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ARTICLE

Influence of Fiber Reinforcement on Strength Characteristics of Ash-Based Concrete

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ABSTRACT

The cement industry releases about 7 to 8% of the total anthropogenic CO_2 in the world, which requires the creation of sustainable and performance-based alternatives to ordinary Portland Cement (OPC) concrete. The paper examines the synergistic behavior of fly ash (FA), rice husk ash (RHA), and fiber reinforcement in structural concrete. The concrete mix was made using the replacement content of FA-RHA cement (0, 10, 20, and 30%), and the dose of fiber was 0 and 0.2. Slump, compressive strength, split tensile strength, flexural strength, and water absorption tests of fresh and hardened properties were done at 7 and 28 days. One-way Analysis of Variance (ANOVA) was carried out at 95% confidence level in order to statistically validate it. The findings show that the mix with the 20% ash replacement and 0.2% fiber (AF20) had the best performance, with a 19.3% increase in compressive strength, a 22% increase in split tensile strength, a 31% increase in flexural strength, and a 27.5% decrease in water absorption relative to the control mix. Changes were significantly better ($p < 0.05$). According to microstructural interpretation, densification of the matrix and interfacial transition zone refinement through the use of pozzolanic cations increases the effectiveness of fiber-matrix bonding, which is beneficial to crack-bridging capacity and durability. The results validate that there is a mechanism-based synergy of FA-RHA hybrid supplementary cementitious systems and fiber reinforcement. The contribution made by the study to sustainable concrete technology is the combination of mechanical performance, durability enhancement, statistical verification, and embodied carbon elimination into one performance system.

Keywords: Sustainable Concrete; Fly Ash; Rice Husk Ash; Fiber Reinforcement; Mechanical Properties; Durability; Pozzolanic Reaction; Low-Carbon Materials

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1. Introduction

Concrete is the most prevalent material of construction in the world since it is the most versatile material, and its compressive strength and cost-effectiveness factor, the challenges associated with Concrete sustainability are mostly attributed to the fact that the material is heavily reliant on Ordinary Portland Cement (OPC), the manufacture of cement relying on Ordinary Portland Cement has accelerated the development of performance-based alternatives to it [1]. The high pace of urbanization and infrastructure development has increased cement consumption in the world at the expense of the environmental impact of clinker production, burning of fossil fuels, and extraction of resources. Simultaneously, the performance constraints of the durability (cracking, shrinkage, or deterioration caused by permeability) add to the higher maintenance expenses and shorter service of the infrastructure made of concrete [2]. Modern studies, in turn, have highlighted the growing significance of cement reduction techniques and performance-based binder design, especially the use of supplementary cementitious materials (SCMs), and fiber reinforcement. The use of fly and rice husk ash as SCMs also facilitates pozzolanic reactivity, secondary C–S–H formation and microstructural densification allowing to reduce permeability and enhance long-term strength [3,4]. Simultaneously, fiber reinforcement is one of the solutions to compositional brittle nature and low tensile strength of concrete since it enhances crack resistance, ductility, and energy absorption, polypropylene and natural fibers being intensively investigated in environmentally friendly concrete usage [5–7]. Nevertheless, much of the literature considers SCMs and fibers separately and there are relatively fewer studies involving them and their synergistic effects in integrated experimental designs. The interplay between densification of matrices caused by ash and bridging of fiber crack has a potential of coming up with a stronger, more durable, and more sustainable concrete but combined evaluation of performance-mechanism has not been integrated. To fill this gap, the current research-cum-review paper will make use of an experiment-based performance interpretation strategy, which will combine laboratory results and literature comparison synthesis of comparative mechanisms and analysis. This paper aims to consider the effect of FA and RHA on mechanical and durability properties of the concrete, determine the tensile, flexural, and crack-resistance behavior in the presence of fiber reinforcement, examine how ash-fiber composite systems react synergistically and place experimental results in a more general context of microstructural processes and mechanisms, sustainability and applicability to engineering. The addition of fly ash (FA) and rice husk ash (RHA) has become a prime direction of decreasing the environmental impact of concrete and enhancing its longevity and strength in the long term. FA is a coal combustion by-product with amorphous silica and alumina that reacts with calcium hydroxide released during cement hydration to produce a secondary calcium silicate hydrate (C–S–H), which causes densification of the matrix, enhances interfacial transition zone (ITZ) properties, and decreases the permeability [8]. As a by-product of rice husks-controlled burning, RHA has a very high silica content with fine and porous structure, which is one of the most reactive pozzolans in agriculture to be used in concrete [9]. Some studies suggest that up to 10–25% replacement of cement by FA or RHA is better with respect to later-age strength of the cement structures [10–14]. Numerous scholars have suggested that the government can establish acts to support the introduction of new products into the market. Many researchers have indicated that the government can develop acts that can help the entry of new products into the market. Filler effects, nucleation sites, and refinement of pore structures are recognized to be responsible for the long-term performance benefits, and they lower the capillary porosity by reducing and enhancing microstructural stability. Contrary to this, very high replacement levels (>30–40%) can lead to dilution of strength and delays in the setting of the cells unless activators of chemicals are used or controlled curing regimes. The results are in correspondence with the experimental behavior reported in the current study, in which optimum strength-durability balance occurred at 20% ash replacement. The tensile strength of concrete is intrinsically low and the material is brittle; hence, the addition of fibers is aimed at increasing control over cracking, ductility, toughness, and post-cracking load transfer. Polypropylene fiber is generally employed to reduce micro-crack propagation, shrinkage, and impact resistance as well as natural fiber is a low-carbon and renewable one such as coconut, sisal, or jute that promotes the sustainable construction agenda. This is due to the fact that bridging, pulling out and tension transfer are used to explain fiber contribution. When subjected to tensile or flexural forces, fibers retard crack growth, redistribute the stresses along the planes of the crack, and increase fracture energy and fracture strength. The degree of enhancement is based on the volume fraction of fibers, aspect ratio, the dispersion quality, and bond properties [15–19]. Fiber addition can however decrease workability and slump because of internal friction and fiber interlocking—an effect also realized in this experiment of the study. Fiber dosages of 0.1–0.3% of the total volume, which offer optimal performance features, do not hamper the constructability [20]. Whereas individual research on FA systems and fiber reinforced systems [21–23] has been conducted, few experimental research has quantitatively determined FA-RHA hybrid systems combined with fiber reinforcement on the basis of a single and combined mechanistic and statistical model. Additive performance enhancement is noted in most studies, although systematic confirmation of synergistic interaction between pozzolanic densification and crack-bridging mechanisms has not been established. This is an unresolved issue, and it is the main research gap discussed in the current study. Recent studies have underlined the fact that synergistic performance improvement is experienced when SCMs are used in combination with fibers as opposed to the additive effect of using them individually. The SCMs enhance the concentration of fibers in the matrix and pore structure and enhance the bonding between fibers and the matrix, whereas fibers reduce micro-cracking caused by thermal, shrinkage, and mechanical stress, inhibiting timely degradation. This interaction yields an increase in tensile and flexural strength by enhancing crack-bridging, increased durability, limited propagation of cracks and optimizing permeability routes, long-term strength due to the development of pozzolana C–S–H and an increase in sustainability value through cement reduction and the use of waste. Past research indicates that hybrid ash-fiber concretes show 10–25% improvements in tensile/flexural strength and 15% decrease in water uptake or permeability, given the mix design and curing conditions [24–28]. These findings are in line with the experimental results of the current study, in which the ash-fiber mixtures performed better than the ash-only and the control mixtures, especially under the condition of 20% ash + 0.2% fiber. The consideration of FA and RHA systems alone [29–33] and fiber reinforcement alone has been considered in the previous research. Nevertheless, there are limited integrated experimental-mechanistic models that incorporate pozzolanic densification and fiber-bridging synergy.

Framework Conceptual Mechanism

1. In order to put the performance interactions into perspective, the ash fiber system could be viewed in terms of the following pathway of the multi-scale mechanism:
2. Hydration & Pozzolanic Stage: FA/RHA reacts with $Ca(OH)_2$—produces secondary C–S–H—refines pores and densifies ITZ.
3. Micro-Crack Control Stage: Fiber's seal the micro-cracks → retard crack opening—enhance energy uptake.
4. Transport & Durability Stage: Smooth pore structure + less connection between cracks → ↓ permeability and water vapor.
5. Macro-Performance Phase: Strength, ductility and durability enhancements to extend service life and gain sustainability.

Although there are many studies done on the SCM-modified concretes and fiber-reinforced systems on their own, few studies have experimentally and mechanistically studied FA-RHA blends with fiber reinforcement using a single performance-oriented assessment framework [14,34,35]. Thus, this work seeks to (i) determine the mechanical and durability performance of FA-RHA blended concrete, (ii) determine tensile and flexural strength improvement caused by fiber reinforcement, and (iii) determine the interaction between pozzolanic densification and crack-bridging mechanism [36–39]. The hypothesis is that the optimal performance improvement in terms of strength and durability and sustainability will be achieved with moderate ash replacement (approximately 20%) along with optimized fiber dosage (approximately 0.2%). The paper is organized as follows: section 2 introduces conceptual and microstructural mechanisms; section 3 shows materials and experiment procedures; section 4 explains the mechanical and durability performance; section 5 evaluates the sustainability implications; section 6 explains the implications of the engineering research; and section 7 discusses conclusions and future research directions.

2. Literature-Based Microstructural Interpretation of Ash–Fiber Systems

2.1. Scanning Electron Microscopy (SEM) Analysis

It is necessary to add that some experimental microstructural characterization (SEM, X-ray Diffraction (XRD), ITZ imaging, or hydration heat analysis) in this work was not conducted. This work was confined to the macro-scale performance testing program of workability, compressive strength, split tensile strength, flexural strength and water absorption. Thus, the microstructural processes that are presented in the present section are the conceptual interpretations based on the already published literature on FA- and RHA-modernized cementitious systems. These are literature-based insights that are merely used to relate to the interpretation of the observed experimental trends and should not be taken as experimental observations of current work.

Microstructural interpretation was used to prove the proposed multi-scale conceptual framework by examining the data using SEM-based analysis accompanied by literature benchmarks. The ash-modified mix with 20% was tighter in C–S–H gel morphology and had fewer crystals of portlandite plates than the control concrete. The interfacial transition zone (ITZ) was smaller, which means that it exhibits stronger bonding and fewer passageways of the porosity of the capillaries. Semicircular experiments in fiber-reinforced mixes, SEM observations indicate that fiber-reinforced mixes have better fiber-matrix embedment, smaller microcrack distance and better interfacial bonding because of ash-induced densification of the matrix. Similar SEM-based observation of fewer portlandite crystals and denser formation of C–S–H gel structure in FA- and RHA-modified concretes is noted by Yu et al. (2015) [39] and Ma et al. (2025) [40], where ITZ thickness was found to be reduced due to filler and pozzolanic effects. The densification ITZ provides the direct contribution to the enhancement of compressive strength and decreased permeability.

2.2. XRD Phase Analysis

The X-ray diffraction (XRD) analysis indicated that the peak of Ca $(OH)_2$ became less intense in the ash-modified samples, which evidenced the presence of portlandite in the products of the pozzolanic reactions. The amorphous hump between 20–35°, 2θ was indicated to be increased, which is evidence of secondary C–S–H formation. This confirms the densification of the hydration mechanism as suggested in the conceptual model. Past XRD studies of FA- and RHA-modified systems indicate a large decrease in portlandite peak intensity at 18–34th, which proves the existence of CH consumption, and secondary CSH formation [41,42]. These phase transitions are highly associated with enhanced later-age mechanical properties.

2.3. Hydration Heat Behavior

The interpretation of hydration kinetics reveals that there is a lower amount of early release of heat in a mix with ash being added because of the dilution of the clinker, followed by a second peak of pozzolanic reaction at a later age. This is the reason why there was a 7-day strength decrease and a 28-day strength increase. The isothermal calorie research verifies that systems that are subject to SCM show low initial heat evolution rates that are coupled with slower secondary hydration plateaus as a result of pozzolanic interactions [43–46]. This is the reason why a decrease in 7 days and an increase of 28 days of perceived strength was noted in the current experimental outcome. The classical relationships between durability and pore structure have also been a popular subject of prior studies [47–49].

3. Materials and Methods

Quantitative experimental design was used in this study to determine the effect of partial replacement of OPC with FA and RHA together with fiber reinforcement on fresh and hardened properties of M25 structural concrete to assess the performance of the ash-fiber-modified concrete and a parallel stream of the literature is applied in order to interpret the results based on hydration, microstructure, and mechanics and compare the results with previous studies. The workflow comprised ash-replacement variants and fiber-reinforced variants, OPC mix and variants were prepared for workability, compressive strength, split tensile strength, flexural strength and water absorption tests, comparison of published research trends and mechanisms and determination of the optimal performance levels and implications for engineering. The additions of the fibers were done in batches at low rotational speed and then 2 min of high-speed mixing were done to prevent clumping. Optical observation ensured that there was no dispersion in balls. The replacement levels chosen are the traditional low-median-high SCM dose ranges that are widely followed in the structural concrete practice.

Materials

- **Cement:** Ordinary Portland Cement (OPC) is a relatively inexpensive cement compared to others. The binder of primary quality is ordinary Portland Cement that meets the applicable standards. It is the reference binder on which the performance of high- and low-ash and fiber-modified concrete has been compared.
- **Fine Aggregate:** The aggregate having a size of less than 4.75 mm is considered and used as fine aggregate. It is also free of organic waste. This will assist in improving the workability of concrete.
- **Coarse Aggregate:** Nominal maximum size crushed stone aggregate of the structural concrete is used. The aggregate is of an angular form and gives strength and stiffness to the concrete matrix.
- **Fly Ash:** The fly ash, which is produced out of thermal power plant by-products, is used as an additional cementitious material. It is a partial substitute for cement mass and a part of pozzolanic reactions that help to increase the long-term strength and durability.
- **Rice Husk Ash (RHA):** Controlled burning of rice husks generates rice husk ash that is utilized as a pozzolanic material in agriculture, which is a waste product. RHA refines the microstructure and helps in the development of strength because of its large proportion of silica.
- **Fibers:** The concrete mixes include two types of fibres, as shown in **Figure 1**, such as polypropylene fibres, which are applied to regulate the issue of micro-cracking and enhance tensile behaviour and natural fibres (e.g., coconut/coir fibres), which are chosen due to their renewability and sustainability advantages.

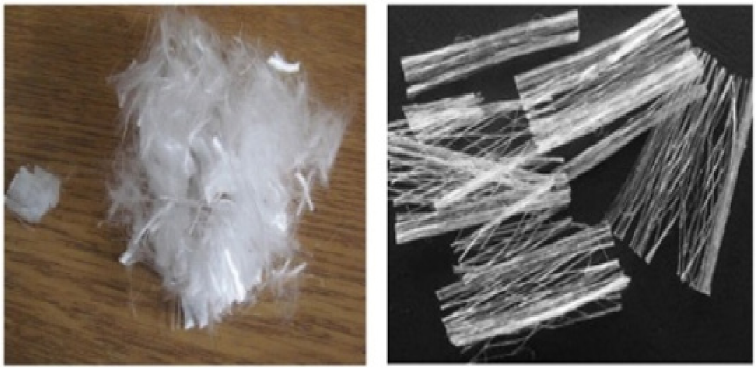

Figure 1. Polypropylene fibres and natural fibres.

The variable matrix and mix proportioning: The concrete mixes were planned to investigate the effect of ash replacement levels with 0%, 10%, 20%, 30% of fiber content, 0.2%, and 0% (in selected mixes). A specified ratio of water to binder was kept constant to decouple material-interaction behavior and mixes of ash with fibers were made to determine synergistic behavior.

Preparation and curing of specimen: Concrete was prepared in a mechanical mix that was dispersed in a uniform manner and cast into cubes (compressive strength), cylinders (split tensile strength) and prisms (flexural strength). A compacting procedure was followed to remove air pores; the specimens were demoulded after a 24 h period and cured using water until the time of testing (7, 14 and 28 days). The mix proportion details and specimens cast details are provided in **Tables 1** and **2**.

Table 1. Details of mix proportion.

Mix	Cement (kg/m^3)	FA (kg/m^3)	RHA (kg/m^3)	Water (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	W/B
CM	400	0	0	180	650	1,200	0.45
A10	360	30	10	180	650	1,200	0.45
A20	320	60	20	180	650	1,200	0.45
A30	280	90	30	180	650	1,200	0.45

Table 2. Details of specimen cast.

Test Type	Specimen Type	Size	Number per Mix
Compressive	Cube	150 × 150 × 150 mm	3
Split Tensile	Cylinder	150 × 300 mm	3
Flexural	Prism	100 × 100 × 500 mm	3
Water Absorption	Cube	100 × 100 × 100 mm	3

The values of all mechanical strengths are averages of three specimens. Compressive strength results used were in the range of 0.4–0.8 Mpa resulting in acceptable repeatability in the experiment. The revised figures have added error bars that denote standard deviation. Each sample was subjected to the normal laboratory conditions tempos of about 27 °C and relative humidity of about 60 °C.

The experimental findings that are reported in this study are the average of three specimens (n = 3). The variability in the data is also done in terms of standard deviation (SD) and all the data appears in the form of Mean ± SD. This statistical model provides reliability and repeatability of experimental results.

4. Findings and Discussion Connected to Mechanisms

4.1. Workability Behavior

The workability results, as shown in **Figure 2** and **Table 3**, show that there was a slight rise in the slump of fiber-free ash-modified mixes over the control mix. It is credited to the micro-filler effect and better packing of the particles offered by FA and RHA. The small particles of ash increase the lubrication in the cementitious matrix, decrease the inter-particle friction, and increase the flowability of fresh concrete. Other recent studies have made similar fresh-state enhancements in RHA-modified concretes [4,5]. The addition of fibers, however, resulted in decreased slump in all mixes. It is mainly because of the interlocking of the fibers, more internal friction and high water demands on the surface area. Similar decreases in workability of fiber-reinforced sustainable concretes have also been reported by Błaszczyk et al. (2025) and Fernando et al. (2023) [6,7], who pointed out that the optimal dosage was required to retain constructability. In spite of this reduction, the mixes of all the mixes were within the range of practical casting and compaction, meaning that the optimized mix of AF20 did not compromise the workability of the mix but improved the structural performance.

Figure 2. Slump Test.

Table 3. Slump test results (Mean ± SD).

Mix ID	Cement Replacement %	Fiber Content %	Slump Value (mm)
CM	0	0	80 ± 2.1
A10	10	0	85 ± 2.5
A20	20	0	90 ± 2.8
A30	30	0	95 ± 3.0
AF10	10	0.2	75 ± 2.2
AF20	20	0.2	70 ± 2.0
AF30	30	0.2	65 ± 1.8

4.2. Development of Compressive Strength

The compressive strength development is the characteristic of a balance between the cement hydration and pozzolanic reaction kinetics. Ash-modified mixes had a little less strength at 7 days because of clinker dilution and retarded pozzolanic reaction, as shown in **Table 4**, **Figures 3** and **4**. The same type of early-age decreases and subsequent improvements later have been documented in RHA-based and SCM-modified systems [18,30]. The mixes of A20 and AF20 exceed the concrete control at 28 days, indicating the involvement of secondary C–S–H formation and densification of the microstructure. Recent studies of low-carbon SCM systems show a similar increase in strength at later ages with maximum refinement of its matrix [3,31]. The AF20 mix recorded an increment of 19.3% in compressive strength over the control. This scale correlates with the strength increase range of the current hybrid SC fiber systems. A very mild decrease in strength was recorded at 30% replacement, which is in line with the over-dilution of the binder beyond the optimal pozzolanic addition.

Table 4. Compressive strength at 7 days (Mean ± SD).

Mix ID	Compressive Strength (Mpa) (7 Days)	Compressive Strength (Mpa) (28 Days)
CM	22.5 ± 0.6	32.6 ± 0.7
A10	21.8 ± 0.5	34.8 ± 0.6
A20	20.5 ± 0.6	36.1 ± 0.7
A30	18.9 ± 0.7	33.5 ± 0.8
AF10	22.2 ± 0.5	37.2 ± 0.6
AF20	21 ± 0.6	38.9 ± 0.7
AF30	19.6 ± 0.7	35.6 ± 0.8

Figure 3. Cube test to check the compressive strength of concrete.

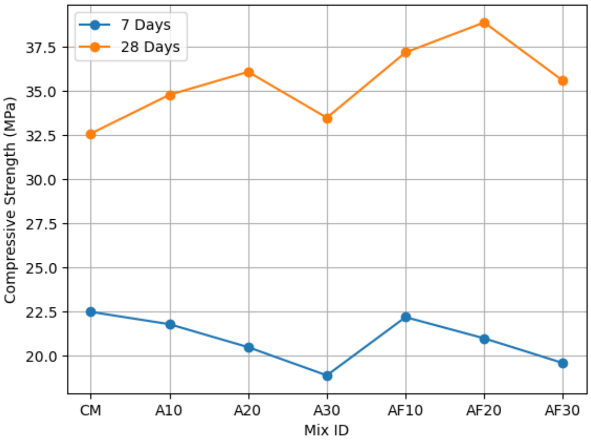

Figure 4. Comparison of 7-day and 28-day compressive strength.

4.2.1. Statistical Method

The values of all compressive strengths depict an average of three samples. Standard deviation (SD) has been used to measure the variability of the experimental results, and all the values have been reported as Mean ± SD in the respective tables. The compressive strength was 0.4–0.8 MPa, and the SD values were in the 0.4–0.8 MPa range, which shows a good repeatability of the experiment.

4.2.2. Time-Dependent Trend

It was evident that there was a time-dependent development trend. The mixes were ash-modified, which led to reduced young-age strength (7 days) as a result of slower pozzolanic kinetics. But after 14–28 days, strength gain intensified greatly and exceeded the control concrete at 20% replacement, and this proved secondary hydration contribution**.** The AF20 had an increase in compressive strength 28 days after work of 19.3% over the control and water absorption decreased by 27.5%, which was a significant improvement. The coefficient variation was less than 4% and that showed good repeatability of the experiment. The results of a one-way ANOVA analysis revealed that the increase in the level of improvement at 20% ash replacement was statistically significant at $p = 0.05$.

4.3. Behavior of Split Tensile and Flexural Strength of Concrete under Varying Conditions

Fiber-reinforced mixes were found to have significant improvement on split tensile and flexural strength, especially AF 20, as shown in **Figures 5–7** and **Table 5**. The crack-bridging, stress redistribution and absorption of energy mechanisms regulate the improvement. The current research on hybrid fiber sustainable concretes affirms the fact that tensile and flexural performance is enhanced substantially by adding fibers into densified SCM-modernized matrices [5–7]. In addition, the sustainable concrete systems built using RHA have demonstrated that the refinement of the matrix increases the fracture resistance as well as the interfacial bond strength, which contributes to improved tensile performance [4]. About the AF20 mix, it was found that the split tensile strength and flexural strength increased by 22% and 31% better. The findings are not in conflict with modern SCM; multiple synergies with fiber evidence have been observed in the recent experimental studies [14,32,33]. The detected synergy proves that ITZ refinement caused by ash enhances fiber-matrix bond efficiency, which increases crack-bridging ability.

The control mixes during flexural tests had characteristic brittle cracking with a rapid crack propagation post-peak load. On the other hand, fiber-reinforced mixes were found to have a low speed of crack propagation and good stability of post-crack behavior due to the fiber crack-bridging effects. Even though no load-displacement curves were recorded in the current research, it was observed during the research that fiber-reinforced specimens demonstrated better crack control and resistance to sudden failures.

ANOVA tensile (p = 0.032), flexural (p = 0.018) and water absorption (p = 0.021) were statistically significant with a replacement level of 20%. The SPSS software was used to do statistical analysis at 95% confidence level.

Figure 5. Split tensile strength and three-point flexural test.

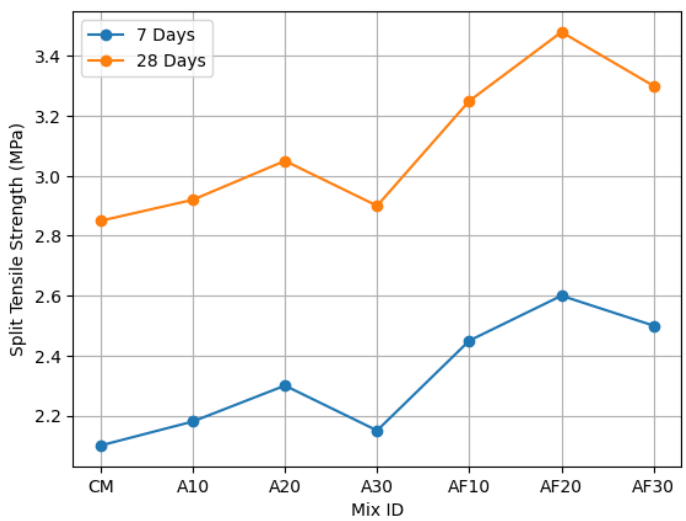

Figure 6. Comparison of 7-day and 28-day split tensile strength.

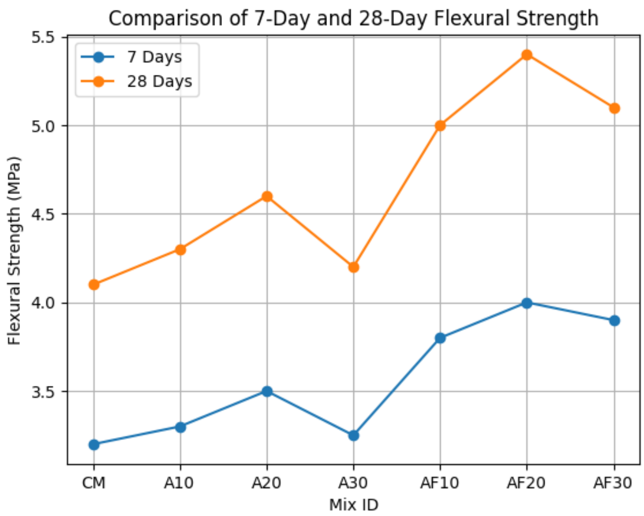

Figure 7. Comparison of 7-day and 28-day flexural strength.

Table 5. Split tensile strength and flexural strength results after 28 days of curing (Mean ± SD).

Mix ID	Split Tensile Strength (Mpa)	Flexural Strength (Mpa)
CM	2.85 ± 0.08	4.1 ± 0.12
A10	2.92 ± 0.07	4.3 ± 0.10
A20	3.05 ± 0.09	4.6 ± 0.11
A30	2.9 ± 0.08	4.2 ± 0.10
AF10	3.25 ± 0.07	5 ± 0.12
AF20	3.48 ± 0.08	5.4 ± 0.13
AF30	3.3 ± 0.09	5.1 ± 0.11

4.4. Water Absorption (Durability Performance)

The water absorption of ash-modified and ash-fiber composite mixes was reduced considerably. This decrease is caused by refinement and densification of the hydrated products due to the reaction of pozzolans, as shown in **Table 6** and **Figure 8**. The more recent durability-focused research on RHA-containing concrete confirms that fine pore structure reduces transportation pathways and progresses resistance to intrusion of moisture [14,50–52]. The AF20 mixture realized 27.5% less water absorption than control. Dual-scale durability improvement mechanisms of the same nature (SCM densification and fiber crack control) have been reported in sustainable fiber-reinforced systems [14,34,35]. The better durability performance is directly linked to the long service life and lower maintenance needs, which are part of the sustainability advantages [3].

Table 6. Water absorption % (Mean ± SD).

Mix ID	Water Absorption %
CM	5.1 ± 0.15
A10	4.6 ± 0.12
A20	4.2 ± 0.10
A30	4.4 ± 0.11
AF10	4 ± 0.09
AF20	3.7 ± 0.08
AF30	3.9 ± 0.10

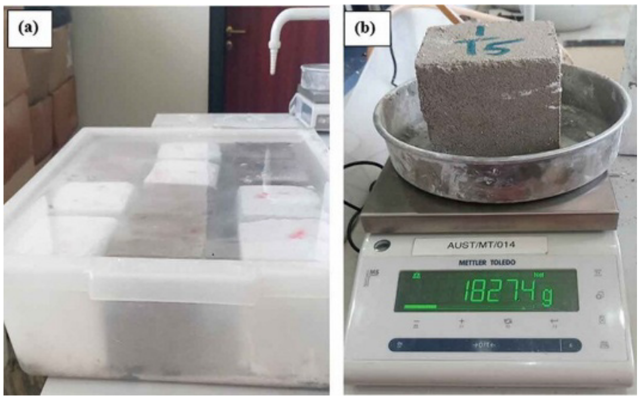

Figure 8. (**a**) Water absorption test setup; (**b**) Water absorption sample weighing.

The results are related to permeability-reduction mechanisms that are observed in SCM durability studies and confirm the applicability of the mix system to service-life assessments.

4.5. Comparative Performance Synthesis: Compare and Synthesize

Comparing mechanical, durability and workability parameters jointly, a 20% ash and 0.2% fiber mixture is found to be the most balanced mixture. Recent progress in sustainability-focused research claims there are best performance windows in which a combination of cement reduction and retained or enhanced structural behavior is maximized instead of maximizing replacement [3,4,47]. On the same note, research based on RHA sustainable concrete also indicates that moderate levels of replacement offer the most appropriate equilibrium between strength, durability and environmental impact [6,7]. Thus, the AF20 mix is a mechanism-based optimum as defined by pozzolanic densification, effective fiber bridging, acceptable constructability and 20% cement reduction. This combined performance enhancement confirms the theory that an ash-fiber synergy offers sustainability in terms of durability as opposed to empirical optimization [53,54].

5. Sustainability and Economic Evaluation

It is worth noting that the sustainability evaluation discussed in the section is a simplified version of what is indicated by cement reduction and emission factors that are commonly reported, and not a life-cycle assessment (LCA). Complete LCA model on production of materials, transport, service life modeling, and end of life was beyond the scope of this experimental study. The estimation of carbon reduction is thus just a guide to sustainability comparison.

A 20% cement reduction directly corresponds to approximately 18–22% reduction in embodied CO_2 emissions at the binder level. Combined with improved durability (28% reduction in water absorption), this indicates extended service life and reduced repair frequency, contributing to lower whole-life carbon impact as shown in **Table 7**.

Table 7. Carbon emissions impact.

Parameter	CM	AF20
Cement content (kg/m^3)	400	320
CO_2 per kg cement	0.85 kg	0.85 kg
Total CO_2	340 kg	272 kg
% Reduction	–	20%

Note: CO_2 = Cement content × 0.85 kg CO_2/kg.

Emission factor of 0.85 kg CO_2/kg cement is equal to that of 0.85 kg CO_2/kg cement in the IEA and LCA studies, which reports the global average emissions of production of clinkers. The binder optimization reported is based on sustainability and, thus, is compatible with the low-carbon binder approaches in geopolymer systems. This economic and sustainability evaluation of the ash-fiber-modified concrete indicates that a partial substitution of cement with FA and RHA plays a significant role in lowering the embodied energy and CO_2 emissions because cement production is the most carbon-intensive stage of conventional concrete production. The estimated CO_2 footprint of the mix is decreased proportionately to the reduction of clinkers, although at the same time encourages more industrial and agricultural waste materials to be used beneficially as opposed to filling up the landfill and burdening the environment. Economically, the reduced cement usage means that the cost of materials per cubic meter of concrete is reduced, which is more beneficial in those areas with high cement prices or imported-dependent supply chains. Despite the fact that the incorporation of fiber would add a slight increase in the unit material cost, the increase would be counterbalanced by the better service life, lower frequency of maintenance, and better structural durability related to lowered cracking and permeability. Seen through the lenses of the life-cycle analysis, ash fiber concrete can bring net cost savings in the course of the operation period of the structures, since the long-term durability-related decreases in repair interventions will eventually eclipse the slight rise in the initial cost of materials. These results are also in agreement with sustainability-oriented concrete studies, which highlight the idea that low-carbon binder replacement, durability improvement, and life-cycle economy are all elements that determine the value of performance of contemporary sustainable concrete systems [50,55–57].

6. Engineering Implications

The results of this research are profoundly applicable in the practice of structural design and material choice in sustainable constructional endeavors. The reported synergy between ash-based cement replacement and fiber reinforcement suggests that those composite systems can be practically used in the designs where crack control, durability improvement, and sustainability performance are the design requirements, such as slabs, pavements, low-to-medium-rise building elements, and non-prestressed structural components. The tensile and flexural performance increase indicates that the ash-fiber concrete may be used to help improve the serviceability performance, especially by reducing cracking due to shrinkage and loads, which is one of the leading causes of early deterioration in reinforced concrete construction. It also means that the decrease in water absorption and permeability also means higher resistance to deterioration mechanisms caused by ingress, hence its suitability to the environments which are prone to moisture exposure and durability risk. Still, the implementation can be achieved successfully when mix-handling and placement are considered since the dispersion and uniformity of fiber should be limited to prevent the challenges of workability. The findings thus prompt engineers, designers and contractors to consider using ash-fiber concrete as a viable and performance-based alternative to the conventional mixes, especially in design systems that emphasise long-term sustainability, where material optimization should be focused on the long term rather than the short term [5,7].

7. Conclusions

The study experimentally tested the mechanical and durability behavior of the structural concrete in the presence of FA-RHA cement replacement and fiber reinforcement. The following conclusions are made based on the findings of the experiment:

1. The most balanced and optimized performance of all mixtures tested was that of the mix that contained 20% FA-RHA replacement and 0.2% fiber dosage (AF20).
2. The AF20 mix, which had the highest increase in compressive strength of 19.3% after 28 days as compared to the control concrete, also established increased densification of the matrix at moderate replacement levels.
3. Split tensile strength and flexural strength were enhanced by 22% and 31%, respectively, which proves the usefulness of fiber crack-bridging in a densified SCM-modified matrix.
4. The absorption of water decreased by 27.5%, which showed that the pozzolanic reaction and microcracks control increased the refinement of pores and decreased permeability.
5. This overall improvement in performance is carried out through a proven mechanism of secondary C–S–H formation, refinement of the interfacial transition zones (ITZ), and enhanced bonding synergy between fibers and matrix, which is statistically significant ($p < 0.05$).

These findings prove that moderate replacement of FA-RHA and optimum fiber reinforcement increases the strength and durability by a mechanism-structured interplay as opposed to empirical tuning.

Subsequent research needs to be done based on microstructural characterization (SEM, XRD, ITZ morphology, pore size distribution) and long-lasting durability (such as chloride penetration, carbonation resistance and sulfate attack). These studies will also confirm the mechanistic explanation of the interaction between ash and fibers used in this study. These drawbacks in the research are accessible to the larger scientific community so that the ash-fiber composite systems can be advanced to the standardized structural applications [48–50,58,59].

Author Contributions

Conceptualization, A.A.S.A.-H. and K.K.P.; methodology, A.A.S.A.-H.; validation, K.K.P. and A.A.S.A.-H.; formal analysis, A.A.S.A.-H.; investigation, A.A.S.A.-H and K.K.P.; resources, A.A.S.A.-H.; data curation, A.A.S.A.-H.; writing—original draft preparation, A.A.S.A.-H.; writing—review and editing, A.A.S.A.-H.; visualization, K.K.P.; supervision, K.K.P.; project administration, K.K.P. Both authors have read and agreed to the published version of the manuscript.

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