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Enhancement of the Durability Properties of Lightweight Coconut Shell Concrete by Incorporating Mineral Admixtures

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Abstract

Introduction

Coconut shell concrete (CSC) is a lightweight concrete (LWC) made from waste coconut shells (CSs). CSs have high porosity, which may lead to durability issues. Adding mineral admixtures to LWC can overcome this issue. Hence, this study examined the durability of lightweight CSC that employs fly ash (FA) and silica fume (SF) in lieu of cement.

Methods

Crushed CSs of 12.5 mm size replaced the conventional coarse aggregate. The effects on water permeability, chloride permeability, capillary water absorption, thermal conductivity, and fire resistance of CSC at varying levels (0%, 5%, and 10%) of FA and SF were evaluated. All the specimens were tested after 28 days of curing.

Results

The permeability coefficient of CSC at 28 days decreased significantly with 10% SF, ranging from 0.945 $\times 10^{-11}$ to 1.824 $\times 10^{-11}$ m/s. The sorptivity coefficient was reduced below the accepted value of 0.1 mm/min$^{0.5}$ with mineral admixtures. At 28 days, rapid chloride permeability values improved, varying from 1160 to 1640 Coulombs. The thermal conductivity, measuring between 0.61 and 0.68 W/mK in CSC was influenced more by FA than SF. CSC with 10% SF could withstand a fire attack for nearly 2 hours, making it suitable for Type three building according to the National Building Code standards.

Conclusion

Adding mineral admixtures enhanced durability by improving the pore structure, with 10% SF demonstrating optimal results. This research underscores the potential of mineral admixtures for enhancing the performance and applicability of lightweight CSC in construction applications.

Categories: Structural Engineering, Environmental and Sustainable Engineering, Environmental Engineering and Sustainability
Keywords: coconut shell concrete, mineral admixtures, permeability, sorptivity, thermal resistance, fire resistance

Introduction

The increasing need for concrete has severely depletes natural rock deposits, producing environmental damage and an ecological imbalance. Therefore, a suitable alternative material must be identified to replace the natural stone aggregates. The mining process entails the manufacture of stone aggregate by a variety of dangerous techniques, which may result in several negative environmental repercussions and ecological collapse. Cement production also generates a substantial amount of carbon dioxide, which pollutes the environment. This has necessitated investigations into alternate materials. Consequently, attempts have been undertaken to improve the quality of concrete by replacing conventional aggregates with different substitute materials. Supplementary materials such as fly ash (FA) and silica fume (SF) can partially replace cement in concrete to achieve sustainability. Experimental studies [1-3] indicated that coconut shells (CSs), an oil industry by-product, have been used as a coarse aggregate in the process of producing lightweight concrete (LWC). Coconut trees are cultivated on around 12 million hectares across the globe. These are abundant in the world's tropical regions, particularly Asia, Africa, and the United States. Coconuts are recognized as having originated in Southeast Asia. India produced 19247 million nuts in 2021-2022, accounting for 31.45% of global coconut production [4]. The white flesh accounts for 28% of its total weight in a fully grown coconut, while the hard protective shell (12%) and thick husk make up

35% [5]. While the flesh and husk are useful in the food and coir industries respectively, the shell is consistently thrown away as waste. These waste materials are often burnt, causing harm to the environment. Hence, utilizing this agricultural waste as an aggregate in the construction sector assists in preserving natural resources and is environmentally sustainable.

A concrete structure is susceptible to deterioration due to environmental exposure, and its ability to withstand such changes is a measure of its durability. Concrete, when durable, increases its service life and reduces its replacement and repair costs [6]. Generally, concrete has a porous structure that gets affected by microclimate factors. Permeability is one of the primary transport mechanisms that contribute to the durability of concrete. The permeation through concrete is dependent on porosity, pore size, and the degree of pore continuity. Lightweight aggregates are naturally porous, allowing for a larger pore area in the interfacial zone. The weak zone consequently results in more infiltration of fluids into concrete, affecting its durability. A lower density of LWC than conventional concrete may also lead to moisture movement and chloride ingress. It has been emphasized that mineral admixtures in concrete can reduce permeability by altering the pore structure [7]. The alumina content in mineral admixtures dictates the permeability of concrete. High alumina content in the admixture decreases the permeability of concrete [8]. The literature [9-11] provides evidence that the strength and durability of concrete can be enhanced with the inclusion of mineral admixtures.

Three different curing conditions (full, intermittent and dry) were adopted by Gunasekaran et al. [12] to test the coconut shell concrete (CSC) for its durability properties. Water absorption and the permeable voids were less in CSC specimens when cured fully and intermittently. Sorptivity values of less than 0.1 mm/min$^{0.5}$ were achieved through better compaction and the internal curing provided by the lightweight aggregates. The Rapid Chloride Permeability Test (RCPT) results showed lower chloride ion penetration, which increases with curing age, indicative of the enhanced pore structure of the concrete. On the other hand, the chloride profile was high in dry-cured CSC. The durability of CSC with coconut fibers was investigated by Sekar and Kandasamy [13]. It was found that proper curing conditions (full water curing) of CSC played a crucial role in reducing water absorption and permeable voids. The permeability of chloride ions in CSC was moderate. The lower sorptivity values of CSC indicated the efficiency of internal curing provided by the CS aggregates. A reduction in water absorption was observed by Prakash et al. [2] in CSC that partially replaced CSs with stone aggregates (50%) and cement with FA (0%, 10%, 20%, and 30%). The volume of permeable voids was reduced to a maximum of 11.1% with 30% FA replacement. CSC also had low alkalinity, favoring its use in reinforced concrete. The sorptivity value and chloride ion permeability decreased with increasing age of the concrete. The durability of partially incorporated CS aggregates (18.5%) in concrete was studied by Nadir and Sujatha [14]. Cement was replaced with FA (30%) and ground granulated blast furnace slag (15%). The improved microstructure of concrete, achieved through the addition of mineral admixtures, played a significant role in enhancing the porosity, water absorption, chloride ion penetration, and sorptivity of the concrete. The abrasion resistance of the concrete was also within the codal limits. Palanisamy et al. [15] replaced stone aggregates with CS aggregates at 0%, 25%, 50%, 75%, and 100% replacement levels to test the permeability properties of self-compacting CSC. Rice husk ash and SF were used in the development of binary and ternary blended concrete. The saturated water absorption of ternary blended LWC with 75% replaced CS aggregates was the highest, indicating the efficiency of self-compaction. Also, at the same replacement level of CS, the ternary blended concrete had improved sorptivity than the binary blended concrete. The chloride concentration values of less than 1% were found in ternary blended concrete, particularly at the later ages. Thilagashanthi et al. [16] used treated CSs in CSC to determine their durability. It was observed that sago flour-treated CSs had decreased the water absorption and volume of permeable voids in CSC considerably by reducing the voids. The sorptivity coefficient of treated CSC was improved by enhancing its quality. An improvement in the pore structure of treated CSC was revealed by the moderate chloride permeability. Both treated and untreated CSC provided a fire resistance of 2 hours at 200°C. Additionally, over the past few decades, there has been a growing emphasis on enhancing building comfort, resulting in reduced energy consumption. To do that, steps have been made to increase building thermal insulation and the effectiveness of heating appliances. Sengul et al. [17] discovered that the thermal conductivity of concrete rises with an increase in density, pore size, and moisture content.

Experiments in abundance have been carried out to examine the mechanical properties of LWC produced with CS as a coarse aggregate, while its durability aspects have drawn little attention, and the thermal conductivity of CSC has not been explored yet. Hence, the primary goal of the study is to assess the influence of mineral admixtures on the durability of lightweight CSC. To accomplish this, research was undertaken on the durability properties in CSC having 0%, 5%, and 10% FA and SF, such as capillary water absorption, water and chloride permeability, and fire and thermal resistance.

Materials And Methods

Materials

Ordinary Portland cement (OPC), grade 43, was used for making samples of concrete and complies with ASTM C150-12 [18]. During the experiment, Class F FA [19] and SF [20] were used. The chemical composition of cement and its substitutes are listed in Table 1. The specific gravity of OPC, SF, and FA are 3.15, 2.12, and 2.56, respectively. Table 2 presents the properties of CS aggregates. Crushed coconut shell aggregates (CSAs) of 12.5 mm maximum size was used as the coarse aggregate for making LWC. A sample of CSAs is shown in Figure 1. Since crushed CSs have greater water absorption than conventional aggregates, it was first kept soaked in water for about 24 hours and then kept in a saturated surface dry state prior to being mixed with other ingredients in the concrete mixer. The fineness modulus of fine aggregate was 2.88. To optimize the efficiency of the CSC, Glenium B233, a superplasticizer with a specific gravity of 1.09 was employed.

FIGURE 1: Sample of CSAs

CSAs, coconut shell aggregates

Chemical component	Cementitious materials		
	OPC	SF	FA
SiO_2 (%)	19.6	94.0	45.8
Al_2O_3 (%)	5.2	0.1	3.4
Fe_2O_3 (%)	2.5	0.1	5.85
CaO (%)	62.2	0.4	17.5
MgO (%)	3.5	0.4	2.86
SO_3 (%)	3.2	1.4	0.1
LOI (%)	2.5	4.0	0.5

TABLE 1: Chemical composition of cementitious materials

Refer to [21]. OPC, Ordinary Portland cement; FA, fly ash; SF, silica fume

Physical and mechanical properties	Coconut shell	Granite aggregate	River sand
Water absorption (24 h) (%)	17.67	1.5	-
Specific gravity	1.16	2.78	2.63
Impact value (%)	7.8	19.8	-
Crushing value (%)	2.3	8.4	-
Fineness modulus	6.56	7.68	2.88
Shell thickness (mm)	3-8	-	-
Bulk density (kg/m^3)	570	1460	-
Abrasion value (%)	1.92	1.71	-
Flakiness index (%)	71.43	13	-
Elongation index (%)	14.9	21	-

TABLE 2: Physical and mechanical properties of aggregates

Refer to [21].

Mix proportion

The method of designing lightweight CSC differs from traditional normal-weight concrete (NWC) due to its physical characteristics, like the texture and the shape of CSA, as compared to other lightweight aggregates. According to Gunasekaran et al. [1], the desired strength of CSC is hardly achieved by utilizing the ACI approach, the IS method, or the Short and Kinniburgh [22] method. A mix proportion of 1:1.58:0.6 was optimal for this investigation through the trial-and-error method; the proportions are presented in Table *3*. This investigation utilized five concrete mixtures. The L_1 mixture is CSC with no cement substitution and was taken as the control concrete. Two of the five mixes (L_2 and L_3) contain cement replacements of 5% and 10% FA, while the remaining two (L_4 and L_5) contain cement replacements of 5% and 10% of SF. The slump, density, and compressive strength obtained in each mix are given in Table *3*.

Mix	Cement	Silica fume	Fly ash	Water	River sand	Coconut shell	Super plasticizer	Slump (mm)	Density (kg/m^3)	Compressive strength (N/mm^2)
L_1	510	-	-	200.43	805.8	306	3.57	50	1948	19.01
L_2	487.5	-	25.5	200.43	805.8	306	3.57	45	1934	18.5
L_3	459	-	51	200.43	805.8	306	3.57	40	1917	20.11
L_4	487.5	25.5	-	200.43	805.8	306	3.57	85	1938	20.7
L_5	459	51	-	200.43	805.8	306	3.57	98	1924	22.66

TABLE 3: Mix proportions of coconut shell concrete (kg/m3)

Refer to [21].

Test methods

In the following section, the testing techniques for durability parameters such as water permeability, sorptivity, RCPT, fire resistance, and thermal conductivity are described.

Water Permeability Test

Being a carrier of harmful agents, water is one of the major factors that determine the durability of concrete. Hence, it is crucial to determine the permeability of water in concrete. The resistance of CSC to permeability under steady-state flow was examined using a water permeability test according to IS 3085:1965 [23] guidelines. For this, cubes of size 150 mm × 150 mm were water-cured for 28 days. The vertical faces of the cubes were completely coated with a water-resistant material, leaving the upper and lower horizontal sides similar to those shown in Figure *2a*. The samples were then kept in a permeability cell as seen in Figure *2b*. At the top and bottom surfaces of the specimen, a 150 mm × 150 mm × 8 mm-sized elastic sheet with a central hole of 100 mm × 100 mm was fixed and tightened with a plate. The setup had a water reservoir provided with valves for admitting and draining water and compressed air. Two pressure gauges in the reservoir indicated the pressure inside the cylinder and the air pressure. An air compressor unit of sufficient capacity was employed. The intended test pressure of 7 kg/cm^2 was applied after the reservoir had been completely filled with water. A collection bottle placed beneath the reservoir collected the percolated water. After reaching the steady-state flow (water inflow and outflow become equal), the percolated water was measured at periodic intervals from the collection bottle. The permeability test was conducted for approximately 100 hours. Then, the average outflow observed over these 100 hours was noted, and Equation (1) was used to calculate the permeability coefficient.

$$K_p = qL/AtH \quad (1)$$

Where Kp is the permeability coefficient in m/sec, q is the amount of percolated water in m^3, L is the thickness of the specimen in meters, A is the area of cross-section of the specimen in m^2, t is the time of flow in seconds, and H is the water head in meters.

FIGURE 2: Water permeability test (a) test specimen (b) experimental setup

Sorptivity Test

Sorptivity refers to the ability of a porous material to absorb and move water through its capillaries [24]. Capillaries form the pathway to the entry of aggressive chemicals. The amount and rate of water absorbed can be determined using a sorptivity test. A sorptivity test in CSC was conducted as per ASTM C1585-04 [25]. A total of 100 mm cube specimens were preconditioned in a manner similar to that of Gunasekaran et al. [12]. The specimen's sides are water sealed, except for the top and bottom, to allow for unidirectional water flow. The specimen's initial weight is recorded, and then placed in water 5-10 mm deep, as shown in Figure *3*. The specimen is taken out of the water after 1 minute, wiped of excess water, and weighed. This process is repeated at 2, 3, 4, 6, 9, 12, 16, 25, 30, 45, and 60-minute intervals. The plotting of the increase in mass per unit area against the square root of time (t) shows how dense the material becomes relative to water. Equation (2) can be used to compute the water absorption per unit area, and sorptivity is represented by the slope of the best-fit curve.

$$i = s\sqrt{t} \quad (2)$$

Where i is the cumulative water absorbed per unit area, s is the coefficient of sorptivity, and t is the time of weight determination.

FIGURE 3: Testing of capillary water absorption for CSC

CSC, coconut shell concrete

Rapid Chloride Permeability Test

Chloride infiltrates the microstructure of concrete and is a key factor that affects its durability. Chlorides can lead to corrosion in Reinforced Cement Concrete structures, and thus, chloride permeability is an important aspect of durability studies. The chloride ions take a lot of time to enter the pores of concrete. This process is hence accelerated in an acceptable period of time by the RCPT. ASTM C1202-19 [26] outlines the method for evaluating the chloride ion permeability of concrete. A 50 mm thick and 100 mm in diameter CSC specimen was soaked in water and treated to a 60 V DC current for a period of 6 hours, which is shown in Figure *4*. The test setup has two reservoirs, and in between them, the test specimen was placed. This arrangement was made leak-proof using epoxy resin. The reservoir with 0.3 M sodium hydroxide (NaOH) solution was connected to the positive terminal of the DC. The reservoir containing 3% sodium chloride (NaCl) solution was connected to the negative terminal of the DC. The anode and cathode were made of stainless steel and passed a 60 V current. The flow of electricity through the sample was recorded regularly to calculate the total charge, measured in Coulombs, following the trapezoidal rule indicated by Equation (3).

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_t + \cdots + 2I_{330} + 2I_{360}) \quad (3)$$

Where Q represents the charge transmitted (Coulombs), I_0 is the current transmitted instantly following the application of voltage (Amperes), and I_t is the current transmitted at "t" minutes following the application of voltage (Amperes).

FIGURE 4: CSC specimen tested in RCPT apparatus

CSC, coconut shell concrete; RCPT, Rapid Chloride Permeability Test

Thermal Conductivity Test

Heat transfer through conduction in concrete is referred to as thermal conductivity. Buildings can save energy by lowering the thermal conductivity. An effective method of assessing the thermal conductivity of concrete is the hot plate technique. ASTM C177-04 [27] depicts a guarded hot plate setup that can be employed for measuring the thermal conductivity of construction materials at 28 days of curing. The setup consists of a metered section thermally connected to a concentric guard with a clear gap, as shown in Figure 5a and b. Before testing, specimens measuring 300 mm × 300 mm × 25 mm, as depicted in Figure 5c, were kept for drying in an oven for 24 hours set at 105 ± 5°C and put between hot and cold plates. Glass wool insulation is provided on all sides of the specimens to make sure that heat conduction occurs only upwards. The temperature of the cold and hot plates represents the inside and outside room temperature, respectively. A temperature controller was utilized to regulate the heat, and after the stable temperature state, a digital watt meter was used to measure the one-way heat transfer (Q). Next, using Fourier's rule, the thermal conductivity was determined as indicated by Equation (4).

$$k = Qh/A\Delta T \quad (4)$$

Where k is the thermal conductivity (W/mK), Q is the flow of heat (W), h is the thickness of sample (m), A is the area of sample (m^2), and ΔT is the difference in temperature between hot and cold plates (K).

FIGURE 5: Experimental setup for thermal conductivity (a) pictorial view, (b) schematic view, and (c) test specimen

Temperature Resistance of CSC

Thermal resistance in concrete refers to its capacity to prevent heat flow. A building structure's ability to resist heat depends on the quality of the materials used in construction. The building materials must resist elevated temperatures to maintain the structure's stability. Because of their lower thermal conductivity and thermal expansion coefficient, LWC exhibits stronger fire resistance than NWC. However, the fire resistance of LWC with CSs as aggregate needs to be improved as CSA is a naturally flammable material. To test CSC for fire resistance, 100 mm × 100 mm × 100 mm size cubes with 0%, 5%, and 10% of SF and FA were cast. After 24 hours of casting, the specimens were released from the mould. The samples were then weighed and stored for 28 days of curing. After this period, the fire resistance of CSC was tested by exposing the specimens to temperatures of 100°C, 200°C, 300°C, 400°C, and 500°C in an oven for 28 days. Figure 6a and b depict the fire test set up in which the specimens were heated up to 200°C and >200°C, respectively. The temperature was increased at an average rate of 5°C every minute. Each temperature was kept constant for 2 hours in order to attain thermal equilibrium, as illustrated in Figure 6c. After this process, the cubes were cooled at a rate of 2°C per minute to reach room temperature. Equation (5) estimated the compressive strength loss induced by the temperature.

$$\text{Compressive strength loss} = [(f_{28} - f_T)/f_{28}] \times 100 \quad (5)$$

Where f_{28} is the compressive strength (at room temperature) in N/mm^2, and f_T is the compressive strength (at T°C) in N/mm^2.

FIGURE 6: Fire resistance test (a) oven for temperatures up to 200°C, (b) oven for temperatures >200°C, and (c) method of heating the cubes in furnace

Results And Discussion

Water permeability of CSC

Figure 7 and Table 4 display the water permeability test results determined after 28 days of testing. The permeability ratio was determined by dividing the permeability of CSC with mineral admixtures by the permeability of control concrete. CSC without any mineral additives was found to have a permeability coefficient of 1.824×10^{-11} m/sec. This result shows that there is a high rate of water penetration into CSC because of the pervious lightweight CSA material that increases permeability.

The coefficient of permeability of CSC mix, containing 5% and 10% FA, was found to be 1.544×10^{-11} m/sec and 1.076×10^{-11} m/sec, respectively. These values indicate moderate permeability. These mixes exhibit permeability ratios of 0.85 and 0.59, representing a 15.4% and 41% reduction compared to the control concrete. This might be because the incorporation of FA results in increased sites of nucleation for hydration product precipitation, lowered calcium hydroxide ($Ca(OH)_2$) and enhanced impermeability of the concrete [28]. By increasing the bonding between the aggregate and cement matrix, FA makes concrete more impervious. Substituting FA for cement also enhances the interfacial structure of lightweight CSC, and a thick layer of cement paste is formed at the contact area. The addition of FA reduces the amount of cement and subsequently the amount of hydration heat, thus reducing the occurrence of microcracks caused by thermal stress [28]. Consequently, the inclusion of FA greatly decreases the permeability of the CSC.

Figure 7 shows that the SF addition improved the resistance to permeability of water, with coefficients of 1.312×10^{-11} m/sec and 0.945×10^{-11} m/sec for 5% and 10% SF, respectively. The ratio of permeability was 0.72 for 5% SF and 0.52 for 10% SF. This decreased permeability by 29% for 5% and 48% for 10% SF substitution, as compared with the control concrete. Mo et al. [29] point out that the densely packed cement paste resulting from the presence of SF narrows the pores and reduces permeability. Moreover, a significant amount of calcium-silicate-hydrate (C-S-H) gel produced in mixtures with SF at 5% and 10% substitution effectively fills the pores, resulting in poor permeability. By incorporating 10% SF as a substitute for cement, the lowest permeability coefficient of 0.945×10^{-11} m/s was obtained. This value was lower than the minimum limit of 10^{-11} m/s and nearly half that of the control concrete (1.824×10^{-11}m/s). Further, compared to the FA mix, the permeability of the SF mix was lower.

FIGURE 7: Effect of mineral admixtures on water permeability

Mix	Depth of penetration (m)	Coefficient of permeability (m/sec)	Permeability ratio
L_1	0.125	1.824×10^{-11}	-
L_2	0.115	1.544×10^{-11}	0.85
L_3	0.096	1.076×10^{-11}	0.59
L_4	0.106	1.312×10^{-11}	0.72
L_5	0.09	0.945×10^{-11}	0.52

TABLE 4: Water permeability of CSC

CSC, coconut shell concrete

Figure 8a and b depict the Scanning Electron Microscope (SEM) images of CSC with 10% FA and 10% SF, respectively. The distance between the cement paste and the CSA is roughly 1.44-7.86 µm and 2.934-5.355 µm for CSC with 10% FA and 10% SF, respectively. The distance between hydrated cement paste and CSA was between 24.94 µm and 26.63 µm in a study by Gunasekaran et al. [30] for CSC without any mineral admixtures. This comparison shows that adding mineral admixtures to lightweight CSC improves concrete strength and decreases porosity.

FIGURE 8: SEM images of CSC with (a) 10% FA and (b) 10% SF

SEM, Scanning Electron Microscope; CSC, coconut shell concrete; FA, fly ash; SF, silica fume

Sorptivity resistance of CSC

Figure 9 illustrates the correlation involving cumulative water absorption and time, from which the sorptivity coefficient of the CSC was calculated. The sorptivity coefficients of the CSC mixtures at 28 days of age are depicted in Figure 9, ranging from 0.0603 to 0.1439 mm/min$^{0.5}$. EuroLightCon [31] shows that a sorptivity value of less than 0.1 mm/min$^{0.5}$ is deemed good quality concrete, while a value greater than 0.1 mm/min$^{0.5}$ indicates medium permeability concrete. The greatest sorptivity coefficient was 0.1439 mm/min$^{0.5}$ for the control concrete, above the 0.1 mm/min$^{0.5}$ threshold, as shown in Figure 9. This indicates that the capillary water absorption of lightweight CSC without mineral additions was average. This figure is comparable to the sorptivity values of other LWCs manufactured from oil palm shell concrete (OPSC), which range between 0.06 and 0.14 mm/min$^{0.5}$ [32]. These findings are also consistent with those of Gunasekaran et al. [12], who determined the sorptivity of CSC at 28 days of age to be between 0.095 and 0.104 mm/min$^{0.5}$ under complete water curing. The low sorptivity of plain CSC can be attributed to its porous structure, but this also reduced its compressive strength due to the high sorptivity coefficient.

FIGURE 9: Cumulative water absorption versus elapsed time

The concrete mixture's sorptivity coefficient decreased as the percentages of FA and SF increased, as illustrated in Figure 10. It is observed that the absorption values of concrete mixtures containing 5% and 10% FA decreased by 35% and 40%, respectively, compared to the control concrete. The sorptivity of concrete made with FA as a cement replacement was found to be higher at the early age of concrete compared to SF. However, as the pozzolanic reactions progress over time, it is believed that the capillary absorption of the concrete will decrease. Due to the early stage (28 days) slower pozzolanic reaction of FA, this may increase capillary water absorption [33]. Additionally, the larger particle size of FA compared to SF results in larger capillary pores in the concrete, leading to higher capillary absorption and lower compressive strength.

At 28 days, the concrete containing 5% and 10% SF showed sorptivity values of 0.0825 mm/min$^{0.5}$ and 0.0603 mm/min$^{0.5}$, which were 43% and 58% lower, respectively, than those of the control concrete. Overall, the concrete with SF exhibited better performance in terms of capillary action, in comparison to the control concrete. This is owing to the tiny particle size of SF that reduces the pores and blocks the entry of corrosive substances, as well as the rapid pozzolanic reaction, resulting in decreased capillary water absorption and allowing for the progress of high strength concrete at an early age. A lower sorptivity value implies greater resistance of the concrete to water absorption.

FIGURE 10: Sorptivity coefficient of CSC with mineral admixtures

CSC, coconut shell concrete

Chloride permeability of CSC

Figure 11 presents the RCPT results of CSC with and without the incorporation of FA and SF. The 28-day RCPT results showed that concrete without mineral admixtures had moderate resistance to penetration of chloride ions with a value of 2150 Coulombs. This high charge transfer value was made possible by the porous structure of CSC. Teo et al. [32] pointed out that the concrete's resistance to chloride ions is strongly affected by its porosity, including factors such as the size of the pore, its connection, and distribution. The RCPT value of CSC is comparable to other LWCs made with expanded clay, which had values ranging from 2115 to 3336 Coulombs [34].

FIGURE 11: Variation of RCPT values for CSC with mineral admixtures

CSC, coconut shell concrete; RCPT, Rapid Chloride Permeability Test

CSC containing 5% and 10% FA had an average charge transfer of 1640 and 1250 Coulombs, respectively, as shown in Figure 11. The use of 5% FA in CSC resulted in a significant decrease in charge transfer, of around 23.7% compared to CSC without FA. The reduction was even greater, reaching 42%, when 10% FA was used. The pozzolanic reaction creates a stronger link between the cement paste and aggregate, and makes the concrete harder and less permeable, limiting the penetration of chloride ions. Furthermore, the decrease in the permeability to chloride in CSC incorporating FA is most likely due to the pozzolanic reactions and fine-filling characteristics of FA, which are known characteristics of binders containing FA.

The presence of SF enhanced the resistance against the penetration of chloride ions, as illustrated in Figure 11. This is owing to the excessive fineness and pozzolanic characteristics of SF. Also, CSC incorporating SF reduces chloride ion penetration by filling micropores, thereby densifying the concrete's microstructure. All CSCs were shown to have low chloride permeability, except CSC without admixture, which was shown to be moderate. Chloride permeability declined substantially in CSC with FA and SF. Table *5* displays the chloride permeability rating of concrete, as determined by RCPT. CSC exhibited moderate to low chloride permeability both with and without mineral admixtures, resulting in good quality. Furthermore, the reduction in charge transfer was significant, reaching 33% and 46% in CSC having 5% and 10% SF, respectively, relative to the control mix. This highlights the effectiveness of incorporating SF into CSC to significantly reduce charge transfer, thus increasing the durability and overall performance of concrete.

Chloride ion permeability	Charge passing (Coulombs)	Typical concrete type
High	>4000	High w/c ratio (>0.6) conventional PC concrete
Moderate	2000 to 4000	Moderate w/c ratio (0.4 to 0.5) conventional PC concrete
Low	1000 to 2000	Low w/c ratio (<0.4) conventional PC concrete
Very low	100 to 1000	Latex modified concrete, internally sealed concrete
Negligible	<100	Polymer impregnated concrete, polymer concrete

TABLE 5: Rating of chloride permeability of concrete according to the RCPT

Refer to [30]. RCPT, Rapid Chloride Permeability Test

Thermal conductivity of CSC

According to ASTM C177-04 [27], thermal conductivity is the phenomenon that characterizes the heat flow through concrete materials. CSC has thermal conductivity, which ranges from 0.61 to 0.68 W/mK, as shown in Figure *12*. These values are within the acceptable range of 0.05 to 0.69 W/mK for LWC and less than 0.76 to 3.68 W/mK for normal-weight concrete [35]. As seen in Figure *12*, the control CSC had the highest thermal conductivity. The absence of mineral additives in CSC results in higher thermal conductivity due to the presence of pores, which contribute to the flow of moisture and elevate thermal conductivity [36]. In addition, the thermal conductivity of CSC increases as cement content increases.

The thermal conductivity of CSC without any mineral additives was higher, as indicated in Figure *12*. The graph showed a significant decrease as the amount of FA increased. It is also evident that CSC with FA and SF decreased the thermal conductivity. In the absence of mineral additions, CSC has a thermal conductivity of 0.68 W/mK. This number declined relative to the control specimens by 5.15% and 10.15% for 5% and 10% FA replacement, respectively. Similarly, the thermal conductivity decreased by 2.65% and 8.38%, respectively, when 5% and 10% SF were introduced.

Heat conductivity and compressive strength of CSC are related, as illustrated in Table *6*. It reveals that the thermal conductivity of CSC decreases with an increasing quantity of FA and SF. The low density and amorphous structure of mineral admixtures are partly responsible for this decrease in heat conductivity. Saygili and Baykal [37] indicated that the thermal conductivity of amorphous silica is 1/15 times that of crystalline silica; thus, it is anticipated that concrete containing amorphous silica will have lower heat conductivity. Compared to SF, FA had a greater impact on CSC's thermal conductivity at 5% and 10% substitution levels. CSC containing 10% FA (0.61 W/mK) had a thermal conductivity similar to that of OPSC (0.59 W/mK), which utilized FA at 5% and SF at 10% as a binding agent [35]. Lightweight CSC with low thermal conductivity results in excellent insulation, reducing energy consumption and contributing to a more sustainable environment.

FIGURE 12: Effect of mineral admixtures on thermal conductivity of CSC

CSC, coconut shell concrete

Mix	Thermal conductivity (W/mK)	Density (kg/m^3) [21]
L_1	0.68	1948
L_2	0.645	1934
L_3	0.611	1917
L_4	0.662	1938
L_5	0.623	1924

TABLE 6: Relation between thermal conductivity and density

The temperature of the concrete has a considerable effect on its density (ρ), as illustrated in Figure *13*. A clear relationship is observed, indicating that with the decrease in CSC density, its thermal conductivity also decreases. Specifically, the highest coefficient of thermal conductivity (k) recorded among the mineral admixtures was 0.662 W/mK, observed in CSC containing 5% SF with a density of 1938 kg/m^3. This is approximately 7.7% greater than its lowest k value of 0.611 W/mK, which was obtained with CSC containing 10% FA and a density of 1917 kg/m^3. Without replacement, CSC exhibited the highest density, 1948 kg/m^3, and k-value 0.68 W/mK. Equation (7) was derived from the experimental data to predict the thermal conductivity of CSC from its density, and a polynomial pattern was found between thermal conductivity and density. The coefficient of regression (R^2) value from Figure *13* was 98.77%, derived with the help of Equation (7), which indicates an accurate prediction of the value k.

$$k = 5e^{-06}\rho^2 - 0.0612\rho + 14.038 R^2 = 0.9877 \quad (7)$$

FIGURE 13: Relationship between density and thermal conductivity of CSC

CSC, coconut shell concrete

Temperature resistance of CSC

Figure *14a* shows the residual compressive strength of CSC containing FA. It illustrates a decline in compressive strength as the temperature rises. When exposed to 100°C, CSC with 0%, 5%, and 10% FA had residual strength of 79%, 82%, and 85%, respectively. These values have decreased by 15-21% compared to room temperature (28°C). At 200°C, CSC without FA had a residual strength of 68%. With 5% and 10% FA, the residual strength of CSC was 70% and 73%, respectively. These data indicate that at 100°C and 200°C, FA at 10% in CSC performed more effectively than CSC without FA. The residual strength of CSC with 0%, 5%, and 10% FA, when exposed to 300°C, was found to be 49%, 45%, and 50%, respectively. These values show a decrease of 50-55% in compressive strength of CSC at room temperature. The strength of CSC containing 10% FA at 300°C was found to be higher by 1% and 5%, as compared to CSC containing 0% and 5% FA, respectively. The residual strength of the FA mix, when exposed to 400°C, was 30%, 31%, and 38%, respectively, for 0%, 5%, and 10% replacements. Compared to ambient temperature, these values are lower by 62-70% and lower than at 300°C by 12-19%. As per Figure *14a*, when exposed to 500°C, CSC with 0%, 5%, and 10% FA had residual strengths of 22%, 18%, and 24%, respectively.

Concrete generally undergoes changes in the microstructure, leading to the decline of compressive strength when subjected to temperature. In CSC with FA, the loss of strength at temperatures of 100°C and 200°C may be related to the loss of free and fractional water from concrete. Further heating to 300°C decreased the strength of CSC. Increased strength loss at about 400°C is attributed to the breakdown of products of hydration like C-S-H gel and $Ca(OH)_2$ and/or a combination of both. However, this breakdown is absent at temperatures lower than 350°C. At approximately 500°C, it was observed that all the mixtures underwent almost complete dehydration. The decreased compressive strength with temperature increase indicates the formation of both macro and microcracks on the lightweight CSC.

It is also observed that when the content of FA increased, the residual compressive strength also increased at all temperatures. It emerged that 10% FA had a residual strength higher than that of 5% FA. This is because the addition of FA helps to mitigate the adverse effects of $Ca(OH)_2$. Through pozzolanic interaction, reactive SiO_2 from FA reduces $Ca(OH)_2$. Similar results were also highlighted in the fire resistance of FA in pumice LWC by Aydin and Baradan [38]. The image of the CSC specimen without FA after being exposed to 500°C can be seen in Figure *15a*. Figure *15b* and c depict the external appearance of CSC with FA after exposure to 500°C, supporting the conclusion that the CSC containing 10% FA suffered significantly less damage than any other mixture.

FIGURE 14: Effect of FA and SF on residual compressive strength after fire

FA, fly ash; SF, silica fume

FIGURE 15: Specimens after 500°C fire exposure: (a) CSC, (b) CSC with 5% SF, (c) CSC with 10% SF, (d) CSC with 5% FA, (e) CSC with 10% FA

CSC, coconut shell concrete; FA, fly ash; SF, silica fume

The illustrated Figure *14b* shows the amount of SF used in CSC and the residual compressive strength of CSC following exposure to fire. At room temperature, the addition of 5% and 10% SF exhibited improved compressive strength by 9% and 19%, respectively. This increase was attributed to the filling effect of small SF particles and the increased formation of C-S-H due to the interaction between SF and $Ca(OH)_2$. The exposure of CSC to 100°C resulted in a significant decrease in strength, as shown in Figure *15b*. At 100°C, CSC with SF at 0%, 5%, and 10% had residual strength of 79%, 80%, and 83%, respectively. These values indicate a strength loss of 17-21% compared to room temperature. CSC at 200°C, containing 0%, 5%, and 10% SF, had residual strength of 68%, 71%, and 75%, respectively. These values indicate a decrease by 8-11% in comparison with 100°C, respectively. The residual compressive strength of CSC was impacted by the presence of SF at 300°C. At 300°C, the strength with 0% SF was 49%, with 5% SF was 47%, and with 10% SF was 43%, with a strength loss of approximately 51-57% that at room temperature. At 400°C, the residual strengths are 30%, 27%, and 25%, respectively, of the initial strength. These values are 70-75% less than the room temperature, and 18-20% less than at 300°C. CSC with 0%, 5%, and 10% SF at 500°C had residual compressive strength of 22%, 16%, and 15%, respectively. At 500°C, 5% and 10% SF in CSC had 6% and 7% less strength than CSC without SF.

CSC with SF exhibited a decrease in strength at 100°C and 200°C, which may be due to the elimination of water, leading to increased stresses between gel particles. It was observed that at 10% substitution of SF, the residual strength increased than the control concrete without SF. The difference in strength between the two may be due to the fine SF particles filling the microholes, creating a thick structure and preventing the removal of free water. At 300°C, the decrease in strength is due to the development of a dense microstructure, which led to a rise in internal pressure from the transition of interlayer water to water vapor. The loss of strength with 10% SF was significantly higher at elevated temperatures of 400°C and 500°C. This resulted from forming a denser transition zone linking the aggregate with the cement paste that was created with a high quantity of SF. At high temperatures, the shrinkage of cement paste and the expansion of aggregate cause increasing stress along the transition zone. This weakens the aggregate and SF paste adhesion, leading to the chemical decomposition of the hydration products and significant degradation and loss of strength. Thus, the rate of strength loss is higher in SF than in OPC. CSC with 5% SF had more residual compressive strength than CSC with 10% SF, as shown in Figure *15b*. The SF content had no appreciable impact on the residual strength at 100°C and 200°C. However, the SF content had a substantial impact on the residual strength with higher temperatures of 400°C and 500°C, with the strength of CSC containing 10% SF being 2% and 1% lower compared to that of CSC with 5% SF. Data suggest that 5% SF was less degraded than 10% SF. The image of CSC with SF after being exposed to 500°C can be seen in Figure *15d* and e.

The fire resistance that increases under unforeseen circumstances is limited to an average of 150°C or a maximum of 180°C, according to the NBC 2005 [39]. After 2 hours at 100°C, CSC containing 10% FA had a residual strength of approximately 17.1 N/mm^2. Conversely, after 2 hours, the residual strength at 100°C was 18.8 N/mm^2 and at 200°C was 17 N/mm^2, for CSC with 10% SF. The aforementioned values comply with the ASTM C330-05 [40] standards for structural LWC, which dictate an acceptable compressive strength of over 17 N/mm^2 following 28 days. Thus, SF at 10% substitution in CSC is capable of offering fire resistance for 2 hours, and in accordance with NBC 2005 [39], it can be designated as a Type Three building material.

Conclusions

This paper tested some durability parameters of CSC incorporating FA and SF at 5% and 10% substitution levels for cement. The following conclusions have been drawn from the investigation.

a. The water permeability coefficient of CSC with 10% SF showed 48% lower water permeability than that of CSC without admixtures. The corresponding depth of penetration was 0.09.

b. The sorptivity coefficient of CSC with mineral admixtures was within the accepted quality threshold.

c. The charge transferred through CSC with mineral admixtures ranged from 1160 to 1640 Coulombs, indicating low chloride ion permeability.

d. The thermal conductivity in CSC ranged from 0.61 to 0.68 W/mK, with FA having a greater impact on thermal conductivity compared to SF.

e. CSC with 10% SF had a temperature resistance of 2 hours and maintained a residual strength of 18.81 N/mm^2. Hence, this concrete can be classified as a Type Three building material according to NBC standards.

The results show that lightweight CSC with mineral admixtures FA and SF can be used in concrete to provide sustainability and durability for its practical application. However, there are certain limitations. Adding mineral admixtures may cause agglomeration if not well dispersed in concrete. This might lead to uneven pore structure, resulting in increased permeability. Permeability and thermal conductivity become less if CSC has a weak interfacial transition zone. The residual strength of concrete decreases if the CSAs get charred and thermal cracks develop at high temperatures. Furthermore, there is a risk of concrete spalling if water vapor becomes trapped in the refined pores developed by the addition of mineral admixtures.

The results reflect only the short-term durability properties of CSC with mineral admixtures. However, long-term durability studies such as creep, shrinkage, chloride diffusion, carbonation, and corrosion monitoring are needed for its practical application.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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References

1. Gunasekaran K, Kumar PS, Lakshmipathy M: Mechanical and bond properties of coconut shell concrete. Construction and Building Materials. 2011, 25:92-98. 10.1016/j.conbuildmat.2010.06.053
2. Prakash R, Thenmozhi R, Raman SN, Subramanian C, Divyah N: An investigation of key mechanical and durability properties of coconut shell concrete with partial replacement of fly ash. Structural Concrete. 2021, 22: E985-E996. 10.1002/suco.201900162
3. Prithika AJ, Sekar SK: Mechanical and fracture characteristics of eco-friendly concrete produced using coconut shell, ground granulated blast furnace slag and manufactured sand. Construction and Building Materials. 2016, 103:1-7. 10.1016/j.conbuildmat.2015.11.035
4. Coconut industry and exports. Accessed: November 24, 2024: https://www.indiantradeportal.in/vs.jsp?lang=0&id=0,31,24100,29378.
5. Rodriguez NJ, Limon MY, Miceli FAG, Guzman OG, Ortiz TPM, Rivera LL, Feijoo JAV: Assessment of coconut fibre insulation characteristics and its use to modulate temperatures in concrete slabs with the aid of a finite element methodology. Energy and Buildings. 2011, 43:1264-272. 10.1016/j.enbuild.2011.01.005
6. Mehta KP: Reducing the environmental impact of concrete. Concrete International. 2001, 23:61-66.
7. Meddah MS, Tagnit-Hamou A: Pore structure of concrete with mineral admixtures and its effect on self-desiccation shrinkage. ACI Materials Journal. 2009, 106:241-50.
8. Ayub T, Shafiq N, Khan SU, Nuruddin M: Durability of concrete with different mineral admixtures: a review. International Journal of Civil Science and Engineering. 2013, 7:273-84.
9. Supit SWM, Shaikh FUA: Durability properties of high volume fly ash concrete containing nano-silica. Materials and Structures. 2014, 48:2431-445. 10.1617/s11527-014-0329-0
10. Cheng A, Huang R, Wu JK, Chen CH: Influence of GGBS on durability and corrosion behavior of reinforced concrete. Materials Chemistry and Physics. 2005, 93:404-11.
11. Keck RH, Riggs EH: Specifying fly ash for durable concrete. Concrete International. 1997, 19:35-38.
12. Gunasekaran K, Annadurai R, Kumar PS: A study on some durability properties of coconut shell aggregate concrete. Materials and Structures. 2013, 48:1253-264. 10.1617/s11527-013-0230-2
13. Sekar A, Kandasamy G: Study on durability properties of coconut shell concrete with coconut fiber. Buildings. 2019, 9:107. 10.3390/buildings9050107
14. Nadir Y, Sujatha A: Durability properties of coconut shell aggregate concrete. KSCE Journal of Civil Engineering. 2018, 22:1920-926. 10.1007/s12205-017-0063-6
15. Palanisamy M, Kolandasamy P, Awoyera P, Gobinath R, Muthusamy S, Krishnasamy TR, Viloria A: Permeability properties of lightweight self-consolidating concrete made with coconut shell aggregate. Journal of Materials Research and Technology. 2020, 9:3547-557. 10.1016/j.jmrt.2020.01.092
16. Thilagashanthi T, Gunasekaran K, Satyanarayanan KS: Durability properties of treated coconut shell-used concrete for sustainability. Innovative Infrastructure Solutions. 2023, 8:244. 10.1007/s41062-023-01211-9
17. Sengul O, Azizi S, Karaosmanoglu F, Tasdemir MA: Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete. Energy and Buildings. 2011, 43:671-76. 10.1016/j.enbuild.2010.11.008
18. ASTM C150-12: Standard specification for Portland cement. Annual book of ASTM standards, USA; 2012.
19. ASTM C618-12: Standard Specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. Annual book of ASTM standards, USA; 2012.
20. ASTM C1240-04: Standard specification for silica fume used in cementitious mixtures. Annual book of ASTM standards, USA; 2004.
21. Regin JJ, Vincent P, Ganapathy C: Effect of mineral admixtures on mechanical properties and chemical resistance of lightweight coconut shell concrete. Arabian Journal for Science and Engineering. 2017, 42:957-71. 10.1007/s13369-016-2240-1
22. Aziz W, Aslam M, Ejaz MF, Ali MJ, Ahmad R, Raza MWUH, Khan A: Mechanical properties, drying shrinkage and structural performance of coconut shell lightweight concrete. Structures. 2022, 35:26-35. 10.1016/j.istruc.2021.10.092
23. Short A, Kinniburgh W: Lightweight Concrete. 3rd Edition. Applied Science Publishers limited, London, England; 1978.
24. IS 3085: Method of test for permeability of cement mortar and concrete. BIS, New Delhi, India; 1965.
25. ASTM C1585-04: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. Annual book of ASTM standards, USA; 2004.
26. ASTM C1202-19: Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. Annual book of ASTM standards, USA; 2019.
27. ASTM C177-04: Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded hot plate apparatus. Annual book of ASTM standards, USA; 2004.
28. Saloni, Singh A, Jatin, Kumar J, Parveen: Influence of fly ash, cement and ground river sand on compressive strength and chloride penetration of mortar. Materials Today: Proceedings. 2020, 33:1690-694. 10.1016/j.matpr.2020.07.269
29. Mo KH, Alengaram UJ, Jumaat MZ, Liu MYJ, Lim J: Assessing some durability properties of sustainable lightweight oil palm shell concrete incorporating slag and manufactured sand. Journal of Cleaner Production. 2016, 112:763-70. 10.1016/j.jclepro.2015.06.122
30. Gunasekaran K, Annadurai R, Kumar PS: Long term study on compressive and bond strength of coconut shell aggregate concrete. Construction and Building Materials. 2012, 28:208-15. 10.1016/j.conbuildmat.2011.08.072
31. EuroLightCon: Properties of LWC Containing Lytag and Liapor, European Union-Brite Eu Ram III BE96-3942/R8. 2000. https://www.researchgate.net/publication/339460461_LWAC_Material_Properties_-_State-of-the-Art.
32. Teo DCL, Mannan MA, Kurian VJ: Durability of lightweight OPS concrete under different curing conditions. Materials and Structures. 2010, 43:1-13. 10.1617/s11527-008-9466-7
33. Tasdemir C: Combined effects of mineral admixtures and curing conditions on the sorptivity coefficient of concrete. Cement and Concrete Research. 2003, 33:1637-642. 10.1016/s0008-8846(03)00112-1
34. Chia KS, Zhang MH: Water permeability and chloride penetrability of high-strength lightweight aggregate

concrete. Cement and Concrete Research. 2002, 32:639-45. 10.1016/s0008-8846(01)00738-4

35. Alengaram UJ, Al-Muhit BA, bin Jumaat MZ, Jing MLY: A comparison of the thermal conductivity of oil palm shell foamed concrete with conventional materials. Materials & Design. 2013, 51:522-29. 10.1016/j.matdes.2013.04.078
36. Liu MYJ, Alengaram UJ, Jumaat MZ, Mo KH: Evaluation of thermal conductivity, mechanical and transport properties of lightweight aggregate foamed geopolymer concrete. Energy and Buildings. 2014, 72:238-45. 10.1016/j.enbuild.2013.12.029
37. Saygili A, Baykal G: A new method for improving the thermal insulation properties of fly ash. Energy and Buildings. 2011, 43:3236-242. 10.1016/j.enbuild.2011.08.024
38. Aydin S, Baradan B: Effect of pumice and fly ash incorporation on high temperature resistance of cement based mortars. Cement and Concrete Research. 2007, 37:988-95. 10.1016/j.cemconres.2007.02.005
39. National Building Code (NBC): BIS, Manak Bhavan. New Delhi, India; 2005.
40. ASTM C330-05: Standard Specifications for Lightweight Aggregates for Structural Concrete. Annual book of ASTM standards, USA; 2005.