (CSA) improved compressive strength up to an optimum level of roughly 10% replacement, after which further increase reduced strength. CSA is rich in reactive silica and alumina, which function as supplementary cementitious materials through pozzolanic reactions, the amorphous silica present in coconut stem as reacts with calcium hydroxide ($Ca(OH)_2$) released at the time of cement hydration and form additional calcium silicate hydrate (C–S–H) gel, thus refining the pore structure, increasing density, and enhancing compressive strength and durability. Therefore, combining recycled aggregate (RA) with CSA offers a balanced approach which leverage waste materials to enhance sustainability while still achieving satisfactory strength performance at moderate replacement levels.

### 3.3 Splitting Tensile Strength Test Results

The splitting tensile strength of concrete followed a similar trend (Fig. 5) to compressive strength, showing a slight improvement with moderate coconut stem ash (CSA) content and a decrease with higher recycled brick aggregate (RA) replacement. The control mix (N0CS0) achieved a tensile strength of 2.95 MPa, which gradually increased to 3.17 MPa at 10% CSA (N0CS10) and slightly dropped to 3.12 MPa for N0CS15. For the 50% RA replacement group, tensile strength ranged from 2.87 MPa to 3.07 MPa, while for 100% RA mixes, it varied between 2.78 MPa and 2.94 MPa.

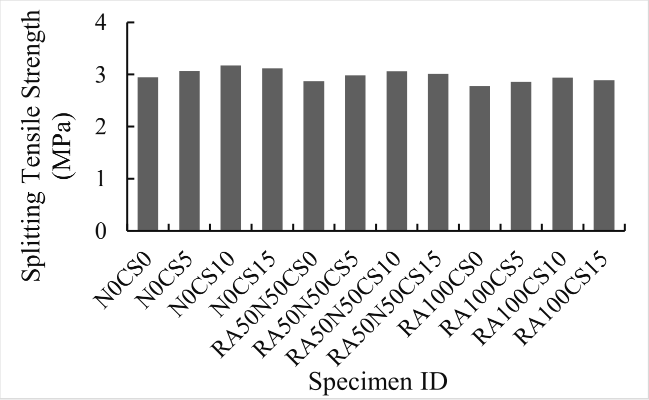


Figure 5: Splitting tensile strength of concrete samples after 28 days normal curing period

The small improvement at 10% CSA is attributed to the pozzolanic activity of coconut stem ash, which refines pore structure and enhances the bond between paste and aggregate. However, higher CSA content reduces tensile strength due to less cementitious material available for hydration. The reduction in tensile strength with increasing RA content is mainly due to the weak and porous nature of recycled brick aggregates, which causes poor interfacial bonding and higher micro crack formation under tensile stress. These observations align with general findings that recycled brick tends to reduce tensile strength because of its porous texture, higher water absorption, and weaker interfacial transition zone. Nevertheless, using small amounts of agricultural ashes such as coconut stem ash as a partial cement replacement can enhance the concrete microstructure and improve tensile performance through pozzolanic activity and stronger bonding at lower replacement levels

### 3.4 Performance in Chloride Ion Penetration

The compressive strength of several concrete mixes after 28 days of immersion in a 10% NaCl solution is displayed in Fig. 6. The entirely recycled aggregate concrete (RA100) had a discernible decrease in compressive strength, whereas the normal concrete (NWC) attained the maximum. The increased porosity and thinner interfacial transition zones found in recycled aggregates may be the cause of this decline. In contrast to the 100% RCA mix, mixtures with 50% recycled and 50% natural aggregates along with trace amounts of coconut stem ash (RA50N50CS5–C10) showed better strength. Coconut stem ash's (CSA) pozzolanic reaction promotes the production of more calcium silicate hydrate (C–S–H) gel, which improves pore structure and boosts resistance to deterioration brought on by chloride.

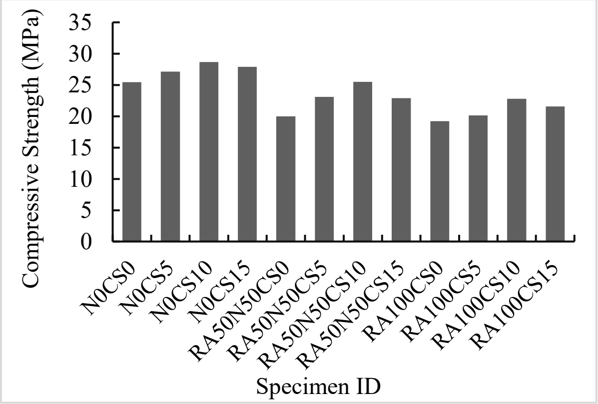


Figure 6: Compressive strength after 28 days curing in 10% NaCl solution

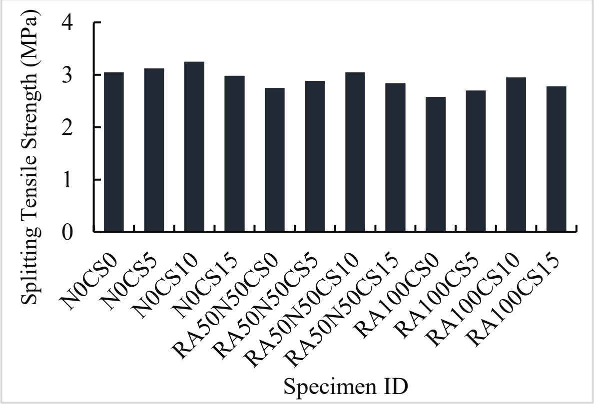


Figure 7: Splitting tensile strength after 28 days curing in 10% NaCl solution

Fig. 7 presents the splitting tensile strength of the same mixes under 10% NaCl exposure. The pattern is comparable to that of compressive strength: NWC achieved the highest tensile strength, while 100% RCA mixes had the lowest. The reduction in tensile strength for recycled concrete is attributed to microcracks and weaker bonding between old and new paste layers. Nevertheless, the mixes containing CSA (especially RA50N50CS5–C10) showed moderate improvement, indicating that the pozzolanic effect of CSA strengthens the interfacial transition zone and enhances the concrete’s tensile resistance even in aggressive chloride environment which indicate that the inclusion of supplementary pozzolanic materials enhances bond strength and increases the microstructural density of recycled concrete.

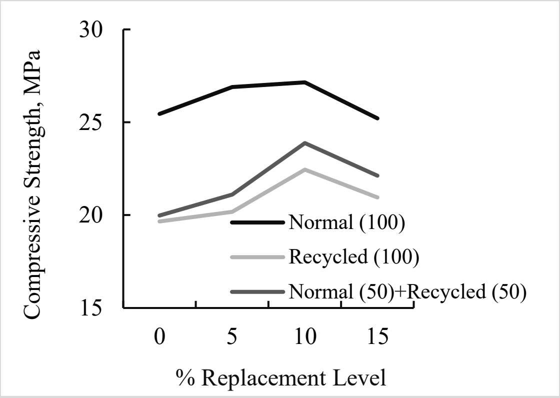


Figure 8: Effect of % replacement level of cement by coconut stem ash on compressive strength

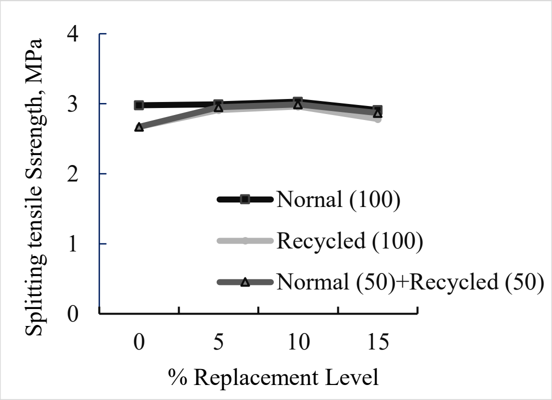


Figure 9: Effect of % replacement level of cement by coconut stem ash on tensile strength

According to Fig. 8, chloride ion exposure on the mechanical performance of coconut stem ash-modified recycled aggregate concrete was investigated by comparing specimens immersed in a 10% NaCl solution to those cured under normal conditions as described in section 3.2. Most mixes showed a modest drop in compressive strength following chloride exposure, especially 100% recycled aggregate concrete, due to increased porosity and weaker interfacial transition zones. However, mixtures containing 5-10% CSA demonstrated relatively superior strength retention, which can be related to CSA's pozzolanic reaction, which produces more C-S-H gel and refines pore structure all mixes compressive strength rose as the proportion of coconut stem ash (CSA) rose up to 10%, after which it slightly decreased at 15%. This improvement is explained by the pozzolanic reaction between the calcium hydroxide from cement hydration and the reactive silica in CSA, which produces more calcium silicate hydrate (C–S–H) gel that fortifies the concrete matrix. Fig. 9 illustrates how replacing up to 10% of the concrete with coconut stem ash (CSA) increases its splitting tensile strength before slightly declining at 15%.This improvement at lower levels is the result of multiple combined effects: their rough texture improves interlocking; their silica content contributes to limited pozzolanic reactions, forming additional binding compounds; and the fine CSA particles fill micro voids, improving particle packing and bond strength between the paste and aggregates. When combined, these elements produce a stronger, denser matrix that is resistant to crack development. Excessive ash lowers the cement content and available hydration products beyond 10%, which results in a little decrease in strength**.**

## 4. CONCLUSIONS

The results of the experiment show that sustainable concrete with enough strength and durability may be produced by combining recycled coarse aggregate (RCA) with coconut stem ash (CSA). Due to increased water absorption and the tiny particle size of CSA, the workability of concrete decreased with increasing RCA and CSA concentration; yet, the mixes were still workable for practical uses. The pozzolanic activity of CSA boosted the development of extra calcium silicate hydrate (C–S–H) gel, refined the pore structure, and improved bonding between the paste and aggregates. The compressive and splitting tensile strengths demonstrated optimal performance at 10% CSA replacement. Because of its porous and weak structure, 100% RCA replacement decreased strength; however, partial substitution (50% RCA plus 10% CSA) produced mechanical qualities that were on par with or better than the control mix. By decreasing permeability and strengthening the concrete's resistance to chloride ion penetration, CSA successfully increased durability under chloride exposure, hence lowering the detrimental impacts of RCA. Overall, the study finds that the best mix of 10% CSA and 50% RCA provide a structurally sound and ecologically friendly substitute for traditional concrete. This method not only makes use of construction and agricultural waste, but it also helps conserve resources, use less cement, and create sustainable building materials with minimal carbon emissions.

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## DECLARATION OF AI

The authors used an artificial intelligence–based language assistance tool (ChatGPT, Gemini, Grammarly) to support language editing, grammar correction, and improvement of clarity and readability of the manuscript. The AI tool was used only for writing support and did not contribute to the research design, data collection, experimental procedures, data analysis, interpretation of results, or generation of figures, tables, or scientific conclusions. All technical content, data, and interpretations were produced, verified, and approved by the authors.

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