Development of environmentally friendly fibre reinforced concrete using agricultural byproduct as a cement substitute to reduce the ecological footprint of cement

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Abstract:
One of the most common types of waste produced by the agriculture sector all over the world is coconut shells. However, cement manufacturing in the construction industry is responsible for billions of tons of carbon dioxide emissions annually. This study investigated the feasibility of using coconut shell ash (CSA) as a cement substitute in concrete manufacturing to mitigate the aforementioned agro waste disposal issue and the environmental consequences of the expanding construction sector. In addition, treated and untreated coconut fibers were used as reinforcements in concrete. The CSA proportions in the blend designs used in the investigation varied from 0-20 % at 5 % increments, while the coconut fiber reinforcements varied from 0-1 % at 0,25 % increments. Tests were performed on both fresh and hardened concrete, including slump tests and mechanical property evaluations after 28 days of curing. The results indicated that adding more than 10% coconut shell ash decreased the workability and compressive strength of the concrete when compared to conventional mixes. At 28 days of curing, the compressive strengths of concrete mixes with 5, 10, 15 and 20 % replacement levels were 29,50; 26,50; 24,80; and 22,67 MPa, respectively.

Keywords:
supplementary cementitious material; coconut fiber; coconut shell ash; compressive strength; sustainability

1 Introduction

Globally, a significant portion of solid waste approximately 44 % consists of agricultural byproducts [1]. A correlation has been established between the rise in agricultural waste and population expansion, and it is believed that the majority of these wastes are disposed of by undesirable means, such as burning. Nevertheless, sustainable methods exist to manage the environmental implications of agricultural waste disposal [2]. In particular, coconuts are a major source of trash in the agricultural sector. To find a solution to the problem of eliminating biowaste, some researchers, especially those working in the building industry, have examined the idea of using coconut-shell waste instead of regular concrete [3]. Cement manufacturing causes large amounts of greenhouse gas emissions, which are responsible for more than 7 % of emissions [4], but cement itself makes up to only a small part of these emissions (approximately 10-15 % by volume) [5]. Cement usage in the construction of buildings significantly contributes to human-caused global warming [6]. Alternative materials are required to reduce the environmental effects of concrete, and supplementary cementitious ingredients may improve the quality of concrete [7]. Supplementary Cementitious Material SCMs exhibiting hydraulic activity can solidify when exposed to water, resulting in the formation of Calcium Silicate Hydrate (CSH) gel. SCMs with pozzolanic activity can be hardened via reactions with water and calcium hydroxide. Various industrial wastes have been used for the partial replacement of cement [8; 9]. Slag, fly ash, metakaolin, and silica fumes are frequently used as supplemental cementitious materials. The efficacy of concrete is influenced by the chemical composition and particle size of the supplementary cementitious material [10]. This method involves the reaction of silica fume with calcium hydroxide, which results in the production of a large volume of CSH [11].

Silica fume incorporated in the concrete as an SCM exhibits increased compressive strength, but the rate of strength gain may be slower. With an increase in slag cement content, the compressive strength of the concrete can reach its optimal level. However, this negatively affects the early strength of concrete [12]. Numerous studies have been conducted on metakaolin to assess its impact on concrete properties, and it has proven to be an exceptional alternative to cement [13]. Due to various factors, the construction sector is experiencing a lack of traditional supplementary cementitious materials. Many countries are considering the retirement of coal-fired power plants because of concerns regarding air pollution and its impact on fly ash supplies [14]. The annual global cement production had reached a staggering 5,17 billion tons in 2020, and experts predict that the cement market will experience a steady growth rate of 3,3 % per year during the forecast period of 2023-2028. Therefore, the development of alternative cementitious materials is a critical global necessity. Coconut shells are often discarded in landfills in many tropical countries. Every year, a staggering number of coconuts (50 billion) are grown, with 85 % of the coconut shells considered as waste [15]. Traditional landfilling methods release greenhouse gases, particularly methane, during the decomposition of coconut shells into organic matter [16].

CSA is generated by the combustion of coconut shells. It often appears black due to the significant presence of unburned carbon [17; 18]. The chemical and physical characteristics of CSA vary depending on its source and production method. Appropriate processing techniques can enhance various physical and chemical properties and the involvement of reactive oxides in pozzolanic reactions. Certain chemical constituents of CSA are similar to those found in cement [19]. Consequently, the water demand increased as the CSA content increases. Based on these studies, it was determined that the grinding process of coconut shell ash could enhance the slump of concrete. Previous research indicates that by maximising the replacement level, the CSA content can be increased to reduce the density of concrete. Concrete density plays a significant role in the overall weight of concrete structures. The addition of various fibres to concrete has become more common owing to its delayed post-cracking behaviour, and these fibres act as crack arrestors [20]. The compressive strength of concrete increased by approximately 20-25 % with the addition of coconut fibre compared to conventional concrete [21]. With the addition of coconut fibres, the water absorption and flexural strength increased by up to 33 % [22]. Furthermore, the compressive strength increased by 19 % at an optimal fibre content of 0,25 % [23]. This research aimed to analyse the various properties of concrete mixes using CSA as a substitute for cement, with a particular focus on accurately measuring the environmental effects.

This study aimed to achieve a certain structural performance while reducing the negative environmental effects of concrete production. Coconut shells are agricultural by-products that frequently pose disposal challenges. Using CSA as a substitute for cement partially aids efficient waste management, thereby promoting sustainability. Additional studies and developments are necessary to fully exploit this potential and use CSA in conventional construction methods. The use of CSA as a partial replacement for cement in concrete has attracted considerable research attention because of its potential advantages in terms of sustainability, cost-effectiveness, and performance.

2 Materials and methodology

2.1 Materials

Ordinary Portland Cement (OPC) grade 53 was used in this study. CSA was used as a supplementary cementitious material to partially replace cement. Various microstructural analyses such as scanning electron microscopy (SEM) were performed to analyse the properties of the materials used. Clean river sand was used as the fine aggregate, and a sieve analysis test was performed according to IS 383 to determine the particle size distribution. The specific gravity and water absorption of the Fine Aggregate (FA) were 2,64 and 0,93 %, respectively. The crushed aggregate had a range of 20 mm, and the specific gravity and water absorption of the Coarse Aggregate (CA) were 2,78 and 0,60 %, respectively.

2.2 Experimental procedure

The experimental procedure consisted of four stages. In the initial phase, CSA was generated by processing the coconut shells. The second phase involved performing a range of tests on the CSA. The third phase focused on ascertaining the ideal quantity of CSA required to attain a specified level of compressive strength. Various mechanical and durability tests were conducted in the fourth stage by employing the optimal CSA quantity.

2.2.1 Preparation of coconut shell ash

In the present study, ash was obtained from coconut shells that had been recently used for domestic purposes. The shells were first cleaned and then sun-dried for approximately 6 h to remove water. Subsequently, they were heated to 800 °C and left to burn for 2 h. When the coconut shells were burned, up to 32 % of their full weight was lost. A machine was used to cut the samples into smaller pieces. After 10 min of milling, the sample was sieved through a 75-µm mesh. Figure 1 illustrates the CSA generation process from coconut hulls.

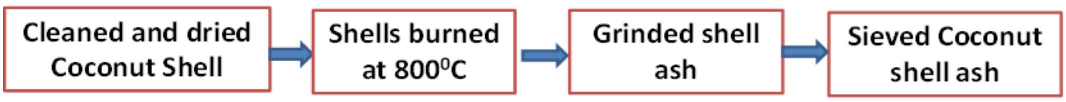

Figure 1. Process of extracting ash from coconut shell

2.2.2 Properties of materials

The morphologies of the CSA and cement particles were determined by SEM. Adding water to concrete hardens the cement. Consequently, it was necessary to determine the chemical compositions of the cement and CSA. Both coarse and fine aggregates were tested for water absorption, specific gravity, moisture content, and sieve analysis in compliance with the IS code to establish a mix design calculation. Table 1 presents the chemical composition of the CSA and cement, and Figure 2 presents the physical properties of the CSA and cement.

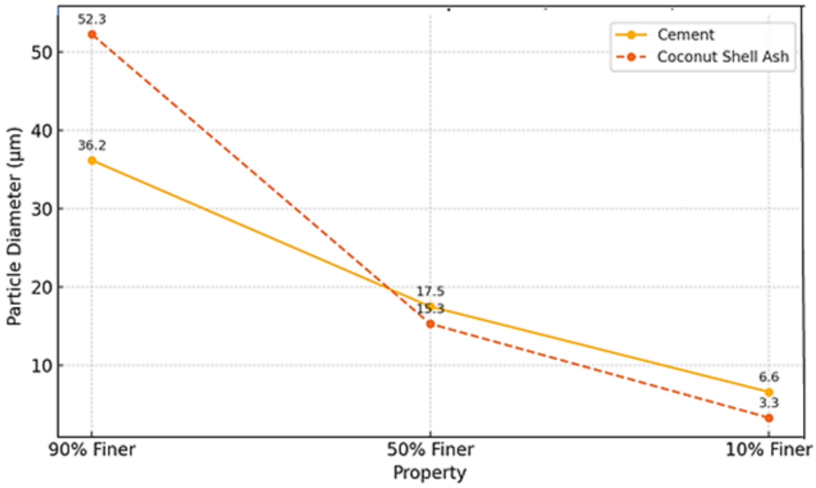

Figure 2. Physical characteristics of CSA and cement

Table 1. Chemical composition of CSA and cement

Element (wt %)	Si	Fe	Al	Ca	Mg	Mn	K
Cement	9,18	5,53	0,56	83,68	--	--	0,05
Coconut shell ash	2,34	52,19	0,98	10,59	6,76	3,36	23,78

2.2.3 Coconut shell ash concrete development

A mix design for the control concrete was designed according to the 10262:2013 standard to achieve the desired compressive strength. In the concrete, cement was partially replaced by CSA at replacement percentages of 5, 10, 15, and 20 %. The mix proportions are shown in Figure 3. For the concrete formed by the mixes, various tests were conducted at both fresh and hardened state according to Indian Standards. To develop coconut shell ash concrete, the mixes were designated as CSA0 (control concrete without coconut shell ash), CSA5 (concrete with 5 % of coconut shell ash), CSA10 (concrete with 10 % of coconut shell ash), CSA15 (concrete with 15 % of coconut shell ash), and CSA20 (concrete with 20 % of coconut shell ash), and the properties of the concrete were determined.

2.2.4 Properties of concrete with coconut shell ash

Various experiments have been conducted to ascertain the microstructural, fresh, and hardened properties of concrete. The temperature of the concrete and its slump were measured throughout a casting process to ascertain the fresh concrete parameters during the casting stage for each mix. For each mix, the hardened concrete parameters were determined by testing three cubes after various curing periods. Owing to the longer duration required for pozzolanic reactions compared to hydraulic reactions, and because the supplementary cementitious material is partially substituted for cement, the concrete characteristics were evaluated after 56 days.

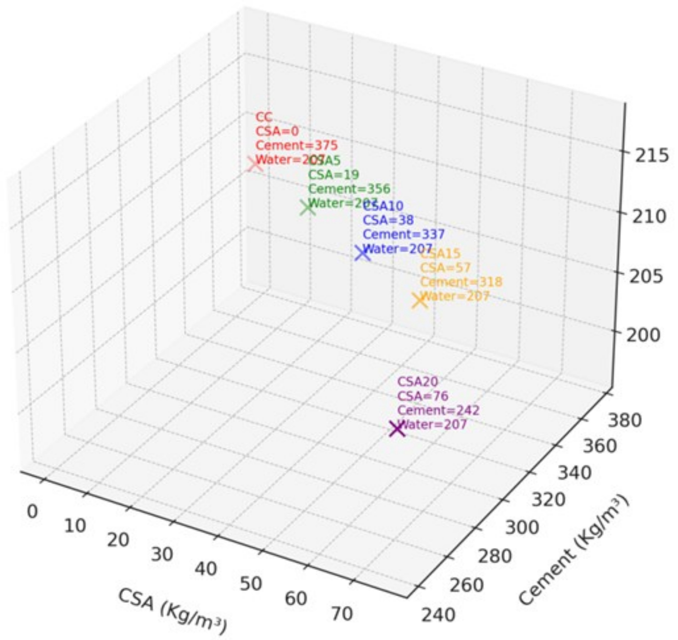

Figure 3. 3D visualisation of concrete mix proportions for a 1-m^3 cube

3 Results and discussions

3.1 Physical properties of CSA and cement

The particle percentage versus particle size is presented in Figure 4. Concrete hydration, strength, workability, and other qualities depend on the size and shape of the cement and CSA particles. Crushed CSA was sieved through a 75-μm sieve. The lubrication effect of spherical particulates contributes to the enhancement of concrete workability. Because of its sphericity, CSA has the potential to improve the workability of concrete.

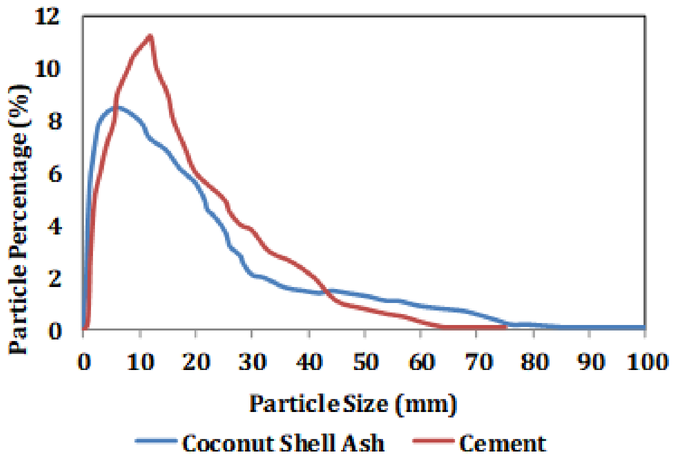

Figure 4. Particle size distribution of cement and coconut shell ash

The grinding machine and cement mill used different crushing techniques, resulting in variations in the CSA particle size from 0-100 μm and cement particle size from 0-70 μm (Figure 4). Table 2 shows that 90 % of cement and CSA particles had sizes greater than 36,2 and 52,3 μm, respectively. Compared to cement, CSA has finer particles smaller than 8,9 μm. Figure 1 shows that 10 % of CSA and cement particles had sizes less than 3,3 and 7,6 μm, respectively. Overall, CSA had a greater quantity of coarse particles and fewer fine particles

(Figure 4). Higher carbon content combined with inadequate grinding produces coarse particles. As CSA has a smaller surface area, it can make concrete more workable and reduce its reactivity during hydration.

3.2 Microstructural properties

The microstructural characteristics of cement and CSA must be examined to understand the effects of CSA on concrete behaviour. Surface SEM images of the cement and CSA were obtained using SEM testing. It was challenging to evaluate the general sphericity between the cement and CSA using the SEM images. As shown in Figure 5, small particles fill the spaces between larger particles; hence, CSA produces a denser SEM image than cement.

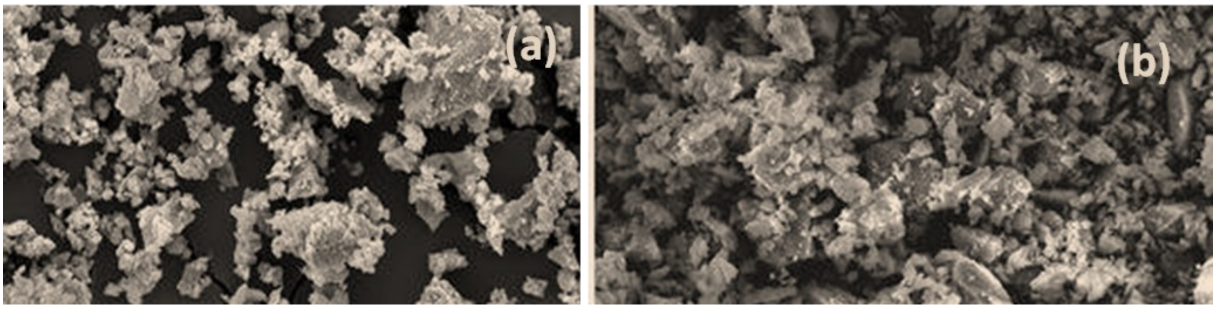

Figure 5. SEM images of: a) cement, and b) coconut shell ash

3.3 Properties of fresh concrete

3.3.1 Slump

The slumps of all concrete mixes were assessed using the slump cone test. Figure 6 illustrates the changes in the slump of the concrete mix at the initial slump and 1 h. The slump of the concrete decreased as the CSA content increased from 145 mm in the control mix (CSA0) to 65 mm in the mix with 20 % cement replacement with coconut shell ash (CSA20). For this study (the w/b) ratio was consistently kept at 0,50; with the addition of the admixture. The percentage decreases in slump for CSA05, CSA10, CSA15, and CSA20 compared with CSA0 were 29,66; 41,38; 51,72; and 55,17 %, respectively. The reduction in the slump value was significant compared to that of the control mix. Furthermore, after 60 min of mixing, the consistencies of the concrete mixes containing CSA05, CSA10, CSA15, and CSA20 decreased, as shown in Figure 6. Coconut shell ash in the concrete mitigated the decrease in the consistency of the concrete when the water-to-binder ratio remained constant. Two factors contributed to this decrease in workability. The primary factor was the presence of carbon particles. Based on its physical and chemical properties, CSA has a higher carbon content than cement. Carbon particles have a high capacity to absorb water from concrete mixtures, resulting in a decrease in the amount of free water. Consequently, the slump of the concrete mixes decreased because of the inadequate lubricating action of the cement paste.

As shown in Figure 6, the slump of the concrete mixes decreased as the CSA content increased. This was due to a decrease in the amount of free water in the mixture. Furthermore, the carbon particles played a role in rapidly absorbing the available free water within 30 min after mixing. Another factor contributing to this issue is the uneven texture of CSA. According to the microstructural characteristics, the surface of the CSA particles exhibit a rougher texture than the surface of the cement particles. A coarse surface offers a less extensive lubricating effect than a polished surface.

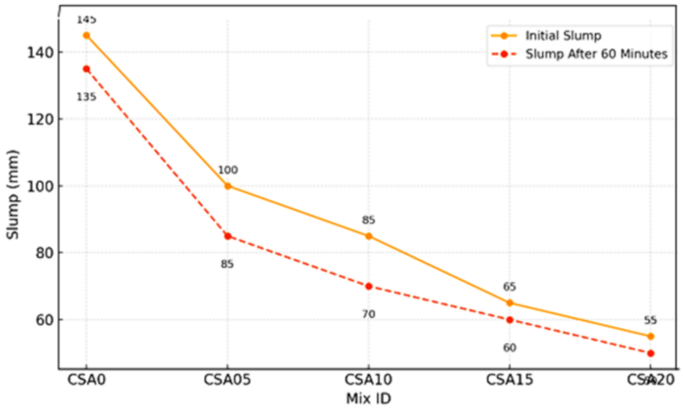

Figure 6. Slump value of all mixes

3.4 Properties of fresh concrete

3.4.1 Compressive strength

Figure 7 shows the compressive strength of the concrete mix. The compressive strength of each concrete mix exhibited a consistent increase over a period of 56 days because of the predominant reaction of tricalcium silicate and dicalcium silicate in cement with water, which resulted in the formation of CSH. The CSA0 mix design attained the desired compressive strength of 28,30 MPa after 28 days of curing. As shown in Figure 6, the compressive strength increases with higher CSA content, reaching a peak at the 10 % replacement level (CSA10) and decreasing thereafter.

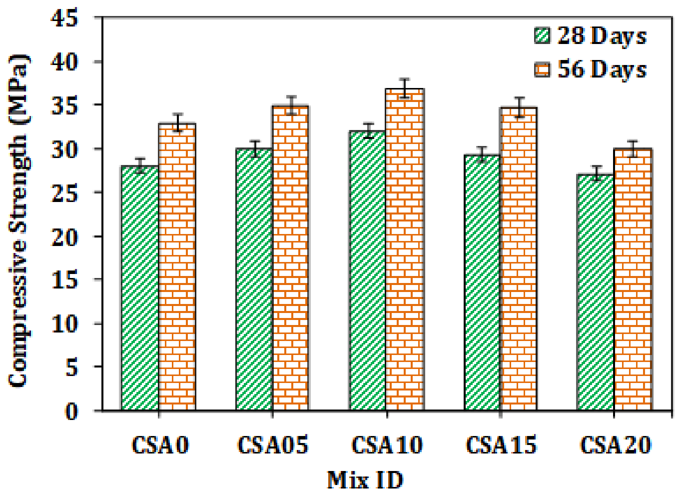

Figure 7. Compressive strength of all mixes

The compressive strength of concrete reached a maximum of 32,06 MPa after 28 days, indicating that the use of CSA can enhance the compressive strength of the concrete. After 58 days, the variations in the compressive strength for the mixes CSA05, CSA10, CSA15, and CSA20 were 6,07 %; 11,99 %; 5,31 %; and −8,92 %, respectively. The increase in strength for CSA10 was significant at both 28 and 56 days. The variation in the compressive strength of concrete at 28 days can be attributed to two aspects of CSA: the filler and pozzolanic effects. As discussed earlier, CSA exhibits exceptional gradation, which allows it to effectively the fill empty spaces in concrete—a phenomenon referred to as the filler effect. This filler effect leads to an initial increase in strength, owing to the filling of the holes, followed by a subsequent decrease in strength. The CSA chemically combines with the water-containing components of cement to produce a gel called the CSH gel via a phenomenon known as the pozzolanic effect.

This leads to a decrease in strength, because CSA generates a lower amount of CSH gel than cement.

3.4.2 Flexural strength

The addition of CSA to the concrete improved the flexural strength. The strengths at 14 and 28 days are presented in Figure 8. Compared with the control concrete, CAS05, CSA10, CSA15, and CSA20 exhibited strength differences of 3,59; 9,28; 5,99; and −4,19 %; respectively, at 14 days and 4,61; 11,84; 3,95; and −12,28 %; respectively, at 28 days. With the addition of coconut shell ash up to 10 %, there was an increase in flexural strength; beyond 10 %, the strength started decreasing. However, with the addition of 5 % NaCl, the strength enhancement was insignificant. The addition of a high percentage of CSA to the concrete mix reduced the initial strength-inducing components of cement, leading to a reduction in the hydration products; hence, the strength decreased. In addition, a high percentage increase in CSA alters the concrete pore structure. Figure 9 shows the correlation properties of the compressive and flexural strengths.

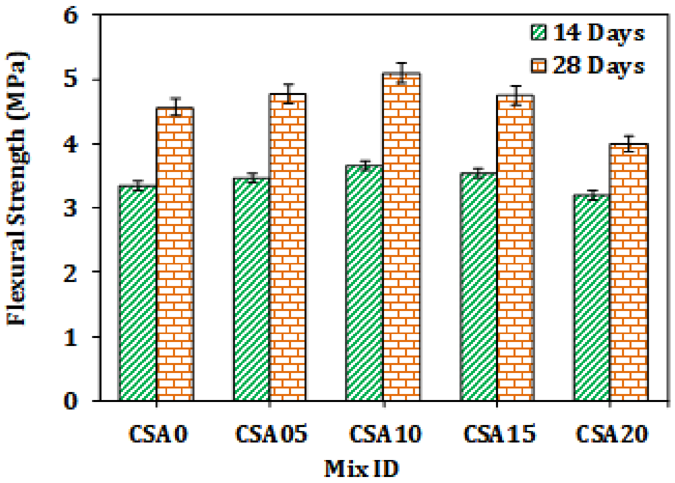

Figure 8. Flexural strength of all mixes at 14 and 28 days

A scatter plot showing the compressive strength (MPa) and flexural strength relationships was obtained using linear regression. The two variables showed a significant positive correlation, as indicated by the coefficient of determination (0,9076). The flexural strength increased with compressive strength, consistent with the anticipated behavior of concrete. With a positive slope of 0,1969; the linear regression indicated that the flexural strength increased by almost 0,2 MPa for every 1 MPa increase in the compressive strength. A close alignment of the data points along the trend line further confirmed the consistency of this compressive-flexural strength relationship. This linear relationship suggests that the cohesiveness of the concrete matrix improves as the compressive strength increases, thereby improving the flexural performance.

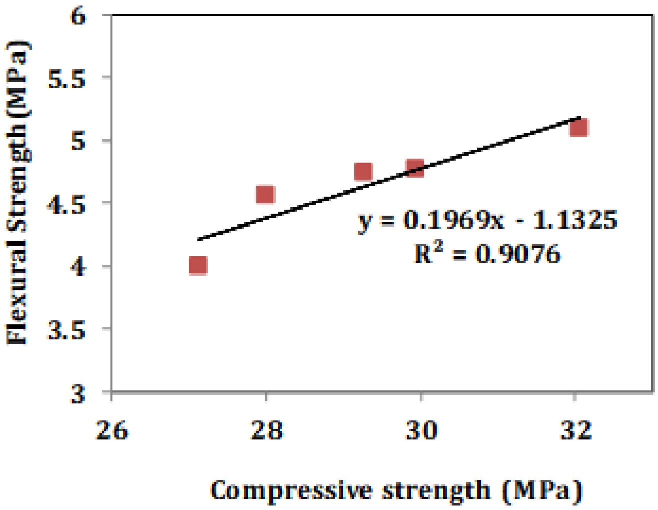

Figure 9. Correlation between compressive strength and flexural strength

3.4.3 Density

The densities of the various mixes are shown in Figure 10. With curing, the density of all concrete mixes increased up to 56 days owing to the increase in the amount of the CSH gel with the curing period. Furthermore, the CSH gel contributed to the increase in the weight of the concrete.

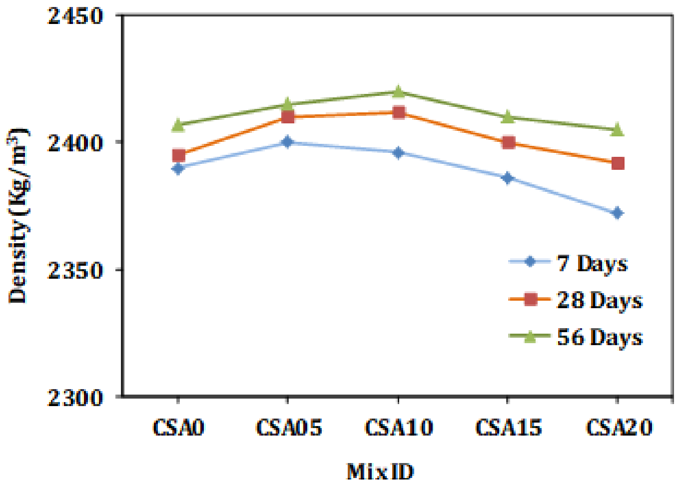

Figure 10. Density values of all mixes at 7, 28, and 56 days

At the ages of 7, 28, and 56 days, as the percentage of CSA increased from 5-25 %, the density of the concrete also increased, reaching its highest point and decreasing thereafter. A lower-hydration CSH gel was formed in the concrete because of the contribution of the CSA. CSA is composed of a large number of carbon particles and can absorb a large quantity of water. Consequently, the weight of the concrete increased as the percentage of CSA in the mixture increased. Owing to the overall impact, the density of concrete increased as the percentage of CSA increased. Compared with the CSA0 mix, the CSA05 mix had a higher density. This is because the weight increase that occurred because of water absorption was greater than the weight decrease that occurred because of the reduction in the CSH gel. There is a wide variation in the density of all concrete mixes that contain CSA (ranging from 2330 kg/m^3 to 2460 kg/m^3). When CSA is added to concrete, the density of the concrete increases until it reaches a 10 % replacement (CSA10), after which the density begins to drop as the CSA concentration increases. The drop in replacement after 10 % was probably caused by the larger porosity resulting from partial hydration, a lower amount of cement, and possibly weak bonding in the matrix. When cement is replaced with coconut shell ash, the density of the concrete is affected. For the same curing time, the density was the highest for the CSA10 compared to the other samples. However, because of an increase in porosity, the density decreased in the cases of extensive replacement (CSA15 and CSA20). Based on these findings, it appears that sparingly using CSA can enhance the properties of concrete, whereas going overboard may compromise its compactness and longevity.

3.4.4 Water absorption

Figure 11 shows the degree to which the concrete mixtures absorbed water for various curing durations. This phenomenon can be explained by the presence of gaps in the concrete that allow water to enter. As the curing period increased, the amount of CSH gel in the concrete mix increased, and the overall number of voids decreased. After 7 days of curing, the partial hydration and less compact microstructure caused all mixtures to exhibit substantially increased water absorption. As the hydration process progressed and more CSH gel was produced, the pore connections were reduced, and the water absorption declined by day 28. At 56 days, the water absorption values were the lowest, suggesting that the porosity was reduced by protracted curing. At 10 % CSA, a more porous structure was produced because of imperfect particle packing, as indicated by the maximum absorption in CSA05 and CSA10. Concrete with a density beyond addition of 10% of CSA exhibited a slight decrease in water absorption, probably because of improved particle refinement and pozzolanic activity. Low concentrations of CSA (CSA05 and CSA10) cause an initial spike in water absorption because the less dense CSA particles introduce a larger porosity. It is possible that the pozzolanic effect, which gradually refines the pore structure, and the enhanced particle packing are responsible for the subsequent decrease at higher CSA levels (CSA15, CSA20). As the concrete matrix better hydrated and densified during a longer curing period, it absorbed significantly less water. Although the control mix had better absorption rates, CSA20 continued to outperform it, suggesting that a high CSA content can cause more voids to form and affect the compactness.

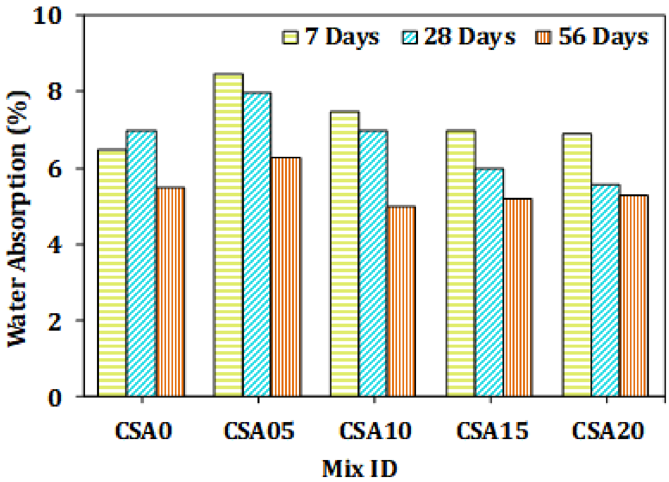

Figure 11. Water absorption percentage of all mixes

3.5 Properties of fresh concrete Optimization of percentage of CPA in concrete

Preliminary testing showed that a 10 % coconut shell ash (CSA) content was an ideal substitute for traditional cement. The addition of coconut fibre to concrete at 0,25; 0,50; 0,75; and 1,00 % improved its performance. Experiments were conducted to evaluate the effects of fibre addition, with an emphasis on mechanical strength, durability, and workability. The primary objective was to determine the ideal fibre content that enhances concrete performance while maintaining structural integrity. The findings include information on the combined impact of

CSA and fibre reinforcement, which helps in the creation of a concrete mix that is both long-lasting and environmentally friendly. Figure 12 shows the compressive strengths of concrete with different amounts of coconut fibre (0,00; 0,25; 0,50; 0,75; and 1,00 %) at 28 and 56 days. The findings indicate that the highest compressive strength is achieved with a coconut fibre content of 0,25 %. The bonding between the fibre and cement matrix is responsible for the increase in strength, as it reduces microcracks and improves load transfer. When the fibre percentage exceeded 0.5%, the compressive strength began to decline. This decrease was probably due to poor workability, fibre clustering, and uneven dispersion, which led to weaker interfacial bonding and more voids in the matrix. All the mixes exhibited discernible strengthening from 28 to 56 days, in line with the inherent hydration process of the cement. However, mixes with reduced fibre content showed a faster rate of strength gain, suggesting that an excess of fibre could slow the strength development. In conclusion, incorporating coconut fibre up to 0,25 % in CSA-blended concrete presents a promising approach for improving its lifetime and fracture resistance. A high fibre content (more than 0,50 %) reduces the strength, most likely owing to workability challenges and unequal fibre distribution.

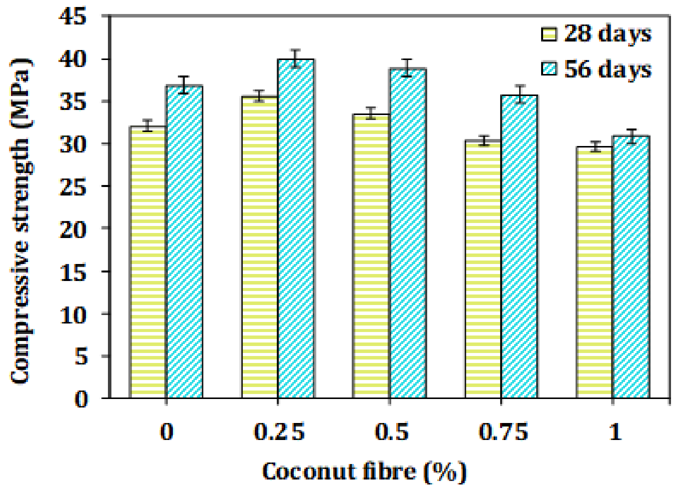

Figure 12. Compressive strength of the fibre added in the CSA10 mix

4 Conclusions

This study aimed to identify the best CSA concrete mix in terms of reduced environmental impact and specified structural performance. To understand the effect of CSA on concrete performance, a SEM analysis was conducted to assess the cement and CSA properties. A perfect concrete mix design was selected by examining the fresh, hardened, and microstructural qualities of all the mixes, as well as how they affected the environment. According to the results of this study, when the CSA concentration increases, the slump and temperature decrease.

- Because of its production method, CSA differs from cement in that it has a rougher surface, more carbon particles, and superior gradation.
- An increase in the CSA content causes a decrease in the slump of concrete.
- At 28 and 56 days of curing, the compressive strength initially increased with CSA content, peaking at the CSA10 mix, but declined thereafter.
- The optimal coconut fibre reinforcement was found to be 0,25 % in the 10,00 % coconut shell ash concrete.
- The most important environmental impact category—global warming potential (GWP) decreased as the CSA content of the concrete mixes increased.

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