

The Effect of Alkali Treatment Concentrations on the Mechanical Properties of Ronier Fiber Reinforced Concrete

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ABSTRACT

This study experimentally investigates the effect of sodium hydroxide (NaOH) treatment on ronier fibers and their influence on the mechanical performance of concrete. With the growing demand for sustainable construction materials, natural fiber-reinforced concrete presents an attractive alternative to synthetic reinforcements. Ronier fibers, derived from the African *Borassus aethiopicum* palm, possess high tensile strength, flexibility, and inherent alkali resistance, making them suitable for cementitious composites. In this study, fibers were treated with 1%, 3%, and 5% NaOH solutions and incorporated into concrete at a constant dosage of 1% by cement weight. Fiber tensile testing, Scanning Electron Microscopy (SEM), and Fourier Transform Infrared (FTIR) analyses were performed to assess the mechanical behavior, surface morphology, and chemical modifications prior to incorporation. Concrete mixes included a control, untreated fibers, and NaOH-treated fibers. Compressive, split tensile, and flexural strengths were evaluated at 7, 14, and 28 days using standard cube, cylinder, and beam specimens. The results showed that fiber inclusion caused a slight reduction in compressive strength, which increased with treatment concentration, whereas significant enhancements were observed in tensile and flexural performance. At 28 days, the split tensile strength increased by approximately 8% for untreated fibers and 19% for the 1% treated fibers, whereas the flexural strength improved by about 6% and 12.5%, respectively. Higher NaOH concentrations reduced the performance due to fiber degradation. Overall, the 1% NaOH treatment was identified as optimal, demonstrating the potential of ronier fiber-reinforced concrete for improved crack resistance and flexural capacity in sustainable and low-cost construction applications.

Keywords-compressive strength; fiber-reinforced concrete; flexural strength; NaOH treatment; Ronier fibers; tensile strength

I. INTRODUCTION

Concrete is one of the most widely used construction materials due to its versatility, availability, and high compressive strength. However, it is inherently brittle and possesses low tensile capacity, making it prone to cracking under tensile and flexural stresses. Fiber reinforcement is therefore an effective strategy for improving tensile response, controlling crack propagation, and enhancing post-cracking behavior of concrete [1, 2].

Natural fibers offer notable environmental advantages over synthetic alternatives. They are renewable, locally available, cost-effective, and produced with far lower energy demand, reducing reliance on petroleum-based materials. Their use in concrete lowers the carbon footprint and resource consumption associated with cement and synthetic reinforcement [3, 4]. In addition, natural fibers enhance crack control, toughness, and post-cracking behavior through effective crack-bridging, supporting sustainable construction and aligning with global efforts to develop greener, more resilient infrastructure [5, 6]. Additionally, their utilization helps in reducing agricultural waste and promotes circular economy practices, particularly in developing regions where these fibers are locally abundant. However, the addition of natural fibers can also influence concrete workability, generally reducing slump and increasing water or admixture demand due to the fibers' high surface area and tendency to form entangled networks within the mix [7].

Despite these benefits, the integration of natural fibers into concrete presents significant challenges such as high-water absorption, fiber degradation in the alkaline cement matrix, and weak fiber-matrix bonding, all of which can compromise long-term performance [8]. When untreated, natural fibers exhibit poor bonding with the cement matrix, limiting their reinforcing potential as well as their performance in the composites [9, 10].

Fiber-matrix interaction depends on mechanical interlocking, chemical bonding with hydration products, and physical attraction forces that govern stress transfer and crack bridging. These interfacial mechanisms can be enhanced through surface modification, which improves fiber wettability, removes impurities, exposes cellulose microfibrils, and increases surface roughness. Therefore, several fiber treatment methods have been widely investigated [11, 12]. Among them, NaOH (alkali) treatment is the most widely adopted because of its cost-effectiveness and ability to modify fiber surface characteristics for improved performance in concrete composites [13, 14].

Several studies have demonstrated that NaOH concentration significantly affects the mechanical performance of natural fibers, with moderate levels generally providing optimal improvement. For example, rice straw fiber-PLA composites exhibited maximum flexural strength at an intermediate treatment level, followed by a decline at higher concentrations due to fiber weakening. Similarly, sugar palm fiber composites achieved their highest performance at 2% NaOH, whereas 4% and 6% treatments resulted in microcracking and reduced integrity, confirming that excessive alkalinity can degrade fiber structure and diminish composite performance [15, 16].

Ronier fibers, extracted from the *Borassus aethiopum* palm, have gained attention due to their strength, toughness, flexibility, and local availability across tropical Africa. They act as efficient crack-bridging elements and offer the potential for durable and sustainable concrete composites [17-19]. Nevertheless, the optimal NaOH treatment level for ronier fibers remains insufficiently explored, and limited research has examined how low-concentration treatments (1-5%) influence their morphology and mechanical performance in concrete.

This study examined the effects of 1%, 3%, and 5% NaOH treatments on ronier fibers incorporated into M30 concrete at a fixed 1% dosage. It was hypothesized that controlled alkalinization enhances fiber-matrix interaction through improved surface characteristics, thereby increasing tensile and flexural performance while limiting compressive strength reduction. The objective of this study was to identify the treatment level that provides the best balance between fiber modification and composite mechanical behavior.

II. MATERIALS AND METHODS

A. Materials Used

1) Material Collection and Preparation

The materials used in this study comprised Ronier fibers, CEM II/B-P 42.5N cement, fine aggregates, and coarse aggregates with a maximum size of 20 mm, along with 98% NaOH pellets, water, and a superplasticizer (Sika ViscoCrete®-20 HE KE). Cement was sourced from Bamburi, Kenya, and aggregates were obtained from local quarries. Ronier fibers were extracted from dried and ripened fruits of the *Borassus aethiopum* tree. Laboratory water was obtained from JKUAT, and NaOH pellets were procured locally. All materials were subsequently delivered to the JKUAT engineering laboratory for preparation and experimental testing.

2) Physical and Mechanical Properties of Aggregates

Through sieve analysis, both coarse and fine aggregates were analyzed to identify their particle size distribution as shown in Figures 1 and 2.

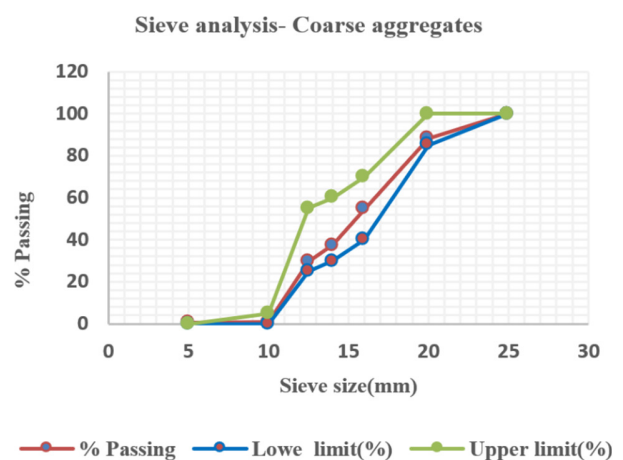


Fig. 1. Grading curve for the coarse aggregates.

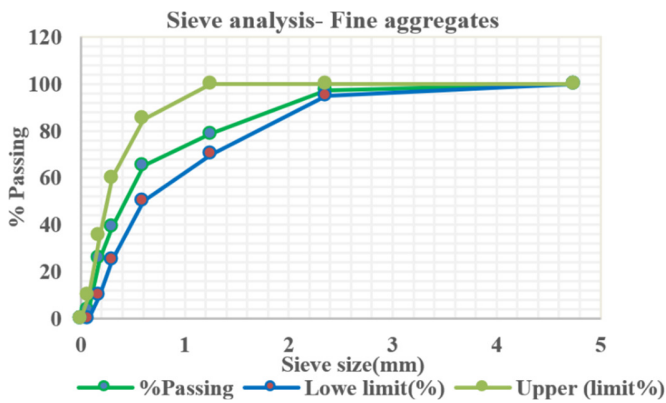


Fig. 2. Grading curve for the fine aggregates.

The coarse aggregate had a maximum size of 20 mm, mostly between 12.5 and 20 mm, with 90% passing the 20 mm sieve, indicating suitability for structural concrete. The fine aggregate was well-graded, with 98% passing the 4.75 mm sieve and minimal very fine particles, ensuring good packing, workability, and strength, in accordance with [20].

Specific gravity and water absorption tests were conducted on the coarse aggregates. The specific gravity and water absorption of the coarse aggregates were 2.67 and 1.96, respectively, indicating dense, normal-weight aggregates with moderate porosity. The specific gravity indicated good strength and durability, while water absorption confirmed that the aggregates would not excessively absorb mix water [21].

The aggregate crushing value test yielded a value of 11.95%. This low aggregate crushing value indicates that the aggregate possesses excellent resistance to crushing and is therefore highly suitable for structural concrete. The specific gravity of the fine aggregates was 2.54, indicating moderately dense sand suitable for structural concrete. The water absorption was 2.72%, indicating moderate porosity and the potential to absorb a noticeable amount of mixing water. Fineness modulus showed that the fine aggregates were suitable for concrete workability and strength [21, 22]. The samples were tested in the laboratory, as shown in Figure 3.



Fig. 3. Aggregate property testing.

The chemical properties of cement used are depicted in Table I and they are in accordance to KS EAS 18-1:2017 standard [23].

TABLE I. CEMENT PROPERTIES

Parameter	Specification (%)	Result (%)
Loss on Ignition (LOI)	≤ 5	4.83
Silicon dioxide (SiO ₂)	18-25	24.88
Insoluble Residue (I.R.)	≤ 5	14.12
Al ₂ O ₃ (aluminum oxide)	2-6	5.30
Fe ₂ O ₃ (iron oxide)	1-6	2.83
CaO (calcium oxide)	55-75	54.42
MgO (magnesium oxide)	≤ 5	1.44
SO ₃ (sulfur trioxide)	≤ 3.5	2.23
Na ₂ O (sodium oxide)	≤ 1.5	0.78
K ₂ O (potassium oxide)	0.5-1	0.86
Pozzolanicity	-	Pass
Cl ⁻ (chloride ion)	-	≤ 0.1

B. Methods Used

1) Fiber Preparation and Treatment

The fibers were first cut to 30 mm in length and 1 mm in diameter, then oven-dried at 60 °C for 24 h until a constant mass was achieved. NaOH solutions of 1%, 3%, and 5% concentrations were prepared on a weight-to-volume basis (w/v) using analytical grade NaOH pellets. The water used complied with the quality requirements of the standard for mixing water in concrete [24]. A constant fiber to solution ratio of 1:10 (mass/volume) was maintained to ensure uniform chemical exposure, in line with established alkali treatment practices for natural fiber modification reported in the literature [25].

The fibers were fully immersed in the solution for 1 h at room temperature, after which they were rinsed with distilled water until the wash water reached a neutral pH to remove the residual alkali, as displayed in Figure 4. The treated fibers were dried prior using [26].



Fig. 4. Fiber cutting, treatment, and drying.

2) Fiber Tensile Strength Testing

Tensile tests of the ronier fibers were performed using a Shimadzu universal testing machine equipped with mechanical wedge grips. The fibers were clamped directly in the grips and loaded in uniaxial tension at a displacement rate of 5 mm/min until failure.

3) Fiber Scanning Electron Microscopy Analysis

The surface morphology of the fibers was examined using SEM. The fibers were placed in the SEM chamber, and a focused electron beam was scanned across the surface at an accelerating voltage of 10.0 kV in the secondary electron mode, with low magnification to locate regions of interest and high magnification to reveal detailed surface structures, fibrillar details, and any defects or irregularities. Multiple images were captured to ensure representative morphology [27].

4) Fiber FTIR Analysis

The chemical structure of the fibers was analyzed using an FTIR spectrometer via the potassium bromide (KBr) pellet method. The sample was weighed, mixed with potassium bromide at a ratio of 1:10 (sample: KBr), and ground into a fine, homogeneous powder. The blended powder was then placed into a die and compressed using a hand press to form a transparent KBr pellet. The prepared pellet was mounted in the sample holder, inserted into the FTIR spectrometer, and spectra were recorded in the wavelength range of 500–4000 cm^{-1} at a resolution of 4 cm^{-1} for 32 scans. Infrared absorption peaks in the FTIR spectrum were analyzed to identify functional groups, understand the chemical structure of the fibers, and assess any chemical modification [28].

5) Concrete Mixing and Casting

The experimental program comprised five mixes: a control mix without fibers, one mix with untreated fibers (UNT), and three mixes incorporating fibers treated with different NaOH concentration levels (1%, 3%, and 5%), designated as 1%T, 3%T, and 5%T, respectively. The concrete grade was M30. Three specimens were cast for each mix at each curing age. The concrete mix design was carried out using the British Department of Environment (DOE) method. The detailed mixing proportions and corresponding slump values are presented in Table II.

Concrete mixing was performed using a mechanical mixer, and all batches followed the same sequence to ensure uniform fiber dispersion and consistent workability. The superplasticizer was incorporated with a fixed 10% water reduction and a constant 0.8% dosage, helping to restore workability and maintain fresh-state behavior across all mixes. Fresh concrete properties were assessed using a standard slump test, after which the mixes were cast into molds, compacted, and cured under water until the designated testing ages, as portrayed in Figure 5.

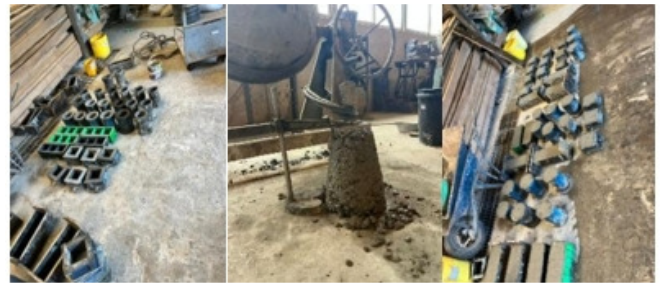


Fig. 5. Concrete mixing and pouring.

TABLE II. CONCRETE MIX PROPORTIONS

Mix ID	Fiber % by cement	Fiber dosage (kg/m ³)	Cement (kg/m ³)	Fine aggregates (kg/m ³)	Coarse aggregates (kg/m ³)	Water (kg/m ³)	w/c ratio	Superplasticizer (kg/m ³)	Slump (mm)
Control	0	0	380	609.73	1047.5	171	0.45	3.04	75
UNT	1	3.8	380	609.73	1047.5	171	0.45	3.04	70
1%T	1	3.8	380	609.73	1047.5	171	0.45	3.04	68
3%T	1	3.8	380	609.73	1047.5	171	0.45	3.04	66
5%T	1	3.8	380	609.73	1047.5	171	0.45	3.04	65

6) Specimen Casting and Testing

Concrete specimens were cast in the form of cubes (100 × 100 × 100 mm), cylinders (100 × 200 mm), and beams (100 × 100 × 350 mm) for compressive, split tensile, and flexural testing, respectively. All specimens were demolded after 24 h and cured in water for 7, 14, and 28 days in accordance with [29]. Mechanical testing was performed following standard procedures: compressive strength [30], split tensile strength [31], and flexural strength [32].

A minimum of three specimens per mix and curing age were tested to ensure statistical reliability. Failure was defined as the point at which the specimen could no longer sustain stress and visible cracking occurred across the cross-section. Figure 6 shows the equipment and the process for the tests.

Test data were subsequently analyzed using ANOVA to assess the significance of treatment effects.

III. RESULTS

A. Fiber Tensile Strength

The untreated fibers (UNT) exhibited a tensile strength of 104 MPa. Treatment with 1% NaOH increased the tensile strength to 116 MPa, representing the highest value among all treatment levels. Increasing the NaOH concentration to 3% reduced tensile strength to 98 MPa, while 5% treatment resulted in a further reduction to 72 MPa.

B. FTIR Analysis of Fibers

Both treated and untreated fibers were analyzed using FTIR, and their spectra are presented in Figure 7.



Fig. 6. Concrete curing and testing.

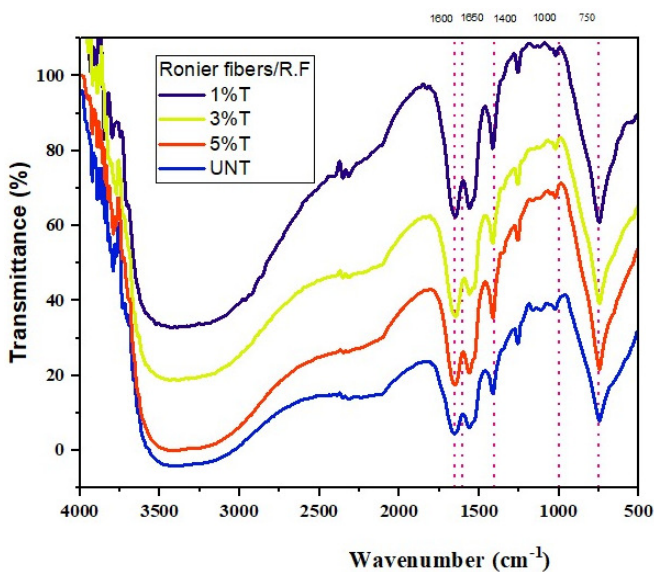


Fig. 7. FTIR spectra.

The FTIR spectrum of the untreated fibers exhibited strong O–H stretching bands at 3300–3400 cm⁻¹, C–H stretching near

2900 cm⁻¹, and a carbonyl peak at approximately 1730 cm⁻¹. For 1%T, a moderate reduction in the carbonyl and C–H peak intensities was observed. The 3% T exhibited further reduction in the carbonyl and lignin-related peaks (1500–1600 cm⁻¹). The 5%T sample showed the most significant reduction in carbonyl and lignin-associated peaks.

C. SEM Characterization

SEM micrographs of the untreated and NaOH-treated ronier fibers are presented in Figure 8.

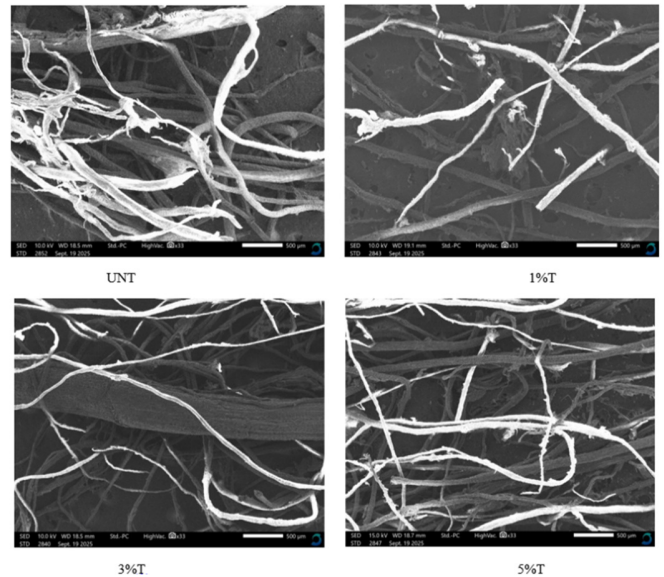


Fig. 8. SEM micrographs of the treated and untreated fibers.

The untreated fibers exhibited smooth, compact surfaces coated with visible impurities. At 1%T, the fibers displayed a rougher and more uniform surface with mild fibrillation. Increasing the treatment to 3% NaOH produced more pronounced fibrillation and partial peeling of the outer layer, with visible microcracks and opened surface pores. The 5% treatment resulted in intense over-fibrillation and significant degradation of the fiber wall structure. The fiber diameter was measured only before treatment, and post-treatment dimensional changes were not quantified.

D. Influence of Alkali Treatment on Mechanical Properties

The mean ± standard deviation values for compressive strength, split tensile strength, and flexural strength at 7, 14, and 28 days for all mixes are presented in Table III.

TABLE III. THE MEAN ± STANDARD DEVIATION VALUES FOR CONCRETE SPECIMENS

Mix	Compressive strength (MPa)			Split tensile strength (MPa)			Flexural strength (MPa)		
	7 days	14 days	28 days	7 days	14 days	28 days	7 days	14 days	28 days
Control	33.15 ± 0.13	36.34 ± 0.05	32.25 ± 0.13	2.20 ± 0.26	3.29 ± 0.10	3.67 ± 0.40	4.84 ± 0.40	5.36 ± 0.45	5.87 ± 0.55
UNT	28.03 ± 0.46	30.57 ± 0.57	31.11 ± 0.30	2.56 ± 0.35	3.72 ± 0.46	3.91 ± 0.45	5.11 ± 0.55	6.57 ± 0.66	7.98 ± 0.85
1% T	30.15 ± 0.64	31.45 ± 0.63	32.89 ± 0.70	3.23 ± 0.35	4.11 ± 0.46	4.25 ± 0.41	6.54 ± 0.45	7.89 ± 0.80	8.88 ± 0.80
3% T	28.62 ± 0.71	30.64 ± 0.86	30.15 ± 0.81	2.61 ± 0.30	3.84 ± 0.45	3.34 ± 0.35	6.31 ± 0.56	5.15 ± 0.61	6.73 ± 0.66
5% T	24.24 ± 0.92	28.52 ± 0.94	29.72 ± 0.96	2.39 ± 0.30	3.02 ± 0.36	3.14 ± 0.41	4.01 ± 0.40	5.64 ± 0.55	6.34 ± 0.55

1) Compressive Strength

Compressive strength generally increased with curing age up to 14 days for all mixes, with minor variations observed at 28 days. At 28 days, untreated fibers reduced compressive strength by approximately 3% relative to the control mix, while 5% NaOH treatment resulted in a reduction of approximately 14%. The 1%T mix exhibited a compressive strength comparable to that of the control at 28 days. The results are shown in Figure 9.

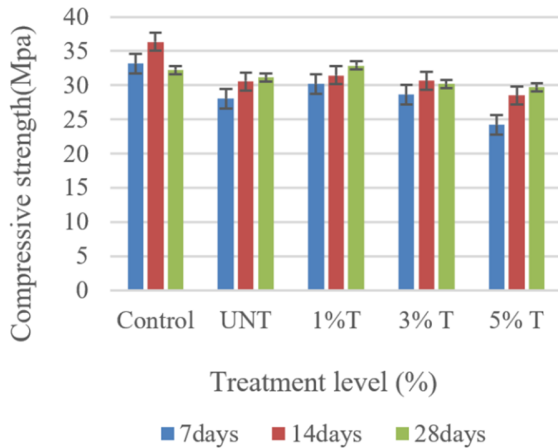


Fig. 9. Compressive strength of cubes.

2) Split Tensile Strength

The split tensile strength increased for all fiber-reinforced mixes compared to the control. At 28 days, the tensile strength increased by approximately 8% for the untreated fibers and 19% for 1%T. The 3% and 5% treatments showed lower improvements compared to 1%T. The results are illustrated in Figure 10.

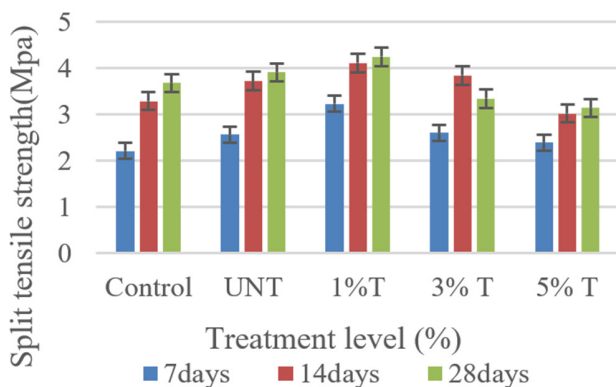


Fig. 10. Split tensile strength of cylinders.

3) Flexural Strength

The flexural strength improved across all fiber-reinforced mixes. At 28 days, untreated fibers increased the flexural strength by approximately 6%, whereas 1%T achieved an improvement of approximately 12.5%. Higher NaOH concentrations showed reduced enhancement, as displayed in Figure 11.

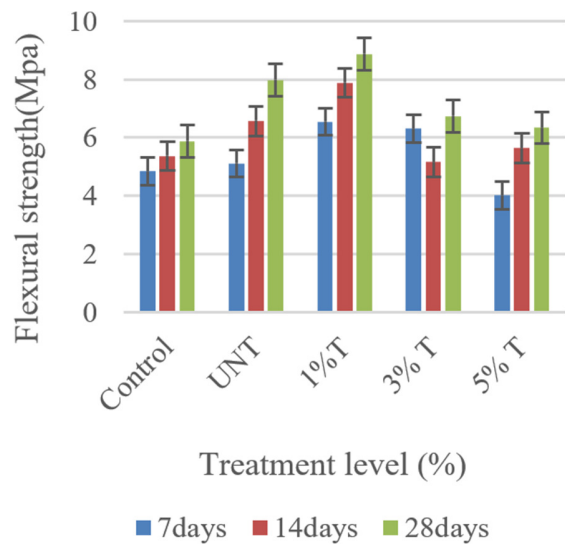


Fig. 11. Flexural strength of beams.

The statistical significance of NaOH treatment effects on mechanical properties was indicated by ANOVA, as presented in Table IV.

TABLE IV. ANOVA SUMMARY RESULTS

Property	Age (days)	F-value	p-value
Compressive strength	7	79.81	1.51×10 ⁻⁷
	14	53.87	9.92×10 ⁻⁷
	28	12.69	6.24×10 ⁻⁴
Split tensile strength	7	4.50	0.024
	14	3.80	0.040
	28	3.50	0.049
Flexural strength	7	14.59	0.00035
	14	9.72	0.00178
	28	9.56	0.00190

For all mechanical properties and curing ages, the p-values were less than 0.05, indicating statistically significant differences among the NaOH treatment levels.

IV. DISCUSSION

A. Fiber Tensile Strength

The increase in tensile strength after 1% NaOH treatment suggests effective surface cleaning and improved cellulose exposure without structural damage. In contrast, the reduction at 3% and 5% NaOH treatment levels indicated excessive removal of lignin and hemicellulose, leading to fiber degradation. Similar trends have been reported for alkali-treated natural fibers [33, 34].

Overall, the results confirmed that moderate alkali treatment enhanced fiber strength, whereas higher concentrations weakened fiber integrity.

B. FTIR Analysis of Fibers

The reduction in the carbonyl and C-H peak intensities at 1%T indicates the partial removal of hemicellulose and surface impurities while preserving the cellulose backbone. This controlled modification enhances fiber surface characteristics without significant structural damage [35].

The further reduction of lignin-related peaks at 3% and 5% NaOH treatment suggests progressive delignification. The substantial weakening of the carbonyl peaks after 5% NaOH treatment implies excessive removal of the amorphous components and early cellulose disruption. These chemical modifications explain the tensile strength trend observed in Section III-A, and are consistent with previously reported alkali treatment effects on natural fibers [36-38].

C. SEM Analysis of Fibers

The smooth and compact surface observed in untreated fibers limits fiber-matrix bonding and reduces compatibility with cementitious composites, consistent with the findings of [39].

The rougher and more uniform surface observed after 1% NaOH treatment suggests effective removal of surface impurities and exposure of cellulose fibrils without structural damage, thereby enhancing adhesion potential, complying with [40].

The pronounced fibrillation and structural degradation observed after 3% and 5% NaOH treatment suggest excessive removal of amorphous components and partial cellulose damage. The severe deterioration observed at 5% NaOH treatment corresponds to the sharp reduction in tensile strength reported in Section III-A, confirming the adverse effects of excessive alkalinity.

D. Influence of Alkali Treatment on Mechanical Properties

The mechanical results demonstrate that the NaOH concentration plays an important role in governing the composite performance. Statistical analysis further supports these observations, as ANOVA indicated statistically significant differences among the treatment levels for all mechanical properties and curing ages ($p < 0.05$). Flexural strength exhibited the strongest statistical differentiation, with p -values below 0.01 across all curing ages, highlighting its high sensitivity to the alkali treatment.

Although fiber incorporation resulted in slight reductions in compressive strength, most pronounced at 3% and 5% NaOH treatment levels, the reduction remained moderate at 1%T, where compressive strength was comparable to the control mix. The decrease at higher concentrations may be attributed to fiber-induced microvoid formation and structural deterioration observed in SEM analysis, which likely reduced effective load-transfer efficiency within the matrix. Similar deterioration has been reported in excessively modified cementitious systems and fiber-reinforced composites [41, 42].

In contrast, the tensile and flexural properties showed a clear improvement at moderate treatment levels. The substantial enhancement observed at 1%T (tensile improvement of approximately 19%) indicates improved fiber-matrix interactions and more effective crack-bridging. Surface roughening and partial removal of impurities, as evidenced by SEM and supported by FTIR analysis, likely enhanced stress transfer across crack interfaces.

At 3% and 5% NaOH treatment levels, reduced mechanical performance corresponded with the decline in fiber tensile

strength and the morphological degradation observed in SEM analysis. Excessive removal of lignin and hemicellulose likely weakened fiber integrity, limiting effective stress transfer under tensile and flexural loading. Although fiber-reinforced specimens exhibited more distributed cracking compared to the brittle splitting of the control mix, the crack-bridging efficiency was lower than that achieved at 1% treatment. This reduction in the mechanical contribution at higher treatment levels is consistent with the behavior reported for alkali-treated natural-fiber concrete systems [43-46].

V. CONCLUSIONS

This study demonstrated that ronier fibers enhance the split tensile and flexural performance of concrete, with only minor reductions in compressive strength. Among the investigated treatment levels, the 1% NaOH treatment consistently produced the highest mechanical improvements. In contrast, higher concentrations (3% and 5%) of NaOH led to fiber degradation, as confirmed by SEM and FTIR, resulting in reduced tensile and flexural capacity. These trends align with observations in sisal, jute, kenaf, hemp, and other natural fibers, which also perform the best at low NaOH levels and degrade at higher concentrations.

The 1% NaOH treatment provides an optimal balance between fiber surface modification and integrity, enabling improved crack bridging, post-cracking response, and flexural capacity, thereby positioning ronier fibers as a sustainable, low-cost reinforcement option for concrete elements requiring enhanced ductility. This study was limited to short-term mechanical evaluation using laboratory-scale specimens; therefore, future research should examine the long-term durability, full-scale structural performance, and detailed fiber-matrix interaction mechanisms under real service conditions.

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