**EVALUATING THE ELASTIC MODULUS OF CONCRETE MODIFIED WITH COCONUT SHELL ASH**

**ABSTRACT**

This study investigates the potential of coconut shell ash (CSA), an agricultural waste product, as a supplementary cementitious material (SCM) for sustainable concrete production. CSA, obtained from calcined coconut shells and rich in reactive silica, alumina, and iron oxides, was used to replace ordinary Portland cement (OPC) at 0%, 10%, 20%, and 30% by weight. A total of 224 concrete cubes were prepared using a 1:2:4 mix ratio and a constant water-to-cement ratio of 0.5, and were tested over 14 curing periods ranging from 3 to 91 days. Workability was measured using slump tests, while the elastic modulus was estimated based on compressive strength using the ACI 318-14 formula. Findings revealed that increasing CSA content led to reduced slump, indicating lower workability due to the ash’s porous and high-surface-area characteristics. However, the mix containing 10% CSA demonstrated an enhanced elastic modulus, peaking at 19.34 GPa on day 28, surpassing the control. This improvement is attributed to CSA’s pozzolanic activity, which promotes additional calcium silicate hydrate (C-S-H) formation, thereby densifying the concrete matrix. Higher replacement levels (20–30%) resulted in performance decline due to cement dilution. The study concludes that 10% CSA substitution offers an optimal balance between mechanical performance and sustainability in concrete.

***Keywords; Elastic modulus, Concrete, Coconut Shell Ash, Compressive strength, Slump, Workability***

1. **Introduction**

The growing emphasis on sustainable construction has led to extensive research into the use of agricultural waste materials as supplementary cementitious materials (SCMs). Among these alternatives, coconut shell ash (CSA), produced through the controlled burning of coconut shells, has emerged as a promising candidate due to its pozzolanic activity and its ability to improve concrete performance while minimizing environmental impacts (Bheel et al., 2021).

CSA contains high levels of reactive silica, alumina, and iron oxides, which facilitate secondary hydration reactions when blended with ordinary Portland cement (OPC). These reactions enhance the formation of calcium silicate hydrate (C-S-H), which improves the density and durability of the concrete matrix (Shanmuga Priya & Padmanaban, 2024). Studies indicate that substituting up to 10% of OPC with CSA can yield increases in compressive, tensile, and flexural strengths by approximately 12%, 10%, and 9%, respectively, over conventional mixes (Pooja et al., 2025).

One key mechanical property influenced by CSA incorporation is the elastic modulus (MOE), which governs a concrete structure's stiffness and resistance to deformation. Research confirms that optimal levels of CSA enhance MOE, thereby improving structural performance and load-carrying capacity (Bheel et al., 2021).

In addition to mechanical improvements, recent empirical investigations have demonstrated that incorporating coconut shell ash (CSA) as a partial replacement for cement in concrete production can significantly enhance the environmental sustainability of the resulting material. This innovation is grounded in the dual advantages of reducing carbon emissions associated with cement production and repurposing agricultural waste materials, thereby supporting circular economy principles. Given that cement production is a major contributor to CO₂ emissions, partially replacing cement with CSA helps lower the carbon footprint of concrete. For instance, Pooja et al. (2025) found that a 15–20% CSA substitution could cut the embodied carbon content of concrete by around 15%, supporting sustainability goals. Ranatunga et al. (2023) examined the environmental impact of substituting cement with CSA at varying proportions, 15%, 20%, 25%, and 30%. The life-cycle assessment, which focused on the cradle-to-gate global warming potential (GWP), revealed a progressive reduction in environmental burden with increased CSA content. Specifically, the study reported that replacing 15%, 20%, 25%, and 30% of cement with CSA led to reductions in GWP of over 10%, 15%, 20%, and 25%, respectively. Importantly, the 20% CSA mix was identified as the most environmentally efficient, achieving a GWP reduction greater than 15% while maintaining a 28-day compressive strength of approximately 27 MPa, sufficient for most structural applications. Further evidence of CSA's environmental merit comes from the work of Bheel et al. (2022), who explored the sustainability performance of a ternary blended concrete incorporating both CSA and groundnut shell ash (GSA). Their study highlighted that at a 20% total replacement level, the embodied carbon of the concrete decreased by approximately 16% compared to conventional mixes. This reduction was achieved without compromising the long-term mechanical properties of the concrete, as the elastic modulus and compressive strength improved over a 90-day curing period. Though a slight reduction in fresh concrete workability was noted, it was considered a manageable trade-off for the significant environmental benefits. Kazmi et al. (2020) provided further validation in their investigation of CSA's influence on workability, mechanical properties, and embodied carbon. At a 10% CSA replacement level, they observed compressive, tensile, and flexural strength increases of 12%, 10%, and 9%, respectively, alongside an embodied carbon reduction of roughly 15%. This demonstrates that environmental gains do not necessarily come at the expense of mechanical performance, especially when CSA content is carefully optimized. Pathanamoorthy et al. (2021) explored the combined use of CSA and sugarcane bagasse ash (SCBA) as SCMs. In mixes containing 15% CSA and 40% SCBA, a 4% reduction in total embodied carbon was recorded, while compressive strength remained relatively high at 28.75 MPa. These findings highlight CSA’s compatibility with other pozzolanic materials in supporting sustainable concrete design.

In terms of pure mechanical performance, Herring et al. (2022) conducted a comprehensive investigation on concrete mixes incorporating 10% CSA and 5% coconut shell particles (CSP) as partial replacements for cement and coarse aggregates. Their results revealed only a slight reduction in 90-day compressive strength (3.23% lower than control), while split tensile strength increased by 2.76%. Moreover, specimens exposed to sulphuric acid exhibited a 9.37% improvement in tensile strength compared to the control. The most remarkable result emerged under thermal stress: after exposure to 500 °C for one hour, compressive strength increased by 30.7%, with just a 24.6% drop in strength retention, significantly better than many other alternative concrete types. Zhang et al. (2023) examined the effect of coconut shell aggregate on the modulus of elasticity and flexural behavior of green concrete. When 10% and 15% of fine aggregate was replaced with coconut shell particles, the modulus of elasticity increased by 11.2% and 12.8%, respectively. Flexural strength also improved by 10.3% at the 15% replacement level, showing that coconut shell aggregates do not merely act as filler but actively contribute to structural stiffness and ductility. Sabeen et al. (2022) emphasized the benefits of using coconut fibers in concrete. Their results showed that incorporating 3% coconut fiber led to a 53.7% increase in flexural strength at 28 days and a 30% increase in split tensile strength relative to unreinforced concrete. These fibers acted as internal reinforcement, bridging micro-cracks and enhancing the post-cracking performance of the composite. Pathanamoorthy et al. (2021) also evaluated the influence of CSA in paving block concrete and found the optimum performance at 9.5% CSA replacement, yielding a 28-day compressive strength of 40.45 MPa, compared to 36.93 MPa for the control. The improved compressive strength was accompanied by better abrasion resistance and acceptable water absorption values, which are critical for pavement applications.

Strictly on MOE investigation using CSA, Bheel et al. (2020) observed that substituting up to 10% of OPC with CSA resulted in approximately a 10% increase in the MOE compared to conventional concrete. This enhancement is primarily attributed to the pozzolanic reaction between the silica-rich CSA and calcium hydroxide produced during cement hydration, leading to additional calcium silicate hydrate (C-S-H) gel formation that densifies the concrete matrix and improves stiffness. Further research by Mahro et al. (2020), indicated that incorporating CSA alongside other additives, such as sisal fibers, can synergistically enhance mechanical properties, including the MOE. Their findings revealed a 7% increase in MOE with a 3% addition of sisal fibers to CSA-modified concrete, highlighting the combined effects of hybrid additives on concrete performance.

The extent of improvement in MOE is influenced by several factors, including the percentage of cement replacement with CSA, particle fineness, and curing duration. While a 10% replacement level appears optimal, higher percentages may lead to a decline in MOE due to dilution effects and reduced availability of calcium hydroxide for pozzolanic activity. Moreover, the fineness of CSA significantly affects its reactivity; finer particles provide increased surface area, facilitating enhanced pozzolanic reactions and improved microstructural bonding. In a study by Kumator Taku (2019), nanoindentation tests on cement paste with 15% CSA replacement demonstrated improved nanomechanical properties, including increased elastic modulus and hardness, due to the formation of additional C-S-H phases and reduced porosity. Similarly, Barveen (2018) reported that the modulus of elasticity of concrete increased with the level of CSA substitution and the age of curing, attributing this to the efficient pore-filling ability of CSA particles due to their fineness.

Furthermore, optimization and statistical studies, including those employing Bayesian methodologies, have validated the feasibility of CSA as a cement replacement without compromising performance when used within optimal thresholds. Replacement rates in the 10–15% range are generally effective in achieving both mechanical enhancement and environmental sustainability (Shanmuga Priya & Padmanaban, 2024).

Overall, incorporating CSA into concrete as an SCM offers a sustainable and efficient means of improving structural performance, particularly the elastic modulus, while reducing dependence on conventional cement and advancing eco-friendly construction practices. This study aimed to validate and support previous findings on CSA as a partial replacement of cement in concrete production with specific focus on the workability and elastic modulus properties of the CSA-cement concrete.

1. **Materials and Methods**

**2.1 Materials and Characterization**

**i. Coconut Shell Ash**

Dry coconut shells were collected from local agricultural sources, oil mills, and food processing outlets in Onne Village, Eleme LGA, Rivers State, Nigeria. The shells were sun-dried, pulverized, and incinerated in a graphite crucible using a diesel-powered furnace at temperatures ranging between 1200 °C and 1400 °C for two hours. After combustion, the ash was left to cool naturally within the crucible to prevent charcoal formation. The cooled residue was sieved through a 75 µm (No. 200) sieve, and the fraction passing was used as the final CSA. X-ray fluorescence (XRF) analysis revealed the oxide composition as: SiO₂ (37.91%), Al₂O₃ (24.13%), Fe₂O₃ (15.41%), with a Loss on Ignition (LOI) of 11.93% and SO₃ content of 0.72%.

**ii Fine Aggregate (Sand)**

Fine aggregate used in this study was dredged from the Federal Ocean Terminal (FOT) area and washed at the PRODECO batching plant, Onne, Rivers State. Particle sizes ranged from 0.074 mm to 4.76 mm, and gradation analysis classified it as uniformly graded per ASTM D2487 (2011). The average bulk density was measured at 1666.67 kg/m³, which falls within the acceptable range of 1200–1750 kg/m³ specified by BS 812 Part 2 and ASTM C29M for normal weight concrete.

**iii Coarse Aggregates**

Granite chippings of two nominal sizes, 5–15 mm and 15–22 mm, were sourced from the INTELS quarry in Akamkpa, Cross River State. Particle size analysis revealed ranges of 1.19–12.7 mm for the 5–15 mm aggregate and 2.36–20 mm for the 15–22 mm aggregate. Both sizes exhibited dense gradation. Bulk density values were 1552.33 kg/m³ and 1543.67 kg/m³ for the smaller and larger aggregates, respectively, complying with BS 812 Part 2 and ASTM C29M specifications for normal weight concrete.

iv **Cement**

Dangote 42.5R grade ordinary Portland cement (OPC), conforming to the standards of BS EN 197-1:2000, was used as the primary binder. The cement was procured locally within Nigeria

v **Water**

Clean, potable water obtained from the INTELS water treatment plant at FOT, Onne, was used throughout the study for both mixing and curing processes. The water met standard requirements for use in concrete production.

**2.2 Methods**

**2.2.1 CSA-Concrete Mix Proportioning and Production**

A standard concrete mix ratio of 1:2:4 (cement: sand: coarse aggregate) was used for all batches, maintaining a fixed water-to-cement (W/C) ratio of 0.5. Ordinary Portland cement was partially substituted with CSA at replacement rates of 0%, 10%, 20%, and 30%. Before mixing, the moisture content of the sand was determined to ensure precise adjustment of the mixing water. To enhance aggregate gradation, the coarse aggregates were combined in a 2:1 ratio, two parts of 5–15 mm chippings to one part of 15–22 mm chippings. Concrete specimens were cured and tested at 14 different intervals: 3, 7, 14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, and 91 days. A total of 224 specimens were cast, with four samples prepared for each level of CSA replacement, including the control mix (0% CSA). Table 1 details the mix proportions of the CSA-blended cement samples, while Figure 1 shows the CSA-blended concrete in cube molds.

**Table 1: Mix proportioning of CSA-cement concrete sample for a cube size of 150 x 150 x 150mm.**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| S/No | MIX  LABEL | MIX  RATIO | W/C | % REPL  Of CSA | WT OF PC  (kg) | WT OF CSA  (kg) | WTOF SAND  (kg) | WT OF  GRAVEL  (kg) | WT  OF  WATER  (kg) |
| 1 | A | 1:2:4 | 0.5 | 0 | 1.66 | 0 | 3.32 | 6.65 | 0.83 |
| 2 | B | 10 | 1.48 | 0.15 | 3.32 | 6.65 | 0.83 |
| 3 | C | 20 | 1.36 | 0.27 | 3.32 | 6.65 | 0.83 |
| 4 | D | 30 | 1.16 | 0.35 | 3.32 | 6.65 | 0.83 |

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**Figure 1. Casting of cube samples**

**2.2.2 Slump test of CSA-Cement Concrete**

The slump test was conducted in accordance with ASTM C134. A steel slump cone with a height of 30 cm, a bottom diameter of 20 cm, and a top diameter of 10 cm, equipped with a handle, was used for the procedure. Fresh concrete was placed into the cone in three equal layers, each about 7.5 cm thick. Each layer was compacted by rodding 25 times using a steel tamping rod measuring 16 mm in diameter and 60 cm in length. After the cone was filled, leveled, and compacted, it was lifted vertically to allow the concrete to settle under its own weight. The upturned cone was placed beside the slumped concrete, and a straight edge was laid across the top. The vertical drop from the underside of the straight edge to the highest point of the concrete was measured with a ruler, accurate to the nearest 5 mm. This vertical measurement, known as the slump, represents the difference between the original cone height (H) and the final height of the slumped concrete (h), as shown in Equation (1). Figure 2 illustrates the procedures for conducting a slump test.

H – h = Slump (1)

A group of men in hardhats and safety vests

Description automatically generated

**Figure 2. Slump test being carried out in the laboratory**

**2.2.3 Elastic Modulus Determination of CSA-Cement Concrete**

The elastic modulus of the coconut shell ash (CSA) blended cement concrete in this study was determined using the compressive strength of concrete specimens containing varying levels of CSA as a partial substitute for Portland cement. An empirical formula from ACI 318-14, which is applicable to concrete with a unit weight between 1440 and 2560 kg/m³, was used to establish the relationship between compressive strength and elastic modulus. This relationship is expressed in Equation (2). The compressive strength of the hardened concrete was evaluated in accordance with BS 1239-3 (2019). During testing, each specimen was carefully positioned in the compression testing machine to ensure proper alignment. The loading was applied automatically, and the rate of load application was closely monitored for accuracy. The failure load displayed by the machine was recorded, and the corresponding compressive strength was calculated and noted. The results were then compared against standard specifications before being documented and analyzed for further interpretation. Figure 3 illustrates the procedure used for conducting the compressive strength test on the concrete specimens.

(2)

Where; = Elastic modulus in GPa; = Compressive strength of CSA concrete (MPa)



**Figure 3. Compressive Strength testing of CSA-Cement Concrete.**

1. **Results and Discussion**

**3.1 Slump of CSA-Cement Concrete**

Figure 4 presents the results of the slump test for concrete incorporating varying proportions of coconut shell ash (CSA) as a partial replacement for ordinary Portland cement (OPC). The results reveal a consistent decrease in slump values with increasing CSA content. Specifically, the slump value dropped from 120 mm for the control mix (0% CSA) to 50 mm at 30% CSA replacement, representing a 58.3% reduction in workability.

The slump test is a standardized procedure for assessing the consistency or workability of fresh concrete. It provides a quick measure of the ease with which concrete can be mixed, handled, placed, and finished without segregation (BS EN 12350-2:2019; ASTM C143/C143M-20, 2020). The observed reduction in slump with increasing CSA content can be attributed to several key material characteristics of CSA. Coconut shell ash typically exhibits a porous and irregular texture, which contributes to increased water absorption during mixing. As a result, less free water is available for lubricating the mix, reducing its workability (Olutoge, 2010). Additionally, CSA particles generally have a higher surface area compared to OPC, thereby increasing the water demand of the mix (Shetty, 2005). Neville (2011) also emphasized that the introduction of supplementary cementitious materials (SCMs) like CSA alters the physical and chemical environment of the cement matrix, potentially affecting the fluidity and compactibility of fresh concrete.

Similar trends have been reported in prior studies. Olutoge (2010) found that increasing CSA content led to reduced slump values, highlighting the ash’s high absorption capacity and its tendency to stiffen fresh mixes. In alignment with this, Shetty (2005) and Neville (2011) noted that SCMs with fine and absorptive characteristics tend to diminish concrete workability unless compensatory measures, such as adjusting the water-to-cement ratio or incorporating plasticizers, are implemented.

International standards offer guidance for acceptable slump ranges depending on the structural element and method of placement. According to ACI 211.1 (1991), recommended slump values range from 25 mm to 100 mm for various construction applications, with higher slumps allowed for manually placed or heavily reinforced elements. The British Standard BS EN 206:2013 further classifies slump into workability classes from S1 (10–40 mm) to S5 (>220 mm), while Nigeria’s NIS 444-1:2003 conforms with these global standards by establishing similar criteria for fresh concrete behaviour.

The reduction in slump caused by CSA replacement has practical implications for construction. Lower slump values can make concrete more difficult to place and compact, especially in complex formworks or heavily reinforced sections. To counteract this, mix designs may require optimization through the use of water-reducing admixtures or slight increases in water content, ensuring, however, that such adjustments do not compromise strength or durability. Incorporating plasticizers or superplasticizers can be especially effective in maintaining workability without increasing the water-to-cement ratio (Neville, 2011).

**Figure 4. Slump of CSA-Cement Concrete**

**3.2 Elastic Modulus of CSA-Cement Concrete**

Figure 5 illustrates the elastic modulus trends of concrete incorporating varying levels of coconut shell ash (CSA) as partial replacement for ordinary Portland cement (OPC), measured at different curing durations from 3 to 91 days. At an early age of 3 days, the control mix (0% CSA) exhibited the highest elastic modulus of 12.04 GPa, while the values for 10%, 20%, and 30% CSA replacements were slightly lower at 11.39 GPa, 10.91 GPa, and 10.58 GPa, respectively. This trend generally continued across subsequent curing days; however, exceptions were observed at 7, 14, and 28 days, where the 10% CSA mix outperformed the control, attaining elastic modulus values of 14.78 GPa, 17.05 GPa, and 19.34 GPa, respectively. By the end of the 91-day curing period, the control concrete exhibited a significantly higher elastic modulus of 28.07 GPa compared to 19.77 GPa (10% CSA), 17.61 GPa (20% CSA), and 17.01 GPa (30% CSA).

The observed reduction in the elastic modulus with increasing CSA content, particularly at higher replacement levels (20% and 30%), can be attributed to CSA’s porous and irregular morphology, which tends to increase water demand and reduce particle packing density. These physical characteristics lead to higher total porosity and, consequently, reduced stiffness (Neville, 2011). However, the superior performance of the 10% CSA concrete at certain curing stages (7–28 days) suggests the activation of pozzolanic reactions. During this period, reactive silica present in CSA reacts with calcium hydroxide released during cement hydration, forming additional calcium silicate hydrate (C–S–H), which improves the microstructure and enhances the stiffness of the concrete (Olutoge, 2010).

This performance trend aligns with findings from recent studies on sustainable concrete. Pacheco-Torgal et al. (2019) reported that partial replacement of OPC with agro-waste materials like CSA can enhance specific mechanical properties, including stiffness, due to both filler effects and secondary hydration. However, exceeding an optimal replacement level (often around 10–15%) may lead to underperformance due to dilution of the binder system and lower availability of calcium hydroxide to support pozzolanic reaction.

In conclusion, while the overall trend shows decreasing elastic modulus with increasing CSA content, a 10% replacement level appears to offer mechanical benefits during intermediate curing stages. This supports the use of CSA as a sustainable cement replacement material, offering environmental advantages without substantial compromise on structural performance. Further optimization studies could help identify the optimal blend ratio for maximizing both mechanical and durability attributes.

**Figure 5. Elastic Modulus of CSA-Cement Concrete for Different Concrete Ages**

**3.3 Conclusions**

The following conclusion are hereby put forward from the results and discussion of this study;

1. Increasing coconut shell ash (CSA) content in concrete consistently reduces slump, indicating lower workability. This reduction, reaching 58.3% at 30% CSA, is due to CSA’s high-water absorption and surface area. Such behaviour aligns with established studies and standards on supplementary cementitious materials. Workability losses can be mitigated using admixtures or slight mix design adjustments.
2. The elastic modulus of CSA-cement concrete generally decreased with increasing CSA content due to higher porosity and reduced stiffness; however, a 10% CSA replacement showed improved performance at 7–28 days, likely from pozzolanic activity enhancing C–S–H formation.
3. Although high CSA contents (20–30%) compromised stiffness, the 10% replacement level demonstrated a balance between sustainability and mechanical performance, highlighting its potential as an optimal blend for durable, eco-friendly concrete.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**REFERENCES**

1. ACI Committee 211.1. (1991). *Standard practice for selecting proportions for normal, heavyweight, and mass concrete* (ACI 211.1-91). American Concrete Institute.
2. ACI Committee 318. (2014). *Building code requirements for structural concrete and commentary (ACI 318-14)*. American Concrete Institute.
3. ASTM C143/C143M-20. (2020). *Standard test method for slump of hydraulic-cement concrete*. ASTM International. https://www.astm.org/c0143\_c0143m-20.html
4. Barveen, S. (2018). *Coconut shell ash as cementitious material in concrete: A review*. Retrieved from <https://www.scribd.com/document/597465949/03>
5. Bheel, N., Mahro, M., & Adesina, A. (2020). *Modulus and strength of concretes with alternative materials*. Retrieved from <https://pmc.ncbi.nlm.nih.gov/articles/PMC7579585/>
6. Bheel, N., Mangi, S. A., & Meghwar, S. L. (2021). Coconut shell ash as cementitious material in concrete: A review. *Jurnal Kejuruteraan*, 33(1), 27–38. https://journalarticle.ukm.my/16471
7. British Standards Institution. (2013). *BS EN 206:2013. Concrete – Specification, performance, production and conformity*. https://shop.bsigroup.com
8. British Standards Institution. (2019). *BS EN 12350-2:2019. Testing fresh concrete – Part 2: Slump test*. https://shop.bsigroup.com
9. Canadian Standards Association. (2014). *Design of concrete structures (CSA A23.3-14)*. CSA Group.
10. Kumator, T. (2019). *Nanomechanical properties of coconut shell ash blended cement mortar*. Retrieved from <https://www.academia.edu/40513175/NANOMECHANICAL_PROPERTIES_OF_COCONUT_SHELL_ASH_BLENDED_CEMENT_MORTAR>
11. Mahro, M., Bheel, N., & Adesina, A. (2020). *Concrete reinforced with sisal fibers (SSF): Overview of mechanical and physical properties*. Retrieved from <https://www.mdpi.com/2073-4352/12/7/952>
12. Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education Limited.
13. Neville, A. M. (2011). *Properties of concrete* (5th ed.). Pearson Education Limited.
14. Nigerian Industrial Standards (NIS 444-1:2003). (2003). *Cement – Part 1: Composition, specifications and conformity criteria for common cements*. Standards Organisation of Nigeria.
15. Olutoge, F. A. (2010). Investigations on sawdust and palm kernel shells as aggregate replacement. *ARPN Journal of Engineering and Applied Sciences, 5*(4), 7–13. http://www.arpnjournals.org/jeas/research\_papers/rp\_2010/jeas\_0410\_245.pdf
16. Olutoge, F. A. (2010). Investigations on sawdust and palm kernel shells as aggregate replacement. *ARPN Journal of Engineering and Applied Sciences, 5*(4), 7–13. http://www.arpnjournals.org/jeas/research\_papers/rp\_2010/jeas\_0410\_245.pdf
17. Pacheco-Torgal, F., Jalali, S., & Silva, N. F. (2019). Sustainable concretes for structural applications. In F. Pacheco-Torgal, S. Jalali, & N. F. Silva (Eds.), *Sustainable construction materials and technologies* (pp. 273–282). Springer. https://doi.org/10.1007/978-3-030-33256-3\_24
18. Pooja, D., Lakshmi, T. S., & Sivasubramani, P. A. (2025). Bayesian statistics for sustainable cementitious systems with a partial replacement of coconut shell ash as a cement material. *Turkish Journal of Engineering*, 9(3), 447–459. <https://pubmed.ncbi.nlm.nih.gov/32970258>
19. Shanmuga Priya, S., & Padmanaban, I. (2024). Effect of coconut shell ash as an additive on the properties of green concrete. *Global NEST Journal*, 26(1), 1–9. <https://www.sciencedirect.com/science/article/pii/S0950061823026958>
20. Shetty, M. S. (2005). *Concrete technology: Theory and practice* (Revised ed.). S. Chand Publishing.
21. Standards Organisation of Nigeria. (2003). *Nigerian Industrial Standard NIS 444-1:2003: Cement – Part 1: Composition, specifications and conformity criteria for common cements*. SON.
22. Bheel, N., Aluko, O. G., & Khoso, A. R. (2022). Synergistic and sustainable utilization of coconut shell ash and groundnut shell ash in ternary blended concrete. *Environmental Science and Pollution Research*, 29(18), 27399–27410. <https://doi.org/10.1007/s11356-021-18455-6>
23. Ranatunga, K. S., del Rey Castillo, E., & Toma, C. L. (2023). Evaluation of the optimal concrete mix design with coconut shell ash as a partial cement replacement. *Construction and Building Materials*, 401, 132978. <https://doi.org/10.1016/j.conbuildmat.2023.132978>
24. Kazmi, S. S. H., Munir, M. J., Khitab, A., Ahmad, M. R., & Ali, A. (2020). Influence of coconut shell ash on workability, mechanical properties, and embodied carbon of concrete. *Environmental Science and Pollution Research*, 29(4), 5207–5223. <https://doi.org/10.1007/s11356-021-16034-3>
25. Pathanamoorthy, P., Thenmozhi, R., Prasad, S., & Kandasamy, S. (2021). Combined effect of coconut shell ash and sugarcane bagasse ash on the workability, mechanical properties and embodied carbon of concrete. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-021-18455-6>
26. Herring, A., Thuo, J., & Nyomboi, T. (2022). Investigation on the behavior of concrete with partial replacement of cement and coarse aggregate using coconut shell ash and particles. *Results in Engineering*, 15, 100511. <https://doi.org/10.1016/j.rineng.2022.100511>
27. Sabeen, A., Younis, A., & Javed, M. F. (2022). Mechanical performance of concrete incorporating natural coconut fibers: A review of recent findings. *Sustainability*, 14(4), 2032. <https://doi.org/10.3390/su14042032>
28. Zhang, X., Wu, Y., & Rauf, M. (2023). Development and characterization of basalt fiber‑reinforced green concrete utilizing coconut shell aggregates. *Sustainability*, 16(17), 7306. https://doi.org/10.3390/su16177306