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ORIGINAL ARTICLE

Enhancing eco-concrete: the role of natural fibres and water content to improve the strength and lifespan of sustainable pavement materials

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Abstract: Many concerns have been raised about the adverse environmental impacts of conventional concrete. Using natural sponge fibre (NSF) in concrete to improve mechanical and durability properties makes it a sustainable innovation in construction materials. Hence, this study aims to explore the combine effects of NSF content (0.00%, 0.25%, 0.50%, 0.75%) and water-to-binder (wb) ratios (0.45, 0.50, 0.55) on the performance of natural sponge fibre reinforced concrete (NSFRC) for pavement applications. Experimentally, concrete mixtures were prepared by adding NSF and wb ratios. The impact of fibre content (*F*c) and wb on the physical and mechanical properties of NSFRC was evaluated and compared with those of plain concrete (*P*c). The results indicate that advancing NSF content decreases flowability, density, and compressive strength compared to the *P*c. However, tensile splitting strength increases significantly enhances at 0.75% fibre and wb 0.50, improving crack resistance and toughness, as shown by the stress-strain curves and evidenced by the scanning electron microscopy (SEM) microstructure. Research indicates NSFRC serves as a sustainable pavement material suitable for engineering applications, warranting further research into its long-term field performance and standardization.

Keywords: fibre content, water/binder ratios, sustainable pavement material, mechanical properties

1 Introduction

Natural fibre reinforced concrete (NFRC) is an innovative, eco-friendly alternative that can replace conventional concrete, leveraging renewable plant fibres such as hemp, coir, sisal, and jute to improve mechanical and durability properties while minimising environmental impact [1]. The addition of natural fibres improves toughness, tensile strength, and crack resistance in the cementitious matrix, which addresses the characteristic (brittleness) of plain concrete [2], especially in pavement construction. However, the performance of NFRC in service is extremely dependent on the main mix design parameters, especially fibre content (*F*c) and water-to-binder (wb) ratio. These two parameters influence workability, hydration kinetics, fibre-matrix bonding, and eventually structural performance.

Fibre content directly associates with improvements in mechanical properties up to a certain point, after which issues such as fibre balling and poor dispersion can adversely affect strength and durability [3]. Also, increasing the quantity of fibre (fibre volume) generally controls cracks and improves toughness [4], but extreme fibre addition may decline compressive strength due to hindered compaction and rise in porosity [6].

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The wb ratio in concrete mix design is a key parameter that influences porosity and the strength of the cement matrix. Typically, lower wb ratios result in higher compressive strength but can reduce workability and fibre distribution if not porosity adjusted [5]. The interplay between different *F*c and wb ratio is complex but essential for improving the mechanical properties and durability of NFRC. Finding the right balance enhances fibre dispersion, creates a stronger fibre-matrix interface, and reduces porosity, thereby improving resistance against freeze-thaw cycles, chloride access, and sulphate attack [6]. Study shows that natural fibre content with carefully controlled fibre content and maximum wb ratio exhibit better impact resistance, flexural strength, and durability, which is crucial characteristics for structural applications engineering [7].

Previous studies have shown the effect of fibre contents and wb ratio on NFRCs such as jute, coir, sisal, and hemp. On the contrary, NFRC-related studies have not focused on the relationship between fibre content and wb ratio in natural sponge fibre-reinforced concrete (NSFRC). Hence, this study aims to systematically examine the relationship between varied fibre content and water-binder ratio on NSFRC, and to provide a quantitative analysis of their combined effect on mechanical properties and durability; to support the development of resilient, sustainable construction materials for pavement construction. The findings of this study will go a long way toward helping researchers further study the characteristics of NSFRC as a future construction material.

2 Experimental Procedures

2.1 Materials

The materials used for preparing the concrete mixtures are Ordinary Portland Cement (OPC), fine aggregate, coarse aggregate, natural fibre, and water. The OPC was Type CEM I 42.5N, conformed to [8,9,10], and was ISO 9001-certified by GHACEM. The fine aggregate was air-dried natural pit sand, passing a 4.75 mm sieve and retained on a 200 µm sieve, in accordance with [11]. The coarse aggregate was crushed granite having a maximum size of 10 mm. The water used is potable drinking water supplied by Ghana Water Company Limited (GWCL). The natural fibre used was natural sponge fibres (NSFs), with an average diameter of 0.40 mm and an average length 40 mm. **Table 1** gives the chemical compositions and physical properties of the binder.

Table 1. Cement compositions and physical properties of the binder

Type	OPC
Oxide (wt%)	
SiO_2	18.4 - 24.5
Al_2O_3	3.1 - 7.56
Fe_2O_3	0.16 - 5.78
CaO	58.1 - 68.0
MgO	0.02 - 7.1
SO_3	0.00 - 5.35
K_2O	0.04 - 1.66
Na_2O	0.00 - 0.78
MnO	Less
P_2O_5	~0.04
TiO_2	~0.1
LOI	2 – 4
Physical property	
Density (kg/m^3)	3100
Blaine fineness (m^2/kg)	350 – 400

*OPC - Ordinary Portland cement

2.1.1 Preparation of Natural Sponge Fibre

The natural plant from which the natural sponge fibre is extracted was obtained from a forest near "Fahyea kobo" town in the Amansie North district of the Ashanti Region of Ghana. The sponge plant was water-retted for 2 weeks to dissolve the bark. The sponge plant was then beaten against two sticks to loosen the bark from the bundle fibre. The natural sponge fibres (NSFs) were obtained by using a chemical (sodium hydroxide) solution, where the bundle fibres were immersed in a 10% concentration of sodium hydroxide (NaOH) solution for thirty (30) minutes to dissolve the lignin and the celluloses. Subsequently, the treated bundle fibres were immersed in a 2% maleic anhydride solution for 40 minutes to facilitate extraction. The bundle fibres were then immersed in an Acetic acid solution without a catalyst for 15 minutes to neutralise the NaOH and maleic anhydride contents. The bundle fibres were further rinsed thoroughly in five separate baths of drinking water to remove any residual chemicals. The bundle fibres were air-dried in an open laboratory area. The fibres were correctly shaped, and a digital micrometre screw gauge was used to determine an average fibre diameter of 0.4 mm. An aspect ratio of 100 was used to achieve an average fibre length of 40 mm, with mechanical cutting machine used. The obtained fibres, referred to as natural sponge fibre (NSF) in this study, were placed in plastic bags and sealed to prevent further moisture absorption until the date of the concrete mixture preparation. **Fig. 1** shows the natural fibre used in this study.

Fig. 1. Natural sponge fibre: (a) unprocessed, (b) after beating, (c) treatment, and (d) processed.

2.2 Methods

2.2.1 Concrete Mixtures

Concrete mixtures were prepared at a 1:1.5:3 binder-to-fine-to-coarse aggregate ratio, using three water-binder (wb) ratios of 0.45, 0.50, and 0.55. The NSF was incorporated at 0.00%, 0.25%, 0.5%, and 0.75% as a fibre enhancer. The concrete mixtures were denoted as Fi-Wj, where “I” is the proportion of NSFs, and “j” is the wb ratios. **Table 2** illustrates the proportions of the mixture prepared.

Table 2. Proportions of concrete mixtures

Samples ID	Constituents of concrete (g)				
	OPC	Stones	Sand	Fibre	Water
F0.00-Wb0.50 (control concrete)	116520	349640	174820	0	280080
F0.25-Wb0.45	116520	349640	174820	291.38	258628
F0.25-Wb0.50	116520	349640	174820	291.38	280080
F0.25-Wb0.55	116520	349640	174820	291.38	316170
F0.50-Wb0.45	116520	349640	174820	582.75	258628
F0.50-Wb0.50	116520	349640	174820	582.75	280080
F0.50-Wb0.55	116520	349640	174820	582.75	316170
F0.75-Wb0.45	116520	349640	174820	874.13	258628
F0.75-Wb0.50	116520	349640	174820	874.13	280080
F0.75-Wb0.55	116520	349640	174820	874.13	316170

*OPC - ordinary Portland cement; Wb - water binder; F - fibre.

2.2.2 Casting and Curing of Concretes

Fresh concretes were machine mixed and used to cast 150 mm cubes and 150 mm x 300 mm cylindrical samples. During casting, concrete was placed into molds (cleaned with oil) in three layers, each layer compacted on a vibrating table. Following casting, the samples were wrapped with a polyethylene sheet and kept at room temperature for 24 hours. The samples were then demoulded and cured in water for 28 days. **Figure 2** illustrates the curing of concrete mixtures.

Fig. 2. Curing of concrete mixtures.

2.3 Test Methodology

2.3.1 Testing of Samples

This experimental study included tests on the physical and mechanical properties of both fresh and hardened mixed concretes study.

2.3.1.1 Fresh Concrete Property

The freshly placed concrete was examined by measuring wet flow. The fresh flow of the concrete mixtures was determined in accordance with [12]. Twenty mixes were prepared, and flowability was calculated for each test results using the slump cone.

2.3.1.2 Hardened Concrete Properties

The properties of the hardened concrete were assessed through measurements of dry density, compressive strength, and tensile split strength. Nine samples were tested to calculate average values for each property. The density of the cubes was measured following [13] standards. The tensile split strength was determined according to [14], using the formula

$$f_{TSS} = \frac{2p}{\pi dl} \quad (1)$$

where p represents the applied load; d is the sample diameter (150 mm); and l is the sample length (300 mm).

The compressive strength (f_{CS}) was obtained as per [15], by using the equation

$$f_{CS} = \frac{P}{A} \quad (2)$$

where P represents the applied load at failure; and A denotes the area of the cube's bearing surface. **Figure 3** shows the tested concretes.

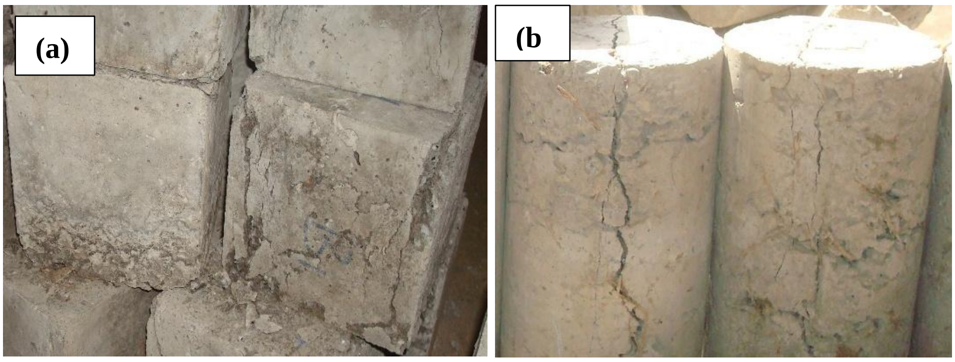

Fig. 3. Tested concrete mixtures: (a) cubes and (b) cylinder.

2.3.1.3 Surface Morphology Analysis

The smallest piece of each specimen was cut, and well-shaped and then mounted on aluminium stubs. The specimens were examined and analysed using an X-max Zeiss EVOSEM/LS 15/80 mm^2 SEM (Germany) device. The SEM images were then enhanced gradually using a rotating ball to improve their quality. The images were then acquired at a digitised resolution of 20 µm.

3 Results and Discussion

3.1 Fresh Concrete Properties

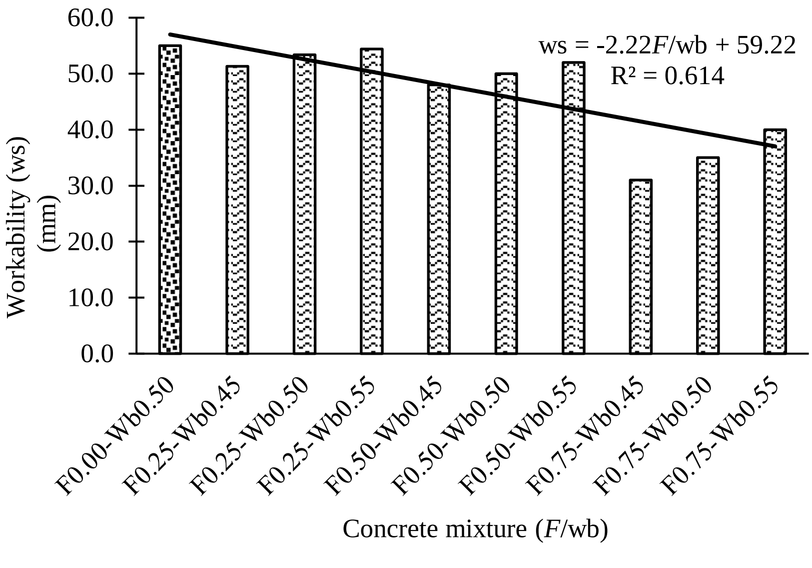

Fig. 4. Workability of the concrete mixtures.

Figure 4 shows the variation in the flow of natural sponge fibre reinforced concrete. As shown in the figure, the flow values of mixes 0.00%, 0.25%, 0.50%, and 0.75% NSF were 55.0 mm, 54.4 mm, 52.0 mm, and 40.0 mm, respectively, when the wb ratio was the highest at 0.55. Evidently, as the NSF content increased, the concrete flow decreased. The flow of the control concrete decreased by 9.1% upon *F*c and wb enhancement of F0.00-Wb0.50 with F0.50-Wb0.50. The result aligns with that of [16], who noted that advancing natural fibre content generally decreases the workability or flowability of concrete mixtures due to the fibres' higher surface area and water absorption properties. These fibres tend to absorb water during mixing and entangle within the matrix, thereby hindering flow. R^2 = 61%, indicating that approximately 61% of the variation in density is explained by *F*c and wb.

3.2 Hardened Concrete Properties

3.2.1 Density of the Concrete Mixtures

Figure 5 highlights the density of NSFRC cubes at different fibre contents and wb ratios. The concrete mixture without NSF addition achieved a maximum density of 1778 kg/m^3. As the fibre content increased, the density of the concrete mixtures decreased, as expected. For instance, when the concrete mix without fibres was enhanced with fibre content from 0.25% to 0.75%, the density of the concrete blend F0.75-Wb0.55 declined from 1778 kg/m^3 to 1530 kg/m^3. This finding aligns with a study that natural fibres as one of their characteristics, have lower masses than traditional concrete constituents, thereby enhancing or replacing denser aggregates and reducing the overall mixture density [17]. At the same fibre content, concrete mixtures with a moderate wb of 0.50 exhibit the highest density compared to those with wb ratios of 0.45 and 0.55. This suggests that maximum hydration, attached with minimal porosity, increases mix compactness [18, 19].

The decline in density with fibre addition is attributed to the fibres' low density and to the possible increase in entrapped air voids resulting from mixing challenges and fibre clustering. The result is a reduction in the compactness of the concrete matrix [1]. Furthermore, moderate wb ratios (around 0.50) improve hydration and maximise particle arrangement, thereby increasing matrix density and enhancing mechanical and durability properties compared with higher or lower wb ratios that lead to incomplete hydration or excess water porosity [19]. There is a negative correlation between the two endogenous variables and the exogenous variables, as confirmed by the results. The R^2 = 68.64 indicates that approximately 69% of the variance in density is explained by *F*c and wb.

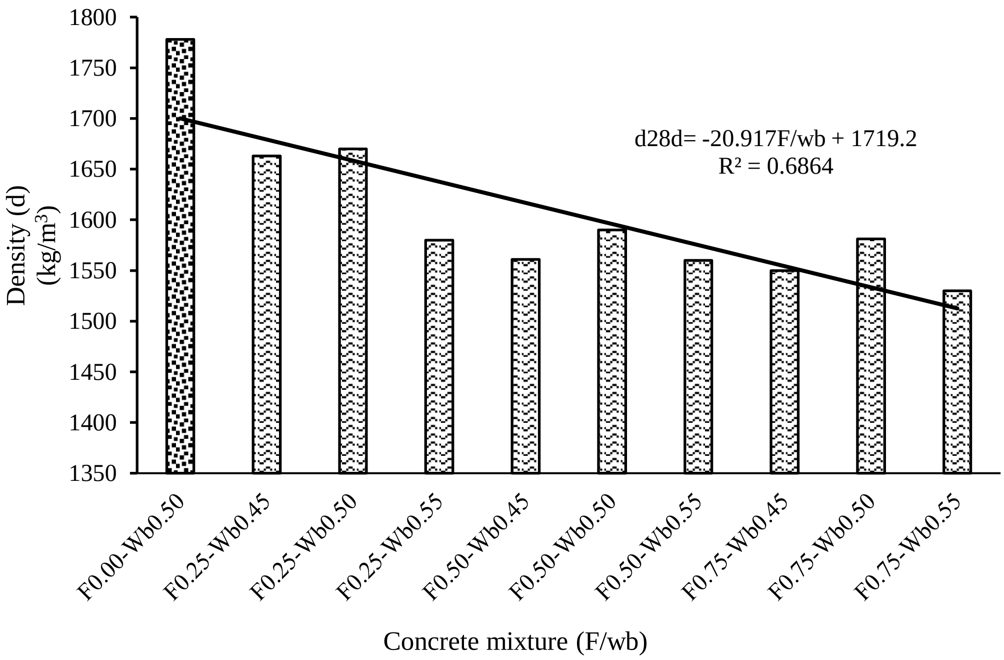

Fig. 5. Density of the concrete mixtures.

3.2.2 Compressive Strength (f_{CS})

Figure 6 illustrates the relationship between varying NSF content and wb ratio with $\boldsymbol{f_{CS}}$ and durability performance of NSFRC cubes. The control sample without fibre at a wb ratio of 0.50 recorded the highest compressive strength of 42.48 MPa. For samples with fibre inclusions ranging from 0.25% to 0.75%, $\boldsymbol{f_{CS}}$ generally decreases as the wb ratio exceeds 0.50, with values dropping to approximately 35.66 MPa at a fibre content of 0.75% and 0.55 wb.

This result aligns with a study showing that increasing the wb ratio causes more porosity and lowers fibre-matrix density, which negatively impact $\boldsymbol{f_{CS}}$ and durability [19,20]. Higher *F*c ratios improve water access and capillary porosity, weakening durability by making it more vulnerable to chemical attack and chloride penetration [6].

Regarding fibre percent, moderate inclusions (approximately 0.25% - 0.50%) improve mechanical properties by bridging microcracks. However, fibre content exceeding the maximum threshold (e.g., 0.75%) may reduce strength due to inadequate dispersion, fibre clustering, and increased voids, thereby compromising durability. A study reported that $\boldsymbol{f_{CS}}$ generally increases due to natural fibres [21, 22] but may increase concrete permeability if not properly maximised [20, 23, 24].

The durability performance of NSF reinforced concrete is closely linked to fibre content and wb ratio. For instance, fibre-concretes with low to moderate wb ratios (0.45 – 0.50) exhibit reduced permeability and improved resistance to environmental degradation. The collective fibre-matrix structure limits crack progression pathways and the access of aggressive agents such as sulphates and chlorides [3]. Equally, at maximum wb ratios (>0.55), even fibre-reinforcement cannot compensate for losses in matrix quality, leading to diminished durability.

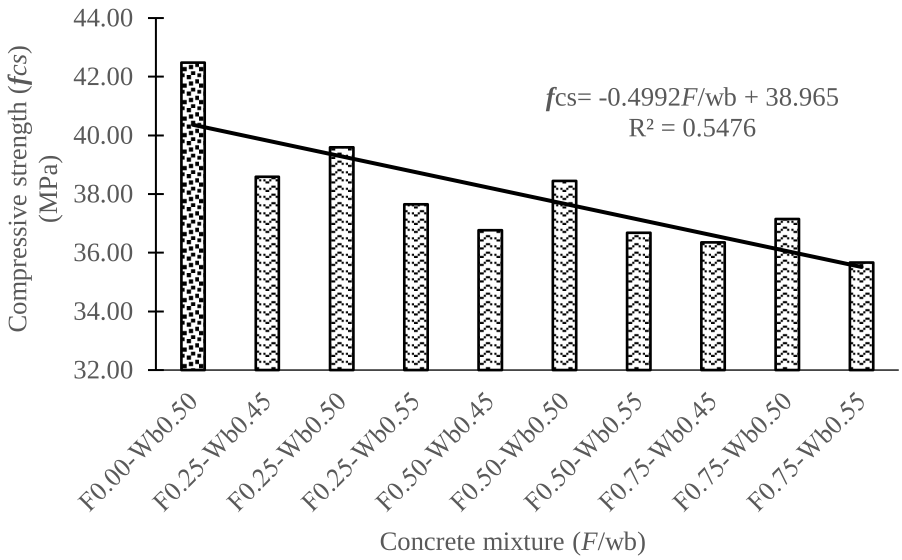

Fig. 6. Compressive strength of the concrete mixtures.

A multiple Regression equation is formulated to validate the compressive strength analysis results.

$$f_{CS}\left(MPa\right) = 42.48 - 5.33Fc\left(\%\right) - 22.4wb \quad (3)$$

Equation (3) quantifies both fibre content and wb influence on compressive strength. Fibre content and wb are negatively correlated to compressive strength. If *F*c increased by 1unit and keeping wb constant, the compressive strength ($\boldsymbol{f_{CS}}$) would decrease by 5.33%. Likewise, the compressive strength will decrease by 22.4 MPa when wb is increased by 1 unit, while *F*c is kept constant. **Table 3** shows that approximately 65% of the variation in compressive strength is explained by *F*c and wb. It would appear that *F*c ratio explained the bulk of the variance in the compressive strength while wb ratio is not (t = -5.01, p = 0.019; t = -4.01, p = 0.085). The F-value (6.59) suggests that all the factors significantly affect compressive strength, as the p-value is 0.025 at the 5% significance level.

Table 3. Regression Analysis of compressive strength versus *F*c, w/c ratio

Term	Coef	R-square	R-sq(adj)	F-Value	t-value	P-value
Constant	40.09	75.32%	65.41%		8.83	0.000
Fc (%)	-5.33				-5.02	0.019
wb ratio	-22.4				-4.01	0.085
Regression				6.59		0.025

3.2.3 Toughness

Figure 7 shows the stress-strain curve for the mechanical behaviour and toughness of NSFRC samples with varying fibre contents and wb ratios. The average toughness values were calculated from the strain-stress curves of the samples. The figure reveals these important observations in correlation with toughness and durability performance:

Samples with the highest fibre content (0.75%) and an optimal wb ratio of 0.50 exhibit the highest peak stress (~8.9 – 9 MPa) and strain capacity (~1.4 mm), indicating superior toughness. The extended strain-hardening region of the curve reflects improved toughness (energy absorption) and fibre interceding crack abridging, thereby enhancing durability by restraining crack propagation [20].

The correlation between 0.25% (Lower fibre content) and 0.55 (higher wb ratios) show reduced peak stress and lower strain (strain capacity). This is consistent with a report that weaker fibre-matrix adhesion and enlarged matrix porosity lower mechanical quality and durability [1]. Hence, these samples exhibit brittle behaviour, indicative of low toughness, and fail at lower strains, which is counterrally to [24].

Samples with transitional fibre contents (0.50%) and moderate-to-low wb ratios (0.45 to 0.50) exhibit stable behaviour, with moderate peak stresses and strain capacities. These compositions combine fibre distribution and matrix density, enhancing toughness and durability in real-world engineering applications.

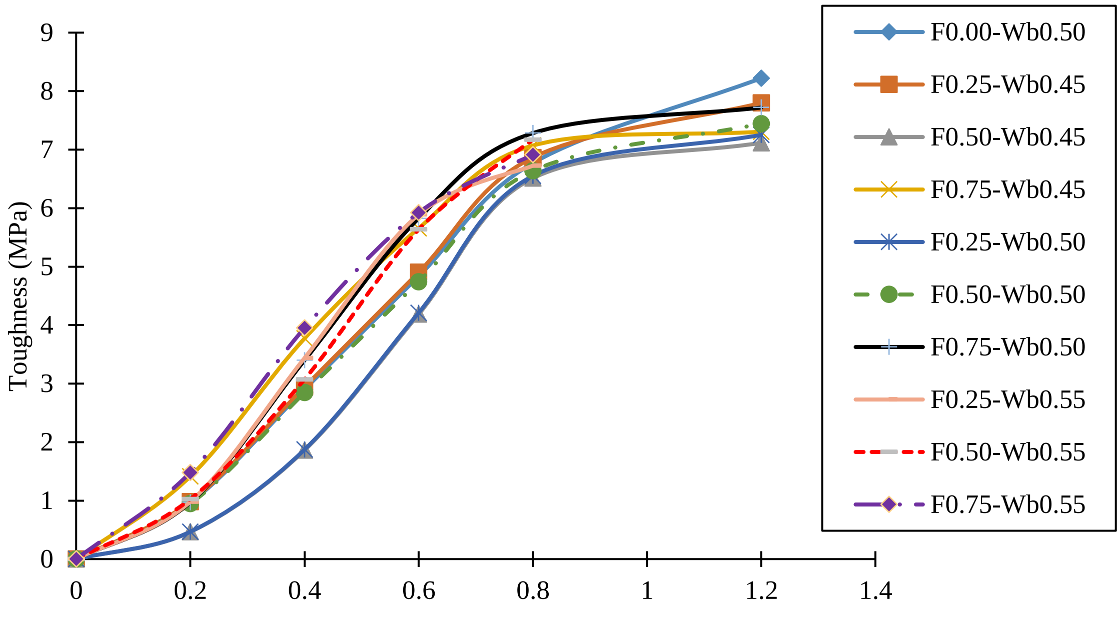

Fig.7. Compressive toughness of concrete mixtures.

3.2.4 Tensile Split Strength (f_{TSS})

Figure 8 presents the average tensile split strength values of concrete cylinder containing varying NSF contents and water-cement ratios. There is an apparent increase in tensile strength with increasing fibre content across all water-binder ratios. The mixture (F0.00-wb0.50) recorded a ($\boldsymbol{f_{TSS}}$) of 2.24 MPa**.**

There is a marginal improvement from 3.42 to 3.55 MPa when the control concrete was enhanced with 0.25% fibre, depending on the wb ratio. At 0.50% NSF addition, tensile splitting strength further advances, reaching an extreme strength of 3.73 MPa at 0.50 wb ratio. The highest NSF (0.75%) and 0.50 wb ratio exhibited the highest tensile strengths, peaking at 4.16 MPa. This demonstrates that fibre addition positively influences tensile performance by bridging microcracks and enhancing toughness. This assertion is consistent with studies in the literature on concrete made with natural fibre [1, 2, 3, 25].

Regarding the water-binder ratio, 0.50 generally yielded the maximum tensile strength across all fibre contents. Still, the strength declines slightly at a water-binder ratio of 0.55, indicating that the optimum water content is positively related to concrete porosity and limits fibre-matrix bonding and integrity [19]. Yet, due to fibres enhancement, the tensile strength is maintained either above or below that of the control, unreinforced concrete, even at maximum wb ratios, indicating improved crack resistance.

From a long-term durability perspective for NSFRC, greater tensile capacity is accompanied by enhanced resistance to concrete crack propagation and lower mechanical strength under service conditions [1,23]. The primary purpose of fibres is to resist crack growth [20,23], thereby reducing permeability, the ingress of aggressive agents, and associated durability risks, such as chloride-induced corrosion. The maximum collaboration of a mixture with a modest water-binder ratio (~0.50) and higher fibre content (~0.75%) yields the best combination of mechanical and durability performance, harmonising workability, fibre-matrix compactness, and fibre reinforcement effectiveness. The figure shows that approximately 57% of the variation in f_{TSS} can be attributed to the *F*c and wb.

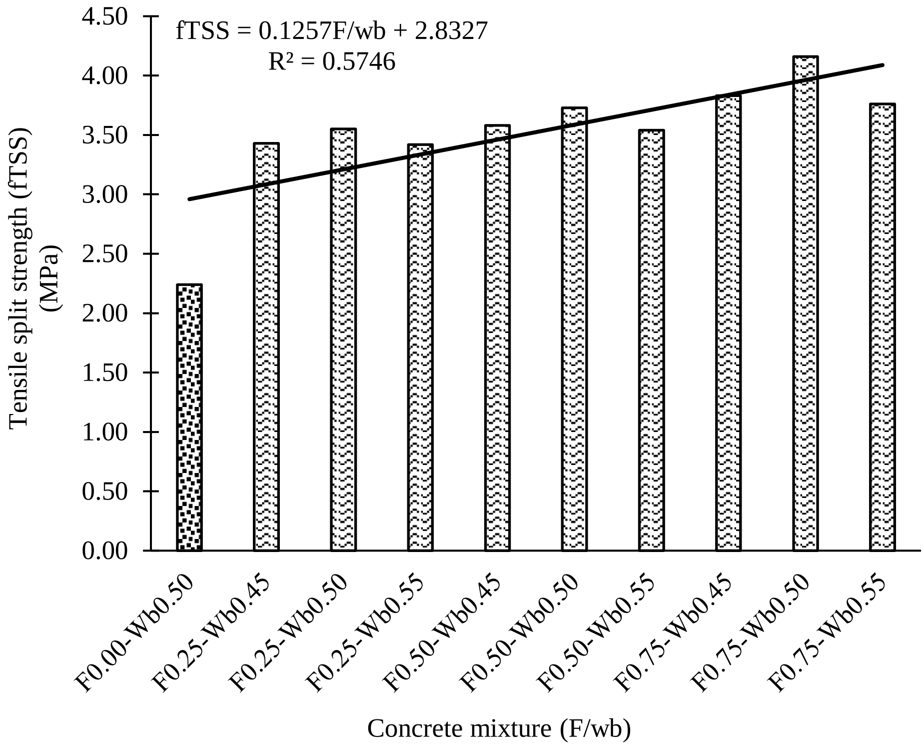

Fig. 8. Tensile strength of the concrete mixtures.

3.3 Surface Characterization of NSF Samples

Figure 9 illustrates the morphology of NSF under various treatment conditions. Figures (a), (b), and (c) show microstructure images of the untreated, NaOH-treated, and maleic-treated NSFs using SEM. The results show that the surface morphology in the microstructure of the maleic-treated NSF is enhanced compared to the untreated, and NaOH treated NSF. The additional treatment with Maleic anhydride solution, which esterifies the excess hydrophilic content that might existed after NaOH treatment, could be the reason for the improved microstructure quality of the NSF surface [26].

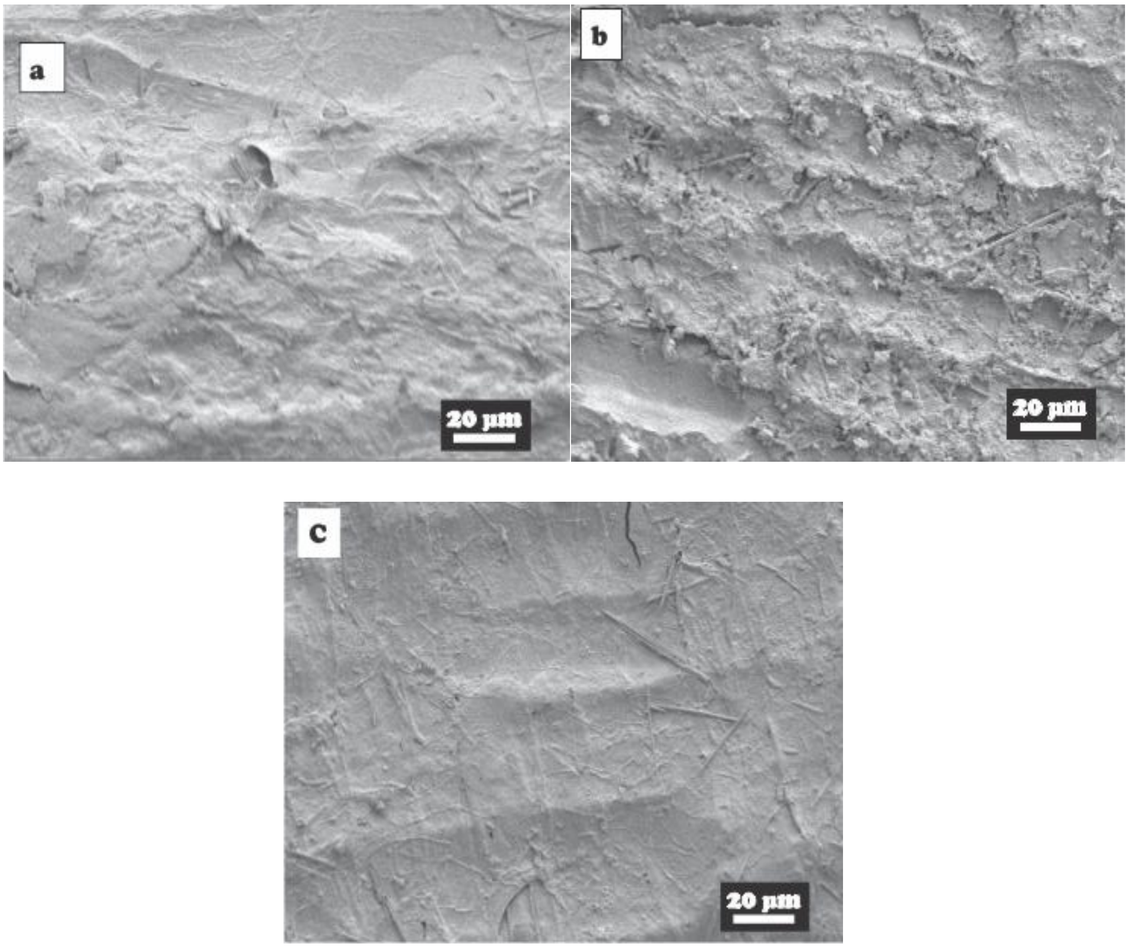

Fig. 9. Microscopic images of the NSF surfaces obtained by SEM: (a) Untreated, (b) NaOH treated, and (c) Maleic anhydride treated.

4 Conclusions

The study assesses the effects of fibre contents (0.00%, 0.25%, 0.50%, and 0.75%) and water-to-binder ratios (0.45, 0.50, and 0.55) on the durability and strength of reinforced concrete. Compressive strength and tensile split strength were used to assess the mechanical properties of NSFRC composites. The density and fresh flow of NSFRC composites were also evaluated as physical characteristics. Results showed that:

An increase in NSF content is negatively associated with concrete flow. This is due to the fibres' greater surface area and water-absorbing properties, which cause them to absorb mixed water and entangle in the matrix, obstructing flow.

A moderate wb of 0.50 concrete mixtures, at a constant fibre content relative to wb ratios of 0.45 and 0.55, indicating highest density and compressive strength.

Increasing the NSF dosage to 0.75% and a wb ratio around 0.50 significantly improves tensile strength, toughness and long-term durability, which the results is also due to the SEM morphology.

Generally, the result occurs between 0.25 and 0.50% fibre and wb 0.45 to 0.50, harmonizing workability, strength, and durability against environmental threat.

The findings indicate that NSFRC could be a promising eco-friendly pavement material, warranting further research into long-term field performance and standardization.

4 Application of NSFRC

Conventional pavement slabs could be effectively replaced based on the strength and durability criteria established in this study. The maximum *F*c and wb ratio in NSFRC could reduce the environmental impact associated with the conventional production of the fibre and its use in pavement concrete.

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CRediT authorship contribution statement

Braimah Kassum: Conceptualization, Investigation, Formal analysis, Writing – original draft, Review & Editing, Methodology, Supervision**,** Funding acquisition.

Conflicts of Interest

The author declares that he has no conflicts of interest to report, regarding the present study.

Data Availability Statement

Data will be made available upon reasonable request.

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