
MECHANICAL PROPERTIES OF CONCRETE MODIFIED WITH SODOM APPLE SAP (CALOTROPIS PROCERA) AS AN ADMIXTURE

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ABSTRACT

This study investigates the strength and durability performance of concrete made with Sodom apple sap (*Calotropis procera*) as an admixture. The need for affordable and locally available admixtures in developing countries has prompted interest in bio-based alternatives in improving concrete properties. Using a Central Composite Design (CCD), the effects of water–cement ratio (0.45–0.55) and sap dosage (0.5–1.5%) on fresh and hardened properties of C25/30 concrete were evaluated. Tests conducted includes compressive strength, flexural strength, splitting tensile strength, density, and microstructure using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). Results show that optimal sap dosages (1.0%) improved density (23.85–24.45 kg/m³), compressive strength (up to 52 N/mm² at 90 days), flexural strength (up to 5.4 N/mm²), and tensile strength (up to 3.1 N/mm²). Over-dosage and high water–cement ratios slightly reduced performance due to increased organic interference in hydration. Findings from this study show that, Sodom apple sap is a strong potential as a sustainable and cost-effective admixture that enhances later-age strength and microstructural refinement. Findings support its suitability for structural concrete applications in line with Eurocode requirements.

Keywords: Sodom apple sap; *Calotropis procera*; bio-admixture; concrete modification; strength properties; water–cement ratio; Central Composite Design; durability

INTRODUCTION

Concrete remains the most widely used construction material globally due to its versatility, strength, and cost-effectiveness (Mehta & Monteiro, 2019). It is fundamentally combination of a material consisting of cement, water, fine and coarse aggregates, with or without admixtures, that hardens into a durable mass (Salahaldein,

2018). Its performance in both fresh and hardened states is critical for ensuring structural serviceability. Fresh concrete properties such as workability, consistency, segregation resistance, and setting time significantly influence the resulting density, porosity, and mechanical performance of hardened concrete (Girish & Ajay, 2017; Heinemann, 2017). Hardened properties including compressive, tensile, and flexural strength as well as durability indicators largely determine long-term performance, particularly in aggressive environments (Singh, 2025; Ali, 2025).

One of the most influential mix parameters is the water–cement (w/c) ratio. Low w/c ratios typically produce denser microstructures and higher strengths, while elevated ratios increase capillary porosity, reduce durability, and heighten permeability (Mehta & Monteiro, 2019). Achieving a balance between adequate workability and long-term durability has led to widespread use of admixtures that modify hydration, improve workability, and enhance microstructural development. Chemical admixtures such as superplasticizers, retarders, and accelerators have been well documented for improving both early- and later-age concrete performance (Aïtcin, 2016; Liu & Plank, 2020). Mineral admixtures, including fly ash and silica fume, further contribute to reduced permeability and enhanced durability through pozzolanic reaction mechanisms (Suguma, 2018).

However, the high cost and limited availability of imported admixtures in developing countries have prompted research into sustainable, locally sourced alternatives. Natural admixtures derived from plant-based materials have gained attention due to their potential to modify cement hydration, reduce permeability, and improve overall durability (Ogbo & Ugwu, 2023). Despite the technical benefits, many plant-based admixtures such as vegetable oils are edible and thus compete with food resources, creating economic and ethical concerns (Adedayo et al., 2023). Consequently, attention has shifted toward non-edible, abundantly available plant extracts, such as sap from *Calotropis procera* (Sodom apple), which contains latex, saponins, alkaloids, tannins, and bioactive compounds capable of influencing hydration and pore structure (Abdin, 2021; Adedayo et al., 2020).

Preliminary studies indicate that Sodom apple sap can act as a hydrophobic agent, reduce permeability, and enhance durability through polymerisation of its organic constituents during cement hydration (Ohams, 2015). Its chemical constituents linoleic acid, oleic acid, ricinoleic acid derivatives, and glycosides suggest potential for pore refinement and improved resistance to fluid ingress. Importantly, its non-edible nature eliminates competition with food resources, making it a more sustainable alternative than vegetable-oil-based admixtures in regions such as Nigeria.

Despite its potential, the use of Sodom apple sap as a concrete admixture remains largely unexplored. Existing literature highlights the beneficial role of plant extracts in reducing porosity, refining pore connectivity, and enhancing long-term strength (Onuaguluchi &

Banthia, 2016; Akinwumi & Adeyemi, 2023). Yet, no comprehensive study has systematically evaluated the combined effects of sap dosage and water–cement ratio on fresh, mechanical, and durability properties using a rigorous experimental design. This gap is particularly relevant in Nigeria, where reliance on imported chemical admixtures remains economically and environmentally unsustainable.

In response, the present study employs the Central Composite Design (CCD) framework to assess the influence of Sodom apple sap dosage (0.5–1.5%) and water–cement ratios (0.45–0.55) on key performance indicators of C25/30 concrete. Fresh properties, density evolution, compressive strength, tensile strength, flexural strength, and durability indices were evaluated at multiple curing ages. The goal is to establish the optimum sap dosage that enhances performance without compromising structural requirements in accordance with Eurocode provisions. The findings offer both theoretical insights into bio-admixture mechanisms and practical guidelines for sustainable concrete production in resource-limited contexts.

STATEMENT OF THE PROBLEM

The mixing water in concrete is partially consumed in the chemical reaction of hydration; while the excess fills capillary cavities, rendering the concrete porous. This porosity can lead to capillary rise and the transport of minerals or salts, causing deterioration and potential structural weakening (Li et al., 2022). This degradation, whether physical, mechanical, or chemical, is exacerbated by materials that lower the pH of the concrete pore solution. Admixtures offer a potential solution, particularly water-repellent admixtures like Olive oil, which reduce fluid movement, permeability, and absorption in concrete as documented by Albin, (2021).

However, in Nigeria, where multinational construction companies predominantly use imported chemical admixtures, accessibility, affordability, and environmental compatibility pose challenges. Bamigboye et al. (2021) observed the effectiveness of Olive oil as water-repellent admixtures in enhancing concrete durability, but the availability of such vegetable oil admixtures remains limited due to their multifunctionality, like nutritional value, food industry applications, biodiesel production, industrial uses, economic impact, health benefit and edible nature. Vegetable oils have been used as concrete admixtures in the past due to their chemical properties like, linoleic acid, oleic acid, saponins, flavonoids, alkaloids, cardiac glycosides, and tannins that can influence workability and hydration (Smith et al. 2019). These oils, being edible and widely studied, offer a clear understanding of their impacts on concrete.

On the other hand, non-edible admixture, like Sodom apple sap (*Calotropis procera*), despite its potential applications in other fields such as traditional medicine (Ohams, 2015). But its application as a concrete admixture has not been explored, therefore unexplored gap remains. However, utilization of locally sourced, non-edible

admixture becomes imperative in Nigeria. Preliminary survey shows that Sodom apple sap exhibits promising characteristics, including linoleic acid, oleic acid, saponification value, alkaloids, cardiac glycosides, iodine value, tannin, and cerium nitrate to act as hydrophobic agent. It is anticipated that Sodom Apple Sap, when introduced into a cementitious matrix, may cause the ricinoleic acid lose its hydrophilic properties and becomes more hydrophobic, enhancing water repellency. Additionally as aging progresses, the double bond on carbon 9 may reacts through free radicals to give a polymerised film, thereby increasing the hydrophobic properties. Therefore, the utilisation of locally sourced, non-edible admixture is crucial, and this forms the basis of this research.

RESEARCH QUESTIONS

This research is predicated on answering the following questions.

1. What are the effects of Sodom Apple Sap at varying concentrations on the strength properties of hardened concrete.
2. What will mix design optimisation using response surface methodology (RSM) reveal about the strength properties of concrete modified with Sodom Apple Sap
3. How does the addition of Sodom Apple Sap affect the microstructural properties of concrete?

AIM AND OBJECTIVES OF THE STUDY

The aim of the study is to establish the performance of Sodom Apple Sap as an admixture in concrete with the view of producing durable concrete.

The specific objectives of the study:

1. Evaluate the effects of Sodom Apple Sap at varying concentrations on the mechanical properties of hardened concrete.
2. Optimise the mix design based on the strength of concrete using response surface methodology
3. Examine the effect of Sodom Apple Sap on the microstructural properties of concrete.

Experimental Design

A Central Composite Design (CCD), a robust class of Response Surface Methodology (RSM), was used to evaluate the combined effects of water–cement ratio (w/c) and Sodom apple sap (SAS) dosage on the performance of concrete. CCD is particularly effective for modeling nonlinear responses and interaction effects using fewer experimental runs compared with full factorial designs (Montgomery, 2017). The design incorporated:

Factorial points (w/c = 0.45–0.55; SAS = 0.5–1.5%)

Axial points to capture curvature

Center points for replication and error estimation

This approach ensured efficient prediction of concrete performance while minimizing material loss.

Factors and Levels

Water–cement ratio: 0.45, 0.50, 0.55 (Eurocode 2 durability range)

Sodom apple sap dosages: 0.5%, 1.0%, 1.5% (based on prior natural admixture studies: Mahmood et al., 2019; Thirougnaname, 2019)

A total of 14 CCD-generated experimental runs plus a control mix were performed.

Cement

Ordinary Portland limestone cement (Dangote brand), conforming to EN 197-1, was used. Standard tests for consistency, setting time, soundness, and strength were conducted per BS EN 196.

Fine Aggregate

Clean river sand sourced from Mubi North, Adamawa State, was tested following BS 882 (1992) and BS 812 (1995) for: Particle size distribution, Specific gravity, Bulk density and Water absorption

Coarse Aggregate

Crushed granite (20 mm maximum size) was tested for: Grading, Bulk density, Specific gravity

Aggregate impact and crushing values (Tests performed per BS 812:1991).

Water

Potable tap water satisfying BS 3148 (1980) was used for mixing and curing.

Sodom Apple Sap (*Calotropis procera*)

Sap was collected from mature plants during active growth periods. Clean, sterilized tools were used to extract sap from cut branches. The sap was filtered progressively through coarse and fine mesh sieves to remove impurities. Physicochemical analyses included: pH, Specific gravity, Total solids content. These were used to characterize its suitability as a bio-admixture.

Preliminary Material Tests

Before mix preparation, all materials were subjected to standard characterization tests to ensure conformity with relevant codes:

Cement: fineness, consistency, setting time, and soundness Sand: grading, moisture content, and absorption. Granite: impact and crushing values. Water: pH and turbidity. Sap: density, pH, and chemical constituents. These ensured the reliability and quality of inputs for mix development.

Mix Ratio

Although the CCD matrix includes variable water–cement ratios, a 1:1:2 nominal mix was adopted, representing a widely used proportion for structural applications in developing regions and approximating C25/30 strength class when combined with w/c ratios between 0.45–0.55 (BS EN 206, 2013).

Cement Content and Target Strength

A fixed cement content of 320 kg/m³ was selected in line with Eurocode 2 recommendations for achieving a target compressive strength of C25/30.

Mix Quantification

Batch quantities for each experimental run were computed using the CCD output matrix. A sample of the calculated ingredient quantities is shown in Table 6 (extracted from the original analysis). Values were rounded to suitable laboratory batch sizes.

Randomization

Experimental runs were conducted in random order to minimize systematic bias, following Montgomery (2017). The CCD matrix included factorial, axial, and center runs, represented in two-dimensional (2D) and three-dimensional (3D) response surfaces (Figures 7 and 8 in the supplied document).

Mixing Procedure

Concrete materials were weighed for each batch according to the mix proportions and CCD specifications. The procedures included:

Dry mixing of cement, fine aggregate, and coarse aggregate. Introduction of water calculated based on w/c ratio. Preparation of SAS solutions corresponding to specified dosages. Uniform incorporation of SAS solution into the mixing water. Mechanical mixing until homogeneity was achieved. Mix consistency and appearance were visually checked before casting.

Workability

Workability was assessed using: Slump test (BS 1881:1993) Compacting factor test (for low- to medium-workability mixes)

These were performed immediately after mixing to evaluate the influence of sap dosage and water-cement ratio.

Moulding and Curing Specimens were cast in: 100 × 100 × 100 mm cubes (compressive strength, density) 100 × 100 × 500 mm prisms (flexural strength) 100 × 100 × 300 mm cylinders (splitting tensile strength)

Moulds were oiled, filled in layers, and compacted using a vibrating table per ASTM C192 (1982). After 24 hours, specimens were demoulded and placed in water tanks for curing at 3, 7, 28, 56, 90, and 180 days.

Hardened Concrete Tests

Density was determined at various curing ages by measuring the mass and volume of hardened cubes.

Compressive strength was tested following EN 12390-3 (2009). The loading rate was maintained at $0.6 \pm 0.2 \text{ N/mm}^2/\text{s}$.

Flexural strength was evaluated using three-point bending on prism specimens, per EN 12390-5 (2009).

Splitting tensile strength tests were performed using the indirect tension method specified in EN 12390-6 (2009). Plywood bearing strips were placed to distribute load uniformly.

All tests followed appropriate EN or BS standards to ensure accuracy and repeatability.

Table 1: Effect of Sodom Apple Sap and Water Cement Ratio on Density Values of Hardened Concrete Cubes Mix C25

Std	Block	Run	Factor 1		Factor 2	Response 1	Response 2	Response 3	Response 4
			A:Sodom apple sap	B:Water cement ratio		Density at 7 days	Density at 28 days	Density at 56 days	Density at 90 days
	C25		%	%		Kg/m ³	Kg/m ³	Kg/m ³	Kg/m ³
1	Block	1	0.5	0.45		34.1	24.3	24.4	24.5
7	Block	2	1	0.429289		24.05	24.25	24.35	24.45
2	Block	3	1.5	0.45		23.85	24.05	24.15	24.25
10	Block	4	1	0.5		23.95	24.15	24.25	24.35
6	Block	5	1.70711	0.5		23.9	24.1	24.2	24.3
12	Block	6	1	0.5		23.85	24.05	24.15	24.25
13	Block	7	1	0.5		23.72	23.85	23.95	24.05
5	Block	8	0.292893	0.5		23.75	23.95	24.05	24.15
9	Block	9	1	0.5		23.6	23.8	23.9	24
11	Block	10	1	0.5		23.55	23.75	23.85	23.95
8	Block	11	1	0.570711		23.35	23.55	23.65	23.75
3	Block	12	0.5	0.55		23.45	23.65	23.75	23.85
4	Block	13	1.5	0.55		23.65	23.75	23.85	23.95
14	CM	14	0	0.5		34.1	24.3	24.4	24.5

Table 2: Effect of Sodom apple sap on the compressive strength properties

Std	Block	Run	A:Sodom apple sap	B:Water cement ratio	Compressive strength at 7 days	Compressive strength at 28 days	Compressive strength at 56 days	Compressive strength at 90 days
			%	%	N/mm ²	N/mm ²	N/mm ²	N/mm ²
1	Block 1	1	0.5	0.45	17.0	27.0	42.0	47.0
7	Block 1	2	1	0.429289	20.0	29.0	44.0	49.0
2	Block 1	3	1.5	0.45	20.0	31.0	46.0	51.0
10	Block 1	4	1	0.5	21.0	32.0	46.0	52.0
6	Block 1	5	1.70711	0.5	19.0	29.0	44.0	49.0
12	Block 1	6	1	0.5	21.0	32.0	46.0	52.0
13	Block 1	7	1	0.5	21.0	32.0	46.0	52.0
5	Block 1	8	0.292893	0.5	15.0	25.0	40.0	46.0
9	Block 1	9	1	0.5	21.0	32.0	46.0	52.0
11	Block 1	10	1	0.5	21.0	32.0	46.0	52.0
8	Block 1	11	1	0.570711	21.0	32.0	46.0	52.0
3	Block 1	12	0.5	0.55	16.0	26.0	41.0	46.0
4	Block 1	13	1.5	0.55	17.0	27.0	42.0	47.0
14	CM	14	0.0	0.5	31.0	41.0	43.0	46.0

Table 3: Effect of Sodom Apple Sap and Water Cement Ratio at Various Dosage on Flexural Strength Properties

Std	Block	Run	Sodom apple sap (%)	Water cement ratio	Flexural strength at 7 days (N/mm ²)	Flexural strength at 28 days (N/mm ²)
1	Block	1	0.5	0.45	3.7	5.1
7	Block	2	1.0	0.429289	3.9	5.3
2	Block	3	1.5	0.45	4.0	5.4
10	Block	4	1.0	0.5	3.9	5.3
6	Block	5	1.70711	0.5	3.8	5.1
12	Block	6	1.0	0.5	3.9	5.3
13	Block	7	1.0	0.5	3.9	5.3
5	Block	8	0.292893	0.5	3.6	4.7
9	Block	9	1.0	0.5	3.9	5.3

Std	Block	Run	Sodom apple sap (%)	Water cement ratio	Flexural strength at 7 days (N/mm ²)	Flexural strength at 28 days (N/mm ²)
11	Block	10	1.0	0.5	3.9	5.3
8	Block	11	1.0	0.570711	3.9	5.3
3	Block	12	0.5	0.55	3.3	4.7
4	Block	13	1.5	0.55	3.6	5.0
C	Block	14 (Ctrol)	0.0	0.5	3.5	4.9

Table 4: Splitting Tensile Strength of Hardened Concrete at 7 and 28 Days

Std	Block	Run	Factor 1	Factor 2	Response 5	Response 6
			A:Sodom apple sap	B:Water cement ratio	Splitting tensile strength at 7 days	Splitting tensile strength at 28 days
			%	%	N/mm ²	N/mm ²
1	Block	1	0.5	0.45	2.7	3.0
7	Block	2	1	0.429289	2.8	3.1
2	Block	3	1.5	0.45	2.8	3.1
10	Block	4	1	0.5	2.8	3.1
6	Block	5	1.70711	0.5	2.5	2.7
12	Block	6	1	0.5	2.8	3.1
13	Block	7	1	0.5	2.8	3.1
5	Block	8	0.292893	0.5	2.4	2.6
9	Block	9	1	0.5	2.8	3.1
11	Block	10	1	0.5	2.8	3.1
8	Block	11	1	0.570711	2.8	3.1
3	Block	12	0.5	0.55	2.5	2.8
4	Block	13	1.5	0.55	2.6	2.9
14	c/m	14	0.00	0.5	2.2	2,5

Density

As seen in Table.1 and Fig 4.The density evolution of concrete incorporating Sodom apple sap (SAS) shows consistent trends across varying dosages and water-cement ratios. At moderate dosages (0.5–1.0%) and lower w/c ratios (0.429–0.45), densities at 28–90 days ranged from 23.95–24.45 kg/m³, values comparable to the control mix, which recorded 24.30–24.50 kg/m³. This indicates that SAS does not adversely affect compactness when used within optimal ranges.

Lower w/c ratios consistently produced higher densities due to reduced pore volume and improved hydration product packing. Mixes such as Run 2 (1.0% SAS at w/c = 0.429) exhibited enhanced density, supporting findings that moderate bio-admixture incorporation can refine pore structures (Joseph, 2025; Akinwumi & Adeyemi, 2023).

Conversely, higher SAS dosages ($\geq 1.5\%$) combined with elevated w/c ratios (0.50–0.55) resulted in slight density reductions (23.55–23.95 kg/m³). This behavior is attributed to excess organic matter inhibiting cement hydration, aligning with previous observations on overdosing natural admixtures (Ali & Brooks, 2020).

Overall, results confirm that SAS at 0.5–1.0% enhances densification, while overdosing or high w/c ratios increase porosity. Eurocode 2 durability expectations for structural concrete remain satisfied

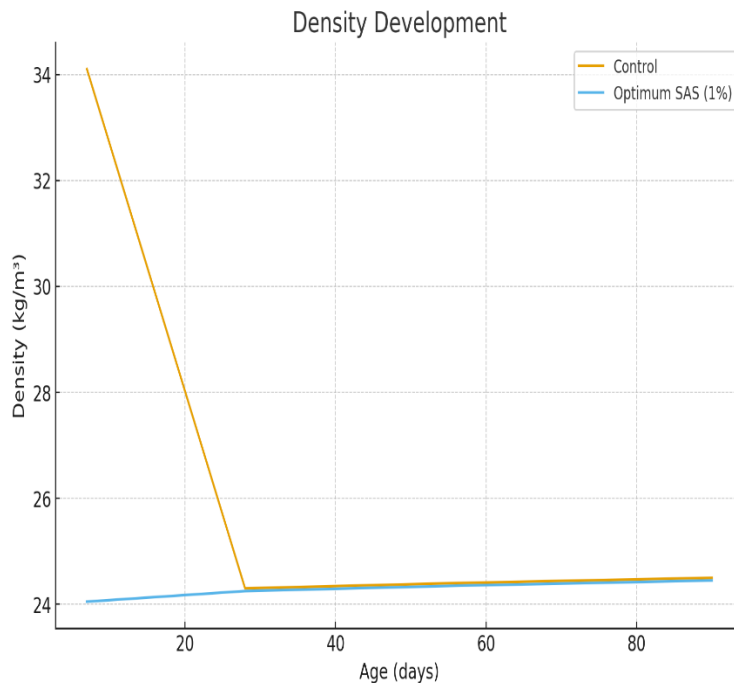


Fig 1 Density against curing age

Compressive strength

As seen in Table 2 and Fig 2. The compressive strength development clearly reflects the dual influence of SAS dosage and w/c ratio. Mixes with 1.0–1.5% SAS and lower w/c ratios (0.429–0.45) achieved the highest strengths, at 90-day values reaching 49–52 N/mm², surpassing the control (46 N/mm²).

Run 3 (1.5% SAS at w/c 0.45) showed the peak performance: at 28 days: 31 N/mm², at 90 days: 51 N/mm²

These enhancements support earlier findings that bio-based admixtures can improve hydration kinetics at later ages, densify microstructures, and refine pore networks (Olutoge et al., 2021; Onuaguluchi & Banthia, 2016).

However, higher SAS dosages combined with higher w/c ratios (Runs 5 and 13) as shown in Table 2, reduced strengths to (29–47 N/mm²), suggesting hydration retardation due to organic compound excess.

Most importantly, all SAS modified mixes met or exceeded the Eurocode C25/30 requirement at 28 days, confirming structural suitability. The trend is consistent with the classical w/c–strength relationship and validates the optimum SAS range of 1.0–1.5%.

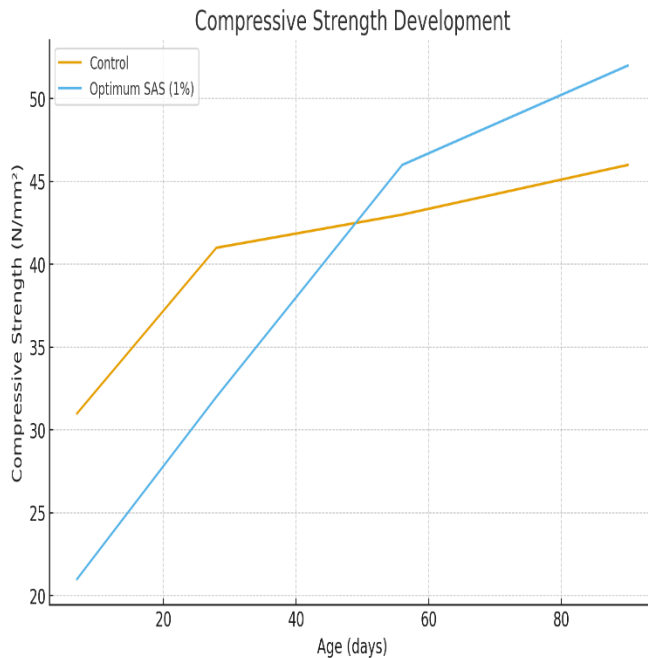


Fig: 2 Compressive strength against curing age

Flexural strength

Table 3 and Fig 3 clearly shown that, Flexural strength increased between 7 and 28 days across all mixes, reflecting ongoing hydration and ITZ refinement. Control flexural strength at 28 days was 4.9 N/mm², while SAS-modified mixes achieved values between 5.1–5.4 N/mm² within the optimal dosage range.

Best performance: 1.5% SAS at w/c 0.45 → 5.4 N/mm²

Mixes with lower w/c ratios

(0.429–0.45) consistently recorded higher flexural strengths due to reduced capillary voids and stronger aggregate–paste bonding. Very low (0.29%) or high (1.7%) SAS dosages exhibited slight reductions, confirming a critical effective dosage range.

All measured values fall within or above the typical range for C25/30 concrete according to Eurocode, indicating compliance with structural requirements.

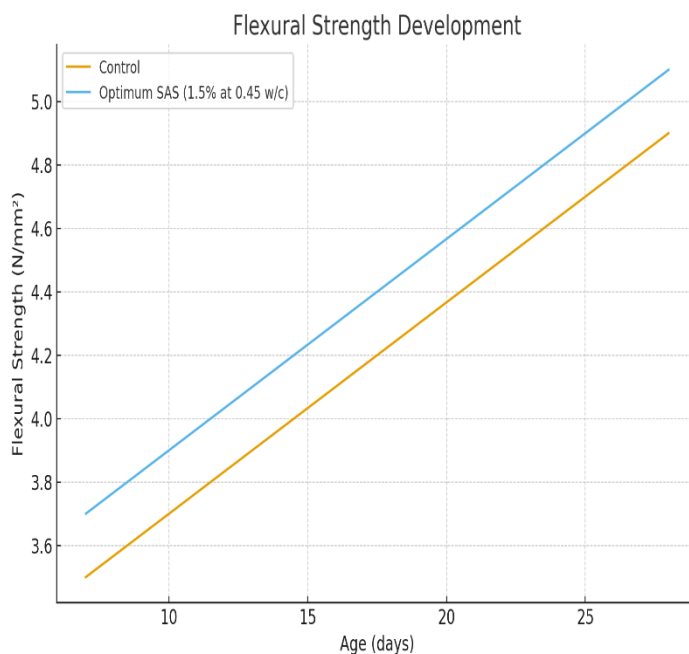


Fig 3: Flexural strength Against curing age

Splitting tensile strength

Splitting tensile strength exhibited moderate increases from 7 to 28 days across all mixes.

SAS-modified concretes showed improved tensile performance relative to the control shown in Table 4. and Fig 4

Control (28 days): 2.5 N/mm², SAS-modified mixes: 2.8–3.1 N/mm², (for 0.5–1.5% dosages)

The enhancements are linked to: Improved cohesion within the cement matrix, reduced microcracking, Enhanced ITZ due to bio-polymeric compounds

These results agree with published findings on plant-based admixtures improving tensile-related properties by refining pore connectivity (Akinyemi & Bamigboye, 2023). Excessive dosage (1.7%) produced a gradual reduction (2.7 N/mm^2), consistent with hydration interference at high organic load.

All tensile strength values meet Eurocode expectations for C25/30 mean tensile strength ($\sim 2.6 \text{ N/mm}^2$).

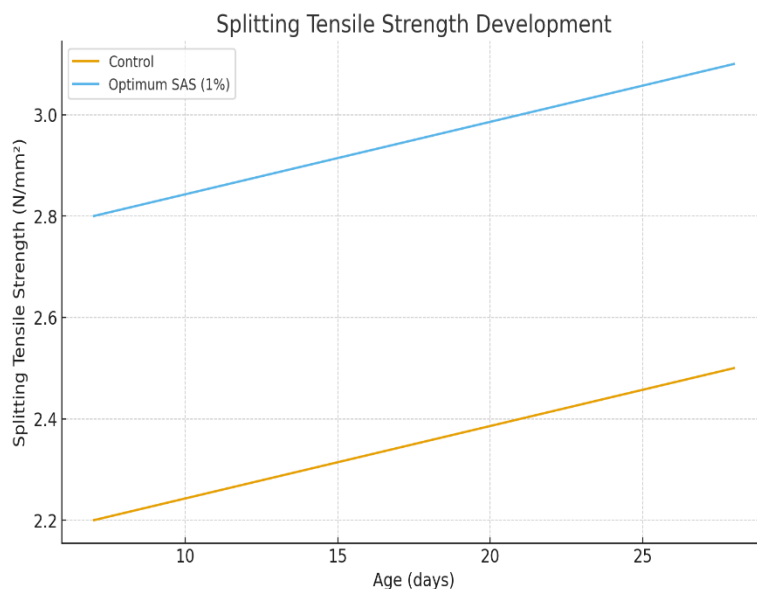


Fig 4: Splitting tensile strength against curing age

Concrete Exposed to 5% Na_2SO_4 (Sulphate Solution)

The SEM micrograph of the control concrete (Fig. 5a) shows a matrix dominated by large voids and wide capillary pores, with a weak and poorly bonded interfacial transition

zone (ITZ). The aggregates appear detached from the surrounding paste, illustrating low sulphate resistance. At 0.5% SAS, the microstructure (Fig. 5b) exhibits noticeable pore refinement, where capillary voids seen in the control convert into micropores. The ITZ becomes more compact, and early formation of C-S-H gel becomes visible. This improvement suggests that SAS enhances hydration and early densification. The SEM image of 1% SAS concrete (Fig. 5c) shows the densest and most uniform morphology among all mixes. Needle-shaped ettringite, well-distributed C-S-H gel, and tightly packed micropores dominate the matrix. The ITZ appears significantly strengthened, reflecting reduced permeability and improved resistance to sulphate ingress. The structured and non-expansive ettringite crystals indicate a controlled sulphate reaction, not a destructive one. At 1.5% SAS, the microstructure (Fig. 5d) reveals increased gel phases, including both C-S-H and M-S-H, along with ettringite. Although these hydration products are beneficial, slight microcrack openings indicate that excessive sap may reduce uniformity. Nevertheless, the overall microstructure remains far denser than the cont

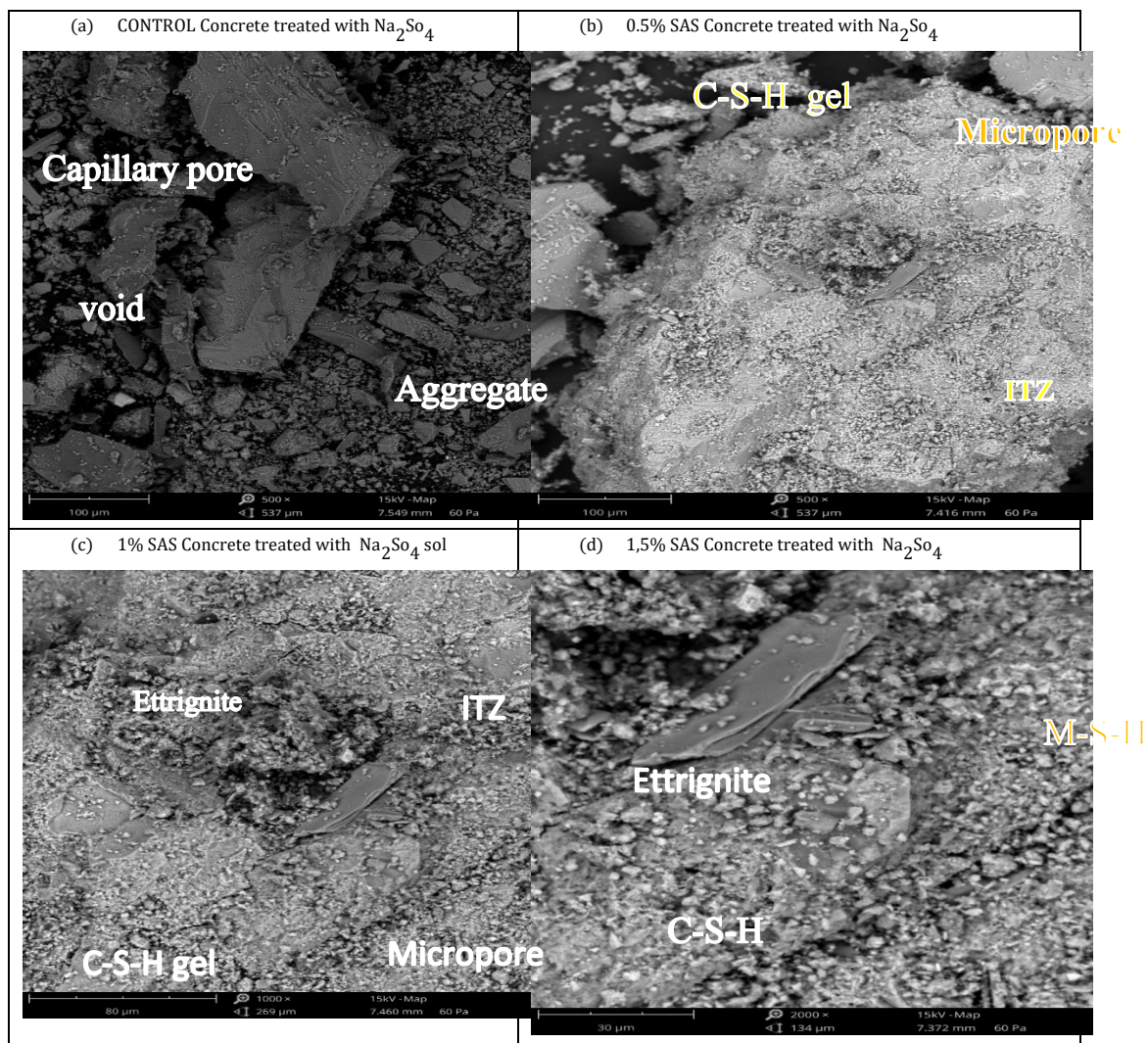


Fig 5 Morphology of Concrete treated with 5% sulphate solution at varying concentration of Sodom Apple Sap

Concrete Exposed to Acid (HCl Solution)

The SEM morphology of the acid-treated control concrete (Fig. 2a) shows severe deterioration. The ITZ is visibly degraded, with large voids, widened pores, and loss of cementitious compounds. This confirms the aggressive decalcification effect of HCl. At 0.5% SAS, the image (Fig. 2b) reveals more micropores and early C-S-H gel formation compared to the control. The ITZ becomes more refined, suggesting that SAS begins to shield the matrix from acid attack. The 1% SAS concrete (Fig. 2c) shows the most improved matrix under acid exposure. Dense C-S-H gel, stable ettringite, compact ITZ, and limited microvoids are clearly visible. The morphology illustrates substantial

resistance to HCl attack due to the protective polymeric components introduced by SAS. For 1.5% SAS, the SEM micrograph (Fig. 2d) shows extensive formation of C-S-H, M-S-H and fine ettringite crystals. Although densification improves, a few dispersed microvoids indicate slight overreaction of the organic components at higher doses.

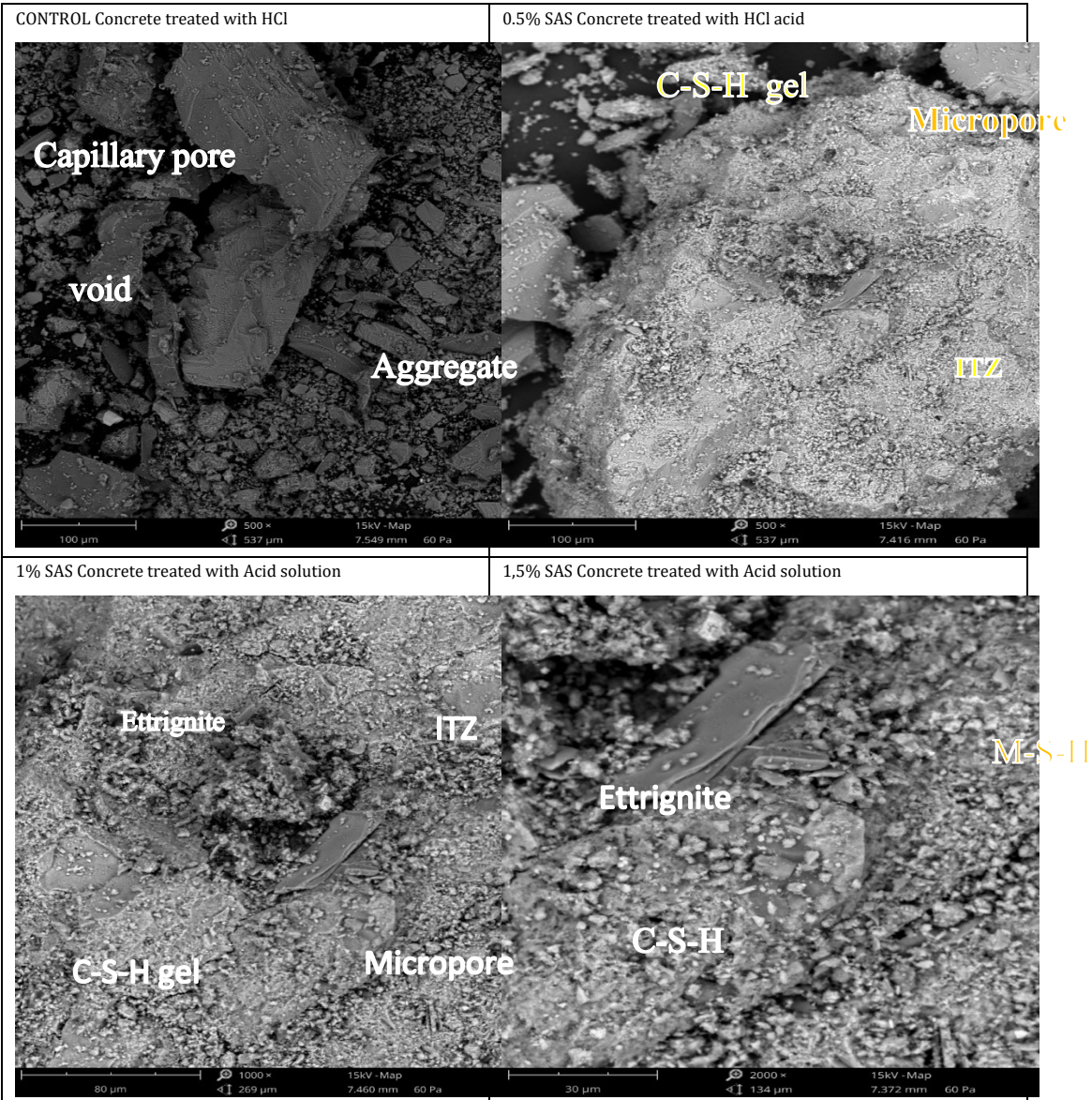


Fig 6 Morphology of Concrete treated with Acid solution at varying concentration of Sodom Apple Sap

XRD of Control Concrete

The control XRD pattern in Fig. 7 shows lower Portlandite (2.3%) and lower Calcite (3.3%) compared to SAS-modified samples. The reduced portlandite implies weaker

hydration activity, while the low calcite shows limited matrix stabilization. This correlates directly with the porous and weak SEM morphology seen in Fig. 1a and Fig. 2a.

Quantitative analysis report
Multiple Profile

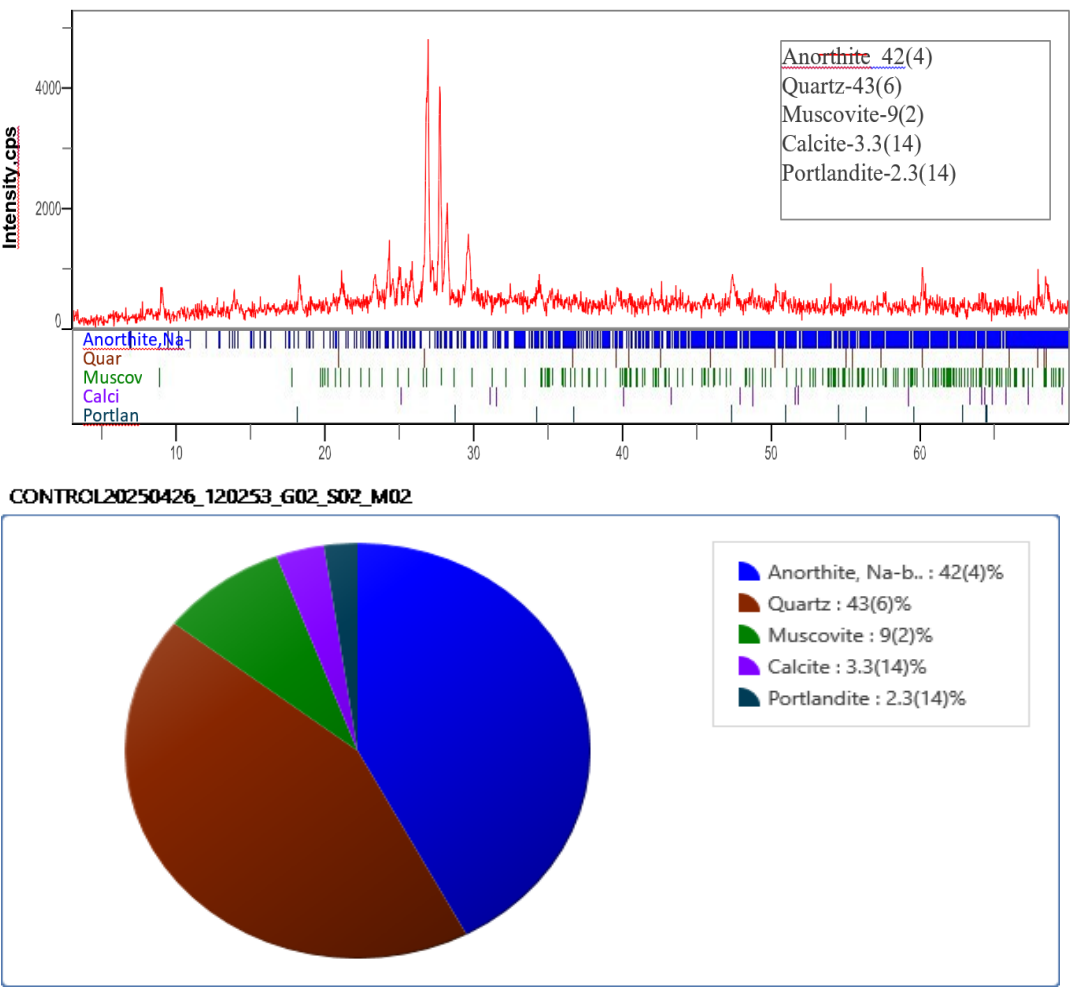
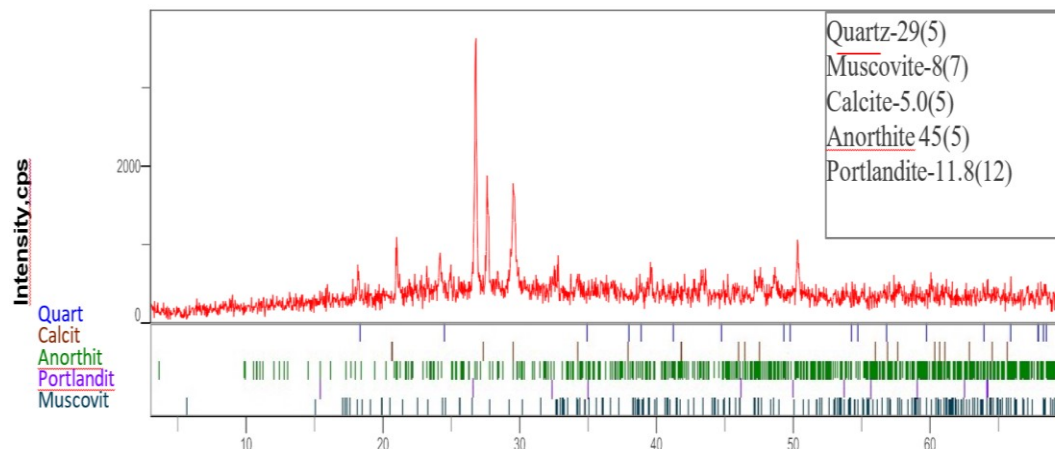


Fig 7

XRD Pattern of 1% SAS Concrete (Fig. 8)

The XRD quantitative report in Fig. 8 shows dominant crystalline phases including Calcite (29%), Anorthite (45%), Portlandite (11.8%), and Muscovite (8%). The high anorthite suggests improved silicate gel formation, while the moderate portlandite level indicates active hydration. The relatively high calcite content reflects beneficial stabilization through carbonation. This mineralogical profile is consistent with the dense microstructure observed in Fig. 1c and Fig. 2c.

Quantitative analysis report
Multiple Profile



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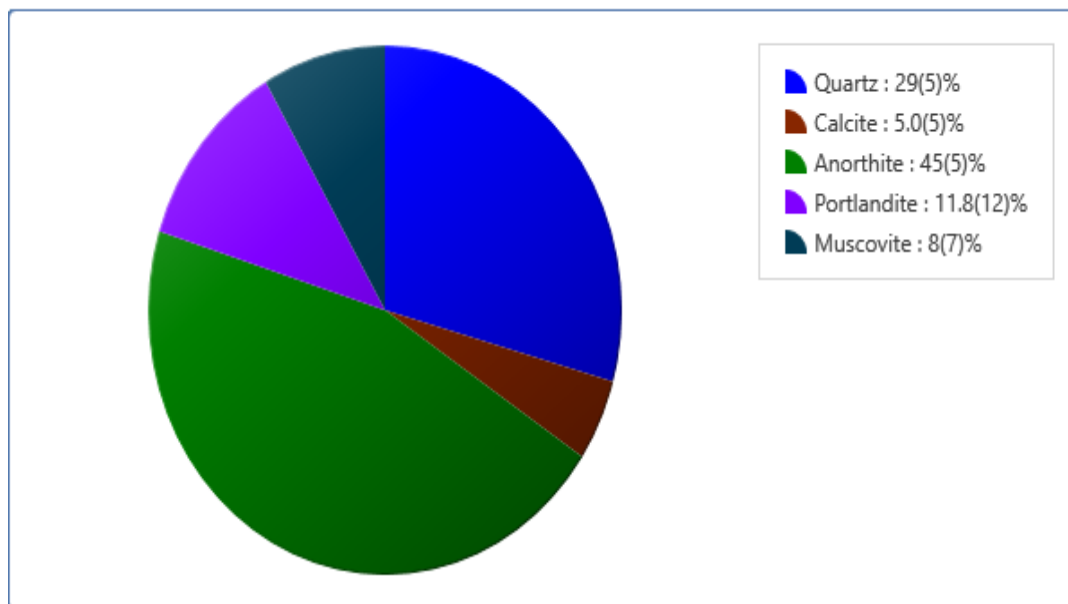


Fig 8

XRD of Concrete Treated with Na_2SO_4 Solution (Fig. 9)

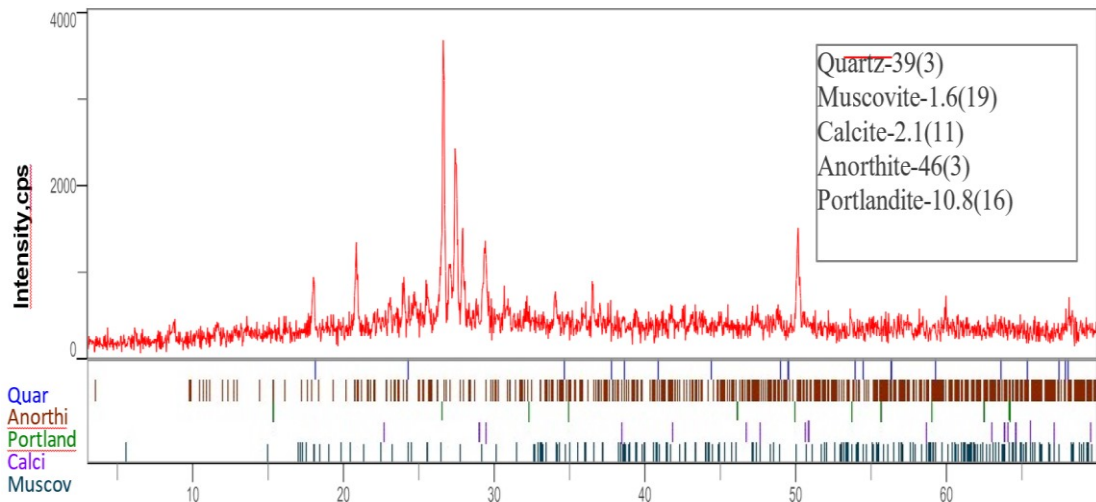
The mineral composition in Fig. 9 includes high Quartz (39%) and Anorthite (46%), along with Portlandite (10.8%). The low calcite content (2.1%) suggests limited carbonation. The abundance of anorthite indicates strong reaction between SAS-modified hydration products and sulphate ions.

This corresponds to the strong and compact microstructure seen in Fig. 1c.

Quantitative analysis report

General information

Multiple Profile



Na2SO420250426_120253_G03_S03_M03

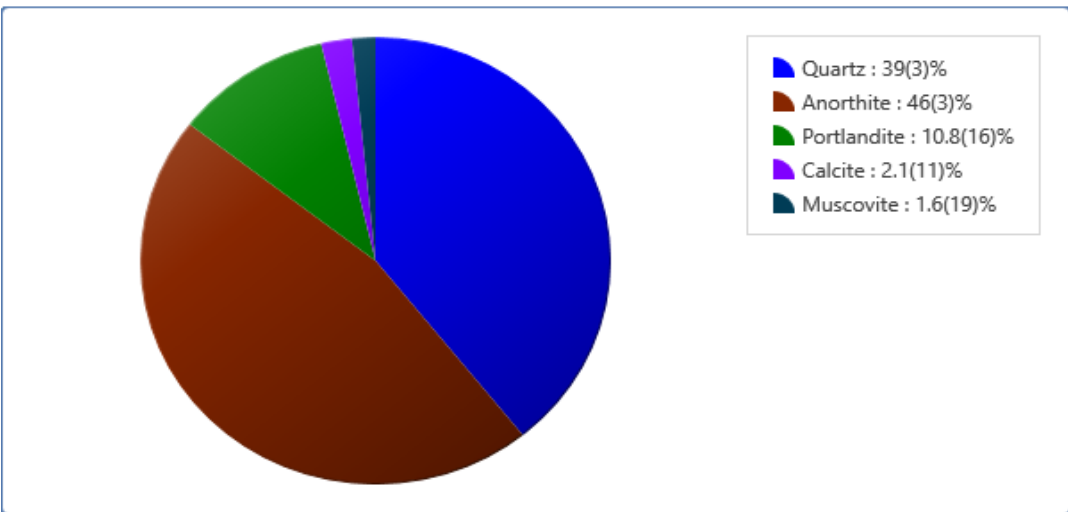


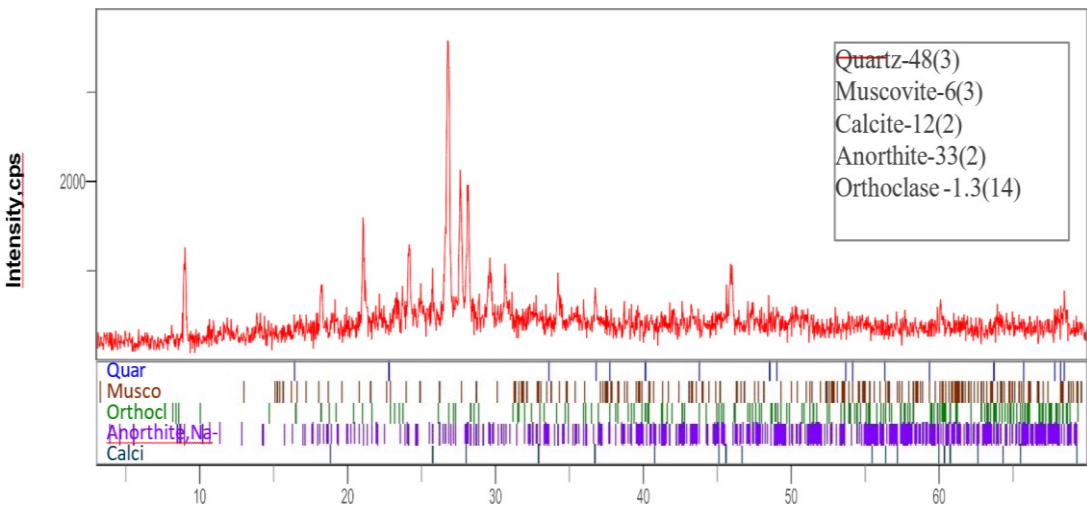
Fig 9

XRD of Concrete Treated with NaCl Solution (Fig. 10)

The XRD pattern in Fig. 10 reveals: High Quartz (48%), Anorthite (33%), Calcite (12%), Muscovite (6%), Orthoclase (1.3%)

The presence of orthoclase and high quartz indicates stable inert phases, while increased calcite suggests carbonation-assisted densification. These results confirm that SAS enhances chloride resistance by producing more stable phases—consistent with the dense morphology seen in SEM.

Quantitative analysis report
Multiple Profile



Plot of results

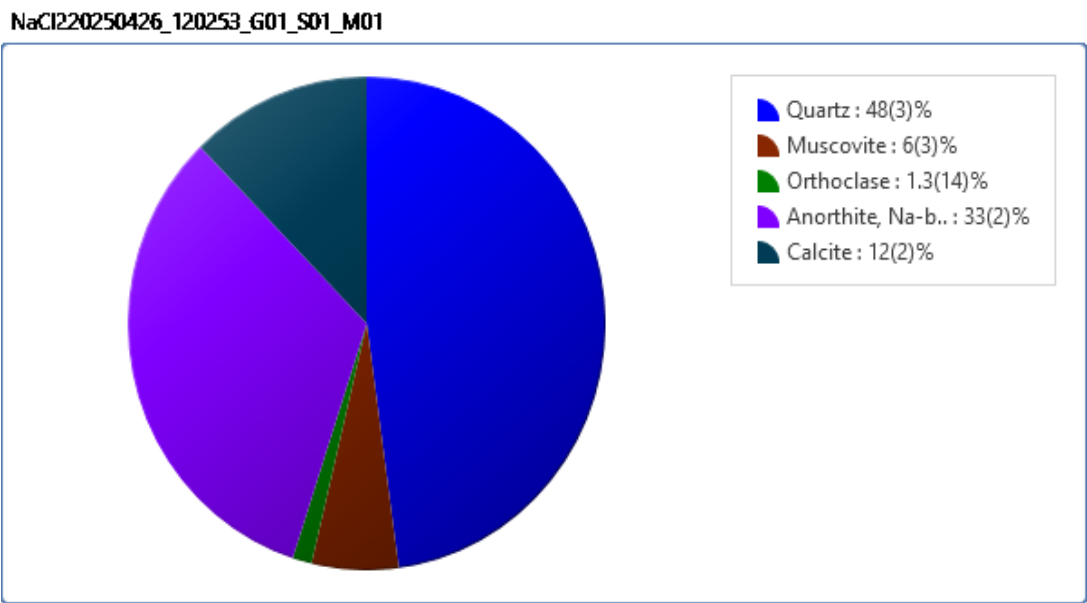


Fig 10

CONCLUSION

Across all performance indicators (density, compressive strength, flexural strength, tensile strength):

Optimum SAS dosage = 1.0%. This range produced: Higher density Improved compressive strength (up to 52 N/mm²) Higher flexural strength (up to 5.4 N/mm²) Higher splitting tensile strength (up to 3.1 N/mm²)

High w/c ratios (≥ 0.55) or overdosing ($\geq 1.7\%$) reduced performance due to increased porosity and interference with hydration. All mixes met Eurocode 2 (EN 1992-1-1) minimum requirements, confirming structural suitability.

Figure 1 clearly demonstrates that 1% SAS produces the most compact and sulphate-resistant microstructure, with optimum formation of C-S-H and controlled ettringite crystals. Figures in Fig. 2 reveal that 1% SAS remains the optimum concentration for acid resistance, with the highest gel formation and ITZ integrity.

The correlation between the SEM Figures (1–2) and the XRD Figures (3–6) confirms that: 1% SAS produces the most chemically stable and densified concrete matrix. Figures 1c and 2c show dense C-S-H and controlled ettringite, consistent with the strong mineral phases in Fig. 3. Control samples in Fig. 1a, Fig. 2a, and Fig. 6 consistently show weak hydration and poor durability.

RECOMMENDATIONS

Based on the experimental results and analytical findings of this study, the following recommendations are proposed to guide practical application, quality control, and further research on the use of Sodom apple sap (*Calotropis procera*) as a natural admixture in concrete:

Practical Recommendations for Field Application

- i. **Optimum Dosage:** The study identifies 1.0–1.5% Sodom apple sap (by weight of cement) as the most effective dosage range for improving density, compressive strength, flexural strength, and splitting tensile strength. These dosages should be adopted in practical applications for structural concrete of grade C25/30.
- ii. **Water–Cement Ratio Control:** For best performance, the water–cement ratio should be maintained between 0.45 and 0.50. Higher ratios (≥ 0.55) negatively affect porosity, density, and strength, even with the addition of sap.
- iii. **Mixing Procedure:** Sodom apple sap should be dissolved thoroughly in the mixing water before introduction to the concrete mixer. Uniform distribution improves hydration control and reduces the risk of localized organic concentration.
- iv. **Suitability for Normal Structural Works:** Concrete modified with optimum SAS dosages meets and exceeds the Eurocode 2 strength requirements for C25/30 and is therefore recommended for beams, slabs, columns, and general reinforced concrete applications.
- v. **Curing Requirements:** Prolonged curing up to 56–90 days further enhances the benefits of SAS due to its late-age strength development characteristics. Adequate curing should be emphasized, particularly in hot and dry climates.

Durability and Performance Considerations

- i. **Use in Aggressive Environments:** Based on reduced porosity and improved strength, SAS-modified concrete shows potential for use in environments prone to moderate chemical attack. However, durability-specific tests such as chloride penetration and sulphate resistance should be conducted for final validation.
- ii. **Avoid Overdosing:** Dosages above 1.5% should be avoided as they may introduce excessive organic content that retards hydration, reduces density, and lowers mechanical performance.
- iii. **Compatibility with Other Admixtures:** Where chemical or mineral admixtures are included, compatibility tests should be conducted to ensure that interaction effects do not compromise workability or strength development.

Policy and Economic Recommendations

- i. **Promotion of Local Bio-Admixtures:** Government and regulatory bodies should encourage the use of locally sourced, non-edible admixtures, such as Sodom apple sap, to reduce dependence on expensive imported admixtures.
- ii. **Development of Local Standards:** Standards organizations should consider developing guidelines for extraction, preparation, and quality control of Sodom apple sap used in concrete production.
- iii. **Training and Awareness:** Construction professionals should be sensitized on proper sap preparation, dosage control, and mix design adaptation to maximize the sustainability benefits.

Recommendations for Future Research

- i. **Long-term Durability Studies includes:** Investigate the effects of SAS on: Chloride ingress. Carbonation depth, Freeze-thaw cycles, Sulphate and acid attack under extended exposure
- ii. **Microstructural Analysis includes:** Employ SEM, XRD, FTIR, and TGA analyses to elucidate the interaction between sap constituents and cement hydration products.
- iii. **Behavior in High-Performance Concrete includes:** Evaluate the suitability of SAS in: High-strength concrete (HSC), Self-compacting concrete (SCC), Fiber-reinforced concrete
- iv. **Optimization through Multi-Factor RSM includes:** Incorporate additional factors such as curing temperature, aggregate type, and chemical admixture interaction for advanced optimization.

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