Mechanical Properties of Sustainable Concrete Reinforced with Micro Steel Fibers

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Received: 27 June 2025 | Revised: 25 July 2025 and 4 August 2025 | Accepted: 14 August 2025

DOI: https://doi.org/10.48084/etasr.12928

ABSTRACT

One of the most important solutions for producing sustainable concrete is the utilization of old concrete as coarse aggregate. This study evaluates the full replacement of coarse aggregate with recycled aggregate and the impact of micro steel fibers on the mechanical properties of concrete using a combination of non-destructive and destructive tests. The deployed methodology includes five concrete mixes incorporating 0%, 0.4%, 0.6%, 0.8%, and 1% micro steel fibers by volume to produce sustainable concrete reinforced with fibers. The non-destructive tests examined density, Ultrasonic Pulse Velocity (UPV), and dynamic modulus of elasticity, while the destructive tests examined compressive strength, static modulus of elasticity, splitting tensile strength, and flexural strength. The results demonstrate the possibility of adopting zero-cost coarse aggregate produced from old concrete as a sustainable aggregate. Furthermore, the mechanical properties of concrete are enhanced by adding micro steel fibers. The optimal performance was observed at 0.8 % fibers with maximum improvements of 15 % in compressive strength, 39.2 % in splitting tensile strength, and approximately 85 % in flexural strength at 28 % days. The UPV and density values exhibited strong correlations with the compressive strength. Finally, the findings of this study support that the recycled aggregate and micro steel fibers can be used to produce sustainable concrete for modern constructions.

Keywords-compressive strength; concrete mixture; flexural strength; micro-steel fibers; tensile strength

I. INTRODUCTION

Concrete, a highly utilized construction material, has significantly contributed to the global civilization progress owing to the lower cost of production, good durability, wide availability, and ability to withstand severe weather conditions. Concrete has found application in a diverse array of structures, including residential buildings, skyscrapers, bridges, pavements, and dams. Besides the traditional components of concrete; cement, sand, and aggregate, mineral admixtures along with chemical admixtures are increasingly being added to enhance the concrete quality. While concrete exhibits a significant strength in compression, its ability to withstand tensile stress is limited. It has lower toughness, particularly in terms of its capacity to absorb energy, under both compressive and tensile loads. Additionally, under dynamic and impact loading, it exhibits significant cracking and brittle failure leading to a complete deterioration in the loading capacity once the failure initiates, which greatly limits its use and applications [1-3]. To overcome these limitations, Plain Concrete (PC) is reinforced using different reinforcing materials, such as steel (bars or fibers), polymer, or other composite materials.

Fiber Reinforced Concrete (FRC) has gained significant popularity in the construction industry due to its ability to deal with challenges related to excessive loads, bending, shear, dynamic loads, and impact. Several types of fibers are used in concrete, such as steel fibers, glass fibers, polypropylene fibers, and organic fibers [4–6]. However, the steel fibers have experienced growing acceptance in the construction of pavements, bridges, airports, and parking areas owing to their widespread applicability, which results in improving the structural performance of the construction. Adding steel fibers to the concrete leads to significant enhancements in the split tensile strength, compressive strength, flexural strength, shear strength, and bond strength [7]. Authors in [8-10] confirmed improvements in compressive and flexural strengths through the use of hooked-end or double-hooked steel fibers, particularly in sustainable and recycled aggregate concrete. Authors in [11] noted a small reduction in compressive strength, despite the improvements in tensile strength and shrinkage behavior. Authors in [12] emphasized the dependence of mechanical enhancements on fiber volume fractions. Authors in [13, 14] demonstrated that steel fibers, compared to other fiber types, significantly enhanced the tensile strength and modulus of elasticity in fiber-reinforced and geopolymer concretes. The static and dynamic moduli of elasticity were also enhanced with the integration of steel fibers by restricting the initiation and propagation of micro-cracks, leading to increased stiffness and energy absorption. It has been shown that the dynamic modulus of elasticity becomes higher than the static modulus due to the rapid stress application, which restricts the time-dependent deformations [15]. Furthermore, the fiber content and its distribution play a significant role, as higher fiber volumes typically result in improved behavior under both static and dynamic loading conditions [16]. These enhancements make Steel Fiber Reinforced Concrete (SFRC) particularly suitable for structures subjected to dynamic loads, such as pavements, bridges, and seismic structures. Authors in [17] reported a 29% increase in the modulus of elasticity with 1% fiber content, while authors in [18] observed increases ranging from 0.6% to 12.8%, with fiber volumes between 1% and 3%. However, authors in [19] highlighted that the influence of steel fibers on elasticity can be negligible, indicating that the impact depends mostly on the fiber type, volume fraction, and matrix composition.

Fatigue resistance and crack resistance position SFRC as a crucial advancement in modern concrete technology. This improvement enables its application in a wide range of structural applications, with or without traditional internal reinforcement bars. Authors in [20] reported that straight, low-cost steel fibers enhanced the impact resistance and ductility, with optimal results being achieved at a 1.25% fiber content. Authors in [21] observed increased flexural fatigue life and energy dissipation in SFRC, although the performance declined under high-cycle fatigue conditions. Authors in [22] demonstrated that the electromagnetic alignment of steel fibers in the cementitious matrix improved the fracture performance by over 80% compared to randomly oriented fibers, emphasizing the critical role of the fiber orientation and distribution in enhancing the mechanical durability. SFRC exhibits enhanced mechanical properties due to the ability of the steel fiber to bridge the cracks and improve the load transfer within the matrix. Non-destructive tests, particularly the UPV test, enable the comprehensive assessment of the quality, uniformity and integrity of concrete without causing any damage to the concrete itself. They measure the speed of the ultrasonic waves through the concrete, providing insights into the density and internal defects. Typically, the inclusion of steel fiber results in increased UPV values due to the increased matrix density and a reduction in the voids and micro-cracks. However, an excessive fiber content can scatter the ultrasonic waves and introduce local heterogeneities, potentially reducing the UPV values [23]. Authors in [24] reported that the UPV values increased with fiber additions of up to 2% by volume, but declined beyond this threshold. Authors in [25] utilized UPV to assess high-strength micro SFRC exposed to elevated temperatures, successfully predicting the compressive strength degradation. Similarly, in [26], it was found that the optimum fiber content for maximizing the concrete performance was 0.75%, and that the direct UPV testing was the most reliable method. Authors in [27] further demonstrated that the influence of steel fibers on the UPV values depends largely on the fiber dosage and the inherent strength of the concrete, with variations observed at 7, 28, and 90 days of curing.

Despite the research on SFRC, the studies specifically focusing on using micro steel fibers in normal concrete remain limited. Authors in [28] investigated varying micro steel fiber ratios in high-strength lightweight self-compacting concrete, observing increased flexural and splitting strengths with higher fiber contents, although the compressive strength declined. Authors in [29] examined the hybridization of macro and micro steel fibers in Ultra-High-Performance Concrete (UHPC), reporting improvements in the bond strength for straight fibers, but reduced performance for hooked and twisted fibers, highlighting the complex relationship between the fiber type, replacement ratio, and mechanical behavior. Authors in [30] studied fiber-reinforced concrete with ultra-high-strength micro fibers under active confinement, concluding that both the confining pressure and fiber volume significantly enhanced then axial strength and peak strain. Authors in [31] demonstrated that incorporating nano-silica with micro steel fibers in fly ash-based geopolymer composites resulted in a denser matrix and improved the mechanical performance. Authors in [32] reported that hybrid mortars containing 0.75% micro steel fibers and 3% basalt fibers achieved the highest compressive strength when incorporating silica fume. While micro steel fibers have a minimal impact on the compressive strength of UHPC mixes, they significantly enhance the splitting tensile and flexural strengths when combined with an optimal nano-silica content [33].

Drawing from the extensive previous research, the utilization of micro steel fibers in concrete has attracted significant attention due to their potential to enhance the mechanical properties and durability of concrete structures. The present study focuses on evaluating the performance of micro SFRC using a combination of destructive and non-destructive testing methods. While destructive tests, such as compressive strength, splitting tensile strength, and flexural tensile strength, provide direct insights into the structural performance, non-destructive methods, including UPV and density assessments, provide valuable information on the internal quality without compromising its integrity. By integrating these testing approaches, the current research aims to comprehensively assess the influence of varying micro steel fiber contents on the mechanical properties of normal concrete.

II. MATERIALS AND MIX PROPORTIONS

A. *Material Properties*

Ordinary Portland Cement (OPC) type I was used in this study, which conforms to the Iraqi specification No. 5/2019 [34]. The water used in the concrete mixes was drinking water. The fine aggregate was natural sand with a maximum size of 4.75 mm, meeting the requirements of the Iraqi specification No. 45/202 1 [35]. Recycled coarse aggregate from old normal concrete was utilized and then crushed to a maximum size of 20 mm, as shown in Figure 1, which meets the requirements specified in Iraqi Specification No. 45/2021 [35]. High-tensile micro-steel fibers with 13 mm length, 0.2 mm diameter, and an aspect ratio of 65 were used in this study. Figure 2 provides a photographic representation of the utilized micro steel fibers. To improve the flowability, superplasticizer, specifically SikaViscoCete-PC 20, was used with a dosage of 3.5 L per 100 kg of cement.

Fig. 1. Recycled coarse aggregate.

B. *Mix Proportion*

The concrete mixes were designed for a target compressive strength of 30 MPa at 28 days using the British Research Establishment (BRE) method, in alignment with the typical structural requirements for recycled aggregate concrete. The mix proportion was 1:1.3: by weight (Cement: Sand: Coarse aggregate), with 0.45 water to cement ratio (*W/C*) to achieve the required workability of a 60 mm ∓ 5 mm slump. The micro steel fibers were added with four different volume fractions that represent a range frequently used in practical applications. All concrete mixes were prepared with identical proportions: 430 kg/m^3 cement, 559 kg/m^3 sand, 1118 kg/m^3 recycled coarse aggregate, and 4.3 L/m^3 superplasticizer. Micro steel fibers were added at varying volume fractions of 0%, 0.4%, 0.6%, 0.8%, and 1% in mixes M0 to M4, respectively.

Fig. 2. Micro steel fibers used in the study.

The mixing process was carried out using an electrically operated mechanical mixer, as portrayed in Figure 3. First, the dry ingredients, consisting of cement, sand and gravel, were mixed at a high speed for 2 min. Then the micro steel fibers were added gradually to the dry mix to avoid the balling or clumping at a moderate speed.

Fig. 3. Electrically operated mechanical mixer.

During the mixing process, the micro steel fibers dispersed randomly through the mixture. After that, the required amount of water and superplasticizer was added. Finally, the concrete was mixed at a low to moderate speed for about 3-5 min until the mix was uniform and workable. The mixture was visually inspected to ensure that the steel fibers were not clustered or sticking together. At the end, the mixtures underwent a standard curing process, which involved immersing them in water in a controlled environment at room temperature.

III. TESTING METHODS

The mechanical property tests (destructive and non-destructive) were performed on five concrete mixes, utilizing three specimens per test at the age of 28 days. Cubical specimens of 150 mm were used to determine the dry bulk density, the ultrasonic velocity pulse, and the compressive strength in accordance with ASTM C642 [36], ASTM C597 [37], and BS EN 12390-3 [38], respectively. Cylindrical specimens with dimensions of 100 mm × 300 mm were used to determine the dynamic modulus of elasticity, based on ASTM C215 [39], employing the impact resonance method. The static modulus of elasticity was determined using the uniaxial compression test; the chord–modulus method was used as proposed by ASTM C469 [40], and the splitting tensile strength test of the concrete conforming to the ASTM C496/C496M [41]. The flexural strength test was conducted using prism specimens with dimensions of 100 mm × 100 mm × 400 mm, complying with ASTM C78/C78M [42].

IV. RESULTS AND DISCUSSION

The experimental results are presented in Table I. The primary parameters evaluated during the study include the density, UPV, compressive strength, dynamic modulus, static modulus, splitting tensile strength, and flexural strength.

A. *Density Test*

The dry density for all concrete mixes is presented in Table I. As seen in Figure 4, the density of the concrete reinforced with fibers increases progressively with the inclusion of micro steel fibers, reaching its peak at 2367 kg/m^3 for M3 (0.8 % fiber content). This increase can be ascribed to the role of micro steel fibers in enhancing the matrix compaction by reducing the voids and improving the aggregate interlocking. However, at 1% fiber content (M4), a slight decrease to 2356 kg/m^3 is noted, likely due to fiber clustering, which can introduce micro voids and reduce the packing efficiency of the mix, which is consistent with the findings in [43].

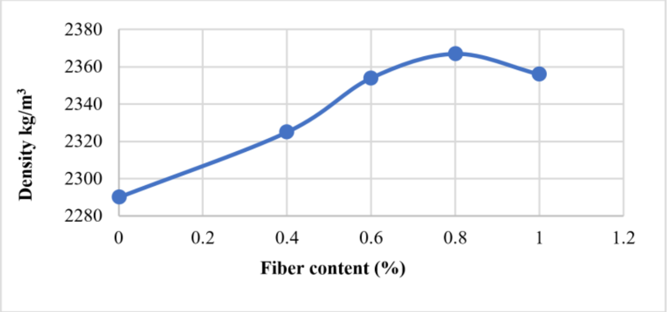

Fig. 4. Relationship between density and steel fiber ratio.

B. *UPV Test*

Figures 5 and 6 illustrate the correlation between UPV and two fundamental properties of concrete: compressive strength and density for concrete mixes containing different ratios of micro steel fibers after 28 days of curing. The control mix recorded a UPV of 4430 m/s, while the velocity reached 4690 m/s for M3 (0.8 % fiber content), and was even higher for the mix with more than 0.8 % fiber content (M4). It can be seen that there is a slight decrease in the pulse velocity due to the irregular clumping of fibers, which affected the homogeneity of the concrete. However, the fibers contributed to controlling the microcracks and improving the stress distribution under compression, resulting in a more uniform and compact matrix. Finally, these results show a behavior similar to that reported in [26, 27, 44]. Figure 7 displays the process of conducting a UPV test.

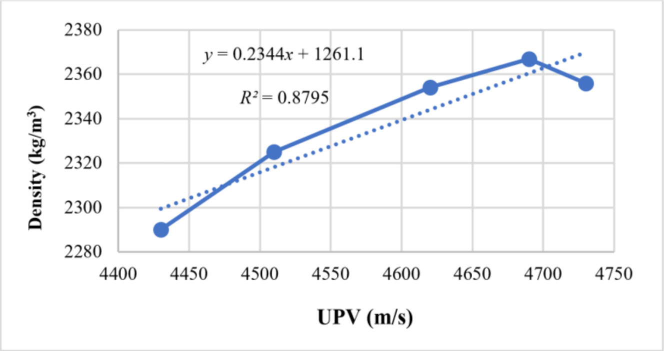

Fig. 5. Relationship between density and UPV of concrete reinforced with steel fibers.

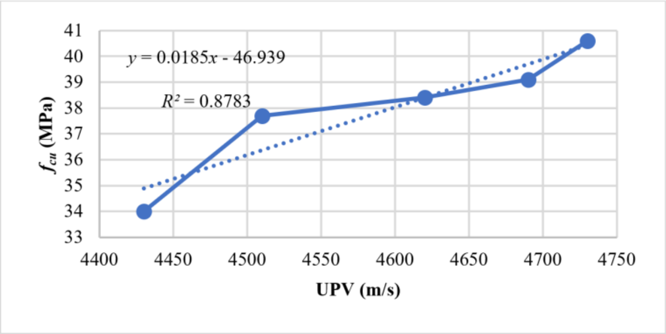

Fig. 6. Relationship between compressive strength and UPV of concrete reinforced with steel fibers.

C. *Compressive Strength Test*

The results of the compressive strength test for all concrete mixes at the age of 28 days are illustrated in Table I and Figure 8. The control mix (M0) had a compressive strength of 34 MPa, while M1, M2, M3, and M4 demonstrated improvements of 10.8%, 12.9%, 15%, and 13.2%, respectively, compared with M0. The optimum ratio of micro steel fibers was 0.8 %. This significant increase in compressive strength can be attributed to the crack-bridging effect of the micro steel fibers, which enhances the confinement and delays the crack propagation under compressive loads, complying with the findings of [45-47]. Authors in [9] also observed similar improvements in compressive and flexural strengths of recycled aggregate concrete by incorporating steel fibers.

TABLE I. TEST RESULTS OF THE CONCRETE MIXES

Mixes	**Density (kg/m^3)**	**UPV (m/s)**	**Compressive strength (MPa)**	**Dynamic modulus (GPa)**	**Static modulus (GPa)**	**Splitting strength (MPa)**	**Flexural strength (MPa)**
M0	2290	4430	34.0	23.7	23.4	2.8	3.3
M1	2325	4510	37.7	24.2	23.9	3.0	3.9
M2	2354	4620	38.4	24.9	24.8	3.4	5.2
M3	2367	4690	39.1	26.4	26.1	3.9	6.1
M4	2356	4630	38.5	26.3	25.2	3.7	5.8

Fig. 7. Conduction of UPV test.

While the peak strength was achieved at 0.8% fiber content, a slight reduction was observed at 1%. This is likely due to the decreased workability and fiber clustering, which negatively affected the fiber dispersion and created weak zones in the concrete matrix. This behavior is consistent with the findings of [24, 27, 48], which suggest that an excessive fiber content may lead to fiber clustering, reduced matrix uniformity, and stress concentration effects. Authors in [28] also noted a similar compressive strength decline, reporting approximately a 7% reduction in compressive strength when the steel fiber content increased from 0.5% to 1.25%. The failure of a concrete cube after the compressive strength test is shown in Figure 9.

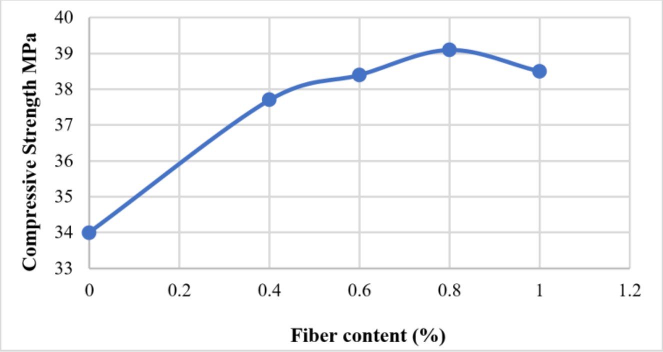

Fig. 8. The relationships between the compressive strength and steel fiber ratios.

Fig. 9. Crushed concrete cube after the compressive strength test.

D. *Static and Dynamic Test*

The static and dynamic moduli of elasticity exhibit positive correlations with the fiber content, as demonstrated in Figure 10. The dynamic modulus rises from 23.4 GPa (M0) to 26.4 GPa (M3), reflecting a maximum improvement of 11.3 %. Similarly, the static modulus rises from 23.7 GPa to 26.1 GPa with maximum improvements of 11.5 % compared with M0. Figure 11 illustrates the relationship between the static and dynamic moduli of elasticity of concrete mixes containing different ratios of steel fibers. Previous research [13] suggests that the fiber reinforcement enhances the stiffness and resistance to deformation under loading, additionally authors in [17] noted that the incorporating of steel fibers can increase the modulus of elasticity by up to 29%, which supports the trends observed in the current study. Finally, the inclusion of fibers improves both the static and dynamic responses, making concrete reinforced more suitable for applications requiring high stiffness and structural integrity. Figure 12 displays the results of the static and dynamic modulus of elasticity tests.

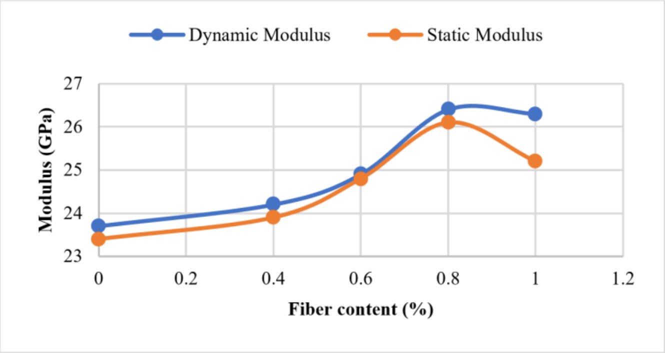

Fig. 10. Relationship between the static and dynamic modulus of elasticity of concrete and the steel fiber ratio.

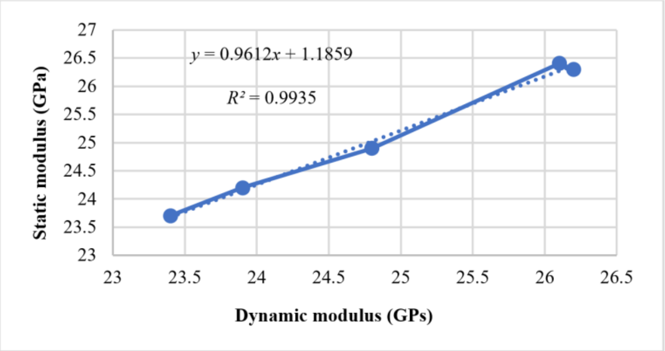

Fig. 11. Relationship between static and dynamic modulus of elasticity of concrete mixes containing different ratios of steel fibers.

(a) (b)

Fig. 12. (a) Static modulus of elasticity tests, (b) dynamic modulus of elasticity tests.

E. Splitting Tensile Strength Test

The splitting tensile strength results of concrete mixes at the age of 28 days are shown in Table I and Figure 13. The inclusion of fibers significantly improves the tensile resistance of concrete. The control mix (M0) records a strength of 2.8 MPa, peaking at 3.9 MPa for M3 (0.8% fiber content), indicating a 39.2 % improvement. Micro steel fibers act as bridges across these cracks under impact loading, effectively bearing tensile stresses and maintaining the bond between the two sides of the crack. Consequently, the appearance of the first crack was delayed, and failure was postponed for several impact blows. These findings are consistent with those of [49], where a 28.5% and 17.1% improvement in splitting tensile strength was reported for medium and high-strength concrete specimens, respectively, with the addition of 2 % steel fibers. However, the results show a slight reduction in the splitting strength from 1% to 3.7 MPa. This is likely due to the fiber agglomeration and decreased workability at higher volumes, which may impair the fiber distribution and reduce the effective stress transfer [48]. Figure 14 displays the splitting tensile strength test.

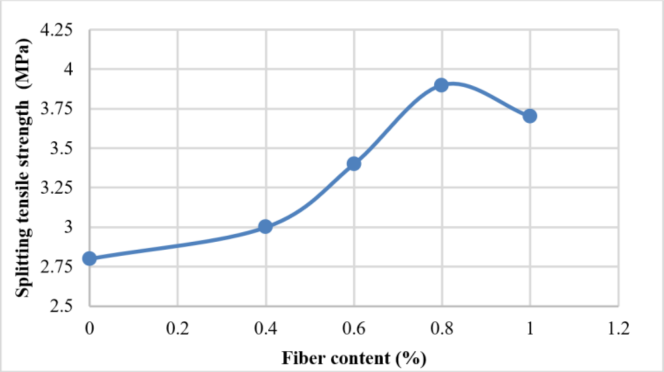

Fig. 13. Relationship between the splitting tensile strength and the steel fiber ratio.

Fig. 14. Splitting tensile strength test.

F. Flexural Strength Test

The flexural strength results of the concrete mixes at the age of 28 days are displayed in Table I and Figure 15. The control mix (M0) had a flexural strength of 3.3 MPa. In comparison, the mixes M1, M2, M3, and M4 demonstrated improvement with ratios of 18.1%, 57.5%, 84.8%, and 75.7%, respectively, compared with M0. This significant increase can be attributed to the enhanced post crack load bearing capacity. The ideal ratio of micro steel fibers was determined to be 0.8 %. These results are consistent with the findings in [46, 50, 51].

However, there was a minor reduction at 1 % fiber content (M4), where the flexural strength decreased to 5.8 MPa. An excessive fiber content may create inconsistencies in fiber distribution, leading to local stress imbalances. Figure 16 presents the flexural strength test.

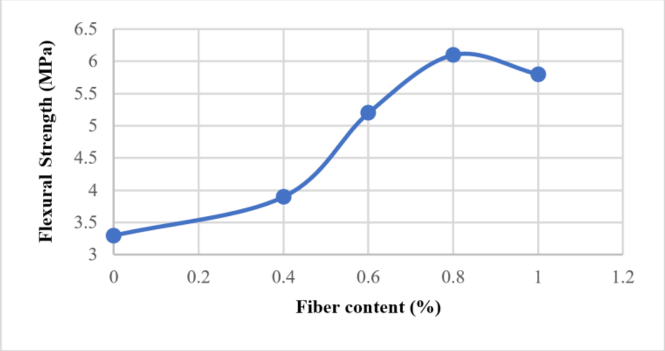

Fig. 15. Relationship between flexural strength and steel fibers ratios.

Fig. 16. Flexural strength test.

V. CONCLUSIONS

The combined analysis of both the destructive and non-destructive testing results shows that the micro steel fibers enhance the mechanical properties of sustainable concrete and improve its internal integrity and homogeneity. The Ultrasonic Pulse Velocity (UPV) testing proves to be a valuable non-destructive method to predict the compressive strength, assess the crack resistance, and evaluate the overall quality of micro Steel Fiber-Reinforced Concrete (SFRC). An optimal fiber content of 0.8% achieves a balance between the mechanical performance and material integrity, serving as a reliable guide for practical applications. Based on the results and analyses, the following conclusions are drawn:

- The results indicate the possibility of adopting zero-cost coarse aggregate produced from old concrete as a sustainable aggregate for producing concrete reinforced with micro steel fibers.
- The inclusion of micro-steel fibers resulted in significant improvements in compressive strength, with maximum increments observed at 0.8 % fiber content, representing a 15 % enhancement over the control mix. This finding aligns with the UPV results, where the highest velocity was recorded at the same fiber content, indicating a more compact and uniform concrete matrix with fewer internal defects. The positive correlation between the compressive strength and UPV demonstrates that UPV effectively predicts the compressive strength in fiber-reinforced concrete.
- The incorporation of micro-steel fibers improved both the static and dynamic moduli of elasticity, with an optimal performance observed at a fiber content of 0.8%. The relationship between the enhanced dynamic modulus and higher UPV values indicates better stiffness and crack resistance under cyclic and impact loading. Since the dynamic modulus relies on the wave propagation, the strong correlation between the UPV and the dynamic modulus confirms the efficiency of UPV in assessing the concrete stiffness.
- The maximum splitting tensile strength was achieved at 0.8% fiber content, showing a 39.2 % improvement.
- The flexural strength significantly improved with the inclusion of fibers, reaching an 84.8 % at 0.8% fiber content. This improvement aligns with the observed increase in concrete density up to 0.8 % fiber content, as denser concrete typically exhibits greater flexural strength. The slight decrease in flexural strength and density beyond 0.8 % suggests a potential issue of fiber agglomeration.

ACKNOWLEDGMENT

The authors express their gratitude to Mustansiriyah University, Baghdad, Iraq, for supporting this work.

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