

Original article

Enhancing Mechanical and Durability Properties of Concrete Using Recycled HDPE Fibers: Experimental Evaluation

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Abstract

This experimental study examines the effects of introducing High-Density Polyethylene (HDPE) fibers at volume fractions of 0%, 1.0%, 1.5%, and 2.0% on key properties of concrete. Among the traits evaluated are impact resistance, flexural strength, compressive strength, and ultrasonic pulse velocity (UPV). The results demonstrate that the UPV values, which varied from 4.38 to 4.42 km/s, remained essentially constant, suggesting no alteration in the composite's density and homogeneity. The 28-day compressive strength improved gradually with the addition of fibers, reaching a high of 36.42 MPa at 2.0% fibers, a 9.8% improvement over the plain concrete. However, flexural strength and impact resistance peaked at 4.18 MPa and 4 blows, respectively, at 1.5% fiber content, indicating the best improvement in toughness-related characteristics. A decrease in performance was observed beyond this ideal dosage, which was probably caused by impaired fiber dispersion and workability. The results support previous research on how synthetic fibers can improve post-cracking behavior by efficiently bridging cracks.

Keywords. HDPE Fibers, Ultrasonic Pulse Velocity, Flexural Strength, Impact Resistance, and Crack Width.

Introduction

By using the crack bridging mechanisms that scattered fibers provide, fiber-reinforced concrete (FRC) is frequently employed to increase post-cracking behavior, toughness, and durability [1, 2, 3]. HDPE fibers are appealing among polymeric alternatives because of their low density, chemical resilience, and recycling potential [4, 5]. While the effects on compressive strength are minor and mix-dependent, the literature consistently shows that synthetic fibers enhance flexural behavior and impact resistance [4, 6, 7]. Although ultrasonic pulse velocity (UPV) is frequently employed as a non-destructive measure of concrete quality, there is no general association between UPV and strength since it varies on the kind of mixture and microstructure. The experimental findings for concretes containing 0–2% HDPE fibers are presented in this study, along with a discussion of the trends based on recent research. The mechanical and durability impacts of fibers in cementitious composites have been consolidated in recent studies, with a focus on fiber stiffness/geometry and dose as critical factors [1, 3, 8]. In particular, HDPE has limited gains in compressive strength at higher contents because of trapped air and workability loss, but it offers benefits in flexure, impact resistance, and shrinkage management when doses are adjusted, per a 2021 study [4].

Experiments using produced or recycled HDPE fibers frequently reveal: (1) Compressive strength: may vary little or even rise; when workability or dispersion declines, compressive strength may decrease [4, 9, 10]; (2) Flexural tensile behavior: steady improvements brought about by crack bridging and improved ductility after cracking; for standard concretes, the ideal contents are typically between 0.75 and 1.5% by volume [4, 9]. (3) Impact resistance and toughness are noticeably superior to those of plain concrete; matrix-fiber bond and fiber dispersion affect performance [6, 7]. (4) UPV: At constant w/b and compaction, it usually varies little with polymer fibers, showing little change in bulk density or continuity; moreover, correlations between UPV and strength are mixture specific [11, 12, 13]. These patterns often correspond with findings from other plastic fibers (such as PET or PP), where a volume percentage of 1–1.5% is frequently close to ideal for striking a balance between toughening and workability. However, few studies have thoroughly examined the ideal amount of recycled HDPE fibers in traditional concrete mixtures, especially with regard to the combination of mechanical and ultrasonic qualities. This study investigates the effects of varying HDPE fiber volume fractions on key concrete properties, aiming to determine the optimal dosage for enhancing the strength of compressive, flexural, and Impact while addressing potential issues related to workability and fiber dispersion.

Materials and methods

The binder used in all mixtures was Ordinary Portland Cement (OPC), conforming to the CEM I 42.5R classification. For mixing and curing, drinkable water devoid of harmful chemicals was used. The aggregate was made by combining two different kinds of fine aggregate. The first was sand that came from the Misurata region. Its absorption ratio was 0.355%. An aggregate of Italian gravelly marble with an absorption rate of 2.02% and a specific weight of 2.63. Both types conform to the grain gradation curve given in the Libyan Specification for Fine Aggregates [14]. The mixing rates for the two aggregate types were 60% sand and 40% gravel. In this investigation, recycled HDPE fibers, sourced from manufacturing waste, were employed in this study.

The waste material underwent a process of size classification and manual cutting to produce fibers with average dimensions of 40 mm in length, 3 mm in width, and 1.8 mm in thickness. The fibers of polyethylene are seen in (Figure 1). The study relied on an experimental program consisting of four concrete mixes containing varying amounts of HDPE fibers based on their particle gradation. The mixing ratios of the materials were used according to the volumetric equation to create the mixes. Three HDPE fiber-reinforced concrete mixes with volume fractions of 1.0% (F1), 1.5% (F1.5), and 2.0% (F2) were evaluated, along with a reference mix (R0). The components of the different mixtures are shown in (Table 1).

The materials, which included three beams measuring 100x100x500 mm, six 100 mm cubes, and two 150 mm diameter cylinders with a height of 300 mm, were manufactured in the necessary quantities for each mix. In order to perform an impact test, the cylinders were later sliced to a height of 60 mm. After carefully mixing the materials while they were dry, water was added, and the mixtures were blended until a workable concrete mix was achieved, with all mixes producing a 70 mm slump. After the mixing process was completed and the slump test was conducted, the fresh concrete was poured directly into the molds and compacted, eliminating any air trapped within the concrete. Samples were placed at laboratory temperature for 24 hours without any external influences. The samples were numbered, the molds were taken out the following day, and they were submerged in water tanks to cure prior to testing.



Figure 1. Polyethylene fibers used in mixtures

Table 1. Concrete mix components in kg/m³

Mix	Contents			
	Cement	Water	Aggregate	HDPE fiber
R0	350	183.67	1200	0.00
F1	350	183.67	1200	3.13
F1.5	350	186.04	1200	4.69
F2	350	187.75	1200	6.25

Experimental program

Compressive, impact, ultrasonic, and flexural strength tests were conducted on hardened concrete, and density was calculated to determine the role of polyethylene fibers at 1.0%, 1.5%, and 2.0% levels on these properties. For each blend, the following were measured:

Compressive Strength

The measurement of compressive strength at 7 and 28 days is a standard practice for concrete and cementitious materials. These two time points provide critical, yet different, insights into the material's performance. The significance of the 28-day strength is universally regarded as the reference and specified strength of concrete. On the seventh day, the compressive test was performed after three cube samples were taken out of the water treatment. The remaining three cube samples were taken out on the twenty-eighth day to perform the compressive test after measuring the density and UPV on them. For the test, a machine from the AUTOTEST firm was utilized.

Ultrasonic The UPV test findings depend on how quickly sound waves travel through concrete. The test was performed on cubic samples using the direct technique at 28 days of curing, which was done prior to the compressive strength test, at a distance of 100 mm between the transmitter and receiver. (Figure 2) illustrates the UPV device and test setup.

Pulse Velocity UPV



Fig. 2. Ultrasonic Pulse Velocity test device and setting

Density

The density of hardened concrete is essential characteristic since it indicates the material's strength and cohesiveness following the completion of the curing process. After being removed from the water on the twenty-eighth day and dried, the concrete cubes were used to measure the density prior to the completion of the compressive strength test.

Impact resistance

The aggregate impact value test device in accordance with the British Standard [15] was developed to accommodate a cylindrical specimen of 150 mm in diameter and 60 mm in height. In compliance with the ACI committee [16], A drop-weight test was performed to assess FRC's impact resistance under dynamic loading. A 61 mm diameter steel ball, encircled by a ring that permitted vertical movement and restricted horizontal movement. The sample was structured by a 4.54 kg weight that was repeatedly dropped from 310 mm above the ground. The schematic and the test setup of the impact apparatus in operation are shown in (Figure 3). The apparatus was used to determine the impact strength of concrete by counting the number of blows required to produce the first apparent crack.

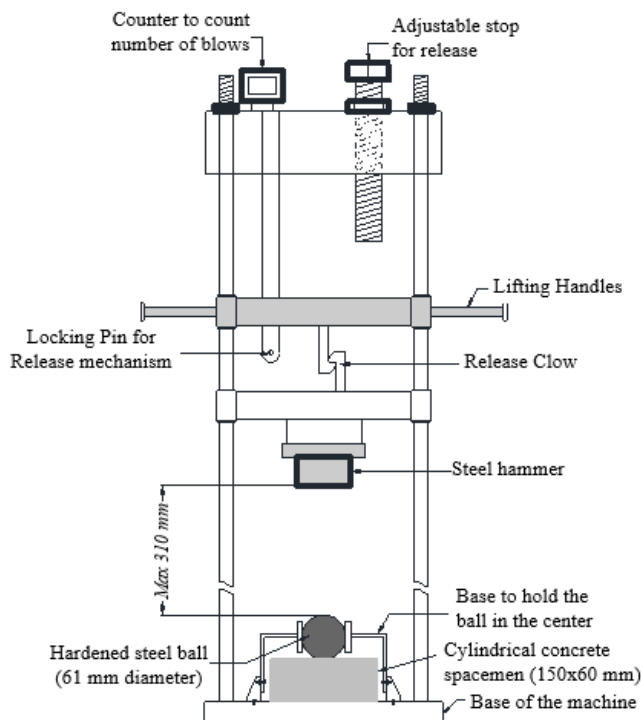


Fig. 3 Impact test device, Schematic, and setup

Flexural strength

Third point loading, often known as nominal, is a measure of flexural strength. The test was carried out using a machine from the AUTOTEST firm. The test was conducted to evaluate the concrete behavior under flexural loads and crack resistance for all mixes after 28 days. The comparative analysis focuses on the effect of fiber volume fraction while controlling for other variables, even if exact fiber geometry, aspect ratio, and mix proportions influence absolute results.

Results and discussion

The experimental results for the fiber-reinforced mixes (F1, F1.5, F2) are presented and compared against the baseline performance of the plain concrete control mix (R0). Key parameters such as workability, density, UPV, compressive strength, flexural strength, and Impact resistance are analyzed and discussed. The discussion interprets these results in the context of fiber-matrix interactions, focusing on how the different fiber percentages influence crack-bridging mechanisms, post-cracking ductility, and overall structural integrity. (Table 2) shows the properties of all the mixes that resulted.

Table 2. The results of the mechanical properties

Mix	Density (Kg/m ³)	Compressive strength (MPa)		UPV (km/s)	Impact (blows)	Flexural (MPa)
		7d	28d			
R0	2309	28.0	33.2	4.38	2	3.92
F1	2308	27.6	34.4	4.39	3	4.06
F1.5	2305	27.5	34.7	4.42	4	4.18
F2	2294	27.4	36.4	4.41	3	3.85

Fresh Concrete (workability)

After the mixing process, a slump test was performed on all mixes to determine the workability of fresh concrete. The quantity of slump for each mix was set at 70 mm. This step in workability stabilization focuses on the comparison of the amount of change in the percentage of fiber addition, without considering other criteria, such as the increase in water to the mixture.

Density of concrete

The density of hardened concrete is an essential property since it shows the material's cohesion and hardness once the hardening process is finished. The test's concrete cube's edges are 100 mm. The concrete mix density results in (Table 2) show a slight and continuous decrease with the addition of HDPE fibers. The density of the reference mix (R0) was 2309 kg/m³, gradually decreasing to 2294 kg/m³ for the mix containing 2% fibers (F2). This decrease is expected because the lower specific gravity of the polymeric HDPE fibers compared to the cementitious mix introduces lighter components into the mix, reducing the overall density.

Ultrasound Pulse Velocity Test

The velocity at which sound waves travel through concrete determines the results of ultrasonic testing. After 28 days, the test was carried out using the direct approach, with the transmitter and receiver placed 100 mm apart. The UPV readings in (Table 2), which range from 4.38 km/s to 4.42 km/s and are a measure of the concrete's homogeneity and internal integrity, were continuously high for all mixtures. The fiber-reinforced mixtures' (especially F1.5) little rise in UPV indicates that there were no appreciable voids or flaws introduced by the fibers. Rather, they might have helped create a denser composite that permits sound waves to move a little more quickly by fostering a more cohesive and crack-resistant interior structure. However, in accordance with research demonstrating that, when w/b, compaction, and air content are regulated, polymer fibers at modest concentrations do not significantly alter wave speed, UPV varied within 1% across all blends specifically [11, 12].

Compressive Strength

In line with earlier research, the inclusion of HDPE fibers resulted in slight increases in 28-day compressive strength, most likely as a result of improving confinement under load and preventing the formation of microcracks [2, 3, 4]. The findings were predictable in (Table 2), which illustrates the concrete's compression strength values both seven and twenty-eight days after casting. The compressive strength results reveal a clear trend of improvement in the long-term (28-day) strength with increasing fiber content. The compressive strength value is shown in (Figure 4), and the error bars show the Standard Error of the Mean (SEM).

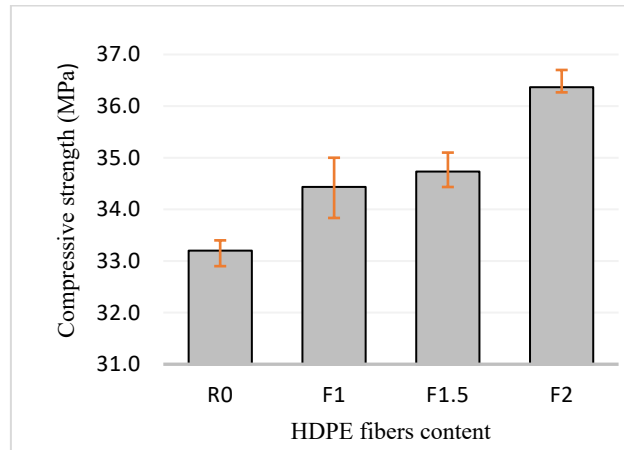


Fig. 4. Effect of fiber content on compressive strength

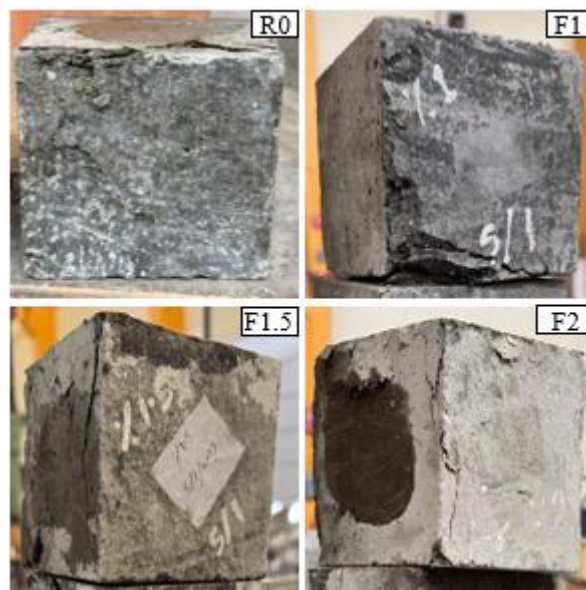


Fig. 5. Failure pattern of samples due to the compressive test

All HDPE-reinforced mixes showed a slight drop in compressive strength after seven days when compared to the control mix. This initial decrease may be explained by a small amount of air entrainment or a small amount of fiber-induced interference with early-age cement hydration. However, after 28 days, a new pattern appeared, where all of the fiber-containing specimens outperformed the plain concrete in strength, reversing the previous trend. The improvement is attributed to the cementitious matrix's fibers' capacity to bridge and arrest cracks, which enhances stress distribution and reduces crack propagation under compressive loads. The strength of all fiber-reinforced mixes exceeded that of the control mix (33.2 MPa). For F1, F1.5, and F2, the strength increased gradually by 3.6, 4.5, and 9.6%, respectively.

The rise in compressive strength in HDPE fibers in mixes aligns with the results of polypropylene fibers in concrete in a study by [17], although the rate of increase is not the same, as compressive strength increases with the dose up to 1.5% by 19.79%. However, the size of the fiber differs between HDPE and standard PP fiber, influencing the strength behavior. The fibers' capacity to restrict and bridge microcracks that form under compressive pressure is responsible for this improvement, which enables the matrix to support greater loads. The steady increase in fiber of up to 2% indicates that improved crack arrest either prevented or controlled any loss of workability. However, compressive strength is not the primary benefit of polymer fibers and is highly sensitive to mixture details [4, 7]. The overall pattern seen in the specimens due to the compressive test in (Figure 5) indicates that adding polyethylene fibers (from 1% to 2%) significantly alters the concrete's failure mechanism. It was changed from a brittle failure (R0) with severe spalling to a more ductile and contained failure (F1.5, F2) with improved crack control and possibly higher residual strength. By keeping the concrete matrix together, the fibers stop the instantaneous and total disintegration that occurs when unreinforced concrete is compressed. This is a typical and anticipated result of concrete fiber reinforcement.

Impact resistance and flexural behavior

The most evident benefits are seen in toughness assessments. Impact resistance and flexural strength both

peak at approximately 1.5% fibers, which is consistent with literature showing optimal doses for standard concretes in the 0.75–1.5% range [4, 6]. Generally, a practical optimum is reached when there are enough fibers to fill in fractures without sacrificing the matrix's integrity. The results in (Table 2) show that the use of HDPE fiber significantly improves impact resistance. After just two blows, the reference concrete (R0) broke brittlely. This was raised to three blows with the addition of 1% fibers (F1), and it was 100% improved to four blows with the F1.5 combination. This demonstrates how well the fibers absorb energy and fill in cracks. The F2 mix's minor decline to three blows can be attributed to the competing mechanisms governing fiber-reinforced concrete. At lower fiber contents (up to 1.5%), the increase in fibers improves crack-bridging efficiency, delays crack propagation, and enhances energy dissipation capacity, resulting in higher impact resistance. However, beyond the optimal content (2.0%), fiber clustering, poor dispersion, and increased void content lead to weaker interfacial bonding and stress concentrations. These effects reduce the efficiency of stress transfer and crack-bridging, thereby decreasing the overall energy absorption capacity.

In (Figure 6), the brittle and catastrophic breakdown (R0) leads to a more flexible and energy-absorbing failure phase, which is evident in finer fracture patterns at F1, F1.5, and F2. Toughness and resistance to spalling and disintegration under impact are greatly enhanced by the fibers' efficient inhibition of fracture development and distribution of impact energy. Increasing the HDPE fiber percentage from 1.0% to 2.0% gradually enhances crack management and energy absorption ability, according to the trend. To accurately measure crack width, a high-resolution image of the surface cracks was captured using a Digi Micro Mobile (dnt) camera with a 100×500 magnification, 12-megapixel. By analyzing the crack widths of the samples, (Figure 7) shows the deference cracks width from the widest to the narrowest crack widths in the specimens. In reference to concrete mixes R0, once a crack appears, it widens rapidly, leading to failure. However, when HDPE fibers are added at a rate of 1.5% (the optimal percentage in the last analyses), the fibers act as mechanical bridges across the crack. Instead of the crack becoming a single, wide one, the fibers force the concrete to form very fine, multiple micro-cracks.

The result is a significant reduction in the width of each crack. Comparing the results, which showed an increase in the number of blows of impacts from 2 to 4 at a 1.5% concentration, we find a direct correlation with the crack width, as each crack is narrower than the others. In the post-cracking stage, the fibers prevent the crack from widening suddenly, a phenomenon known as toughness. At a 2% concentration, the strength decreases because the fiber clustering creates weak pathways, allowing the crack to widen more rapidly due to the presence of voids. To explain this behavior of the crack width structurally, before the addition of fibers, the crack width increases linearly with increasing load until failure, and after the addition of HDPE, strain hardening behavior appears, where the fibers continue to resist crack widening even after exceeding the maximum tensile stress of the concrete.

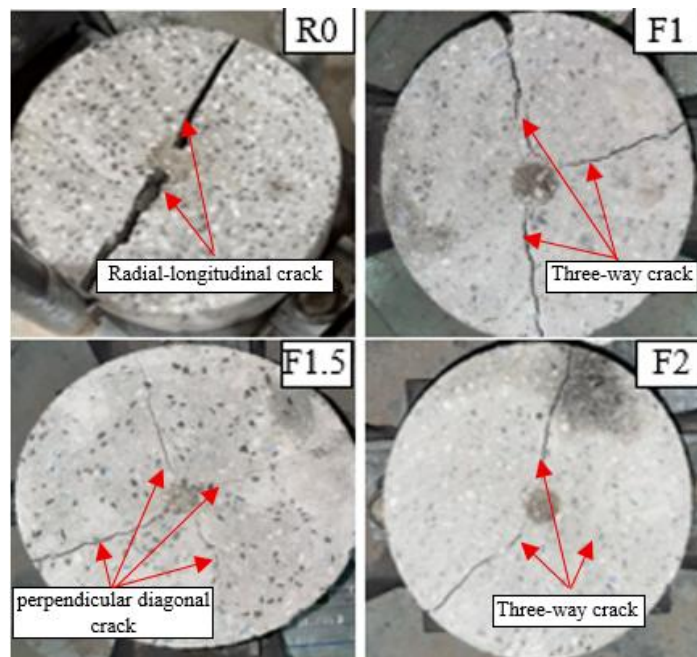


Fig. 6 Failure pattern of samples due to Impact test



Fig. 7. The widest and narrowest crack widths of the samples due to the impact test

Flexural strength

Referring to the results in (Table 2), flexural strength was increased from 3.92 MPa (R0) to a peak of 4.18 MPa at 1.5% fibers (F1.5). The fibers were shown to be useful in bridging cracks and enhancing tensile performance. Strength dropped to 3.85 MPa at 2% fibers (F2), though, suggesting that this greater dose is above the ideal level and will probably result in fiber balling and lower mix homogeneity. The 4.18% boost at 1.5% of the recycled HDPE fibers utilized in this work highlights their potential as a low-cost alternative to regular polypropylene fibers, due to their high tensile capacity, which improves flexural strength by up to 3%, according to Bhagwat et al. [18]. The concrete beams' flexural failure in (Figure 8) mode is significantly changed by the inclusion of polyethylene fibers. The fiber-reinforced specimens (F1, F1.5, F2) undergo a change from a brittle, catastrophic failure in the reference specimen (R0) to a more ductile, controlled failure.



Fig. 8 Failure pattern of samples due to the flexural test

By filling up the fractures on the tension face and keeping the beam from separating entirely, the fibers serve as crack arrestors, greatly increasing the concrete's toughness and residual strength. In general, ductility and post-cracking energy absorption increase when the fiber content rises from 1.0% to 2.0%. Recycled HDPE fibers offer a sustainable and cost-effective alternative to commercial Polypropylene (PP)

fibers, which are specifically designed for concrete reinforcement. However, the slightly lower flexural strength observed at higher dosages (2%) compared to PP can be attributed to the smooth surface texture of HDPE, which affects the mechanical bond with the cement matrix.

Microstructural and Mechanical Correlation

The testing results showed a strategic relationship between the concrete's mechanical reaction at the 2.0% HDPE fiber dosage and its internal structure. This enhanced micro-porosity and possible (fiber balling) impact are responsible for the synchronized fall in flexural strength and UPV values, as in (Figure 9). Entrapped air and a weaker Interfacial Transition Zone (ITZ) result from the difficulty in attaining uniform dispersion as fiber content approaches 2.0%. These internal flaws lower the UPV by acting as barriers to ultrasonic waves. They also operate as sites of failure initiation under flexural stress, where the cement matrix's ability to adhere to the hydrophobic HDPE surface is weakened. On the other hand, with the same dosage of 2.0%, the compressive strength kept rising.

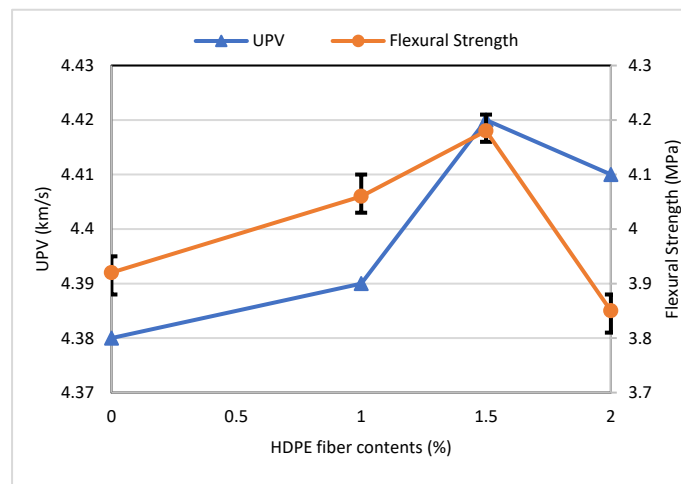


Fig. 9. The relationship between flexural strength and UPV (vertical) and the HDPE content (horizontal)

The stitching effect that the fibers provide explains this divergence; even in the presence of small holes in the matrix, the HDPE fibers function as lateral connections under axial compression, preventing the concrete's transverse expansion (confining effect). Compressive loading 'closes' micro-defects, enabling the fibers to efficiently contribute to the load-bearing capacity, whereas flexural loading 'opens' cracks and reveals bond flaws. Because it offers the optimal balance between matrix uniformity (high UPV) and overall mechanical performance, 1.5% is determined to be the ideal dosage.

Conclusions

The conclusion of the study demonstrates that incorporating High-Density Polyethylene (HDPE) fibers into concrete mixes has measurable effects on mechanical performance, with outcomes varying according to fiber dosage. At early ages (7 days), strength changes were minimal, but by 28 days, compressive strength increased by nearly 10% compared to the reference mix, indicating long-term benefits of fiber reinforcement. Ultrasonic pulse velocity (UPV) remained stable across all mixes, suggesting that bulk density and continuity were unaffected, and that improvements were primarily due to fracture bridging. Impact resistance and flexural strength reached their peak at 1.5% fiber content, after which performance declined at 2.0%, consistent with dispersion and workability challenges at higher dosages. Overall, the results indicate that an HDPE fiber content of 1.0–1.5% by volume provides the most balanced enhancement, improving flexural strength and impact resistance without compromising workability. Although a 2.0% dosage yielded the highest compressive strength, the associated reduction in toughness-related parameters and potential placement difficulties suggest that exceeding the 1.5% threshold is not optimal for applications requiring crack control and energy absorption. Future research should expand the performance profile by quantifying workability through slump and rheological testing, measuring air content, and reporting fiber geometry and surface treatment. Durability studies—including freeze–thaw resistance and permeability—are also recommended to establish the long-term suitability of HDPE fiber-reinforced concrete in diverse environmental conditions.

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Conflict of interest. Nil

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