Performance Analysis of Ronier Fibers (Borassus Aethiopum) with Silica Fume on the Mechanical Properties of Concrete

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ABSTRACT

This research examines how Silica Fume (SF) and Ronier Fibers (RF) (Borassus aethiopum) affect concrete's mechanical and durability properties. Natural fibers are sustainable and have the potential to improve concrete performance. Thus, their inclusion into concrete has attracted considerable research. This study used SF as an additional cementitious material at a replacement rate of 10%. RF were utilized at 0.5%, 1%, and 1.5% by weight of cement, including Untreated (UN) and Treated (TRT) forms. An alkali treatment was utilized to increase the adherence of TRT fibers to the cement matrix. In addition to the durability traits, like Water Absorption (WA) and resistance to chemical attack, the mechanical qualities, including compressive strength, tensile strength, and flexural strength, were measured. The findings showed that while SF increased the composite's strength and durability, the addition of RF, especially in the TRT form, significantly increased the concrete's tensile and flexural strengths. The ideal mechanical strength-to-durability ratio was found to be 1% TRT fiber and 10% SF content. Moreover, fiber treatment strengthened the fiber-matrix bond by decreasing the WA and enhancing the resilience to harsh environmental factors. This study's results revealed that using SF along with RF offers a viable homogenous and compact concrete matrix, making it appropriate for use in environmentally friendly construction projects.

Keywords-silica fume; ronier fiber; concrete durability; concrete strength

I. INTRODUCTION

Concrete is one of the most widely utilized construction materials globally, prized for its durability, versatility, and ability to withstand various environmental conditions [1]. However, traditional concrete formulations often exhibit inherent limitations, such as low tensile strength and susceptibility to cracking under stress [2]. These challenges have spurred extensive research into innovative reinforcement methods, particularly the integration of natural fibers and supplementary cementitious materials, like SF, to enhance concrete's mechanical and durability properties [3]. RF derived from the Borassus aethiopum palm tree, has emerged as a promising natural fiber for reinforcing concrete [4]. Its unique properties, including high tensile strength, flexibility, and lightweight nature, make it an attractive alternative to synthetic fibers commonly used in construction [5, 6]. The sustainability aspect of RF and its cost-effectiveness position it as a viable option in the push for greener building materials, especially as environmental concerns continue to rise within the construction industry [7, 8]. In parallel, SF a byproduct of silicon production has gained recognition for its pozzolanic properties, which significantly improve the mechanical performance of concrete [9, 10]. When incorporated into concrete, SF reacts with calcium hydroxide to produce additional calcium silicate hydrates, effectively enhancing strength and reducing permeability [11]. This dual action not only boosts compressive strength but also improves the material's resistance to chemical attacks, thereby extending the lifespan of concrete structures [12, 13].

Another significant focus of the current research was to determine the impact of varying dosages of RF, specifically 0.5%, 1%, and 1.5% on the mechanical properties of concrete. This study also assessed essential mechanical properties, such as compressive strength, tensile strength, and flexural strength to identify the optimal fiber content that enhances the structural integrity of concrete. The systematic comparison between the UN and TRT fibers provided insights into how fiber treatment affects overall concrete performance.

The treatment of RF with 1% sodium hydroxide (NaOH) was designed to improve the bonding characteristics between the fibers and the cement matrix. Enhanced adhesion and interlocking between the fibers and the concrete can lead to superior mechanical performance compared to UN fibers. The research aimed to elucidate the advantages of fiber treatment in concrete applications by evaluating both TRT and UN fibers.

In addition to the mechanical properties, this study evaluated the durability aspects of concrete containing RF [14]. Key durability indicators, such as WA, chloride penetration, and resistance to chemical attacks, were analyzed to assess the long-term performance of the concrete mixes [15, 16]. Durability is essential for ensuring the longevity of concrete structures, particularly in harsh environmental conditions, where exposure to moisture and chemicals can lead to premature degradation.

This research aligns with the increasing demand for sustainable construction materials and practices. Utilizing natural fibers, like RF, not only reduces the dependence on synthetic alternatives, but also promotes the use of agricultural byproducts, contributing to a circular economy [17-20]. By integrating RF and SF into concrete, eco-friendly practices that are increasingly relevant in today's construction landscape are supported.

The findings from this study are expected to provide valuable insights into the synergistic effects of RF and SF on the properties of concrete. The current research will enhance the understanding of how these components can work together to improve concrete performance by characterizing these materials and evaluating their combined impact on the mechanical and durability properties. The implications of this study extend beyond the academic interest, offering practical solutions for enhancing the quality and resilience of concrete structures in various applications.

The primary objective of this study was to investigate the performance of RF in combination with 10% SF on the mechanical and durability properties of concrete. A critical component of this research was utilizing Coarse Aggregates (CA) and Fine Aggregates (FA), cement, and both UN and NaOH-TRT RF. By understanding these materials' properties, this study can better evaluate their efficacy in enhancing concrete performance.

II. EXPERIMENTAL PROGRAM

A. *Materials*

The study used Portland pozzolanic cement (CEMI/B-P 42.5 N) from a local manufacturer that meets the EN 197 standard [21]. The CA utilized was crushed stone up to 12.50 mm in size, sourced from Kasarani in Nairobi, Kenya. The FA was river sand with a maximum size of 5 mm, obtained from Mlolongo quarries in Nairobi, Kenya. Sika ViscoCrete 20HE KE Superplasticizer (SP) from Sika Chemicals in Nairobi, Kenya, was added to improve concrete workability. Sodium hydroxide (NaOH) pellets with a purity of 98% were also acquired in Nairobi, Kenya. Finally, potable water from the Jomo Kenyatta University of Agriculture and Technology (JKUAT) water pump was used in all concrete mixes. The RF employed in this study were collected from mature ronier (Borassus aethiopum fruits) extraction in Pissa, Central African Republic, a renowned area with abundant ronier fruits. Table I shows the properties of the used materials.

TABLE I. THE USED MATERIALS

Materials	Properties
Cement (CEM I/B-P 42.5 N	Specific gravity of 3.12
FA (river sand)	Maximum size of 5 mm
CA (crushed stone)	Maximum size of 12.5 mm
Water (potable water)	Specific gravity of 1.00
Superplasticizer (Sika Viscoflow 20HE KE)	Specific gravity of 1.06
Sodium hydroxide pellets (NaOH)	98% extra pure
Untreated ronier fiber (UT-RF)	Specific gravity of 1.16
Treated (with NaOH) ronier fiber (T-RF)	Specific gravity of 1.21

B. *Methods*

1) *Characterization of CA and FA*

The particle size distribution of FA and CA was evaluated to determine their suitability for concrete, as shown in Figures 1 and 2.

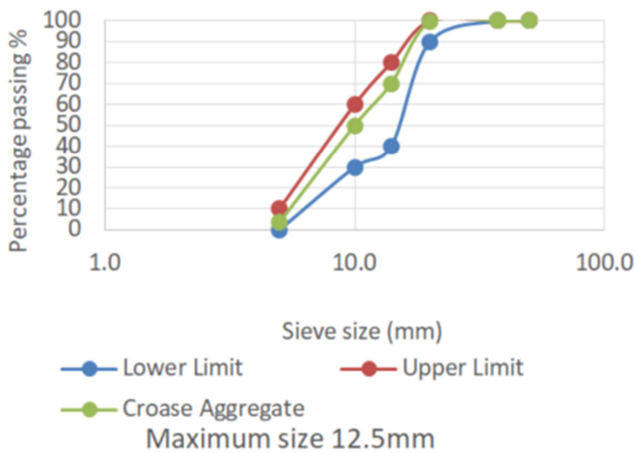

Fig. 1. Particle size distribution of CA.

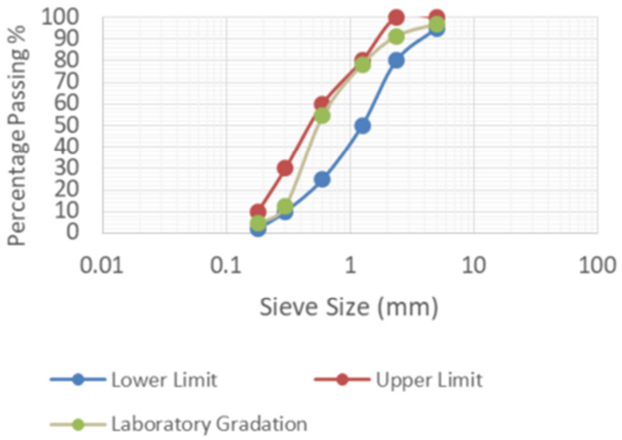

Fig. 2. Particle size distribution of FA.

Before usage, both FA and CA distribution was 2.00 kg/m^3. They were meticulously cleaned to remove impurities, dried in the sun to ensure complete moisture removal, and then the specific gravity was measured at 3.02 and 3.62. The aggregates were sieved and graded according to [22], adhering to specified upper and lower limits. The results confirmed that both aggregates were suitable for concrete mixtures, as outlined in [23]. The maximum particle size of FA was 5 mm, while the CA sizes ranged from 12.5 mm to 2.36 mm, indicating that they passed through a 12.5 mm sieve but were retained by a 2.36 mm sieve. The fineness modulus for FA and CA was determined to be 2.50 and 2.41, respectively, meeting the requirements of [23] for the fineness modulus of aggregates in concrete, falling within the range from 2.3 to 3.1.

2) Physical and Mechanical Properties of Aggregates

The compacted dry bulk density of FA and CA designated for the blend was determined to be 1,170 and 1,103 kg/m3, correspondingly, satisfying the specifications for the dry rodded bulk density of aggregates utilized in concrete, which falls within the range of 1,400. The Aggregate Impact Value (AIV) for CA was recorded at 3.76% and the Aggregate Crush Value (ACV) at 12.91%, with both of them being below the specified limits of 10% and 30%, respectively, as stipulated in [24, 25]. This demonstrates that the aggregates fulfill the suitability criteria for concrete use, as illustrated in Table II.

TABLE II. PHYSICAL AND MECHANICAL PROPERTIES OF AGGREGATES

Properties	FA	CA
Specific gravity on an oven-dry basis	3.02	3.62
Specific gravity on an oven-dry basis	2.71	2.69
WA (%)	2.92	3.21
Bulk density-dry rodded (kg/m^3)	1,170	1,103
AIV (%)	/	5.5
ACV (%)	/	12.91

3) Characterization of RF

a) Fourier Transform Infrared (FTIR)

FTIR spectroscopy was deployed to identify the chemical functional groups present in the sample. The sample powder was prepared via the Potassium bromide (KBr) pellet method by grinding 10 mg of sample along with 1000 mg KBr (analytical grade). The pellets were then prepared using a 75 kN/cm^2 pressure device for 1 minute, and were subsequently transferred to a sample holder for analysis. This was then loaded onto a Shimazdu FTIR spectrophotometer, and the spectrum was recorded between the wavelength range of 400–4000 cm^{-1} at a resolution of 4 cm^{-1} for 32 scans [26 - 29].

b) Examining Electron Scanning Microscopy Test

With the use of Scanning Electron Microscopy (SEM), the surface morphology of the RF was investigated. Any changes in the surface structure of the fibers following the treatment were examined using an electron detector, which is specifically made to detect secondary electrons, operating at a voltage of 5.0 kV. The analysis was carried out in the food fortification lab at Jomo Kenyatta University of Agriculture and Technology (JKUAT). The scanning electron microscope, VEGA3, was made available by TESCAN for the inquiry.

4) Treatment of RF

The alkaline treatment of the RF involves the use of NaOH, modifying the surface properties of the fibers, and hence improving their chemical reactivity and capacity to bond with the cement paste. After being boiled, the fibers are soaked in an 1% NaOH solution for 60 minutes [30 - 32], as depicted in Figure 3. Subsequently, the RF are thoroughly rinsed with drinkable water until the pH reaches a neutral level of 7 ± 0.5. This rinsing procedure removes any remaining alkali from the fibers.

Fig. 3. Treatment of RF with NaOH.

5) Silica Fume (SF)

The characteristics of SF can be affected by the production method and the specific processes employed. The former is a fine powder consisting of spherical particles that are 100 times smaller in diameter than those of Portland cement, as outlined in Tables III and IV [33].

TABLE III. CHEMICAL COMPOSITION OF SF

Composition	Composition (%)
	SF
Al_2O_3	0.469
CaO_2	1.535
SiO_2	93.042
SO_3	0.189
K_2O	0.215
LOI	3.36

SF can be found in three different forms: powder, condensed, and slurry. Its color can vary from light to dark grey, which is determined by the manufacturing process and various factors, such as the composition of wood chips, furnace temperature, wood chips to coal used ratio, exhaust temperature, and type of metal being produced.

TABLE IV. PHYSICAL PROPERTIES OF SF

SF	
Specific gravity	2.215
Setting time (min)	
Initial	135 min
Final	152 min
Setting Time Duration (min)	15 min

6) Superplasticizer (SP)

Sika ViscoCrete-20 HE KE, a commercially available SP, was used to improve the workability and flowability of freshly mixed concrete. It is intended to increase concrete's strength by improving its workability and flow while reducing its water content by up to 30%. Furthermore, it helps to lessen bleeding and segregation in ready-mix and precast concrete applications. It has a specific gravity of 1.09 and a pH value of 1.09, and it meets the SP requirements, as specified in [34, 35].

C. Mix Method

1) Mix Design

The research aims to achieve a Grade 60 concrete strength deploying the Design of Experiments (DOE) approach. The cube specimens have dimensions of 100 mm x 100 mm x 100 mm, while the cylindrical mold has 200 mm height and 100 mm diameter. The rectangular beam mold measurements were 100 mm x 100 mm x 350 mm. The specific concrete mix ratios for the samples are presented in Table V.

TABLE V. MIX DESIGN

Mix	Fiber content (%)	Cement (kg/m^3)	SF (%)	Water	SP	Fine Aggregate	CA	W/C ratio
Mix 0	0%	4.70	0%	1.64	0.4	5.4	8.17	0.35
Mix 1	0.5% UN	4.70	10%	1.64	0.4	5.4	8.17	0.35
Mix 2	1% UN	4.70	10%	1.64	0.4	5.4	8.17	0.35
Mix 3	1.5% UN	4.70	10%	1.64	0.4	5.4	8.17	0.35
Mix 4	0.5% TRT	4.70	10%	1.64	0.4	5.4	8.17	0.35
Mix 5	1% TRT	4.70	10%	1.64	0.4	5.4	8.17	0.35
Mix 6	1.5% TRT	4.70	10%	1.64	0.4	5.4	8.17	0.35

2) Concrete Mixing, Pouring, and Curing Procedure

The CA, FA, cement, water, SP, and RF components were all combined using a rotary drum mixer. To make fresh concrete, a lubricant was made by combining water and SP, which was then progressively added to the mixer containing the RCs to guarantee an even dispersion. After that, the lubricated molds were filled with the freshly mixed concrete, as portrayed in Figure 4.

Fig. 4. Casting concrete.

Slump and Compaction Factor (CF) analyses were performed to evaluate concrete workability and density in the fresh state, and compaction was guaranteed with an electric vibrator. After 24 hours, the samples were demolded, and they were cured in water until they were examined at days 3, 7, 14, and 28. For the cement to be properly hydrated, bonded with the particles, solidified, and gain strength, water curing made sure that the concrete obtained enough moisture. By guaranteeing a steady flow of fluids, this technique prevents early drying and insufficient hydration. Furthermore, keeping a damp atmosphere minimizes shrinkage, which lowers the possibility of cracking and jeopardizes the durability and structural integrity of concrete constructions. Cylindrical molds were utilized for split tensile strength, prismatic molds for flexural strength, and cubic molds for compressive strength, WA, and sulfuric acid testing [36-39], as can be seen in Figure 4.

3) Fresh Concrete Density and Air Void Content

According to [40], the density and air content of freshly mixed concrete were measured for every batch in this investigation.

D. Mechanical and Physical Properties

1) Compressive Strength Test

The RF and RC cubes underwent compressive strength testing at 3, 7, 14, and 28 days, with three cubes having been prepared for each fiber percentage. These cubes' measurements were 100 mm x 100 mm x 100 mm and were crushed after curing to determine the maximum compressive load according to [41], as displayed in Figure 5(a).

2) Tensile Strength Test

Split tensile strength tests were conducted on 100 mm diameter and 200 mm height cylinders according to [41]. Both the plain concrete and RF-reinforced concrete samples, with and without sodium hydroxide treatment, were cast with fiber percentages of 0.5%, 1%, and 1.5%. A compression machine was used to record the strength values at 7, 14, and 28 days, and the average strength for each percentage was calculated based on three samples, as evidenced in Figure 5(b).

3) Flexural Strength Test

The flexural strength test was carried out on RF and RC beams at 7, 14, and 28 days. Three beams with dimensions of 100 mm x 100 mm x 350 mm were tested for each fiber percentage in accordance with [42]. Equal loads were applied on both sides and at the center of the support points to assess their flexural strength, as can be seen in Figure 5(c).

(a) (b) (c)

Fig. 5. (a) Compressive test, (b) tensile test, (c) clexural test.

E. Durability Properties

1) Water Absorption (WA)

WA in concrete is defined as the percentage of water absorbed relative to the dry mass of the concrete. This measurement reflects the rate at which water is absorbed by the concrete's outer and inner surfaces. To conduct the WA test, cubes with 100 mm edges were air-dried for 24 hours, then molded and submerged in water for 28 and 56 days, following the guidelines provided in [43]. The cubes were then dried in an oven at 105°C for 72 hours to determine the dry weight. Three cubes were tested for each concrete mix, and the average value was calculated to determine the WA percentage, which was computed using:

$$WA(\%)=\frac{W_w-W_d}{W_d}\cdot 100 \qquad (1)$$

where W_w and W_d represent the weight (kg) of the wet and dry cube, respectively.

2) Sulphuric Acid

The resistance to the sulphuric acid was tested following the requirements outlined in [44]. Concrete cubes with an edge length of 100 mm were cast and cured in normal water for 28 days. After the curing period, the cubes were air-dried for 7 days, weighed, and then immersed in plastic containers containing 3%, 5%, and 7% sulphuric acid solutions for 28 and 56 days [45]. After their removal from the acid solution, the cubes were washed with normal water utilizing a plastic brush, wiped with an absorbent cloth, and reweighed to determine the percentage change in weight using:

$$\text{Weight change }(\%)=\frac{w-c}{c}\cdot 100 \qquad (2)$$

where c and w are the weight (kg) before and after the immersion in the acid, respectively.

The cubes were then subjected to compressive strength tests to assess the percentage change in compressive strength using:

$$\text{Compressive Strength change }(\%)=\frac{s_1-s_2}{s_2}\cdot 100 \qquad (3)$$

where s_2, s_1 are the compressive strength (kPa) values after and before the immersion in the acid, respectively.

For each concrete mix, three cubes were tested, and the average result was recorded, as depicted in Figure 6.

Fig. 6. Sulphuric acid immersion and durability test.

III. RESULTS AND DISCUSSIONS

The FTIR spectra, observed in Figure 7, reveal strong alkyne (C=H) and amino (N-H) absorptions from the cellulose at 3450 cm^{-1} for the UN product, while the TRT product shows a multitude of peaks between 3300 and 3800 cm^{-1}.

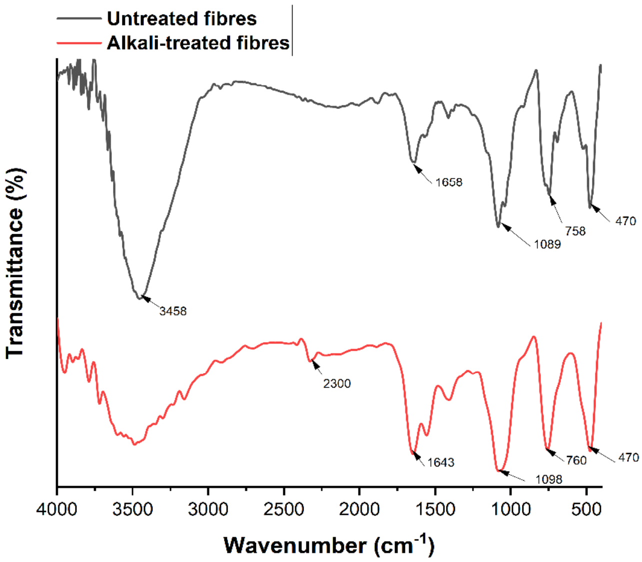

Fig. 7. FTIR spectra.

At 2337 cm^{-1}, the stretching vibrations of the alkyne of the cellulose are also represented, implying the presence of a tertiary amine in the product's chemical composition. These two absorptions occur because the biomass has numerous N-H and C-H bonds [32-33]. The strong band above 1646 cm^{-1} corresponds to the carbonyl stretching absorption (C=O) of the carboxyl and ester groups of hemicellulose. The absorption at 1394, 1078, and 766 cm^{-1} corresponds to the vibrations of the aromatic skeleton with C-O stretching and C-H reorientation in and out of the plane of the syringyl ring in the lignin of the TRT product. The strong band at 1074 cm^{-1} corresponds to the C-O and C-O-C stretching in hemicellulose, lignin, and cellulose. The small net absorbance at 911 cm^{-1} was completely reduced in the alkali-TRT fibers, as it is attributed to the β-1, 4-glycosidic linkages of the monosaccharides in the hemicellulose [46-48].

The disappearance of these characteristic stretching vibrations indicates that the alkaline treatment significantly reduced the hemicellulose content. Thus, the FTIR studies confirm a reduction in hemicellulose content during the alkaline treatment of the RF [49-51].

A. Scanning Electron Microscopy (SEM)

According to the SEM analysis, the surface morphology of the RF is considerably improved by the NaOH treatment. The smooth surface of the UN fibers with apparent spaces prevents them from competently connecting as well with the cement matrix, making the reinforcement less strong. The NaOH-TRT fibers, on the other hand, have a rough, fibrillated surface that increases the surface area and allows for a mechanical interaction with the cement matrix. When compared to the UN fibers, TRT fibers are far more effective as reinforcement due to their improved bonding, which also increases the concrete's tensile and flexural strength, as illustrated in Figures 8 and 9.

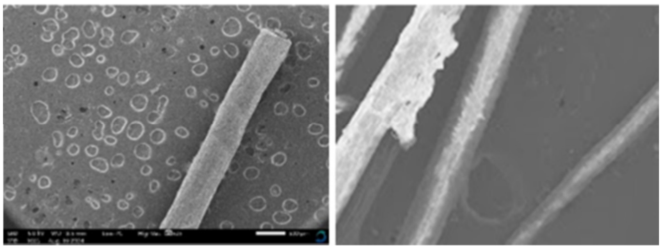

Fig. 8. SEM micrograph of UN RF.

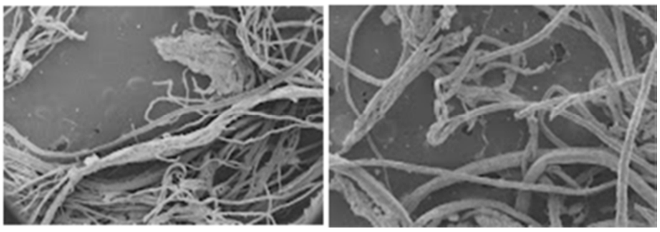

Fig. 9. SEM micrograph of TRT RF with 1% NaOH.

B. Concrete Workability

Workability in concrete refers to how easily the concrete can be laid, compacted, and finished without bleeding or segregating. The amount of cement to water/the Water to Cement (W/C) ratio, the kind of aggregates used, and the presence of fibers or chemical admixtures are some of the variables that affect this property. The slump test, demonstrated in Figure 10, in compliance with [52], and the CF test in compliance with [53], were used in this study to assess the workability of freshly mixed concrete for each new batch.

Fig. 10. Slump test.

C. Compressive Strength

The findings of the compressive strength test demonstrate that the addition of SF and RF improves the performance of the concrete when compared to the control mix, as portrayed in Figure 11. The best mixture for producing the highest compressive strength at all curing ages, 3, 7, 14, and 28 days, is the 1% TRT RF and 10% SF. The NaOH-TRT fibers outperform the UN fibers by a wide margin. The UN fibers are stronger than the TRT fibers, but the TRT fibers bind with the cement matrix better and distribute the stress more evenly, giving more strength. Due to the possibility of fiber clumping, an excessive fiber concentration of 1.5% somewhat lowers concrete compressive strength. All things considered, the ideal ratio for high-performance concrete is 10% SF and 1% TRT fibers.

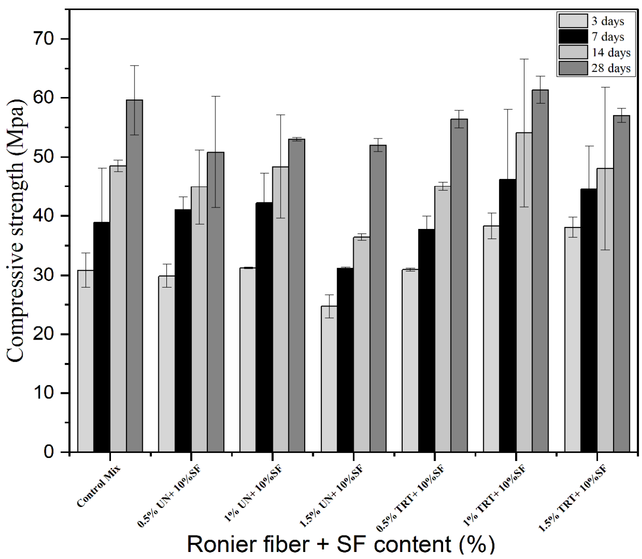

Fig. 11. RF impact on compressive strength.

D. Tensile Strength

Comparing the concrete performance to the control mix, the tensile strength data demonstrate that adding SF and RF greatly enhances productivity. Tensile strength is increased by the UN fibers, while the NaOH-TRT fibers perform better every time, as can be seen in Figure 12.

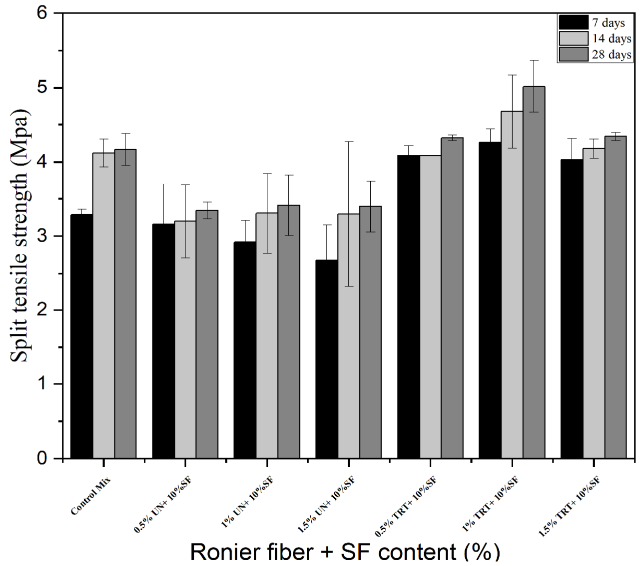

Fig. 12. RF impact on split tensile strength.

The combination with the maximum tensile strength at all testing ages, 7, 14, and 28 days, was the one comprising 10% SF and 1% TRT RF. The tensile strength and crack resistance are increased by the treatment, which strengthens the link between the fibers and the cement matrix. It is suggested that the optimal proportion for optimum tensile strength is 1% TRT fiber, since an excess of 1.5% fiber content causes a little drop in performance.

E. Flexural Strength

The addition of SF and RF to concrete enhances its performance when compared to the control mix, as shown by the results of the flexural strength tests. The UN fibers perform substantially worse than the TRT fibers, particularly those treated with sodium hydroxide (NaOH). For the best flexural strength at all curing ages, 7, 14, and 28 days, the ideal blend is 1% TRT fiber with 10% SF. The UN fibers perform worse than the TRT fibers, particularly at larger fiber contents, while TRT fibers link better with the cement matrix, improving weight transmission and crack resistance. Therefore, the greatest reinforcement for flexural strength in concrete is a combination of SF and fibers treated with NaOH, as depicted in Figure 13.

F. Durability Properties

1) Water Absorption (WA)

This study evaluated the WA of concrete reinforced with UN and TRT RF combined with SF over 28 and 56 days. The control sample (no fibers), which served as a baseline, showed a consistent WA of 3.808%. An 1% dosage of UN fibers led to the highest WA at both curing times, suggesting increased porosity due to the hydrophilic nature of the fibers. However, the UN fibers at 0.5% and 1.5% dosages demonstrated lower absorption than the control mix, likely due to a better matrix compaction at a higher fiber content. The TRT fibers demonstrated improved performance, with 1.5% of TRT fibers showing the lowest WA at both 28 and 56 days (3.304 – 4.23%). This indicates that fiber treatment enhances the bonding with the cement matrix, reducing permeability and improving durability over time. Overall, the results suggest that 1.5% TRT RF are optimal for reducing WA in concrete, making them suitable for applications requiring improved durability and moisture resistance, as illustrated in Figure 14.

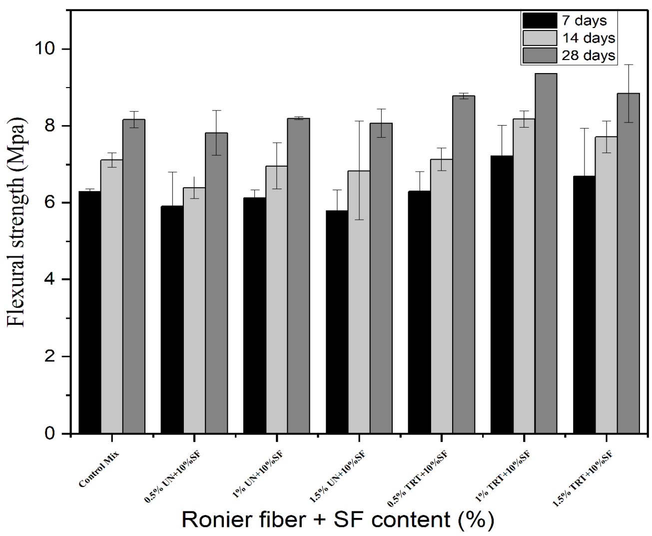

Fig. 13. RF impact on the flexural strength.

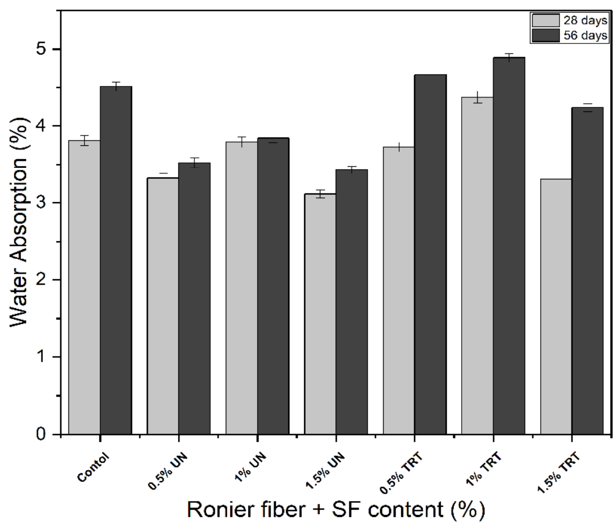

Fig. 14. WA of high-strength concrete reinforced with RF.

2) Resistance to Sulphuric Acid

By measuring the weight loss and compressive strength loss under 3% and 5% sulfuric acid exposure, this study investigated the resistance of high-strength concrete with UN and TRT RF to a sulfuric acid attack. According to the findings, UN fibers were more vulnerable to acid attack, which resulted in greater weight loss and a reduction in compressive strength because of the increased porosity and microcracking. On the other hand, TRT fibers showed a notable improvement in acid resistance. At both acid concentrations, the concrete with 1.5% TRT fibers exhibited the least amount of weight loss and compressive strength loss, indicating its increased durability. According to this, treating RF strengthens their link with the concrete matrix, resulting in a structure that is denser and more resistant to acid assault, as displayed in Figures 15-18.

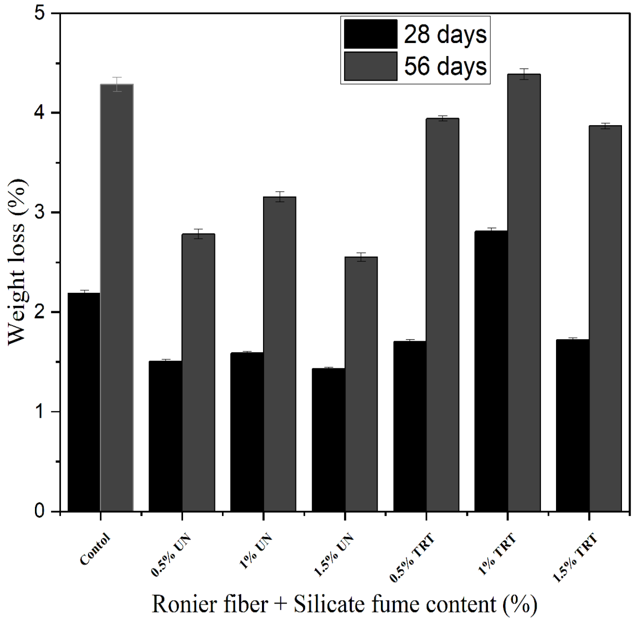

Fig. 15. Percentage loss in weight of high-strength concrete reinforced with RF under 3% sulphuric acid attack.

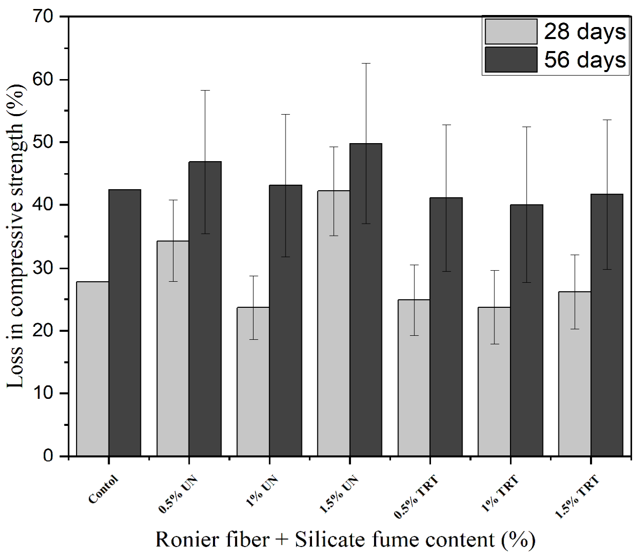

Fig. 16. Percentage loss in compressive strength of high-strength concrete reinforced with RF under 3% sulphuric acid attack.

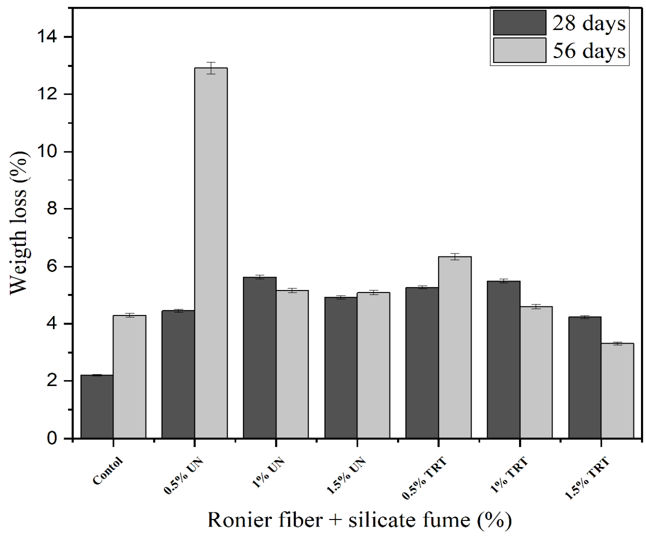

Fig. 17. Percentage loss in weight of high-strength concrete reinforced with RF under 5% sulphuric acid attack.

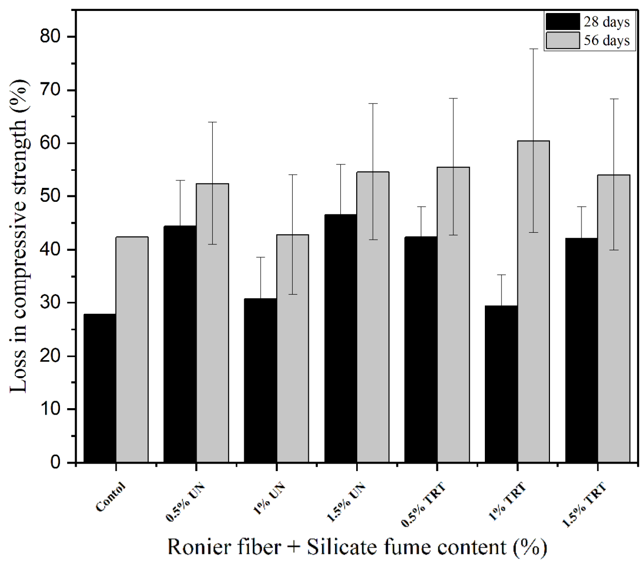

Fig. 18. Percentage loss in compressive strength of high-strength concrete reinforced with RF under 5% sulphuric acid attack.

IV. CONCLUSION

The results of this investigation show that adding Silica Fume (SF) and Ronier Fibers (RF) to concrete greatly improves its mechanical and durability qualities. The overall strength and durability of the concrete were enhanced by the 10% cement replacement rate of SF.

The incorporation of Treated (TRT) RF, improved the connection between the fibers and the cement matrix, resulting in an additional increase in tensile and flexural strengths. This bond enhancement improved the resistance to chemical assaults and environmental conditions while reducing Water Absorption (WA). A blend including 10% SF and 1% TRT RF demonstrated the highest performance, providing the ideal ratio of strength to durability. Given these results, the blend of 1%

TRT RF and 10% SF is proposed for concrete projects requiring both excellent mechanical performance and durability, particularly for structural applications, like pavements and bridges.

Enhancing the fiber-matrix bond through the use of TRT natural fibers will decrease WA and increase durability. Furthermore, using RF in concrete promotes environmentally friendly building techniques, especially in areas where it is easily accessible. To maximize the performance of concrete in more severe circumstances, additional investigation should be performed into different fiber treatments and their relative quantities.

DATA AVAILABILITY

The data presented in this study are available from the corresponding author upon request.

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