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Baseline Strength Differences and Post-Immersion Compressive Performance of Concrete Reinforced with Chemically Untreated Abaca Fibers under Sulfuric Acid Exposure

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Abstrak

Penilaian komparatif terhadap kuat tekan setelah perendaman memerlukan pertimbangan mengenai perbedaan mekanis awal di antara formulasi beton yang digunakan. Studi ini meneliti beton normal (BN) dan beton semen Portland biasa yang diperkuat dengan serat abaka tanpa perlakuan kimia (BSPA; panjang 55 mm, 0,70% dari massa semen), tanpa penambahan bahan semen tambahan (supplementary cementitious materials). Spesimen berbentuk silinder (150 × 300 mm; tiga buah per kelompok) diuji pada usia 28 hari tanpa paparan, atau pada usia 42 hari setelah melalui perendaman selama 14 hari dalam larutan asam sulfat komersial dengan konsentrasi nominal 5% (v/v). Sembilan data kuat tekan yang belum pernah dipublikasikan sebelumnya dianalisis bersama dengan tiga data referensi BN yang telah dipublikasikan. Rata-rata kuat tekan untuk BN dan BSPA pada kondisi referensi masing-masing adalah 35,171 MPa dan 47,310 MPa, sedangkan setelah perendaman, nilainya menjadi 29,819 MPa dan 43,669 MPa. Perbedaan kuat tekan antara BSPA dan BN adalah 12,139 MPa dan 13,850 MPa, yang menghasilkan estimasi interaksi antara formulasi dan kondisi sebesar +1,711 MPa (interval kepercayaan 95% Welch–Satterthwaite: −11,404 hingga +14,826 MPa). Dengan demikian, BSPA menunjukkan keunggulan kuat tekan yang signifikan pada kedua kondisi pengujian, meskipun perubahan tambahan dalam keunggulan tersebut masih belum dapat dipastikan secara statistik. Mengingat usia spesimen dan paparan asam sulfat bervariasi secara bersamaan, serta tidak adanya konfirmasi mengenai replikasi dari kelompok produksi (batch) yang independen, perbandingan ini tidak secara mandiri membuktikan adanya peningkatan ketahanan terhadap asam. Dengan mengintegrasikan pengukuran baru yang spesifik untuk formulasi tersebut ke dalam perbandingan berbasis data acuan, studi ini menyajikan interpretasi yang lebih cermat mengenai kinerja kuat tekan beton yang diperkuat serat abaka tanpa perlakuan kimia setelah melalui proses perendaman.

Kata kunci*—Serat abaka; Asam sulfat; Kuat tekan; Kekuatan dasar; ANOVA faktorial.*

Abstract

Comparative assessment of post-immersion compressive strength requires consideration of the initial mechanical differences between concrete formulations. This study investigated normal concrete (BN) and ordinary Portland cement concrete reinforced with chemically untreated

abaca fibers (BSPA; 55 mm length, 0.70% by cement mass), without supplementary cementitious materials. Separate cylindrical specimens (150 × 300 mm; three per group) were tested at 28 days without exposure or at 42 days following 14 days of immersion in a nominal 5% v/v dilution of commercial sulfuric acid reagent. Nine previously unpublished compressive-strength observations were analyzed alongside three attributed, previously published BN reference measurements. The mean compressive strengths of BN and BSPA were 35.171 and 47.310 MPa, respectively, at the reference condition, compared with 29.819 and 43.669 MPa after immersion. The corresponding BSPA–BN strength differences were 12.139 and 13.850 MPa, yielding a formulation-by-condition interaction estimate of +1.711 MPa (Welch–Satterthwaite 95% confidence interval: −11.404 to +14.826 MPa). BSPA therefore exhibited a substantial compressive-strength advantage under both testing conditions, although the additional change in this advantage remained statistically uncertain. Because specimen age and sulfuric acid exposure varied simultaneously and independent production-batch replication was unconfirmed, the comparison does not independently establish improved acid resistance. By integrating new formulation-specific measurements with a baseline-informed comparison, this study provides a more rigorous interpretation of post-immersion compressive performance in chemically untreated abaca fiber-reinforced concrete.

Keywords—*Abaca fiber; Sulfuric acid; Compressive strength; Baseline strength; Factorial ANOVA.*

1. INTRODUCTION

Sulfuric acid exposure alters cementitious materials through coupled dissolution, decalcification, precipitation of sulfate-bearing reaction products, and transport processes, with the extent of deterioration influenced by material composition and exposure conditions [1–3]. Investigations involving different cementitious binders and fiber-reinforced concrete have demonstrated the relevance of mechanical measurements alongside complementary indicators of chemical deterioration [4,5]. These processes must also be distinguished from sulfate-salt attack, for which the chemical environment and associated deterioration mechanisms differ [6]. Studies of metallic and synthetic fiber-reinforced concrete under acidic or sulfate-containing environments [5,7,8], together with research on kenaf textile-reinforced composites using corresponding laboratory reference conditions [9], further demonstrate that the interpretation of mechanical performance depends on reinforcement characteristics, exposure duration, and the experimental comparison structure. Consequently, post-immersion compressive strength is most informative when evaluated in relation to the material's initial mechanical condition rather than as an isolated measure of environmental resistance.

Plant-based fibers have attracted considerable interest as reinforcement constituents in cementitious composites, although their mechanical performance is strongly influenced by fiber geometry, moisture absorption, dispersion, and compatibility with the cementitious matrix [10–13]. Among these materials, abaca *(Musa textilis)* has been investigated for its influence on cement hydration and autogenous shrinkage [14], the effects of physical and chemical fiber treatments [15], and the mechanical and durability-related performance of alkali-treated fiber-reinforced concrete [16]. Particularly relevant investigations have examined ordinary Portland cement concrete incorporating 35 mm abaca fibers at different reinforcement dosages [17] and zeolite-containing concrete reinforced with treated and untreated abaca fibers under chemically aggressive conditions [18]. These studies establish a scientific foundation for abaca-reinforced cementitious materials while highlighting the importance of formulation-specific evidence when the binder composition, fiber condition, and exposure characteristics differ. The present investigation builds upon this foundation by addressing the compressive performance of a defined

chemically untreated abaca-fiber formulation under the recorded reference and post-immersion testing conditions.

An important methodological consideration arises when the compared concrete formulations possess unequal reference strengths. A higher post-immersion compressive strength may reflect an advantage already established before exposure, together with any additional change associated with the recorded testing conditions. Previous durability-integrated concrete research has emphasized the relevance of initial-strength comparability when interpreting subsequent structural and material performance [19]. For formulations evaluated using separate reference and post-immersion specimen groups, examining the initial and final between-formulation strength differences provides a more informative basis for assessing their relative mechanical behavior than comparing final strengths alone. The resulting question is whether the compressive-strength advantage of the abaca-reinforced formulation changes across the investigated testing conditions and how precisely that additional change can be estimated.

Building on the existing evidence for abaca-reinforced cementitious materials, this study examines the compressive performance of ordinary Portland cement concrete incorporating chemically untreated abaca fibers at a nominal length of 55 mm and a dosage of 0.70% by cement mass, without supplementary cementitious materials. The selected dosage corresponds to a reinforcement level previously investigated in the related mechanical-performance study [17], whereas the 55 mm fiber configuration and 14-day sulfuric acid immersion period represent the specific experimental series documented in the available records. Rather than treating fiber geometry or exposure duration as independently optimized variables, the investigation focuses on the mechanical evidence provided by this defined formulation and testing program. By integrating nine previously unpublished compressive-strength measurements with the explicitly attributed normal-concrete reference observations from [17], the study quantifies the strength advantage already present before immersion, the corresponding post-immersion difference, and the uncertainty associated with their change. This comparison extends the empirical evidence for chemically untreated abaca-reinforced concrete beyond the mechanical conditions examined in [17] and complements the durability investigation of zeolite-containing abaca concrete reported in [18]. The principal objective is therefore to establish a formulation-specific, baseline-informed interpretation of compressive performance that distinguishes an observed mechanical advantage from evidence of an additional response across the recorded testing conditions.

2. MATERIALS AND METHODS

2.1. Materials and Mixture Proportions

Two concrete formulations were investigated: normal concrete without fiber reinforcement (BN) and concrete reinforced with chemically untreated abaca fibers (BSPA). Type I Portland cement was used as the sole cementitious binder. The other constituent materials comprised crushed river-stone coarse aggregate with a nominal maximum size of 25 mm, natural river sand separated into fine and coarse fractions, and clean mixing water. Neither supplementary cementitious materials nor chemical admixtures were incorporated. Natural abaca fibers *(Musa textilis)* were obtained from Simeulue Regency, Aceh Province, Indonesia. The BSPA formulation contained fibers with a nominal length of 55 mm at a dosage of 0.70% by cement mass, equivalent to approximately 3.00 kg/m³. The dosage was expressed relative to cement mass rather than total concrete mass or volume.

The mixture proportions were based on the experimental concrete formulation reported in [17], providing continuity with the previously investigated ordinary Portland cement system. The same nominal quantities of cement, coarse and fine aggregates, and mixing water were maintained for BN and BSPA, with a designed water-to-cement ratio of 0.45 and no additional water compensation for fiber incorporation (Table 1). The associated material-preparation procedure included aggregate conditioning to a saturated-surface-dry state and moisture

determination by oven drying at temperatures not exceeding 105 °C. The BSPA fiber dosage of 0.70% by cement mass corresponds to a reinforcement level examined in [17], establishing a common dosage reference while allowing the present experimental evidence to be distinguished by its fiber configuration and post-immersion testing condition. Whereas Farizal et al. [17] investigated 35 mm abaca fibers, the present experimental records document a nominal length of 55 mm for the chemically untreated fibers. This length represents the specific configuration available for analysis rather than a systematically varied fiber-length factor. Accordingly, the study characterizes the mechanical performance of the documented 55 mm formulation without attributing differences from the previously published series exclusively to fiber length.

Table 1. Nominal mixture proportions of normal concrete and concrete reinforced with chemically untreated abaca fibers.

Constituent	BN (kg/m³)	BSPA (kg/m³)
Type I Portland cement	428.9	428.9
Mixing water	193.0	193.0
Coarse aggregate	1101.3	1101.3
Fine sand	624.0	624.0
Coarse sand	32.8	32.8
Abaca fibers	0	3.00
Water-to-cement ratio (–)	0.45	0.45

Note: BN denotes normal concrete and BSPA denotes chemically untreated abaca fiber-reinforced concrete. The base mixture proportions were adopted from [17]*. The BSPA formulation investigated here contained 55 mm fibers at 0.70% of cement mass. Values are nominal quantities per cubic metre of concrete.*

2.2. Abaca Fiber Preparation and Concrete Mixing

Before incorporation into concrete, the abaca fibers were washed with clean water to remove surface impurities, dried under sunlight for approximately 24 h, and cut to a nominal length of 55 mm. The prepared fibers were subsequently stored indoors before mixing. No alkaline treatment, silane modification, chemical coating, or other chemical surface treatment was applied. Accordingly, chemically untreated refers to fibers subjected to physical preparation without chemical modification.

Concrete was mixed mechanically using a laboratory mixer. Farizal et al. [17] documented the use of a horizontal laboratory mixer with a nominal capacity of 100 L and a digital weighing scale with an accuracy of 0.01 kg in the associated experimental program. BN and BSPA were prepared separately using the mixture proportions presented in Table 1. The base concrete constituents were mixed before the abaca fibers were introduced into BSPA in successive small portions to promote dispersion and minimize localized fiber accumulation. The specified mixing-water quantity was maintained without adjustment following fiber incorporation, and no chemical admixtures were added. Fresh-concrete consistency was evaluated using the slump test, with ASTM C143/C143M-26b [20] cited as the relevant methodological reference. Because only one slump measurement was available for each formulation, the results were interpreted descriptively, as presented in Section 3.1.

2.3. Specimen Preparation, Curing, and Experimental Design

Cylindrical specimens with nominal dimensions of 150 mm in diameter and 300 mm in height were prepared for compressive-strength testing. Farizal et al. [17] documented the associated casting procedure, which involved placing concrete in three layers with manual compaction following mechanical mixing. ASTM C192/C192M-26a [21] was cited as the relevant methodological reference for laboratory specimen preparation and curing. All specimens underwent an initial 28-day water-curing period. Although the related experimental publication reported a nominal curing temperature of 25 ± 2 °C, the present 55 mm fiber series was cured

under ambient laboratory conditions without a separately documented continuous temperature record.

The experimental comparison involved two concrete formulations and two testing conditions. The first condition comprised unexposed reference specimens tested at 28 days. The second comprised separate specimens exposed to sulfuric acid solution for 14 days after water curing and subsequently tested at 42 days. The BN reference group, the 55 mm BSPA reference group, and the two post-immersion groups originated from the same experimental casting program. BN and BSPA were prepared as separate mixtures because their constituent compositions differed. Three cylindrical specimens were assigned to each formulation–condition combination, resulting in 12 compressive-strength observations. Table 2 summarizes the analytical structure, and Fig. 1 illustrates the corresponding preparation, curing, exposure, and testing sequence.

Table 2. Experimental comparison matrix for the investigated concrete formulations.

Concrete formulation	Testing condition	Water curing	Acid immersion	Testing age	Cylinders
BN	Unexposed reference	28 days	None	28 days	3
BSPA	Unexposed reference	28 days	None	28 days	3
BN	Post-immersion	28 days	14 days	42 days	3
BSPA	Post-immersion	28 days	14 days	42 days	3
Total					12

Note: Different cylinders were tested under the reference and post-immersion conditions. The three BN reference observations were previously published in Farizal et al. [17]. *The two testing conditions differ in both specimen age and sulfuric acid exposure.*

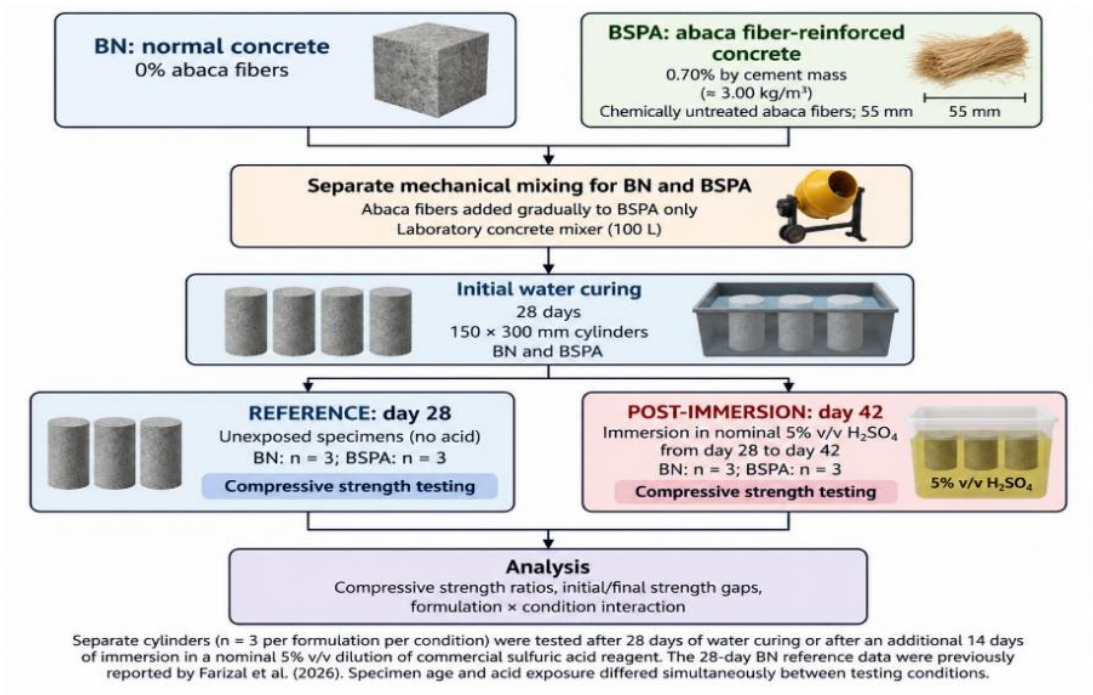


Fig. 1. Experimental arrangement and analytical comparison structure for normal concrete and chemically untreated abaca fiber-reinforced concrete. Separate cylinders (n = 3 per formulation per condition) were tested after 28 days of water curing or after an additional 14 days of immersion in a nominal 5% v/v dilution of commercial sulfuric acid reagent. The 28-day BN reference data were previously published in Farizal et al. [17]. Specimen age and acid exposure differed simultaneously between testing conditions.

Compressive-strength testing was destructive, and each specimen was tested once. Reference and post-immersion measurements were therefore obtained from independent cylinder groups rather than repeated measurements of the same specimens.

2.4. Sulfuric Acid Solution Preparation and Immersion

The exposure solution was prepared using a commercial concentrated sulfuric acid reagent labeled as containing 98% H_2SO_4. The documented dilution basis consisted of 5 mL of the commercial reagent diluted with water to a final solution volume of 100 mL. The resulting exposure solution is designated as a nominal 5% v/v dilution of commercial sulfuric acid reagent. This designation refers to the volumetric proportion of the original concentrated reagent and does not represent a measured 5% mass concentration of pure H_2SO_4.

The nominal dilution procedure was applied consistently to prepare the solution volumes required for immersion, with tank dimensions and solution quantities adjusted to accommodate the cylindrical specimens. Sufficient solution was provided to maintain complete submersion, and the 100 mL preparation basis described above was used to define the dilution proportion rather than the total immersion-bath volume. Following the initial 28-day water-curing period, the specimens assigned to the exposure condition underwent 14 days of immersion, corresponding to the exposure interval documented in the available experimental records. This interval defines the investigated post-curing exposure condition and was not varied as an independent duration factor. The available documentation does not establish a separate predefined duration-response hypothesis or an experimentally optimized exposure interval; accordingly, the 14-day period is treated as a specified feature of the experimental comparison rather than a demonstrated threshold for sulfuric acid deterioration. The solution was replaced during immersion, although a fixed renewal interval was not documented.

Immersion was conducted under ambient laboratory-temperature conditions without active temperature control. Solution pH was not measured, and the actual bath volume and temperature history were not quantified. The exposure protocol is therefore characterized by its nominal reagent dilution, complete specimen submersion, solution replacement, and exposure duration. Following immersion, the specimens were subjected to compressive-strength testing at a concrete age of 42 days.

2.5. Compressive Strength Determination and Data Provenance

Compressive-strength testing was conducted under axial loading to failure using a digital hydraulic compression testing machine. Farizal et al. [17] documented a machine capacity of at least 2000 kN and identified ASTM C39/C39M-23 and SNI 1974:2011 as testing references in the associated experimental publication. ASTM C39/C39M-24 [22] is cited here as a subsequent methodological reference rather than as evidence that the experimental measurements were performed in accordance with that specific edition. The compressive strength of each cylinder was calculated as follows:

$$f'c = Pmax / A = 4 \times Pmax / (\pi \times D^2) \quad (1)$$

where $f'c$ is the compressive strength (MPa), $Pmax$ is the maximum applied compressive load (N), A is the loaded cross-sectional area (mm²), and D is the cylinder diameter (mm). The nominal cylinder diameter was 150 mm. The associated publication identifies the compression-testing equipment and principal testing procedure. However, the available records do not independently establish the specific machine model, loading-rate history, cylinder-end preparation, or calibration information for the present analytical dataset. Accordingly, full compliance with every requirement of the later ASTM edition is not claimed.

The experimental evidence was assembled with explicit distinction between previously published reference measurements and previously unpublished observations. The three unexposed BN specimens tested at 28 days exhibited compressive strengths of 42.080, 29.734,

and 33.698 MPa, corresponding to the normal-concrete control data reported in [17], with minor differences in displayed precision attributable to rounding. These measurements were retained with attribution to establish a traceable reference for the present comparison. The nine previously unpublished observations comprise three 28-day reference measurements of concrete incorporating chemically untreated 55 mm abaca fibers (BSPA-28), three post-immersion measurements of normal concrete (BN-42A), and three corresponding post-immersion measurements of the abaca-reinforced formulation (BSPA-42A). Their inclusion extends the available experimental evidence from the previously reported mechanical comparison involving 35 mm fibers [17] to a defined 55 mm untreated-fiber formulation and its recorded post-immersion performance. Importantly, these additional measurements complete the four-group analytical structure required to quantify both the initial and final between-formulation strength differences and to estimate the uncertainty associated with their change. The resulting contribution is therefore not simply the addition of individual strength values, but the formulation-specific experimental evidence needed to distinguish an established reference-strength advantage from the estimated additional response across testing conditions. Because fiber length was not varied within the current experimental comparison, this extension is interpreted as evidence for the investigated formulation rather than as an isolated fiber-length effect.

2.6. Descriptive Metrics and Baseline Strength Comparison

The individual-cylinder observations were retained for analysis. Descriptive statistics included the sample mean, sample standard deviation, and coefficient of variation for each formulation–condition combination. The coefficient of variation was expressed as the sample standard deviation divided by the corresponding mean, multiplied by 100%. For the following calculations, $M(g,28)$ represents the mean compressive strength of formulation g in the unexposed 28-day reference condition, whereas $M(g,42A)$ represents the mean compressive strength of the same formulation after sulfuric acid immersion and testing at 42 days. The symbol g denotes BN or BSPA. The post-immersion-to-reference compressive strength ratio was defined as:

$$R(g)\ (\%) = 100 \times M(g,42A) / M(g,28) \quad (2)$$

This ratio compares two independent specimen groups tested at different ages and exposure conditions. It is therefore a descriptive strength comparison rather than a direct measure of acid-induced strength retention. The initial between-formulation strength gap was calculated as:

$$G28 = M(BSPA,28) - M(BN,28)$$

The corresponding post-immersion strength gap was calculated as:

$$G42A = M(BSPA,42A) - M(BN,42A)$$

The difference between the observed condition-related strength changes of the two formulations was calculated as:

$$\Delta\Delta = [M(BSPA,42A) - M(BSPA,28)] - [M(BN,42A) - M(BN,28)] = G42A - G28 \quad (3)$$

This contrast quantifies the change in the between-formulation strength difference across the two recorded testing conditions. The initial-to-final strength-gap ratio was defined as:

$$Sbaseline\ (\%) = 100 \times G28 / G42A \quad (4)$$

where $Sbaseline$ represents the percentage ratio of the initial between-formulation strength gap to the corresponding post-immersion strength gap. This descriptive ratio was calculated for the present dataset because the final strength gap was nonzero. It provides an algebraic comparison of observed group-mean differences, not a causal estimate of the contributions of fiber reinforcement, hydration, or sulfuric acid deterioration. The difference-in-differences contrast defined in Eq. (3) was subsequently examined using the interaction term of the factorial model.

2.7. Statistical Analysis

To distinguish the compressive-strength advantage already present in the reference condition from an additional formulation-specific response across testing conditions, the statistical analysis was centered on the change in the between-formulation strength difference and its uncertainty. This distinction is particularly relevant when mixtures differ substantially in their initial mechanical properties, because higher post-immersion strength alone cannot establish whether the response across testing conditions differs between formulations. Accordingly, the interaction contrast was designated as the primary exploratory estimand, while conventional factorial analyses were retained to characterize the broader structure of the observed strength differences.

The dataset comprised 12 cylindrical specimens arranged in a balanced 2 × 2 factorial structure, with three observations for each formulation–condition combination. Concrete formulation (BN and BSPA) and testing condition (28-day unexposed reference and 42-day post-immersion) were treated as categorical factors, denoted A and B, respectively. A fully interacted categorical model was fitted using Design-Expert 13, with effect coding of −1 for BN and the reference condition and +1 for BSPA and the post-immersion condition:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 AB + \varepsilon \quad (5)$$

where Y denotes compressive strength, β_0 is the intercept, β_1 and β_2 represent the formulation and testing-condition coefficients, β_3 represents their interaction coefficient, and ε denotes residual variation. With the specified effect coding, the interaction contrast defined in Eq. (3) is related to the fitted coefficient by $\Delta\Delta = 4\beta_3$. The contrast quantifies the difference between the formulation-specific changes across the recorded conditions and is algebraically equivalent to the change in the BSPA–BN strength gap. Because the fully interacted categorical model estimates the four observed group means, it was used to examine experimental contrasts rather than to establish predictive capability for untested mixture compositions or exposure conditions.

Given the unequal specimen-level dispersions, the precision of the interaction contrast was evaluated primarily through a Welch–Satterthwaite confidence interval. The standard error was obtained from the sum of the four estimated group-mean variances, allowing each formulation–condition group to contribute its observed variance rather than imposing a common residual variance. A two-sided 95% confidence interval and the corresponding hypothesis test were calculated using the Welch–Satterthwaite approximation to the degrees of freedom. Conventional two-factor analysis of variance, based on Type III partial sums of squares with $\alpha = 0.05$, and heteroscedasticity-consistent HC3 covariance estimation were used as supporting analyses. This hierarchy prioritizes the magnitude and precision of the interaction over statistical significance alone.

The robustness of the interpretation was further examined using Shapiro–Wilk residual testing, median-centered Levene testing, and influence diagnostics based on Cook's distance and DFFITS. An exploratory leave-one-observation-out analysis assessed the sensitivity of the interaction estimate to a potentially influential specimen. All 12 measurements were retained in the primary analysis. The individual cylinder was the observational unit, but the available records did not establish independent production-batch replication. Consequently, the inferential results were treated as exploratory and conditional on cylinder-level independence, rather than as evidence of reproducibility across independently produced concrete batches.

The experimental comparison also imposes a distinct limitation on the interpretation of the interaction. The reference specimens were tested at 28 days without acid exposure, whereas separate specimens were tested at 42 days after 14 days of sulfuric acid immersion. Because specimen age and exposure history varied simultaneously, the estimated contrast cannot distinguish age-dependent strength development from acid-related deterioration. It therefore measures differences in compressive performance across the recorded testing conditions, without identifying a causal formulation-specific effect of sulfuric acid exposure.

3. RESULTS AND DISCUSSION

3.1. Fresh-Concrete Consistency And Compressive Strength Characteristics

The incorporation of chemically untreated abaca fibers was associated with a reduction in fresh-concrete consistency and a substantial difference in compressive strength. The recorded slump decreased from 94 mm for normal concrete (BN) to 73 mm for abaca fiber-reinforced concrete (BSPA), corresponding to a reduction of 21 mm (22.34%). Both formulations employed the same nominal water-to-cement ratio of 0.45, without supplementary cementitious materials, chemical admixtures, or additional mixing water. The observed difference is therefore consistent with the influence of fiber incorporation on fresh-concrete behavior under the investigated mixture and processing conditions.

Previous investigations have established that the fresh-state behavior of abaca-containing cementitious composites is influenced by fiber configuration, reinforcement content, moisture-related characteristics, and mixture design. Panugalla et al. [23] examined hybrid abaca–polypropylene concrete, while Arvizu-Montes et al. [16] investigated concrete incorporating alkali-treated abaca fibers. Lee and Choi [14] further demonstrated the relevance of abaca fibers to moisture-related behavior in cementitious materials.

Together, these studies provide scientific context for the lower slump recorded for BSPA, although their material systems and experimental procedures differ from those investigated here. Because only one slump measurement was available for each formulation, the observed reduction is interpreted descriptively rather than attributed to a specific fiber-absorption or dispersion mechanism. The individual compressive-strength observations and corresponding descriptive statistics are presented in Table 3 and Fig. 2.

Table 3. Individual compressive-strength measurements and descriptive statistics for normal concrete and chemically untreated abaca fiber-reinforced concrete.

Group	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Mean ± SD (MPa)	CV (%)
BN-28	42.080	29.734	33.698	35.171 ± 6.303	17.92
BSPA-28	48.336	45.336	48.257	47.310 ± 1.710	3.61
BN-42A	35.659	25.494	28.303	29.819 ± 5.249	17.60
BSPA-42A	44.440	42.136	44.430	43.669 ± 1.327	3.04

Note: BN denotes normal concrete, while BSPA denotes concrete containing chemically untreated abaca fibers with a nominal length of 55 mm at 0.70% of cement mass. The suffix 28 identifies the unexposed reference condition tested at 28 days, whereas 42A identifies specimens tested at 42 days after 14 days of sulfuric acid immersion. Each group comprised three separately tested cylinders. SD denotes sample standard deviation and CV denotes coefficient of variation. The BN-28 observations were previously published by Farizal et al. [17] and are reused with attribution.

The BSPA formulation exhibited higher mean compressive strength than BN under both testing conditions (Table 3). At the 28-day reference condition, its mean strength was 34.51% higher than that of BN. The magnitude of the between-formulation strength advantage and its change across testing conditions are examined in Section 3.2, allowing the descriptive observations to be distinguished from the subsequent interaction analysis.

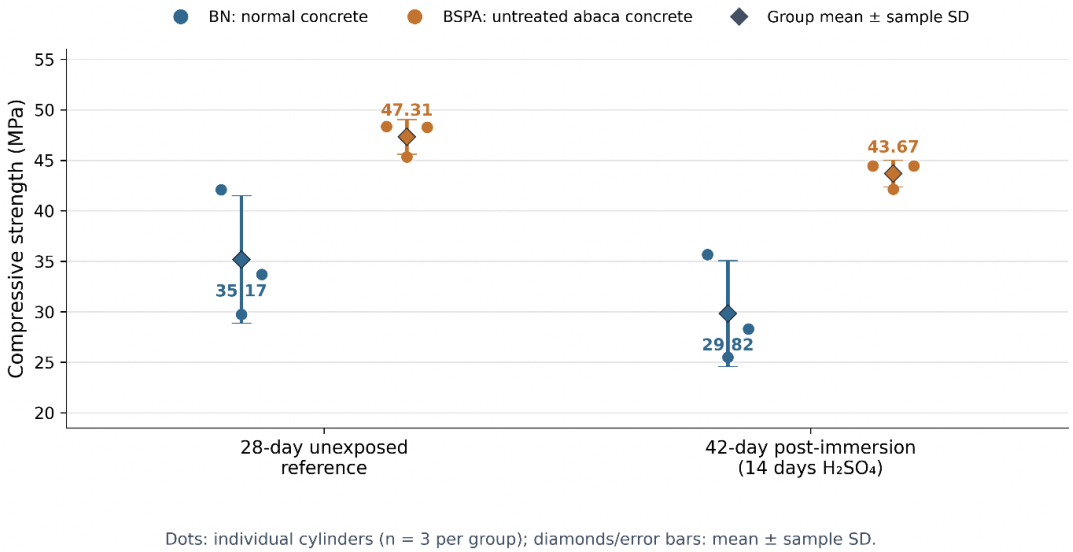


Fig. 2. Individual compressive-strength observations and group mean responses of normal and chemically untreated abaca fiber-reinforced concrete. Individual markers represent separately tested cylinders, diamonds indicate group means, and error bars represent sample standard deviations (n = 3 per group). The reference and post-immersion conditions involved different specimens. The BN-28 observations were previously reported by Farizal et al. [17].

The individual measurements confirm that BSPA exhibited higher mean compressive strength than BN under both testing conditions. A further distinguishing characteristic of the dataset is the difference in within-group dispersion. The coefficients of variation for BN were 17.92% and 17.60% under the reference and post-immersion conditions, respectively, compared with 3.61% and 3.04% for BSPA. The narrower specimen-level distributions observed for BSPA characterize the investigated cylinder groups without establishing batch-level production consistency. These findings provide the descriptive foundation for the subsequent evaluation of the initial and post-immersion strength gaps in Section 3.2 and their interaction uncertainty in Section 3.3.

3.2. Baseline Strength Differences And Post-Immersion Compressive Performance

The between-formulation strength difference observed after immersion must be interpreted in relation to the mechanical advantage already present under the unexposed reference condition. Accordingly, the analysis compares the BSPA–BN strength gaps at both testing conditions and quantifies their change. This baseline-informed approach distinguishes an observed difference in mechanical capacity from an additional condition-related response without presupposing its direction or attributing it exclusively to sulfuric acid exposure.

At 28 days, the mean compressive strength of BSPA was 47.310 MPa, compared with 35.171 MPa for BN, corresponding to a between-formulation difference of 12.139 MPa. Following 14 days of sulfuric acid immersion, the respective mean strengths at 42 days were 43.669 and 29.819 MPa, yielding a difference of 13.850 MPa. Thus, the higher compressive strength of BSPA was not confined to the post-immersion condition but characterized both experimental comparisons. The numerical differences between the condition means and their corresponding strength ratios are summarized in Table 4.

Table 4. Reference and post-immersion compressive performance of BN and BSPA

Parameter	BN	BSPA
Mean reference strength at 28 days (MPa)	35.171	47.310
Mean post-immersion strength at 42 days (MPa)	29.819	43.669
Difference between condition means (MPa)	−5.352	−3.641
Relative difference from reference (%)	−15.22	−7.70
Post-immersion-to-reference strength ratio (%)	84.78	92.30

Note: The reported differences and ratios compare separate cylinder groups tested at different ages and under different exposure histories. They characterize observed compressive performance rather than independently measured acid-induced strength losses.

The differences between the post-immersion and reference means were −5.352 MPa for BN and −3.641 MPa for BSPA, corresponding to strength ratios of 84.78% and 92.30%, respectively. Although BSPA exhibited a smaller numerical reduction relative to its reference strength, these values cannot be interpreted as direct measures of differential acid deterioration. The comparison incorporates an additional 14 days of specimen aging together with sulfuric acid exposure, and the absence of age-matched unexposed controls prevents their separate contributions from being established. The interpretation must therefore focus on the observed mechanical contrasts rather than assuming that the differences between testing conditions represent acid-induced strength losses.

To determine whether the post-immersion advantage reflects a distinct change in the relative mechanical performance of the formulations, the between-formulation strength gaps were compared directly. The initial gap was:

$G28 = 47.310 - 35.171 = 12.139$ MPa

The corresponding post-immersion strength gap was:

$G42A = 43.669 - 29.819 = 13.850$ MPa

The difference was:

$\Delta\Delta = 13.850 - 12.139 = 1.711$ MPa

Applying the initial-to-final strength-gap ratio defined in Eq. (4) gives:

$Sbaseline = 100 \times 12.139 / 13.850 = 87.65\%$

This value is strictly a descriptive ratio of two estimated between-formulation strength differences. It does not quantify the causal contribution of the initial strength advantage to post-immersion performance, nor does it represent a durability-retention index. The scientifically relevant contrast is the change in the strength gap, $\Delta\Delta$, because it directly characterizes whether the relative compressive performance of the two formulations differed across the recorded conditions.

Figure 3 distinguishes the observed mechanical advantage from uncertainty in its additional change. Panel (a) presents the two between-formulation strength gaps, whereas panel (b) shows the interaction estimate and its unequal-variance confidence interval. This distinction is important because the apparent persistence of the BSPA strength advantage and the evidence for a formulation-specific difference in condition-related response are separate findings. The former is directly supported by the measured group means, while the latter requires an assessment of statistical precision and sensitivity, as examined in Section 3.3.

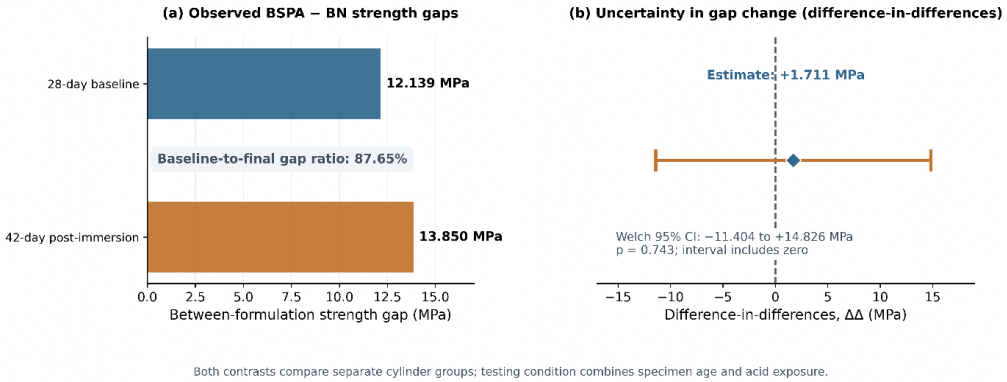


Fig. 3. Between-formulation compressive-strength gaps and uncertainty in the interaction contrast. (a) Differences between BSPA and BN mean compressive strengths under the 28-day unexposed reference condition (G28 = 12.139 MPa) and the 42-day post-immersion condition (G42A = 13.850 MPa). (b) Difference-in-differences estimate (ΔΔ = +1.711 MPa) with its two-sided Welch–Satterthwaite 95% confidence interval (−11.404 to +14.826 MPa). The dashed vertical line denotes zero. The comparisons involve separate cylinder groups tested at different ages and under different exposure conditions; the interaction cannot be interpreted as an isolated estimate of sulfuric acid resistance.

3.3. Factorial Analysis, Interaction Uncertainty, And Model Adequacy

The formulation-by-condition interaction was evaluated as the primary exploratory contrast for assessing changes in the BSPA–BN strength gap across the two testing conditions. Given the unequal within-group dispersions, its interpretation rests primarily on the estimated effect and the precision of the Welch–Satterthwaite confidence interval. Conventional factorial ANOVA and heteroscedasticity-consistent HC3 analyses provide supporting assessments of the same cylinder-level observations rather than independent confirmation of the interaction or production-batch reproducibility.

The estimated formulation-by-condition interaction was +1.711 MPa, corresponding to the increase in the BSPA–BN strength gap from 12.139 MPa at the reference condition to 13.850 MPa after immersion. However, the precision of this estimate was constrained by pronounced differences in within-group variability. At 28 days, the standard deviations were 6.303 MPa for BN and 1.710 MPa for BSPA, while the corresponding post-immersion values were 5.249 and 1.327 MPa (Table 3). The resulting sample-variance ratios between BN and BSPA were approximately 13.6 at the reference condition and 15.6 after immersion. Such differences are consequential for inference because the uncertainty of a contrast involving four independently estimated means depends on their individual variances, not merely on a single pooled residual estimate.

Using the Welch–Satterthwaite approximation, the interaction contrast had a standard error of 4.898 MPa and approximately 4.409 degrees of freedom. Its two-sided 95% confidence interval extended from −11.404 to +14.826 MPa ($p = 0.743$). Although the point estimate indicates a small numerical increase in the BSPA strength advantage, the interval encompasses both negative and positive changes of potentially meaningful magnitude. Consequently, the data do not establish whether the difference in compressive response across the recorded conditions favored either formulation. This uncertainty is not equivalent to evidence of identical responses: the observations are insufficiently precise to distinguish a modest interaction from substantially different effects in either direction.

Influence diagnostics identified the BN-28 observation of 42.080 MPa as potentially influential, with Cook's distance of 0.497 and DFFITS of 1.861. In an exploratory leave-one-

observation-out refit of the conventional categorical model, omitting this cylinder changed the estimated interaction from +1.711 to −1.744 MPa, while the interaction remained statistically nonsignificant ($p = 0.671$). The reversal in sign indicates that the direction of the estimated additional response is sensitive to an individual observation. However, statistical influence does not establish measurement error, and no documented experimental evidence justified excluding the cylinder. All 12 observations were therefore retained in the primary analysis. This sensitivity underscores the uncertainty of the interaction without invalidating the observed group-level strength differences.

Conventional factorial ANOVA was retained as a supporting assessment of the observed strength differences. As shown in Table 5, the formulation term was statistically significant ($F = 28.15$, $p = 0.0007$), consistent with the higher compressive strength of BSPA across both testing conditions. The overall model was also significant ($F = 10.55$, $p = 0.0037$). In contrast, the testing-condition term ($F = 3.37$, $p = 0.1037$) and formulation-by-condition interaction ($F = 0.122$, $p = 0.7359$) did not reach the nominal significance threshold. The formulation term accounted for approximately 71.01% of the corrected total sum of squares, indicating that the dominant source of variation in this dataset was the difference between the investigated concrete formulations. Nevertheless, this statistical dominance characterizes the observed specimen-level responses and does not establish the underlying reinforcement mechanism or reproducibility across independently produced batches.

Table 5. Supporting two-factor ANOVA for compressive strength under the investigated formulation and testing conditions.

Source	Sum of squares	df	Mean square	F-value	p-value
Model	569.42	3	189.81	10.55	0.0037
A — Concrete formulation	506.57	1	506.57	28.15	0.0007
B — Testing condition	60.66	1	60.66	3.37	0.1037
AB — Formulation × condition	2.20	1	2.20	0.122	0.7359
Residual error	143.94	8	17.99	—	—
Corrected total	713.37	11	—	—	—

Note: Type III partial sums of squares were obtained from the complete categorical interaction model in Design-Expert 13. Factor A denotes concrete formulation, whereas Factor B combines differences in specimen age and sulfuric acid exposure. The tests are exploratory cylinder-level analyses conditional on the model assumptions.

The HC3 heteroscedasticity-consistent analysis yielded the same qualitative inferential pattern as conventional ANOVA. The formulation effect remained statistically significant ($p = 0.0025$), whereas the testing-condition effect ($p = 0.1722$) and formulation-by-condition interaction ($p = 0.7827$) did not reach the nominal significance threshold. This agreement indicates that the formulation-associated strength difference remained statistically significant under HC3 covariance estimation. However, both analyses rely on the same cylinder-level observations and therefore cannot independently establish production-batch reproducibility or eliminate the uncertainty surrounding the interaction estimate. The HC3 results consequently complement, rather than replace, the primary unequal-variance assessment.

Under the effect-coding scheme described in Section 2.7, the fitted categorical model was:

$$\textit{Fitted compressive strength (MPa)} = 38.9919 + 6.4973A - 2.2483B + 0.4278AB \quad (6)$$

where $A = -1$ for BN and +1 for BSPA, and $B = -1$ for the 28-day reference condition and +1 for the 42-day post-immersion condition. The interaction coefficient of 0.4278 corresponds to the estimated difference-in-differences contrast of approximately +1.711 MPa. Because the full categorical model reproduces the four observed formulation–condition means, its fitted values

describe the investigated experimental combinations rather than independently predicting compressive strength under alternative fiber dosages, fiber lengths, acid concentrations, or exposure durations. Accordingly, predictive R^2, adequate precision, PRESS, AICc, and BIC were not used as evidence of predictive validity or durability performance. The principal interaction estimates, uncertainty measures, and supporting diagnostics are consolidated in Table 6.

Table 6. Primary interaction uncertainty and supporting statistical diagnostics.

Parameter	Value
Difference-in-differences estimate, ΔΔ	+1.711 MPa
Unequal-variance standard error	4.898 MPa
Welch–Satterthwaite degrees of freedom	4.409
Welch–Satterthwaite 95% confidence interval	−11.404 to +14.826 MPa
Welch two-sided p-value	0.743
HC3 interaction p-value	0.7827
Shapiro–Wilk residual test	W = 0.921; p = 0.297
Median-centered Levene test	p = 0.461
Influential observation	BN-28: 42.080 MPa
Cook's distance	0.497
DFFITS	1.861
Interaction estimate after exploratory omission	−1.744 MPa
Interaction p-value after exploratory omission	0.671

Note: The statistics were obtained from the complete two-factor interaction model fitted in Design-Expert 13. The predicted R^2 and other model statistics do not constitute independent external validation across concrete production batches or untested experimental conditions.

The residual diagnostics provide no basis for a stronger inferential claim. The Shapiro–Wilk test yielded W = 0.921 (p = 0.297), and the median-centered Levene test yielded p = 0.461. Although neither test rejected its respective null hypothesis, the limited number of specimens per group restricts the sensitivity of these assessments. The observed variance differences therefore remain relevant despite the nonsignificant Levene result. Similarly, the absence of a recommended transformation in the Box–Cox assessment does not increase the experimental information available for estimating the interaction. These diagnostics support transparent evaluation of the statistical assumptions, but they cannot establish independence among specimens originating from potentially shared production batches.

Taken together, the experimental observations and supporting statistical analyses document a substantial BSPA-associated compressive-strength advantage under both testing conditions. In contrast, the wide unequal-variance confidence interval and sensitivity of the interaction estimate to an influential cylinder preclude a reliable directional conclusion regarding the additional change in that advantage. The central analytical finding is therefore the distinction between a pre-existing formulation-associated strength difference and an additional condition-related response that remains uncertain. This interpretation is conditional on the investigated cylinder groups and does not establish an independently identifiable effect of sulfuric acid exposure, because specimen age and exposure history varied simultaneously and independent production-batch replication was not confirmed.

3.4. Macroscopic Specimen Observations And Sulfuric Acid Exposure

Representative photographs of the four investigated specimen groups are presented in Fig. 4. The images document the macroscopic appearance of BN and BSPA during compressive-strength testing following the specified curing and exposure procedures.

(a) BN: 28-day reference (b) BSPA: 28-day reference



(c) BN: 42-day post-immersion (d) BSPA: 42-day post-immersion



Fig. 4. Representative appearance of normal concrete and chemically untreated abaca fiber-reinforced concrete during compressive-strength testing. (a) BN tested at 28 days without sulfuric acid exposure; (b) BSPA tested at 28 days without sulfuric acid exposure; (c) BN tested at 42 days following 14 days of sulfuric acid immersion; and (d) BSPA tested under the corresponding post-immersion condition. The panels were assembled from original experimental photographs without alteration of specimen features. The photographed loading stages were not independently standardized. Visible cracks and local surface damage may reflect compressive loading and should not be interpreted independently as evidence of sulfuric acid-induced deterioration.

Figure 4 shows longitudinal and branching cracks, exposed aggregates, local surface irregularities, and variations in surface texture at the photographed stages of compressive loading. Because the photographs were obtained during destructive testing rather than through a standardized post-immersion inspection, these features cannot be attributed specifically to sulfuric acid-induced deterioration. Huber et al. [1] and Grandclerc et al. [2] described dissolution, precipitation, and transport processes associated with sulfuric acid attack on cementitious materials. Although these processes provide a mechanistic context for interpreting concrete deterioration, the present photographs do not independently establish which reactions, if any, contributed to the observed specimen features.

Complementary material characterization is essential for distinguishing chemical deterioration from mechanical damage in fiber-reinforced concrete. Youssari et al. [5] investigated metal fiber-reinforced concrete under acidic exposure using mechanical, chemical, and microstructural evidence, while Xu et al. [8] examined long-term mechanical and mineralogical changes in steel fiber-reinforced concrete exposed to sulfuric acid. In abaca-containing cementitious systems, Lee and Choi [14] investigated hydration-related behavior,

whereas Arvizu-Montes et al. [16] evaluated mechanical and durability-related properties of concrete incorporating alkali-treated abaca fibers. These studies demonstrate the importance of material-specific characterization, although their reinforcement systems and experimental conditions differ from those of the present investigation. Without direct measurements of chemical penetration, mineralogical transformation, or fiber–matrix interactions, the photographs in Figure 4 provide qualitative documentation of specimen appearance during compression rather than independent evidence of a chemical deterioration pathway or fiber-mediated protection mechanism.

3.5. Critical Comparison With Previous Research and Scientific Contribution

The scientific relevance of previous abaca-concrete and acid-exposure investigations depends on how differences in binder composition, reinforcement treatment, exposure conditions, response variables, and experimental controls influence the interpretation of mechanical performance. Table 7 critically examines these characteristics across related studies, distinguishing direct formulation precedents from methodological and material-specific evidence. This comparison establishes the basis for interpreting the present findings within the existing literature without treating differences in experimental configuration alone as evidence of novelty.

Table 7. Critical comparison of material formulations, exposure conditions, reference designs, and their implications for interpreting the present findings.

Study	**Binder and fiber configuration**	**Exposure and reference conditions**	**Implications for the present study**
[17]	Ordinary Portland cement concrete incorporating 35 mm abaca fibers at different dosages, including 0.70% by cement mass	Compressive-strength evaluation at early and design ages; no corresponding sulfuric acid immersion comparison	Provides the previously published BN reference measurements and a relevant formulation precedent, while the additional 55 mm BSPA and post-immersion observations extend the available experimental evidence
[23]	Concrete incorporating hybrid abaca–polypropylene fibers	Mixture optimization based on mechanical performance and water absorption, without an equivalent sulfuric acid immersion comparison	Hybrid reinforcement and mixture optimization affect the interpretation of mechanical performance; the reported responses cannot be directly attributed to the untreated abaca configuration investigated here
[16]	Reinforced concrete incorporating chemically alkali-treated abaca fibers	Workability, mechanical properties, and durability indicators associated with reinforcement corrosion	Chemical fiber treatment and corrosion-related response measures differ from the present untreated-fiber and post-immersion compressive-strength comparison, limiting direct quantitative transfer
[5]	Metal fiber-reinforced concrete exposed to aggressive chemical environments	Sulfuric, hydrochloric, and acetic acid exposure over 135 days, supported by mechanical and chemical or	Demonstrates the relevance of exposure chemistry and complementary deterioration indicators, while differences in reinforcement and exposure

Study	Binder and fiber configuration	Exposure and reference conditions	Implications for the present study
		microstructural assessments	duration preclude direct ranking against the present results
[8]	Steel fiber-reinforced concrete	Sulfuric acid exposure extending to 36 months, with mechanical and mineralogical characterization	Provides evidence of time-dependent deterioration in a metallic-fiber system; its exposure duration and reinforcement characteristics differ fundamentally from the present short-term untreated-abaca comparison
[9]	Kenaf textile-reinforced cementitious composites	Sulfuric acid and corresponding laboratory reference conditions over 2–6 months, with principally flexural and microstructural assessments	Demonstrates the methodological value of age-corresponding reference groups for interpreting exposure effects, although reinforcement geometry and mechanical response differ from the present compressive-strength measurements
[18]	Concrete incorporating natural zeolite and treated or untreated abaca fibers	Mechanical and durability-related assessments under aggressive exposure, incorporating additional durability indicators	Zeolite incorporation and fiber-treatment variations modify the material system and the basis of comparison; the findings provide a relevant durability precedent but cannot be directly extrapolated to the present Portland cement formulation without supplementary cementitious materials
[19]	Concrete mixtures designed to achieve approximately equivalent initial compressive strengths	Strength-matched comparison of chloride-related durability and structural performance	Establishes a conceptual precedent for separating initial mechanical capacity from durability-related performance; its strength-matched design differs from the present independent-group comparison with unequal reference strengths
Present study	Ordinary Portland cement concrete containing chemically untreated 55 mm abaca fibers at 0.70% by cement mass, without supplementary cementitious materials	Unexposed reference specimens tested at 28 days and separate specimens tested at 42 days following 14 days of immersion in a nominal 5% v/v dilution of commercial sulfuric acid reagent	Adds nine previously unpublished compressive-strength observations and integrates the initial strength gap, post-immersion strength gap, and interaction uncertainty to characterize formulation-specific mechanical performance

Note: The comparison emphasizes differences that affect the interpretation of mechanical performance, rather than ranking the investigated materials according to apparent durability. Binder composition, fiber treatment and configuration, exposure chemistry and duration, mechanical response variables, and reference-group design influence the extent to which results can be compared. In particular, strength-matched comparisons and age-corresponding controls provide different inferential information from independent specimen groups with unequal reference strengths.

The relevance of previous abaca-concrete investigations is closely linked to the interaction between binder composition and fiber characteristics. Farizal et al. [17] established a mechanical-performance reference for ordinary Portland cement concrete incorporating 35 mm abaca fibers, including the normal-concrete measurements reused in the present analysis. Maintaining a comparable base binder system provides continuity with that investigation, whereas the present 55 mm chemically untreated-fiber configuration supplies additional formulation-specific compressive-strength evidence. However, the mechanical implications of fiber geometry cannot be interpreted independently of dosage, dispersion, and the characteristics of the surrounding cementitious matrix. This distinction is reinforced by studies of hybrid abaca–polypropylene concrete [23] and alkali-treated abaca-reinforced concrete [16], in which reinforcement configuration and surface treatment form integral components of the investigated material systems. Consequently, differences in reported mechanical responses across these studies cannot be assigned exclusively to the intrinsic contribution of abaca fibers or used to establish a common formulation-independent performance effect.

Azeem et al. [18] investigated mechanical and durability-related responses of zeolite-containing concrete reinforced with treated and untreated abaca fibers, establishing a relevant precedent for the assessment of abaca-based cementitious materials under aggressive conditions. The incorporation of natural zeolite and variation in fiber treatment create material conditions that differ from the present ordinary Portland cement system containing chemically untreated 55 mm abaca fibers. These differences are consequential because binder composition and fiber condition may influence both initial mechanical capacity and the measured response to aggressive exposure, limiting the direct transferability of the reported results. The present investigation contributes complementary formulation-specific evidence through a four-group compressive-strength comparison that relates the pre-existing BSPA–BN strength difference to its post-immersion counterpart and quantifies uncertainty in their change. Its scientific contribution therefore lies in the additional experimental evidence and its baseline-informed interpretation, rather than in constituent differences alone or an unsupported claim of superior sulfuric acid resistance.

Studies of fiber-reinforced concrete subjected to acidic environments further demonstrate that exposure duration, chemical conditions, and response indicators influence the interpretation of durability-related performance. Youssari et al. [5] investigated metal fiber-reinforced concrete under sulfuric and other acidic solutions over 135 days, integrating mechanical measurements with chemical and microstructural characterization. Xu et al. [8] examined steel fiber-reinforced concrete under sulfuric acid exposure extending to 36 months, incorporating mechanical and mineralogical evidence to characterize the material response over a substantially longer period. These investigations illustrate why compressive-strength measurements and complementary indicators of chemical deterioration address related but distinct aspects of material performance. Differences in reinforcement chemistry, exposure duration, and characterization methods also prevent the direct extrapolation of their reported responses to the present 14-day immersion experiment. Accordingly, the higher compressive strength observed for BSPA is most appropriately interpreted within its own formulation and experimental comparison structure, rather than through quantitative rankings against materially different fiber-reinforced systems.

Reference-group design provides an equally important basis for evaluating the relevance of previous findings. Kohzadi and Behfarnia [9] examined kenaf textile-reinforced cementitious composites under sulfuric acid exposure and corresponding laboratory conditions at comparable testing ages over two, four, and six months. Although their reinforcement geometry and principal flexural response differ from those investigated here, the use of age-corresponding reference groups provides a more direct basis for examining exposure-related changes against concurrent

material development. The distinction is consequential for the present study, in which the reference and post-immersion compressive-strength measurements were obtained from independent cylinder groups tested at different ages. Thus, the methodological value of [9] lies in its reference-condition structure rather than in the direct transfer of its flexural-performance results to abaca-reinforced concrete. Together, these comparisons indicate that the interpretation of post-exposure mechanical behavior must account for both the initial material condition and the experimental controls against which subsequent performance is evaluated.

The methodological relevance of baseline-strength comparability is further supported by Sharma et al. [19], who examined durability-related structural performance using concrete mixtures with approximately equivalent initial compressive strengths. Their strength-matched approach provides an important conceptual basis for distinguishing inherent mechanical capacity from durability-related effects. The present investigation extends this discussion to a different experimental context in which the compared formulations exhibit unequal reference strengths and are evaluated using independent groups under distinct testing conditions. Rather than assuming that their higher post-immersion strength reflects superior resistance to chemical deterioration, the analysis explicitly quantifies how the between-formulation strength difference changes relative to its initial magnitude. The BSPA–BN strength gap increased numerically from 12.139 MPa at the unexposed reference condition to 13.850 MPa following immersion, corresponding to an interaction estimate of +1.711 MPa. However, the associated Welch–Satterthwaite 95% confidence interval (−11.404 to +14.826 MPa) encompasses changes in either direction. This comparison establishes the importance of separating an observed formulation-associated strength advantage from the statistical evidence for an additional condition-related response. In this respect, the methodological contribution lies in applying a baseline-informed interpretation to a specific untreated-abaca concrete dataset with unequal reference strengths, while maintaining a clear distinction from the strength-matched durability assessment adopted in [19].

The principal scientific contribution of this study is the integration of previously unpublished experimental evidence with a baseline-informed assessment of the compressive performance of a specific chemically untreated abaca fiber-reinforced concrete formulation. Building upon the earlier investigation of 35 mm abaca fibers and their mechanical performance [17], the present study contributes nine additional compressive-strength observations that establish the reference performance of a 55 mm untreated-fiber formulation and the post-immersion responses of both fiber-reinforced and normal concrete. This experimental extension also provides a distinct complement to the durability investigation reported in [18], where natural zeolite incorporation and fiber-treatment variations formed part of a different cementitious system and assessment framework. The additional observations make it possible to quantify the pre-existing between-formulation strength difference, examine its persistence after sulfuric acid immersion, and evaluate the uncertainty surrounding its change within the investigated experimental structure. The resulting evidence demonstrates a substantial compressive-strength advantage for the abaca-reinforced formulation under both testing conditions, while distinguishing this observed mechanical performance from an additional formulation-specific response that remains statistically uncertain. By connecting new formulation-specific measurements with an explicit assessment of unequal reference strengths, the study advances the interpretation of post-immersion concrete performance beyond comparisons based solely on final strength or descriptive strength ratios. This contribution provides a clearer empirical and methodological basis for evaluating comparative mechanical behavior in natural fiber-reinforced cementitious materials subjected to aggressive exposure conditions.

3.6. Implications for Durability Assessment and Scope of Inference

The principal implication for comparative durability assessment is that post-immersion compressive strength must be interpreted relative to the initial mechanical characteristics of the investigated formulations. Although BSPA exhibited higher mean strength under both testing

conditions, the estimated additional change in this advantage remained insufficiently precise to establish a directional formulation-specific response. Importantly, an inconclusive interaction does not demonstrate equivalence between the formulations. The baseline-informed comparison therefore clarifies the mechanical evidence without equating higher final strength with superior sulfuric acid resistance, providing a more defensible basis for evaluating formulation-specific performance under aggressive exposure conditions.

The inferential scope of this comparison is defined by the experimental testing structure. Separate cylinders were tested at 28 days without exposure and at 42 days following 14 days of immersion, so differences between the recorded conditions incorporate both specimen aging and sulfuric acid exposure. Furthermore, the three cylinders tested within each group were not accompanied by documented independent production-batch replication. The three BN reference measurements previously reported in [17] were retained with explicit attribution and combined with nine previously unpublished observations, providing a traceable basis for the four-group comparison without constituting additional independent batch replication. The nominal acid-solution dilution defines the documented exposure procedure, while direct chemical and microstructural deterioration measurements were not available to establish specific degradation or fiber-mediated protection mechanisms. Accordingly, the findings characterize formulation-specific compressive performance within the investigated testing conditions rather than independently identifying an acid-resistance effect.

A confirmatory evaluation should prioritize age-matched unexposed control groups for both formulations and independently replicated concrete production batches. These two design features would provide a stronger basis for distinguishing exposure-related mechanical changes from continued strength development and for evaluating the reproducibility of the formulation-specific response. Monitoring the chemical exposure environment and incorporating complementary deterioration indicators would further strengthen the interpretation of the measured mechanical behavior. Within the present experimental scope, the study contributes new compressive-strength evidence for chemically untreated abaca fiber-reinforced concrete and demonstrates the analytical value of considering initial strength differences together with the precision of the formulation-by-condition contrast.

4. CONCLUSIONS

This study provides new compressive-strength evidence for ordinary Portland cement concrete reinforced with chemically untreated 55 mm abaca fibers at 0.70% by cement mass. At the 28-day unexposed reference condition, BSPA attained a mean compressive strength of 47.310 MPa, compared with 35.171 MPa for normal concrete (BN). Following 14 days of sulfuric acid immersion, the corresponding 42-day mean strengths were 43.669 and 29.819 MPa, respectively. BSPA therefore exhibited a substantial compressive-strength advantage under both testing conditions, with between-formulation differences of 12.139 and 13.850 MPa. The numerical similarity of these differences indicates that the substantial post-immersion strength advantage was already largely evident under the reference condition.

The additional change in the BSPA–BN strength difference was estimated at +1.711 MPa (Welch–Satterthwaite 95% confidence interval: −11.404 to +14.826 MPa). Although the initial and post-immersion strength gaps were numerically similar, the substantial uncertainty does not establish a definitive additional formulation-specific response or equivalence between the formulations. Because specimen age and sulfuric acid exposure varied simultaneously, the comparison does not independently establish improved acid resistance. Age-matched unexposed controls and independently replicated concrete production batches are therefore priorities for confirmatory investigations. Importantly, integrating nine previously unpublished compressive-strength observations with three attributed reference measurements completes the four-group experimental comparison required to quantify the initial strength advantage, its post-immersion

counterpart, and the uncertainty associated with their change. This formulation-specific experimental contribution strengthens the empirical basis for a baseline-informed interpretation of comparative post-immersion mechanical performance in chemically untreated abaca fiber-reinforced concrete.

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