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Bayesian Statistics for Sustainable Cementitious Systems with a Partial Replacement of Coconut Shell Ash as a Cement Material

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Abstract

As urbanization continues to increase on a daily basis, the demand for infrastructure has become a global priority. Developing nations encounter considerable obstacles in managing solid waste, particularly in the handling of construction materials. Concrete, an essential element in construction, depends significantly on cement as its binding agent. While cement offers benefits such as robust binding properties and improved concrete strength, its production poses considerable environmental challenges. The study explores the potential of using coconut shell ash (CSA) as an alternative to traditional binding materials in M20 grade concrete. Burned coconut shells produce CSA, which possesses pozzolanic properties, making it an attractive material for cement substitution. By integrating coconut shell ash into the concrete formulation, the overall cement requirement can be diminished, resulting in substantial energy conservation, lower carbon releases, and the safeguarding of natural resources. To evaluate the effectiveness of CSA as a replacement, various proportions (0%, 5%, 10%, 15%, 20%, 25%, and 30%) were examined. The findings revealed that using 10% CSA as a binding material replacement led to enhanced mechanical properties. A total of 36 concrete cubes were cast using both ordinary Portland cement (OPC) and 10% CSA, followed by comprehensive testing and statistical analysis using SPSS V-26. Bayesian statistical analysis demonstrated that incorporating 10% of CSA as a cementitious material in concrete yields effective results.

1. Introduction

A world deficient of concrete is unbelievable due to its vital nature. Concrete holds the second position among the most extensively consumed substances, with an annual production exceeding 10 million tons. Especially, unlike other construction materials, concrete, being an engineered substance, can be customized to meet desired standards and qualities. Consequently, concrete stands as the most widely utilized building material [1]. The production of concrete heavily relies on natural resources, with approximately 70-80% of the total volume comprised of aggregate, predominantly coarse aggregate supplemented by fine aggregate [2]. The quality of concrete is considerably influenced by the properties and characteristics of the aggregate used. As the construction industry continues its rapid expansion, the demand for resources has surged, resulting in the depletion of natural resources. Immediate action must be taken to conserve these invaluable resources. Statistical research reveals that coconut production reached an astounding 23,904.10 million units in the year 2016–17, with Tamil Nadu, Kerala, and Karnataka playing pivotal roles in this production [3]. The increase in population, urban development, and technological progress, which have enhanced living standards, have all played a significant role in the notable rise in both the quantity and diversity of solid waste produced by agricultural, residential, industrial, and mining sectors. Notably, Asia accounts for an astonishing 4.4 billion tonnes of solid waste each year [4]. Specific information regarding the generation of agro-industrial waste from various sources in India is provided in Figure 1.

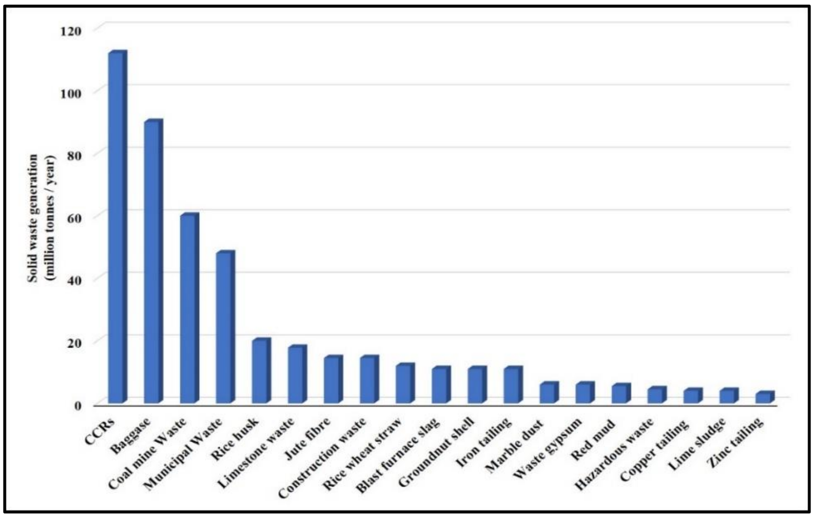

Figure 1. Solid waste generation in India

Global coconut production amounted to 61.5 metric tons, with Indonesia, Future research could explore the Philippines, Brazil, India, and Sri Lanka being the primary contributors [5]. The Asia-Pacific region encompasses the majority, approximately 93%, of the total coconut plantations, estimated at around 12 million hectares [6]. Annually, the global coconut production stands at a staggering 10 million tons, with more than half processed into dried coconuts [7]. Coconut shells, a significant by-product, are extensively utilized as natural fillers, primarily in tropical nations like Indonesia, Malaysia, Thailand, and Sri Lanka. Recent focus in composite material research has shifted towards exploring natural fillers, with coconut shell fillers gaining traction due to their inherent advantages. These include high strength, specific measured attributes, and a notable lignin content. Composites incorporating coconut shell fillers exhibit superior weather resistance, making them ideal for structural material applications.

The Indian construction industry is currently in need of a considerable amount of cement and concrete to facilitate its ecological growth. But the production of cement is recognized as one of the most energy-demanding sectors, significantly contributing to CO_2 emissions in the environment [8-11]. To address this challenge, the construction industry has begun utilizing supplementary cementitious materials and alternative aggregates in concrete manufacturing. Recent studies indicate that silica-rich minerals derived from agricultural waste can effectively replace conventional industrial by-products such as fly ash, metakaolin, and GGBS (ground granulated blast furnace slag). In this context, coconut shell burnt ash has been employed as a sustainable material to improve both the workability and strength of concrete mixes, thereby reducing waste disposal in landfills [12-16].

1.1 Objectives of the Study

The present study was formulated with specific objectives in mind, considering the relevant concerns and limitations:

i. To examine the workability, pozzolanic activity, and setting time of concrete when CSA is added as a partial substitute for cement.

ii. To evaluate the feasibility of constructing workable concrete by incorporating CSA as a partial substitute for cement.

iii. To assess the mechanical properties of concrete incorporating CSA as a partial substitute for cement.

iv. To analyze the impact of CSA as a binding material in concrete using SPSS V-26 software by Bayesian statistics.

2. Experimental Investigation

2.1 Materials used

Cement: 53 grade of OPC grade confirming to Bureau of Indian Standard (BIS) 12269:2013 [17], which had specific gravity 3.12 was used in this research, shown in Figure 2(a). Aggregates: M-sand with specific gravity 2.57 and density 1680 kg/m^3 was taken from the local resources, and it was confirmed to grading of zone III as per IS 383:2016 [18] was shown in Figure 2(b). Conventional coarse aggregate with specific gravity 2.68 and density 2450 kg/m^3 was taken as per IS 383:2016, shown in Figure 2(c). Water acts as the hydrating agent for cement. As a result, it is crucial to ensure that the water used for mixing and curing is devoid of harmful substances and chemicals that could hinder the hydration process or compromise the durability of the concrete. To meet these requirements, drinkable water with a pH value of 6.8 was employed for both mixing and curing the concrete.

Coconut shell ash (CSA): Coconut shells, usually considered as waste products in the agricultural industry, present challenges for disposal due to their lack of economic value and potential ecological issues. However, their unique natural structure and low ash content make them suitable for producing carbon black. The physical properties of the coconut shell are a specific gravity of 1.49, an absorption capacity of 15.2%, a density of 600 kg/m^3 with high porosity, high hardness, and a rough and granular surface texture. Chemical properties include cellulose of 25.6%, lignin of 29%, pentosans of 26.9%, and water solubility of 5.25%. To make use of coconut shells, the broken pieces of sundried coconut shells underwent uncontrolled combustion in the open air for three hours. These pieces were then subjected to calcination in a muffle furnace at 800°C for six hours to remove the carbonaceous material and transform the ash's crystalline form into an amorphous one. Subsequently, the coconut shell ash underwent sieving with #200 mesh screens. The specific surface area of the ash was noted as 325 m^2/kg. The chemical composition of the coconut shell ash, outlined in Table 1, validated its appropriateness as a cementitious material, in accordance with ASTM C618 standards [19]. CSA's high silica and alumina content enable pozzolanic reactions, forming C-S-H gel that enhances concrete strength and durability, while low carbon content ensures minimal impurities.CSA is selected for its sustainability, pozzolanic activity, and ability to enhance concrete properties. It repurposes agricultural waste, improves strength and durability, reduces dead load, and lowers construction costs, making it an eco-friendly and cost-effective alternative.

Table 1. Chemical composition of OPC and CSA

Compounds	OPC	CSA
SiO_2	20.7	41.89
Al_2O_3	5.75	20.27
CaO	64	4.57
Fe_2O_3	2.5	13.67
Na_2O	0.6	0.89
MgO	1	1.78
K_2O	0.15	0.81
MnO	0.2	0.1
P_2O_5	0.05	0.38
SO_3	2.75	0.69
LOI	2.3	8.45

The total percentage of Al2O3, SiO2, and Fe2O3 in the ash was determined to be 72.34%. Additionally, the potential of CSA as a substitute for cement in concrete applications is illustrated in Figure 3.

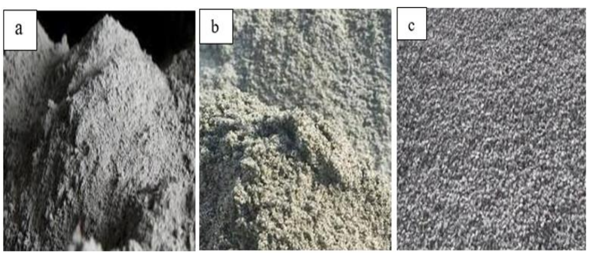

Figure 2. Raw materials used

a) OPC b) M-sand c) Conventional coarse aggregate

Figure 3. Coconut shell into CSA

2.2 Mix design

In the concrete testing process, the researchers utilized a standard strength grade of M20, following the mix proportion guidelines outlined in IS: 10262 - 2009, (2009) [20]. Cement was partially replaced with CSA at varying levels of 5%, 10%, 15%, 20%, 25%, and 30%. The simplified mix ratio for M20 grade concrete can be represented as approximately 1:1.05:2.1:0.5 (Cement:CSA:FA:CA). The water content and admixture are not included in this ratio and are added based on specific requirements and the desired w/c ratio. The eventual mix proportions of the concrete were determined after three experiments, as shown in Table 2.

3. Testing methods

In this study, the CSA was partly replaced with concrete binder material. To determine the qualities of the concrete, initially, the cement's setting time was examined. The workability of the combinations was evaluated using their fresh qualities, especially the slump. Following the requirements specified in BS 12350-2 [21], the slump test was carried out immediately after the mixing procedure. The measured slump values give useful information about the combinations capacity to be dealt with, indicating their practical suitability. According to IS 516 (2021), the compressive strength of the concrete was assessed using a cube with a volume of 15 cm^3 [22]. To estimate the splitting tensile strength, a cylinder with a diameter of 10 cm and a height of 20 cm was employed. The flexural strength was evaluated using a prism with dimensions of 50 cm x 10 cm x 10 cm. After 7,14, and 28 days of curing, the casted, hardened concrete was tested.

Bayesian statistics integrates prior knowledge with empirical data using Bayes' theorem, yielding posterior distributions that quantify updated probabilities and uncertainty. Unlike frequentist methods, it is flexible, managing complex or limited data and enabling probabilistic predictions. In this research, it aids in determining the optimal CSA replacement percentage, balancing mechanical performance and sustainability.

Table 2. Mix design as per the mix proportion of 1:1.05:2.1:0.5 same as OPC:CSA:FA:CA:Water in (kg/m³)

Various Mixes	OPC	CSA	FA	CA	w/c ratio
CC	400	0	420	840	0.5
95%OPC+5% CSA	380	20	420	840	0.5
90%OPC+10% CSA	360	40	420	840	0.5
85%OPC+15% CSA	300	60	420	840	0.5
80%OPC+20% CSA	320	80	420	840	0.5
75%OPC+25% CSA	300	100	420	840	0.5
70%OPC+30% CSA	280	120	420	840	0.5

4. Results and Discussion

4.1 Initial and final setting time

Figure 4 illustrates the impact of the amount of CSA on setting times. The initial setting time rises from 1 hour and 3 minutes with no replacement to 5 hours and 3 minutes when 30% replacement is applied. In a similar manner, the final setting time extends from 1 hour and 25 minutes with no replacement to 7 hours and 45 minutes when there is a 30% replacement. As per BS12 (1978), the initial and final setting times must not surpass 45 minutes and 10 hours, respectively, and these criteria are satisfied by the CSA/OPC pastes in terms of ultimate setting time [23].

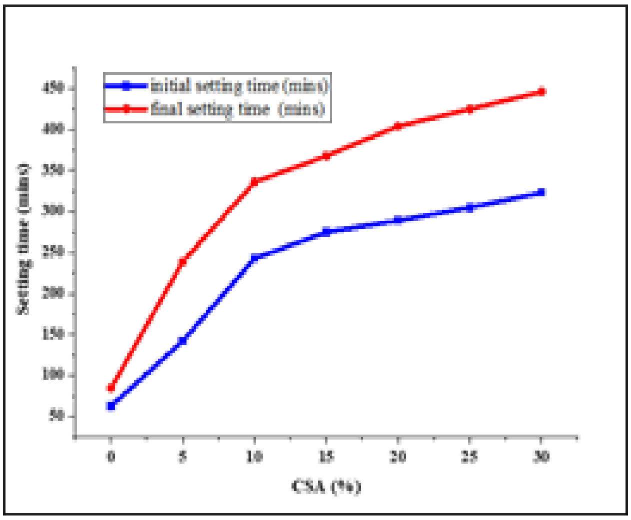

Figure 4. Initial and final setting time of CSA in concrete

4.2 Workability

This research evaluated the workability of the concrete mixtures through the slump test. Figure 5 demonstrates how varying concentrations of CSA affect the slump of the concrete mixes. The results reveal that using CSA as a partial substitute for OPC lessened the decline in slump values. Specifically, the slump measurements for mixes with 5%, 10%, 15%, 20%, 25%, and 30% CSA substitution of OPC showed reductions of 15%, 29%, 42%, and 58%, respectively, when compared to mixtures without CSA. This reduction may be linked to the improved water absorption characteristics of CSA. Similar results were noted in a study on alkali-activated concrete that included CSA [24]. Additionally, the research highlighted that the addition of palm oil shell ash and rice husk ash to concrete mixtures also led to a decrease in slump [25]. Despite the observed reductions in slump values, all mixtures maintained slump measurements above 20 mm, making them appropriate for practical use. CSA generally reduces the workability of concrete mixtures due to its high surface area and porous nature, which increases water demand. To enhance workability as needed, the use of chemical admixtures like high-range water reducers can be employed.

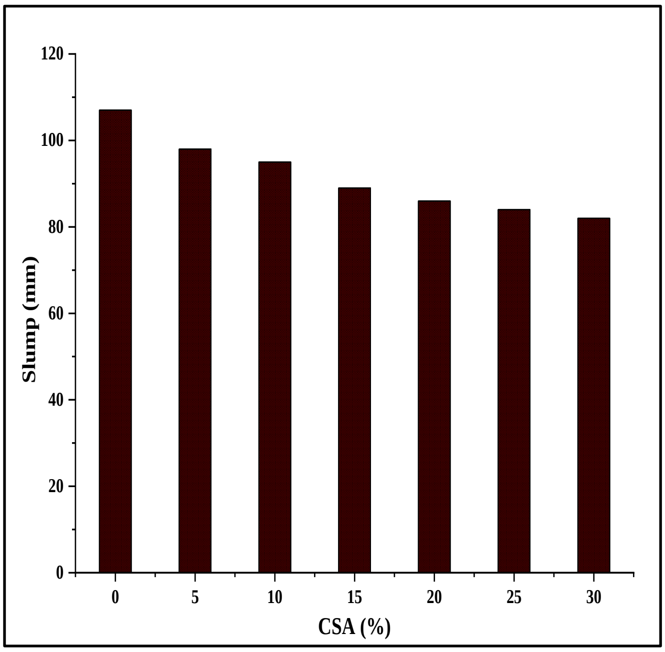

Figure 5. Workability of CSA in concrete

4.3 Pozzolanic Activity

Figure 6 demonstrates the pozzolanic activity of the 0% to 30% replacement of the cement by CSA. It shows that, by using 5% to 10% of CSA in place of cement, it increases the pozzolanic activity of the cement. If an increase in the CSA, the pozzolanic activity decreases. The primary feature that sets apart additional concrete materials is the activity of volcanic debris. This material has the ability to consume calcium hydroxide, which leads to the formation of calcium silicate hydrate (C-S-H). Various techniques exist to assess the pozzolanic properties of a material, and understanding its composition can provide insights into its pozzolanic potential. According to ASTM C618, pozzolanic materials should consist of approximately 70% silicon dioxide, alumina, and iron oxide. Analysis of coconut shell debris typically reveals a significant presence of these components, indicating that volcanic debris exhibits enhanced reactivity.

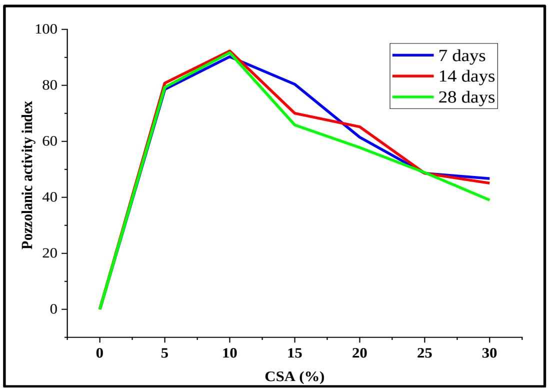

Figure 6. Pozzolanic Activity Index

Silica, often referred to as silicon dioxide, is the key element in OPC that contributes to the early strength of concrete and mortar. Therefore, the presence of silica in CSA suggests its potential as a binding material that can serve as a substitute for OPC. Based on the compositional criteria outlined in ASTM C618, CSA qualifies as a class N pozzolan, it is characterized as a natural or calcined pozzolan that meets specific standards, including certain types of diatomite, such as tuff and pumice, which may require calcination. The loss on ignition for class N volcanic debris is typically below the 10% threshold, indicating a minimal presence of unburned carbon in CSA. This characteristic is advantageous for N-type volcanic debris, as a loss on ignition exceeding 10% would suggest a higher level of unburned carbon, which could diminish pozzolanic activity and, consequently, strength. However, the moisture level in CSA exceeds the fundamental standards for class N volcanic debris; therefore, it is recommended to dry it in a broiler before utilization.

4.4 Compressive strength

The Indian Standard code IS 456:2000 outlines important guidelines for both plain and reinforced concrete, highlighting the significance of the compressive strength of hardened concrete in evaluating its quality and longevity [26]. To evaluate this strength, tests were performed following the IS 516:1959 standard method, which involved measuring the compressive strength at 7, 14, and 28 days of curing for various proportions of CSA used as a partial substitute for OPC.

Figure 7 shows that at the 7-day curing interval, a reduction in compressive strength was observed as the percentage of OPC replaced by CSA increased. The compressive strength decreased from 31.73 N/mm^2 for pure OPC to 13.8 N/mm^2 when 30% of the OPC was substituted with CSA. This downward trend continued at the 28-day curing period, where the compressive strength dropped from 38.6 N/mm^2 for OPC to 20.43 N/mm^2 for the 30% CSA replacement. However, it was found that a 10% replacement level of CSA actually enhanced the compressive strength, reaching a peak value of 42.75 N/mm^2 at 28 days for the OPC-CSA mix with this substitution.

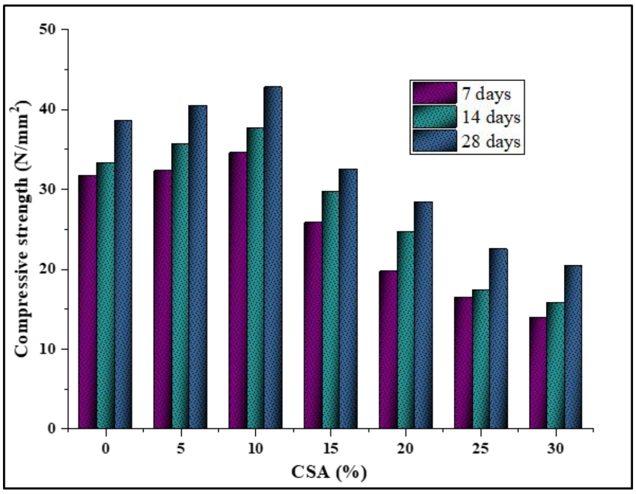

Figure 7. Compressive strength test results

The compressive strength of all mixtures tends to increase with age, with a 10% substitution rate increase in compressive strength across all ages [27]. By using CSA in place of OPC resulted in a lower compressive strength compared to pure OPC. Hence, it is concluded that the optimal replacement of OPC with CSA is 10%, as higher CSA content leads to diminished compressive strength [28-31].

4.5 Splitting tensile Strength

Figure 8 shows the splitting tensile strength of the concrete for the 7-day, 14-day and 28-day of curing period. The study results reveal that after 7- days of curing the splitting tensile strength results 2.58 N/mm^2 for the OPC concrete and 1.1 N/mm^2 for the CSA used concrete. Likewise, for the 28 days of curing, 3.92 N/mm^2 on OPC concrete and 2.54 N/mm^2 for the CSA concrete. It is observed that 10% of CSA used concrete shows the increase in splitting tensile strength as 4.19 N/mm^2 after 28- day of curing.

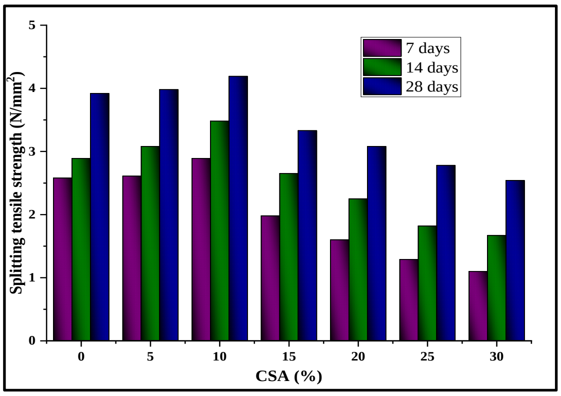

Figure 8. Splitting tensile test results

In their study, concrete consisting solely of POC (Partial Oil Palm Concrete) and not OPS (Oil Palm Shell) demonstrated a peak splitting tensile strength of 2.9 MPa after a duration of 28 days [32-35]. However, the incorporation of OPS as coarse aggregate resulted in a 55% reduction in tensile strength, primarily attributable to the weak interfacial zone present in OPSC (Oil Palm Shell Concrete). According to the findings, the splitting tensile strength exhibited a decline across all ages when different percentages of POC aggregate were replaced with OPS aggregate (0-60% at 20 % intervals). By increasing the volumetric content of steel fibre by 0.5 to 1 percent, it might improve the splitting tensile strength of OPSC. Furthermore, the splitting tensile strength of OPSC may be most effectively enhanced by including 20 percent GGBS and 0.1 percent acrylic fibre volume.

In their study, the tensile strength of OPSC after 28 days of splitting ranges from 2.85 MPa to 3.54 Mpa. Notably, OPSC including FA (Fly ash) exhibited a reduced tensile strength in comparison to the control specimen. Moreover, By incorporating 0.1 percent polypropylene hybrid fibre and 0.9 percent steel fibre into OPSC led to a significant increase of 83 percent in the splitting tensile strength, which ultimately reached 5.81 Mpa [36-38].

4.6 Flexural strength

The alterations in the flexural strength of prism specimens made from 28-day-cured concrete were assessed and are illustrated in Figure 9.

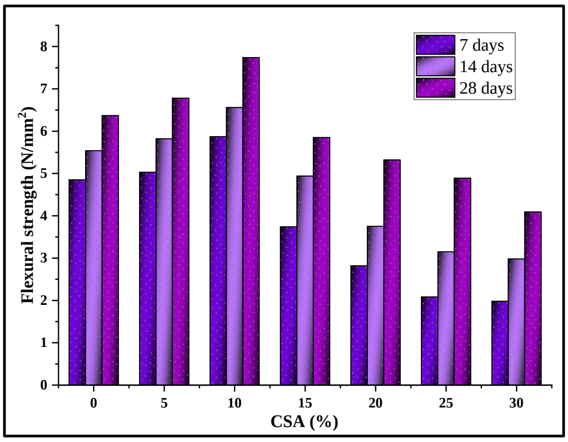

Figure 9. Flexural strength test results

The inclusion of CSA has been verified to enhance flexural strength by 12–15 percent and 10–12 percent, respectively. This improvement in flexural strength is likely associated with a stronger adhesion between the binding material and the aggregate. However, increasing the aggregate surface area through additional CSA may compromise this bond, leading to a decrease in the concrete's flexural strength. Furthermore, a reduction in flexural strength was noted when the substitution level surpassed 12 percent, which can be attributed to a greater presence of unhydrated cementitious particles after 28 days of curing [39]. In light of the results from this study regarding flexural and compressive strength, it is advisable that the substitution of CSA as 10% in concrete enhances the flexural strength to 7.74 N/mm^2 at 28 days.

5. Statistical Analysis

5.1 F-Test and ANOVA

Table 3 shows the F-test table, which indicates the results of an analysis of variance (ANOVA) for a model that seems to be assessing the effect of different design factors (compressive, splitting tensile and flexural strength) on some outcome, possibly related to cementitious systems with CSA. The F-value is 6.875. This value indicates the proportion of variance attributed to the differences between groups (resulting from design factors) compared to the variance observed within the groups (residual variance) [40]. A higher F-value implies that the variation among the groups exceeds the variation within the groups, potentially highlighting significant differences related to the design factors. This is the degrees of freedom for the numerator, which is 3 in this case. It corresponds to the number of design factors minus one. This is the degrees of freedom for the denominator, which is 8. It corresponds to the number of observations minus the number of design factors. The p-value linked to the F-test is 0.013, indicating that the observed F-value is statistically significant at the 0.05 level, assuming a conventional significance threshold [41-44]. This suggests substantial evidence against the null hypothesis, which posits that all design factors do not influence the outcome.

5.2 Bayesian statistics

Bayesian statistics offers a flexible framework for analyzing the properties of cementitious systems with CSA. Table 4 and Table 5 show the Bayesian estimates of coefficients and error variance. By incorporating prior knowledge and updating beliefs with new data, it allows for a more nuanced understanding of parameters like design factors. This approach provides comprehensive uncertainty quantification, accommodates complex models, and aids decision-making in designing and optimizing sustainable cementitious systems, considering both prior knowledge and observed data.

Table 3. ANOVA table for design factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.162	3	0.721	6.875	0.013
Residual	0.838	8	0.105	-	-
Total	3.000	11	-	-	-
a. Dependent Variable: Groups					
b. Model: (Intercept), Compressive Strength, Split-Tensile Strength, Flexural Strength					

Table 4. Bayesian estimates of co-efficients.

Parameter	Posterior			95% Credible Interval	
	Mode	Mean	Variance	Lower Bound	Upper Bound
(Intercept)	-3.710	-3.710	2.414	-6.813	-0.607
Compressive Strength	0.095	0.095	0.002	2.807	0.190
Split-Tensile Strength	-0.047	-0.047	0.150	-0.820	0.727
Flexural Strength	0.218	0.218	0.032	-0.140	0.576
a. Dependent Variable: Groups					
b. Model: (Intercept), Compressive Strengh, Split-Tensile Strength, Flexural Strength					
c. Assume standard reference priors.					

Table 5. Bayesian estimates of error variance.

Parameter	Posterior			95% Credible Interval	
	Mode	Mean	Variance	Lower Bound	Upper Bound
Error variance	0.084	0.140	0.010	0.048	0.385
a. Assume standard reference priors.					

Table 6. Group statistics for design factors.

Groups	Comparative Mix	N	Mean	Std. Deviation	Std. Error Mean
Compressive Strength	0% of CSA	5	39.3800	1.42548	0.63750
	10% of CSA	5	44.0300	2.01358	0.90050
Split-Tensile Strength	0% of CSA	5	3.8720	0.44718	0.19998
	10% of CSA	5	4.1580	0.25801	0.11539
Flexural Strength	0% of CSA	5	7.1480	0.74035	0.33110
	10% of CSA	5	7.3280	0.82760	0.37011

Table 7. t-test for Equality of means.

Variables	Assumptions	Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Compressive Strength	Equal variances assumed	0.778	0.403	-4.21	8	0.003	-4.650	1.103	-7.194	-2.105
	Equal variances not assumed			-4.21	7.20	0.004	-4.650	1.103	-7.243	-2.056
Split-Tensile Strength	Equal variances assumed	3.603	0.094	-1.23	8	0.251	-0.286	0.230	-0.818	0.246
	Equal variances not assumed			-1.23	6.39	0.259	-0.286	0.230	-0.842	0.270
Flexural Strength	Equal variances assumed	0.013	0.913	-.36	8	0.726	-0.180	0.496	-1.325	0.965
	Equal variances not assumed			-.36	7.90	0.727	-0.180	0.496	-1.327	0.967

5.3 Interpretation

The design comprising different design factors significantly influences the outcome being studied (possibly a property of the cementitious system with CSA). The low p-value (0.013) suggests that at least one of these design factors has a significant effect, but it doesn't specify which one(s). Given that the overall F-test is significant, you may want to conduct post-hoc tests to determine which specific design factors are significantly different from each other. This can help in identifying which factor(s) are driving the observed differences. Calculate the effect size to quantify the practical significance of the differences observed. This can help in understanding the magnitude of the differences between the design factors. Ensure that the assumptions of ANOVA (e.g., homogeneity of variances, normality of residuals) are met. If not, consider transformations or non-parametric alternatives. If the overall model is significant but individual predictors are not, consider refining the model by adding interaction terms or removing non-significant predictors. Relate the findings back to the practical implications for sustainable cementitious systems with CSA. Understanding which design factors are most influential can guide optimization efforts for desired properties.

Table 8 provides the ANOVA test results; on the 28th day, the compressive strength for 10% of CSA is higher than 0% of CSA.

Table 8 ANOVA test results.

Variables	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
Compressive Strength for 7 Days	356.421	1	11.759	5	30.311	0.003
Compressive Strength for 14 Days	375.92	1	16.163	5	23.259	0.005
Compressive Strength for 28 Days	374.863	1	18.435	5	20.335	0.006
Split-Tensile Strength for 7 Days	2.407	1	0.114	5	21.209	0.006
Split-Tensile Strength for 14 Days	2.119	1	0.11	5	19.253	0.007
Split-Tensile Strength for 28 Days	1.908	1	0.111	5	17.217	0.009
Flexural Strength for 7 Days	11.404	1	0.545	5	20.932	0.006
Flexural Strength for 14 Days	10.053	1	0.337	5	29.857	0.003
Flexural Strength for 28 Days	6.309	1	0.54	5	11.692	0.019

The F tests are intended solely for descriptive analysis, as the clusters have been selected to enhance the differences between cases in various clusters. The significance levels observed are not adjusted for this factor and, therefore, should not be interpreted as tests of the hypothesis that the means of the clusters are equal.

5.4 Mann-Whitney U Test

For flexural strength, the test statistic was 33.000 with p-values of 0.016 (asymptotic) and 0.015 (exact). These p-values were all below the alpha level of 0.05, indicating significant differences. In contrast, splitting tensile Strength did not show a significant difference between the groups, with a Mann-Whitney U test statistic of 25.000 and p-values of 0.262 (asymptotic) and 0.310 (exact), both greater than 0.05. These findings suggest that compressive strength and flexural strength are influenced differently by the design factors being studied. Whereas splitting tensile strength remains relatively consistent across the groups. These results provide valuable insights for designing and optimizing sustainable cementitious systems with CSA, focusing on compressive and flexural strength as they demonstrate significant variability among the studied groups.

Table 7 shows the t-test for equality of means. The hypothesis tests using the independent-samples Mann-Whitney U Test were conducted to assess the distributions of different design factors across different groups, potentially related to cementitious systems with CSA, as shown in the Figure 11.

The exact p-values for compressive strength, splitting tensile strength, and flexural strength were 0.002, 0.310, and 0.015, respectively. Based on these results and a significance level of 0.050, the null hypotheses were rejected for compressive strength and flexural strength, indicating significant differences in their distributions across the groups. Conversely, the null hypothesis for splitting tensile strength was retained, suggesting its distribution remains consistent across the groups. These findings offer insights into the variability of properties in cementitious systems with CSA across different design categories.

Figure 12 shows the comparison of mean values for the design factors. From that, it clearly shows that the replacement of CSA as a cementitious material in concrete by 10% gives better results.

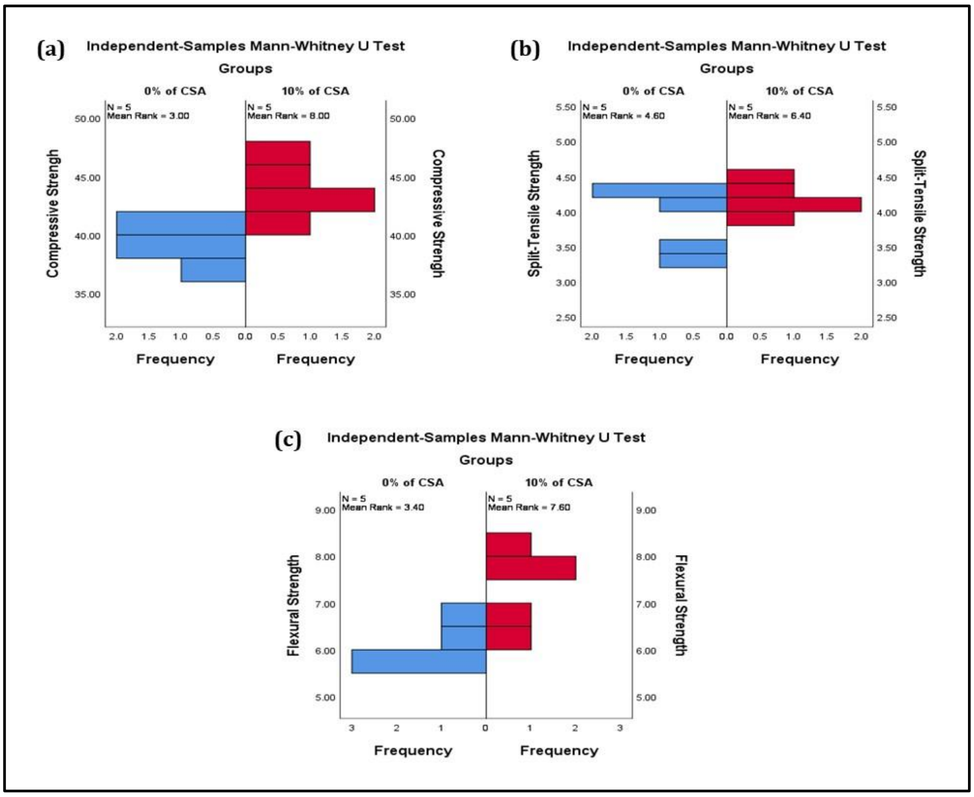

Figure 10. Independent-Samples Mann-Whitney U test for design factors

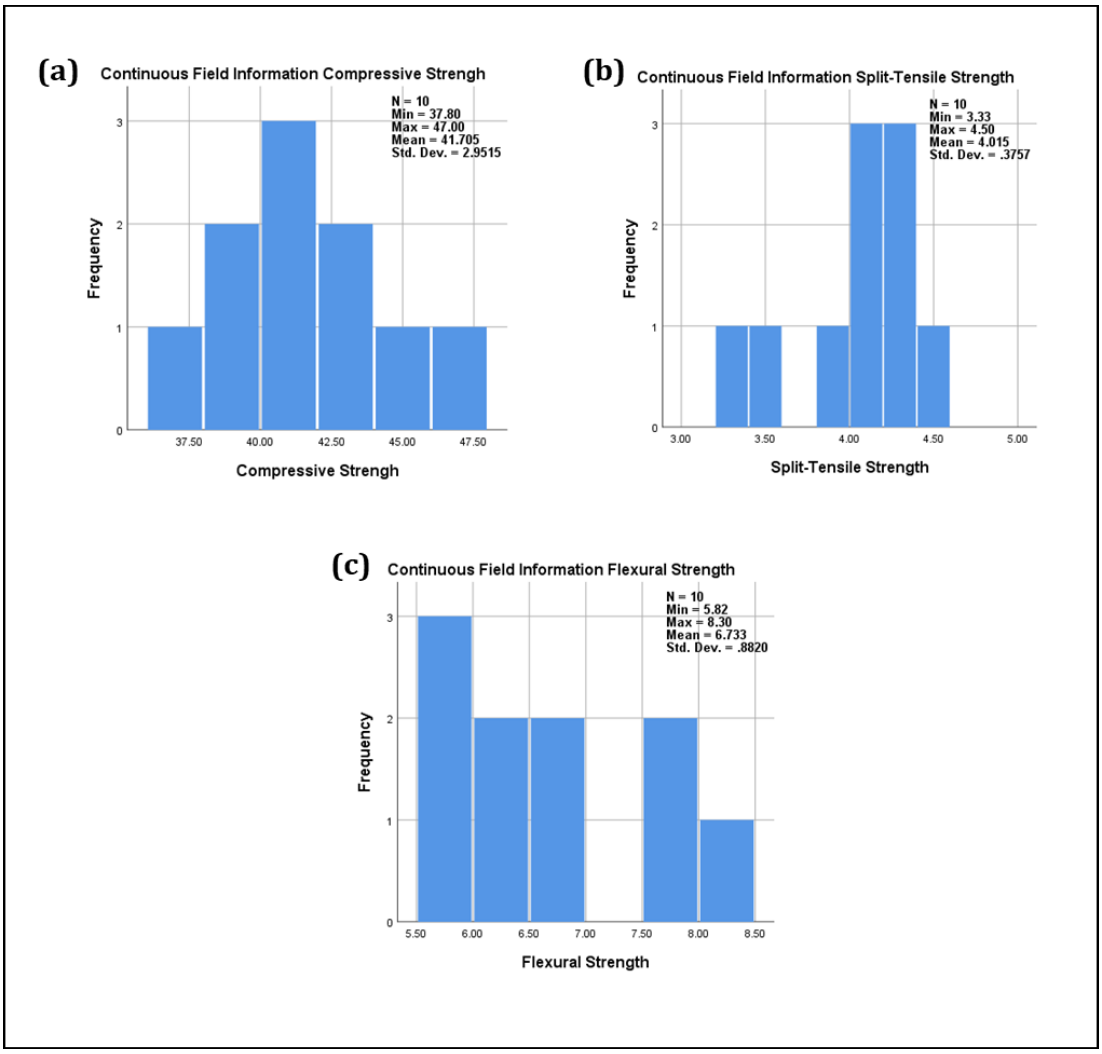

Figure 11. Continous field information about design factors

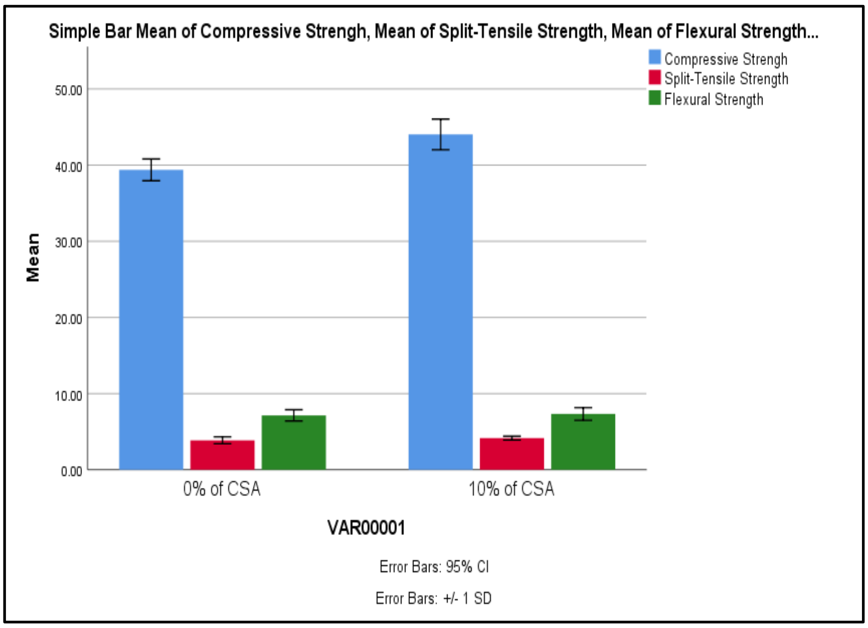

Figure 12. Comparison of mean values for design factors

6. Conclusion

Bayesian analysis was utilized to examine the effects of varying percentages of CSA on the properties of cement, revealing notable differences in compressive strength, tensile strength, and flexural strength. A comparison of the mean values was conducted.

- The addition of 10% coconut shell ash (CSA) resulted in significant improvements across all three properties: compressive strength increased by 11.8%, splitting tensile strength improved by 7.5%, and flexural strength increased by 2.5%.
- Bayesian analysis offers a robust method for interpreting these enhancements and provides a foundation for optimizing sustainable cementitious systems.In contrast to traditional frequentist methods, Bayesian analysis facilitates the incorporation of prior knowledge and offers a more thorough quantification of uncertainty.
- The percentage improvement in compressive strength with 10% of CSA relative to 0% can be more accurately assessed using Bayesian credible intervals, which account for both uncertainty and prior information. Assess the long-term durability and performance of cementitious systems that include CSA to guarantee sustainability and longevity.
- Using CSA as partial cement replacement reduces CO_2 emissions, manages agricultural waste, conserves natural resources, saves energy in cement production, and promotes sustainability in construction.
- Future research could explore the novel applications of CSA beyond traditional cementitious systems, including lightweight and high-performance concrete, to enhance its potential applications.

Author contributions

Pooja Damodaran: Conceptualization, Methodology, Data curation, Writing-Original draft preparation, Software, and Validation. **Lakshmi Thangasamy:** Visualization, and Investigation. **Sivasubramani Perumal Arulselvan:** Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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