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MICROSTRUCTURAL ANALYSIS AND MECHANICAL PROPERTIES OF SISAL FIBRE IN HIGH-PERFORMANCE CONCRETE

MIKROSTRUKTURNE ANALIZE IN MEHANSKE LASTNOSTI SISALOVIH VLAKEN V VISOKO KAKOVOSTNEM BETONU

K. B. Shoba[1], Pachaivannan Partheeban[2*], C. Chella Gifta[3], Felix Kala T.[4]

[1]School of Architecture, St. Peter's College of Engineering and Technology, Chennai, Tamilnadu, India
[2]Department of Civil Engineering, Chennai Institute of Technology, Chennai, Tamilnadu, India.
[3]Department of Civil Engineering, National Engineering College, Kovilpatti, Chennai, Tamilnadu, India
[4]Department of Civil Engineering, Dr. MGR Educational and Research Institute, Chennai, Tamilnadu, India

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Natural fibre-reinforced concrete has gained attention in recent years as a sustainable solution in the construction industry. This study examines sisal fibre-reinforced concrete's mechanical and microstructural properties, developed with a high-strength concrete matrix. To enhance the characteristic strength of the concrete, sisal fibre was incorporated as a reinforcing element in the matrix to produce high-performance natural fibre-reinforced concrete. Sisal fibre was added in various proportions, i.e., 0.5 %, 1 %, 1.5 %, and 2 % by volume fraction, and fibre-reinforced concrete samples were cast and tested to explore the mechanical properties, including compressive strength, tensile strength and flexural strength. Microstructural analyses, such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD), were conducted to study the surface structure of the concrete. According to the findings, 1 % sisal fibre provides the highest compressive strength in concrete production. Similar to other types of fibres, adding sisal fibres enhanced the strength of the concrete up to an optimal level. Split tensile and flexural strength results indicate the effective reinforcement sisal fibres provide. Microstructural studies revealed an enhanced fibre-matrix bond, reduced porosity, and improved fibre-bridging effects. The results of this study support the potential of using sisal fibre to produce stronger concrete with reduced environmental impact. Sisal fibre-reinforced concrete can be used in suitable engineering applications, promoting sustainability in the construction industry.

Keywords: environmentally friendly, mechanical properties, micro-structural analysis, and sisal fibre

Z naravnimi vlakni ojačan beton v zadnjih letih privlači pozornost kot trajnostna, okolju prijazna rešitev v gradbeni industriji. V tem članku avtorji predstavljajo študijo mehanskih in mikrostrukturnih lastnosti betona ojačanega z naravnimi Sisalovimi vlakni (vlakna listov mehiške agave) vgrajenimi v betonsko matrico z visoko trdnostjo. Da bi avtorji izboljšali trdnostne lastnosti betona so Sisalova vlakna vgrajevali v betonsko matrico v različnih volumskih deležih: 0,5 %, 1 %, 1,5 %, in 2 %. Preizkušance iz tako izdelanega kompozitnega betona so ulili v modele in po utrjevanju ugotavljali njihove mehanske lastnosti (tlačno, cepilno in natezno trdnost). Mikrostrukturno analizo prelomov površine preizkušancev so izvajali s pomočjo vrstične elektronske mikroskopije (SEM) in rentgenske difrakcijske spektroskopije (XRD). Na osnovi preiskav so avtorji ugotovili, da ima beton z dodatkom 1 % Sisalovih vlaken najvišjo tlačno trdnost. Podobno tudi druge vrste vlaken, tako kot dodatek Sisalovih vlaken, vplivajo na trdnost izdelanega betona. Izmerjene vrednosti za cepilno in upogibno trdnost betona, kažeta na učinkovitost Sisalovih vlaken za ojačitev betona. Mikrostrukturne analize so pokazale izboljšanje kohezije med matrico in vlakni, manjšo poroznost betona in izboljšan (zmanjšan) učinek nastanka mostičkov med vlakni (angl.: Fibre-bridging effects). Rezultati raziskave podpirajo tezo za potencialno uspešno uporabo Sisalovih vlaken v proizvodnji visokotrdnega betona z istočasnim zmanjšanjem negativnega vpliva na okolje. Kompozitni beton ojačan s Sisalovimi vlakni se lahko uporablja za primerne inženirske aplikacije in s tem promovira usmeritev gradbene industrije k uporabi okolju prijaznih materialov.

Ključne besede: okolju prijazni materiali, mehanske lastnosti, mikro strukturne analize, Sisalova vlakna

1 INTRODUCTION

Modern civil-engineering technology has led to a growing demand for high-performance materials with superior characteristics, such as high strength, improved tensile resistance, energy absorption, and toughness. One of the primary limitations of concrete is its inherent weaknesses, including low durability, high shrinkage, and limited resistance to impact loads. These deficiencies can be addressed by integrating randomly distributed fibres, whether metallic, synthetic, or natural, into the concrete mix. The addition of fibres enhances the overall performance of concrete, helping to overcome its inherent shortcomings. However, synthetic fibres tend to be expensive, and their production is energy-intensive, posing significant risks to human health. Steel fibres are popular and widely used to enhance the impact resistance of concrete, increasing it by 4 to 18 times, regardless of the type of concrete. However, the production of these man-made fibres involves the extraction of natural resources and is highly energy consuming. On the other hand, polypropylene (PP) fibers have gained interest due to their resistance to shrinkage, enhanced toughness, and

*Corresponding author's e-mail:
parthi011@yahoo.co.in (Pachaivannan Partheeban)

impact resistance. However, being hydrocarbons, their excessive use contributes to the depletion of natural resources and greenhouse-gas emissions. As a result, there is growing interest in plant fibres as environmentally friendly alternatives in civil engineering. Plant fibres offer several key benefits, including wide availability, low cost, renewability, decomposing without causing environmental harm, and an eco-friendly production process that requires minimal energy.[1]

Sisal fibre is naturally biodegradable, and its manufacturing process generates less environmental pollution compared to synthetic fibres, which contribute to waste accumulation.[2] It is easily produced with minimal environmental impact, as its processing requires fewer chemical treatments, thereby reducing contamination and health risks.[3] Furthermore, sisal fibre is highly cost-effective due to its abundant availability and low production costs compared to synthetic alternatives. Since it is derived from agricultural waste, incorporating it into concrete helps to reduce overall material expenses.

Due to these advantages, natural fibres are gaining attention as a sustainable option for enhancing the performance of concrete in civil-engineering projects. As a result, researchers are exploring natural fibres as a potential solution to increase the durability and strength of concrete. Sisal, a type of hard fibre extracted from the leaves of agave plants, is particularly common. Sisal fibres in ultra-high-performance concrete (UHPC) at up to 2.0 % volume fraction and 18-mm length have increased flexural strength by 14.7 % and toughness by 540 %. The increased bonding area leads to higher pull-out loads and effectively bridges cracks, demonstrating excellent performance in UHPC composites.[4]

The remarkable mechanical properties, renewable nature, and widespread availability of sisal set it apart from other fibres.[5–7] With a focus on M50 grade concrete, this study explores the intricate interaction between sisal fibre microstructure and its effects on the mechanical properties of high-performance concrete. The shape, alignment, and interface characteristics of sisal fibres within the concrete matrix are revealed through microstructural analysis, which plays a key role in this study. Various methods, including scanning electron microscopy (SEM) and X-ray diffraction (XRD), are used to examine the complex relationships between fibre dispersion, orientation, and bonding within the matrix.[8] Understanding these microstructural intricacies allows researchers to better comprehend how stress is transferred, how cracks propagate, and the overall reinforcing efficiency of the fibres. Incorporating sisal fibres and nano iron oxide particles into electronic plastic waste (EWP) concrete results in improvements of approximately 15.81 % in compressive strength, 22.80 % in splitting tensile strength, 21.75 % in flexural strength, and 28.79 % in bi-surface shear strength. The durability properties, such as water sorpitivity and absorption, decrease by about 8.04 % and 4.52 %, respectively. Additionally, the linear shrinkage of EWP-modified concrete dropped by 28.79 %, while ultrasonic pulse velocity increased by up to 6.5 %, promoting it as an eco-friendly construction material.[9] Wongsa et al. found that reinforcing sisal fibres in high-calcium fly-ash geopolymer composites improved tensile and flexural strength due to sisal fibres' high tensile strength and elastic modulus, with strength values increasing as the fibre's volume fraction increased. Microstructural studies exhibited that the rough surface of natural fibres enhances the bonding between the matrix, contributing to the strength of the matrix.[10] In studies conducted by Naraganti et al., impact resistance improved threefold at the initial crack with 1.5 % sisal fibre content and by 15 times in sisal-steel hybrid fibre combinations.[11] X. Wang et al. recommended incorporating coir or sisal fibres into foam concrete to create durable, high-performance natural fibre-reinforced foam concrete (NFRFC) for a range of engineering applications. They reported that the compressive strength increased by 42.19 % with the addition of 0.3 % natural fibres, though exceeding this optimal level led to enlarged pores and reduced strength, demonstrating the need for moderation in fibre usage to enhance the mechanical properties.[12]

Sisal fibres offer a renewable alternative for reinforcing concrete, contributing to environmentally friendly and energy-efficient solutions to engineering challenges. These natural fibres are ideal for concrete reinforcement due to their high tensile strength, elastic modulus, excellent thermal and acoustic properties, affordability, safety, and ease of accessibility.[13–15] The improvement in strength and ductility is largely attributed to composite action, where the fibres bridge the cracks in the matrix and transfer loads, enabling the formation of a distributed microcrack system. These composite materials are strong enough to serve as load-bearing structural components in various applications, including structural panels, impact and blast resistance, repair and retrofitting, earthquake mitigation, strengthening unreinforced masonry walls, and beam-column connections.[16] Silva et al. found that the high energy absorption values under tension and bending were approximately 45 kJ/m^2 and 22 kJ/m^2, respectively. Microstructural analysis revealed that sisal fibres effectively bridged and arrested cracks in the tensile zone, resulting in enhanced mechanical performance and greater energy-absorption capacity.[17] H. Amjad et al. analyzed the mechanical strength under various loadings, reporting improvements in compressive strength (14 %), split tensile strength (36.8 %), flexural strength (30.9 %), and bi-surface shear strength (25.4 %) compared to the control mixture. Durability improvements included an 18.3 % reduction in water absorption, a 24 % decrease in chloride ion penetration depth, and a 14.1 % resistance to acid attack.[18]

Sisal fibre-reinforced concrete (SFRC) materials presented an ultimate tensile strength double that of plain concrete composites. The failure of composites was followed by a strain-softening response due to the localization and widening of existing cracks. In cement-based composites with a corrugation effect, the ultimate bending load increased by about 260 % in SFRC laminates.[19] Savastano and Agopyan studied the microscopic structure of composites reinforced with sisal fibres and observed that partial cement replacement with pozzolanic materials resulted in a better fibre-matrix bond, with hydration products contributing to improved mechanical properties.[20–22] The surface treatment of sisal fibres reduced the chemical components like hemicellulose and lignin, increased the cellulose crystallinity, and decreased the water-absorption characteristics of natural fibres. Sisal fibre-reinforced mine tailing waste geopolymer concrete exhibited improvements of 43 % in flexural strength, 100 % tensile strength, and 113 % impact strength compared to the unreinforced matrix.[23] Larger sisal fibres effectively control the cracks and enhance reinforced concrete's ductility by delaying macrocrack penetration.[24] Adding smaller sisal fibres (up to 6 mm in length) reduced the flexural strength by 5.2 % to 8.4 %, while increasing fibre length to 18 mm increased flexural strength at a 2 % volume fraction. However, excessive amounts of long fibres decreased the flowability due to inhomogeneous distribution and reduced the flexural strength of the concrete composites.[25]

Furthermore, the mechanical characteristics of sisal fibre-reinforced concrete (SFRC) play a critical role in evaluating its suitability for structural applications and other purposes. Research on the properties of high-strength concrete with the incorporation of sisal fibres still needs to be completed. Therefore, this study aims to clarify how variables such as fibre content, aspect ratio, and distribution affect the performance of M50-grade concrete. The behavior of high-strength concrete is examined through extensive mechanical testing, including tensile, compressive, and flexural strength tests. Most previous research on sisal fibre-reinforced composites has focused primarily on the macro-level properties of hardened concrete, while microstructural studies in high-strength concrete with sisal fibres still need to be made available. This research aims to determine the ideal parameters for enhancing the mechanical strength and durability of SFRC by comparing experimental results with microstructural observations. By bridging the gap between the mechanical properties of sisal fibre in high-performance concrete and microstructural analysis, this study will contribute to the development of durable and sustainable building materials. The findings are expected to pave the way for the broader use of natural fibre-reinforced concrete in engineering applications, improving the built environment and positively impacting sustainability by revealing the intricate interactions between fibre structure, distribution, and mechanical performance.

1.1 Sisal fibre

Sisal fibre is a vascular bundle type of fibre produced by the well-known plant agave sisalana, which is native to southern Mexico. The United Nations Food and Agriculture Organization reported that worldwide production of sisal fibre was roughly 233,700 metric tons in 2022.[1] These fibres are green, lightweight, and biodegradable. Using sisal fibres as reinforcement in concrete has gained popularity in recent years. After undergoing a semi-automatic peeling process, the fibres are mechanically characterized following their extraction from the agave plant's leaves. The mechanical properties of the fibres are evaluated with tensile testing, using gauge lengths ranging from 10 mm to 40 mm. For each gauge length, 15 tensile tests were conducted, yielding average values of 530–630 MPa. Due to their toughness, sisal fibres are often used to make ropes and other products such as paper, fabrics, dartboards, headgear, bags, carpets, and shoes. Also, sisal fibres reinforce fibreglass, rubber, and concrete composite components. Compared to other crops, sisal plants are relatively easy to maintain because they thrive in various soil types. However, they do prefer well-drained soils and are resistant to diseases. The most common method for propagating sisal is using bulbs that grow from flower stalks, blossoms, or runners around the base of the plant. During its 7–8 year lifespan, a mature sisal plant can produce more than 200–250 leaves, each containing 1000–1200 fibre bundles. The leaves are chopped and pounded with a revolving wheel fitted with a dull knife to extract the fibres. Variations in species, climate, and soil conditions can affect the size and quality of sisal fibre.

To maintain a constant aspect ratio of fibre length at 1:50, this study examined the effects of adding different percentages of sisal fibre in varying volume fractions to concrete. The goal was to improve the tensile strength, reduce brittleness, and enhance the resistance to condensation and impact by incorporating short fibres. Sisal fibres have a glossy appearance and are typically creamy white, average 80–120 cm long, and 0.2–0.4 mm in diameter. The investigation aimed to thoroughly explore the significant impact of sisal fibres on high-strength concrete with a target strength exceeding 50 MPa, focusing on transforming the concrete's mechanical and thermal properties. The primary objective was to promote the creation of high-performance concrete by using sisal fibres as a sustainable alternative to traditional reinforcement, thus contributing to more environmentally friendly concrete structures. However, observations revealed that adding sisal fibres directly to the wet mix did not result in an ideal and uniform distribution. Instead, fibre clumping and uneven diffusion within the concrete matrix were noted. Despite this, the study found that incorporating sisal fibres in concrete provides a sustainable and environmentally friendly option, aligning with the growing demand for green building techniques. As

Figure 1: Sisal fibre

shown in **Figure 1**, this study used 40-mm-long sisal fibres to develop the SFRC composite.

The novelty of this research lies in using natural fibres, particularly sisal fibre, which has been commonly used in conventional concrete, but its application in high-performance concrete (HPC) is less widespread. Therefore, this study makes a unique attempt to evaluate the behaviour of sisal fibre composites with fibre content ranging from 0.5 % to 2.0 % by volume in high-performance, high-strength concrete. In sustainable construction, this study may lead to the development of innovative material combinations. It provides a comprehensive understanding of the microstructural interactions between sisal fibres and the HPC matrix, offering insights that could improve the design specifications of fibre-reinforced concrete. The results of this research offer experimental evidence of the enhancement of mechanical properties and microstructural characteristics, specifically in HPC reinforced with sisal fibres. This study serves as a valuable reference for future research and promotes the use of sisal fibre in green building practices. It aligns with global trends in sustainable construction materials.[26]

2. EXPERIMENTAL INVESTIGATION

2.1 Materials and Mix Design

Concrete is a hard material from a cementitious medium embedded with aggregate and other admixtures. The following materials were used in this study to develop composites. Commercially available Ordinary Portland Cement (OPC) 53 grade, by the IS 12269-2013 [27] specification, was used as the primary binder (90 %) in the concrete's development. To increase the workability of the fresh concrete mixture, fly ash conforming to IS 3812 – 2013 [28] was added up to 10 % as a supplementary cementitious material. Manufactured sand and coarse aggregate, sourced from local quarries, were used as the main aggregate components in the concrete. The maximum size of the coarse aggregate was 20 mm, with water absorption, specific gravity, and dry rodded density measured at 0.3 %, 2.92, and 1793 kg/m^3, respectively. Fine aggregate, with a particle size between 4.75 mm and 0.075 mm, had a specific gravity of 2.68 and an absorption rate of 1.28 %. Tap water available on our campus was used to prepare and cure the specimens.

A polycarboxylic ether-based high-range water-reducing admixture with a long lateral chain was employed to facilitate water reduction in the fresh concrete mixture and to achieve the required workability of the sisal fibre-reinforced concrete. In this study, 40-mm-long sisal fibres with a diameter of 0.2 mm were selected based on findings from previous studies. The fibres were boiled in hot water at 70°C for one hour to remove surface impurities and then air-dried for 48 hours before use. The fibre morphology comprises approximately 55–66 % cellulose, 12–17 % hemicellulose, 7–14 % lignin, 1 % pectin, and 1–7 % ash. The density, elongation, Young's modulus, and tensile strength of the fibres are 1.3 g/cm^3, 12 %, 35 GPa, and 668 MPa, respectively.

The mix design for M50-grade concrete was carried out following the guidelines provided in IS 10262: 2019.[29] A trial mix proportion was determined based on the density values of cement and aggregates, with a water-cement ratio of 0.35 adopted from prior experience. A polycarboxylate-based superplasticizer was added at 0.8 %–1.0 % of the binder's mass. A 40-liter capacity pan mixer was used to prepare the fresh concrete and achieve a homogeneous concrete mixture. The sequence of raw-material mixing is crucial for developing fibre-reinforced concrete, and it was followed as per literature specifications. The coarse aggregate and fibres were initially placed in the mixer and mixed thoroughly for 2 min. Then, cement was added, followed by 50 % of the total water and the polycarboxylate-based solution, and mixed for another 2 min. Sisal fibres were then sprinkled over the mixture and allowed to disperse uniformly for an additional 2 minutes. Four series of specimens were produced based on the fibre volume fraction. Based on the cement content, the composites were designed with sisal fibre volume fractions of 0.5 %, 1 %, 1.5 %, and 2 %. The fresh mix was poured into steel moulds and compacted using a vibrating machine to ensure proper settling. The vibration was carefully controlled to prevent balling and clumping of the fibres in the concrete. After casting, the specimens were covered with wet burlap, and after 24 h, they were demoulded. The hardened concrete specimens were then cured by immersion for (3, 7 and 28) d.

2.2 Mechanical properites of hardened concrete

In this experimental program, compressive strength, split tensile strength, and flexural strength tests were conducted to assess the concrete's mechanical properties. The axial compressive load was evaluated using cube specimens measuring (150 × 150 × 150) mm in accordance with the IS 516: 1959 [30] specifications. The compressive strength test was performed using a compression testing machine with a capacity of 2000 kN at a loading rate of 14 MPa per minute.

The same testing machine was used to examine cylindrical specimens measuring (150 × 300) mm's split tensile strength. A four-point flexural bending test was conducted on specimens measuring (100 × 100 × 500) mm using a Universal Testing Machine (UTM) with a capacity of 600 kN, maintaining a loading rate of 3.33 kN/min to determine the flexural strength of all the tested specimens. Three specimens were tested for each series, and the average value was calculated.

2.3 Durability Analysis

A Rapid Chloride Penetration Test (RCPT) was conducted in the 100-mm diameter and 50-mm-thick concrete disc specimens to evaluate the durability of sisal FRC following ASTM C1202 [31] guidelines. RCPT evaluates the coulombs current flow from one channel to the other channel and coulomb values increase if there is any barrier for the chloride ion penetration. The diffusion cell, specifically fabricated for this test, comprised two transparent chambers. Chamber 1 contained a 2.4-M NaCl solution, while Chamber 2 held a chloride-free 0.3-M NaOH solution. Chloride ions from Chamber 1 migrated into Chamber 2 through the centrally positioned concrete specimen, driven by both the applied voltage and the chloride concentration gradient across the specimen. Observations were recorded over six hours under an electric voltage of 60V, and the total charge passed was computed using Simpson's rule. The test was conducted at specimen ages of 28 d and 56 d in all the sisal FRC specimens and reference concrete mix.

Water absorption is another important indicator for assessing the durability of the concrete specimens. The test was conducted on 100-mm cube specimens made with different volume fractions of sisal fibres after 28 d and 56 d of curing. The specimens were immersed in a water bath for 48 h to record their wet weight and then dried in a hot-air oven for 24 h. Based on the wet and dry weights, the water absorption percentages are calculated for both sisal fibre-reinforced concrete (FRC) and control specimens.

2.4 Micro Structural Examination

In this experiment, the internal structure of the materials is examined at the microscopic level as part of the microstructural analysis of concrete. Understanding the preparation, distribution, and organization of the various phases within the concrete matrix is essential for this study. Generally, Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses are performed in concrete microstructural studies to achieve these objectives.

Scanning Electron Microscopy (SEM) facilitates the observation of morphological features and the orderly organization of constituents such as fibres, aggregates, and cement particles by providing precise images of concrete microstructures. The elemental composition of various phases within the concrete matrix can be analyzed using SEM in conjunction with Energy-Dispersive X-ray Spectroscopy (EDS). SEM is particularly useful for examining the sisal fibres' morphology, surface characteristics, and structural properties in the context of sisal fibre-reinforced concrete. Researchers utilize SEM to understand how sisal fibres interact with the concrete matrix and their effects on mechanical and durability characteristics. A detailed SEM inspection reveals critical information about sisal fibres' diameter, length, and surface roughness. Its remarkable resolution and depth of field capabilities allow for a comprehensive examination of its internal structure. By employing SEM analysis, researchers can investigate the interactions between sisal fibres and the concrete matrix, providing insights into the mechanisms behind the mechanical properties and durability improvements. This enhanced understanding aids in developing durable and sustainable construction materials, enabling well-informed decisions regarding material design and optimization.

X-ray Diffraction (XRD) is a particularly effective tool for analyzing the crystalline structure of materials, including concrete reinforced with sisal fibres. It enhances our understanding of the properties and behavior of both sisal fibres and the concrete matrix. XRD is valuable for identifying essential phases in the concrete matrix composition, such as portlandite ($Ca(OH)_2$), calcium silicate hydrates (C-S-H), and various forms of crystalline and amorphous silica. Under XRD examination, sisal fibres primarily composed of lignin, cellulose, and hemicellulose reveal their crystalline structure, providing insights into the orientation and arrangement of the molecules within the fibres. Additionally, XRD can detect any chemical reactions or interactions between sisal fibres and the concrete matrix, including new crystalline phases that arise from the alkaline conditions present in concrete.

XRD identifies several hydration processes during concrete curing, such as the formation of ettringite and portlandite phases, thereby monitoring the advancement of hydration and offering insights into microstructural development. Moreover, XRD analysis facilitates the investigation of changes in the crystalline structure of sisal fibre-reinforced concrete under various environmental conditions. By providing statistical information on the relative abundance of different crystalline phases, XRD helps determine the overall structure of the material and predict its mechanical properties.

3 RESULTS AND DISCUSSION

The tests were conducted to determine the mechanical properties and perform a microstructural analysis of conventional concrete and SFRC specimens with 0.5 %, 1.0 %, 1.5 %, and 2.0 % volume fractions of sisal fibre in M50-grade concrete. The outcomes of the various tests are presented and discussed below.

3.1 Compressive Strength

Compressive strength is a critical parameter in structural design and is essential for assessing the quality of concrete. The compressive strength of the concrete mixture was evaluated at different curing ages: 3 d, 7 d, and 28 d. The control mix (CC) exhibited compressive strengths of 19.86 MPa, 35.73 MPa, and 54.20 MPa at (3, 7 and 28) days, respectively. For the 0.5 % volume fraction of sisal fibre, the compressive strengths measured 19.43 MPa, 35.26 MPa, and 54.51 MPa after 3 d, 7 d, and 28 d of curing. In comparison, the concrete mixture containing 1 % sisal fibre demonstrated higher strength values of 20.67 MPa, 37.41 MPa, and 58.68 MPa for the same curing periods. Adding 1.5 % and 2 % sisal fibre resulted in compressive strengths of 19.89 MPa, 36.90 MPa, and 56.53 MPa at 3, 7, and 28 days, respectively. These findings indicate that the 1 % sisal fibre contributed the maximum compressive strength to the concrete mix, with strength variations in fibre volume fraction and curing period shown in **Figure 2**. Including 1 % sisal fibre led to increases in the compressive strength of approximately 4.07 %, 4.70 %, and 8.26 % compared to the control concrete. At this volume fraction, sisal fibres help to reduce pore size and provide better adhesion to the cementitious materials, thereby constraining microcracks and marginally enhancing compressive strength. However, the chemical composition of natural fibres can dissolve in an alkaline environment, negatively impacting the cement hydration process and disrupting the bond between the fibres and the matrix, resulting in minimal improvements in compressive strength.[32,33]

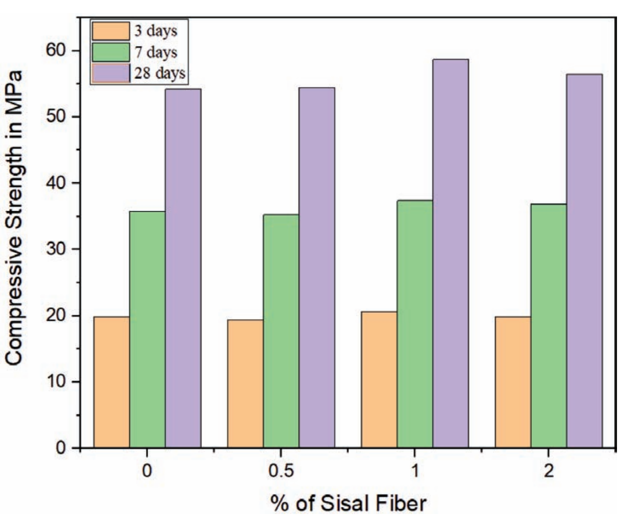

Figure 2: Compression strength variation with a mix

Beyond 1 %, the fibre content does not exhibit the same positive trend; consolidation becomes difficult, and pore structures are adversely affected. The improvement in compressive strength for 1.5 % and 2 % sisal fibre was only 0.15 %, 3.27 %, and 4.29 %, respectively, which is lower than the results observed for the 1.0 % sisal fibre series. It is evident that up to a 1 % volume fraction, fibre dithe stribution remains uniform, and the strength of the matrix significantly increases with curing time in both fibre-reinforced and conventional concrete series. Similar findings were reported by Okealo et al.[34] In contrast, excessive fibre content (1.5 % and 2.0 %) may lead to clumping and increased pore size formation. Fortunately, the compressive strength results in this experimental program did not fall below that of the control concrete produced without fibres. Test results from Antwi-Afari et al. indicated a slight reduction in the compressive strength of fibre-reinforced concrete.[35]

Nevertheless, most literature suggests that increases in compressive strength can be observed up to a volume fraction of 10 %. In the experimental studies, the length of the fibres used was considerable, and they only effectively contributed to load-carrying capacity once the failure load was reached. The failure observed on the surface of the specimens indicates ductile behavior, as severe brittleness did not occur in sisal fibre-reinforced concrete (SFRC) composites.

3.2 Split Tensile Strength:

The split tensile strength of the specimens containing various fibre volume fractions is presented in **Figure 3**. Unlike the compressive strength results, a continuous increase was observed in the split tensile strength of the concrete with increasing fibre content and testing age. Compared to the control concrete, SFRC specimens with 0.5 %, 1.0 %, and 2.0 % volume fractions exhibited an increased split tensile strength of 15.3 %, 17.4 %, and 20.6 % at 3 days of curing. Similarly, these values were enhanced up to 43.8 %, 46.8 %, and 66.4 % for the three different volume fractions after 7 d. However, the improvement after 28 days could have been more impressive, with increases of only 16.9 %, 18.8 %, and 22.5 %. This decline is attributed to the excess fibre content that exceeds the optimum level, distorting the cementitious matrix and causing a reduction in improvement. When splitting occurs, the sisal fibre strands in the crack zone help bridge the gap by transferring stress from the concrete matrix to the fibres. This simultaneously enhances the tensile strain capacity of the concrete matrix, increasing the tensile strength. It is also evident that the rise in split tensile strength is related to both the additional fibre content and the curing age. The failure mode in the cylindrical specimens is predominantly brittle across the cross-section, and the fracture of the specimens shows

Figure 3: Split tensile strength variation with a mix

multiple cracks where stress is transferred from the initial point of cracking to nearby intact areas.

The most significant improvement in split tensile strength occurred at a 1.0 % fibre volume fraction, which surpassed the control concrete by 66.46 %. This same percentage was also reported as the optimum in terms of compressive strength. Silva et al. noted a similar trend in their research on geopolymer composites made with sisal or jute fibres, which concluded that the split tensile strength increases with fibre volume fraction only up to the optimum fraction. [36]

Due to the high tensile strength of sisal fibres, failure is primarily caused by pullout rather than tensile failure of the specimens. Along with the pullout failure, some portions of the cement matrix adhered to the surface of the fibres also fractured. Wei and Meyer investigated thermally treated sisal fibres and reported enhancements in tensile strength and modulus of 45 % and 70 %, respectively; these properties could be further modified with excess dosages of sisal fibres.[37]

3.3 Flexural Strength:

Flexural strength, modulus of rupture, bending strength, or transverse rupture strength, is the stress at which a material fails when subjected to transverse loading. The flexural strength of different concrete mixes was evaluated at various curing periods, specifically on the 3rd, 7th, and 28th days. The control mix (CC) exhibited flexural strengths of 1.62 MPa, 2.25 MPa, and 3.83 MPa on the 3rd, 7th, and 28th days, respectively. Introducing 0.5 % sisal fibre resulted in flexural strengths of 1.03 MPa, 3.08 MPa, and 4.74 MPa at the corresponding curing periods. The mix with 1 % sisal fibre displayed flexural strengths of 2.59 MPa, 3.79 MPa, and 4.86 MPa on the 3rd, 7th, and 28th days. Meanwhile, the 1.5 % and 2 % sisal fibre mixes demonstrated varying flexural strengths over the curing periods, ranging from 2.15 N/mm^2 to 4.98 N/mm^2. Overall, the results indicate the influence of sisal fibre on the flexural strength of the concrete mixes, with the 1 % volume fraction yielding a notable improvement in strength, particularly at the later stages of curing. The variation in flexural strength with the mix was between 24 % and 32 %, as shown in **Figure 4**. Increasing the fibre content enhances the flexural strength, demonstrating superior flexural properties and supporting their role as a reinforcing material in the composite. The flexural strength of sisal fibre-reinforced concrete increases with fibre volume fraction and curing age. Maximum values were observed in the 2 % sisal fibre fraction, while minimum values were noted in the 0.5 % series compared to the no-fibre concrete.

From the above data, flexural strength generally increases with the addition of fibre content. Only a slight popping sound was observed in the specimens during the initial stage, and no cracks were noted. As the applied load increased over time, small cracks began to form in the tensile zone, mainly at the bottom of the specimens, indicating that cracking initiated internally and progressed outward. When the load peaked, specimens without sisal fibres failed abruptly, whereas fibre-reinforced concrete (FRC) specimens with sisal fibres failed only after significant bending and deflection. In these specimens, a distinct crack developed in the center, extending

Figure 4: Flexural strength variation with a mix

across the entire test block. No specimen fell below the strength of the control concrete due to the fibre bridging effect across the cracks, which also improved the flexural strength.

The results of this study align with those of G. Ren[4] who reported that the incorporation of 2 % sisal fibres yields the best results, with an increase in concrete's flexural strength of up to 10.8 %. Other researchers observed similar trends.[38,39] Furthermore, a strong correlation exists between the splitting tensile strength, flexural strength, and compressive strength of concrete reinforced with sisal fibres.

3.4 Durability Properties

The RCP test results show how much chloride ions flowed from one reservoir to another in sisal FRC specimens. Control concrete mixture the low range of coulombs indicates that the flow of current is very high and the composite has internal voids and cracks that allow the current to pass through it. Whereas the concrete disc specimens with different volume fraction of sisal fibres 0 %, 0.5 %,1 %,2 % RCP test values are calculated are much lower than the control concrete made without sisal fibres specimens. Coulomb passage is mucg less for fibre additions and it is almost same in all the fibre series (around 1570 Coulombs). As the fibre content increases, Coulomb's passage decreases, contributing to the formation of a denser microstructure through the development of C-S-H gel. **Figure 5** presents the comparison of RCPT Test Results.

The water absorption of sisal fibre-reinforced composites increases as the fibre volume fraction rises, with specimens containing 2 % sisal fibres exhibiting the highest absorption compared to concrete without fibres. This is due to the hydrophilic nature of natural fibres, which create passage channels and facilitate capillary-water movement within the concrete. Furthermore, the reduced workability caused by the balling effect of natural fibres increases permeability when the fibre content becomes excessive.

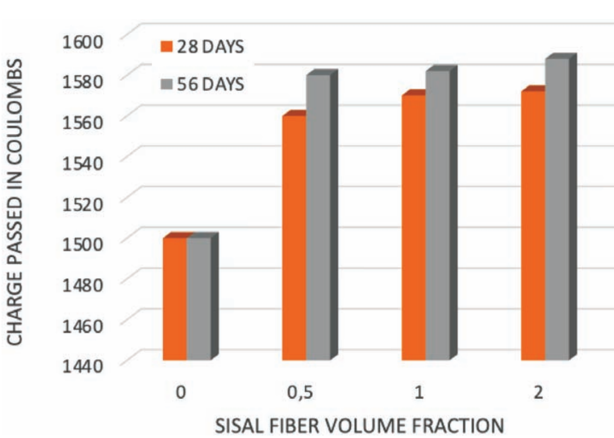

Figure 5: RCPT Test Results

3.4 SEM Analysis

Figure 6 shows the SEM analysis of the microstructural studies of 28-day-aged conventional concrete. **Figure 7a** to **7d** illustrates the SEM analysis of 0.5 %, 1 %, 1.5 %, and 2 % sisal fibre-reinforced concrete (SFRC) specimens cured for 28 d. The changes in the compressive strength characteristics are closely associated with the phase changes in the microstructures. The SEM analysis was conducted at a high voltage (HV) of 20.00 kV, with a magnification size of 5 μm. Specimens fractured during the compression test were used for the microstructural investigation. The figures depict the bridging effect of sisal fibres across crack expansions and the presence of sisal fibres bonded with the matrix. The adhesion between the fibres and the matrix is crucial in augmenting the micropores and converting larger pores into smaller fractions, significantly contributing to concrete's mechanical characteristics. Sisal fibres within the matrix act as nucleation sites and encapsulate the cementitious slurry, promoting an increased production of calcium silicate hydrate (C-S-H).

The bond between the fibres and the cement matrix enhances the stress transfer and improves the formation of expansive products within the composites. fibres disperse uniformly in the cement matrix, and their varying proportions reduce the size of pores. Additionally, sisal fibres decrease the number of microcracks, helping achieve a denser microstructure than other fibre volume fractions. However, excessive fibre content can lead to congestion, creating larger voids and pores, which results in an uneven stress distribution due to air intrusion in the voids. When coir fibre is used in higher proportions, it forms interconnections, with minor bonding points occurring at specific locations within the sample. Small fibre agglomerations are also observed in cement pastes, increasing porosity. According to Khan and Ali,[40] incorporating plant-based fibres may increase the porosity and pore connectivity despite numerous attempts to utilize natural fibres. The presence of sisal fibres confirms that the reinforcement strengthens the concrete matrix and alters the brittle behavior of concrete into ductile fracture.

Samples for microstructural analysis were taken after 28 d of curing to better understand the role of sisal fibres in concrete. Microscopic studies reveal that the rough surface of surface-treated sisal fibres enhances the bond strength between the fibres and the concrete matrix, elevating the compressive strength by forming hydrated products. This study focuses on sizes less than 20 μm, where the hydration process produces aggregates of brittle ettringite and calcium silicate hydrate (C-S-H). Their chemical reactions significantly influence the performance of sisal fibre-reinforced concrete. The primary constituents of sisal fibre are cellulose, hemicellulose, lignin, and trace amounts of other components. Specifically, the amount of cellulose significantly influences the fibre's stiffness and strength. Compatibility is essential for the durability of concrete structures made with si-

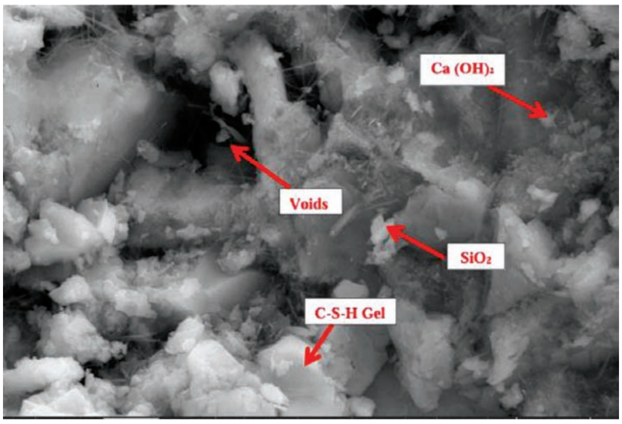

Figure 6: SEM analysis of CC

sal fibres. Additionally, SEM analysis can identify potential fibre pullout or separation indications, providing insights into a material's resistance to crack development.

3.5 X-Ray Diffraction

X-ray diffraction (XRD) is a proper analytical technique for determining a material's crystal structure. XRD analysis reveals sisal fibre-reinforced concrete's chemical composition and crystalline phases due to the incorporation of sisal fibres. Typical peaks of calcium silicate hydrate (C-S-H) and silicate are identified as prominent components in the XRD plots of control concrete and 1 % sisal fibre-reinforced specimens. Additionally, quartz, portlandite, calcite, and ettringite are visualized in the SFRC composites, which are byproducts of the hydration process in the mixes. The presence of sisal fibres positively influences the compressive strength at lower fractions, while overdosing on fibres negatively impacts the concrete's performance. XRD can provide invaluable insights into the composition and behavior of the concrete matrix and the sisal fibres in the context of sisal fibre-reinforced concrete. Determining the mineralogical composition of the concrete matrix is possible through XRD assessment. Standard concentrations found in concrete include calcium silicate hydrates (C-S-H), portlandite ($Ca(OH)_2$), and various forms of crystalline and amorphous silica. The existence and distribution of these components may affect the concrete's overall electrical resistance and durability

.As shown in **Figures 8** and **9**, the primary constituents of sisal fibres include cellulose, hemicellulose, lignin, and other naturally occurring substances. XRD can also provide quantitative data regarding the relative quantities of different crystalline phases in concrete. These statistics enable predictions about the overall composition of the material and its mechanical properties.

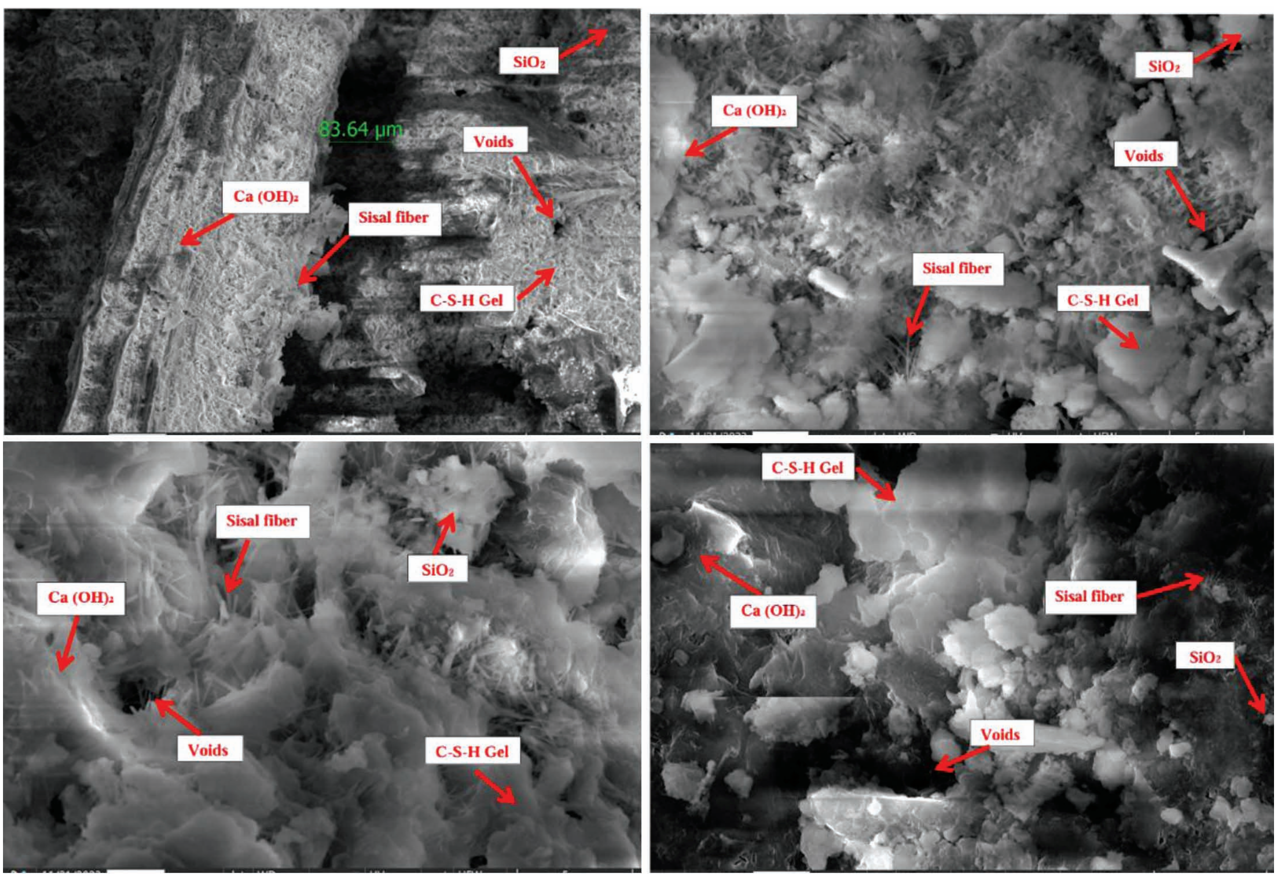

Figure 7: a) SEM analysis of 0.5 % of sisal, b) 1 % of sisal, c) 1.5 % of sisal, d) 2 % of sisal

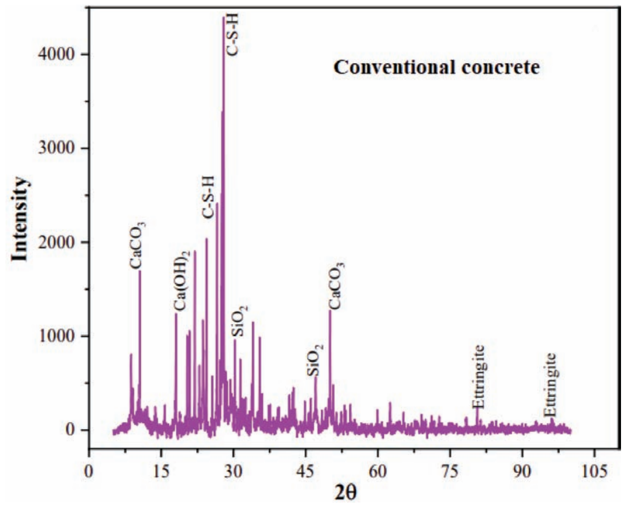

Figure 8: XRD of CC

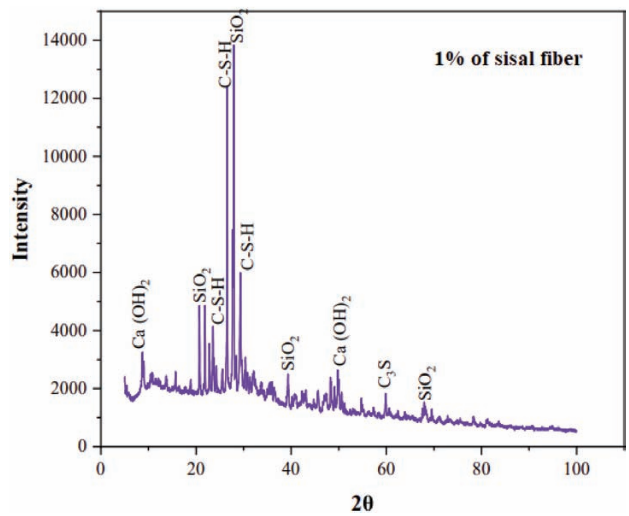

Figure 9: XRD of 1 % of sisal

5 CONCLUSIONS

This investigation demonstrates the mechanical and microstructural properties of sisal fibre-reinforced, high-strength concrete, leading to the following conclusions based on the experimental findings:

Sisal fibres at a 1 % volume fraction effectively reduce pore size and improve adhesion to cementitious materials, which helps to constrain microcracks and marginally enhances compressive strength. Pretreated sisal fibres reduce water absorption capacity, leading to an increase in compressive strength of up to approximately 8.25 %. However, excessive fibre content reduces compressive strength, indicating that moderate usage of fibres can improve mechanical properties. In the split tensile and flexural bending tests, the longer sisal fibres exhibit excellent toughness properties, making the concrete ductile. Split tensile and flexural strength values increase with the volume fraction of sisal fibres. Specifically, the enhancement in split tensile strength after 7 days ranges from 43.8 % to 66.4 % for the three different volume fractions of 0.5 %, 1.0 %, and 2.0 %, respectively. A higher sisal fibre content increases water absorption due to its structural characteristics, but this effect can be minimized by adding superplasticizers to the concrete mixture and chloride permeability values are within the admissible limits .

Incorporating sisal fibres into the concrete mixtures at volume fractions of 0.5 % and 1.0 % showed a considerable increase of up to 32 % in flexural strength. The addition of 2 % sisal fibre further increases flexural strength due to the fibre bridging effect across cracks, and there is a notable increase with curing age. Superior performance under flexure and split tension contrasts with compressive behavior due to the high tensile strength of sisal fibres. The SEM analysis of all mixtures revealed improvements in C-S-H gel and ettringite, a material characterized by a needle-like structure. The enhanced interface between the fibre and matrix, evident from the microscopic images, shows that the uniform dispersion of fibres controls microcracks and permeable pores through effective bridging mechanisms. The XRD analysis of all mixes demonstrated high intensities of C-S-H, $CaCO_3$, $Ca(OH)_2$, ettringite, and their crystalline phases in the concrete matrix. Eco-friendly concrete was produced using sisal fibres, reducing carbon emissions and production costs. Sisal fibre-reinforced concrete (SFRC) offers a significant opportunity to mitigate the negative environmental effects of industrially produced fibres. Future research should focus on comprehensive analyses of shrinkage studies and the effects of internal curing, considering the limitations of these studies.

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