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Assessing the Durability, Mechanical, and Microstructural Properties of Nanosilica-enhanced Coconut Shell Concrete: A Sustainable Approach

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ABSTRACT

This study explores the properties of concrete as a sustainable substitute for cement through the use of nanosilica in an eco-friendly aggregate system. Daily life generates a larger amount of coconut shell waste from the tropical zone. In India, the yearly deposition of coconut shell is about 80,000 tonnes, which is 6.7% of total agricultural waste. Crushing gravel production emits CO_2, which is an environmental concern. Simultaneously, to diminish waste disposal of coconut shell can be effectively utilised as coarse aggregate in lightweight concrete. The conventional concrete (CC) was fully replaced by coconut shell coarse aggregate and crushed gravel sand (Msand) as fine aggregate in plain Portland cement. Nanosilica replaces cement in the conventional blend at 0%, 1%, 2%, 3%, and 4%. This study describes the concrete's hardened properties, such as compressive strength, splitting tensile strength, and flexural strength. Among all the mechanical performances, the N2 blend is significant. The N2 mix exhibits a trend that aligns with the correlation between compressive strength and splitting tensile strength. The transport durability performance related to capillary wick action of the optimum blend (N2 mix) has 0.018 mm/min 0.5. The pore filler mechanism and pozzolanicity of 2% NS is more synergic than other combinations. The N2 mix in H_2SO_4 environment has less mass and strength loss. The N2 blend's morphology is robust relative to the CC mix because of the secondary C-S-H gel and homogeneous, smooth hydrated grain. As a result, the report concludes that using coconut shell as an aggregate in concrete can reduce waste disposal in landfills, while using nanosilica in place of cement can reduce CO_2 emissions.

Keywords: Nanosilica; Coconut shell; Morphology; Durability.

1. INTRODUCTION

Concrete is the most widely commonly utilized material in construction around the world (Tam *et al.* 2018). Efforts to reduce its weight have become a major focus in academia, presenting scientists and engineers with complex challenges. The primary goal is to reduce the density of concrete without compromising its strength or increasing costs (Amran *et al.* 2023). One common method is to introduce new aggregates into the mix design. Traditional concrete is composed of four primary elements: cement, crushed stone, river sand, and water. To reduce the weight of concrete, lightweight aggregates—either natural or synthetic—can be utilized in place of traditional components, or air can be incorporated into the mixture. Frequently employed lightweight aggregates consist of pumice, expanded clay, perlite, vermiculite, sintered fly ash, coal slag, straw, rice husk, coconut shell, oil palm shell, wheat husk, cork granules, and sawdust. These materials have been thoroughly researched and documented. India produces around 960 million tonnes of solid waste each year, originating from municipal, mining, industrial, agricultural, and various other activities. (Pappu *et al.* 2007). Of this, 350 million tonnes come from organic agricultural waste, while 290 million tonnes are inorganic waste from industrial and mining sectors. Agricultural sources alone produce around 600 million tonnes of waste (Koul *et al.* 2022). This encompasses sugarcane bagasse, agricultural residues, food items, straw and husk from paddy and wheat, by-products from oil production, tea leaves, jute fibers, groundnut shells, and waste from wood milling, coconut husks, and cotton stalks. (Hiloidhari *et al.* 2020). Utilizing agro-industrial wastes for creating innovative building materials offers significant potential for introducing cost-effective building components. Coconut shell, classified as an agricultural solid waste, is a promising alternative as a coarse aggregate in the production of concrete, especially in regions where aggregates are expensive (He *et al.* 2020; Chinnu *et al.* 2021). India is a leading coconut producer, accounting for about 27% of global production, with an annual yield exceeding 12 million tonnes. The rapid increase in waste production is driven by factors such as population growth, industrial and technological development, and societal advancement. Effective waste management strategies are increasingly necessary due to the growing volume of waste materials generated each year. Using alternative aggregates in construction offers economic, environmental, and technological benefits (Zhang *et al.* 2019).

The substantial price of traditional building materials represents a major challenge for housing development in India. In developing countries that generate significant agricultural and industrial waste, these by-products can be utilized as alternative construction materials, which not only reduce expenses but also address the waste disposal issues. This approach is both practical and valuable (Abdel-Shafy *et al.* 2018; Koul *et al.* 2022). Incorporating Nano-sized additives in concrete accelerates hydration, improving mechanical properties (Rahman *et al.* 2022). These nanoparticles can be generated through processes such as volcanic eruptions, mining, quarrying, and industrial waste. Typically measuring between 1 nm and 100 nm, these particles enhance concrete's strength, durability, and sustainability (Paul *et al.* 2018). Nanoparticles, such as TiO_2, Al_2O_3, ZnO, Fe_2O_3, and SiO_2, are often used to study concrete properties. Nano SiO_2, in particular, has shown exceptional compressive strength (Huseien *et al.* 2023). Nanosilica (NS) extends hydration by forming additional calcium silicate hydrates (C-S-H) through its high specific surface area-to-volume ratio.

Adding up to 3% nanosilica by cement weight enhances the pozzolanic reaction, resulting in a denser interfacial transition zone (ITZ) and decreased water absorption (Vivek *et al.* 2021). NS improves the cement matrix's toughness and increases strain in the maximum tensile stress region by up to 3%. Using a super plasticizer helps control the water-cement ratio in NS concrete, though the high surface area of NS increases water demand (Paul *et al.* 2018; Huseien *et al.* 2023). The 1% nanosilica of powdered form along the cement accelerates the hydration at early days (3 to 7 days). Nevertheless, the secondary C-S-H is formed by nanosilica addition to form dense microstructure and refines ITZ. The gel and capillary pore of the hydrated grains are arrested and accelerates the longevity, mechanical performance in concrete (Manigandan *et al.* 2024). This study focuses on the mechanical characteristics such as compressive strength, splitting tensile strength, and flexural strength, as well as the durability properties, including sorptivity, and acid resistance, of coconut shell concrete. The use of nanosilica in this type of concrete has not been previously explored by researchers. Therefore, the findings of this study contribute to environmental sustainability and offer eco-friendly solutions.

2. Material Properties and Mix Proportion

The 53 grade Ordinary Portland cement (OPC) used in this experimental work. The coconut shells were collected from the canteens inside the college campus. Nanosilica was purchased from the laboratory of size 10-20 nm and containing the SiO_2 of above 95%. Physico-chemical properties of the Nanosilica and cement were listed in the table Fig. 1 demonstrates the SEM, EDS mapping, elemental analysis, and TEM image of nanosilica. Fig. 1a) shows the cluster of spherical nanosilica but the particle size cant able to find at the micro scale of 2 µm. The Fig. 1b) demonstrates mapping of Si and O elements. The green colour represents the Silica and red colour element represents the Oxygen. Fig. 1c) illustrates the Si-O element are predominant from the EDS report.

Table 1. Properties of cement and Nanosilica

Properties	Cement (%)	Nanosilica (%)
Density	-	<0.16 g/cm^3
Particle size	< 7 nm	15 nm
Specific gravity	2.81	2.3-2.7
Loss of ignition	2.5	-
Surface area (m^2/g)	2385	160
CaO	63.6	-
MgO	2	-
MnO	-	-
P_2O_5	-	-
SO_3	2.5	-
Na_2O	-	-
SiO_2	20.3	99
Fe_2O_3	2.8	-
Al_2O_3	4.8	-
TiO_2	-	-
K_2O	-	-

Table 2. Properties of the Aggregates

Properties	CSA (12.5 mm)	Msand (<4.75 mm)
Water absorption (%)	15.2	2.5
Specific gravity	1.45	2.58
Size (mm)	12.5	<4.75
Bulk density (kg/m^3)	701.80	15.3
Crushing value (%)	2.6	20
Fineness modulus	3.21	2.63
Impact value (%)	5.62	-
Flakiness index (%)	16	-
Thickness (mm)	10	4.75

Transmission Electron Microscope (TEM) image (Fig. 1d)) of nanosilica at 20 nm scale. There are no any stripes and fringes present in the nanosilica are noted and average size is 15 nm. Locally available crushed gravel sand (Msand) is used in the place of conventional aggregate due to the scarcity of Virgin river bed sand. The properties of the aggregates, coconut shell aggregates (CSA) and Msand were listed in the Table 2. The M20 grade of concrete was prepared using the mix proportion detailed in Table 3. Super plasticizer of chloride free sulphonated naphthalene polymers is utilized at 1% of weight of cement to maintain the workability of the concrete. The Mix proportion of the concrete specimen was listed in the Table 3.

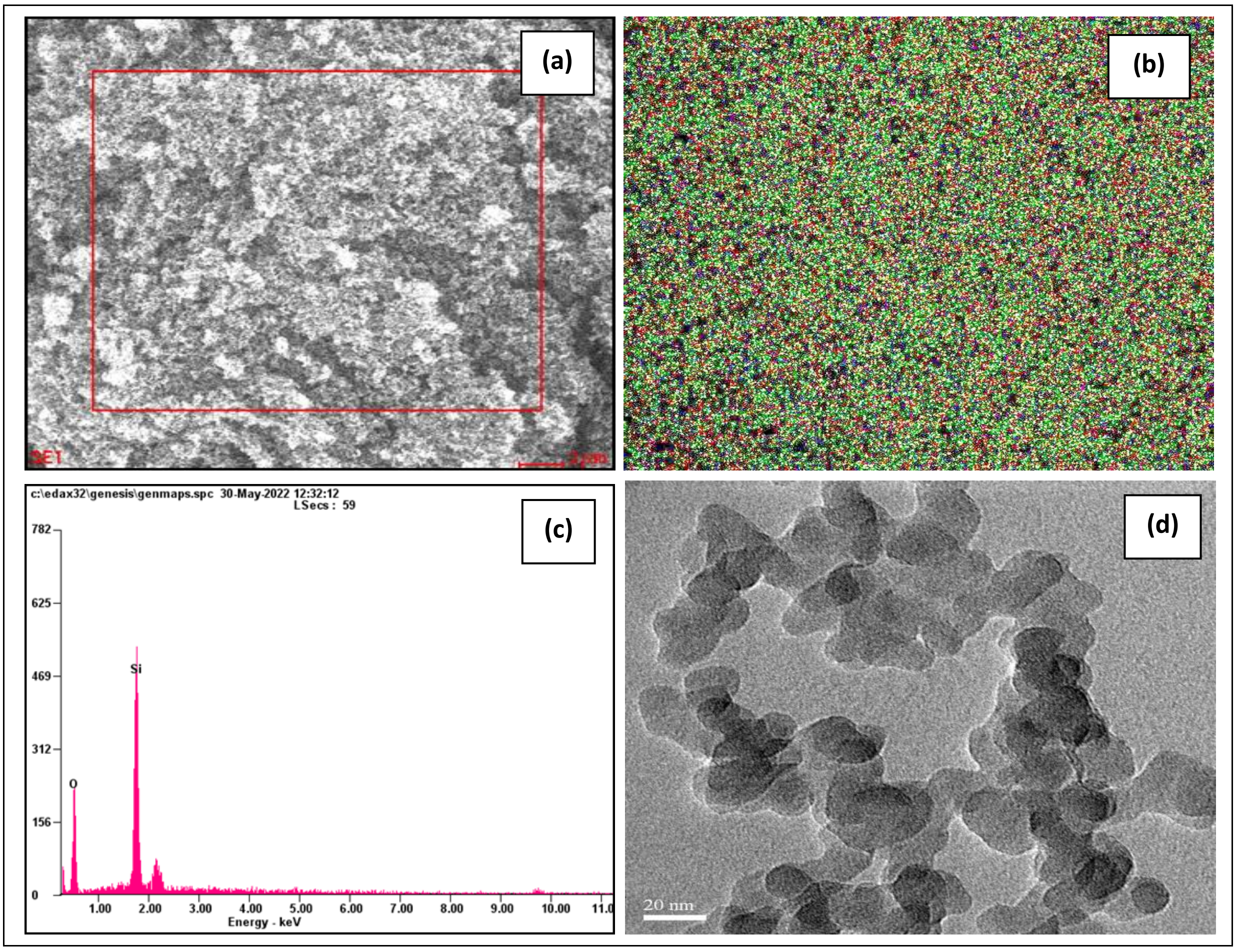

Fig. 1: (a) SEM image (scale 2 µm), (b) Elemental Mapping (Green-Si; Red-O), (c) EDS, (d) TEM image (scale 20 nm)

Table 3. Mix proportion of light weight concrete – M20 grade

Mix ID	Cement (kg/m^3)	Nanosilica (%)	Nanosilica (kg/m^3)	Msand (kg/m^3)	Coconut shell aggregate (CSA) (kg/m^3)	W/C
CC	510	-	-	816	331.5	0.42
N1	504.9	1%	5.1	816	331.5	0.42
N2	499.8	2%	10.2	816	331.5	0.42
N3	494.7	3%	15.3	816	331.5	0.42
N4	489.6	4%	20.4	816	331.5	0.42

Following the thorough mixing of all components, the concrete is introduced into molds in three separate layers. Each layer is compacted by delivering 25 blows with a tamping rod to ensure the removal of air voids. The molds, once filled, are allowed to remain undisturbed for 24 hours to enable the concrete to set properly. In this research, the molds employed consisted of a 10 cm³ cube, a cylinder with a diameter of 10 cm and a height of 20 cm, and a prism measuring 10 cm x 10 cm x 50 cm. After the initial 24-hour period, the concrete specimens are demoulded and placed into a curing tank for 3, 7, and 28 days. The curing tank's temperature is kept at a stable 27±2 °C throughout the curing duration.

3. TESTING METHODS

After thoroughly mixing all components, the concrete is poured into molds in three distinct layers. Each layer is compacted by applying 25 blows with a tamping rod to eliminate any air voids. Once the molds are filled, they are left undisturbed for a period of 24 hours to allow the concrete to set adequately. In this study, the molds used included a cube measuring 10 cm³, a cylinder with a diameter of 10 cm and a height of 20 cm, and a prism with dimensions of 10 cm x 10 cm x 50 cm. Following the initial 24-hour setting period, the concrete specimens are removed from the molds and placed in a curing tank for durations of 3, 7, and 28 days.

The temperature of the curing tank is maintained at a consistent 27±2 °C throughout the entire curing process.

4. RESULTS AND DISCUSSION

4.1 Mechanical Properties

After the completion of 3, 7, 28 days of curing for concretes, the test for the estimation of their compressive strength was conducted for all the concrete mixture proportions (Fig. 2). The results indicate that the compressive strength of conventional concrete (CC) is measured at 28.9 MPa. With the incorporation of 1% Nano Silica (N1), the compressive strength rises to 29.38 MPa after 28 days of curing, reflecting an increase of 1.66%. Further enhancing the CC, the introduction of 2% Nano Silica (N2) elevates the compressive strength to 31.75 MPa, marking a significant increase of 9.86%. However, increasing the concentration of Nano Silica beyond this point does not significantly contribute to further strength gains. In an extended analysis, the addition of 3% Nano Silica (N3) results in a compressive strength of 30.42 MPa, corresponding to a 5.26% increase, while 4% Nano Silica (N4) yields a compressive strength of 29.78 MPa, with a 3.04% increase.

Ultimately, the findings suggest that 2% Nano Silica (N2) provides the optimal strength enhancement for the concrete. Additionally, substituting 2% of the cement with Nano Silica and replacing 25% of the natural aggregate with coarse coal gangue aggregate results in an improved strength of 33.15 MPa. (Al Khazaleh *et al.* 2023). The existence of unreacted silica in place of cement contributes to the development of a weak zone, which ultimately diminishes compressive strength. Additionally, the larger surface area of unreacted silica enhances water absorption, facilitating the formation of Si-OH bonds and accelerating the hydration process. (Manigandan *et al.* 2024). This further decreased the feasibility. The splitting tensile strength of the concrete curing after 3, 7 and 28 days were tested and the results shown in the Fig. 3.

The presence of nanosilica in the coconut shell concrete gives higher strength compared to the CC. Results of CC, N1, N2, N3, and N4 were 2.89 MPa, 3.38 MPa, 4.11 MPa, 3.67 MPa and 3.35 MPa. There is an increase in the nanosilica in coconut shell concrete compared to CC. This is due to the better interlocking of ITZ with the aggregates and cement hydrates packing (Manigandan *et al.* 2020; Jagadisha *et al.* 2021). Therefore, the decrease in the splitting tensile strength is due to increase in nanosilica in the concrete gives lack of bonding between the cementitious material and coconut shell aggregates. The results of the splitting tensile strength test also indicate the significant influence of the aspect ratio (Seifan *et al.* 2020).

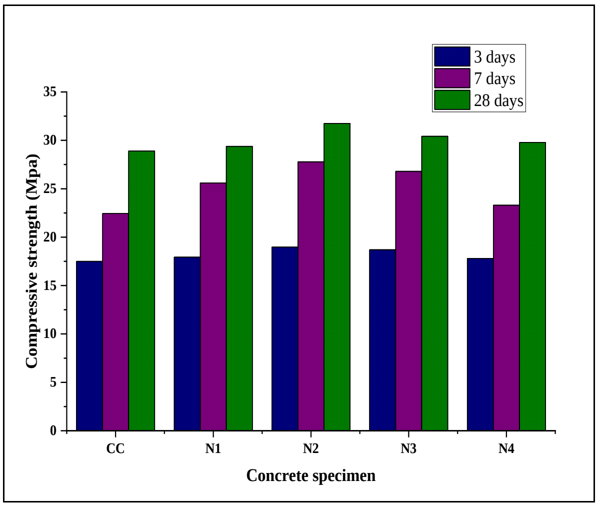

Fig. 2: Compressive Strength

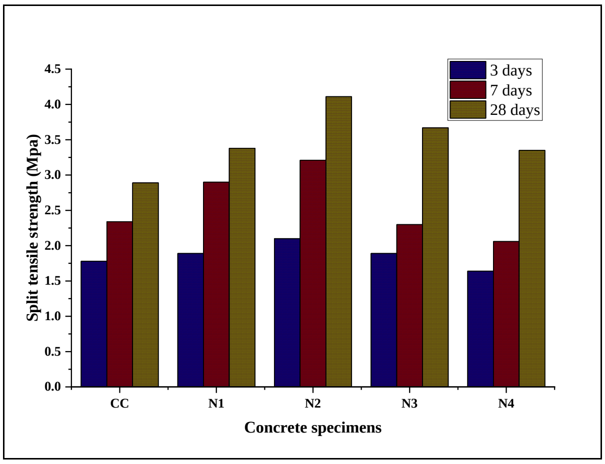

Fig. 3: Splitting Tensile Strength

The relationship between cube compressive strength and splitting tensile strength were plotted in the Figure 4 and the following equation (1) was obtained. The measured value of the splitting tensile strength was compared to the linear fitting equation (1). Also, the measured value is compared to the followings. A comparison result shows the analytical values are similar to the measured values.

$$f_t = -8.89766 + 0.41105 f_c \qquad \text{........ (1)}$$

Therefore, f_c and f_t are the compressive strength and splitting tensile strength are in MPa. The analytical values of compressive strength, derived from equation (1), were compared with the experimental values of splitting tensile strength across various mix proportions, as shown in Table 4. This table presents the measured values alongside the analytical values obtained from different formulas.

Figure 5 portrays the flexural strength of the concrete curing after 3, 7 and 28 days. The presence of nanosilica in the coconut shell concrete gives higher strength compared to the CC. Results of CC, N1, N2, N3, and N4 were 5.25 MPa, 5.32 MPa, 5.5 MPa, 5.38 MPa and 5.34 MPa respectively.

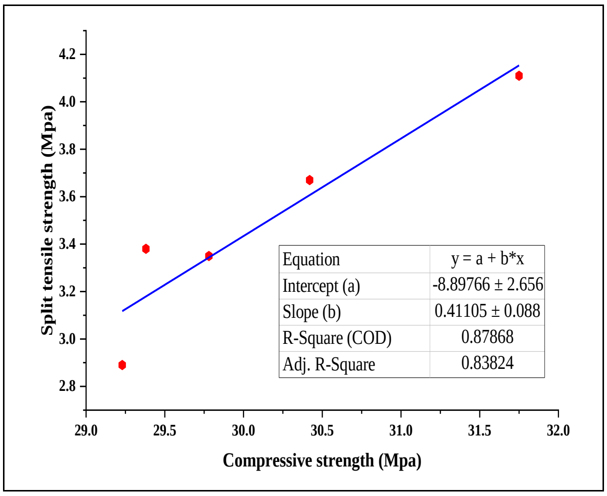

Fig. 4: Relationship between compressive strength test and splitting tensile strength

The results indicate that the incorporation of nanosilica up to 2% in coconut shell concrete yields a higher flexural strength compared to other mixtures. This observation supports the notion that a considerable degree of pozzolanic reactivity is achieved with the addition of 2% nanosilica to the coconut shell concrete formulation. However, when 3% nanosilica is added to the concrete mix, agglomeration occurs, leading to a reduction in the flexural properties of the prism. The synergistic effect of increased pozzolanic activity from nanosilica, along with improved bonding between the interfacial transition zone and aggregates, contributes to the enhanced flexural strength of the concrete. (Hakeem *et al.* 2023; Nagarajan *et al.* 2023). The hydration process experiences a delay when an increased quantity of nanosilica is incorporated. Specifically, the addition of 2% nanosilica along with 25% coarse coal gangue aggregate in concrete yields a flexural strength that is similar to that of conventional concrete (Al Khazaleh *et al.* 2023).

Table 4. Comparison of measured values and predicted values

Mix Id	Compressive strength (MPa)	Splitting tensile strength (MPa)				
		Measured value	Analytical value	(American Concrete Institute *et al.* 2014)	(CEB-FIB Model Code for Concrete Structures *et al.* 1991)	(Lavanya *et al.* 2015)
			f_t=-8.89766 + 0.41105 f_c	$f_t = 0.56\ f_c^{\ 0.5}$	$f_t = 0.3\ f_c^{\ 0.66}$	$f_t = 0.249\ f_c^{\ 0.772}$
CC	28.9	2.89	2.98	3.01	2.76	3.34
N1	29.38	3.38	3.18	3.04	2.79	3.38
N2	31.75	4.11	4.15	3.16	2.94	3.59
N3	30.42	3.67	3.61	3.09	2.86	3.48
N4	29.78	3.35	3.34	3.06	2.82	3.42

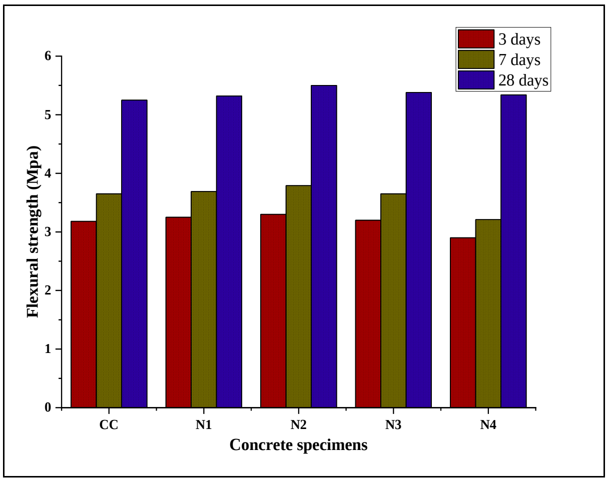

Fig. 5: Flexural Strength

4.2 Durability Properties

The test results of the sorptivity were shown in the Fig. 6. The sorptivity of the CC, N1, N2, N3 and N4 were 0.091, 0.067, 0.018, 0.054 and 0.075 mm/min$^{0.5}$ respectively. The test results indicate that the incorporation of Nano silica leads to a decrease in sorption, which suggests a reduction in the pore structure of the concrete. This finding demonstrates that the addition of Nano silica effectively diminishes sorption levels in concrete, thereby implying a decrease in its porosity. Notably, a substantial reduction in sorptivity of 48% was recorded when Nano silica was utilized as a partial replacement for cement at a concentration of up to 1% (Li *et al.* 2021). The improved aggregate interface zone, along with the internal curing properties of CS aggregate, resulted in a decrease in the sorptivity of the cured specimens in comparison to the uncured specimens. Therefore, to diminish the sorptivity of concrete, it is essential to adopt a suitable curing method. (Sekar *et al.* 2019). Therefore, the inclusion of 2% nanosilica in the coconut shell concrete shows decrease in sorption compared to other mixes.

The test focuses on finding the resistance of the concrete by dipping the concrete specimens in acid. Here, sulphuric acid solution was used. These test results were shown in the Fig. 7. Sulphuric acid, an inorganic acid, is naturally present in groundwater and soil. Its formation results from the oxidative weathering of specific sulphide minerals, such as iron disulphides and pyrites. To prepare a 5% solution, concentrated sulphuric acid at 98% concentration was used. In each test interval, the specimens were weighed and entirely submerged in the solution for the specified duration. During the testing procedure, the specimens were carefully extracted and rinsed with tap water. Any surface moisture was removed, and the specimens were permitted to air dry for 30 minutes. A visual assessment was performed to detect any colour changes, and the test solution was changed whenever a colour shift was noted.

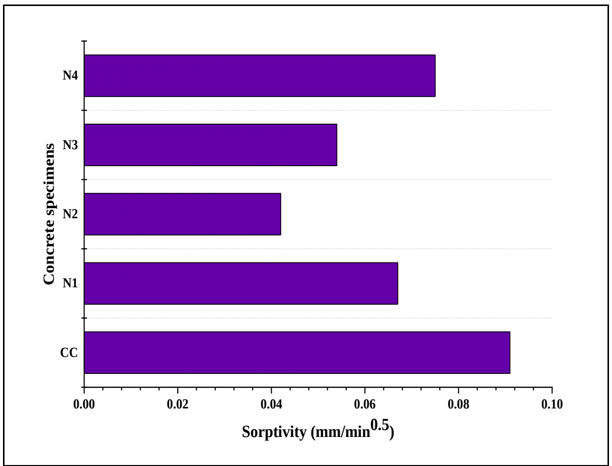

Fig. 6: Sorptivity Test

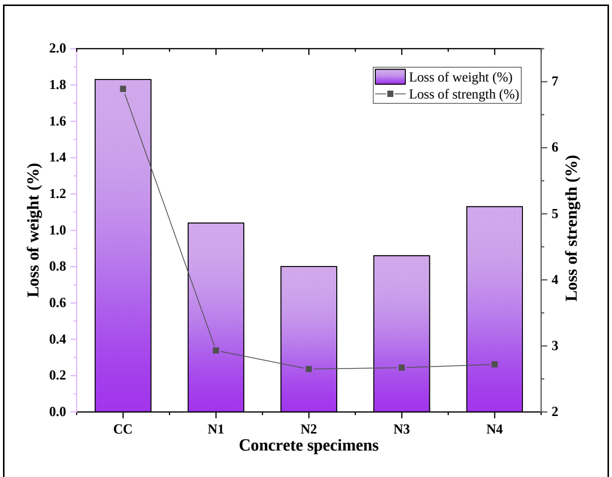

Fig. 7: Acid Resistance

The compressive strength was evaluated after 30 and 90 days of immersion, and the changes in compressive strength along with weight loss were computed. From the test results, it shows that there is an increase in acid attack except 2% of nano silica added coconut shell concrete. The incorporation of up to 2% nanosilica showed a notable improvement in resistance to acid attack when evaluated against traditional concrete and coconut shell concrete. However, when the nanosilica content exceeded 2%, a slight decrease in the rate of compressive strength loss was noted. The results indicated that the optimal dosage for enhancing resistance to acid attack was 2% of the cement weight. As observed in the compressive strength test, uneven distribution of nanosilica, excess unreacted nanosilica, or insufficient hydrated lime delays the hydration, and hence the strength loss occurs at higher dosages (Al Khazaleh *et al.* 2023).

4.3 Morphology of CC and N2 Mix

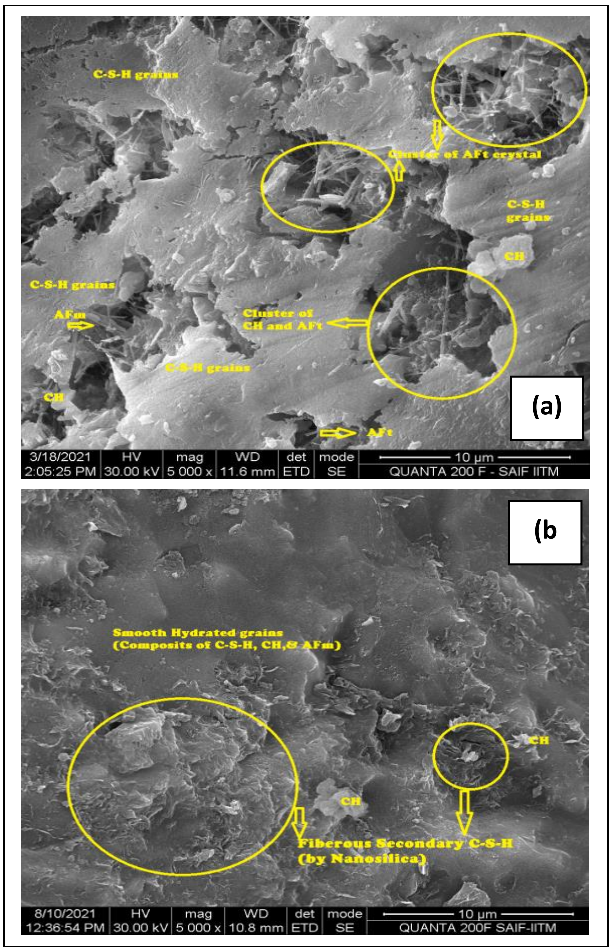

Fig. 8: (a) Morphology of Nanosilica Concrete (CC mix), (b) Morphology of Nanosilica Concrete (N2 mix)

Fig. 8 illustrates the morphology of the concrete, which was obtained from the 28-day water-cured specimen. The SEM image of concrete sample potrats the hydrated grains and curvature of the sample from the re-capturing of electrons. The CC mix has a calcium silicate hydrate (C-S-H) grains and calcium hydroxide or portlandite (CH). The circle parts of Fig. 8.a illustrates the needle form of ettringite (AFt) cluster are formed in combination with CH. Moreover, the monosulfo aluminate phsases (AFm) are in prismatic needle form is noted in the CC blend. Fig. 8.b demonstrats the optimum mix (N2) morphology based on the strength and durability performance. The N2 blend shows the fiberous structure of secondary C-S-H formed by the consumption of CH. Adding nanosilica of amorphous phase reacts with the portlandite to form secondary C-S-H gel. The smooth hrdrated grains repreştes the density of cement matrix esclates by combided action of C-S-H gel, CH, and other aluminate and ferrite phases. This homogenous morphology of concrete are behind the superior strength and longivity behaviour in 2% of nanosilica matrix.

4. CONCLUSION

The conclusions drawn from the inspection and finding are as follows:

- Compared to CC, N1, N3, and N4, the 98% cement with 2% nanosilica in the coconut shell aggregate system improves both mechanical and durability properties.

- Therefore, the strength due to axial compression and indirect tensile strength of the N2 mix is higher (i.e., 31.75 and 4.11 MPa) than all the combinations, respectively. The relationship between the compressive and splitting strengths confirms the findings with current data.

- The flexural performance of the N2 blend is 5.5 MPa, whereas the control concrete (CC) has 5.25 MPa. Nanosilica filler acts to bridge the bonding action between aggregates and the cement paste bleed channel.

- A 2% nanosilica content in the weight of cement, combined with coconut shell concrete, improves the resistance to capillary absorption more than CC and other nanosilica blends. Meso- and micro-capillary filler action of the N2 blend tends to minimize the sorptivity as 0.0018 mm/min 0.5. In an acidic (H_2SO_4) environment, the N2 mix has lower mass and strength losses of 0.8% and 2.65%, respectively.

- The CC mix's morphology includes C-S-H gel, Portlandite, a combination of Ettringite, and Afm phases. Whereas, the N2 blend demonstrates that homogenous and smooth hydrated grains with secondary C-S-H gel improve concrete's strength, longevity, and microstructural behaviour. The pozzolanic reaction and filler action of 2% nanosilica conclude significant in all properties in an eco-friendly coconut shell concrete.

- This innovative method employs coconut shells, often regarded as waste, to mitigate environmental pollution and alleviate the pressure on landfills. The use of coconut shells not only lessens dependence on conventional aggregates, thus preserving natural resources, but also minimizes the carbon footprint linked to the manufacturing and transportation of standard materials. Additionally, the process of creating coconut shell aggregate concrete demands less energy, resulting in reduced greenhouse gas emissions.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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