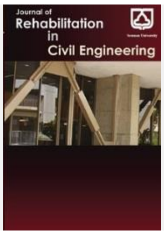

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Mechanical and Fracture Properties of Hybrid Fiber-Reinforced Concrete with Variable Recycled Aggregate Content

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ABSTRACT

Rapid urban development has significantly increased construction waste, contributing to the depletion of natural resources and environmental degradation. As a result, the use of recycled aggregates has gained global attention as a sustainable alternative in construction materials. In the current study, experimental tests were performed on 72 samples where the coarse normal aggregate was replaced by 0%, 25% and 50% by volume with coarse recycled aggregate. Furthermore, the test samples comprised four types of specimens with Polypropylene fibers (PP) and steel fibers, including with no fibers, with 0.4% PP and 0% steel fibers, with 0.4% PP and 0.5% steel fibers, and with 0.4% PP and 1.0% steel fibers, wherein all ratios are volumetric. This study investigated the energy absorption and ductility of notched recycled concrete beams reinforced with hybrid combinations of polypropylene and steel fibers under three-point bending tests. The results were validated using analysis of variance (ANOVA). Findings demonstrated that polypropylene fibers contributed to homogenizing stress distribution by delaying micro-crack initiation, while steel fibers enhanced pull-out resistance and bridged macro-cracks, synergistically improving the energy absorption capacity. However, increasing the recycled aggregate content generally led to a reduction in fracture energy, attributed to the weaker residual cement paste and damage induced during aggregate processing.

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1. Introduction

Rapid urbanization and the frequent occurrence of natural disasters such as earthquakes and floods have significantly increased the volume of construction and demolition waste worldwide [1–4]. In addition to environmental concerns, the high costs of waste disposal, low degradability of construction materials, and the substantial CO_2 emissions from cement production have intensified the need for sustainable waste management practices[5,6]. Recycled aggregates, derived from demolished structures, present an eco-friendly alternative to natural aggregates and contribute to reducing landfill burden and conserving natural resources [7,8].

Previous research on the use of recycled aggregates in concrete production generally agrees that partial replacement of natural aggregates (typically up to 30% by volume) does not significantly affect the physical and mechanical properties of the resulting concrete [9–12]. Knaack et al [13]. reported that while increasing recycled aggregates beyond 50% by volume leads to reduction in tensile strength and elastic modulus, it also increases shrinkage. However, a critical review of the literature reveals varying results depending on mix design, water-cement ratio, and the quality of the recycled aggregate used. Some studies overlook the long-term durability or fracture performance of these concretes, focusing mostly on compressive strength.

Among these, polypropylene (PP) fibers have gained attention due to their low cost, light weight, and ease of dispersion in the concrete matrix [14,15]. While Catal et al [15]. found no significant improvement in compressive strength due to PP fiber inclusion, Ahmad et al. [16]identified an optimal fiber content of 0.39% by volume for enhancing the performance of recycled aggregate concrete. In parallel, studies on steel fibers show a more consistent enhancement in both strength and ductility. Avanaki et al. reported a 15% average increase in compressive strength with 0.5% steel fiber addition, and other researchers confirmed that steel fibers contribute significantly to tensile, flexural, and shear capacities while also reducing crack propagation [17]. Fakharian et al [18,19]. applied AI models (GMDH-NN, GMDH-Combi, and MLR) to predict the compressive strength of RCA concrete, showing that GMDH-Combi achieved the highest accuracy, and their analysis included ANOVA-based evaluation to identify the most influential factors.

Existing studies mainly fall into two categorized: those on the mechanical behavior of recycled aggregate concrete (RAC) without fibers, and those examining the effects of single or hybrid fibers. The latter underscores the need for further research on fracture behavior, which remains insufficiently explored.

Recent studies have extensively investigated the influence of fiber reinforcement on the mechanical behavior of concrete, particularly in terms of flexural, tensile, and shear strength [20,21]. It is now well established that incorporating fibers, either as a single type or in hybrid combinations, can significantly improve concrete performance by controlling crack initiation and propagation. This enhancement is attributed to the fibers' ability to bridge cracks, distribute stresses more uniformly, and absorb fracture energy, thereby delaying crack development.

Furthermore, fiber reinforcement is known to markedly enhance the deformation capacity, toughness, and ductility of concrete materials [22,23]. Among various fiber types, steel fibers play a critical role by controlling micro-crack propagation and delaying the formation of macro-cracks, which in turn increases flexural stiffness and post-cracking load-bearing capacity [24,25]. This phenomenon is particularly beneficial under cyclic or dynamic loads such as seismic excitations, where multiple micro-cracking improves energy dissipation capacity and prevents sudden brittle failure.

In a broader context, fiber-reinforced concrete (FRC) has been increasingly applied in specialized engineering fields where enhanced mechanical performance is essential. Typical examples include load-bearing elements of high-rise buildings, bridge decks, tunnel linings, shell structures, seismic-resistant components, and industrial floors with high abrasion resistance [26].

Despite these improvements, a critical review of the literature reveals that the extent of mechanical enhancement strongly depends on several factors, including fiber type, dosage, aspect ratio, dispersion quality, and the compatibility of the fiber with the matrix, especially in recycled concrete where the interfacial transition zone (ITZ) is weaker than in conventional mixes. This highlights the importance of optimizing hybrid fiber combinations to compensate for the deficiencies introduced by recycled aggregates.

The initiation and propagation of cracks in concrete can occur due to several mechanisms. Shrinkage-induced microcracking often originates within the cement paste during the early stages of curing, primarily caused by moisture loss and volumetric contraction [27]. In contrast, cracks resulting from applied loading may propagate through the cement paste, aggregate particles, or more critically, through the ITZ, which is considered the weakest link in the composite matrix [28].

To quantify the fracture characteristics of concrete, various theoretical and numerical approaches have been developed, including the Griffith model, fictitious crack model, crack band model, J-integral, smeared crack model, size effect law, two-parameter fracture model, cohesive crack model, and Dugdale's approach[29]. Each of these methods has its specific applicability, depending on the material behavior, loading conditions, and computational complexity.

Recent studies have shown that the incorporation of fibers into concrete substantially improves its fracture parameters. For instance, the addition of steel, polyethylene (PE), and carbon fibers has been reported to significantly enhance initial fracture toughness, unstable fracture toughness, and total fracture energy (GF) One notable study indicated that multi-scale fiber-reinforced specimens exhibited up to 28.6 times higher unstable fracture toughness and 302 times greater fracture energy compared to control specimens[30]. Similarly, Gassan et al[31]., demonstrated that integrating 2% steel fibers by volume resulted in a tenfold increase in fracture energy. This enhancement is primarily attributed to the fiber bridging mechanism, which effectively dissipates energy and arrests crack growth.

While numerous studies confirm the positive influence of fiber reinforcement on fracture behavior, limited research has systematically evaluated the interaction between fiber type, and recycled aggregate content on fracture energy, especially under flexural loading. This underscores the necessity of more targeted investigations, such as the current study, which aims to fill this research gap.

This study experimentally investigates how coarse recycled aggregates and hybrid fiber reinforcement (polypropylene and steel) affect the fracture energy and mechanical properties of concrete. It aims to enhance toughness and ductility while promoting sustainability through reduced CO_2 emissions and reliance on natural resources.

2. Experimental program

In the current study, experimental tests were performed on 108 samples wherein the coarse normal aggregate was replaced by 0%, 25%, or 50% by volume with coarse recycled aggregate. Furthermore, the test samples comprised four types of specimens with polypropylene fibers (PP) and steel fibers, including with no fibers, with 0.4% PP and 0% steel fibers, with 0.4% PP and 0.5% steel fibers, and with 0.4% PP and 1.0% steel fibers, wherein all ratios are volumetric. These combinations are summarized in Table 1 representing a total number of tested specimens of 36.

Table 1. Test specimen matrix.

Specimen	Recycled aggregate (%)	PP fiber (%)	Steel fiber (%)	No. specimens tested
R0-P0-S0	0%	0.0%	0.0%	3
R25-P0-S0	25%	0.0%	0.0%	3
R50-P0-S0	50%	0.0%	0.0%	3
R0-P4-S0	0%	0.4%	0.0%	3
R0-P4-S0.5	0%	0.4%	0.5%	3
R0-P4-S1	0%	0.4%	1.0%	3
R25-P4-S0	25%	0.4%	0.0%	3
R25-P4-S0.5	25%	0.4%	0.5%	3
R25-P4-S1	25%	0.4%	1.0%	3
R50-P4-S0	50%	0.4%	0.0%	3
R50-P4-S0.5	50%	0.4%	0.5%	3
R50-P4-S1	50%	0.4%	1.0%	3
			Total	36

2.1. Materials

2.1.1. Cement

Ordinary Portland cement type II was used for this study and tested according to ASTM C150[32]. Tables 2 and 3 show the chemical and physical properties of this type of cement, respectively.

Table 1. Chemical specification of cement.

SiO_2	MgO	CaO	Al_2O_3	Fe_2O_3	SO_3
21.11%	1.37%	63.63%	4.48%	3.91%	2.58%

Table 3. Physical composition of cement.

Density (g/cm^3)	Specific surface (g/cm^2)	Compressive Strength (MPa)
3.1	3155	435

2.1.2. Fine aggregate

Natural sand was used as fine aggregate. Its maximum size was 4.75 mm, absorption was 3.75%, and specific gravity–based density (solid particles only) is 2543 $\left({}^{kg}/_{m^3}\right)$ were within the limits of ASTM C33[33]. The grading is shown in Figure 1.

2.1.3. Coarse aggregate

Recycled aggregate was used as coarse aggregate in the fiber reinforced concrete (FRC). Moreover, limestone aggregate was used as natural aggregate with a maximum dimension of 12 mm, and recycled aggregate was obtained from crushed concrete specimens with a strength of 35 MPa with a maximum dimension of 12 mm. This recycled coarse aggregates was crushed by a jaw crusher machine. The grading curves of natural and recycled aggregate are illustrated in Figure 1. In addition, max and min range of natural aggregates were obtained according to ASTM C33, and quantities of abrasion of coarse aggregates were calculated according to ASTM C131[34].

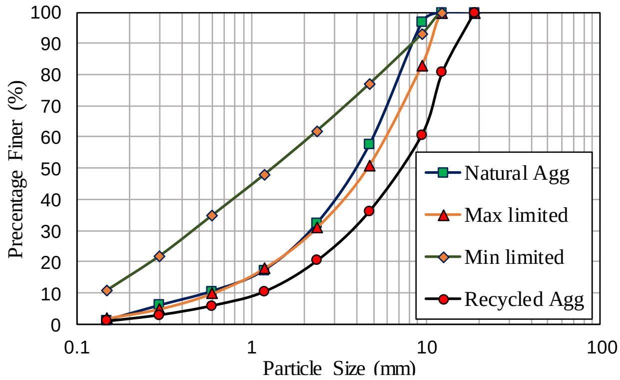


Fig 1. Grading of aggregate.

Natural aggregate has a higher density and lower water absorption than recycled aggregate, in addition, water absorption of recycled aggregate is about 3.6% higher than that of natural aggregate. The physical properties of the natural and recycled aggregates used in the test specimens are listed in Table 4.

Table 4. Physical properties of natural and recycled aggregate used in the test specimens.

Type of aggregate	Absorption (%)	Density (kg/m^3)	Abrasion (%)
Natural coarse aggregate	0.95	2611	24.18
Recycled coarse aggregate	4.5	2036	27.54
Natural sand	3.75	2543	-

2.1.4. Water

Potable water with 40 grams of lime per cubic meter was used for mixing and curing the specimens of concrete. Added water in mix proportion of specimens with 25% and 50% volumetric replacement of recycled aggregates was calculated based on water absorption of recycled aggregates. Mix proportion and water to cement ratios are listed in Table 5.

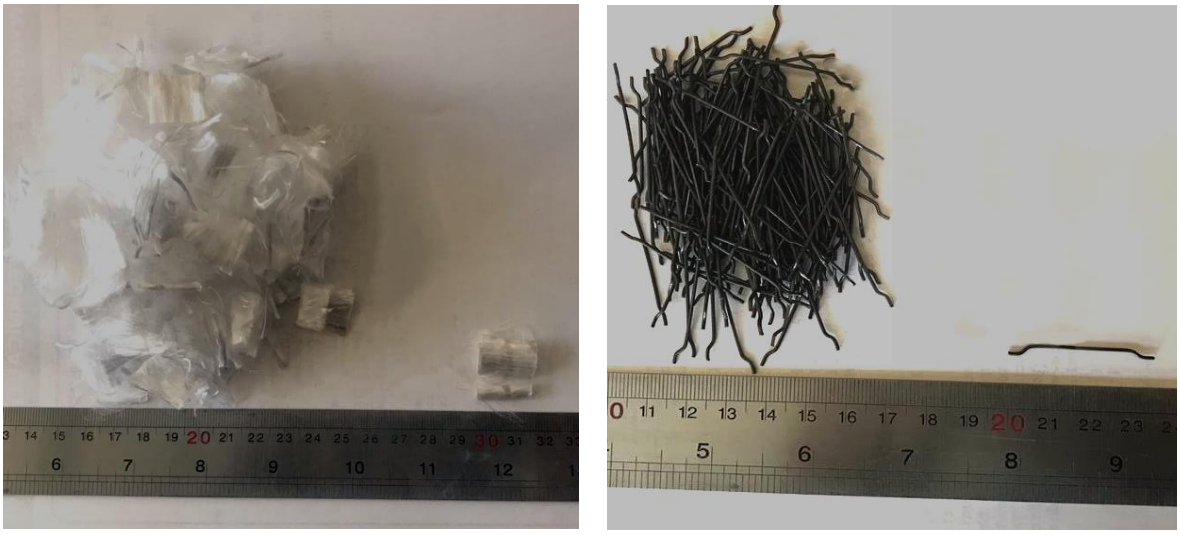
Table 5. Materials used for all concrete mixture.

Percentage of replacement	Water (kg/m^3)	Cement (kg/m^3)	W/C	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	PP (kg/m^3)	Steel (kg/m^3)
R0-P0-S0	185	400	0.46	850	800	0	0
R0-P4-S0	185	400	0.46	850	800	3.64	0
R0-P4-S0.5	185	400	0.46	850	800	3.64	39.25
R0-P4-S1	185	400	0.46	850	800	3.64	78.50
R25-P0-S0	189	400	0.46	850	800	0	0
R25-P4-S0	189	400	0.46	850	800	3.64	0
R25-P4-S0.5	189	400	0.46	850	800	3.64	39.25
R25-P4-S1	189	400	0.46	850	800	3.64	78.50
R50-P0-S0	193	400	0.46	850	800	0	0
R50-P4-S0	193	400	0.46	850	800	3.64	0
R50-P4-S0.5	193	400	0.46	850	800	3.64	39.25
R50-P4-S1	193	400	0.46	850	800	3.64	78.50

Specimens were identified by nomenclature representing the constituent materials. R represents “recycled aggregate” followed by the volumetric replacement percentage using recycled aggregates of 0%, 25% or 50%. P and S stands for “PP fiber” and “steel fiber”, respectively. For example, R50-P4-S1 indicates concrete containing 50% recycled aggregate, 0.4% PP fiber, and 1% steel fiber.

2.1.5. Fibers

The PP fibers are simple type and the steel fibers are hooked-end type (see Figure 2), respectively. The physical and mechanical characteristics of the PP fibers and steel fibers are presented in Table 6.



(a) (b)

Fig 2. a. PP fibers. b. steel fibers.

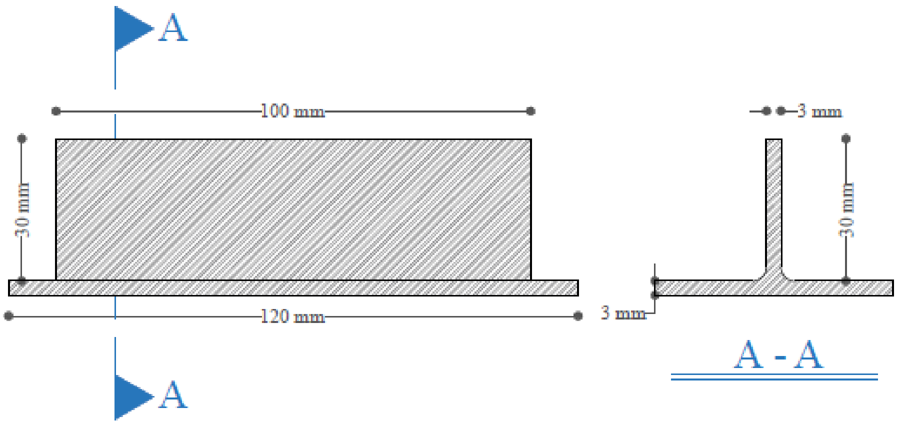
Table 6. Physical properties of steel & PP fibers.

Specification	PP fiber	Steel fiber
Density (g/cm^3)	0.91	7.85
Length (mm)	18	35
Diameter (mm)	0.2	0.8
Ratio of Length per Diameter (L/D)	90	43.75

2.2. Specimens

Cylindrical specimens with 100 x 200 mm dimensions were adopted for compressive tests. For the three-point bending tests, prismatic specimens with dimensions of 100 × 100 × 350 mm were cast. A steel T-profile, 30 mm in height and 3 mm in thickness, was used to form a notch in the concrete beams. The T-profile was inserted into the mold after pouring the concrete, positioned at the center of the bottom face, and oriented perpendicular to the longitudinal axis of the specimen, followed by vibration to ensure proper compaction. The vertical portion of the T-profile faced upward into the mold, ensuring that once the concrete had set, a notch would be formed exactly at mid-span. After curing, the steel insert was removed, resulting in a clean, well-defined notch on the tension face of the beam. This notch was intended to control crack initiation during flexural testing and to facilitate accurate measurement of fracture energy (see Figure 3).

(a)



(b)

Fig 3. a) molds, b) detail of notch piece.

2.3. Mixing, casting, and curing of specimens

To cast fiber reinforced concrete containing recycled aggregate, the coarse and fine aggregate were poured into a cylindrical mixer and mixed for two minutes. Then, the cement was slowly added to the mixer and mixed for two to three minutes. The mixing water was divided into two portions: the first was added during the initial mixing stage. Polypropylene and steel fibers were then gradually introduced by hand. Finally, the remaining water was added, and the mixture was blended for an additional three to five minutes to improve the uniformity and consistency of the mix. After casting the concrete, the slump of the fresh mix measured between 10 and 15 cm, and its temperature ranged from 26 °C to 28 °C, indicating acceptable workability and proper mixing conditions for fiber-reinforced recycled aggregate concrete. Figure 4 illustrates the procedure followed for casting and curing the concrete specimens.

(a) (b)

Fig 4. a) process of casting, b)Process of curing.

3. Result & discussion

3.1. Specific gravity

Specific gravity of fresh concrete is an important indicator regarding the consistency of the mix design and the uniformity of the concrete. Per ACI 544R [35], the specific gravity of FRC up to 2% by volume is similar to the specific gravity of normal concrete. Per ASTM C138 [36], Equation 1 can be used to calculate the specific gravity of fresh concrete.

$$T = \frac{m}{v} \tag{1}$$

T, M, and V represent the specific gravity, weight of concrete, and measured volume of the FRC specimens containing recycled aggregate, respectively. Specific gravity results are presented in Figure 5 for recycled aggregates concrete. The inclusion of 1% steel fibers increased the specific gravity of conventional specimens by 2%, attributable to the high density of steel fibers (Table 7). In contrast, the addition of 0.4% PP fibers and 0.5% steel fibers had a negligible impact on specific gravity due to their lower volumetric fraction. When replacing natural aggregate with recycled aggregate at 25% and 50%, the specific gravity of concrete decreased by 0.8% and 2.5%, respectively (Figure 5). This reduction stems from the accumulated porosity in recycled aggregates. Notably, the high specific gravity of steel fibers effectively counteracted the density loss in recycled concrete.

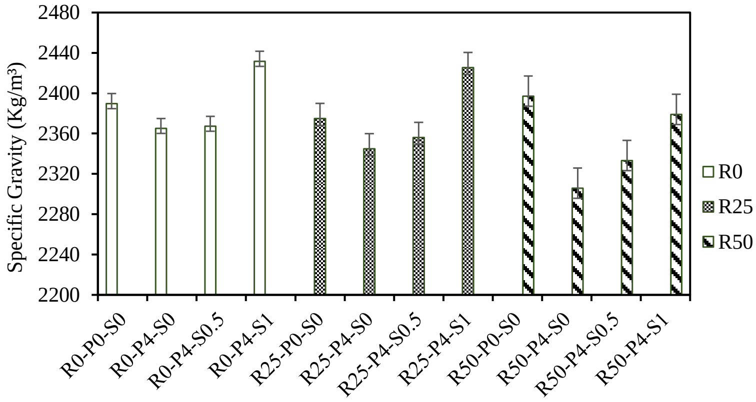


Fig 5. Effect of fiber volume fraction and recycled aggregate on specific gravity.

3.2. Compressive strength

The 28-day compressive strength of all concrete mixes decreased with increasing replacement levels of recycled aggregates. The compressive strength of the control concrete (without fibers and recycled aggregates) was measured at 36.29 MPa. However, increasing the recycled aggregate replacement to 25% and 50% resulted in reductions of 14.53% and 15.13%, respectively (see Figure 6). This decline is attributed to increased porosity and weakened adhesion within the Interfacial Transition Zone (ITZ) of the old cement paste. The minimal difference in compressive strength between the 25% and 50% replacement levels suggests that the primary deterioration occurs at lower replacement thresholds. Additionally, increasing the fiber content did not lead to improvements in compressive strength. In particular, mixes containing 1% steel fiber, 0.4% polypropylene fiber, and 50% recycled aggregate exhibited signs of the balling phenomenon, which hinders proper fiber dispersion and further contributes to strength reduction.

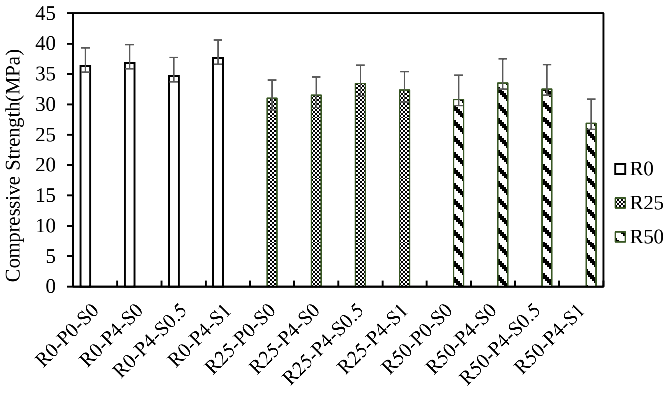
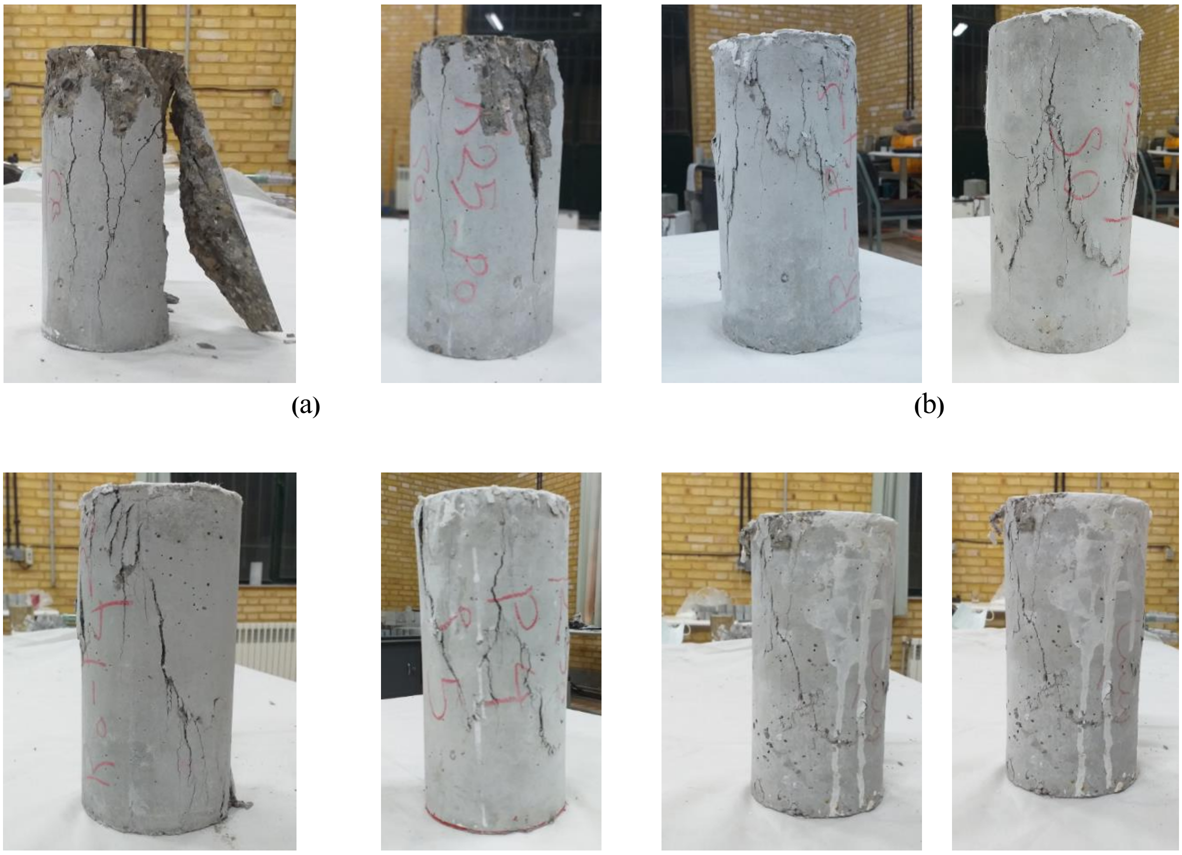


Fig 6. Effect of fiber volume ratio and recycled aggregate on compressive strength.



(a) (b)

(c) (d)

Fig 7. Failure pattern of compression cylinder specimens, a) without fibers, b) with 0.4% PP fibers and 0% steel fibers, c) with 0.4% PP fibers and 0.5% steel fibers, d) with 0.4% PP fibers and 1% steel fibers.

According to ASTM C39 [37], the created vertical cracks indicate an acceptable failure pattern under compressive load. Figure 7 shows the details of the failure pattern of compression cylinder specimens. In Fig. 7a, specimens under compressive load are exposed to local failure at the top and middle of the specimens and showed fewer but wider vertical cracks and occasional spalling, evidencing a brittle and localized failure.. Lateral tensile stress leads to longitudinal cracks, while at the bottom of the specimens, the magnitude of this stress is reduced. According to Fig. 7b, Using only PP fibers (0.4%) produced more numerous but narrower cracks, indicating partial control of microcracks while some continuous vertical cracks remained. In Fig. 7c, the presence of hybrid fibers (0.4% PP+0.5% steel) improves the post-peak response and prevents the growth of longitudinal cracks and promotes the formation and propagation of cracks at various angles. This change in crack orientation is due to the restraining effect of fibers, which disrupts the direct path of crack development. Additionally, incorporating 1% steel fibers along with 0.4% polypropylene (PP) fibers has a significant effect in reducing crack opening and enhancing post-cracking resistance (see Figure. 7d). This pattern reflects effective crack-bridging, steel fibers carrying macro-cracks and PP fibers controlling microcracks, and thus a clear shift from brittle to quasi-ductile failure with enhanced post-peak deformation capacity. Recycled aggregates tend to promote earlier localization and wider cracks due to weaker old-mortar interfaces; the fibers counteract this by restraining crack widening and fostering multiple cracking, especially in the hybrid configuration.

The comparison between fiber-reinforced and plain concrete specimens clearly demonstrates the role of fibers in altering the failure mechanism. While plain specimens exhibit sudden and brittle failure characterized by dominant longitudinal cracks, fiber-reinforced specimens show a more ductile behavior with multiple distributed cracks and delayed failure. This indicates that fibers not only control the crack width and propagation but also enhance energy absorption capacity. The combined use of steel fibers and polypropylene fibers provides synergistic effects by bridging cracks at different scales. Steel fibers enhance mechanical strength and toughness, while polypropylene fibers help reduce microcracking and control shrinkage at early ages. Overall, fiber reinforcement changes the failure mode from a localized brittle fracture to a more gradual and distributed damage process, thereby improving both the strength and durability of concrete under compressive loading.

The energy absorption of specimen (Toughness) containing 0.4% PP with 0.5% and 1.0% steel fibers is 3.17 and 4.08 times higher than the specimen containing 0.0% PP and 0.0% steel fibers, respectively (see Figure 8.a). Increasing the fiber percentage can prevent crack opening. The combination of PP and steel fibers enhances energy absorption through a synergistic effect. By replacing 25% and 50% volumetric replacement of recycled aggregate, the amount of energy absorption decreased by 21.7% and 26% on average compared to the control specimens, respectively (see Figures 8.b and 8.c). this information indicates that, increasing recycled aggregates replacement can lead to brittleness.

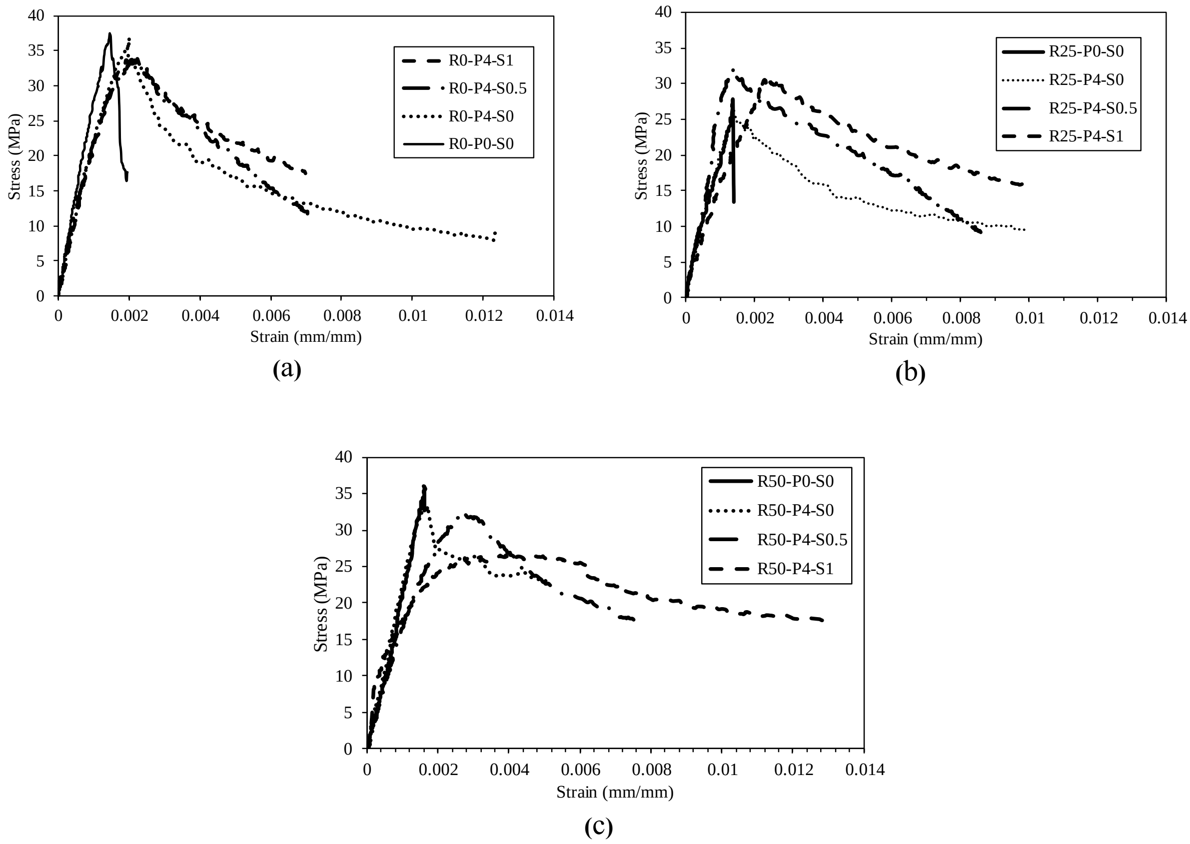


Fig 8. Stress-strain curve for FRC, a) without recycled aggregate, b) with 25% of recycled aggregate, c) with 50% of recycled aggregate

3.3. Flexural strength (three-point bending test)

The flexural strength concrete test evaluates the tensile strength of concrete indirectly, this test is performed both in three-point test. According to ASTM C1609 [38], the length of flexural specimens must be fifty millimeters greater than three times the height of the flexural specimen or at least 350 mm. Also, the height and width of the flexural specimens should be more than three times the length of the fibers. According to ASTM C1609, flexural specimens with dimensions of 350*100*100 mm are subjected to the three-point to investigate the mechanical behavior of FRC containing recycled aggregate. In the notched beam, A notch with a depth and thickness of 30 and 3 mm respectively, is created in the middle of the specimen. The notch is created to prevent cracking in the tensile area of the beam. Flexural specimens are loaded at speed of 0.075 mm/min, up to L/150 (2 mm). According to Figure 9, the effective length of specimen (L), amount of peak load (P_p), and P_{600}^{D}, P_{150}^{D}loads, corresponding to the displacement of L/600 and L/150, respectively, are presented in Table 7.

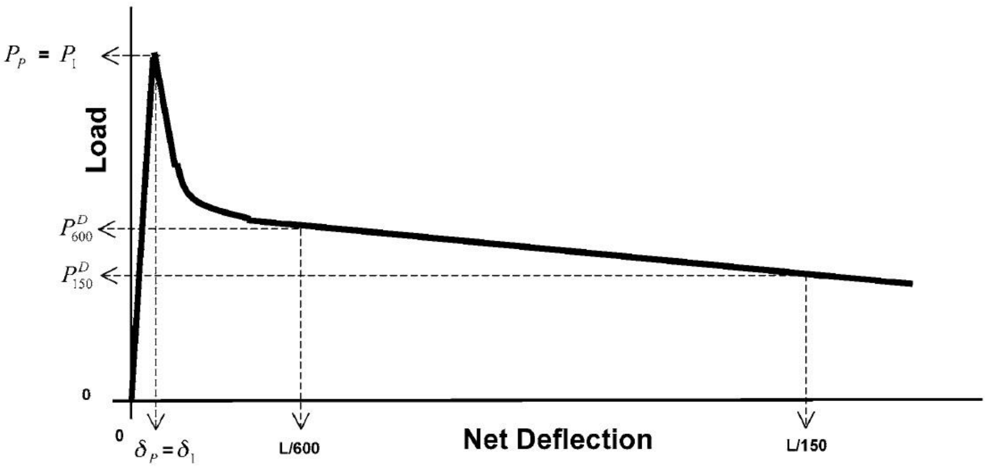
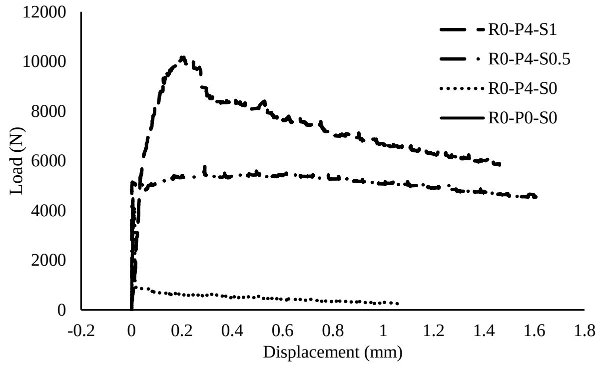


Fig 9. Load-deflection curve according to ASTM C1609.

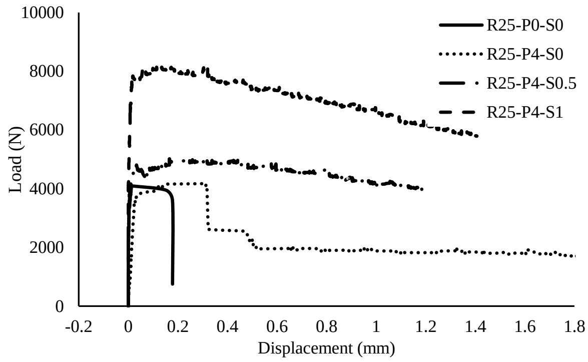
The peak load in three point bending tests of notched beams does not increase with the addition of 0.4% PP fibers alone. The notch creates a stress concentration that forces cracks to initiate and propagate from this specific point. As a result, PP fibers near the notch are often not optimally aligned to resist crack propagation. However, when combining 0.4% PP fibers with 0.5% steel fibers, the peak load increases by approximately 23%. These results demonstrate that the combination of PP and steel fibers creates a positive synergistic effect for resisting crack initiation at the notch tip (see table 7 and Fig 10). The applied load corresponding to L/300 shows that specimens with PP fibers alone exhibit brittle failure. In general, Hybrid fiber reinforcement mechanism is here, First, PP fibers homogenize stress distribution, delaying initial crack formation. then, steel fibers activate, providing pull-out resistance and effectively bridging macro-cracks. Fig 11 shows the test set-up for three point bending test.

Table 7. Result of applied load in beams under three-point loading test.

Specimens	Three-point loading test		
	P_p(N)	P_{600}^{D}(N)	P_{300}^{D}(N)
R0-P0-S0	4478	0	-
R0-P4-S0	4200	519	-
R0-P4-S0.5	5773	5447	4976
R0-P4-S1	10175	8116	6373
R25-P0-S0	4163	0	-
R25-P4-S0	4205	2193	-
R25-P4-S0.5	5022	4733	4029
R25-P4-S1	8144	7390	6146
R50-P0-S0	4701	0	-
R50-P4-S0	4537	1438	-
R50-P4-S0.5	5630	3778	3073
R50-P4-S1	5724	4849	4349



(a)



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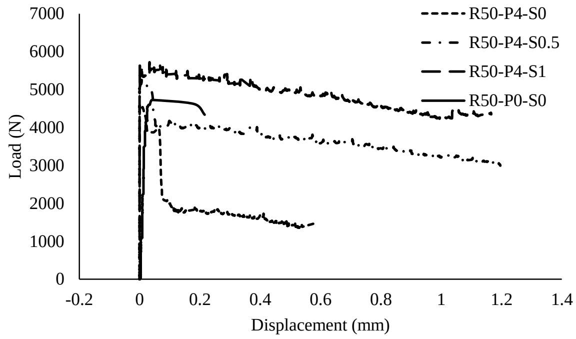


(c)

Fig 10. Load–Displacement curve, a) without recycled aggregate, b) with 25% of recycled aggregate, c) with 50% recycled aggregate.

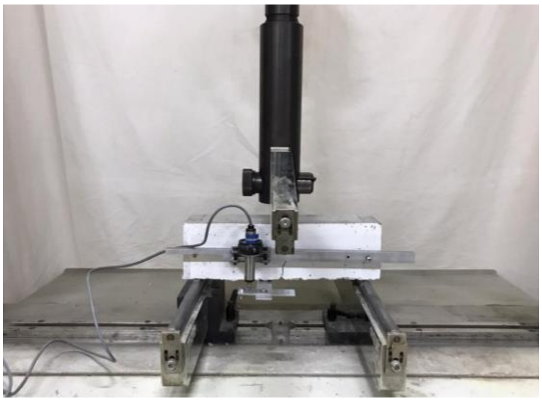


Fig 11. test set up for three-point bending test.

3.4. Fracture energy

The risk of fracture in metals and most material such as concrete due to crack growth is known as "fracture mechanics." Fracture mechanics can be a suitable method to calculating the tensile stiffness of concrete [28]. In General, two main methods are applied to calculate the fracture energy of cementitious base materials: the three-point loading test and the direct tensile test. In the three-point loading test, to calculate the amount of required energy to create a unit of crack, if the crack propagation path is correct and the absorbed energy by the crack propagation is in the correct direction. In this method, the amount of fracture energy is equal to the ratio of absorbed energy to the area of the cracked surface. The amount of energy input through the applied force must be equal to the amount of absorbed energy by the crack propagation.

To calculate the fracture energy in a three-point bending test as shown in Figure 12. The fracture energy can also be calculated according to Equations 2 and 3.

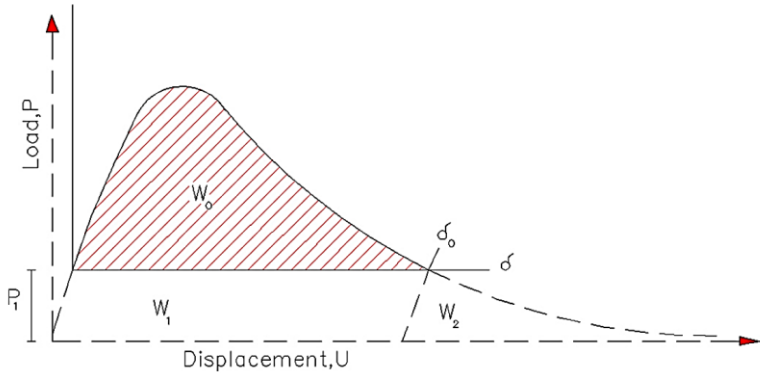


Fig 12. Load-deflection curve.

$$T_{300}^{D} = W = W_0 + W_1 + W_2 = \int_0^{l/300} P.\, d\delta \qquad (2)$$

$$G_f = \frac{w}{b(d-a)} \left({}^{J}\!/_{m^2} \right) \qquad (3)$$

$\boldsymbol{\delta_0}$ is the deflection, P is the applied force corresponding to the beam weight in the midspan, w is the surface area below the load-displacement diagram in 3 point bending, and 4 point bending test, b is the beam width, d is the depth of the beam and a is the depth of the notch.

Table 8. Test results of notched beams. The mean values of fracture energy.

Specimens	Three-point loading test		
	A (m^2)	T_{300}^{D}*(J)	G_f (J/m^2)
R0-P0-S0		0	0
R0-P4-S0		0.46	65.72
R0-P4-S0.5		6.53	932.85
R0-P4-S1		9.32	1331.42
R25-P0-S0		0	0
R25-P4-S0		2.94	420
R25-P4-S0.5	0.007	5.73	818.57
R25-P4-S1		8.94	1277.14
R50-P0-S0		0	0
R50-P4-S0		1.23	175.71
R50-P4-S0.5		4.42	631.4
R50-P4-S1		6.24	872.9

* Measured the area under curve up to 1.16 mm displacement

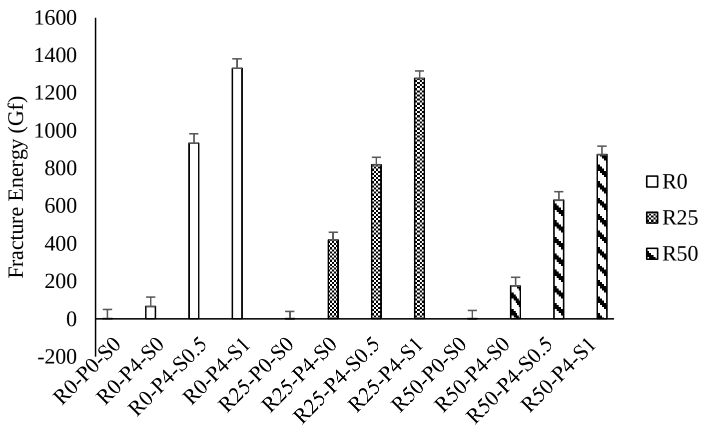


Fig 13. Effect of fiber volume ratio and recycled aggregate on fracture energy.

Energy absorption was measured up to a deflection of ($L/_{300} = 1.16\ mm$). PP fibers exhibited a negligible effect on increasing fracture energy, and the specimens remained relatively brittle, though they delayed crack widening. In the three-point bending test on specimens without recycled aggregates, the combination of 0.4% PP with 0.5% and 1% steel fibers increased fracture energy $\boldsymbol{G_f}$ by 14 and 20 times, respectively (see Table 8, Fig 13). This increase stems from the synergistic effect of PP fibers (which bridge micro-cracks) and steel fibers (which bridge macro-cracks and require more energy to pull out). Doubling the steel fiber content further enhanced post-crack ductility. Maximum fracture energy is reached 1331.42 (J/m^2) by combination 0.4% PP and 1% steel fibers (see Table 8, Fig 13). When the steel fiber content was further increased to 1%, the material transitioned from brittle to quasi-ductile behavior, significantly enhancing its energy absorption capacity through mechanisms such as fiber pull-out, crack bridging, and distributed damage.

Table 9. Two-way ANOVA results for fracture energy based on fiber content.

Source of Variation	S	df	MS (SS/df)	F-value	P-value	F-critical
Recycled aggregates replacement	284351	2	142175.5	37.11	4.5E-05	4.25
Steel Fiber	2557273	2	1278637	333.77	3.61E-09	4.25
Interaction	269596.3	4	67399	17.59	0.000278	3.63
Within	34477	9	3830.82			
Total	3145698	17				

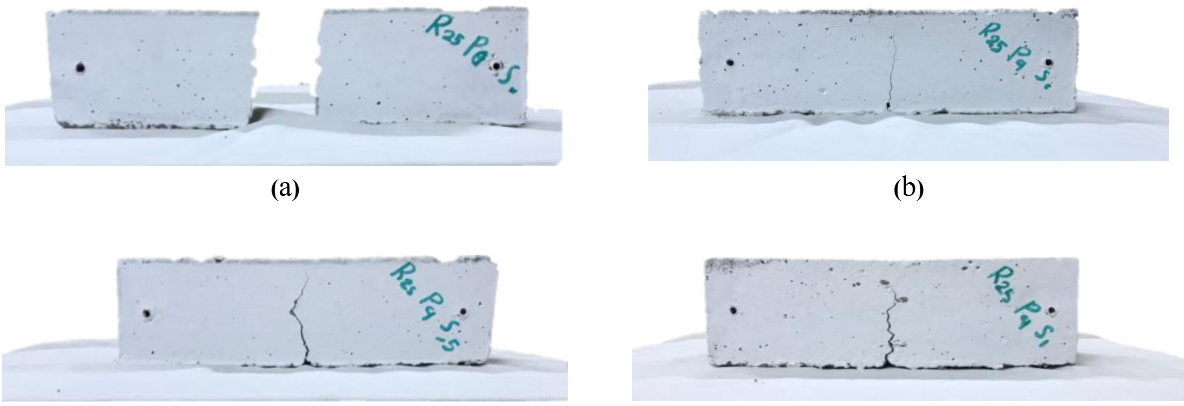
S (sum of squares) quantifies the total variation in the data, df (degrees of freedom) reflects the number of independent values that can vary, and MS (mean square) is calculated by dividing the sum of squares by its corresponding degrees of freedom. The F-value represents the ratio of variance between groups to variance within groups. F-critical is the threshold value obtained from the F-distribution table, which is used to determine statistical significance based on the degrees of freedom and the chosen significance level. The P-value indicates the probability of obtaining the observed results, or more extreme outcomes, assuming the null hypothesis is true. Statistical significance is typically concluded when p-value < 0.05 and F > F-critical.

A two-way ANOVA was performed to investigate the effects of recycled aggregate content (0%, 25%, 50%) and steel fiber percentage on the fracture energy of concrete. The analysis revealed that both recycled aggregate content ($F = 37.11$, $p = 4.5 \times 10^{-5}$) and steel fiber percentage ($F = 333.77$, $p = 3.61 \times 10^{-9}$) had statistically significant effects on fracture energy. Furthermore, the interaction between these two factors was significant ($F = 17.59$, $p = 2.78 \times 10^{-4}$), indicating that the effect of steel fibers on fracture energy varies depending on the recycled aggregate content. These results suggest that both factors, individually and synergistically, significantly influence the fracture energy of concrete (see Table 9).

(a) (b)

(c) (d)

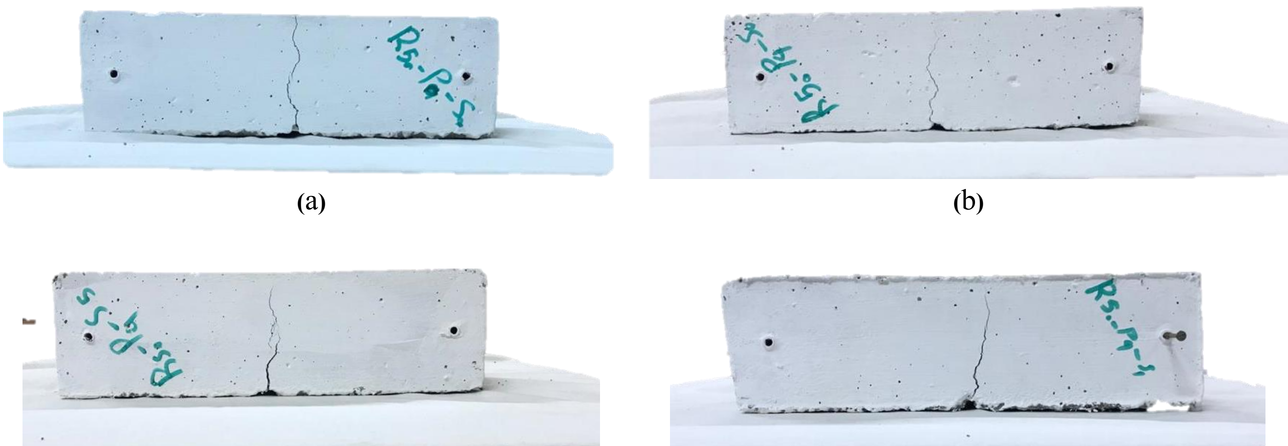
Fig 14. Failure pattern of notched beams with no recycled aggregates, a) without fibers, b) with 0.4% PP fibers and 0% of steel fibers, c) with 0.4% PP fibers and 0.5% of steel fibers, d) with 0.4% PP fibers and 1% of steel fibers.



(a) (b)

(c) (d)

Fig 15. Failure pattern of notched beams with 25% recycled aggregates, a) without fibers, b. with 0.4% PP fibers and 0% of steel fibers, c) with 0.4% PP fibers and 0.5% of steel fibers, d) with 0.4% PP fibers and 1% of steel fibers.



(a) (b)

(c) (d)

Fig 16. Failure pattern of notched beams with 25% recycled aggregates, a) without fibers, b) with 0.4% PP fibers and 0% of steel fibers, c) with 0.4% PP fibers and 0.5% of steel fibers, d) with 0.4% PP fibers and 1% of steel fibers.

Considering the presence of a notch helps to predict the path of crack propagation. In specimens without fibers, the failure mode is completely brittle. However, in notched beams reinforced with both steel and polypropylene (PP) fibers, the failure behavior changes significantly compared to that specimens without fibers. The addition of fibers, particularly the combination of steel and PP fibers, enhances resistance to crack propagation and prevents the rapid development of cracks. Although recycled aggregates can create weaker zones within the concrete matrix, their adverse effects are significantly reduced when used in combination with fibers. Under these conditions, failure occurs more gradually, with smaller and more widely distributed cracks, resulting in a more ductile structural response (see Figure 14-16).

3.5. The comparison between compressive strength and fracture energy

In recycled aggregate concrete specimens, the compressive strength and fracture energy are influenced by the type and dosage of fibers used. The addition of steel fibers leads to a moderate increase in compressive strength and a significant enhancement of fracture energy, as these fibers inhibit microcrack propagation and improve stress distribution; therefore, compressive strength has a direct relationship with fracture energy. According to Figures 6 and 13, by increasing the recycled aggregate content from 0% to 50% in specimens containing 0.4% PP and 0.5% steel fibers, the rate of decrease in compressive strength and energy absorption is reduced. Polypropylene (PP) fibers also contribute to a notable increase in fracture energy by reducing stress concentrations and controlling surface crack development, although their effect on compressive strength is limited. Therefore, combining recycled aggregates with both steel and PP fibers enables the development of concrete with optimized mechanical performance and fracture behavior.

4. Conclusions

In the current study, experimental tests were performed on 108 samples wherein the coarse normal aggregate was replaced by 0%, 25%, or 50% by volume with coarse recycled aggregate. Furthermore, the test samples comprised four types of specimens with polypropylene fibers (PP) and steel fibers, including with no fibers, with 0.4% PP and 0% steel fibers, with 0.4% PP and 0.5% steel fibers, and with 0.4% PP and 1.0% steel fibers, wherein all ratios are volumetric. These tests were carried out to investigate the mechanical behavior and energy absorption of concrete containing recycled aggregate with different fiber reinforcing ratios. The following conclusions may be drawn from the test program; The specific gravity of recycled aggregate concrete decreased by up to 2.5% with 50% aggregate replacement due to porosity but was offset by steel fibers (1%), which increased density by 2%. Fiber type and dosage significantly influence concrete density, with steel fibers effectively countering the lightweight nature of recycled aggregates.

Increasing recycled aggregate replacement (25% and 50%) reduced compressive strength by 15% due to porosity and weak ITZ, with most damage occurring at lower replacement levels. The addition of fibers did not restore the original strength but significantly improved the toughness of the concrete. The use of hybrid fibers, consisting of 0.4 % PP and 1% steel, increased energy absorption by up to four times. However, a higher content of recycled aggregates led to increased brittleness, reducing overall toughness by as much as 26%. While crack resistance improved with fiber inclusion, the potential for fiber balling limited the effectiveness of strength recovery.

The peak load in notched beams did not increase with 0.4% PP fibers alone due to stress concentration at the notch, limiting fiber effectiveness. However, combining 0.4% PP with 0.5% steel fibers increased peak load by 23%, demonstrating a synergistic effect. PP fibers delayed crack initiation, while steel fibers bridged macro-cracks, enhancing ductility. Specimens with only PP fibers failed brittlely under load. Hybrid reinforcement thus optimizes crack resistance through complementary mechanisms.

While PP fibers alone had minimal impact on fracture energy, combining them with steel fibers (0.4% PP + 1% steel) increased it 20-fold, reaching 1331.42 J/m². This synergy, with polypropylene fibers bridging microcracks and steel fibers resisting the propagation of larger cracks, shifted the failure behavior from brittle to quasi ductile. Increasing the steel fiber content further enhanced ductility by improving pullout resistance and crack bridging capacity.

Although the mix R0P4S1 exhibited the highest compressive strength, energy absorption, and density, the primary aim of this study was not only to maximize strength but also to evaluate the feasibility of using recycled concrete aggregates (RCA) as a sustainable alternative to natural aggregates. The use of RCA contributes to reducing construction waste, conserving natural resources, and promoting environmental sustainability. The results demonstrated that certain mixes containing RCA, especially when combined with supplementary materials, can achieve acceptable mechanical performance close to that of natural aggregate concrete. Therefore, depending on project priorities, whether maximizing strength or achieving sustainable construction, different mixes may be preferable.

Appendix

Table A1. Summary of compressive and splitting tensile strengths.

Specimens	Compressive	SD	CV
R0-P0-S0	36.29	0.35	11.67%
R0-P4-S0	36.84	0.70	23.33%
R0-P4-S0.5	34.71	0.31	10.33%
R0-P4-S1	37.6	0.18	6.00%
R25-P0-S0	31.02	0.13	4.28%
R25-P4-S0	31.5	0.36	11.84%
R25-P4-S0.5	33.45	0.40	13.17%
R25-P4-S1	32.37	0.46	15.17%
R50-P0-S0	30.8	0.28	9.46%
R50-P4-S0	33.5	0.43	14.45%
R50-P4-S0.5	32.53	0.32	10.61%
R50-P4-S1	26.88	0.52	17.58%

Note: SD = standard deviation; CV = coefficient of variation

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Sina Hosseini: Conceptualization, Methodology, Datacuration, Software, Writing - original draft, Investigation.

Jalil Shafaei: Supervision, Visualization, Investigation, Validation, Project administration, Writing – review & editing.

Farshid Jandaghi Alaee: Supervision, Visualization, Investigation, Validation, Project administration, Writing – review & editing.

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