

Article

Rheological, Mechanical, and Micro-Structural Property Assessment of Eco-Friendly Concrete Reinforced with Waste Areca Nut Husk Fiber

Noor Md. Sadiqul Hasan ¹, Nur Mohammad Nazmus Shaurdho ¹, Md. Habibur Rahman Sobuz ²,
Md. Montaseer Meraz ², Md. Abdul Basit ¹, Suvash Chandra Paul ¹ and Md Jihad Miah ^{3,*}

¹ Department of Civil Engineering, International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh; nmshasan@iubat.edu (N.M.S.H.); 18306006@iubat.edu (N.M.N.S.); abdul.basit@iubat.edu (M.A.B.); suvashpl@iubat.edu (S.C.P.)

² Department of Building Engineering and Construction Management, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh; habib@becm.kuet.ac.bd (M.H.R.S.); meraz1623050@stud.kuet.ac.bd (M.M.M.)

³ Department of Civil and Architectural Engineering, Aarhus University, 8000 Aarhus, Denmark

* Correspondence: miahmj@cae.au.dk; Tel.: +45-9166-1896

Abstract: Fiber-reinforced concrete (FRC) has become one of the most promising construction techniques and repairing materials in recent times for the construction industry. Generally, plain concrete has a very low tensile strength and limited resistance to cracking prior to the ultimate load, which can be mitigated by the incorporation of fiber. Natural fibers have emerged as an appealing sustainable option in the last few decades due to their lower cost, energy savings, and minimized greenhouse effects. Areca fiber is one of the natural fibers that can be sourced from the waste-producing areca nut industry. Hence, this study aims to assess the mechanical, rheological, and micro-structural properties of areca fiber-reinforced concrete (AFRC). For this purpose, areca fiber was used in the concrete mix as a weight percentage of cement. In this regard, 1%, 2%, 3%, and 4% by weight of cement substitutions were investigated. As key findings, 2% areca fiber enhanced the compressive strength of concrete by 2.89% compared to the control specimen (fiber-free concrete). On the other hand, splitting tensile strength increased by 18.16%. In addition, scanning electron microscopy (SEM) images revealed that the cement matrix and fibers are adequately connected at the interfacial level. Energy dispersive X-ray spectroscopy (EDX) test results showed more biodegradable carbon elements in the areca fiber-mixed concrete as well as an effective pozzolanic reaction. The study also exhibited that adding natural areca fiber lowered the fabrication cost by almost 1.5% and eCO₂ emissions by 3%. Overall, the findings of this study suggest that AFRC can be used as a possible building material from the standpoint of sustainable construction purposes.

Keywords: sustainability; waste recycling; areca fiber; fiber-reinforced concrete; rheological and mechanical properties; microstructure



Citation: Hasan, N.M.S.; Shaurdho, N.M.N.; Sobuz, M.H.R.; Meraz, M.M.; Basit, M.A.; Paul, S.C.; Miah, M.J. Rheological, Mechanical, and Micro-Structural Property Assessment of Eco-Friendly Concrete Reinforced with Waste Areca Nut Husk Fiber. *Sustainability* **2023**, *15*, 14131. <https://doi.org/10.3390/su151914131>

Academic Editors: Marianovella Leone and Alessia Monaco

Received: 13 July 2023

Revised: 4 September 2023

Accepted: 16 September 2023

Published: 24 September 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Each year, 30 billion tons of concrete are consumed globally, rendering it the world's most widely utilized building material [1]. Globally, it is utilized twice as much as steel, aluminum, plastic, and wood combined. The ready-mix concrete market, the biggest component of the worldwide concrete industry, is predicted to produce annual sales of more than USD 624.82 billion by 2025 [2]. Since around 200 years ago, concrete has been applied in construction. Because of its widespread use and the necessity of making concrete more sustainable and durable, the desire to boost its mechanical and durability properties has been ongoing. Concrete inherently exhibits brittleness, primarily owing to its deficient tensile performance, despite displaying commendable compressive strength. An emerging

approach that is gaining popularity in practical applications involves the homogeneous dispersion of fibers within the concrete, resulting in the creation of a material known as fiber-reinforced concrete [3]. Incorporating fibers into concrete mixtures substantially enhances strength, ductility, elastic modulus, crack control, and structural serviceability [4]. This addition transforms the behavior of the fiber matrix composite upon cracking, bolstering toughness and ductility [5]. Numerous studies were conducted using a variety of fibers, including glass [6,7], steel [8–10], polypropylene [11], carbon [12], waste lathe scraps [13,14], polyvinyl alcohol (PVA) [15,16], for the fabrication of fiber-reinforced structural concrete and studying their effect on the engineering properties of concrete mixes. The effects of the addition of natural wastes such as rubber tree seed shells have also been studied by prior researchers [17]. Historical structures built from mud and clay were reinforced using natural fibers, underscoring their pivotal role in enhancing mechanical attributes and structural performance [18]. The application of natural fiber-reinforced concrete (NFRC) has great potential due to its economic viability, biodegradability, and disintegrability, rendering it suitable for reinforcing composite materials [19].

Areca fiber-reinforced polymer composites and areca fibers themselves have been extensively subjected to previous research [20–22]. However, most of the available literature regarding areca fiber-reinforced concrete has considered adding superplasticizing admixtures to mitigate the potential workability loss [21,23]. In contrast, it is important to highlight that the development of a workable formulation for areca fiber-reinforced concrete remains an area that has not yet been fully investigated by prior researchers. While efforts have been directed toward enhancing the mechanical properties and structural performance of these composites, the attainment of an optimal balance between favorable workability and mechanical strength characteristics presents an intriguing avenue that warrants further scholarly attention. Divakar et al. [24] have studied self-compacting concrete's mechanical characteristics that have been enhanced with natural areca nut fiber and reported that adding areca fiber to concrete reduces its compressive strength by 21% to 41%. Makunza [25] investigated the performance of NaOH-treated areca palm fiber-reinforced concrete with varying fiber concentrations (0.1%, 0.3%, 0.5%, 0.7%, and 0.9% by cement weight) and an optimal strength enhancement was achieved at 0.7%, beyond which strength decrement occurred. Srinivasa et al. [26] have done a comparative analysis of the mechanical properties of concrete reinforced with untreated and treated areca fiber. They have demonstrated that the mechanical performance of concrete increased in both cases, whereas treated areca fiber imparted more strength to the concrete compared to untreated areca fiber. These findings collectively highlight areca fiber's substantial potential for enhancing concrete's mechanical characteristics. However, a comprehensive exploration of micro-structure analysis and higher concentrations of fibers remains to be conducted.

A comparison was made between concrete containing alkali-treated natural henequen fiber and artificial polypropylene-reinforced concrete, revealing that the natural fiber exhibited superior enhancements in toughness and ductility [27]. Jamshaid et al. [28] investigated cellulosic fibers from sugarcane, coconut, sisal, and jute for natural fiber-reinforced concrete. Incorporating up to 2% of these natural fibers led to notable improvements in both tensile and compressive strengths, ranging from 11% to 20%. On the other hand, Das et al. [29] examined concrete reinforced with hybrid fibers (i.e., coconut and waste tire steel fiber) and reported slight enhancements in compressive strength and an 18.36% improvement in splitting tensile strength. Vinh et al. [30] demonstrated the efficacy of externally bonded natural sisal fiber-reinforced polymer composite (FRPC) in enhancing the strength and ductility of concrete elements. Zhao et al. [31] introduced polymer-modified fiber concrete for enhanced sustainability, noting significant crack resistance improvements. Cross-sectional SEM comparisons between hybrid fiber-polymer concrete and plain concrete highlighted the former's better integration and thicker cementitious layer. Experimental findings also revealed that the combination of natural fibers with glass fibers significantly enhances durability and mechanical performance, as observed

through the analysis of SEM images [32]. Furthermore, Walbrück et al. [33] targeted a reduced carbon footprint in order to develop sustainability by utilizing environment-friendly natural fibers such as abaca and hemp, which showed a regular improvement in compressive strength.

While artificial fibers and industrial waste enhance concrete performance, they compromise sustainability by increasing carbon emissions and chemical waste generation. The amount of cement in concrete directly relates to the amount of carbon emissions created by humans, with the concrete industry alone accounting for at least 8% of those emissions [34,35]. In 2020, Bangladesh alone produced 328.61 thousand metric tons of areca nuts [36]. These waste shells produced from the areca nut industry are massive in volume, eco-friendly, and offer good performance at a low cost. Many researchers have conducted investigations aiming to study the incorporation of other natural fibers into concrete production [27–29,37,38]. So far, a very limited number of studies have been conducted to understand the rheological and mechanical properties of fiber-reinforced concrete (FRC) by incorporating areca fiber [25,26,39]. Moreover, the micro-structural properties and the effect of adding untreated fiber to a concrete mixture without the addition of a water-reducing agent have not been investigated. Such an investigation is crucial in order to comprehend the isolated influence of untreated fiber on the workability of concrete. As the varying fiber concentrations, fiber orientations, aspect ratios, and preparing methods can substantially affect both the rheological and hardened properties of FRC, it is difficult to understand the behavior of FRC because the existing research does not always have the same concerns. So, attempts were made in this study to examine the influences of incorporating untreated areca fiber at varying weight percentages of cement, ranging from 1% to 4%, on the rheological, mechanical, and micro-structural characteristics of areca fiber-reinforced concrete (AFRC), all while abstaining from the utilization of any admixtures. Additionally, this study aims to propose a means of solid waste recycling for the expanding areca nut industry. Moreover, an in-depth cost analysis and thorough evaluation of eCO₂ emissions were performed to meticulously assess the environmental implications associated with the investigated concrete mixtures. This comprehensive assessment plays a vital role in providing a holistic evaluation of the proposed approach, thereby making a significant contribution to the existing body of literature concerning sustainable concrete production.

2. Experimental Program

2.1. Research Methodology

Experimental investigations of the present study include concrete's fresh qualities, mechanical characteristics, micro-structural properties, carbon analysis, and cost estimation, which are all evaluated and reported. Figure 1 illustrates the successive activities through which these investigations were carried out.

2.2. Materials

Concrete consists of cementitious material, coarse aggregate, and fine aggregate, which adhere together with the binding material in order to attain stone-like rigidity. Ordinary Portland Cement (OPC), which is readily available locally and complies with the American Standard ASTM C 150 Type-I mark, European Standard BS EN 197 type CEM-I, and Bangladesh Standard BDS EN 197-1:2010 (CEM-I, 52.5 N), was utilized in this study for the manufacture of specimens [40–42]. In Table 1, OPC cement constituents are listed as per previous literature [29].

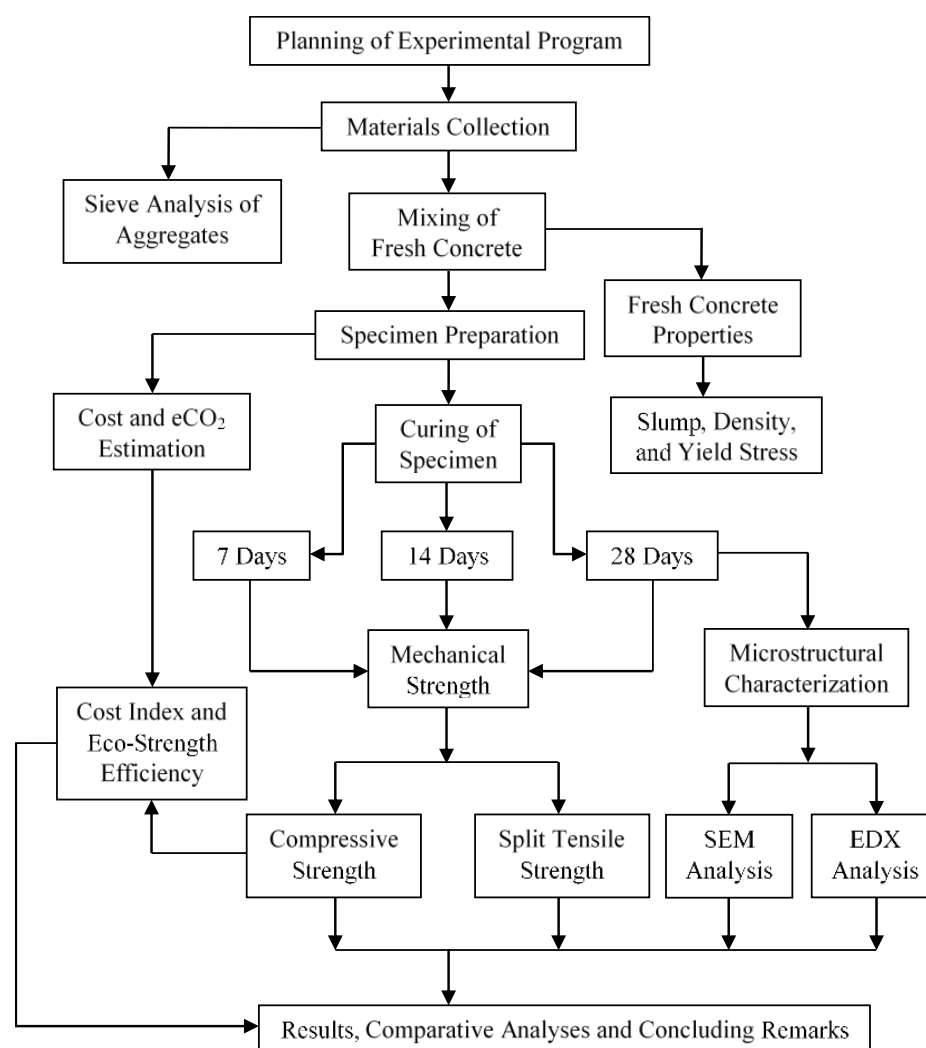


Figure 1. Research methodology flow chart.

Table 1. Chemical constituents of OPC [29].

Constituents	Weight (%)
Silica (SiO ₂)	21.45
Alumina (Al ₂ O ₃)	4.30
Ferric oxide (Fe ₂ O ₃)	3.28
Calcium oxide (CaO)	64.32
Magnesium oxide (MgO)	1.18
Sulfur trioxide (SO ₃)	3.56
Insoluble residue (IR)	0.35
Loss on ignition (LOI)	2.055
Free lime	1.274

For this study, stone chips from a nearby building site were chosen as the coarse aggregate. Briefly, 19 mm downgraded stone chips with a fineness modulus (FM) of 7.07 were utilized. The stone chips were washed thoroughly with water to remove any impurities or dust. Fine aggregate works as a vital filler material in concrete as it can fill the voids among the coarse aggregates. As fine aggregate, Sylhet sand of 4.75 mm maximum grain size was employed. The FM of fine aggregate was found to be 2.91 with a uniformity coefficient (Cu) of 3.93. Figure 2 shows the gradation curve of fine and coarse aggregates produced from the results of sieve analysis, which satisfied the ASTM C33 standard [43].

The graph compares the utilized materials and the higher and lower limits for fine and coarse aggregates as per the aforementioned standard.

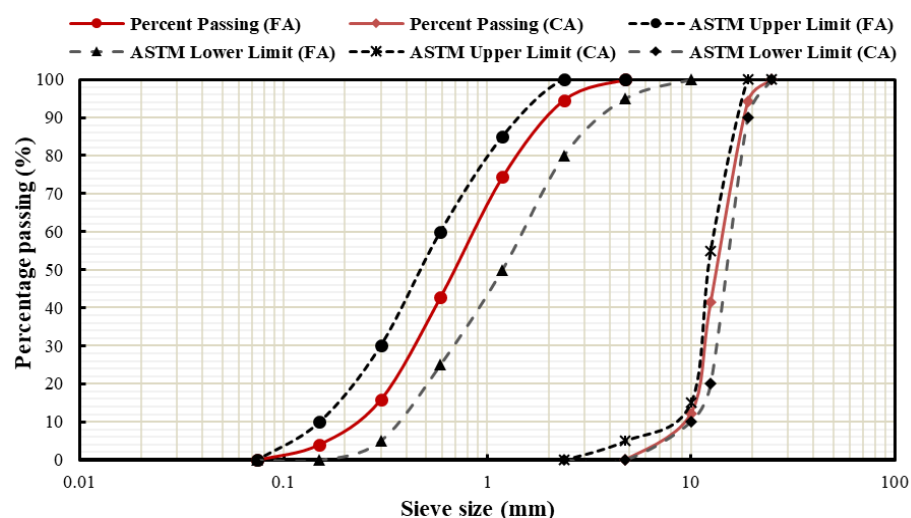


Figure 2. Gradation curve of the aggregates.

2.3. Areca Fiber

For this study, waste areca nut shells were collected from local tea stalls on a regular basis without any associated cost. Upon collecting a hefty amount of areca nut shells, they were thoroughly washed with tap water to remove any dust particles adhering to their surface to reduce impurities. The shells were then submerged in water for 24 h to loosen them up for fiber extraction. Following this, the fibers were separated by hand, with a particular focus on the extraction of rigid and stiff coarse fibers for utilization in the AFRC mixes. The screened fibers were then sun-dried for a duration of 72 h to attain a surface-dry condition before being used for the casting. The extraction process of the areca nut fibers, along with the condition of the fibers (surface dry) before mixing, is illustrated in Figure 3. For the purpose of analysis, ten individual fibers were randomly selected and measured to determine their average length and diameter. The geometry of areca fibers is detailed in Table 2.



Figure 3. Areca fiber extraction process: (a) soaked areca nut husk, (b) mixed fibers, (c) extracted coarse fibers, (d) saturated surface dry fiber (before mixing).

Table 2. Geometry of the areca fibers.

Physical Properties	Areca Fiber
Average length (mm)	50
Average diameter (mm)	0.75
Aspect ratio	66.67

2.4. Mix Proportion of the Specimens

Experiments were conducted to evaluate the effects of different areca fiber concentrations on concrete properties. In this regard, five concrete mixes were prepared, each with varying fiber concentrations. The control specimen, labeled AFRC0, was fabricated without any fiber inclusion and had a target compressive strength of 30 MPa. The remaining four batches were cast with areca fibers added at 1%, 2%, 3%, and 4% (by weight) as cement replacements, denoted as AFRC1, AFRC2, AFRC3, and AFRC4, respectively. To ensure consistency in concrete mix proportions, mix proportions were designed to achieve a target compressive strength of 30 MPa for the control concrete at 28 days strength. The aggregate content and water-to-cement (w/c) ratio of 0.45 remained constant across all mixtures. Although it is acknowledged that natural fibers such as areca have a higher water absorption capacity compared to conventional concrete materials, a constant w/c ratio was maintained to facilitate the evaluation of areca fiber's influence on fresh concrete's workability, density, and yield stress without utilizing any water-reducing admixture. Over 100 cylindrical specimens, with dimensions of 100 mm and 200 mm, in diameter and height, were fabricated for the purpose of testing. The concrete mix proportions are detailed in Table 3.

Table 3. Mix proportion of concrete mixtures.

Mix Id	Fiber Percentage	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Fiber (kg/m ³)	Water (kg/m ³)	w/c Ratio
AFRC0	0%	395	800	985	0	177.8	0.45
AFRC1	1%	391.1	800	985	3.95	176.0	0.45
AFRC2	2%	387.1	800	985	7.90	174.2	0.45
AFRC3	3%	383.2	800	985	11.85	172.4	0.45
AFRC4	4%	379.2	800	985	15.80	170.6	0.45

2.5. Specimen Preparation and Curing

The concrete mixing process began by adding the required amounts of sand and stone chips to a concrete mixer, which were dry-mixed prior to adding the cement. Areca fibers were then gradually introduced by hand spraying into the rotating mixing chamber. To ensure an even distribution of fibers throughout the mixture, the mixing chamber was rotated uniformly. Following that, water was introduced to the amalgamation. A consistent mix without segregation was achieved by maintaining a mixing duration of five to seven minutes, resulting in a visibly homogeneously mixed mixture. To prevent concrete from sticking to the steel molds, a light oil spray was applied to the inner surfaces before pouring the concrete. Following the guidelines outlined in ASTM C 192-88/C192M-19, concrete casting was performed in layers, with each layer being 50 mm thick [44]. Compaction of the concrete was carried out using a tampering rod, with 25 blows applied for 15 to 30 s on each layer to minimize the formation of air bubbles. After casting, the specimens were wrapped in plastic in the laboratory for a period of 24 h to prevent moisture loss from the fresh concrete. Subsequently, the test samples were de-molded and labeled with a unique mix identification, along with the casting date. They were then immersed in water for the curing period until the specified test age was reached. Prior to conducting the mechanical strength tests, the cured cylinders were removed from the curing chambers and allowed to air-dry for 24 h.

2.6. Testing Methods

A slump cone experiment was performed to assess the workability of concrete paste in accordance with ASTM C143/C143M-15a [45]. The density of fresh concrete was tested in accordance with ASTM C138/C138M-17a guidelines [46]. The density and slump value of fresh concrete was used to calculate the analytical yield stress. Using the finite element model (FEM) of a slump cone test, Hu et al. [47] developed an expression for yield stress in terms of slump and concrete density, which is shown in Equation (1). Concrete mixtures with varying slumps were subjected to finite element analyses.

$$\tau_0 = \frac{\rho}{270}(300 - s) \quad (1)$$

where τ_0 = yield stress in Pa, s = slump in mm, and ρ = density in kg/m³

For the mechanical performance assessments, cylindrical concrete specimens of 100 mm diameter and 200 mm height were cast. Compressive and splitting tensile strengths of AFRC0, AFRC1, AFRC2, AFRC3, and AFRC4 were performed after the curing age of 7, 14, and 28 days by the hydraulic compression testing machine (digital display). For the compressive strength test, ASTM C39/C39M-20 standard guidelines were followed [48]. In this test procedure, concrete cylinders were subjected to a compressive axial force at a loading rate that stayed within a pre-determined range of 0.15 to 0.35 MPa until failure. The compressive strength of the specimen was calculated by dividing the maximum load achieved during the test by the cross-sectional area of the specimen. Splitting tensile experiments were conducted according to the ASTM C496/C496M-17 standard [49]. This testing process involves applying a diametral compressive point load at a rate within a pre-determined range along the length of a cylindrical specimen until failure. The mean strength in both cases was determined by reporting the average of three successive test outcomes.

Furthermore, SEM and EDX tests were performed as per the instructions of ASTM C1723-10 guidelines to assemble the micro-structural characterization [50]. The analysis was conducted on the Schottky field emission scanning electron microscope machine (JSM-7610F version), manufactured by JEOL Ltd. (Tokyo, Japan). SEM scans provided a better view of the interfacial transition zone between the fiber and cement matrix in the cross-sectional area. On the other hand, the EDX analysis provided the elemental characterization of conventional and AFRC concrete specimens.

3. Results and Discussion

3.1. Rheological Properties

3.1.1. Slump Value of Fresh Concrete Mixes

Slump tests were conducted for fresh concrete with no fiber added (control) and fresh concrete with various fiber dosages, as represented by Figure 4. It can be seen from Figure 4 that the AFRC0 (control mix) provided the maximum slump value of 82 mm, and the AFRC4 made up the minimum slump value of 22 mm. While the AFRC1, AFRC2, and AFRC3 provided slump values of 65 mm, 54 mm, and 37 mm, respectively. Percent decrement of slump values with respect to AFRC0 was 20.73%, 34.15%, 54.88%, and 73.17% for AFRC1, AFRC2, AFRC3, and AFRC4, respectively. The areca fiber absorbed water and became wet while the mixing was done. As no plasticizing admixture was used in the concrete mixes, the areca fiber and its dosages are the causes of the decreasing trend of the slump value in the concrete. Islam et al. [51] found a similar drop in the workability of using locally available natural coir fiber as a reinforcing agent in concrete.

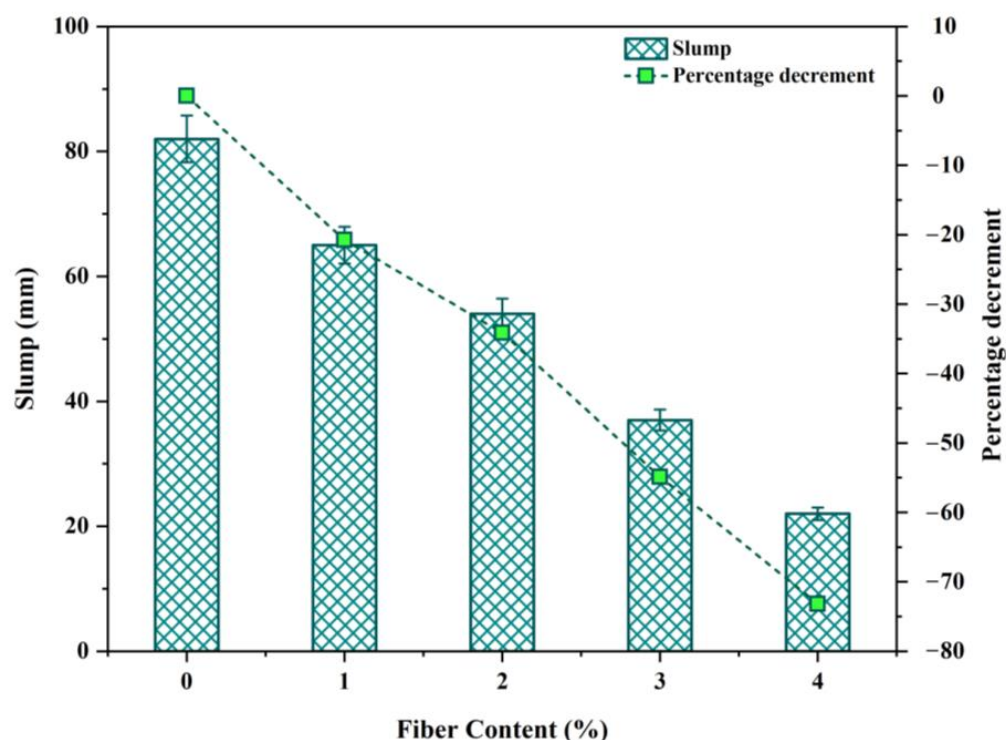


Figure 4. Slump test results of concrete with varying fiber concentrations.

As shown in Table 3, the cement was replaced with areca fibers, which dramatically lessened the density of freshly mixed concrete containing fibers compared to the control mix due to the significantly higher specific gravity of OPC than areca fiber. This decrease is more pronounced with the increased fiber dosages in the mix. This phenomenon dramatically decreases the internal hydraulic pressure (i.e., lower self-weight) at the bottom portion of the slump cone, lowering the concrete's deformation and decreasing the slump magnitude [52]. The visual assessment reveals that the areca fibers have excellent surface roughness, thus significantly enhancing the frictional forces among the fibers and constituents of concrete and providing better interlocking [53]. This behavior helps stabilize the concrete by tying all the concrete materials together and preventing the concrete from dropping more than fiber-free concrete. However, due to the outstanding surface roughness of areca fibers, a tiny portion of water may accumulate on the fibers' surfaces, which decreases the water content in the mix, mitigates the moveability of the particles, and offers a lower slump to the mix containing fibers in comparison with the control mixture.

3.1.2. Density of Fresh Concrete Mixes

The density test of fresh concrete mixtures revealed insights into the effects of using areca fiber in concrete mixes, which are presented in Figure 5. Similar to the slump value, the areca fiber-reinforced concrete density value declined significantly as the concentration of areca fiber inside the concrete paste increased. The maximum density of the control mix (AFRC0) was determined to be approximately 2423 kg/m^3 . On the other hand, AFRC4 fresh mix gained a minimum density of 2144 kg/m^3 . The decrement percentages in density of AFRC1, AFRC2, AFRC3, and AFRC4 compared to the AFRC0 mix are 3.03%, 6.14%, 8.82%, and 11.55%, respectively. The declining trend in the density of fiber-reinforced concrete fabricated with natural coir fiber was observed by Das et al. [29].

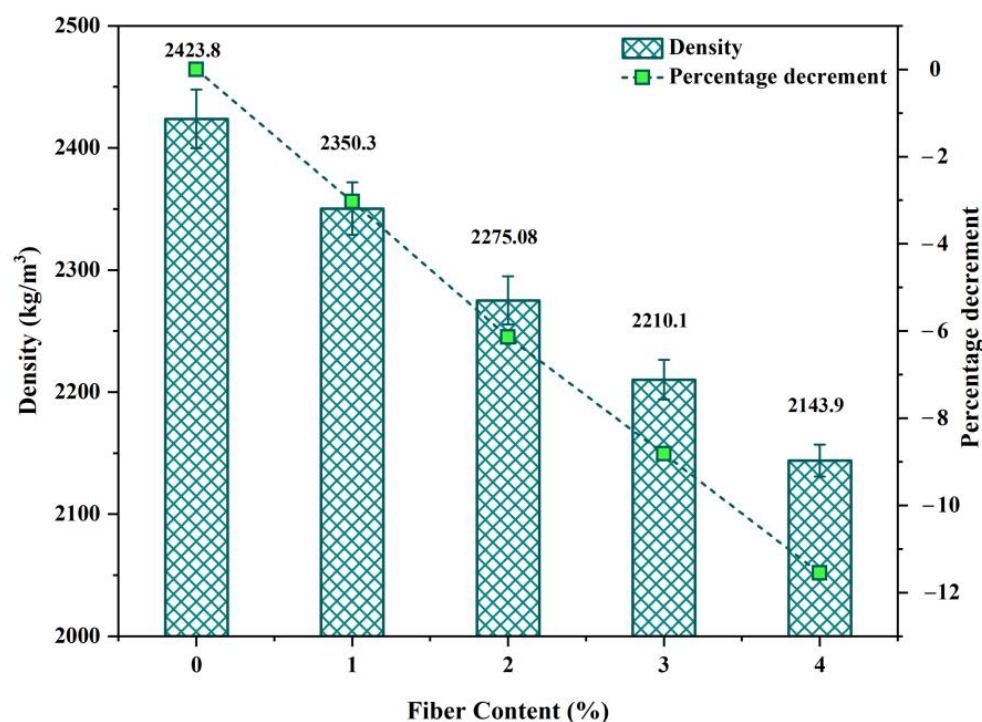


Figure 5. Density of fresh concrete with varying fiber concentrations.

The decrease in density of concrete reinforced with areca fibers could be associated with the significantly lower specific gravity and weight of areca fibers in comparison to cement. As cement was replaced with areca fibers (as documented in Table 3), these lower properties and higher voids due to the lower workability of the fresh concrete mix fabricated with areca fibers than the control mix (as shown in Figure 4) dramatically reduced the density of the mixes. Indeed, the lower density of the concrete mixes cast with areca fibers could remarkably diminish the whole structure's self-weight. It reveals that the mixes with areca fibers may require a smaller size of the structural components and a lower amount of reinforcements for the foundation to sustain its self-weight, leading to a decrease in the project's entire cost.

3.1.3. Relationship between Rheological Properties of Concrete

The relationship among the slump value, density, and yield stress of freshly mixed concrete fabricated with varying dosages of areca fibers is illustrated in Figure 6. It can be seen that the relationships are quite linear. It can also be said that as the fiber concentration increased in the concrete mixture, the density and slump decreased to some extent in a linear proportion. A regression analysis has also been established to predict the density of AFRC from the slump values. The regression coefficient for this equation was found to be $R^2 = 0.9933$, as shown in Figure 6. This showed a proportional and linear linkage between the slump value and density, while the reverse effect of adding areca fiber to both parameters. As the natural areca fiber is very lightweight and takes up much space in the concrete mixture, this can be the reason for this reverse effect.

The qualities of the mixture's plastic viscosity and yield stress significantly impact the slump of the fresh concrete. Figure 6 depicts that the examined yield stress of fresh concrete reveals a linear increment with increasing fiber concentration and an inverse relationship with the slump value of freshly mixed AFRC. The maximum calculated yield stress was 2207 Pa for AFRC4. On the other hand, the minimum value of yield stress of 1957 Pa was calculated for the AFRC0 mix. The percent increments in yield stress of AFRC1, AFRC2, AFRC3, and AFRC4 compared to AFRC0 were 4.53%, 5.92%, 10.01%, and 12.8%, respectively. According to the regression analysis, a substantial association between the

slump value and the yield stress of areca fiber-reinforced fresh concrete can be seen, with a coefficient of determination ($R^2 = 0.9957$, as shown in Figure 6). This connection might be used to predict concrete slumps based on yield stress values without completing any experiments. The decrement in workability validated that the effective water available for concrete mixing was partially absorbed by the natural areca fiber, which increased the viscosity of the concrete paste. This can be attributed to the higher yield stress of concrete with a higher fiber concentration compared to a lower fiber-concentrated mix. Furthermore, it was reported that fiber has a substantial effect on the augmentation of the concrete's yield stress, which remains consistent with the experimental inquiry stated by Tattersall and Banfill [54].

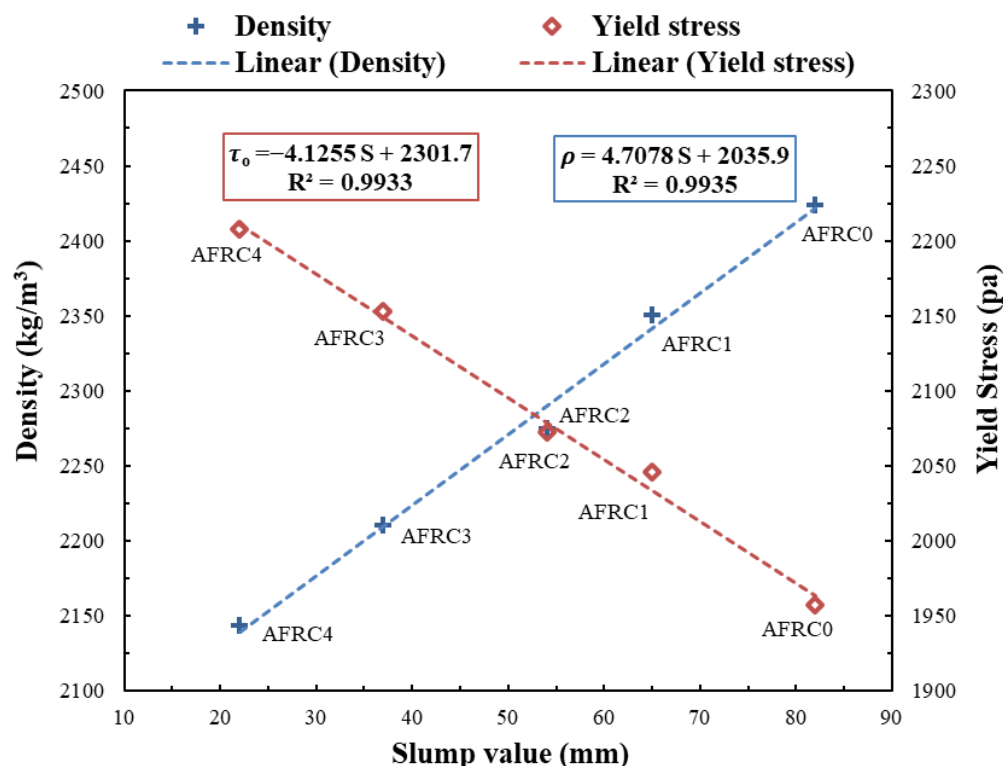


Figure 6. Relationship of slump value versus density and yield stress of concrete mixes.

3.2. Mechanical Properties

3.2.1. Compressive Strength of Concrete Samples

Table 4 presents the achieved outcomes of compressive strength (f'_c) for all five mix designs at different curing intervals (7, 14, and 28 days), considering various numerical constraints such as mean strength, coefficient of variance (CoV), standard deviation, standard error, and the 95% lower and upper confidence intervals. The average of at least three successively examined concrete samples was used to determine every detail. The compressive strength of the AFRC specimens at 7 and 14 days is in the range of 63–68% and 84–87% of the concrete specimens' 28-day strength, respectively. For the 7-day curing period, the compressive strength ranged from 16.70 MPa to 21.08 MPa across all specimens. At 14 days, the strength varied between 21.89 MPa and 27.29 MPa, while at 28 days, it ranged from 25.36 MPa to 32.33 MPa. The test results for all five mixes exhibited deviations within the range of 0.365 to 1.098. Notably, the first three mixes (AFRC0, AFRC1, and AFRC2) with fiber concentrations up to 2% demonstrated lower standard deviation values, ranging from 0.365 to 0.856. Conversely, the last two mixes with 3% and 4% fiber content exhibited higher standard deviation values, ranging from 0.961 to 1.098. Moreover, as the fiber content increased from 0% to 4%, the standard deviation for the test outcomes also kept increasing. This statistical data indicate that higher fiber dosages beyond 2% led to greater deviations from the mean strengths in the compressive strength test results,

making them more scattered. Additionally, the coefficient of variance (CoV) and standard error values for all five mix designs varied from 0.014 to 0.063 and from 0.211 to 0.634, respectively. Similar to the standard deviation, the first three mixes demonstrated lower CoV and standard error values compared to the subsequent two mixes with higher fiber content.

Table 4. Summary of the compressive strength test results.

Mix ID	Curing (Days)	Mean Strength (MPa)	Standard Deviation	CoV	Standard Error	95% Confidence Interval	
						Upper Range	Lower Range
AFRC0	7	20.3	0.365	0.018	0.211	21.17	19.36
	14	26.0	0.523	0.020	0.302	27.33	24.73
	28	30.1	0.420	0.014	0.243	31.10	29.01
AFRC1	7	21.1	0.447	0.021	0.258	22.19	19.97
	14	27.3	0.493	0.018	0.285	28.52	26.07
	28	32.3	0.514	0.016	0.297	33.60	31.05
AFRC2	7	20.6	0.558	0.027	0.322	21.99	19.22
	14	26.5	0.532	0.020	0.307	27.86	25.21
	28	30.9	0.856	0.028	0.494	33.05	28.79
AFRC3	7	18.8	0.751	0.040	0.434	20.68	16.95
	14	24.3	0.777	0.032	0.448	26.27	22.41
	28	28.3	0.961	0.034	0.555	30.69	25.91
AFRC4	7	16.7	1.071	0.064	0.618	19.36	14.04
	14	21.9	1.081	0.049	0.624	24.58	19.20
	28	25.4	1.098	0.043	0.634	28.09	22.63

Figure 7 graphically illustrates the average strength of all mix designs at curing intervals of 7, 14, and 28 days and their enhancement percentages in comparison to the control mix (AFRC0). The results demonstrate that the AFRC1 mix, with 1% fiber content, exhibited the highest compressive strength across all curing stages. Specifically, after 7, 14, and 28 days, the strengths of the AFRC1 mix were recorded as 21.08 MPa, 27.29 MPa, and 32.33 MPa, respectively. Conversely, the AFRC4 mix, containing 4% fiber, displayed the lowest compressive strength after each curing period: 16.70 MPa, 21.89 MPa, and 25.36 MPa for 7, 14, and 28 days, respectively. In comparison, the control mix (AFRC0) without any fiber achieved compressive strengths of 20.26 MPa, 26.03 MPa, and 30.05 MPa at the respective curing intervals. The concrete mix with 2% areca fiber (AFRC2) also exhibited an improvement in compressive strength, although it was comparable to the control mix (AFRC0). Notably, the AFRC1 mix demonstrated the highest increase of almost 8% after 28 days of curing while exhibiting a comparable increment of 5% after 14 days. The AFRC2 mix, comprising 2% fiber, displayed increments of 2% to 3% in compressive strengths for all the curing intervals. In contrast, the AFRC3 and AFRC4 mix, with 3% and 4% fiber content, respectively, exhibited lower compressive strengths compared to the reference mix (AFRC0), experiencing approximate decrements of 6% and 17% after the 28-day curing period. As depicted in Figure 3, it is widely recognized that the areca nut shell contains both thick and thin fibers. The thick fibers, which possess relatively good stiffness, were utilized in the concrete mix. This is likely the reason why there was a lesser decrement in compressive strength across the different mixtures, while other untreated fibers, which were relatively thinner, exhibited a greater decrease in compressive strength [27,38,55]. The test findings suggest that 1% and 2% areca fiber addition can slightly enhance the compressive strength of concrete; nevertheless, beyond that percentage, the strength decreases by a larger margin.

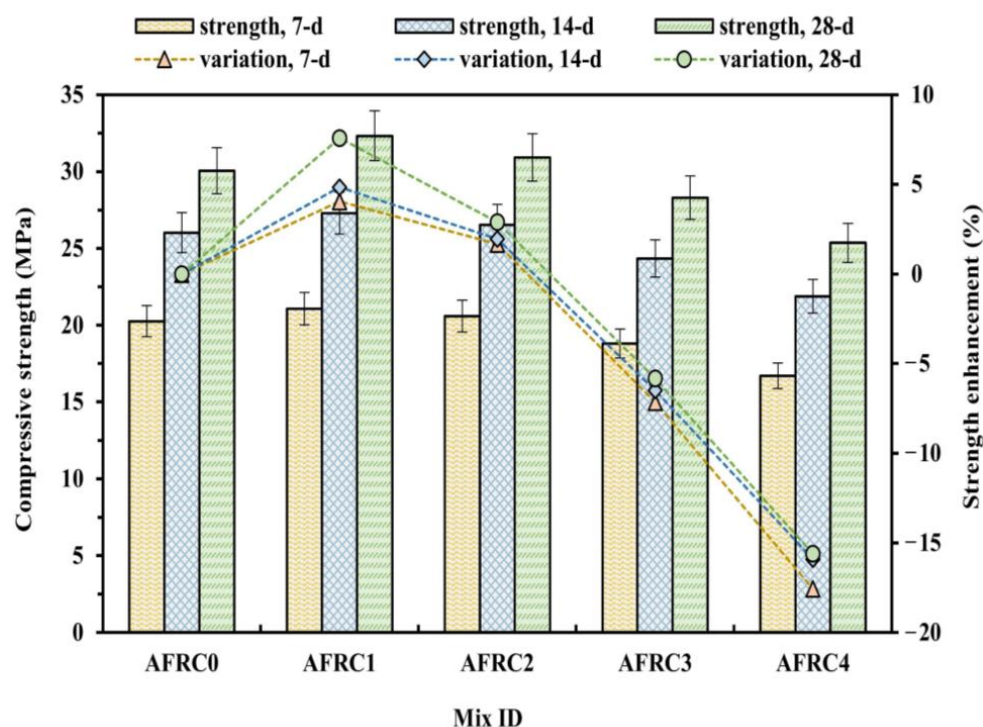


Figure 7. Compressive strength and variation of concrete samples.

The observed improvement in compressive strength upon the addition of areca fibers can be attributed to several factors associated with the fiber's interaction with the concrete matrix. At a 1% fiber addition, the fibers are distributed evenly throughout the concrete mixture, leading to enhanced interlocking and stress distribution mechanisms within the matrix. This counteracts the crack maturation and widening in the concrete matrix. In addition, areca fibers could tie the concrete constituents tightly, thus building a strong bond among them and controlling the lateral expansion (i.e., perpendicular to the uniaxial load) of the specimens by stitching the cracks [56], which is an important factor for withstanding the uniaxial compressive force. These phenomena could limit the stress concentration in the matrix generated by cracks and improve the post-cracking behavior of concrete, thus allowing it to withstand a higher uniaxial compressive force for the mix containing areca fibers than the control mix. Fiber concentrations beyond 2% have reduced the compressive strength significantly. Excessive fiber content might lead to overcrowding and insufficient matrix-fiber interaction, diminishing the bonding effect and subsequently reducing strength. Moreover, higher fiber concentrations led to difficulty in achieving proper mix workability (Figure 4), causing voids and uneven fiber distribution, ultimately impacting compressive strength [57]. A similar increasing and declining trend in concrete compressive strength was reported when the natural jute fiber concentration was increased beyond the optimum dosage [55]. Moreover, the decrease in compressive strength of cement composites (i.e., mortar specimens) fabricated with higher dosages of areca fibers was also reported by Miah et al. [53]. This keeps the previous and current research findings in terms of the compressive strength of natural fiber-reinforced cement composites in line while providing new insight into concrete specimens.

3.2.2. Observed Crack Patterns after Compression Failure

Figure 8 shows the observed crack patterns after the compressive strength test of the concrete specimens. It can be observed that, except for the control specimen, all the specimens exhibit a very uniform failure plane of wedge growth, and the effect of the fiber on the surface of the cylindrical samples altered the failure pattern. In contrast, the AFRC0 (control) specimen showed wide columnar vertical cracks and brittle failure, as illustrated

in Figure 8a. It is also noteworthy that the control specimen showed no well-formed wedge. The wedge formation is more visible in the AFRC1 and AFRC2 specimens, which have 1% and 2% areca fiber concentrations, respectively, as shown in Figure 8b,c. Shear cracks were observed due to the compressive stress in the AFRC3 mix having a 3% fiber concentration, as presented in Figure 8d. AFRC3 also showed a well-formed, distributed crack.

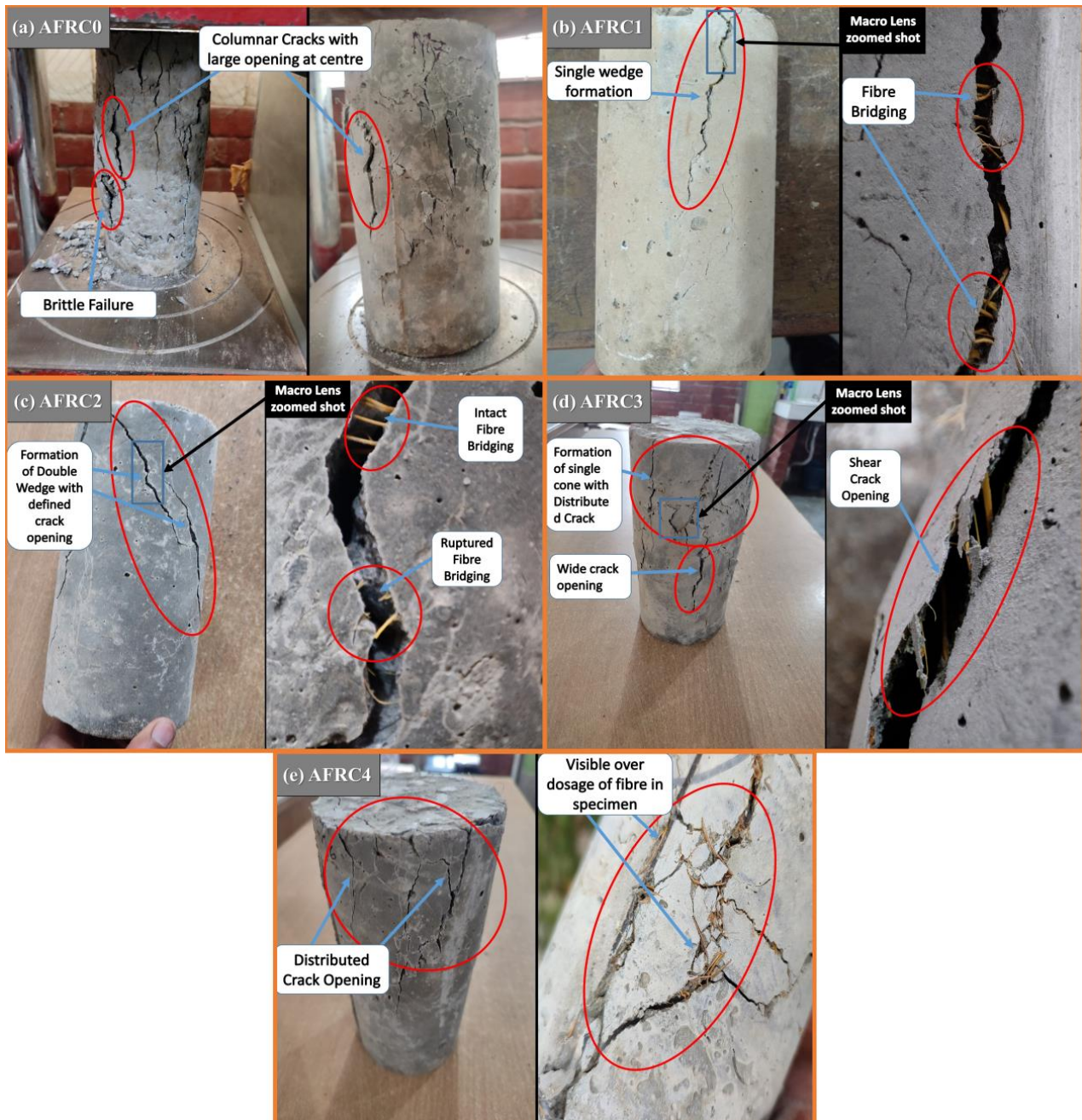


Figure 8. Observed crack patterns of (a) AFRC0, (b) AFRC1, (c) AFRC2, (d) AFRC3, and (e) AFRC4 after compression failure.

Additionally, it was seen that the cracks were irregularly spaced in all directions, with a larger crack in the center in the case of the control mix (AFRC0). The formation of the main crack length was observed to be greater than half the length of the specimen. However, smaller vertical cracks were distributed throughout the length of the specimen. Contrarily, the AFRC mixes (AFRC1, AFRC2, AFRC3, and AFRC4) with varied fiber concentrations showed few fractures, which mostly appeared on the exterior surfaces of the

cylinders. These cracks are not as bad as compression cracks or vertical columnar cracks that occur when concrete specimen control fails. The crack propagation was more visible and distributed in higher dosages of areca fiber. In the case of the AFRC4 mix having 4% areca fiber, the cracks were most distributed towards the middle region of the specimens. This response shows that fiber interlocking produces a bridging and impounding effect that prevents vertical columnar cracks and results in the development of more distributed and narrower crack openings on the specimen's surface. In homogenous concrete mixes, the fiber bridging effect causes the load to transfer towards the whole body of the cylindrical specimen by absorbing a higher amount of energy, thus resisting immediate columnar cracks [58]. This leads to ductile failure of the specimens and, ultimately, long-term serviceability caution before the members' eventual collapse. These crack pattern observations aligned with the findings of Savastano et al. [59] when they investigated the crack patterns of natural fiber-reinforced concrete.

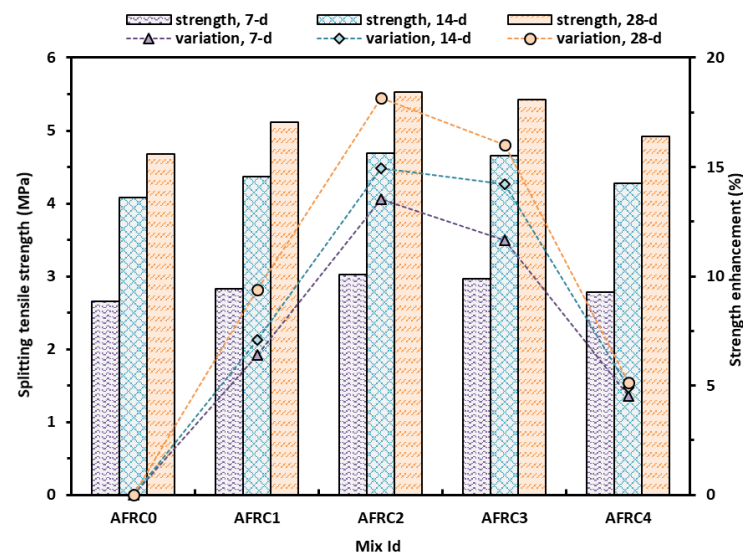
3.2.3. Split Tensile Strength of Concrete Samples

Table 5 displays the outcomes of the split tensile strength (f_{sp}) experiments conducted on five distinct mixtures at various curing intervals along with multiple quantitative constraints, including average strength, coefficient of variation (CoV), standard deviation, and standard error, as well as the 95% lower and upper confidence intervals for 7, 14, and 28 days. For each detail, a minimum of three consecutive concrete samples underwent testing. The split tensile strength measurements for all samples ranged from 2.66 MPa to 3.02 MPa after 7 days, 4.08 MPa to 4.69 MPa after 14 days, and 4.68 MPa to 5.53 MPa after 28 days. From a statistical perspective, the deviation of the test results for all five mixtures varied from 0.092 to 0.264. In line with the findings of the compressive strength tests (Table 4), the first three mixtures (AFRC0, AFRC1, and AFRC2), with a fiber concentration of up to 2%, exhibited lower standard deviation values ranging from 0.092 to 0.161. Conversely, the remaining two mixtures (AFRC3 and AFRC4), with fiber concentrations of 3% and 4%, demonstrated higher values ranging from 0.205 to 0.264. This indicates that an increase in fiber dosage beyond 2% led to a greater deviation of the split tensile strength test results from the mean strengths. The CoV and standard error for all five mixture designs ranged from 0.02 to 0.095 and 0.053 to 0.152, respectively. Similar to the standard deviation, the values of CoV and standard error were also lower for the initial three mixtures compared to the subsequent two mixtures, which aligns with the outcomes observed for compressive strength. With an increased fiber concentration, the homogenous distribution of fiber into the fresh concrete may decline due to the fiber balling phenomenon, which resulted in comparatively inconsistent test outcomes for the specimens.

Figure 9 visually represents the mean split tensile strengths of the concrete mixtures and their enhancement percentages compared to the control mix (AFRC0) following 7, 14, and 28 days of curing. From the graphical representation, it is evident that the AFRC2 mix, containing 2% fiber, exhibited the highest split tensile strength at all the curing intervals, measuring at 3.02 MPa, 4.69 MPa, and 5.53 MPa, with significant improvements of 13.5%, 15%, and 18%, respectively. Concrete with 3% fiber also showed a comparable increment in tensile strength, which subsequently increased by 12%, 14%, and 16% compared to fiber-free concrete. Conversely, the AFRC4 mix, incorporating 4% fiber, demonstrated the lowest split tensile strength among the fiber-reinforced mixtures across all curing stages, measuring at 2.78 MPa, 4.28 MPa, and 4.92 MPa after 7, 14, and 28 days, respectively. Nevertheless, the strength was higher than that of the control concrete (AFRC0), which had no fiber, exhibiting strengths of 2.66 MPa, 4.08 MPa, and 4.68 MPa after the corresponding curing intervals. Overall, the incorporation of areca fiber enhanced the tensile strength of concrete for all fiber concentrations.

Table 5. Summary of the splitting tensile strength test results.

Mix ID	Curing (Days)	Mean Strength (MPa)	Standard Deviation	CoV	Standard Error	95% Confidence Interval	
						Upper Range	Lower Range
AFRC0	7	2.66	0.118	0.044	0.068	2.96	2.37
	14	4.08	0.119	0.029	0.069	4.37	3.78
	28	4.68	0.092	0.020	0.053	4.91	4.46
AFRC1	7	2.83	0.111	0.039	0.064	3.10	2.55
	14	4.37	0.125	0.029	0.072	4.68	4.06
	28	5.12	0.134	0.026	0.077	5.45	4.78
AFRC2	7	3.02	0.141	0.047	0.082	3.37	2.67
	14	4.69	0.111	0.024	0.064	4.97	4.42
	28	5.53	0.161	0.029	0.093	5.93	5.13
AFRC3	7	2.97	0.213	0.072	0.123	3.50	2.45
	14	4.66	0.217	0.047	0.126	5.20	4.12
	28	5.43	0.226	0.042	0.131	5.99	4.87
AFRC4	7	2.78	0.264	0.095	0.152	3.44	2.13
	14	4.28	0.221	0.052	0.128	4.83	3.73
	28	4.92	0.205	0.042	0.118	5.43	4.41

**Figure 9.** Splitting tensile strength and variation of concrete samples.

It is well established that the addition of various natural and artificial discontinuous fibers can significantly enhance the split tensile strength of concrete structures [60,61]. This increase in splitting tensile strength using areca fiber implies that the non-uniform dissemination and irregular alignment of areca fiber inside the concrete mix result in a fiber-interlocking, cohesive mix, and robust bond between the concrete aggregate, areca fiber, and cement matrix, resulting in an increase in concrete strength. Moreover, the enhanced matrix can withstand more tensile strength by distributing the stress evenly throughout the entire concrete structure. This, in turn, results in an overall increase in concrete strength as the fiber reinforces the concrete and helps it resist cracking and breaking. SEM photographs of the fiber-reinforced concrete's well-bonded, tight interfacial transition zone also imply this statement, as can be seen in the figure in Section 3.3. Similar increments in splitting strength for lower natural fiber dosages and further decrements in higher natural fiber dosages were observed by Lumingkewas et al. [62] when they investigated the mechanical characteristics of untreated coconut fiber-reinforced concrete. Divakar et al. [24] and Miah et al. [53]

investigated the effects of incorporating areca fiber in concrete and mortar, respectively, as a reinforcing agent. Outcomes of both studies include significant enhancement of the tensile strength of concrete and mortar containing areca nut fiber.

3.2.4. Observed Crack Pattern after Splitting Tensile Failure

Observed crack patterns after splitting tensile tests of all the AFRC mixes are presented in Figure 10. The control sample had a brittle failure, as seen in Figure 10a. A single, wide crack along the loading axis was seen in the control specimen. In contrast, the mixes containing fiber (AFRC1, AFRC2, AFRC3, and AFRC4) showed gradual crack growth, which spanned both sides of the neutral axis marked line as shown in Figure 10b–e. Observing the lower concentrations of fiber (AFRC1 and AFRC2), it can be said that the cracks formed in the outer region of the cross sections by forming double and single cones, which are represented in Figure 10b,c. Fiber bridging was seen in both cases, which reduced the crack opening width. However, the higher concentrations of fiber (AFRC3 and AFRC4) showed even more distributed cracks and visible fiber bridging, as shown in Figure 10d,e. The AFRC4, having 4% fiber concentration, showed ductile failure where the fiber bridging caused the crack to be almost distributed along both the whole cross-sectional and longitudinal surfaces of the specimen. From the close observations, it can be reported that in the fiber-reinforced specimens, cracks began to appear in the center of the cylindrical face and quickly spread throughout the specimens' length and diameter as the applied force increased. In contrast, the control specimen with no fiber addition showed instant crack propagation and sudden failure as the loading increased.

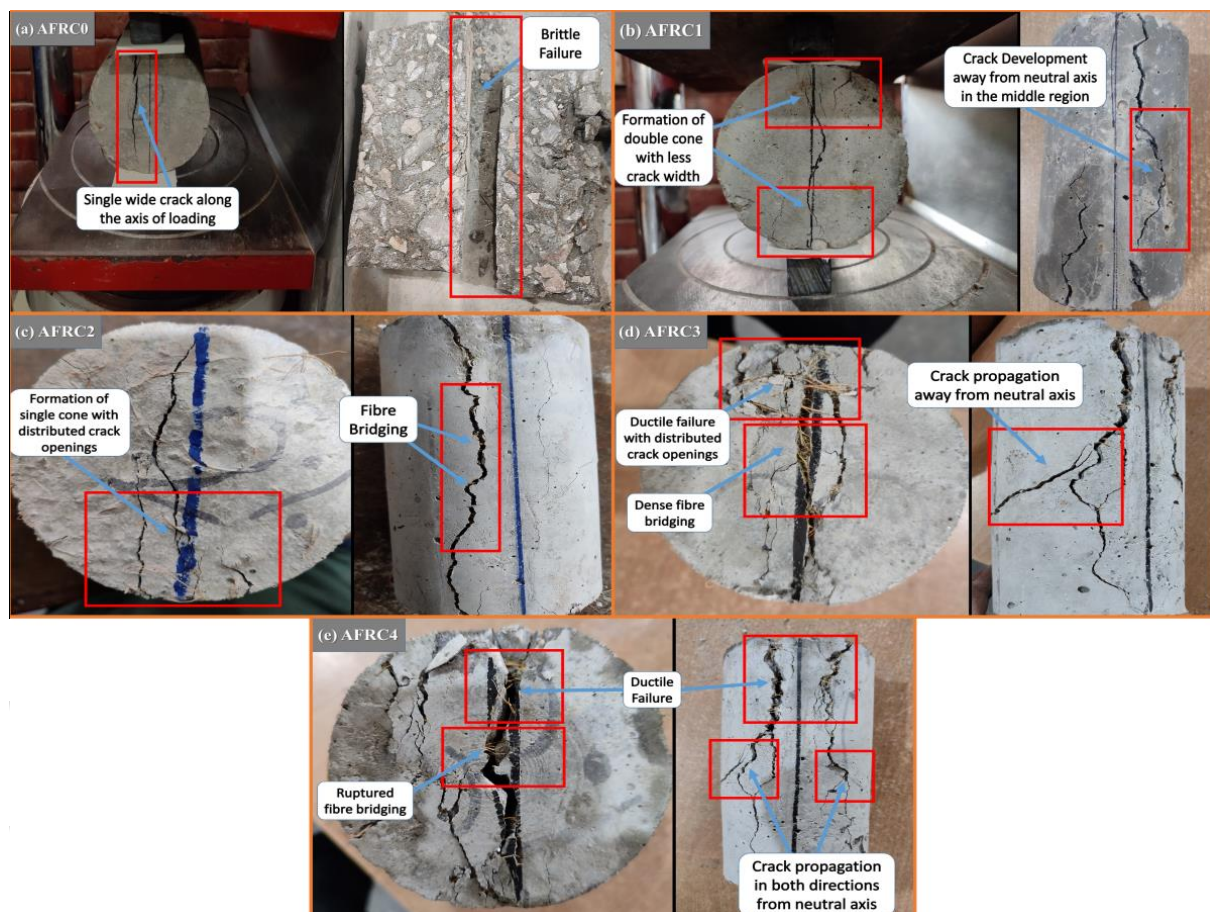


Figure 10. Observed crack pattern of (a) AFRC0, (b) AFRC1, (c) AFRC2, (d) AFRC3, and (e) AFRC4 after tension failure.

With an increase in fiber volume fraction, toughness and post-crack performance both improved. In general, there was a load reduction after reaching the yield stress point (first peak), then a brief hardening period with a second peak. The samples with 4% areca fiber, on the other hand, exhibited a strain-hardening tendency, sustaining more residual strength beyond the first peak load to reach their maximum strength of over 10 kN. Strong bonds between aggregate, fiber, and cement paste were created by the randomly distributed areca fibers, the homogeneity of the mixture, and the interlocking of the fiber, which contributed to the ductile failure of the fiber-reinforced concrete specimens before they failed under the ultimate load and separated the cylinders into two half segments. Boulekbache et al. [63] revealed a comparable discovery in the FRC specimens' crack patterns. The fiber-reinforced samples had a major crack in the center of the specimen, followed by minor secondary cracks, before separating into two half-cylinders, according to their findings. In contrast, conventional concrete exhibits a straight and brittle crack pattern. A similar post-cracking performance was also reported by Tran et al. [64], where they added the textile waste fiber into the concrete mix in order to assess the mechanical performance of waste fiber-reinforced concrete.

3.2.5. Effect of Areca Fiber on the Brittleness of Concrete

Brittleness stands as one of the most pivotal characteristics of load-bearing materials, denoting inherent attributes such as materials' fragile nature, and can lead to failure under mechanical stress in the absence of notable plastic deformation or giving off any cautious indicators. In the event of severe external loading circumstances, such as an earthquake, blast, tsunami, or fire, this could raise the danger of hazards for people. It is widely acknowledged that fibers possess the capability to enhance the ductility (i.e., lessen brittleness) of composites that are based on cement. The ratio of indirect tensile strength (i.e., split tensile strength) to compressive strength offers an avenue for evaluating the brittleness of cement-based materials; in other words, an increase in the ratio results in a decrease in the brittleness of the material, and vice versa. The outcomes of this exploration concerning the tension-to-compression ratio (f_{sp}/f'_c) and the corresponding reductions in brittleness, expressed as percentages at varying curing durations and diverse areca fiber percentages, are visually presented in Figure 11.

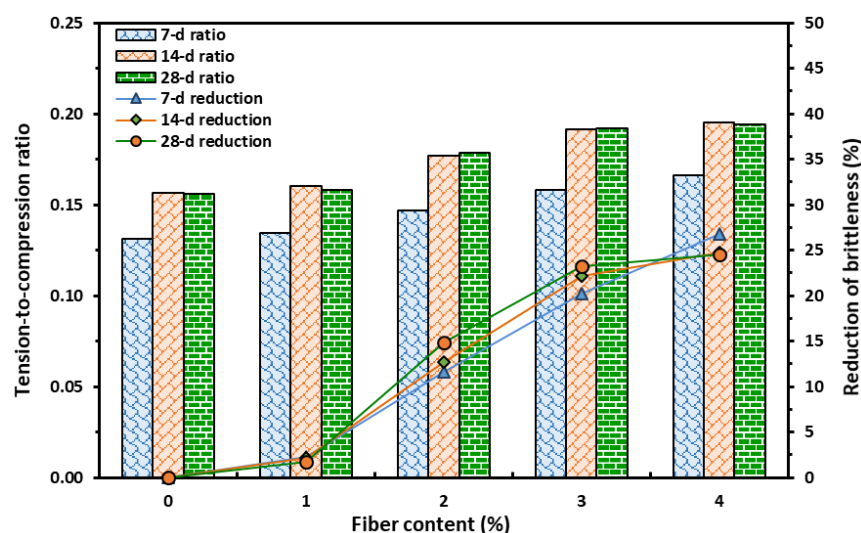


Figure 11. Effect of varying concentrations of areca fiber on the brittleness of concrete.

The graphical representation implies the augmentation of the tensile-to-compressive ratio with an increase in fiber concentration. The tension-to-compression ratio (f_{sp}/f'_c) exhibited a continuous upward trend as the fiber dosage was heightened, peaking at 4% of fiber concentration. Subsequently, for the strength tests conducted at 7 days, reductions in brittleness were observed, measuring 2.25%, 11.66%, 20.26%, and 26.79% at fiber concentra-

tions of 1%, 2%, 3%, and 4%, respectively. Similarly, for the corresponding 14 and 28-day strength tests, the reductions were recorded at 2.16%, 12.74%, 22.15%, and 24.74%, as well as 1.69%, 14.84%, 23.20%, and 24.57%, respectively. As previously documented in Figure 7, the compressive strength displayed an increase up to a fiber dosage of 2%, beyond which it experienced a decline, reaching levels even lower than the control mixture. Conversely, the split tensile strength exhibited an upward trend up to the same dosage level, followed by a decrease. This pattern mirrored the outcomes of the compressive strength test, although the split tensile strength remained higher than that of the control mixture, as evident in Figure 9. The same trend is also apparent in Figure 11, with a progressive increment in the tension-to-compression ratio. The substantial rise in the tension-to-compression ratio suggests a reduced likelihood of catastrophic failures for these cement-based materials, which serves as a significant factor when considering the utilization of areca husk fiber in concrete mixtures, provided that the strength requirements are met.

3.2.6. Relationship between Compressive Strength and Splitting Tensile Strength

The splitting tensile strength can be calculated from the compressive strength value using different standards. For example, ACI 318, ACI 363R, CEB-FIP, and AS 3600 suggest using Equations (2)–(5), respectively, to compute the splitting tensile strength from the compressive strength [65–68].

$$f_{sp} = 0.56\sqrt{f_c} \quad (2)$$

$$f_{sp} = 0.59\sqrt{f_c} \quad (3)$$

$$f_{sp} = 0.3(f_c)^{2/3} \quad (4)$$

$$f_{sp} = 0.4\sqrt{f_c} \quad (5)$$

where f_c = compressive strength (MPa) and f_{sp} = splitting tensile strength (MPa)

Figure 12 illustrates the relationship between the splitting tensile strength and compressive strength of the fiber-reinforced concrete test results and analytical computation using various fiber densities for 7, 14, and 28 days. The experimental data, 95% confidence intervals, and calculated splitting tensile strength by the aforementioned code-suggested formulas are plotted in this two-axis graph to establish the relationship. Best-fitted exponential curves are shown for experimental values and 95% confidence intervals.

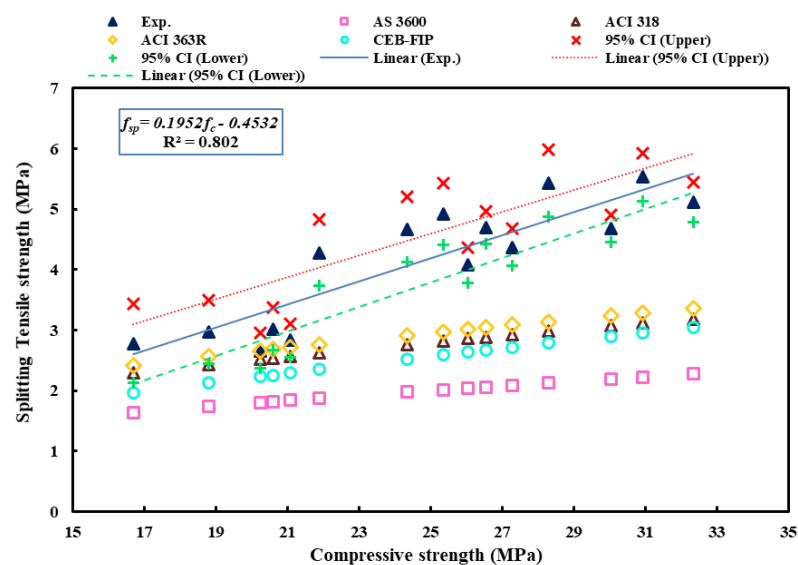


Figure 12. Relation between compressive and splitting tensile strength as per experimental data and code standards.

As shown in Figure 12, the correlation between experimental compressive and tensile strength results is quite linear, and the results exhibit a high degree of concurrence as they match the calculated strength suggested by different standards. However, the experimental values of splitting tensile strengths were closest to ACI 363R recommendations. Therefore, the following Equation (6) is proposed using the best-fitted exponential curve to compute the tensile strength of fiber-reinforced concrete once the compressive strength is known, or vice versa.

$$f_{sp} = 0.1952f_c - 0.4532, R^2 = 0.802 \quad (6)$$

where f_c = compressive strength (MPa) and f_{sp} = splitting tensile strength (MPa)

3.3. Micro-Structural Characterization of Hardened Concrete

3.3.1. Scanning Electron Microscopy (SEM)

The SEM photographs presented in Figure 13 showed that adequate interfacial bonds between the cement matrix and fiber were present. This is a pivotal detail in ensuring the mechanical strength and durability of AFRC mixes, as it helps to transfer stress between the matrix and the fiber. This finding indicates that the AFRC mix has good interfacial bonding and can resist crack propagation, which aligns with the mechanical properties test results obtained in this study. Without interfacial bonding, the fibers may slip out of the matrix, leading to a reduction in strength [69]. In addition, shrinkage cracks were observed in the conventional concrete specimens but not in the AFRC mix samples, which are visually depicted in Figure 13a,b. This suggests that shrinkage cracking, a prevalent issue in concrete constructions, can be lessened by including areca fibers in the concrete mix, which serve as reinforcement, keeping the concrete from breaking as it shrinks during the drying process. Fibers can also help distribute the shrinkage stresses uniformly throughout the composite, thus reducing the risk of early crack formation and propagation [70].

It was observed that the binding material bonded similarly to both the aggregate and the fiber. The effective transmission of stress between the matrix and the coarse aggregates is ensured by proper bonding between the binding material and the aggregate, increasing the composite's ability to carry more load. Similar to this, an adequate connection between the binding substance and the fiber guarantees that the fibers are spread evenly throughout the composite, offering strength and avoiding fracture development, which was also reflected in the observed crack patterns after compression and tension failure, as reported earlier in Figures 8 and 10. A key element in maintaining the mechanical strength and longevity of the AFRC mix is the binding material's compatibility with the aggregate and the fiber, which was observed in the SEM scans. No major pore was observed in the AFRC mixes along the fiber-cement bonding face, which is desirable in concrete structures. However, a ruptured fiber was observed in Figure 13b, which can occur due to the stress received during the cutting or polishing of specimens.

3.3.2. Energy-Dispersive X-ray Spectroscopy (EDX)

EDX was conducted for AFRC0, AFRC2, and AFRC4, which revealed the elemental composition of the composites, and the outcomes are graphically presented in Figure 14. The tabulated mass and atomic percentages for these concrete specimens are shown in Table 6. In comparison to AFRC0, AFRC2 appears to have had a sufficient pozzolanic reaction and coordinated influences, as suggested by its slightly greater silica content [71]. Pozzolanic reactions happen when calcium hydroxide (CH) reacts with silica-rich materials (i.e., sand aggregate) in the presence of water to generate calcium silicate hydrate (C-S-H) gel. By suffusing the pores and spaces in the matrix, the C-S-H gel helps concrete retain its strength and durability.

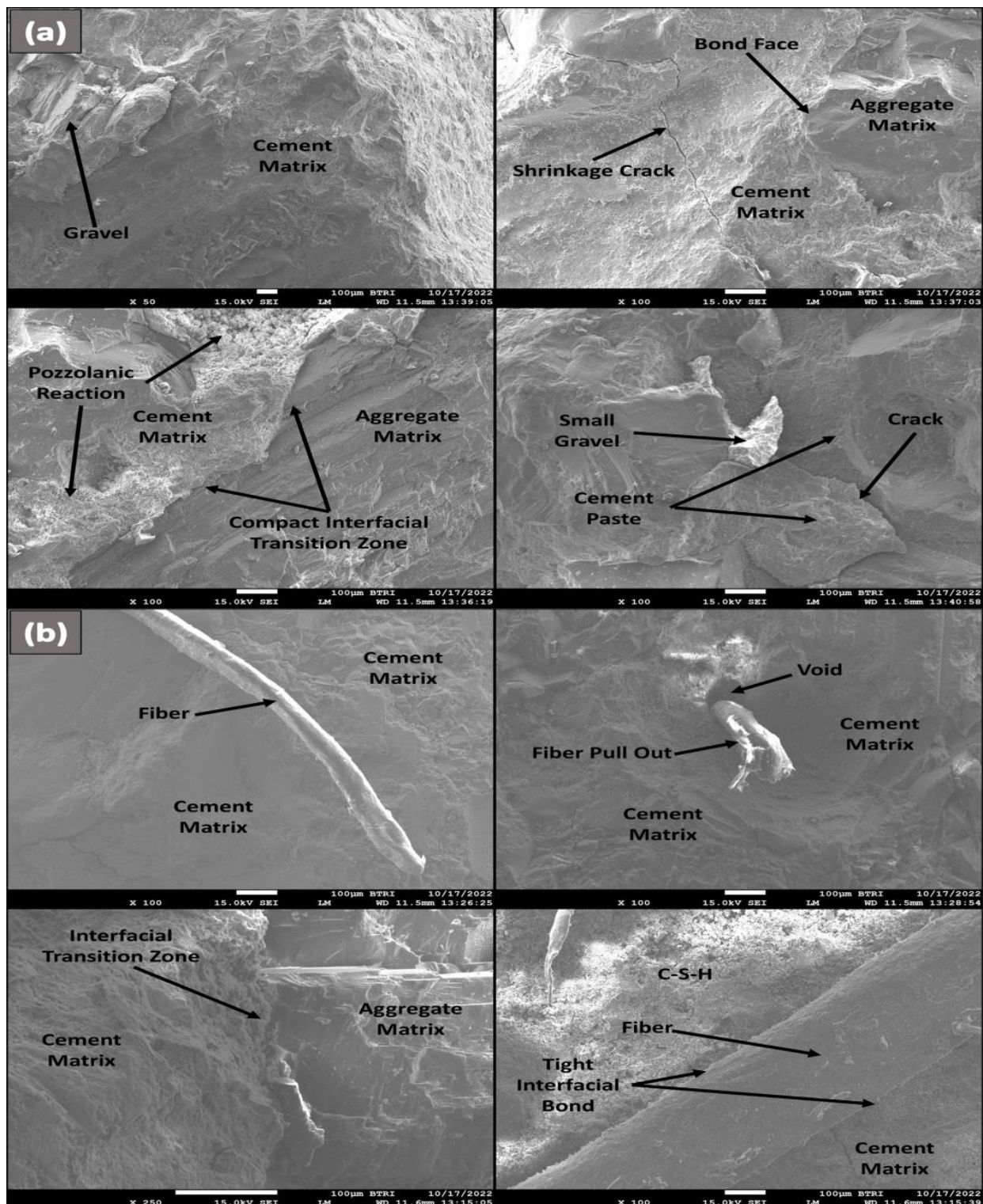


Figure 13. SEM scans of (a) control concrete and (b) areca fiber-reinforced concrete.

The EDX test findings showed that the pozzolanic reaction, which is a crucial process for enhancing the mechanical performance of AFRC mixes, was effective in the AFRC2 mix. This finding is also in line with the mechanical strength test results for AFRC2, as it produced the best results. Additionally, areca fiber-reinforced concrete's (AFRC2 and AFRC4) atomic Ca:Si ratios, as well as the control mix's (AFRC0), were calculated. The Ca:Si ratios of AFRC0, AFRC2, and AFRC4 were 1.13, 0.84, and 1.60, respectively. The increase in

macro-level strength qualities was mirrored in the decrease in this value for AFRC2. On the other hand, the increment in this value for AFRC4 was also reflected as the strength of this mix was lower than the control concrete specimen (AFRC0). The conversion of CH (calcium hydroxide) to secondary C-S-H (calcium silicate hydrate) is the primary reason for the decrease in the Ca:Si ratio of C-S-H. This response results in the creation of secondary C-S-H, which enhances the strength and permeability by reducing overall porosity and fine-tuning the porous structure [72]. The dense micro-structure seen in the micrograph results from the siloxy bridges (Si-O-Si) chains created by the AFRC's SiO₂ concentration, which reduce the gaps in the C-S-H gel and securely connect the particles [73]. These findings indicate that AFRC2 has improved mechanical properties compared to the AFRC0 and AFRC4 mixes. The reduction in micro-crack width could be due to the denser micro-structure of AFRC2, which reduces the propagation of cracks and enhances the overall strength of the composite, as it was also noticed by examining the crack patterns during mechanical strength tests.

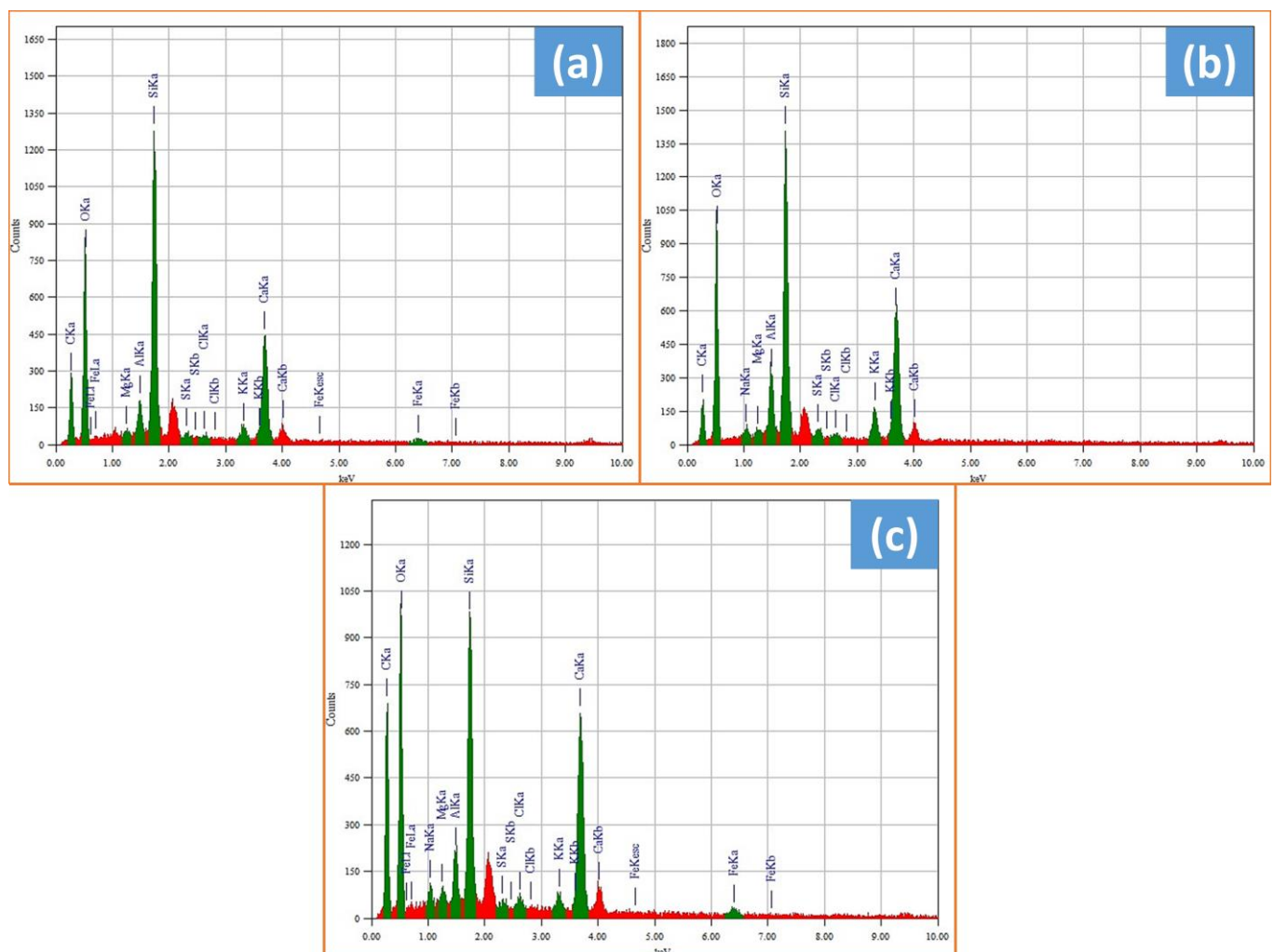


Figure 14. EDX analysis of (a) AFRC0, (b) AFRC2, and (c) AFRC4.

The EDX test reports showed that the control concrete (AFRC0) contained carbon of 14.18% mass of the target area, while AFRC2 and AFRC4, respectively, contained 23.36% and 31.80%. This rise in the amount of carbon can be ascribed to the fact that natural composites, such as areca fiber, contain more carbon than conventional concrete materials. As areca fiber is a carbon composite, the higher fiber concentration in the AFRC mixes resulted in more carbon mass compared to the lower fiber concentration in the control concrete.

Additionally, areca fiber is biodegradable, which means that the increased carbon in the AFRC mixes is also biodegradable, which does not negatively impact the environment. This is in contrast to conventional concrete, which contains non-biodegradable carbon elements from its cement constituents. However, it is of significance to acknowledge that the mechanical properties of composite materials are affected by several factors, and further research would be required to establish a direct correlation between the carbon content and the mechanical properties of AFRC mixes.

Table 6. Elemental composition of AFRC0, AFRC2, and AFRC4.

Element	AFRC0		AFRC2		AFRC4	
	Mass (%)	Atom (%)	Mass (%)	Atom (%)	Mass (%)	Atom (%)
C	14.18	22.37	23.36	34.38	31.80	44.21
O	46.35	54.88	43.18	47.71	40.38	42.15
Na	0.60	0.49	-	-	0.88	0.64
Mg	0.28	0.22	0.35	0.26	0.37	0.26
Al	3.03	2.13	1.54	1.01	1.49	0.92
Si	14.58	9.83	14.99	9.44	8.31	4.94
S	0.90	0.53	0.55	0.30	0.41	0.21
Cl	0.23	0.13	0.23	0.11	0.53	0.25
K	3.32	1.61	1.56	0.71	0.95	0.40
Ca	16.54	7.82	12.66	5.58	13.32	5.55
Fe	-	-	1.58	0.50	1.58	0.47
Total	100.00	100.00	100.00	100.00	100.00	100.00

3.4. Cost Analysis of Concrete Mixtures

The cost of concrete materials can vary from one marketplace to another. The considered unit costs of concrete materials for this study are shown in Table 7. In addition to calculating the cost of each mix owing to production and transportation expenses, the total cost of making per m³ volume of concrete was also calculated and reported in Table 7. All the costs are assessed in Bangladeshi Taka (103 BDT = 1 USD). The production and transportation unit cost breakdown for concrete materials was collected from previous research in conjunction with the latest data and context of the local marketplace [74]. The analysis revealed that the total cost for making concrete mix batches in this study ranges from 10,650 BDT to 10,798 BDT, where the maximum cost was exhibited by the control concrete (AFRC) and the minimum by the concrete mix having 4% areca fiber (AFRC4). It can be seen that the total cost per m³ of concrete can be reduced by almost 1.5% with the inclusion of areca fiber. As the areca fiber that was used to substitute cement was an agricultural waste and was collected locally, it does not have any production or transportation costs, which decreases the fabrication cost of concrete.

Table 7. Cost of per m³ concrete mixture.

Unit Cost				Concrete Mix ID	Mixture Cost (BDT/m³)				Total
Material	Cost (BDT/kg)				Cement	NCA	FA	Water	
	Production	Transportation	Total						
Cement	9	0.34	9.34	AFRC0	3689	5181	1912	16	10,798
NCA	5	0.26	5.26	AFRC1	3652	5181	1912	15	10,761
FA	2.17	0.22	2.39	AFRC2	3616	5181	1912	15	10,724
Water	0.088	-	0.088	AFRC3	3579	5181	1912	15	10,687
				AFRC4	3542	5181	1912	15	10,650

Furthermore, for a comprehensive assessment of cost-effectiveness, it is crucial to incorporate the expenditures associated with attaining 1 MPa of strength for each combination. The cost index of the mixtures, which represents the cost to achieve a 1 MPa compressive

strength at 28 days, is presented in Figure 15 alongside the corresponding reduction percentages. In comparison to the control mixture with a cost index of 359 BDT/MPa, the inclusion of 1% areca fiber resulted in the lowest cost index of 332 BDT/MPa, signifying an approximate 8% reduction in the cost index. Similarly, the incorporation of 2% fiber yielded a 4% decrease in the cost index. However, the addition of 3% and 4% fiber escalated the cost index by 5% and 17%, respectively. This observation stems from the fact that, despite the decline in the cost of concrete mixtures, the compressive strength experienced a more significant reduction. This, in turn, increased the cost of 1 MPa compressive strength for 3% and 4% fiber addition.

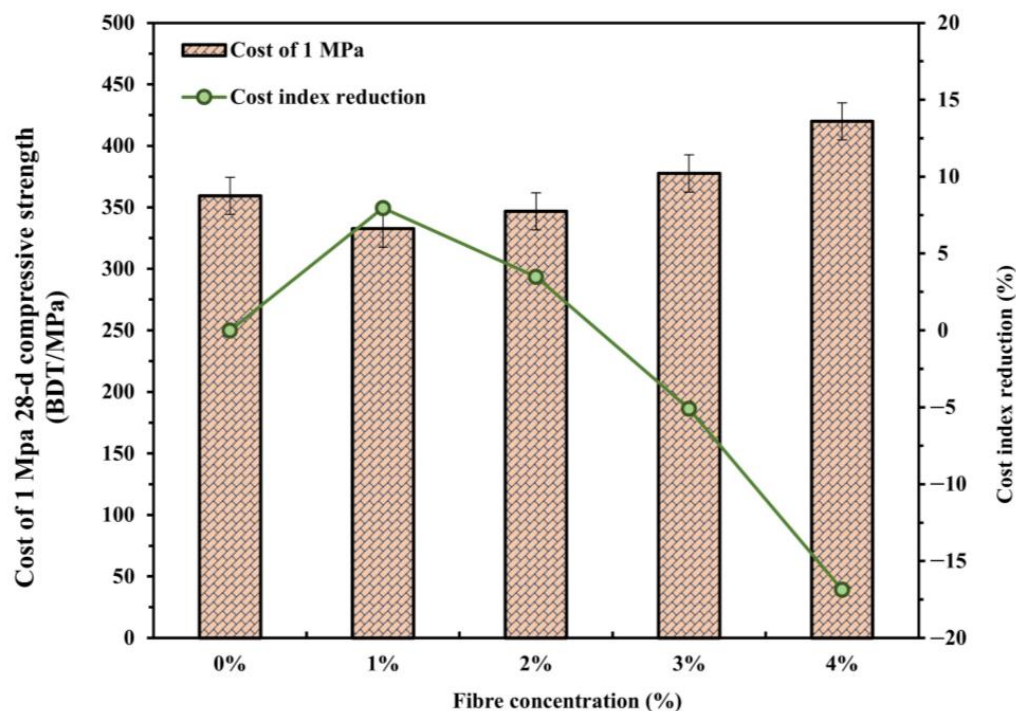


Figure 15. Cost index of concrete specimens with respect to compressive strength.

3.5. Equivalent CO₂ Assessment for Concrete Mixtures

The material embodied energy and eCO₂ emissions during the production and transportation of cement and coarse aggregate were collected from Hammond et al. [75]⁽¹⁾. Moreover, the eCO₂ emissions during production and transportation for fine aggregate and water were collected from Datta et al. [76]⁽²⁾, and Bostanci [77]⁽³⁾, respectively, and are shown in Table 8. The production and transportation of eCO₂ emissions from concrete materials were collected from previous research in conjunction with the latest date and context of Bangladesh standards [74]^(*).

Table 8. eCO₂ emissions of concrete materials.

Material Name	Material Embodied Energy (MJ/kg)	eCO ₂ Emission (kg CO ₂ /kg)		
		Production	Transportation	Total
Cement	5.5 ⁽¹⁾	0.95 ⁽¹⁾	0.021 *	0.971
Coarse aggregate	0.083 ⁽¹⁾	0.005 ⁽¹⁾	0.021 *	0.026
Fine aggregate	0.08 ⁽²⁾	0.0048 ⁽²⁾	0.16 *	0.1648
Water	0.0009 ⁽³⁾	0.00155 ⁽³⁾	-	0.00155

Table 9 represents the eCO₂ emissions per m³ volume of concrete during production, transportation, and their total. The equivalent CO₂ emission for concrete mixes ranged

from 525.92 kg CO₂/m³ to 541.27 kg CO₂/m³ concrete, where the maximum amount was reflected by the conventional concrete mix (AFRC0). On the other hand, AFRC4 concrete mix with 4% areca fiber emitted the minimum amount of CO₂. The replacement of cement by the inclusion of natural areca fiber reduced the amount of CO₂ in concrete mixes, as cement is the most carbon-emitting material of conventional concrete. These overall reductions in carbon dioxide emissions were in the range of 0.7% to almost 3% for fiber concentrations of 1% to 4%.

Table 9. eCO₂ emission per m³ concrete mixes.

Concrete Mix Id	eCO ₂ Emission (kg CO ₂ /m ³ Concrete)			Percentage of CO ₂ Emission	
	Production	Transportation	Total	Production (%)	Transportation (%)
AFRC0	384.29	156.98	541.27	71	29
AFRC1	380.53	156.90	537.43	70.81	29.19
AFRC2	376.78	156.81	533.59	70.61	29.39
AFRC3	373.03	156.73	529.76	70.41	29.59
AFRC4	369.27	156.65	525.92	70.21	29.79

The assessment of environmental impact may involve considering the eco-strength efficiency of concrete as an additional metric for evaluation. The concept of eco-strength efficiency, as mentioned by Alnahhal et al. [78] and referred to as CO₂ intensity by Damineli et al. [79], pertains to the amount of CO₂ emissions generated per unit of performance. The calculation of this parameter was derived using Equation (7).

$$C_i = \frac{CO_2}{C_s} \quad (7)$$

where C_i represents the eco-strength efficiency, which denotes the intensity of CO₂ emissions, CO₂ refers to the embodied carbon dioxide emissions released by the concrete mixes, as determined through the data provided in Table 8. Lastly, C_s represents the compressive strength attained by the mix after 28 days.

To ensure a methodical and consistent comparison of the mixtures, the eco-strength efficiency of various combinations is correlated with their respective compressive strengths. The findings of this analysis are visually represented in Figure 16, wherein the bar chart depicts the compressive strength values at the 28-day mark, while the CO₂ intensity is graphically displayed as a line on the secondary axis. CO₂ intensity serves as a reliable indicator for evaluating the environmental impact of concrete utilization by assessing both the efficacy and the role of concrete mixes in contributing to global warming potential, making it an essential factor for consideration [79]. In the majority of cases, an increase in the quantity of Portland cement in the concrete mixture correlates with an elevation in CO₂ concentration [80]. However, by partially substituting cement with areca fiber, it becomes possible to reduce the CO₂ intensity while maintaining the desired strength level. For instance, with the inclusion of 1% areca fiber, a noticeable reduction in the emission of 1 MPa strength was observed. With the values decreasing from 18.01 kg CO₂/MPa to 16.62 kg CO₂/MPa, an almost 8% reduction in the carbon intensity was noted by the AFRC1 mix. A similar outcome was also seen in a 2% fiber-added mix, where the reduction was more than 4%. However, as the fiber concentration increased further, the eCO₂ intensity increased up to 20.74 kg CO₂/MPa. Due to the concrete mixes with 3% and 4% fiber concentration exhibiting significantly lower compressive strength values, as reported in Table 4, the carbon intensity was increased as a result.

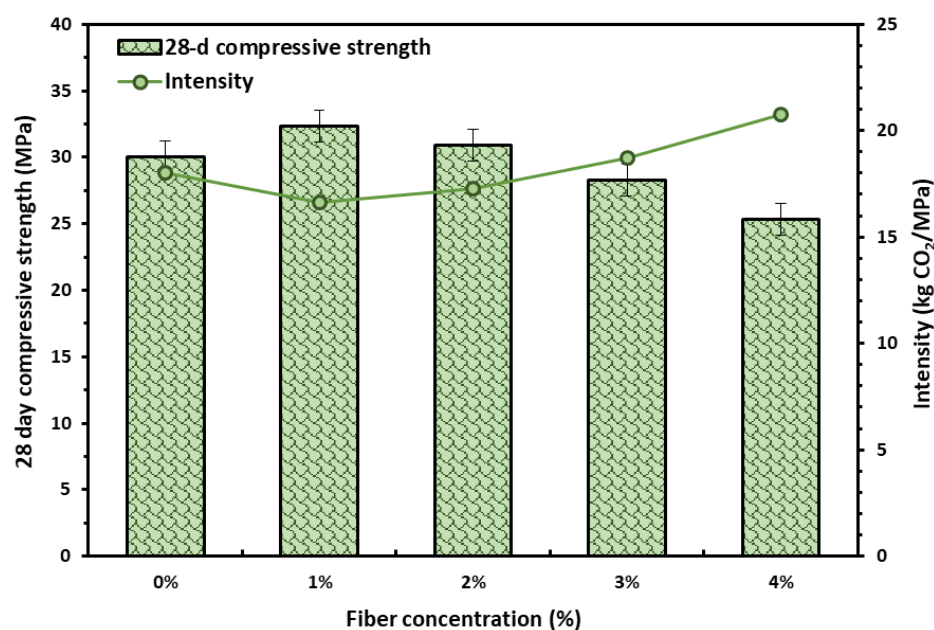


Figure 16. Eco-strength efficiency with respect to compressive strength.

4. Conclusions and Recommendations

The rheological, mechanical, and micro-structure characteristics of control concrete and AFRC specimens with various areca fiber concentrations were investigated experimentally. The major findings and observations that can be made on the basis of the experimental and analytical data obtained in this study are as follows:

- The workability of concrete decreases with the use of areca husk fiber, and by using 2% fiber, concrete with medium workability can be produced. Additionally, areca fiber can reduce the density and increase the yield stress of fresh concrete.
- By using areca fiber up to 2%, the compressive strength of concrete can be slightly enhanced to a degree of 3% to 8%. Further increments in fiber concentration decrease compressive strength due to fiber balling effects, irregularities in fiber distribution, and increased voids.
- In terms of splitting tensile strength, reinforcing concrete with waste areca husk fiber at a 2% dosage can substantially increase the splitting tensile strength by up to 18%. Interlocked fiber bridging of cement and areca fiber increased the splitting tensile strength.
- Observed crack patterns after the compressive and splitting tensile failures revealed that the control mix showed poor performance after the failure in load bearing. In contrast, the fiber-reinforced concrete mixes showed better post-cracking performances. The higher concentration of areca fiber increased the post-cracking ductile response by exhibiting a lesser crack width, more distributed cracks, and no cracks in a single defined plane of the axis.
- The inclusion of fiber reduced the cost and carbon emissions of concrete mixtures. Among all the mix combinations considered, the incorporation of areca fiber as a partial substitute for cement at an optimum dosage of up to 2% exhibited the best outcomes in terms of cost index and carbon intensity, with reductions ranging from almost 4% to 8%.
- SEM analysis showed adequate interfacial bonding between the fiber and cement matrix, while EDX results showed that the Ca:Si ratio was reduced by the incorporation of areca fiber, which proves the proper reaction between Ca and Si. The conversion of CH to secondary C-S-H is the primary reason for the decrease in the Ca:Si ratio of C-S-H.

- Based on all the experiments and analysis, this study suggests that the most suitable areca husk fiber concentration, which replaces 2% of the cement content by weight, offers optimal results in terms of concrete's performance.

This research revealed several notable advantages when compared to the control and subsequent AFRC mixes, including a significant improvement in splitting tensile strength, comparable compressive strength, reduced CO₂ intensity and cost index, and a reasonable enhancement in crack control properties. However, it is important to note that areca fiber is a natural material that may undergo decay over time due to the alkaline solution present in the concrete structure's pores. Thus, future research should focus on investigating the long-term durability of this fiber. Further studies should consider different treatment methods, such as NaOH, SiH₄, KOH, and KMnO₄, as well as varying treatment durations, such as 2 h, 24 h, and 72 h, since different treatments could yield varying outcomes. Furthermore, it is recommended to investigate the impact of areca husk fiber on flexural strength to gain a more comprehensive understanding of its performance in concrete structures. By examining these factors, a deeper insight into the material's behavior can be obtained.

Author Contributions: N.M.S.H. conceptualization and supervision, methodology, validation, formal analysis, investigation, visualization, project administration, resources, writing—original draft, writing—review and editing; N.M.N.S. methodology, validation, formal analysis, investigation, visualization, writing—original draft, writing—review and editing; M.H.R.S. formal analysis, investigation, writing—review and editing; M.M.M. formal analysis, investigation, writing—review and editing; M.A.B. formal analysis, visualization, writing—review and editing; S.C.P. formal analysis, resources, writing—review and editing; M.J.M. formal analysis, visualization, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting these findings are available within the article.

Acknowledgments: The authors would like to thank the technical staff of the Structural and Material Engineering (SME) Laboratory, Department of Civil Engineering, International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh, for their helpful assistance during casting and testing. This study received no specific funding from public, commercial, or not-for-profit funding agencies. The authors would like to pay gratitude towards Mohammad Nyme Uddin and Shuvo Dip Datta for their helpful contributions. The authors also gratefully acknowledged the efforts of Mahabubur Rahman Sakil and Hasibur Rashid for their assistance during the collection of research data and conducting experimental work as part of their research project/thesis.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Monteiro, P.J.M.; Miller, S.A.; Horvath, A. Towards sustainable concrete. *Nat. Mater.* **2017**, *16*, 698–699. [[CrossRef](#)]
2. Hegde, A. *Ready Mix Concrete Market Worth 624.82 Billion USD by 2025*; Market Study Report: Selbyville, DE, USA, 2018.
3. Bentur, A.; Mindess, S. *Fibre Reinforced Cementitious Composites*; Taylor & Francis: London, UK, 2007.
4. Shcherban', E.M.; Stel'makh, S.A.; Beskopylny, A.N.; Mailyan, L.R.; Meskhi, B.; Shilov, A.A.; Chernil'nik, A.; Özkılıç, Y.O.; Aksoylu, C. Normal-Weight Concrete with Improved Stress–Strain Characteristics Reinforced with Dispersed Coconut Fibers. *Appl. Sci.* **2022**, *12*, 11734. [[CrossRef](#)]
5. Zhang, P.; Wang, C.; Gao, Z.; Wang, F. A review on fracture properties of steel fiber reinforced concrete. *J. Build. Eng.* **2023**, *67*, 105975. [[CrossRef](#)]
6. Zhang, C.; Zhu, Z.; Wang, S.; Zhang, J. Macro-micro mechanical properties and reinforcement mechanism of alkali-resistant glass fiber-reinforced concrete under alkaline environments. *Constr. Build. Mater.* **2023**, *368*, 130365. [[CrossRef](#)]
7. Zhang, Q.; Yang, Q.-C.; Li, W.-J.; Gu, X.-L.; Dai, H.-H. Study on model of flexure response of carbon fiber textile reinforced concrete (CTRC) sheets with short AR-glass fibers. *Case Stud. Constr. Mater.* **2023**, *18*, e01791. [[CrossRef](#)]
8. Aksoylu, C.; Özkılıç, Y.O.; Hadzima-Nyarko, M.; Işık, E.; Arslan, M.H. Investigation on Improvement in Shear Performance of Reinforced-Concrete Beams Produced with Recycled Steel Wires from Waste Tires. *Sustainability* **2022**, *14*, 13360. [[CrossRef](#)]

9. Yıldız, S.A.; Özkılıç, Y.O.; Bahrami, A.; Aksoylu, C.; Başaran, B.; Hakamy, A.; Arslan, M.H. Experimental investigation and analytical prediction of flexural behaviour of reinforced concrete beams with steel fibres extracted from waste tyres. *Case Stud. Constr. Mater.* **2023**, *19*, e02227. [[CrossRef](#)]
10. Zeybek, Ö.; Özkılıç, Y.O.; Çelik, A.İ.; Deifalla, A.F.; Ahmad, M.; Sabri, M.M.S. Performance evaluation of fiber-reinforced concrete produced with steel fibers extracted from waste tire. *Front. Mater.* **2022**, *9*, 1057128. [[CrossRef](#)]
11. Shen, D.; Liu, C.; Luo, Y.; Shao, H.; Zhou, X.; Bai, S. Early-age autogenous shrinkage, tensile creep, and restrained cracking behavior of ultra-high-performance concrete incorporating polypropylene fibers. *Cem. Concr. Compos.* **2023**, *138*, 104948. [[CrossRef](#)]
12. Ashraf, M.J.; Idrees, M.; Akbar, A. Performance of silica fume slurry treated recycled aggregate concrete reinforced with carbon fibers. *J. Build. Eng.* **2023**, *66*, 105892. [[CrossRef](#)]
13. Çelik, A.İ.; Özkılıç, Y.O.; Zeybek, Ö.; Özdöner, N.; Tayeh, B.A. Performance Assessment of Fiber-Reinforced Concrete Produced with Waste Lathe Fibers. *Sustainability* **2022**, *14*, 11817. [[CrossRef](#)]
14. Karalar, M.; Özkılıç, Y.O.; Deifalla, A.F.; Aksoylu, C.; Arslan, M.H.; Ahmad, M.; Sabri, M.M.S. Improvement in Bending Performance of Reinforced Concrete Beams Produced with Waste Lathe Scraps. *Sustainability* **2022**, *14*, 12660. [[CrossRef](#)]
15. Wang, L.; Guo, F.; Yang, H.; Wang, Y.; Tang, S. Comparison of fly ash, PVA fiber, MgO and shrinkage-reducing admixture on the frost resistance of face slab concrete via pore structural and fractal analysis. *Fractals* **2021**, *29*, 2140002. [[CrossRef](#)]
16. Wang, L.; Zeng, X.; Li, Y.; Yang, H.; Tang, S. Influences of MgO and PVA Fiber on the Abrasion and Cracking Resistance, Pore Structure and Fractal Features of Hydraulic Concrete. *Fractal Fract.* **2022**, *6*, 674. [[CrossRef](#)]
17. Beskopylny, A.N.; Shcherban', E.M.; Stel'makh, S.A.; Meskhi, B.; Shilov, A.A.; Varavka, V.; Evtushenko, A.; Özkılıç, Y.O.; Aksoylu, C.; Karalar, M. Composition Component Influence on Concrete Properties with the Additive of Rubber Tree Seed Shells. *Appl. Sci.* **2022**, *12*, 11744. [[CrossRef](#)]
18. Mathavan, M.; Sakthieswaran, N.; Ganesh Babu, O. Experimental investigation on strength and properties of natural fibre reinforced cement mortar. *Mater. Today Proc.* **2021**, *37*, 1066–1070. [[CrossRef](#)]
19. Vijayan, D.; Rajmohan, T. Influence of Fiber Content on Tensile and Flexural Properties of Ramie/Areca Fiber Composite—An Algorithmic Approach Using Firefly Algorithm. In *Bio-Fiber Reinforced Composite Materials: Mechanical, Thermal and Tribological Properties*; Palanikumar, K., Thiagarajan, R., Latha, B., Eds.; Springer Nature: Singapore, 2022; pp. 235–252.
20. Aishwarya, K.P.; Muralidhar, N.; Praveen, J.V. Study on areca nut husk fine fiber fabric reinforced composites panels under dynamic loading conditions. *Mater. Today: Proc.* **2022**, *66*, 633–641. [[CrossRef](#)]
21. Loganathan, T.M.; Sultan, M.T.H.; Jawaid, M.; Md Shah, A.U.; Ahsan, Q.; Mariapan, M.; Majid, M.S.b.A. Physical, Thermal and Mechanical Properties of Areca Fibre Reinforced Polymer Composites—An Overview. *J. Bionic Eng.* **2020**, *17*, 185–205. [[CrossRef](#)]
22. Banagar, A.; Chikkol, S.V.; Bennehalli, B. Studies on physical and mechanical properties of untreated (raw) and treated areca leaf sheaths. *Mater. Res. Innov.* **2021**, *25*, 404–411. [[CrossRef](#)]
23. Ashok, R.B.; Srinivasa, C.V.; Basavaraju, B. A review on the mechanical properties of areca fiber reinforced composites. *Sci. Tecnol. Mater.* **2018**, *30*, 120–130. [[CrossRef](#)]
24. Divakar, L.; Babu, A.P.V.; Chethan Gowda, R.K.; Nithin Kumar, S. Experimental Study on Mechanical Properties of Areca Nut Fibre-Reinforced Self-compacting Concrete. In *Green Buildings and Sustainable Engineering*; Springer: Singapore, 2020; pp. 313–321.
25. Makunza, J.K. Application of Areca Palm Fibers as Strength Enhancement in Conventional Concrete. *Adv. Mater. Res.* **2022**, *1168*, 11–22. [[CrossRef](#)]
26. Srinivasa, C.V.; Arifulla, A.; Goutham, N.; Santhosh, T.; Jaethendra, H.J.; Ravikumar, R.B.; Anil, S.G.; Santhosh Kumar, D.G.; Ashish, J. Static bending and impact behaviour of areca fibers composites. *Mater. Des.* **2011**, *32*, 2469–2475. [[CrossRef](#)]
27. Castillo-Lara, J.; Flores-Johnson, E.; Valadez, A.; Herrera-Franco, P.; Carrillo, J.; Gonzalez-Chi, P.; Li, Q. Mechanical Properties of Natural Fiber Reinforced Foamed Concrete. *Materials* **2020**, *13*, 3060. [[CrossRef](#)] [[PubMed](#)]
28. Jamshaid, H.; Mishra, R.K.; Raza, A.; Hussain, U.; Rahman, M.L.; Nazari, S.; Chandan, V.; Muller, M.; Choteborsky, R. Natural Cellulosic Fiber Reinforced Concrete: Influence of Fiber Type and Loading Percentage on Mechanical and Water Absorption Performance. *Materials* **2022**, *15*, 874. [[CrossRef](#)] [[PubMed](#)]
29. Das, S.; Sobuz, M.H.R.; Tam, V.W.Y.; Akid, A.S.M.; Sutan, N.M.; Rahman, F.M.M. Effects of incorporating hybrid fibres on rheological and mechanical properties of fibre reinforced concrete. *Constr. Build. Mater.* **2020**, *262*, 120561. [[CrossRef](#)]
30. Vinh, S.; Hussain, Q.; Joyklad, P.; Chaimahawan, P.; Rattanapitikon, W.; Limkatanyu, S.; Pimanmas, A. Strengthening effect of natural fiber reinforced polymer composites (NFRP) on concrete. *Case Stud. Constr. Mater.* **2021**, *15*, e00653. [[CrossRef](#)]
31. Zhao, C.; Yi, Z.; Wu, W.; Zhu, Z.; Peng, Y.; Liu, J. Experimental Study on the Mechanical Properties and Durability of High-Content Hybrid Fiber-Polymer Concrete. *Materials* **2021**, *14*, 6234. [[CrossRef](#)] [[PubMed](#)]
32. Zaid, O.; Ahmad, J.; Siddique, M.S.; Aslam, F.; Alabduljabbar, H.; Khedher, K.M. A step towards sustainable glass fiber reinforced concrete utilizing silica fume and waste coconut shell aggregate. *Sci. Rep.* **2021**, *11*, 12822. [[CrossRef](#)] [[PubMed](#)]
33. Walbrück, K.; Maeting, F.; Witzleben, S.; Stephan, D. Natural Fiber-Stabilized Geopolymer Foams-A Review. *Materials* **2020**, *13*, 3198. [[CrossRef](#)]
34. Ellis, L.D.; Badel, A.F.; Chiang, M.L.; Park, R.J.; Chiang, Y.M. Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating CaCO₃ while producing useful gas streams. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 12584–12591. [[CrossRef](#)] [[PubMed](#)]

35. Hasan, N.M.S.; Sobuz, M.H.R.; Shaurdho, N.M.N.; Basit, M.A.; Paul, S.C.; Meraz, M.M.; Saha, A.; Miah, M.J. Investigation of Lightweight and Green Concrete Characteristics Using Coconut Shell Aggregate as a Replacement for Conventional Aggregates. *Int. J. Civ. Eng.* **2023**. [CrossRef]
36. Tridge. Overview of Areca Nut Market in Bangladesh. Available online: <https://www.tridge.com/intelligences/areca-nut/BD> (accessed on 8 December 2022).
37. Jena, B.; Patra, R.K.; Mukharjee, B.B. Influence of incorporation of jute fibre and ferrochrome slag on properties of concrete. *Aust. J. Civ. Eng.* **2022**, *20*, 13–30. [CrossRef]
38. Srivastava, V.; Mehta, P.; Nath, S. Natural Fiber in Cement and Concrete Matrices—A Review. *J. Environ. Nanotechnol.* **2014**, *2*, 62–65. [CrossRef]
39. Malkawi, A.B.; Habib, M.; Aladwan, J.; Alzubi, Y. Engineering properties of fibre reinforced lightweight geopolymer concrete using palm oil biowastes. *Aust. J. Civ. Eng.* **2020**, *18*, 82–92. [CrossRef]
40. ASTM-C150; Standard Specification for Portland Cement. ASTM International: West Conshohocken, PA, USA, 2020.
41. BS EN 197; Cement: Composition, Specifications and Conformity Criteria for Common Cements. British Standards Institution: London, UK, 2011.
42. BDS EN-197; Cement—Part 1: Composition, Specification and Conformity Criteria for Common Cements. Bangladesh Standards and Testing Institution: Dhaka, Bangladesh, 2010.
43. ASTM-C33; Standard Specification for Concrete Aggregates. ASTM International: West Conshohocken, PA, USA, 2018.
44. ASTM-C192; Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. ASTM International: West Conshohocken, PA, USA, 2019.
45. ASTM-C143; Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM International: West Conshohocken, PA, USA, 2015.
46. ASTM-C138; Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. ASTM International: West Conshohocken, PA, USA, 2017.
47. Hu, C.; de Larrard, F.; Sedran, T.; Boulay, C.; Bosc, F.; Deflorenne, F. Validation of BTRHEOM, the new rheometer for soft-to-fluid concrete. *Mater. Struct.* **1996**, *29*, 620–631. [CrossRef]
48. ASTM-C39; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2020.
49. ASTM-C496; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2017.
50. ASTM-C1723; Standard Guide for Examination of Hardened Concrete Using Scanning Electron Microscopy. ASTM International: West Conshohocken, PA, USA, 2010.
51. Islam, S.M.; Hussain, R.R.; Morshed, M.A.Z. Fiber-reinforced concrete incorporating locally available natural fibers in normal- and high-strength concrete and a performance analysis with steel fiber-reinforced composite concrete. *J. Compos. Mater.* **2012**, *46*, 111–122. [CrossRef]
52. Khan, M.M.H.; Sobuz, M.H.R.; Meraz, M.M.; Tam, V.W.Y.; Hasan, N.M.S.; Shaurdho, N.M.N. Effect of various powder content on the properties of sustainable self-compacting concrete. *Case Stud. Constr. Mater.* **2023**, *19*, e02274. [CrossRef]
53. Miah, M.J.; Li, Y.; Paul, S.C.; Babafemi, A.J.; Jang, J.G. Mechanical strength, shrinkage, and porosity of mortar reinforced with areca nut husk fibers. *Constr. Build. Mater.* **2023**, *363*, 129688. [CrossRef]
54. Tattersall, G.; Banfill, P. *The Rheology of Fresh Concrete*; Pitman: London, UK, 1983; p. 356.
55. Ahmad, J.; Arbili, M.M.; Majdi, A.; Althoe, F.; Farouk Deifalla, A.; Rahmawati, C. Performance of concrete reinforced with jute fibers (natural fibers): A review. *J. Eng. Fibers Fabr.* **2022**, *17*, 15589250221121871. [CrossRef]
56. Miah, M.J.; Pei, J.; Kim, H.; Sharma, R.; Jang, J.G.; Ahn, J. Property assessment of an eco-friendly mortar reinforced with recycled mask fiber derived from COVID-19 single-use face masks. *J. Build. Eng.* **2023**, *66*, 105885. [CrossRef]
57. Yusof, M.A.; Nor, N.M.; Fauzi, M.; Zain, M.; Ismail, A.; Sohaimi, R.M.; Mujahid, A.Z.A.; Zaidi, A.M.A. Mechanical Properties of Hybrid Steel Fibre Reinforced Concrete with Different Aspect Ratio. *Aust. J. Basic Appl. Sci.* **2011**, *5*, 159–166.
58. Kachouh, N.; El-Hassan, H.; El-Maaddawy, T. Influence of steel fibers on the flexural performance of concrete incorporating recycled concrete aggregates and dune sand. *J. Sustain. Cem.-Based Mater.* **2021**, *10*, 165–192. [CrossRef]
59. Savastano, H.; Santos, S.F.; Radonjic, M.; Soboyejo, W.O. Fracture and fatigue of natural fiber-reinforced cementitious composites. *Cem. Concr. Compos.* **2009**, *31*, 232–243. [CrossRef]
60. Yusra, A.; Triwulan, T.; Safriani, M.; Ikhsan, M. Use of bamboo fiber on the relationship between compressive strength and split tensile strength of high strength concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *933*, 012010. [CrossRef]
61. Gao, D.; Wang, F. Effects of recycled fine aggregate and steel fiber on compressive and splitting tensile properties of concrete. *J. Build. Eng.* **2021**, *44*, 102631. [CrossRef]
62. Lumingkewas, R.H.; Husen, A.; Andrianus, R. Effect of Fibers Length and Fibers Content on the Splitting Tensile Strength of Coconut Fibers Reinforced Concrete Composites. *Key Eng. Mater.* **2017**, *748*, 311–315. [CrossRef]
63. Boulekbache, B.; Hamrat, M.; Chemrouk, M.; Amziane, S. Failure mechanism of fibre reinforced concrete under splitting test using digital image correlation. *Mater. Struct.* **2015**, *48*, 2713–2726. [CrossRef]
64. Tran, N.P.; Gunasekara, C.; Law, D.W.; Houshyar, S.; Setunge, S.; Cwirzen, A. Comprehensive review on sustainable fiber reinforced concrete incorporating recycled textile waste. *J. Sustain. Cem.-Based Mater.* **2022**, *11*, 28–42. [CrossRef]

65. ACI Committee-318. *Building Code Requirements for Structural Concrete (ACI 318-99) and Commentary (318R-99)*; American Concrete Institute: Farmington Hills, MI, USA, 1999.
66. ACI Committee-363. *State-of-the Art Report on High Strength Concrete (ACI 363R-92)*; American Concrete Institute: Farmington Hills, MI, USA, 1992.
67. Béton, C.E.-I.d. *CEB-FIP Model Code 1990: Design Code*; Thomas Telford Ltd.: London, UK, 1990.
68. AS-3600; AS 3600: Australian Standard for Concrete Structures. Standards Association of Australia: Sydney, Australia, 2001.
69. Paglia, C.; Antonietti, S.; Caroselli, M.; Corredig, G. Steel fibre-cement matrix interaction in a ultra high-strength concrete: An investigation at the microstructural level. In *Proceedings of the Bond in Concrete—Bond, Anchorage, Detailing: 5th International Conference*, Stuttgart, Germany, 25–27 July 2022.
70. Aly, T.; Sanjayan, J.; Collins, F. Effect of polypropylene fibers on shrinkage and cracking of concretes. *Mater. Struct.* **2014**, *41*, 1741–1753. [\[CrossRef\]](#)
71. Kannan, V.; Ganesan, K. Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin. *Constr. Build. Mater.* **2014**, *51*, 225–234. [\[CrossRef\]](#)
72. Poon, C.S.; Kou, S.C.; Lam, L. Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. *Constr. Build. Mater.* **2006**, *20*, 858–865. [\[CrossRef\]](#)
73. Hasan, N.M.S.; Sobuz, M.H.R.; Khan, M.M.H.; Mim, N.J.; Meraz, M.M.; Datta, S.D.; Rana, M.J.; Saha, A.; Akid, A.S.M.; Mehedi, M.T.; et al. Integration of Rice Husk Ash as Supplementary Cementitious Material in the Production of Sustainable High-Strength Concrete. *Materials* **2022**, *15*, 8171. [\[CrossRef\]](#)
74. Sobuz, M.H.R.; Datta, S.D.; Akid, A.S.M.; Tam, V.W.Y.; Islam, S.; Rana, M.J.; Aslani, F.; Yalçinkaya, Ç.; Sutan, N.M. Evaluating the effects of recycled concrete aggregate size and concentration on properties of high-strength sustainable concrete. *J. King Saud Univ. Eng. Sci.* **2022**, *in press*. [\[CrossRef\]](#)
75. Hammond, G.; Jones, C.; Lowrie, E.F.; Tse, P. *Embodied Carbon. The Inventory of Carbon and Energy (ICE), Version (2.0)*; BSRIA Limited: Bracknell, Berkshire, UK, 2011.
76. Datta, S.D.; Rana, M.J.; Assafi, M.N.; Mim, N.J.; Ahmed, S. Investigation on the generation of construction wastes in Bangladesh. *Int. J. Constr. Manag.* **2022**, *23*, 2260–2269. [\[CrossRef\]](#)
77. Bostanci, S.C. Use of waste marble dust and recycled glass for sustainable concrete production. *J. Clean. Prod.* **2020**, *251*, 119785. [\[CrossRef\]](#)
78. Alnahhal, M.F.; Alengaram, U.J.; Jumaat, M.Z.; Abutaha, F.; Alqedra, M.A.; Nayaka, R.R. Assessment on engineering properties and CO₂ emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement. *J. Clean. Prod.* **2018**, *203*, 822–835. [\[CrossRef\]](#)
79. Damineli, B.L.; Kemeid, F.M.; Aguiar, P.S.; John, V.M. Measuring the eco-efficiency of cement use. *Cem. Concr. Compos.* **2010**, *32*, 555–562. [\[CrossRef\]](#)
80. Hasan, N.M.S.; Shaurdho, N.M.N.; Sobuz, M.H.R.; Meraz, M.M.; Islam, M.S.; Miah, M.J. Utilization of Waste Glass Cullet as Partial Substitutions of Coarse Aggregate to Produce Eco-Friendly Concrete: Role of Metakaolin as Cement Replacement. *Sustainability* **2023**, *15*, 11254. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.