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Original Article

Assessing the Mechanical and Micro-Structural Properties of Concrete with Silica Fume and Coconut Shell as Partial Replacements of Cement and Fine Aggregates

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Abstract - *The construction industry is a globally important sector due to its significant contributions to growth and economic success. The operation of this industry incorporates concrete as one of its essential components. Additionally, expanding urban areas and developing rural areas are expected to increase demand for concrete. This increase in demand will negatively affect the environment through pollution or the lessening of natural resources. Therefore, it is essential to incorporate eco-friendly substitutes into the concrete manufacturing process. Regarding this, Coconut Shells (CS) have been a successful and widely used alternative material for lightweight concrete production. Nevertheless, it has been documented that using CS in concrete production causes a significant decline in concrete mechanical characteristics. In contrast, Silica Fume (SF) enhances concrete mechanical properties. Thus, this study incorporated silica fume as a CS concrete modifier. The aim was to produce sustainable, normal-strength concrete with reduced structural self-weight. To achieve this, CS partially replaces the fine aggregate at 0, 10, 20, and 30%, while SF partially replaces cement at 0, 5, 10, and 15%. The concrete properties were evaluated, including slump, density, compressive strength, flexural strength, tensile strength, scanning electron microscopy, and energy dispersion spectroscopy. The findings indicate that 10% is optimal for individual material replacements. Adding 10% SF to 10% CS concrete improved the compressive, tensile, and flexural strength by 30.87, 20.04, and 38.63%, respectively, and microstructural properties. The 10% CS-10% SF concrete yielded comparable qualities to conventional concrete, with an improved strength-to-weight ratio of 1.32%.*

Keywords - *Concrete, Coconut shell concrete, Silica fume concrete, Silica fume-coconut shell concrete, Coconut shell fine aggregate.*

1. Introduction

Population growth is a gradual process leading to an increasing demand for infrastructure. According to sources [1], the global populace is projected to grow by 25% from 7.8 billion to 9.9 billion by 2050. This expected growth in population might increase urbanisation and demand for building materials. Concrete has traditionally been a prevalent material in construction. Annually, the global production of concrete amounts to almost one cubic metre per capita [2]. The production of concrete incorporates the use of cement, fine and coarse aggregates, and water. Aspin created cement in 1842, and since the late 19th century, Portland cement has taken over as the predominant cementitious material [3]. Disadvantageously, cement production releases 8% of global carbon dioxide (CO_2) greenhouse emissions [4]

Next, aggregate is an essential concrete constituent, representing 70 to 80% of concrete volume [5]. The high extraction of aggregates for future usage in concrete results in substantial depletion of the earth's resources and pollution of the environment. Moreover, using river sand as fine aggregate leads to sand mining. This results in the expansion of water levels, erosion of closer areas, diminution of river banks, and deterioration of exposed structural elements. Hence, it is necessary to produce sustainable concrete that uses waste or alternative materials as aggregate and partially or entirely replaces cement and sand. This will aid in meeting future concrete demands while preserving natural resources and the environment.

Several agricultural and industrial waste materials have been introduced in studies as alternative materials in concrete production. These comprise Coconut Shells (CS) as agricultural waste and silica fumes as industrial residue. CS is a prospective candidate for partially replacing mineral components in concrete. These shells are agricultural waste generated from coconut fruits. Cultivation spans approximately 90 nations with a total land area of around 14.231 million hectares and yields approximately 11.04 million tonnes of coconuts [6]. Hence, [7] reported that thick coconut shells deteriorate after 100-200 years, which could lead to environmental issues when improperly disposed of. In addition, [8] further asserted that unprocessed coconut shells are disposed of or incinerated, leading to environmental contamination and inadequate hygiene. Therefore, reusing coconut shells has been considered a suitable waste management solution. Consequently, multiple research studies have been conducted to assess the suitability of coconut shells for concrete production [9]. They reported that utilising coconut shells as fine aggregates with a gradation of 1.18 to 4.75 mm decreases concrete density and compressive strength and reduces concrete costs. Similarly, [10] examined the prospect of replacing fine particles with coconut shell ash in concrete manufacturing. An inverse relationship between the dosage and the compressive strength of the concrete was observed. According to [11], utilising coconut shells as a substitution for coarse aggregates partially increases concrete workability and reduces density. The increase in workability enhances the concrete's ease of transportation, flow, compaction, and finishing. Additionally, the reduction in density makes them suitable for lightweight structures. [12] examined the microstructure of concrete incorporating 5-10% coconut shell replacement in brick aggregate concrete. According to the author, the interfacial transition zone exhibits fissures due to including coconut shells. This reduction in mechanical performance limits their structural applications [11]. Hence, ensuring the ideal quality and performance of coconut shell concrete requires detailed investigations.

Consequently, pozzolans reduce cement consumption and enhance concrete strength and durability. One such material is silica fume, a secondary product of silicon or ferrosilicon alloys. Due to the silica fume's high amorphous nature, SiO_2 concentration, and capacity to improve the packing density of the concrete matrix, it is generally considered cementitious [13]. When added to concrete, the SiO_2 reaction with free calcium hydroxide $Ca(OH)_2$ in the cement paste produces C-S-H (calcium silicate hydrate). The C-S-H is accountable for the development of concrete strength. Recently, [14] reported improved mechanical properties, durability and microstructural properties of concrete when adding 5, 10, 15, 20, and 25% silica fumes. In addition, [15] studied the impact of silica fumes on the bond strength of the coconut shell concrete using an inverted metallurgic microscope. A 10%SF dosage was reported to have a strength of approximately 4.5% higher than 100% OPC. They further verified that 10% silica fume is the most effective substitute for cement.

The referenced literature shows that coconut shells have been extensively used as coarse aggregates in concrete production, with little consideration given to their use as fine aggregate. The flaky nature of coconut shells' coarse aggregates is considered to pose challenges during concrete compaction. Also, sand mining has been a concern due to its negative environmental effects. Using coconut shells as a fine aggregate limits the material's flaky nature and promotes the wider application of coconut shells in tropical regions where they are mostly found. Moreover, this conserves natural resources by reducing sand usage in concrete manufacturing.

Nevertheless, using coconut shells as fine aggregate has been reported to negatively affect concrete's mechanical and durability properties while positively reducing concrete's self-weight. On the other hand, SF increases concrete's mechanical strength and durability while lowering cement use and CO_2 emissions. Hence, this study is interested in using coconut shells and silica fume as partial replacements for fine aggregates and cement to produce sustainable, normal-strength concrete.

2. Materials and Method

2.1 Sourcing and Characterising Concrete Constituents

Materials applied in this study were Ordinary Portland Cement (OPC) 42.5N, crushed granite stones, river sand, Silica Fume (SF), Coconut Shells (CS) and tape water. The cement was locally purchased from a local manufacturer in Kenya. Cement chemical composition was determined using Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Fluorescence (XRF). OPC-specific gravity was also determined.

The crushed granite stones (coarse aggregate) and river sand (fine aggregate) were locally sourced from stockpiles in Kenya. According to [16], sand was sieved through a 5.0mm sieve. The maximum size of coarse aggregate was 20mm. These materials were washed and dried to remove unwanted particles.

On the other hand, the SF was purchased from a local manufacturer in Kenya. Its chemical composition was determined using XRF and EDS. Figure 1 shows a sample of the fume used.

Fig. 1 Silica fume

Finally, the CS was locally sourced from Mombasa, a coastal city in South-Eastern Kenya and drenched in water for 18 hours to support the removal of fibbers and contamination. They were air-dried till a crushable state was achieved and were crushed at the Agricultural and Biosystems Engineering workshop at Jomo Kenyatta University of Agriculture and Technology (JKUAT). The machine used was a Hammer Mill with a 3mm diameter sieve. The shells were fractionated using individual sieves as per sand gradation sieves. The coconut shell fine aggregates (CSFA) used were in a saturated surface dried (SSD) state since their water absorption (26.8%) was higher. The coconut shell was saturated for 24 hours and air dried to SSD condition. Figure 2 displays the preparation process of the coconut shell aggregate.

2.2. Mix Design

The British (DoE) was adopted to produce normal-strength M30-grade concrete. The concrete was designed with a mix ratio of 1:1.5:2.7. The experimental work comprised 16 mixes: one (1) conventional concrete, three (3) coconut shell concrete, three (3) silica fume concrete, and nine (9) coconut shells-silica fume concrete. The coconut shell, by volume, replaced river sand as fine aggregate at 10, 20, and 30%. Likewise, silica fume by weight replaced cement at 5, 10, and 15%. Table 1 details the mix proportion of the various concrete. Cubes, cylinders and beams were produced from the mixes for 7, 14, and 28 days of testing. The evaluation of concrete quality was based on workability, density, compressive, flexure, and splitting tensile strength and microstructure.

Fig. 2 Preparation of coconut shell aggregates

Table 1. Concrete mix proportions

Mix Proportion per Meter Cube									
Mix ID	**Coconut shells content (%)**	**Silica Fume content (%)**	**Cement (kg)**	**Silica Fume (kg)**	**Coarse aggregate (kg)**	**Fine aggregate (kg)**	**Coconut Shell (kg)**	**Water (kg)**	**W/C Ratio**
MP0	0	0	382	0	1084	664	0	210	0.55
MP1	10	0	382	0	1084	577.6	29	210	0.55
MP2	20	0	382	0	1084	531.2	58	210	0.55
MP3	30	0	382	0	1084	464.8	87	210	0.55
MP4	0	5	363	13	1084	664	0	210	0.55
MP5	10	5	363	13	1084	577.6	29	210	0.55
MP6	20	5	363	13	1084	531.2	58	210	0.55
MP7	30	5	363	13	1084	464.8	87	210	0.55
MP8	0	10	344	27	1084	664	0	210	0.55
MP9	10	10	344	27	1084	577.6	29	210	0.55
MP10	20	10	344	27	1084	531.2	58	210	0.55
MP11	30	10	344	27	1084	464.8	87	210	0.55
MP12	0	15	325	41	1084	664	0	210	0.55
MP13	10	15	325	41	1084	577.6	29	210	0.55
MP14	20	15	325	41	1084	531.2	58	210	0.55
MP15	30	15	325	41	1084	464.8	87	210	0.55

Where, M = mix, P = proportion and Numerical = order of production

2.3. Concrete Curing

Curing is a system that supports the hydration process of concrete. In this study, concrete samples were cured in polytanks containing water at a temperature of 23 ± 2°C. The samples were cast and removed from the moulds after 24 hours. Concrete final curing was done through a submergence process for 7, 14, and 28 days, and sample curing was conducted as per ASTM C31, (2019). The concrete samples' mechanical properties were determined in a saturated surface dry condition after the curing period.

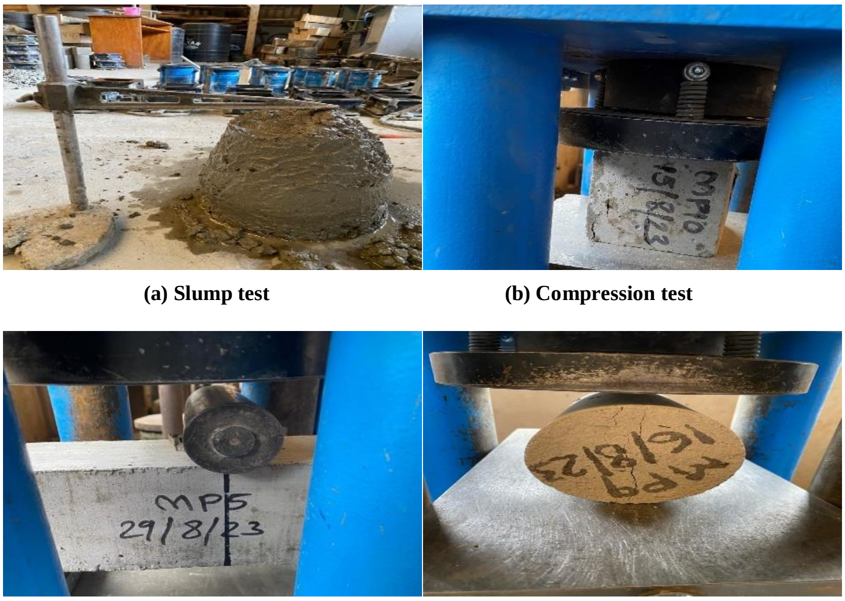
2.4. Determining the Physical Properties of Fresh Concrete and assessing the Mechanical and Micro-Structural Properties of Hardened Concrete

The physical properties of concrete determined included workability and density. The concrete slump test assessed the workability of concrete. Concrete workability is vital because it influences concrete transportation, compaction, and finishing. The slump test is performed per [17]. An illustration of the concrete slump is shown in Figure 3 (a). Concrete density was evaluated after 28 days.

This test was carried out following [18]. Three (3) samples per mix, summing up to 48 cubes of 100mm x 100mm x 100mm for density testing.

The mechanical characteristics of hardened concrete were evaluated based on tension, compression, and flexure tests. Compressive strength was determined for 16 mixes, each containing three specimens at 7, 14, and 28 days of curing, summing to one hundred forty-four (144) cubes of

100mm x 100mm x 100mm. A 1500kN Universal Testing Machine (UTM) was used at a loading rate of 0.5kN/s as per [19]. The tensile strength was measured on the concrete as follows [20]. Three samples per mix with 100mm diameter and 200mm thickness were crushed with 1500kN capacity UTM at 0.05kN/s. The samples were examined at 7, 14, and 28 days of curing. A total of 144 cylinders were tested. Finally, the flexural strength was determined as follows [21]. The test was conducted on three samples per mix with 100mm x 100mm x 350mm, using one-point loading at a mid-span of 300mm with two supporting rollers. Three samples per mix at 7, 14, and 28 days were tested using a 1500kN UTM at a 0.05kN/s loading rate.



(a) Slump test **(b) Compression test**

(c)Flexure test **(d)Tensile test**

Fig. 3 Fresh and hardening concrete tests

The microstructural properties of conventional concrete, optimal coconut shell concrete (10% CSFA), optimal silica fume concrete (10%SF) and optimal silica fume-coconut shell concrete (10%CSFA & 10%SF)) were determined. Following a 28-day water curing period, the sample underwent EDS and scanning electron microscopy (SEM) analysis. The concrete was evaluated utilising (EDS) and (SEM). SEM was carried out to evaluate the morphology, microcracks, air voids and the interfacial transition zone (ITZ). EDS test was done to investigate concrete elementary composition. This investigation was conducted at the Electron Microscopic Unit, University of Cape Town, South Africa. To prepare the samples, carbon tape was used to place them onto aluminium SEM stubs. After that, carbon was applied to the samples to make them conductive. The images were taken at an accelerated voltage of 5.0kV and magnification of 5.00kx using Tescan MIRA SEM. EDS analysis was conducted on the Thermo Fisher Nove NanoSEM using an Oxford X-Max detector and INCA software. The spectra were collected at 20kV for 20 seconds.

3. Results and Discussion

3.1. Characterisation of Concrete Constituents

3.1.1. Chemical and Physical Properties of Ordinary Portland Cement and Silica Fume

Table 2 illustrates the chemical compositions of OPC and SF obtained using XRF. The results show that OPC has 63.859% calcium oxide (CaO_2), while SF contains 93.042% silica (SiO_2). The results for SF conform to the minimum requirement of 85% for reactive pozzolanic material, as specified in [22]. The abundance of SiO_2 in silica fume attests to the material's efficiency in producing cementitious compounds (calcium silicate hydrate). It was found that the silica fume and OPC had Losses on Ignition (LOI) of 3.788% and 3.36%, respectively.

As depicted in Table 3, the specific gravity of OPC and SF was 3.11 and 2.15, respectively. Specific gravity is an important cement parameter that predicts the material's density. The results show that the silica fume's specific gravity is approximately 2.2 and has a lower density than cement.

Figure 4 presents SF's and OPC's particle sizes, shapes, and chemical constituents. The SEM micrographs of SF and OPC show that the SF has a spherical and finer particle, while that of OPC has an irregular and spherical particle. The EDS graphs show cement containing higher calcium, while SF shows a high amount of silicate. The silicon content found in silica fume shows its pozzolanic characteristic.

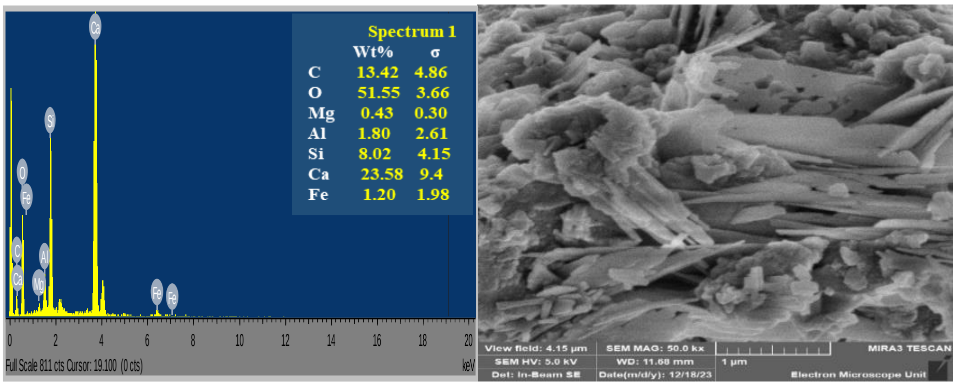
This pozzolan characteristic has a high tendency to aid in strengthening concrete when it reacts with calcium hydroxide. Comparing the x-ray fluorescence and EDS results, they show a consistency of the leading chemical in each material type. Due to the chemical nature, shape, and fineness of silica fumes, they are suitable for high-strength and normal concrete production as their characteristics significantly impact concrete's properties.

Table 2. Chemical constitution of silica fume and ordinary portland cement

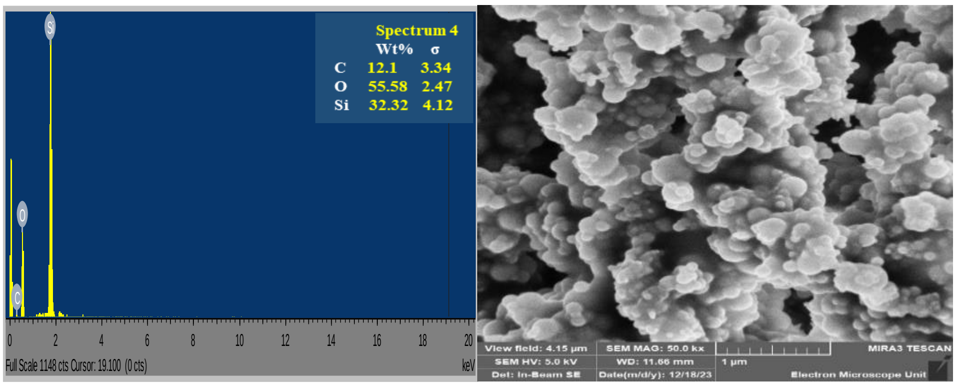
Composition	Composition (%)	
	Ordinary Portland cement	Silica fume
Al_2O_3	5.098	0.469
CaO_2	63.859	1.535
FeO_3	8.197	
SiO_2	21.316	93.042
SO_3	0.46	0.189
K_2O	0.457	0.215
LOI	3.788	3.36

Table 3. Physical properties of silica fume and ordinary portland cement

Test	Standard	Cement	Silica Fume
Specific Gravity	ASTM C188-17	3.11	2.15



(a) Cement



(b) Silica fume

Fig. 4 SEM and EDS of cement and silica fume

3.1.2. Chemical and Physical Properties of Sand and Coconut Shells

Table 4 contains the physical properties of river sand and coconut shells (CS) as fine aggregates. The specific gravity of river sand and coconut shells was 2.55 and 1.33, respectively. The compacted bulk density of river sand and coconut shells are 1690.68 and 740.31kg/m^3, respectively. The coconut shell's low specific gravity and bulk density make it a promising material for lightweight concrete. This is beneficial for better insulation and a lower structural load. The particle size distribution for fine aggregates ranges from 0.075 to 5mm, as revealed in Figure 5. The aggregate particle size falls within the gradation limits [23]. The fineness modulus of river sand was 2.3.

Figure 6 shows the SEM images and EDS of river sand and coconut shells. Coconut shell has an irregular shape and porous nature, as seen in Figure 6(b). While river sand particles have been observed to be rounded in shape, as shown in Figure 6(a).

EDS graphs show that CSFA contains higher carbon levels and some oxygen, indicating its organic nature, while river sand contains silicon, oxygen, and carbon.

Carbon in the sand may have resulted from organic impurities and the carbon used to coat the samples. These differences in shape impact fresh and hardened concrete properties.

Table 4. Mechanical and physical properties of aggregates

Test	River Sand	Coconut Shells	Test Standard
Bulk density compacted (kg/m^3)	1690.68	740.31	ASTM C29
Bulk density loose (kg/m^3)	1598.8	643.94	ASTM C29
Specific gravity of SSD	2.55	1.33	ASTM C128-01
Water absorption (%)	3.1	26.8	ASTM C128-01
Moisture content of sand (%)	4.35	9.01	BS812-109:1990
Percentage void	34	44	ASTM C29
Fineness modulus of sand	2.3		BS-0082-1992 2002

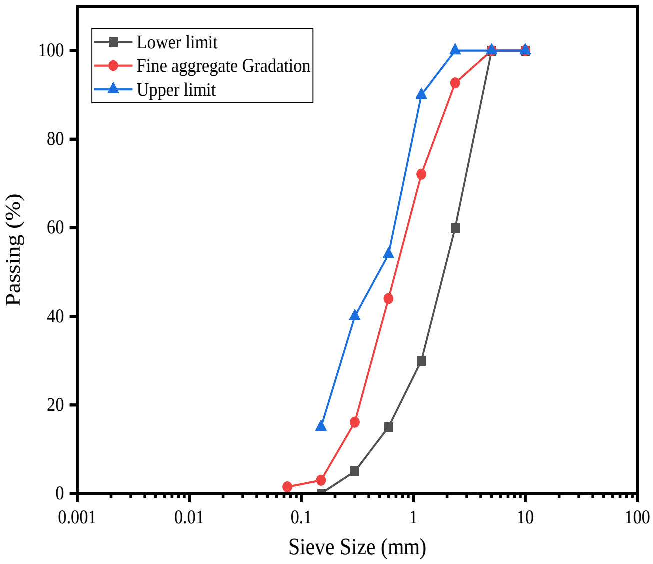
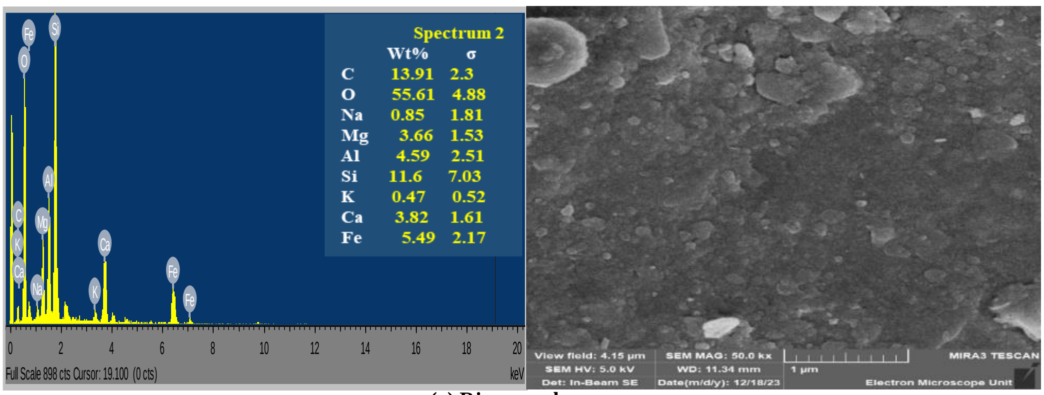
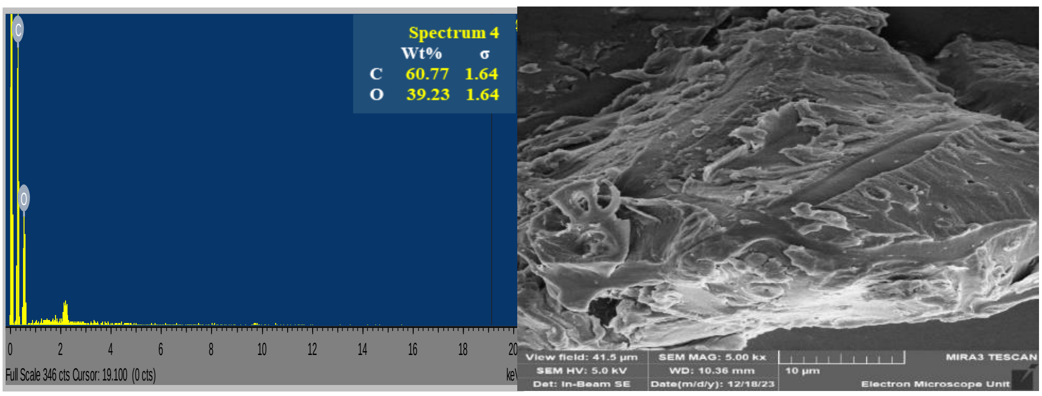


Fig. 5 Fine aggregates particle size distribution



(a) River sand



(b) Coconut shell aggregates

Fig. 6 SEM and EDS of river sand and coconut shell

3.1.3. Mechanical and Physical Properties of Coarse Aggregate

The mechanical and physical properties of coarse aggregate are shown in Table 5. The dry method of determining aggregate impact value was applied during the assessment. Since the fineness of the material influences concrete properties as the concrete strength and AIV are directly correlated [24], the particles passing through the 2.36 sieve were used for the evaluation of impact resistance. BS 812-112 (1990) set the maximum limits as 25%, and the AIV obtained for the aggregate was 6.35%. This shows that the aggregate has a good resistance to shock. Hence, testing aggregate crushing ability gives the measure of resistance to a gradual compressive loading. The average value obtained for ACV was 16.74. The result indicates that the aggregate falls below the maximum limit of 35% [24], giving the suitability of aggregate for the production of concrete. The gradation in Figure 7 also conforms to [23].

Table 5. Mechanical and physical properties of coarse aggregate

Test	Coarse Aggregates	Test Standard
Bulk density compacted (kg/m^3)	1525.93	ASTM C29
Bulk density loose (kg/m^3)	1385.29	ASTM C29
Specific gravity of SSD	2.56	ASTM C128-01
Water absorption (%)	3.2	ASTM C128-01
Moisture content of sand (%)	3.76	BS 812-109:1990
Aggregates impact value (%)	6.35	BS 812-112 (1990)
Aggregates crushing value (%)	16.74	BS 812-110 (1990)
% Void	40	ASTM C29

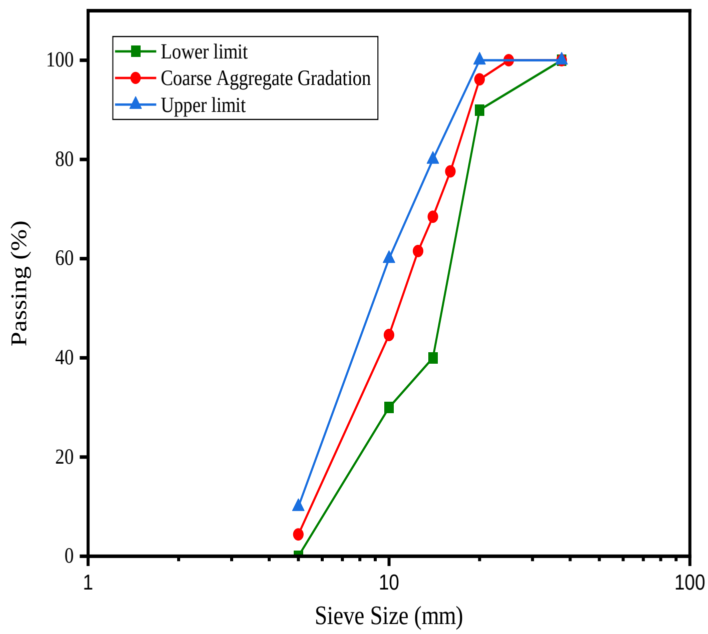


Fig. 7 Coarse aggregates particle distribution

3.2. Physical Properties of Fresh Concrete and Mechanical and Micro-Structural Properties of Hardened Concrete

3.2.1. Physical Properties of Fresh Concrete

Slump values of concrete mixes are shown in Figure 8. The values range from 16 to 67 mm. Adding 10, 20, and 30% coconut shells to the conventional concrete mixture significantly increased slump by 3.3, 8.2, and 9.8%, respectively, as shown in Figure 8(a). This observation suggests that incorporating coconut shells improves the workability of the fresh concrete, which agrees with findings from [9]. In contrast, incorporating silica fume into conventional concrete affects fresh concrete properties by decreasing the concrete slump. Henceforth, compared to the conventional concrete, the slump decreases by 57.4, 62.3, and 73.8% when adding silica fume at 5, 10, and 15%, respectively, as shown in Figure 8(b). The decrease in slump is accredited to the tiny particles and absorption volume of silica fumes due to their extensive surface area. The results shown in Figure 8(c) depict a reduced slump of coconut shell concrete when incorporating silica fume dosage. Generally, the combined effect of silica fume and coconut shells shows a reduced slump compared to conventional concrete. For example, 5%SF-10%CSFA concrete and 10%SF-10%CSFA yielded a 47.5% and 54.1% decrease in the slump, respectively.

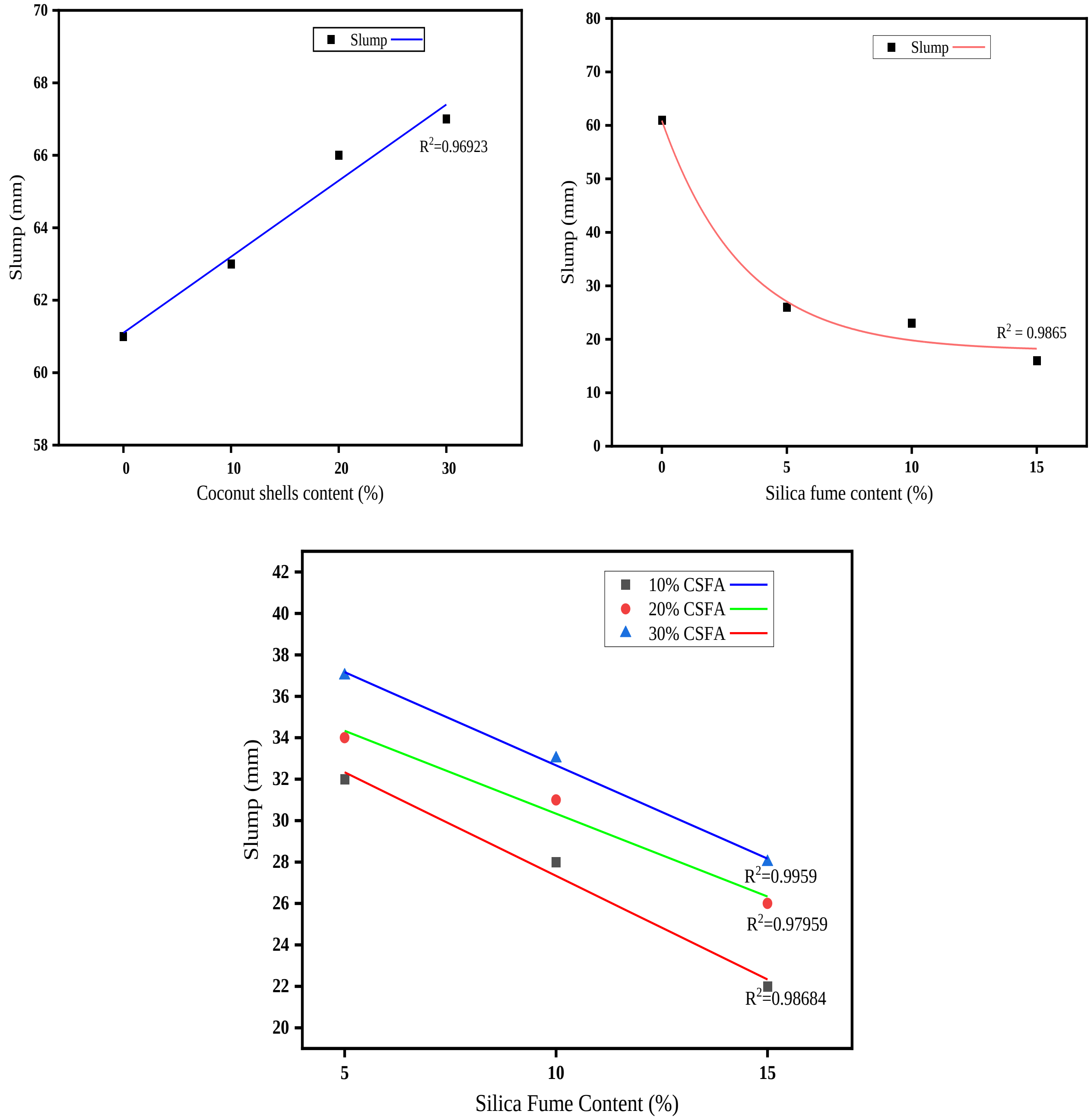


Fig. 8 Slump result for coconut shell, silica fume and silica fume-coconut shell concrete

Concrete density directly influences the magnitude of a dead load in a structural element. According to Figure 9 (a), incorporating 10, 20 and 30% CSFA in conventional concrete caused a reduction in density by 9.6, 12.3 and 12.6%, respectively, as shown in figure 9(a). It is worth noting that even with 30% CSFA replacement, the density (2115kg/m^3) exceeds the range of lightweight concrete. According to [9], lightweight concrete has a density of 1800 to 2000 kg/m3. The reduction in concrete density can be seen in coconut shells' low specific gravity and bulk density. However, Figure 9 (b) revealed an increase in the density of silica fume concrete. Although this trend is observed for all dosages, the maximum density is recorded for 10% SF concrete (2428kg/m^3). This shows the effectiveness of silica fume in increasing concrete density. Consequently, adding SF to CSFA concrete, as depicted in Figure 9 (c), increases the concrete's density. For example, 10% CSFA concrete density (2188kg/m^3) increased to 2219kg/m^3, 2323kg/m^3, and 2243kg/m^3 when adding 5, 10 and 15% SF, respectively. The 10% CSFA-10% SF concrete (2323kg/m^3) yielded the most comparable density to the conventional concrete (2428kg/m^3). This upsurge in density is ascribed to the large surface area and finesses of SF particles. Hence, it can be inferred that SF increases density despite its low specific gravity to cement, as observed with normal silica fume concrete and the increase in density when SF was added to CSFA concrete. SF reduces voids by filling pores and increasing concrete density.

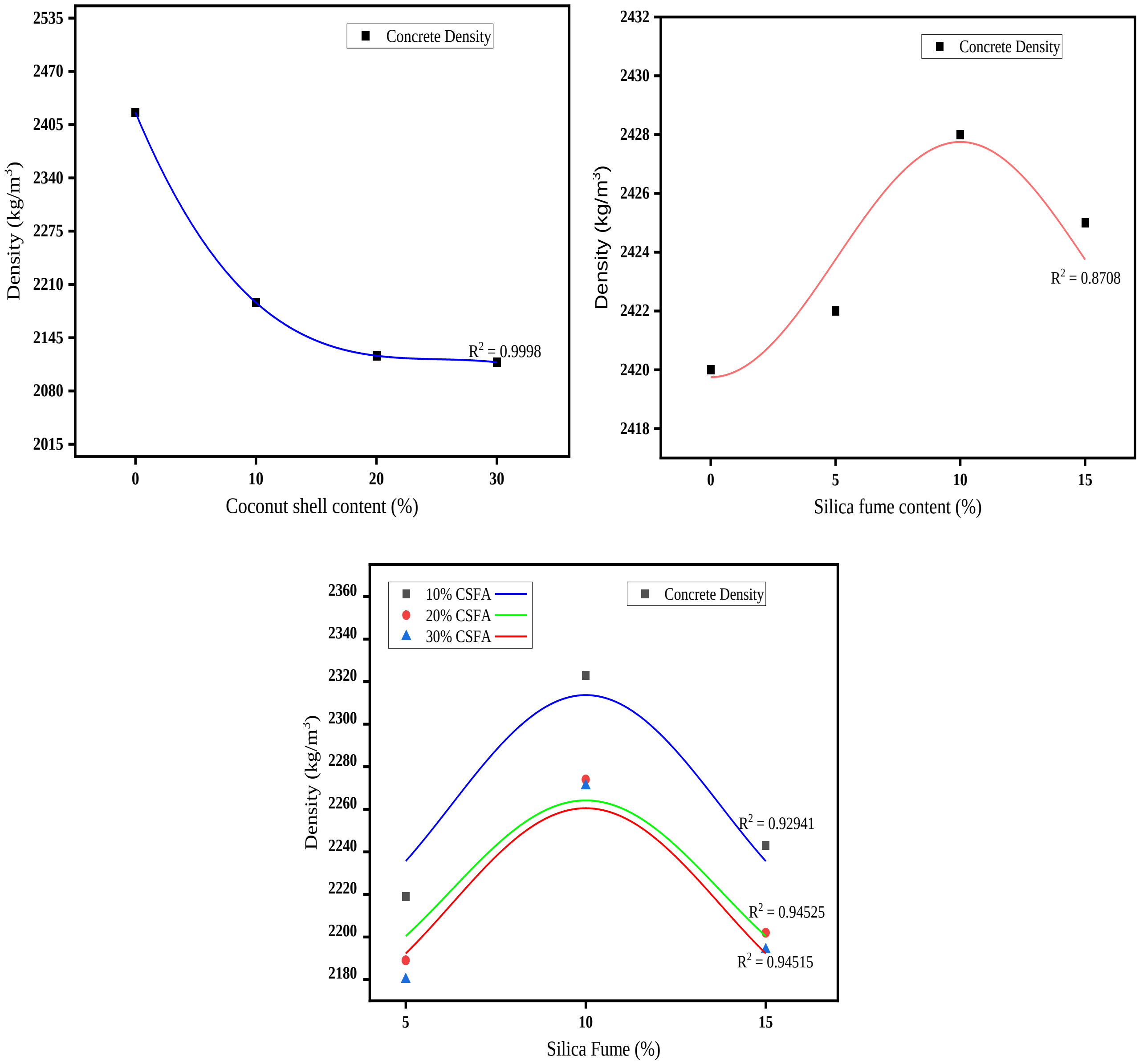


Fig. 9 Density result for coconut shell, silica fume, and silica fume-coconut shell concrete

3.2.2. Mechanical Properties of Hardening Concrete

Generally, Figure 10 shows that the compressive strength of concrete improved as it underwent more days of water curing. The addition of CSFA was observed to weaken concrete strength due to poor bonding, while the addition of SF strengthened concrete property till 10% replacement. The compression resistance of coconut shell concrete at 10, 20 and 30% was found to be 24.8, 37.3, and 43.8%, respectively, lower than the conventional concrete with 40.426MPa. Additionally, 10% CSFA concrete performs better than the 20 and 30%CSFA concrete. However, 30% of CSFA concrete was seen to be feasible as a lightweight concrete. This concrete type satisfies the minimum requirement of 17MPa for lightweight concrete [25]. However, incorporating 5, 10 and 15% SF increased the conventional concrete compressive strength by 13.5, 21.1, and 15.1%, respectively. The increment in compressive strength was due to the accelerated pozzolanic reaction of SF with free calcium hydroxide in the concrete matrix to produce additional C-S-H.

Furthermore, it was observed in Figure 10 that the compressive strength of concrete comprising 10, 20, and 30% replacement of CSFA at 28 days increased to 39.77, 35.21, and 32.34 MPa, respectively, when 10% SF was incorporated. This shows an increment of 30.87, 38.88, and 42.37% compared to CSFA concrete. The most effective combination was seen for 10%CSFA and 10%SF. This concrete obtained a compressive strength of 39.772 MPa at 28 days of curing, and it was 0.654 MPa lower than the conventional concrete. This minimal difference qualified the suitability of 10%CSFA-10%SF concrete as it meets the requirement of M30 normal-strength concrete. This improvement is essential for increasing applications of CSFA concrete.

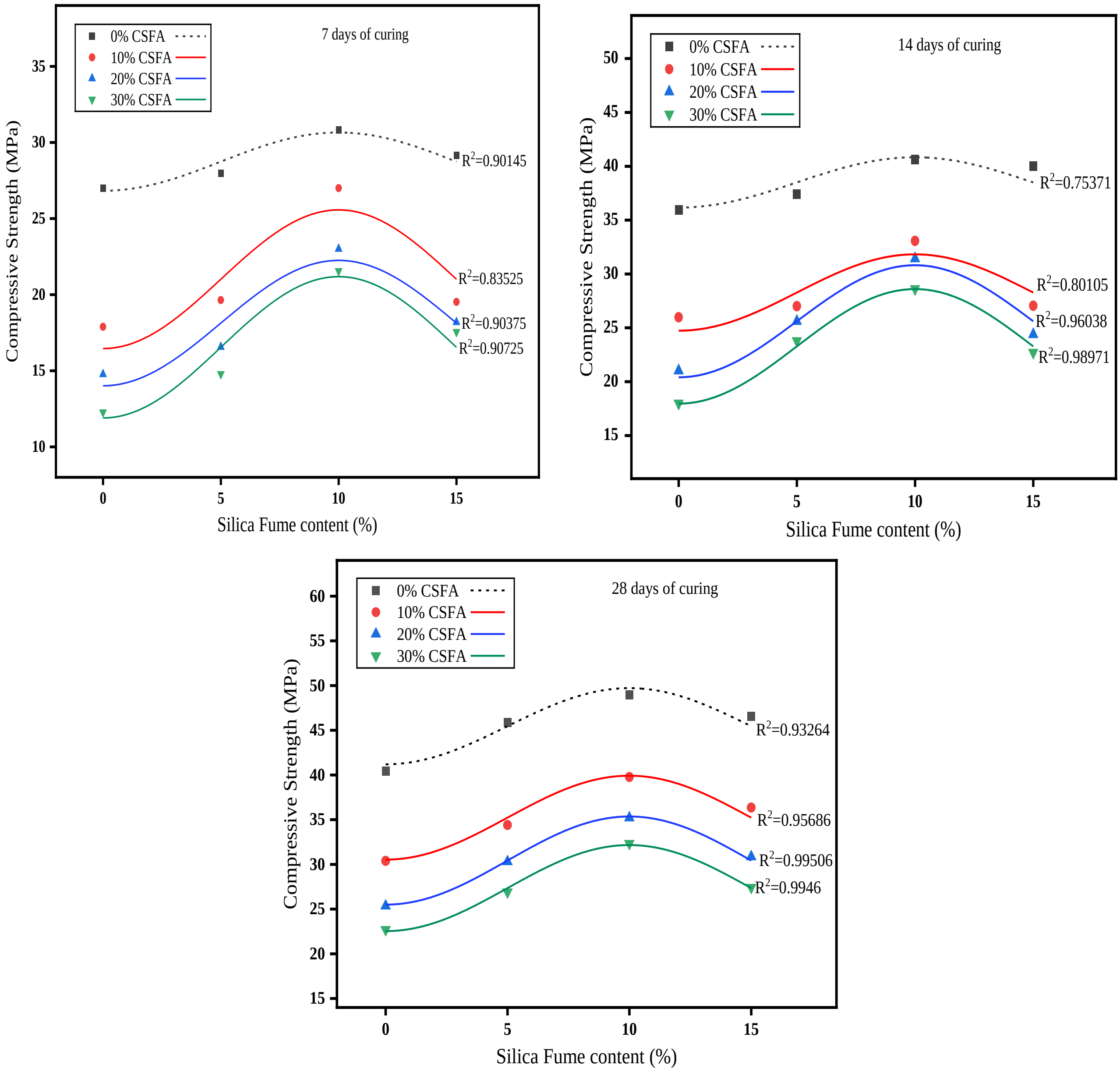


Fig. 10 Compressive strength of concretes for various mix proportions and curing period

Split tensile strength test results are shown in Figure 11. The conventional concrete strength at 28 days was 2.966 MPa. Incorporating 10, 20 and 30% CSFA yielded 2.30, 2.00, and 1.88MPa, respectively, at 28 days of curing. This was equivalent to 22.5, 32.6 and 36.5% reduction, respectively, when compared with the conventional concrete. As discussed in the previous section, the decrease in tensile strength could have perhaps been attributed to a weak bonding of coconut shells with cement paste. However, incorporating 5, 10 and 15 % SF into the conventional concrete yielded tensile strength values of 3.23, 3.54, and 3.27 MPa, respectively, at 28 days, which were higher than the conventional concrete by 9.0, 19.3 and 10.1%, respectively. The increasing split tensile strength is ascribed to the strengthening of calcium silicate hydrate due to the pozzolanic effect between silica fume and cement paste. This reaction enhances the bond between the cement paste and aggregate at the concrete interfacial transition zone. Although this trend is observed for all dosages, maximum tensile strength was recorded for 10% SF concrete (3.54MPa).

Furthermore, Figure 11 demonstrates that the split strength of concrete, which had 10, 20, and 30% of sand replaced by CSFA, improved to 2.76, 2.67, and 2.48MPa, respectively, after 28 days. This improvement was noticed when 10% silica fume was added to the mixture. This indicates an increase of approximately 20.0, 33.5, and 31.9%, respectively, compared to the coconut shell control concrete. The most effective combination was seen for 10% CSFA and 10% SF.

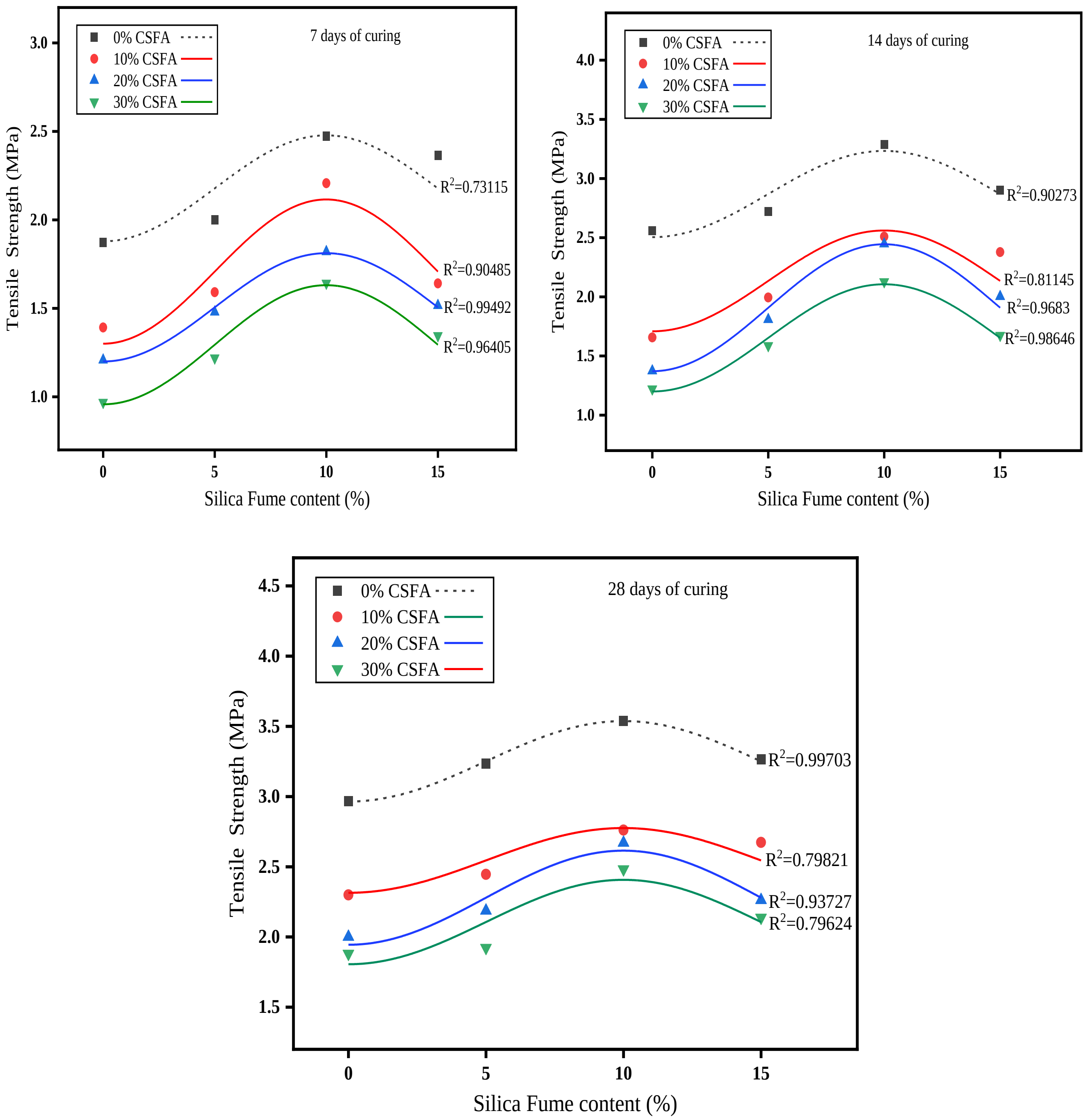


Fig. 11 Split tensile strength of concrete for all mix proportions and curing period

A flexural strength test was conducted to evaluate the deflection characteristics of concrete after 7, 14, and 28 days of curing. Based on the findings depicted in Figure 12, the flexural strength demonstrates a positive correlation with the duration of curing. An increase in concrete strength to 10% SF and a decrease in CSFA concrete with an increase in dosage were observed.

The conventional concrete 28-day flexural strength was 4.66MPa. Incorporating 10, 20, and 30% coconut shells yielded 3.32, 3.15, and 2.96 MPa, respectively, at 28 days. This reduction is equivalent to 28.7, 32.4, and 36.4%, respectively, compared to the conventional mixture. On the contrary, the results in Figure 12 show an increase in the flexural strength of conventional concrete when SF was added. Addition of 5, 10, and 15% SF in concrete was observed to have a flexural strength of 4.81, 5.3, and 5.00MPa, respectively, with 10% silica fume performing best.

Moreover, varying 5, 10, and 15% silica fume into 10, 20, 30% CSFA concrete, 10 % SF, and 10% CSFA gave high value compared to other mixes, as specified in Figure 12. The flexural strength obtained for 10%SF-10%CSFA concrete was 4.60 and was 1.3% less than the conventional concrete flexural strength (4.66MPa). Therefore, the dense hydrated C-S-H gels improved the bending resistance of the concrete.

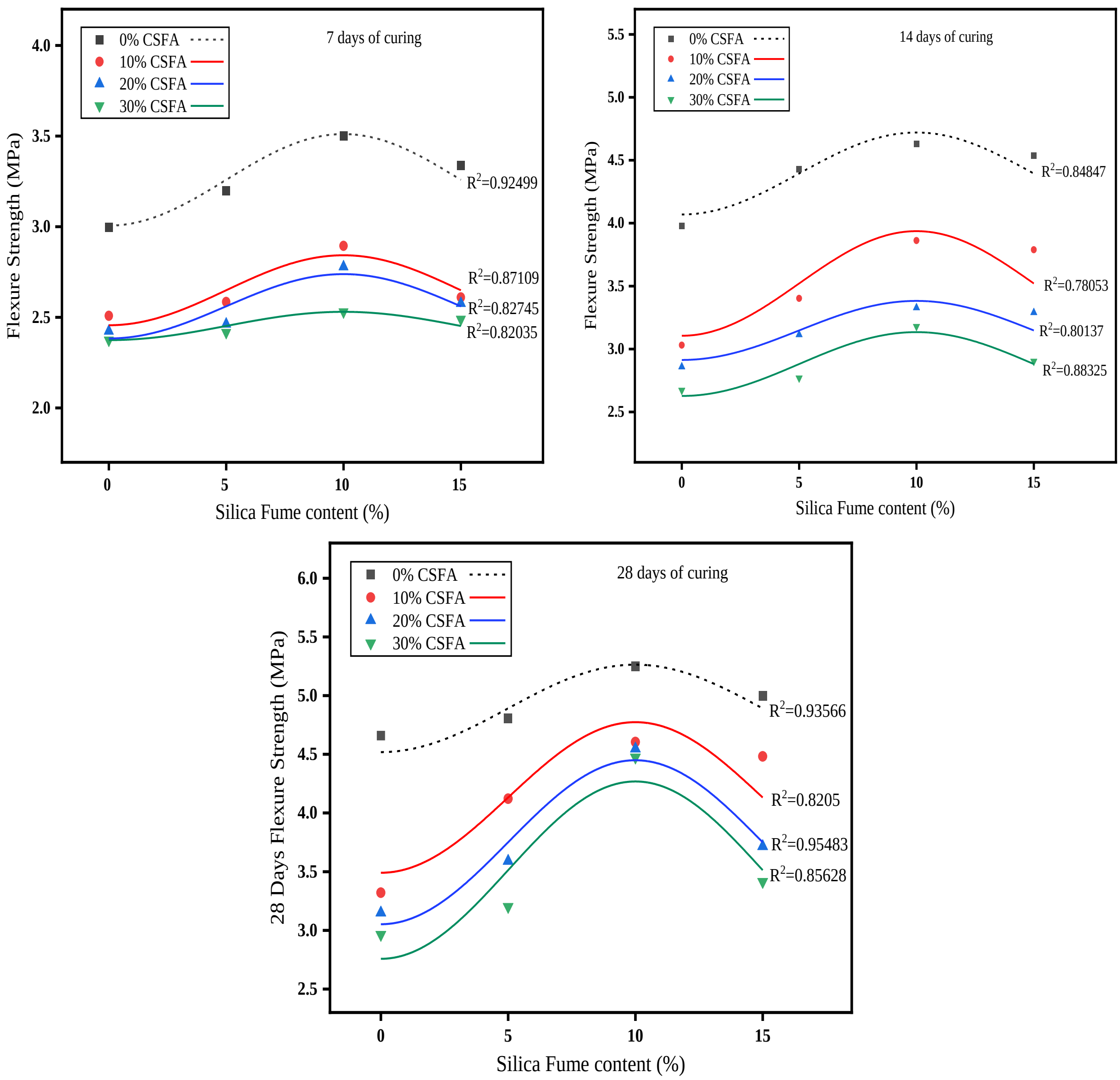
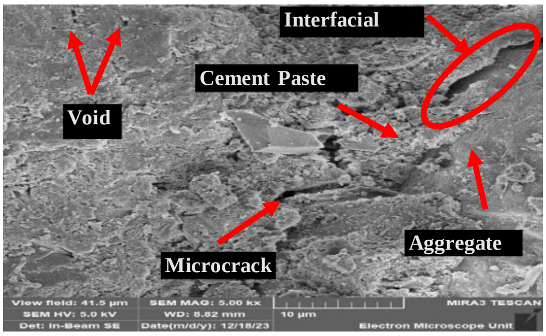


Fig. 12 Flexural strength of concrete for various mix proportions and curing period

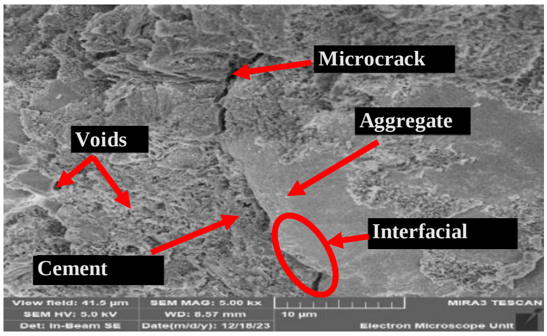
3.2.3. Microstructure Properties of Hardened Concrete

The SEM images results in Figure 13 indicate the micro-morphology of conventional concrete (MP0), optimal coconut shells concrete (MP1), optimal silica-fume concrete (MP8) and optimal coconut shell-silica fume concrete (MP9) after curing 28 days. Compared to conventional concrete, coconut shell concrete in Figure 13(b) shows fewer microcracks and better bonding in the interfacial transition zone. This could be explained by considering the embedded fibres in coconut shells. These fibres can act as reinforcement, reducing the stress on the concrete and thus decreasing the propensity for micro-crack formation during strength gain. However, a 10% silica fume concrete in Figure 13 (c) appears to be denser than the conventional and coconut shell concrete, with good bonding and fewer microcracks and voids. These findings are accredited to the finesses and pozzolanic characteristics of silica fume, which accelerate the hydration of the concrete. It contributes to the densification of the matrix and improves the interface between paste and aggregate. Figure 13 (d) shows the micro-morphology of an optimal coconut shell-silica fume concrete (MP9). Incorporating a 10% silica fume into a 10% coconut shell concrete shows improvement in the interfacial bonding and reduces the microcracks of 10% coconut shell concrete. The improvement in ITZ and reduced microcracks and air voids by silica fume have greatly influenced the properties of coconut shell concrete. This outcome agrees with the findings of the mechanical test.

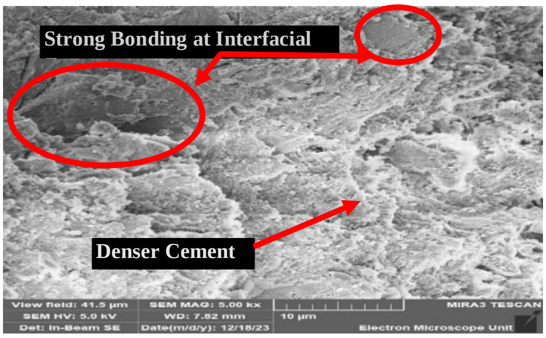
The EDS micrograph in Figure 14 shows that all the concrete is dominant with calcium oxide and silica (SiO_2). Compared to conventional concrete, the silica content increased when incorporating silica fume. These findings are consistent with the chemical constituents of the raw materials. Thus, it can be concluded that the material's chemical compositions significantly impact the concrete chemical properties.



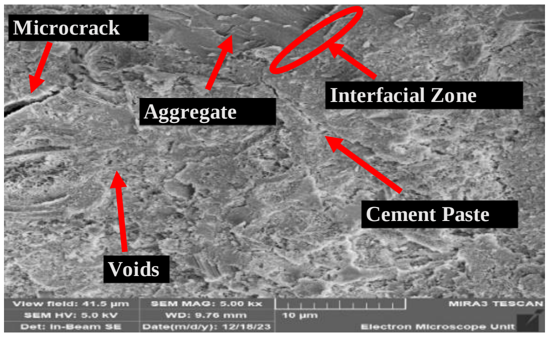
(a) Conventional concrete (MP0)



(b) Optimal coconut shell concrete (MP1)

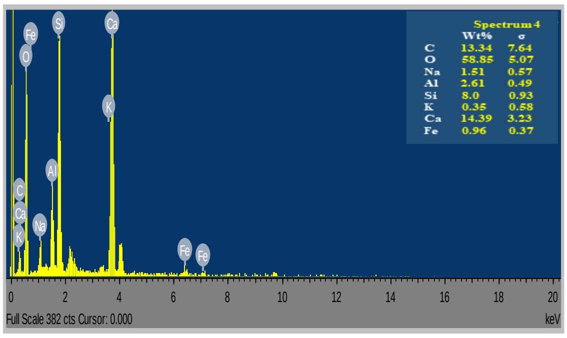


(c) Optimal silica fume concrete (MP8)

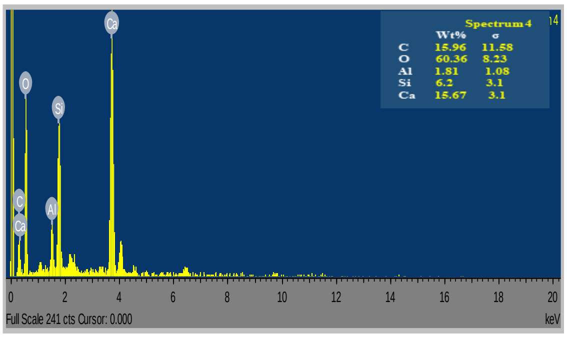


(d) Optimal silica fume-coconut shell concrete (MP9)

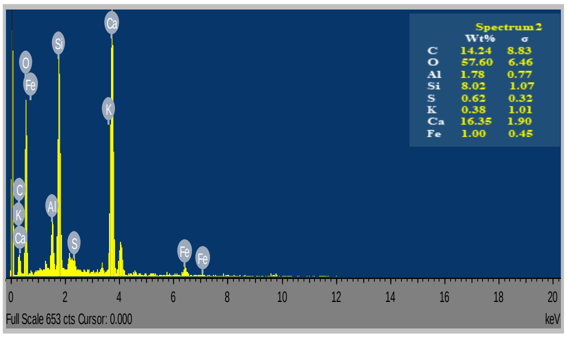
Fig. 13 SEM micrograph of MP0, MP1, MP8 and MP9 concrete



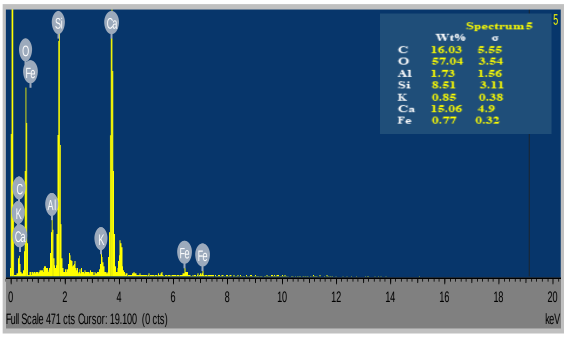
(a) Conventional concrete (MP0)



(b) Optimal coconut shell concrete (MP1)



(c) Optimal silica fume concrete (MP8)



(d) Optimal silica fume-coconut shell concrete (MP9)

Fig. 14 EDS micrograph of MP0, MP1, MP8 and MP9 concrete

4. Conclusion

This study assessed the physical, mechanical and micro-structural properties of concrete with silica fume and coconut shell as partial replacements for cement and fine aggregate. The findings show that:

- Adding coconut shell as fine aggregate (CSFA) increased the overall workability and lowered the hardened density of concrete. However, 30% replacement produced the highest slump and the lowest density values.

- The replacement of CSFA reduces the compressive, tensile and flexural strength, having 30% replacement yielding the lowest values. At 30% replacement, a 28-day compressive strength of 22.71MPa was observed. The value exceeds the minimal requirement of 17MPa for lightweight concrete. However, a 10% CSFA replacement level resulted in optimal performance in terms of mechanical properties.
- The use of 5, 10, and 20% SF as a replacement for cement reduced slump and increased density and mechanical properties, while 10% replacement resulted in optimal mechanical properties.
- The addition of 5, 10 and 15% SF to 10, 20, and 30% CSFA concrete improved the mechanical properties. Moreover, 10% silica fume performed better than 5 and 15% SF when incorporated in CSFA concrete.
- The combined effect of 10%SF and 10%CSFA had the highest performance in the mixes incorporating both materials. The result obtained from this optimal combination of SF and CSFA can be applicable in areas suitable for conventional concrete, considering the proximity in terms of strength and the prioritisation of lightweight characteristics.
- Adding silica reduced the air voids and micro-cracks and improved the conventional and CSFA concrete interfacial bonding.
- The compressive strength and density of 10%CS-10%SF concrete and conventional concrete are 39.77MPa and 2323kg/m3 and 40.426MPa and 2420kg/m^3, respectively. This shows that the modified concrete improved the strength-to-weight ratio by 1.32%.

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