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Effect of Coconut Fiber and Wood Chips on the Physical, Mechanical, and Durability Properties of M21 Concrete

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Abstract The study focused on evaluating the behavior of concrete under sulfate attack in coastal or industrial regions, where concrete is exposed to sulfate solutions that may compromise the durability and safety of structures. Therefore, the objective of this study was to investigate how coconut fibers (CF) influence the physical, mechanical, and durability properties of M21 concrete, incorporating an optimal dosage of wood chips (WC). A total of nine mixtures were analyzed, including a reference mixture designed to meet a minimum compressive strength requirement of 210 kg/cm². The study used WC dosages ranging from 5% to 20% and CF dosages ranging from 1% to 8%, replacing the weight of fine aggregate and addition by weight of cement, respectively. Neither material underwent chemical treatment. In the mixture containing 10% WC and 1% CF, workability improved by 33.33%, unit weight increased by 5.46%, and temperature variation was minimal. Mechanical properties also improved at 28 days, with a 5.09% increase in compressive strength, a 16.97% increase in elastic modulus, a 15.02% increase in flexural strength, and an 11.54% increase in tensile strength. The hybrid combination of 10% WC and 1% CF demonstrated additional enhancements, particularly in flexural strength (23.99%) and tensile strength (20.09%). In terms of durability, the hybrid mixture reduced water absorption by 22.95%, while the mixture containing 10% WC and 5% CF exhibited only a minimal variation in sulfate resistance (0.03%). It was concluded that these combinations improve concrete performance; however, they cannot yet be applied to structural elements due to the need for further long-term studies.

Keywords Coconut Fiber, Wood Chips, Physical Properties, Mechanical Properties, Durability

1. Introduction

The construction industry is a major contributor to environmental degradation due to its high consumption of natural resources and waste generation. Construction activities worldwide generate approximately 635 million metric tons (MT) of waste annually, significantly impacting ecosystems and highlighting the urgency of adopting sustainable practices [1]. Improper disposal of these wastes leads to increased greenhouse gas emissions and depletion of natural resources [2]. The annual consumption of natural aggregates in the construction industry reaches 6,000 MT, contributing to their scarcity and ecosystem degradation [3]. Natural aggregates make up 75% of conventional concrete's volume, yet their overuse poses severe environmental and ecological challenges [4], [5], [6].

To address aggregate shortages, recycling construction and demolition waste has emerged as a viable alternative, given its availability and sustainability benefits [7], [8]. A proactive strategy to achieve sustainable growth in construction involves the adoption of eco-friendly, low-carbon, and energy-efficient materials [9]. One solution is the integration of organic waste, such as wood chips (WC) and coconut fiber (CF), into concrete as partial replacements for traditional components. This not only reduces landfill waste but also enhances the efficient use of natural resources, aligning with global sustainability goals [10].

The incorporation of organic fibers into cementitious materials enhances sustainability and biodegradability, making them attractive for construction applications [11], [12]. Global coconut production in 2020 reached 61.9 thousand MT, with Indonesia, India, the Philippines, Brazil, and Sri Lanka leading production [13]. CF improves mechanical properties, particularly in crack resistance and flexural strength, with optimal dosages around 3% [14]. Studies indicate that coconut shell fiber improves durability and mechanical strength, reinforcing its suitability for concrete applications [15], [16], [17], [18], [19], [20].

Wood waste also plays a crucial role in sustainable construction. The wood processing industry generates substantial waste, with 32.21% of total production classified as waste, of which 2% consists of usable wood chips [21]. Integrating WC into concrete increases ductility, although it may reduce compressive strength by up to 77% compared to conventional concrete [22]. However, WC as aggregate enhances mechanical performance, reduces shrinkage, and improves adhesion [23]. Additionally, studies suggest that recycled wood-based concrete could reduce CO_2 emissions by 31.3%, offering economic and environmental advantages [24], [25].

Both wood chips and coconut fiber have been incorporated into various construction applications, including mortars [26], concrete [27], [28], and soil stabilization [29], [30], [31], due to their enhanced durability and mechanical properties [32]. Coconut shell, known for its high strength and lignin content, is widely used in lightweight concrete [33]. Additionally, CF improves concrete's flexibility, enabling four to six times greater elongation, with 50 mm and 75 mm fibers significantly increasing compressive strength [34]. However, CF reduces fluidity, making it more effective for enhancing flexural rather than compressive strength [14].

Wood waste has also been used for concrete reinforcement and eco-friendly cementitious materials. While WC reduces concrete density, it enhances insulation properties and ductility, making it suitable for non-structural applications [35]. However, in sulfate-exposed environments, such as the Lambayeque region in Peru, the combination of WC and CF is necessary to balance mechanical performance and durability. Studies indicate that WC can improve sulfate resistance, whereas CF may increase sulfate vulnerability, necessitating a careful mix design to optimize performance [36], [37]. The use of both materials together could mitigate sulfate-related degradation, ensuring longer service life in aggressive environments such as coastal and sulfate-rich soil regions in Lambayeque, Peru.

Regarding workability, the impact of wood chips and coconut fiber on fresh concrete varies depending on dosage levels. Alharishawi et al. [38], reported a 4.85% improvement in workability with 5% WC substitution, while Khoshroo et al. [36] found a 2.05% reduction with 10% WC replacement. Similarly, Mütevelli et al. [39] observed a 2.1% decline when incorporating 25% WC, indicating that higher WC content negatively affects workability. Conversely, the addition of CF consistently reduced workability. Ramos [40] reported a 14.27% decrease with 2% CF incorporation, emphasizing its significant impact on fresh concrete properties. These findings suggest that although WC and CF enhance other performance aspects, their influence on workability must be carefully managed to prevent mixing and placement issues. Proper adjustments in water content, admixtures, or mixing techniques may be required to maintain an optimal balance between sustainability and workability.

The effect of wood chips on compressive strength varies depending on the substitution percentage. While some studies report improvements at higher dosages [41], others indicate reductions at lower or excessive replacement levels [38], [42]. For instance, a 20% WC replacement increased compressive strength by 18.9% [41], whereas 5% and 25% WC substitutions resulted in strength reductions of 32.15% and 33%, respectively [41], [42]. This discrepancy suggests that WC's impact is highly dosage-dependent, requiring optimization to balance performance and sustainability. Similarly, coconut fiber incorporation shows a non-linear effect on compressive strength. While Alomayri et al. [43] observed a 25% improvement with 0.25% CF, other studies found lower increases with higher CF dosages, such as 6.97% with 1% CF [44], and 4.91% with 0.5% CF [40]. These findings indicate that excessive CF content does not necessarily enhance strength, reinforcing the need for careful dosage selection.

The addition of WC negatively affects flexural, tensile, and elastic modulus properties, as demonstrated by Alharishawi et al. [38] and Dias et al. [42]. WC substitution led to reductions of 25.57% in flexural strength, 15.55% in tensile strength, and 43.37% in the modulus of elasticity [38], while a 25% WC replacement specifically lowered the modulus of elasticity by 18% [42]. These results suggest that while WC contributes to sustainability, it compromises stiffness and resistance to deformation. Conversely, CF incorporation significantly improved flexural and tensile strength. Studies reported a 30.5% increase in flexural strength and 33% in tensile strength with 0.25% CF [43], while higher CF dosages resulted in even greater flexural improvements, such as 79% with 0.5% CF [44]. These findings indicate that CF is a promising additive for improving specific mechanical properties, particularly flexural and tensile strength, at relatively low dosages.

Studies indicate that wood chips increase water absorption, making concrete more vulnerable to moisture damage. Días et al. [42] and Mütevelli et al. [39] reported that a 25% WC replacement increased absorption by 10% and 67.48%, respectively, while Khoshroo et al. [36] found a 16% increase with 15% WC. Conversely, coconut fiber produced mixed results; Alomayri et al. [43] observed a 1.6% absorption reduction with 0.25% CF, while Mboungou et al. [37] found a 20% increase at the same dosage, highlighting the need for further study on CF's influence on permeability. Regarding sulfate resistance, Khoshroo et al. [36] found a 13.4% increase with 25% WC, whereas Mboungou et al. [37] and Sivakumaresa and Rymond [45] reported CF-related sulfate resistance reductions of 21.42% and 5.5%, respectively, reinforcing the need to optimize dosages and chemical compatibility for durability improvements.

One of the main research gaps in concrete technology is the influence of coconut fiber (CF) and wood chips (WC) on physical, mechanical, and durability properties, particularly regarding unit weight, temperature regulation, and flexural and tensile strength. Additionally, limited research exists on concrete's sulfate resistance when incorporating WC and CF, leaving uncertainties about its short-term performance. This study aims to evaluate the effect of WC and CF on concrete properties, analyzing WC proportions of 5%, 10%, 15%, and 20% to determine its optimal content before integrating CF in percentages of 1%, 3%, 5%, and 8%. The goal is to identify a viable and sustainable alternative for construction, improving durability without relying on chemical additives.

A key novelty of this research is its eco-friendly approach to enhancing sulfate resistance, replacing traditional chemical admixtures with organic materials. WC and CF contribute to reducing water absorption, a critical factor in limiting sulfate reactions that cause structural expansion and deterioration. Additionally, these materials provide internal reinforcement, improving compressive, flexural, and tensile strength while preventing microcracking. Unlike chemical additives, which can weaken concrete over time or pose environmental risks, WC and CF offer an economical, biodegradable, and sustainable solution. This aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry and Innovation), SDG 11 (Sustainable Cities), and SDG 12 (Responsible Consumption), promoting the use of organic waste in construction to reduce the carbon footprint and enhance material durability.

2. Materials and Methods

2.1. Materials

2.1.1. Aggregates, Cement and Water

For this study, aggregates were sourced from the "*Tres Tomas*" quarry in the province of Ferreñafe, Lambayeque, Peru. The fine aggregate was sieved through a No. 4 sieve, while the coarse aggregate had a nominal size of 19 mm. Both aggregates comply with the ASTM C136 standard [46]. Their physical characteristics are summarized in Table 1, and their particle size distribution is illustrated in Figure 1.

Additionally, Type I Portland cement, commonly used in commercial applications, was utilized. It has a density of 3.15 g/cm³. The water used in the concrete mixtures met the requirements of ASTM C1602 [47].

Table 1. Properties of aggregates

Characteristics	Fine Aggregate	Coarse Aggregate	ASTM Standard
Fineness modulus	2.78	-	ASTM C136 [46]
Loose dry unit weight (kg/m^3)	1536	1474	ASTM C29 [48]
Compacted dry unit weight (kg/m^3)	1762	1688	ASTM C29 [48]
Specific gravity	2.63	2.56	ASTM C128 [49]
Absorption capacity (%)	1.55	1.16	ASTM C127 [50]
Moisture content (%)	0.68	0.21	ASTM C566 [51]

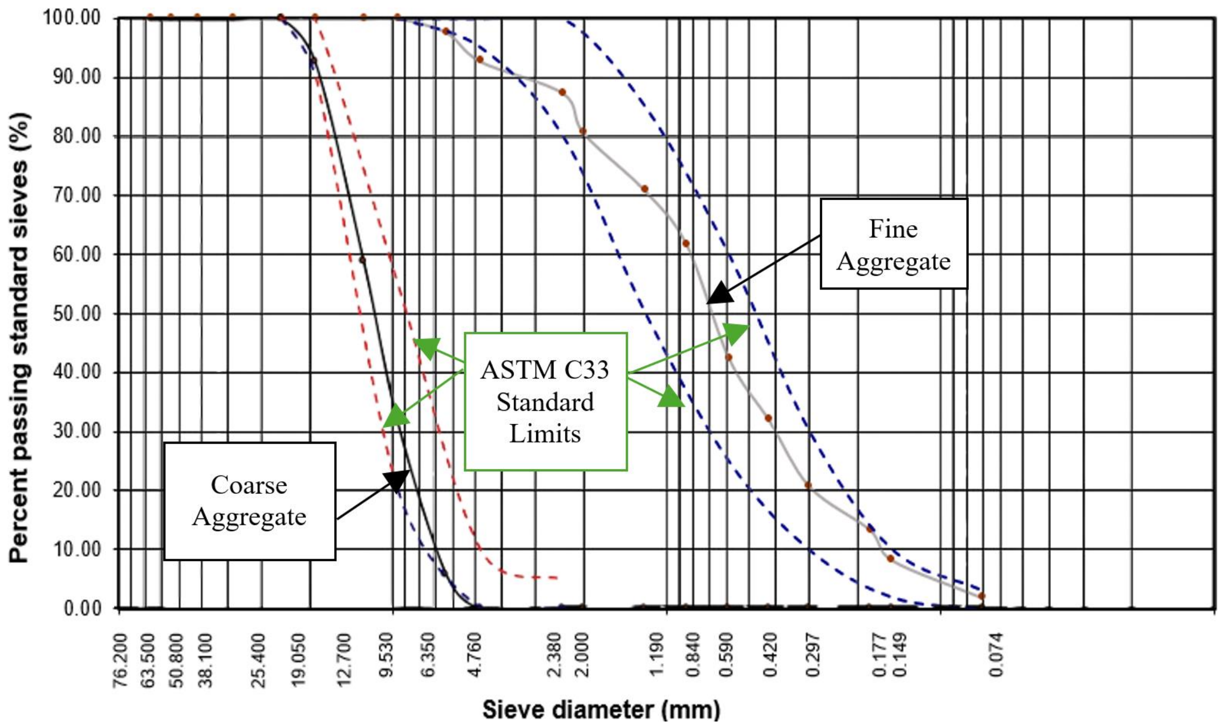

Figure 1. Particle size distribution of aggregate

2.1.2. Wood Chips

Wood waste, in the form of chips, is collected from various industries, including wood processing and furniture manufacturing. Specifically, the wood chips are sourced from a local sawmill in Chiclayo, Peru. The type of wood used is *Cedrelinga cateniformis* (commonly known in Peru as "Tornillo"). The wood chips undergo a screening process using a square hole sieve. Larger particles are separated using a sieve with 16 mm square holes, and the fraction that does not pass through the 2.36 mm sieve is selected. Figure 2 displays the selected wood chips. The physical properties of these chips are outlined in Table 2.

An X-ray fluorescence (XRF) analysis was performed to determine the chemical composition of the sample. This technique enables the identification of chemical elements with atomic numbers (Z) equal to or greater than 13 (such as aluminum) by measuring the characteristic X-rays emitted by the atoms in the sample. The results of the analysis are detailed in Table 3, along with the illustrative diagram shown in Figure 3.

Figure 2. Wood chips used

Table 2. Physical Properties of the WC

Description	Result
Specific gravity	13.85
Absorption (%)	1.60

Table 3. Chemical Properties of WC

Components	Concentration (% mass)
C (Carbon)	52.759
K (Potassium)	25.861
Fe (Iron)	4.283
Mg (Magnesium)	7.315
Na (Sodium)	2.200
Al (Aluminum)	2.177
S (Sulfur)	1.571
Si (Silicon)	1.180
Mn (Manganese)	1.084
Zn (Zinc)	0.570
Mo (Molybdenum)	0.346
Rb (Rubidium)	0.204
Cu (Copper)	0.144
Hg (Mercury)	0.077
Pb (Lead)	0.055
V (Vanadium)	0.047
Br (Bromine)	0.030
Ni (Nickel)	0.029
As (Arsenic)	0.026
Zr (Zirconium)	0.023
He (Helium)	0.019
Total	100.00

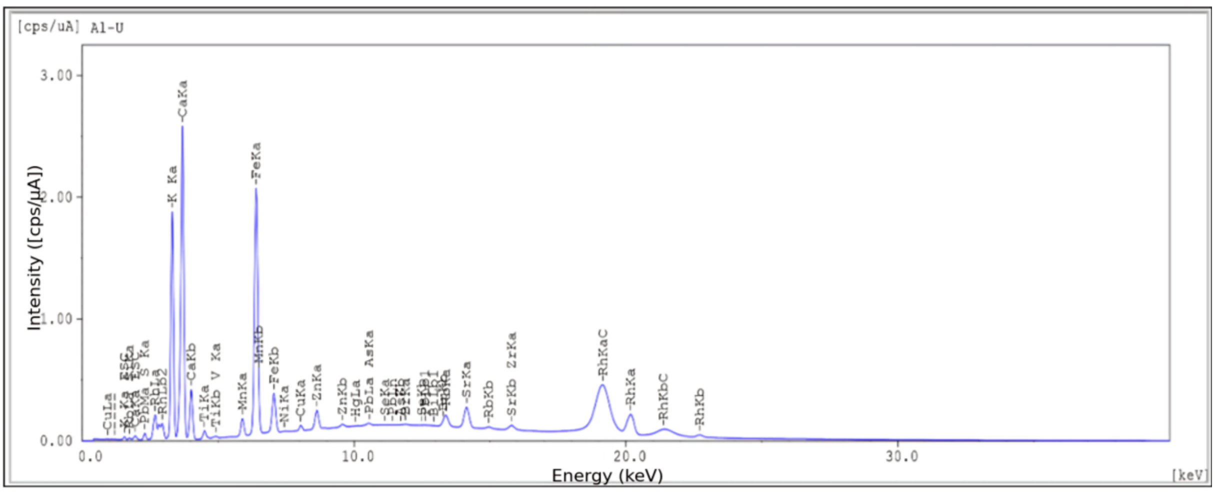

Figure 3. XRF Energy Plot of WC Analysis

2.1.3. Coconut Fiber

The fibers of the coconut fruit (*Cocos nucifera*), specifically from the "dwarf coconut" variety, were collected from a local supplier in Chiclayo, Lambayeque, Peru. These fibers were obtained from coconuts harvested in the region, known for their high quality. The extraction process involved mechanically removing the outer husk through a technique called debarking. Once the husk was removed, the fibers were separated, cleaned, and then shredded into smaller pieces for use.

The raw coconut fibers had an average length of 20-30 cm and a diameter of approximately 0.5-1.5 mm. Initially, the moisture content of the fibers was found to be around 15-20%. After the fibers were processed and before being integrated into the concrete mix, the moisture content was reduced to about 10-12% to ensure optimal bonding with the cement.

Figure 4 shows the raw coconut fibers (a) and those shredded for use (b). The physical properties, including length, diameter, and moisture content, are provided in Table 4.

To determine the chemical composition of the sample, an X-ray fluorescence (XRF) analysis was performed. The results of the analysis are presented in Table 5, followed by the spectral diagram shown in Figure 5.

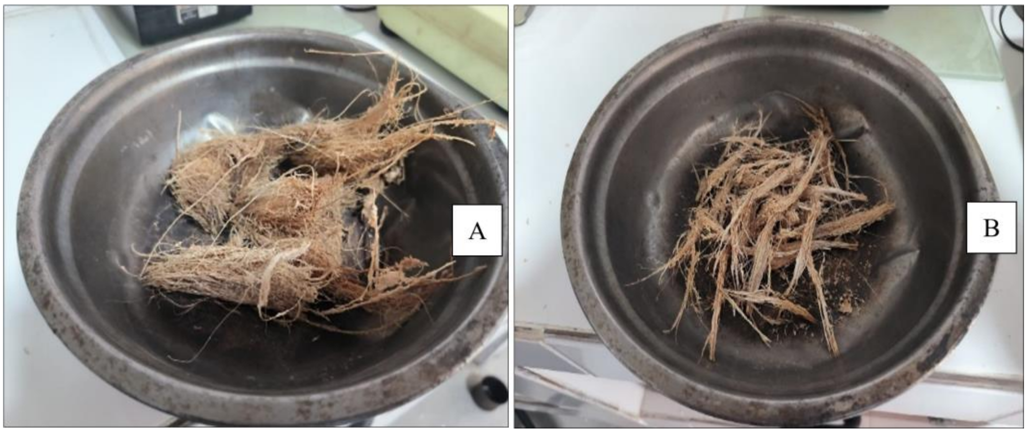

Figure 4. (a) Raw coconut fiber, (b) Coconut fiber used for the preparation of concrete

Table 4. Physical Properties of CF

Description	**Result**
Density (g/cm^3)	1.15
Length (mm)	25-65
Diameter (μm)	10-34
Tensile strength (MPa)	115

Table 5. Chemical Properties of CF

Components	**Concentration (% mass)**
Al (Aluminum)	36.295
K (Potassium)	25.840
C (Carbon)	11.714
Mg (Magnesium)	9.150
Cl (Chlorine)	9.874
P (Phosphorus)	1.368
Na (Sodium)	1.540
S (Sulfur)	0.764
Fe (Iron)	0.291
Mo (Molybdenum)	0.170
Br (Bromine)	0.107
Rb (Rubidium)	0.086
Zn (Zinc)	0.066
Cu (Copper)	0.052
Y (Yttrium)	0.051
As (Arsenic)	0.026
Lu (Lutetium)	0.012
Nd (Neodymium)	0.007
Ni (Nickel)	0.006
He (Helium)	0.003
Total	100.00

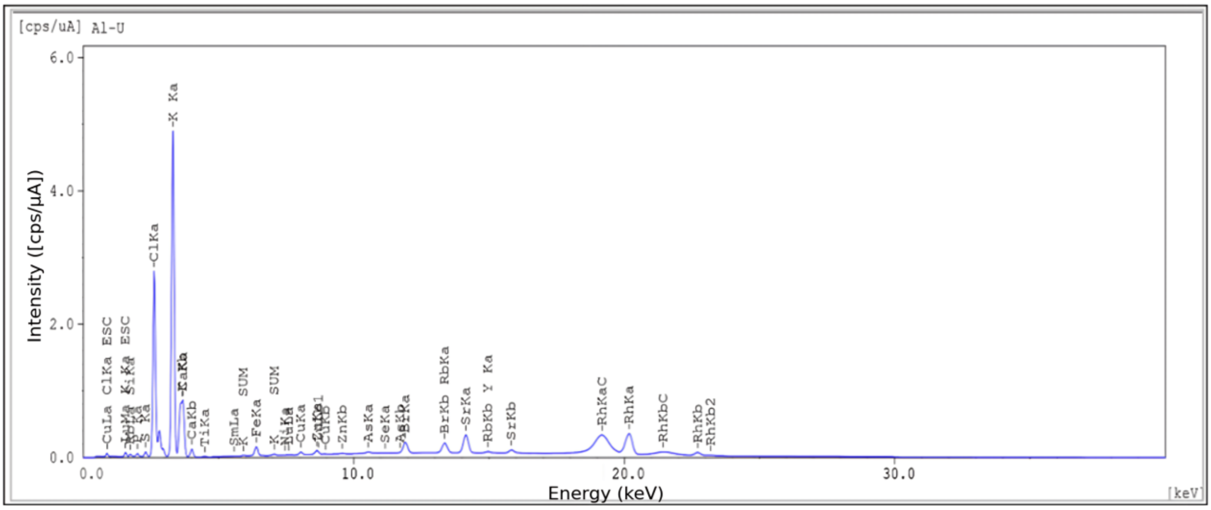

Figure 5. XRF Energy Plot of CF Analysis

The chemical components of untreated coconut fiber influence the properties of concrete. Carbon (C) at a concentration of 36.295% improves durability and strength, while potassium (K) at 25.840% can affect the stability of the concrete. Magnesium (Mg) at 9.150% and chlorine (Cl) at 9.874% may impact reactivity and corrosion resistance. Acetic acid (AC) at 11.714% can interfere with the adhesion between the fiber and the cement, while sodium (Na) at 1.540% and sulfur (S) at 0.764% can alter the hydration and expansion of the concrete.

2.2. Methods

As the first stage, a reference mix was designed to achieve a minimum required strength of 210 kg/cm², following the methodology established by ACI 211.1 [52]. The water/cement (w/c) ratio was set at 0.54, without the use of superplasticizers.

In the second stage, the mix design proportions were determined by incorporating wood chips (WC) in percentages of 5%, 10%, 15%, and 20%, replacing an equivalent weight of fine aggregate.

In the third stage, after determining the optimal WC dosage, coconut fiber (CF) was added in proportions of 1%, 3%, 5%, and 8%, based on the weight of the cement in the mix design. A total of nine mix designs were developed. The labels assigned to each mix design are presented in Table 6, while the specific quantities per cubic meter are detailed in Table 7.

The experimental mixtures were prepared using an electric mixer with a capacity of 180 liters, maintaining a mixing time of approximately 5 to 6 minutes while taking precautions to prevent material segregation. Subsequently, tests were conducted on fresh concrete, including slump, temperature, and density measurements, to analyze the effects with and without the incorporation of WC and CF.

Fresh concrete was poured into cylindrical molds with dimensions of 15 cm in diameter and 30 cm in height, as well as prismatic molds measuring (15 × 15 × 55) cm. After a 24-hour curing period, the specimens were demolded and immersed in potable water for a curing period of 28 days, totaling 168 concrete specimens. These specimens were tested to evaluate the compressive strength, modulus of elasticity, the tensile strength, and the flexural strength.

Finally, once the optimal WC percentage was established based on the hardened-state tests, in the third stage, the samples were evaluated with the addition of CF. The complete procedure is described in Figure 6.

Table 6. Concrete mixed labels

Mix ID	Description
D1	Referencial concrete
D2	Concrete with 5% WC
D3	Concrete with 10% WC
D4	Concrete with 15% WC
D5	Concrete with 20% WC
D6	Concrete optimal % WC and 1% CF
D7	Concrete optimal % WC and 3% CF
D8	Concrete optimal % WC and 5% CF
D9	Concrete optimal % WC and 8% CF

Table 7. Nomenclature and proportion of materials used in the concrete mix

Mix ID	w/c ratio	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (L)	WC (kg/m^3)	CF (kg/m^3)
D1	0.54	370.0	1002	729	183.1	-	-
D2	0.56	357.0	1002	740	183.1	18.5	0
D3	0.55	376.0	1002	662	187.8	37.0	0
D4	0.56	375.0	1002	649	192.8	55.5	0
D5	0.56	364.0	1002	722	187.2	74.0	0
D6	0.57	372.0	1002	701	193.3	37.0	3.70
D7	0.57	351.0	1062	686	182.5	37.0	11.1
D8	0.56	393.0	1022	636	203.3	37.0	18.5
D9	0.57	351.0	1062	686	182.5	37.0	29.6

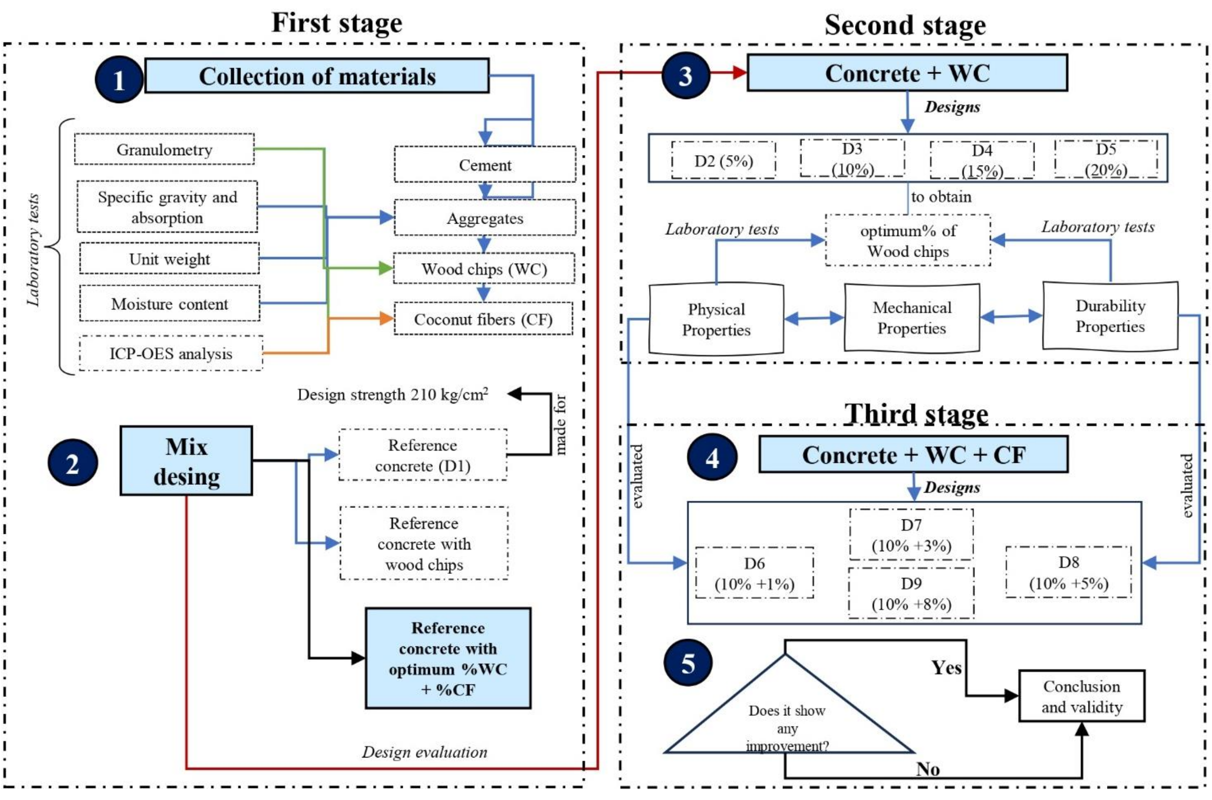

Figure 6. Process flow chart of the study

2.2.1. Physical Properties

Slump is a physical test performed on fresh concrete to evaluate the workability of the mixture. For this test, an Abrams cone was used, which was filled in three layers, each compacted with 25 strokes. The cone was then lifted, and the slump height was measured according to the parameters specified in ASTM C143 [53]. Additionally, unit weight and temperature tests were conducted following ASTM C138 [54] and ASTM C1064 [55] standards, respectively, using a Washington pot and a digital thermometer for each experimental test performed.

2.2.2. Mechanical Properties

Regarding the mechanical properties of the concrete, the compressive strength test was conducted following ASTM C39 [56], the modulus of elasticity according to ASTM C469 [57], and the tensile strength test as per ASTM C496 [58]. For these tests, cylindrical specimens with dimensions of 15 cm in diameter and 30 cm in height were used. The bending strength test, in accordance with ASTM C78 [59], was performed using beams measuring 15 x 15 x 55 cm (width x height x length). Each test involved breaking 3 samples to obtain the average value, with the tests conducted on a compression testing machine. The tests were performed after a curing period of 28 days, with an error variation of 2% and a maximum load capacity of 3000 kN, provided by the machine model "XYZ-3000."

2.2.3. Durability Properties

Water absorption of concrete is defined as the ratio of the mass of water absorbed to the mass of dry concrete, expressed as a percentage. This percentage indicates the rate of water absorption on both the external and internal surfaces of the concrete. After an initial 24-hour air-drying period, 100 mm edge cubes were demolded and immersed in water for 28 days to perform the water absorption test, following ASTM C642 [60]. The saturated weight of the dry cubes on the surface in air after immersion was recorded. The cubes were then subjected to a drying process in an oven at 105 ℃ for 72 hours to obtain their dry weight. Each concrete mixture was tested with three cubes, and the average value obtained was recorded as the water absorption value.

Sulfate resistance testing was performed according to ASTM C267 [61]. The test specimens were cured in water for 28 days. After this curing period, the cylinders were air-dried for 7 days, then weighed and immersed in a plastic container with a 2% sulfate (Na_2SO_4) solution for 28 days. After removal from the container with the sulfate solution, the specimens were washed with running water using a plastic brush and carefully dried with an absorbent cloth. They were then weighed again to calculate the percentage change in weight. The cubes were then subjected to compressive strength tests to determine the percentage change in this property. For each mixture, three specimens were tested, and the average value was calculated.

3. Results and Discussions

3.1. Workability, Unit Weight and Temperature

Table 8 presents the settlement results when incorporating wood chips and coconut fiber into fresh concrete. A notable observation is the overall good performance of the concrete across all tests, as all mixtures remained within the expected range for the settlement test. Specifically, mixtures D2, D4, D5, and D8 exhibited a positive variation of 33.33% in workability compared to the reference mix. This increase can be attributed to the modification of the internal structure of the mix, where WC and CF enhanced the material's ability to retain water, reducing early evaporation and improving plasticity. The high potassium (K) and magnesium (Mg) content in both materials (25.861% K in WC and 25.840% K in CF) may have played a role in improving workability, as these elements can influence water retention and ion exchange, stabilizing the hydration process. Similar improvements were reported by Alharishawi et al. [38], where a 4.85% increase in workability was observed with a 5% addition of WC.

Table 8. Slump test results, unit weight and temperature in fresh concrete

Mix ID	Slump (in)	Variation (%)	Unit Weight (kg/m^3)	Variation (%)	Temperature (℃)	Variation (%)
D1	3.00	-	2273.38	-	30	-
D2	4.00	33.33	2203.24	3.09	30	-
D3	3.00	-	2315.65	1.86	31	3.33
D4	4.00	33.33	2225.72	-2.10	30	-
D5	4.00	33.33	2385.79	4.94	32	6.67
D6	3.00	-	2397.48	5.46	29	-3.33
D7	3.00	-	2276.08	0.12	31	3.33
D8	4.00	33.33	2160.97	-4.94	29	-3.33
D9	3.00	-	2253.60	-0.87	31	3.33

Regarding unit weight, there was a notable density increase in mixture D6, which contained 10% WC + 1% CF, resulting in a 5.46% rise in unit weight. This suggests that, at this proportion, the interaction between WC and CF may have contributed to better compaction and particle distribution, filling voids within the mix and increasing material cohesion. The high concentration of carbon-based compounds (AC) in WC (52.759%) likely contributed to this effect by improving the particle bonding capacity, reducing segregation, and enhancing structural stability. Additionally, the presence of iron (Fe) and sodium (Na) in both materials (4.283% Fe in WC and 0.291% Fe in CF, as well as 2.200% Na in WC and 1.540% Na in CF) could have influenced the hydration reaction, indirectly affecting the density and homogeneity of the mix.

Conversely, a 4.94% reduction in density was recorded in the mixture containing 10% WC + 5% CF. This decrease can be explained by the higher proportion of CF, which has a lower density and higher porosity than the other components, thereby increasing air entrapment and reducing overall density. The chlorine (Cl) content in CF (9.874%) could have also influenced this behavior by affecting the binding characteristics of the cement paste, potentially reducing the overall mass per unit volume.

Additionally, the temperature test demonstrated that all mixtures maintained values comparable to standard concrete, suggesting that the incorporation of WC and CF does not significantly alter the thermal behavior of fresh concrete. This stability in temperature can be attributed to the insulating properties of WC and CF, which may prevent drastic temperature fluctuations during the hydration process. The high AC content in WC (52.759%) and the presence of sulfur (S) in both materials (1.571% in WC and 0.764% in CF) may have contributed to this insulation effect by reducing thermal conductivity within the mix.

3.2. Compressive Strength

The compressive strength test results in Figure 7 show the behavior of standard concrete with wood chips and coconut fiber after 28 days of curing. The reference sample (D1) had a compressive strength of 223.8 kg/cm ? The D3 mixture (10% WC) achieved the highest strength, improving by 5.09% compared to D1. Beyond 10% WC, strength did not increase, suggesting an optimal dosage at this level. The hybrid D6 mixture (10% WC + 1% CF) also improved strength by 3.89% over D1. The chemical composition of WC, particularly its high carbon content (52.759%), may contribute to better cement adhesion and matrix stability, while its iron (Fe) and magnesium (Mg) content (4.283% and 7.315%, respectively) could enhance hydration reactions, improving early-age strength. CF, with a high potassium (K) and chlorine (Cl) concentration (25.840% and 9.874%), might regulate moisture retention and pore distribution, reducing early-age shrinkage. However, exceeding 10% WC may increase porosity due to its lower density and higher organic content, weakening the matrix. While CF aids in crack control and compaction, its high porosity can lead to strength reduction at higher dosages. The results confirm that WC enhances compressive strength up to 10%, while CF provides secondary benefits, reinforcing durability rather than directly improving compressive strength.

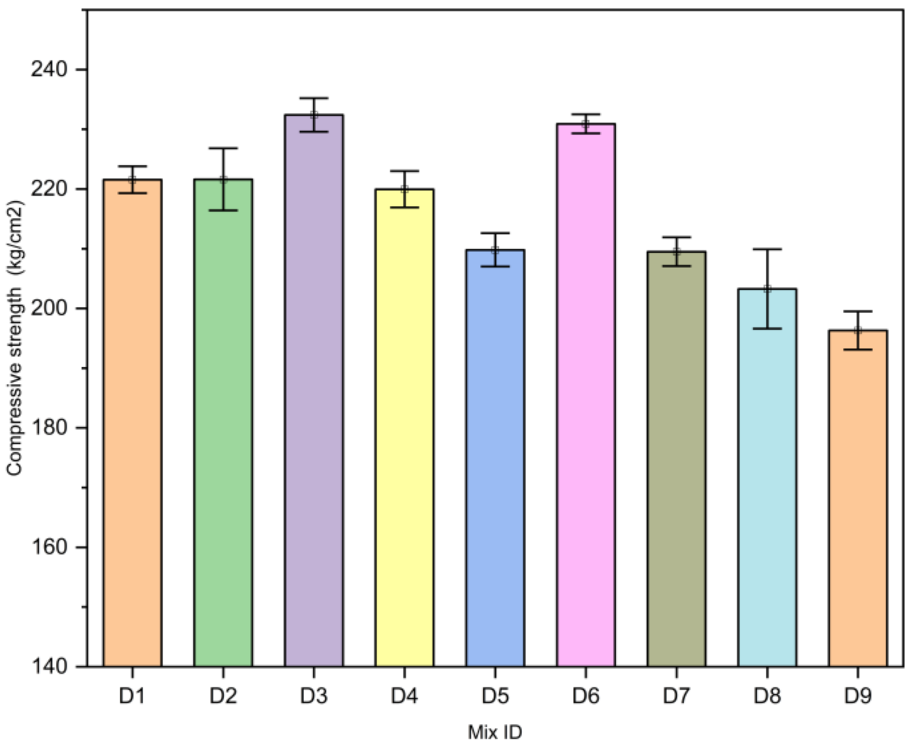

Figure 7. Results of the compressive strength of concrete at 28 days

Various investigations indicate that a significant improvement is observed in the compressive strength of concrete with the addition of wood chips. According to Zhang et al. [41], especially in the fraction of similar volumes used in this research. However, the need to determine the optimal dose of coconut fiber to balance the mechanical benefits is underlined [44].

3.3. Modulus of Elasticity

Figure 8 shows that the elastic modulus of mixture D1 after 28 days of curing was 218,109 kg/cm². With the addition of wood chips, mixture D3 (10% WC) exhibited the highest increase, improving by 16.97% compared to D1, establishing 10% WC as the optimal dosage for enhancing the elastic modulus. The hybrid mixture (10% WC + 1% CF), represented by D6, achieved a 19.49% increase, surpassing all other mixtures in stiffness.

This behavior aligns with the increase in compressive strength, as WC and CF contribute to material stiffness. The chemical composition of WC, particularly its high carbon (52.759%) and magnesium (Mg) content (7.315%), may have enhanced bonding within the cement matrix, improving load distribution. Additionally, iron (Fe) and sodium (Na) content (4.283% and 2.200%) could have reinforced the hydration process, leading to a denser and more compact structure. CF, rich in potassium (K) and chlorine (Cl) (25.840% and 9.874%), likely contributed to moisture retention and fiber-matrix interaction, reducing microcracks and increasing elasticity.

However, previous studies indicate that WC alone does not significantly improve the elastic modulus [38]. Similarly, research with comparable WC proportions showed no improvement in modulus elasticity [42]. In this study, the results suggest that WC and CF enhance adhesion between the cement matrix and aggregates, reducing microcracks and allowing the concrete to better resist deformation stresses, leading to improved stiffness.

3.4. Flexural Strength

The flexural strength test results at 28 days, shown in Figure 9, indicate that the D1 mixture exhibited a strength of 44.6 kg/cm². The D3 mixture (10% WC) demonstrated the highest strength increase of 15.02% compared to D1, while the D6 mixture (10% WC + 1% CF) showed a significant increase of 23.99%, highlighting the synergistic effect of WC and CF on flexural performance.

The observed improvement in flexural strength can be attributed to enhanced bonding and structural integrity, facilitated by the chemical composition of WC and CF. The high carbon (AC) content in WC (52.759%) improves adhesion within the cement matrix, while iron (Fe) and magnesium (Mg) (4.283% and 7.315%) contribute to a denser microstructure, reducing the formation of weak zones. Additionally, potassium (K) and chlorine (Cl) in CF (25.840% and 9.874%) enhance fiber-matrix interaction, helping to control shrinkage and improve crack resistance.

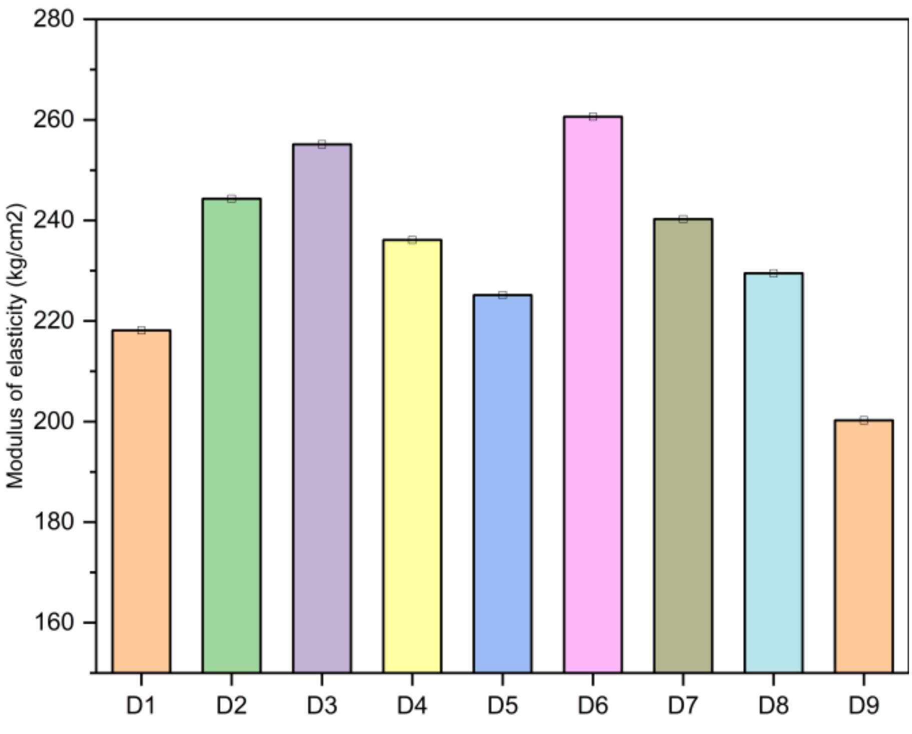

Figure 8. Results of the modulus of elasticity of concrete at 28 days

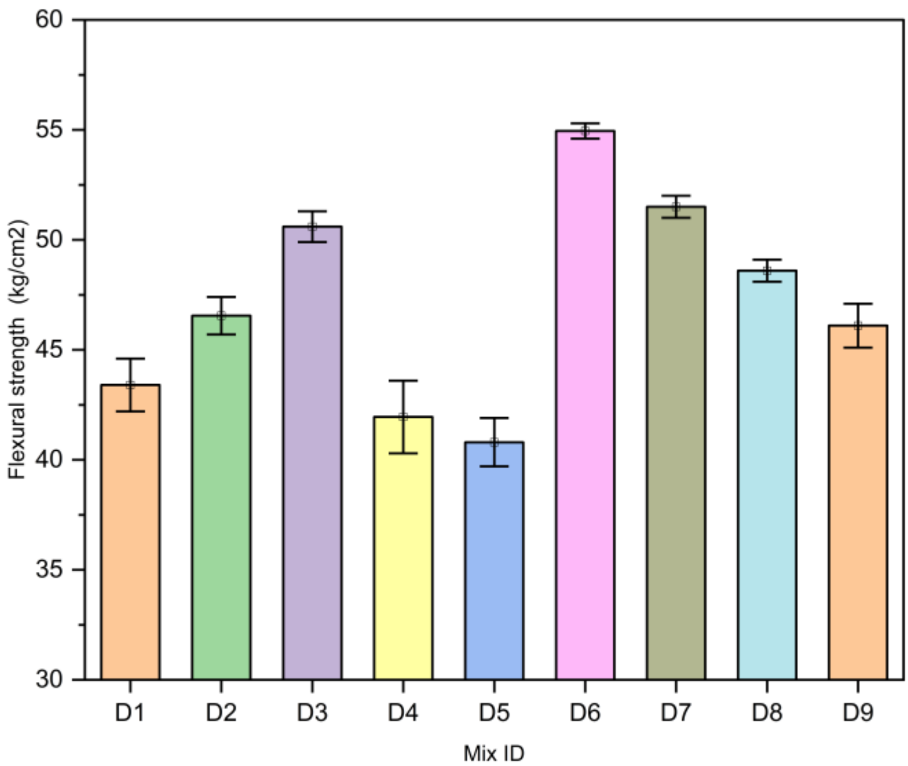

Figure 9. Results of the flexural strength of concrete at 28 days

By reducing microcracks, the inclusion of WC and CF enhances the ability of concrete to resist tensile stress, contradicting the findings of Alharishawi et al. [38], who reported no significant improvement in flexural strength with WC alone. The interaction between WC and CF in this study optimized load distribution, improving crack resistance and overall durability, leading to a higher flexural strength.

3.5. Tensile Strength

Figure 10 presents the tensile strength results, with the D1 mixture serving as the reference at 23.4 kg/cm ^{2}after 28 days of curing. The D3 mixture (10% WC) showed an 11.54% increase in tensile strength, while the D6 mixture (10% WC + 1% CF) achieved a significant 20.09% improvement, reaching 28.1 kg/cm ^{2}, the highest recorded value.

The remarkable increase in tensile strength can be attributed to the synergistic effect of WC and CF, which enhances crack resistance and improves fiber-matrix interaction. The high carbon (AC) content in WC (52.759%) strengthens the cementitious network, reducing microcracking, while magnesium (Mg) and iron (Fe) (7.315% and 4.283%) reinforce the structural integrity by improving hydration. CF, with its high potassium (K) and chlorine (Cl) concentrations (25.840% and 9.874%), promotes fiber dispersion, optimizing load transfer and preventing crack propagation.

Contrary to findings of Alharishawi et al. [38], who reported no benefits of these materials for concrete ductility, this study highlights their positive contribution to tensile strength and durability. These results underscore the importance of considering WC and CF as effective strategies for improving concrete performance, offering new possibilities for applications requiring enhanced durability and mechanical properties.

3.6. Water Absorption

Figure 11 presents the water absorption test results, illustrating the behavior of standard concrete with wood chips and coconut fiber after 28 days of curing. The D1 mixture, serving as the reference, exhibited a water absorption of 6.1%. The D3 mixture (10% WC) demonstrated the most favorable result, reducing water absorption by 9.84% compared to D1. However, higher WC content increased absorption, establishing 10% WC as the optimal dosage for minimizing permeability. The hybrid mixture (10% WC + 8% CF), represented by D9, achieved a remarkable 22.95% reduction in water absorption, demonstrating the beneficial interaction between WC and CF.

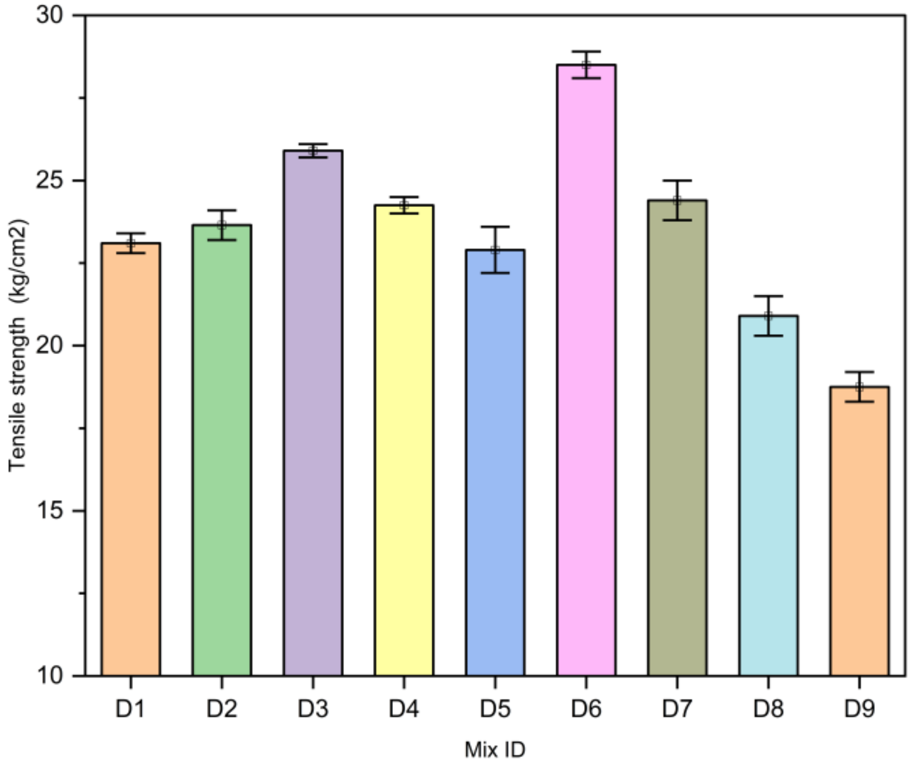

Figure 10. Results of the tensile strength of concrete at 28 days

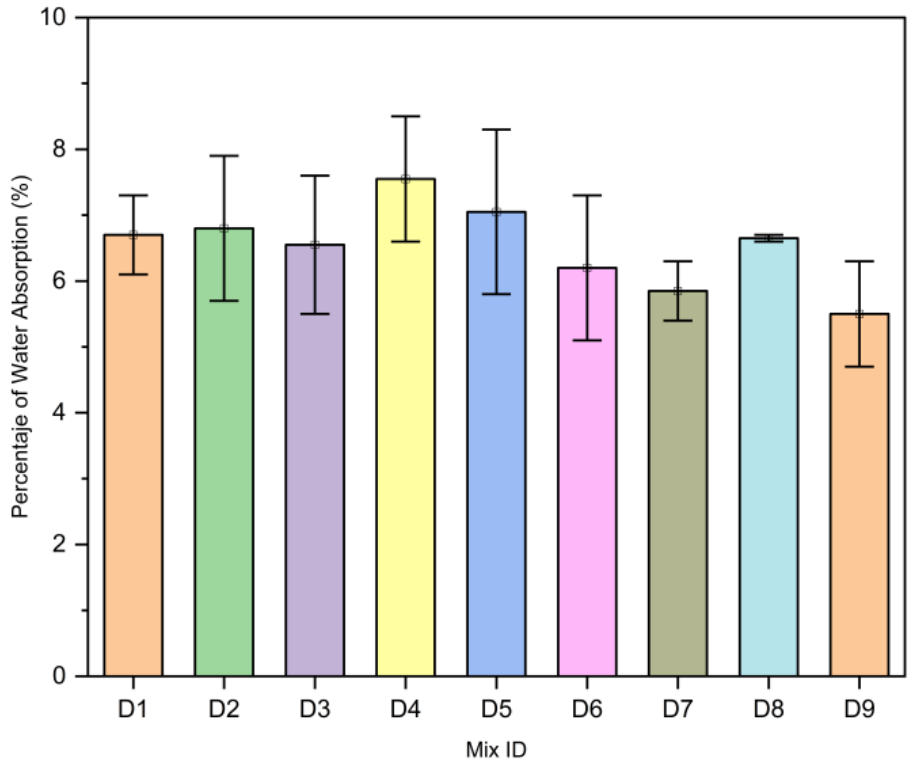

Figure 11. Results of % water absorption of concrete after 28 days

While previous studies indicate that WC increases water absorption due to its high porosity [42], the presence of CF counteracts this effect by enhancing matrix integrity and reducing microcracking. The high carbon (AC) content in WC (52.759%) may contribute to better cement adhesion, while iron (Fe) and magnesium (Mg) (4.283% and 7.315%) reinforce hydration reactions, creating a denser microstructure. Similarly, CF's potassium (K) and chlorine (Cl) content (25.840% and 9.874%) enhances fiber dispersion, sealing pores and delaying moisture penetration.

This synergistic effect between WC and CF significantly improves concrete durability by reducing permeability, supporting their application in structures requiring high water resistance [43]. Their sustainable properties make them viable alternatives for eco-friendly concrete formulations in high-moisture environments.

3.7. Sulfate Resistance

Figure 12 shows the variations in compressive strength after 28 days of immersion in a 2% sodium sulfate (Na_2SO_4) solution. The D1 mixture (without WC) exhibited a minimal strength loss of 0.02%, while mixtures with WC showed slightly higher losses (0.03%–0.06%), with D3 (10% WC) and D5 (5% WC) demonstrating the lowest variations. However, D4 (15% WC) experienced a more significant loss, confirming that 10% WC is the optimal dosage for improving sulfate resistance. Hybrid mixtures with WC + CF, particularly D6 (10% WC + 1% CF), exhibited the highest variation (0.06%), whereas **D8 (10% WC + 5% CF) showed the lowest loss (0.03%), suggesting that higher CF content may enhance sulfate resistance.

The chemical composition of WC and CF influences sulfate resistance. WC's high carbon content (52.759%) enhances cement adhesion, while magnesium (7.315%) and iron (4.283%) may improve hydration stability, reducing sulfate-induced deterioration. However, CF's high chlorine (9.874%) may negatively interact with sulfates, potentially accelerating matrix degradation, as noted by Mboungou et al. [37]. Although previous studies suggest WC enhances sulfate resistance [36], CF's effects remain inconsistent. These results highlight the importance of optimizing admixture proportions to enhance concrete durability in aggressive environments, providing valuable insights for sustainable and resilient concrete design.

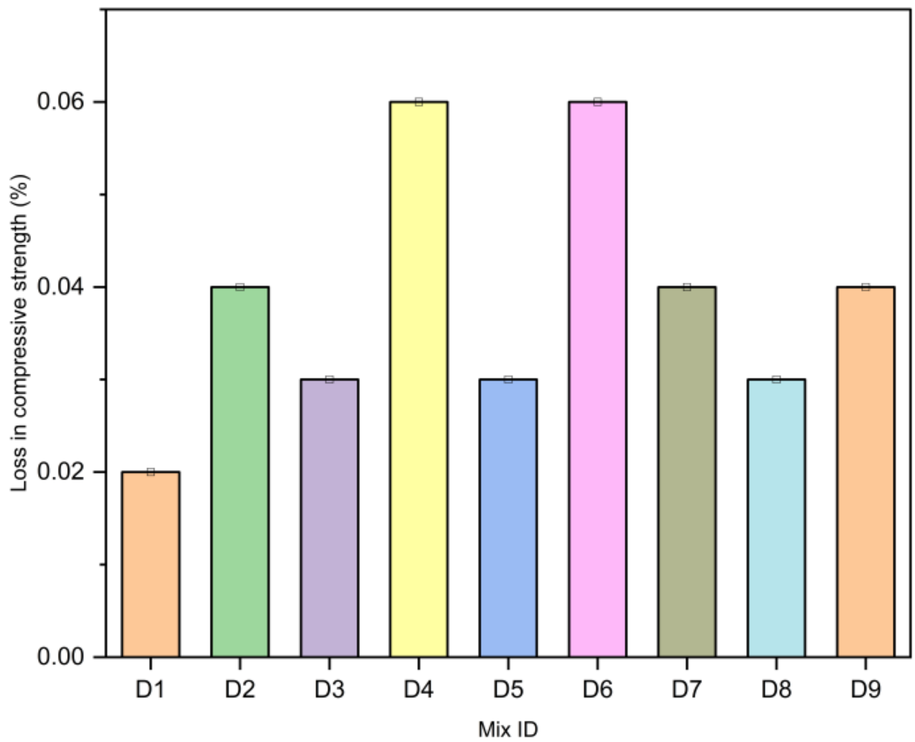

Figure 12. Results of % loss of compressive strength of concrete under sulfate attack

4. Conclusions

The study provides important information on the effects of incorporating wood chips (WC) and coconut fiber (CF) in concrete. Based on the results and discussions obtained, the main discussions are as follows:

The addition of wood chips and coconut fiber alters concrete's density, workability, and thermal stability. WC, due to its low density and porous nature, increases voids, reducing workability and temperature stability. However, controlled dosages (10% WC and 1% CF) help improve material cohesion and maintain acceptable physical performance.

The optimal hybrid mix (10% WC + 1% CF) improved compressive (3.89%), flexural (23.99%), and tensile (20.09%) strength, as well as elastic modulus (19.49%). The presence of CF helped distribute loads more efficiently, while WC contributed to crack control, enhancing the structural integrity of non-load-bearing elements.

The hybrid concrete showed a 9.84% reduction in water absorption and minimal strength loss (0.03%) under sulfate attack, improving durability in moisture-sensitive environments. However, higher WC content (>10%) increased porosity, affecting long-term resistance. Proper dosage and processing techniques are essential to optimize durability.

Given its lightweight nature and improved durability, hybrid concrete is suitable for non-structural applications, such as pavements, sidewalks, partition walls, precast blocks, and insulation panels. However, it is not yet viable for structural elements, as its higher porosity and lower density may compromise load-bearing capacity.

Further studies should evaluate the long-term performance of WC and CF concrete under temperature fluctuations, chemical exposure, and acidic environments. Additionally, optimizing treatment methods for WC and CF could reduce porosity, improving adhesion with the cement matrix and making it viable for broader applications.

The use of organic waste in construction supports SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action). It promotes waste reduction, enhances eco-friendly building practices, and contributes to a circular economy by repurposing organic materials in construction.

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